LA-UR-12-01364

Approved for public release;
distribution is unlimited.

Title: CEM03.03 User Manual

Author(s): Stepan G. Mashnik and Arnold J. Sierk

Intended for: RSICC and the MCNP6 Code Package

Los Alamos
NATIONAL LABORATORY
EST. 1943

CEM03.03 User Manual

Stepan G. Mashnik[a] and Arnold J. Sierk[b],

Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

The Fortran 77 code CEM03.03 is an extended and improved version of the earlier codes CEM03.01 and CEM2k+GEM2, which are based in turn on their predecessor codes CEM2k, CEM97, CEM95, CEM92M, CEM92, and MARIAG, which implement versions of the **C**ascade-**E**xciton **M**odel (**CEM**) of nuclear reactions. CEM03.03 calculates total reaction and fission cross-sections, nuclear fissilities, excitation functions, nuclide distributions (yields) of all produced isotopes separately as well as their A- and Z-distributions, energy and angular spectra, double-differential cross-sections, mean multiplicities, i.e. the number of ejectiles per inelastic interaction of the projectile with the target, ejectile yields and their mean energies for n, p, d, t, ^3He, ^4He, π^+, π^-, and π^0. In addition, CEM03.03 provides in its output separately the yields of **F**orward (**F**) and **B**ackward (**B**) produced isotopes, their mean kinetic energies, A- and Z-distributions of the mean emission angle, their parallel velocities, and the F/B ratio of all products in the laboratory system, distributions of the mean angle between two fission fragments, of neutron multiplicity, of the excitation energy, of momentum and angular momentum, and of mass and charge numbers of residual nuclei after the INC and preequilibrium stages of reactions, as well as for fissioning nuclei before and after fission.

CEM03.03 calculates reactions induced by nucleons, pions, bremsstrahlung and monochromatic photons on not too light targets at incident energies from ∼10 MeV (∼ 30 MeV, in the case of $\gamma + A$) up to several GeV. This Manual describes the basic assumptions of the improved CEM as realized in the code CEM03.03, essential technical details of the code such as the description of the input and output files, and provides the user with necessary information for practical use of and for possible modification of the CEM03.03 output, if required.

The primary authors of CEM03.03 are: S. G. Mashnik[a] (LANL), K. K. Gudima[c] (IAP), and A. J. Sierk[b] (LANL); with important contributions from R. E. Prael[d] (LANL), M. I. Baznat[e] (IAP), and N. V. Mokhov[f] (Fermi National Accelerator Laboratory, Batavia, IL 60510, USA); (IAP = Institute of Applied Physics, Academy of Science of Moldova, Chişinău, Moldova).

[a]E-mail: mashnik@lanl.gov
[b]E-mail: t2ajs@lanl.gov
[c]E-mail: gudima@cc.acad.md
[d]E-mail: rep@lanl.gov
[e]E-mail: baznat@cc.acad.md
[f]E-mail: mokhov@fnal.gov

NOTICE

Contents

1. Introduction

The Cascade-Exciton Model (CEM) of nuclear reactions was proposed 32 years ago at the Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, USSR by Gudima, Mashnik, and Toneev [1, 2]. Is is based on the Dubna IntraNuclear Cascade (INC) [3, 4] and the Modified Exciton Model (MEM) [5, 6]. It was extended to consider photonuclear reactions [7] and to describe fission cross sections using different options for nuclear masses, fission barriers, and level densities [8] and its 1995 version, CEM95, was released to the public via NEA/OECD, Paris as the code IAEA1247, and via the Radiation Safety Information Computational Center (RSICC) at Oak Ridge, USA, as the RSICC code package PSR-357 [9].

The *International Code Comparison for Intermediate Energy Nuclear Data* [10, 11] organized during 1993–1994 at NEA/OECD in Paris to address the subject of codes and models used to calculate nuclear reactions from 20 to 1600 MeV showed that CEM95 had one of the best predictive powers to describe nucleon-induced reactions at energies above about 150 MeV when compared to other models and codes available at that time.

CEM95 and/or its predecessors and its successors CEM97 [12, 13], CEM2k [14], CEM2k+GEM2 [15]–[17], CEM03 [18, 19], CEM03.01 [20, 21], CEM03.02 [22, 23] and the latest version, CEM03.03 [23, 24] are used as stand-alone codes to study different nuclear reactions for applications and fundamental nuclear physics (see, e.g., [25]–[36] and references therein). Parts of different versions of the CEM code are used in many other stand-alone codes, like **PICA95** [37], **PICA3** [38], **CASCADO** [39], **CAMO** [40], **MCFX** [41], **ECM** [42], and **NUCLEUS** [43]. CEM95 and some of its predecessor or successor versions are incorporated wholly, or in part in different transport codes used in many applications, like **CASCADE** [44], **GEANT4** [45, 46], **SHIELD** [47], **RTS&T** [48], **SONET** [49], **CALOR** [50], **HETC-3STEP** [51], **CASCADE/INPE** [52], **HADRON** [53], and others. The latest version, CEM03.03 [23, 24], was recently incorporated as event generator in **MCNP6** [54], **MCNPX2.7.0** [55], **MARS15** [56], and **MRED** [57].

All CEM code versions still have some problems to be solved, just as all similar models do. Following an increased interest in intermediate-energy nuclear data in relation to such projects as the Accelerator Transmutation of nuclear Wastes (ATW), the Accelerator Production of Tritium (APT), the Spallation Neutron Source (SNS), the Rare Isotope Accelerator (RIA), Proton Radiography (PRAD) as a radiographic probe for the Advanced Hydro-test Facility, and others, for several years the US Department of Energy has supported our work on the development of an improved version of the CEM which has led to the code CEM03.03 described here.

2. A Brief Survey of CEM03.03 Physics

The basic version of the modern CEM code is the so-called "03.01" version, namely CEM03.01 [20, 21]. The CEM03.01 code calculates nuclear reactions induced by nucleons, pions, and photons. It assumes that the reactions occur generally in three stages. The first stage is the IntraNuclear Cascade (INC), in which primary particles can be re-scattered and produce secondary particles several times prior to absorption by, or escape from the nucleus. When the cascade stage of a reaction is completed, CEM03.01 uses the coalescence model to "create" high-energy d, t, ^{3}He, and ^{4}He by final-state interactions among emitted cascade nucleons, already outside of the target. The emission of the cascade particles determines the particle-hole configuration, Z, A, and the excitation energy that is the starting point for the second, preequilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of an improved version of the modified exciton model of preequilibrium decay followed by the equilibrium evaporation/fission stage of the reaction. Generally, all four components may contribute to experimentally measured particle spectra and other distributions. But if the residual nuclei after the INC have atomic numbers with $A \leq 12$, CEM03.01 uses the Fermi breakup model to calculate their further disintegration instead of using the preequilibrium and evaporation models. Fermi breakup is much faster to calculate and gives results very similar to the continuation of the more detailed models for much lighter nuclei.

The main difference of the following, so-called "03.02" version of CEM from the basic "03.01" version is that the earlier code only uses the Fermi breakup model to calculate the disintegration of light nuclei, in lieu of the preequilibrium and evaporation models, when the excited nuclei after the INC have a mass number $A \leq 12$, but not when such nuclei are produced after the preequilibrium, evaporation, or fission stages. This problem was solved in the 03.02 versions of CEM and LAQGSM, where the Fermi breakup model is used at all stages of a reaction, when producing an excited nucleus with $A \leq 12$. A schematic outline of a nuclear reaction calculation by CEM03.02 (and by CEM03.03) is shown in Fig. 1.

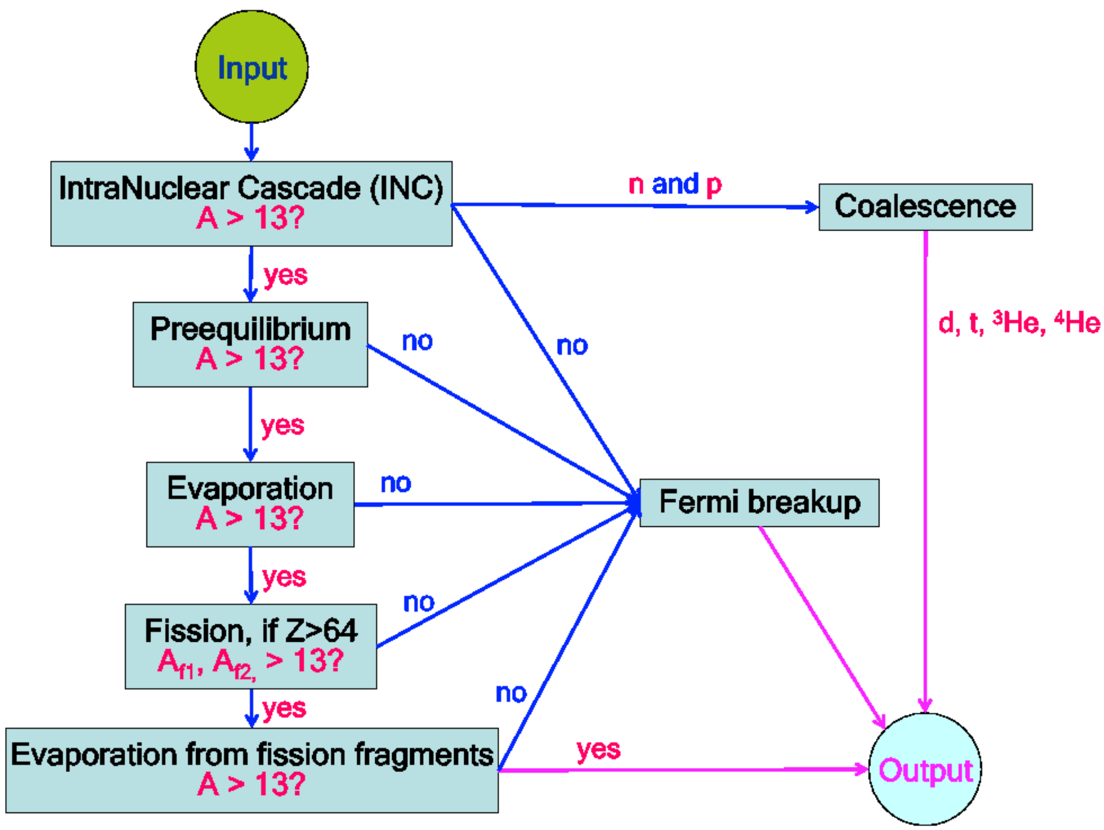

Figure 1: Flow chart of nuclear-reaction calculations by CEM03.03.

In addition, the routines that describe the Fermi breakup model in the basic 03.01 version of our codes were written more than twenty years ago in the group of Prof. Barashenkov at JINR, Dubna, Russia, and are not quite perfect, though they are quite reliable and are still used without any changes in some current transport codes. First, these routines allow in rare cases production of some light unstable fragments like ^{5}He, ^{5}Li, ^{8}Be, ^{9}B, etc., as a result of a breakup of some light excited nuclei. Second, these routines allowed in some very rare cases the production of "neutron stars" (or "proton stars"), i.e., residual "nuclei" produced via Fermi breakup that consist of only neutrons (or only protons). Lastly, in some very rare cases, these routines could even crash the code, due to cases of 0/0. All these problems of the Fermi breakup model routines are addressed and solved in the 03.02 version of our codes [22, 23]. Several bugs are also fixed in 03.02 in comparison with its predecessor. On the whole, the 03.02 versions describe nuclear reactions on intermediate and light nuclei, and production of fragments heavier than ^{4}He from heavy targets better than their predecessors (see Fig. 2 and Ref. [22]), rarely produce any unstable unphysical final products, and are free of the fixed bugs.

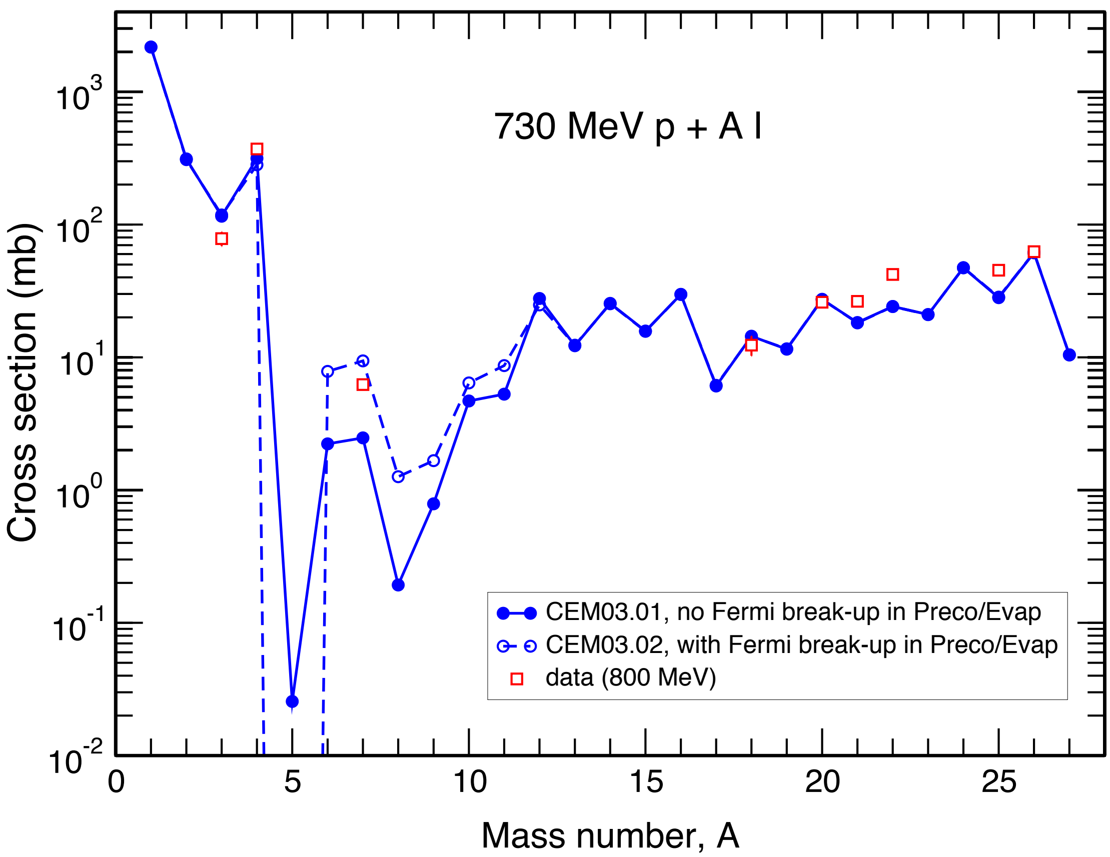

Figure 2: Mass distribution of the product yields from the reaction 730 MeV p + ^{27}Al calculated with CEM03.01 without considering the Fermi-break-up mode during the preequilibrium and evaporation stages of reactions (solid circles connected with a solid line) and with the extended version of the code referred to here and below as CEM03.02, that considers the Fermi break-up mode during the preequilibrium and evaporation stages of reactions (open circles connected with a dashed line) compared with experimental data available at a nearby energy of 800 MeV from the T-16 Lib compilation [58] (open red squares).

However, even after solving these problems and after implementing the improved Fermi breakup model into CEM03.02 [22], in some very rare cases, our code still could produce some unstable products via very asymmetric fission, when the excitation energy of such fragments was below 3 MeV and they were not checked and not disintegrated with the Fermi breakup model (see more details in [59]). This problem was addressed in the "03.03" versions of our

CEM (and LAQGSM) codes, where we force such unstable products to disintegrate via Fermi breakup independently of their excitation energy. Several more bugs were fixed on the "03.03" version as well. We emphasize that the occurrence of these problems even in the "03.01" version is quite rare, allowing stand-alone calculations of many nuclear reactions to proceed without problems, but are unacceptable when CEM (and LAQGSM) are used as event generators inside transport codes doing large-scale simulations.

To maintain historical clarity, we note here that the "standard 03.03" version of CEM produced as described above (see more details in [59]) is used at present only in MARS15 [56]. In MCNP6 [54] and in the latest versions of MCNPX, 2.7.A, 2.7.B, 2.7.C, 2.7.D, 2.7.E, and 2.7.0 (see [55] and references therein), as well as in the Monte Carlo Radiative Energy Deposition (MRED) code developed at Vanderbilt University for single event effect studies [57], we use now a slight modification of CEM03.02 which eliminates the rare fission-fragment problem just discussed by disallowing all fission into fragments with $A < 13$, a slightly simpler remedy of the difficulty. Therefore, there is no need to use the "standard 03.03" version to address this problem.

Until very recently, we have called this latest version of CEM included in MCNP6/X and in MRED as "CEM03.02" (to distinguish it from the "standard 03.03" version used in MARS15) though its physics is essentially identical. We used it to participate in the recent Benchmark of Spallation Models organized at the International Atomic Energy Agency during 2008-2009 [60], and it is referred to there as "CEM03.02". As one can see from the numerous and various results presented at the Web site of that Benchmark [60], the results by "CEM03.02" are practically the same as those by "CEM03.03", just as expected, differing only at the level of statistical fluctuations. The situation of having different names of the latest version of CEM in MCNP6/X and MRED as "CEM03.02" and as "CEM03.03" in MARS15 was confusing for people outside our Group, as kindly pointed out to us by one of the referees of our recent paper on Validation and Verification of MCNP6 [36]. To address this, we decided to call in Ref. [36] and in all our following publications the latest version of CEM we use at LANL (and in MRED at Vanderbilt University) "CEM03.03".

CEM03.03 contains one more important fix relative to its 03.02 and 03.01 precursors. Recently we discovered an error in the calculation of the fission level-density parameter of a few fissioning preactinide nuclei a_f (or more exactly, the ratio of level density parameters for the fission and neutron-evaporation channels, a_f/a_n; see details in Section 2.5.5 below and in Ref. [61]) for reactions on ^{181}Ta and nearby $Z = 72$ or 73 nuclei in CEM03.01 [21], which we produced at the beginning of 2005. That error was not present in versions of CEM before 2005, but was introduced by accident in 2005 in CEM03.01. It migrated later also to the "03.02" and "03.03" versions of CEM, as well as to MCNP6/X, MRED, and MARS transport codes using those versions of CEM as event generators. Unfortunately, that error seriously affected the calculated fission cross section of ^{181}Ta and of nearby nuclei, as well as the yield of fission fragments, and, to a lesser degree, also the spectra of secondary particles from such reactions. We discovered that error in the middle of 2011 and have fixed it in CEM03.03 (see details in Ref. [61] and Fig. 3 below). It was fixed also in the most recent versions of the transport codes MCNP6, MRED, and MARS15. However, users of versions of CEM03.01/.02/.03 and of transport codes MCNP6/X, MRED, and MARS15 produced after 2005 and before the second half of 2011 will still have it and need to update their versions of the codes to eliminate that error. For brevity's sake, when we need to refer to all 03.03, 03.02, and 03.01 versions of CEM or of LAQGSM, we use a generalized notation "03.xx".

Having discovered the 2005 error and knowing how it affects the CEM results, we can now understand why in the recent works by Titarenko et al. [34, 35] it was found that CEM03.02 (which has practically the same physics as the version CEM03.03 described here) provided a poor agreement with the measured yields of the nuclides produced in proton interactions with ^{181}Ta and the nearby target nuclei for energies above 250 MeV.

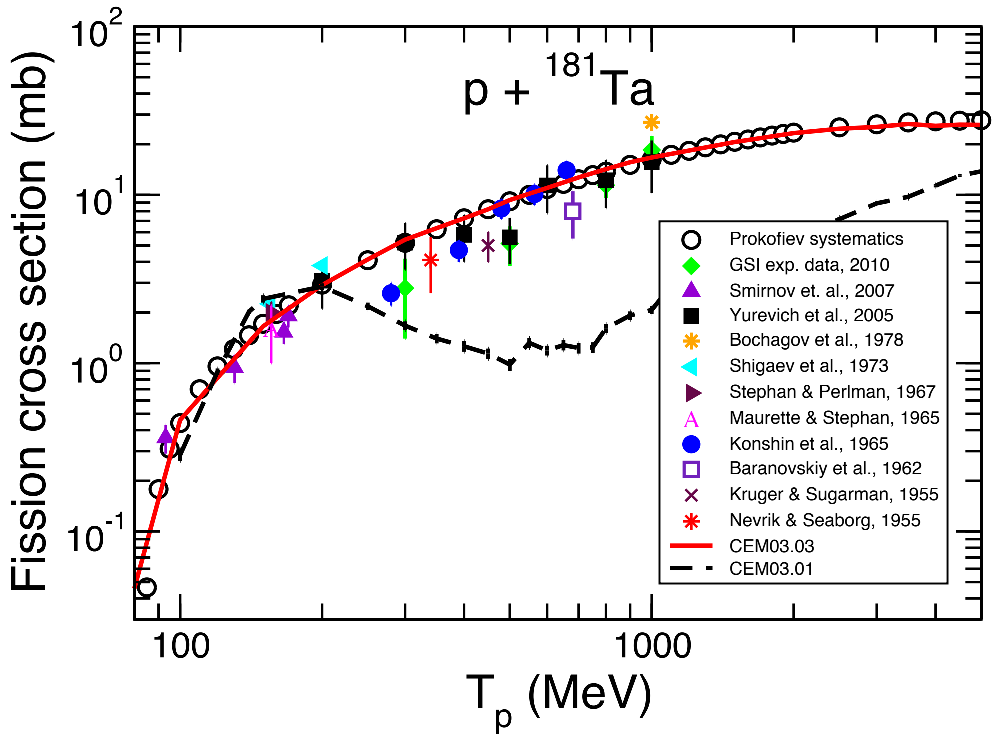

Figure 3: Comparison of Prokofiev systematics (open circles) and of several measured proton-induced fission cross section data for ^{181}Ta (symbols; all references may be found in Ref. [61]) with our old CEM03.xx calculations (black dashed lines) before we found the error in the middle of 2011, and with the updated CEM03.03 (red solid line), including the fix [61].

We have collaborated with the ITEP Group of Prof. Titarenko for more than a decade and have analyzed with different versions of our CEM and LAQGSM codes practically all of the proton-induced activation data measured by this group: some 14,621 product yields, from proton reactions on 24 targets, from ^{nat}Cr to ^{nat}U, at incident energies from 40 MeV to 2.6 GeV. Generally, both the CEM and LAQGSM codes describe quite well the data measured by Titarenko et al. This group defines a mean deviation factor $< F >$, which involves an average of the ratio of the experimental to the theoretical cross sections over all measured nuclide products for a particular reaction energy and target. For most of these reactions, our codes have a value of $< F >$ near or less than 2, nearly the best performance in comparison with about a dozen of other popular codes compared to the ITEP data (see, e.g., Figs. 4–8 and Figs. 9–11 in [35] and, especially, Fig. 9 in Ref. [32]). However, this was only "usually," because in the case of ^{181}Ta, this factor $< F >$ for CEM03.02 presented in Tab. 4 of Ref. [34] was of 1.61, 1.85, 2.21, 1.59, 1.42, 2.86, 4.17, 4.19, 4.30, 3.43, and 3.33 at energies of the bombarding protons of 40, 70, 100, 150, 250, 400, 600, 800, 1200, 1600, and 2600 MeV, respectively. The values of $< F >$ at proton energies above 250 MeV, are significantly higher than 2, and CEM03.02

does not provide, for these cases, the best agreement with the data in comparison with the other models tested in Ref. [34], a result that was unexpected and not understood when this paper was published. Similarly, from Fig. 14 of Ref. [35], we see that the mean deviation factor between results by CEM03.02 and measured data is usually within a factor of two, except for the Ta and nearby target nuclei at energies above ~ 400 MeV, where the agreement was found to be worse, as shown by that "red finger" in Fig. 14 of this paper. Now, we understand that this behavior was due to the 2005 error in the values of a_f in CEM; as we see from Fig. 3; all nuclides arising from fission reactions will suffer from an under-prediction of the same order as the fission cross section. After fixing that problem, CEM03.03 calculates fission cross sections (and fission fragment yields) in a good agreement with available experimental data for reactions induced by nucleons, pions, and photons on both subactinide and actinide nuclei (from ^{165}Ho to ^{239}Pu; see details in Ref. [61]).

Finally, we replaced the random-number generator used in our model: In CEM03.01, CEM03.02, and CEM03.03 through most of 2011, we used an algorithm for the uniform random-number generator RNDM adopted from MARS15 [56], originally published in "Toward a Universal Random Number Generator" by George Marsaglia and Arif Zaman, Florida State University Report FSU-SCRI-87-50 (1987). It was later modified by F. James and published in "A Review of Pseudo-random Number Generators". It is considered as one of the better random number generators available in the literature and is used by various modern Monte-Carlo codes. However, recently we have found that the newer MCNP5/6 random-number generator by Forrest Brown and Yasunobu Nagaya [62] is, because of a much longer period, extensive testing, and a faster execution speed in many implementations, better for our purposes. The MCNP6 version is entirely conformant to the FORTRAN-90 standard, and optionally preserves the exact random sequence of previous MCNP versions and is completely portable. In addition, new skip-ahead algorithms have been implemented to efficiently initialize the generator for new histories, a capability that greatly simplifies parallel algorithms. Finally, it has been subjected to sets of rigorous and extensive tests to verify that it produces a sufficiently random sequence (see, e.g. [63] and references therein). Because CEM03.03 remains in Fortran 77 format, we have adapted the MCNP6 generator to fixed source format, while preserving its basic functionality, but not the parallelization features. We find that with this new generator, CEM03.03 runs about 20% faster than with the older RNDM.

In the following we highlight the main assumptions of the models contained in CEM03.xx.

2.1. The INC

The intranuclear cascade model in CEM03.xx is based on the standard (non-time-dependent) version of the Dubna cascade model [3, 4]. All the cascade calculations are carried out in a three-dimensional geometry. The nuclear matter density $\rho(r)$ is described by a Fermi distribution with two parameters taken from the analysis of electron-nucleus scattering, namely

$$\rho(r) = \rho_p(r) + \rho_n(r) = \rho_0 \{1 + exp[(r - c)/a]\} \ , \tag{1}$$

where $c = 1.07A^{1/3}$ fm, A is the mass number of the target, and $a = 0.545$ fm. For simplicity, the target nucleus is divided by concentric spheres into seven zones in which the nuclear density is considered to be constant. The energy spectrum of the target nucleons is estimated in the perfect Fermi-gas approximation with the local Fermi energy $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m_N)$, where m_N is the nucleon mass. The influence of intranuclear nucleons on the incoming projectile is taken into account by adding to its laboratory kinetic energy an effective real potential V, as well as by considering the Pauli principle which forbids a number of intranuclear collisions and effectively increases the mean free path of cascade particles inside the target. For incident nucleons $V \equiv V_N(r) = T_F(r) + \epsilon$, where $T_F(r)$ is the corresponding Fermi energy and ϵ is the binding energy of the nucleons. For pions, CEM03.xx uses a square-well nuclear potential with the depth $V_\pi \simeq 25$ MeV, independently of the nucleus and pion energy, as was done in the initial Dubna INC [3, 4].

The interaction of the incident particle with the nucleus is approximated as a series of successive quasifree collisions of the fast cascade particles (N, π, or γ) with intranuclear nucleons:

$$NN \to NN, \qquad NN \to \pi NN, \qquad NN \to \pi_1, \cdots, \pi_i NN \ , \tag{2}$$

$$\pi N \to \pi N, \qquad \pi N \to \pi_1, \cdots, \pi_i N \qquad (i \geq 2) \ . \tag{3}$$

In the case of pions, besides the elementary processes (3), CEM03.03 also takes into account pion absorption on nucleon pairs

$$\pi NN \to NN. \tag{4}$$

The momenta of the two nucleons participating in the absorption are chosen randomly from the Fermi distribution, and the pion energy is distributed equally between these nucleons in the center-of-mass system of the three particles participating in the absorption. The direction of motion of the resultant nucleons in this system is taken as isotropically distributed in space. The effective cross section for absorption is related (but not equal) to the experimental cross sections for pion absorption by deuterons.

In the case of photonuclear reactions, CEM03.xx follows [19] the ideas of the photonuclear version of the Dubna INC proposed initially 43 years ago by Gudima, Iljinov, and Toneev [64] to describe photonuclear reactions at energies above the Giant Dipole Resonance (GDR) region [65]. [At photon energies $T_\gamma = 10$–40 MeV, the de Broglie wavelength $\lambda/2\pi$ is of the order of 20–5 fm, greater than the average inter-nucleonic distance in the nucleus; the photons interact with the nuclear dipole resonance as a whole, thus the INC is not applicable.] Below the pion-production threshold, the Dubna INC considers absorption of photons on only "quasi-deuteron" pairs according to the Levinger model [66]:

$$\sigma_{\gamma A} = L \frac{Z(A-Z)}{A} \sigma_{\gamma d} \ , \tag{5}$$

where A and Z are the mass and charge numbers of the nucleus, $L \approx 10$, and $\sigma_{\gamma d}$ is the total photoabsorption cross section on deuterons as defined from experimental data.

At photon energies above the pion-production threshold, the Dubna INC considers production of one or two pions; the specific mode of the reaction is chosen by the Monte-Carlo method according to the partial cross sections (defined from available experimental data):

$$\begin{aligned} \gamma + p \ &\to \ p + \pi^0 \ , & (6) \\ &\to \ n + \pi^+ \ , & (7) \\ &\to \ p + \pi^+ + \pi^- \ , & (8) \\ &\to \ p + \pi^0 + \pi^0 \ , & (9) \\ &\to \ n + \pi^+ + \pi^0 \ . & (10) \end{aligned}$$

The cross sections of $\gamma + n$ interactions are derived from consideration of isotopic invariance, i.e. it is assumed that $\sigma(\gamma + n) = \sigma(\gamma + p)$. The Compton effect on intranuclear nucleons is neglected, as its cross section is less than $\approx 2\%$ of other reaction modes (see, e.g. Fig. 6.13 in Ref. [67]). The Dubna INC does not consider processes involving production of three and more pions; this limits the model's applicability to photon energies $T_\gamma \lesssim 1.5$ GeV [for T_γ higher than the threshold for three-pion production, the sum of the cross sections (8)–(10) is assumed to be equal to the difference between the total inelastic $\gamma + p$ cross section and the sum of the cross sections of the two-body reactions (6)–(7)].

The integral cross sections for the free NN, πN, and γN interactions (2)–(10) are approximated in the Dubna INC model [3] used in CEM95 and its predecessors using a special algorithm of interpolation/extrapolation through a number of picked points, mapping as well as possible the experimental data. This was done very accurately by the group of Prof. Barashenkov using all experimental data available at that time, about 43 years ago. Currently the experimental data on cross sections is much more complete than at that time; therefore we have revised the approximations of all the integral elementary cross sections used in CEM95 and its predecessors. We started by collecting all published experimental data from all available sources. Then we developed an improved, as compared with the standard Dubna INC [3], algorithm for approximation of cross sections and developed simple and fast approximations for elementary cross sections which fit very well presently available experimental data not only to 5 GeV, the upper recommended energy for the present version of the CEM, but up to 50–100 GeV and higher, depending on availability of data (see details in [12, 19]). So far, we have in CEM03.xx new approximations for 34 different types of elementary cross sections induced by nucleons, pions, and gammas. Integral cross sections for other types of interactions taken into account in CEM03.xx are calculated from isospin considerations using the former as input.

The kinematics of two-body elementary interactions and absorption of photons and pions by a pair of nucleons is completely defined by a given direction of emission of one of the secondary particles. The cosine of the angle of emission of secondary particles in the c.m. system is calculated by the Dubna INC [3] as a function of a random number ξ, distributed uniformly in the interval [0,1] as

$$\cos\theta = 2\xi^{1/2}\left[\sum_{n=0}^{N} a_n \xi^n + (1 - \sum_{n=0}^{N} a_n)\xi^{N+1}\right] - 1 , \tag{11}$$

where $N = M = 3$,

$$a_n = \sum_{k=0}^{M} a_{nk} T_i^k . \tag{12}$$

The coefficients a_{nk} were fitted to the then available experimental data at a number of incident kinetic energies T_i , then interpolated and extrapolated to other energies (see details in [3, 64, 65] and references therein). The distribution of secondary particles over the azimuthal angle φ is assumed isotropic. For elementary interactions with more than two particles in the final state, the Dubna INC uses the statistical model to simulate the angles and energies of products (see details in [3]).

For the improved version of the INC in CEM03.xx, we use currently available experimental data and recently published systematics proposed by other authors and have developed new approximations for angular and energy distributions of particles produced in nucleon-nucleon and photon-proton interactions. So, for pp, np, and nn interactions at energies up to 2 GeV, we did not have to develop our own approximations analogous to the ones described by Eqs. (11) and (12), since reliable systematics have been developed recently by Cugnon et al. for the Liege INC [68], then improved still further by Duarte for the BRIC code [69]; we simply incorporate into CEM03.xx the systematics by Duarte [69]. Similarly, for γN interactions, we take advantage of the event generators for γp and γn reactions from the Moscow INC [70] kindly sent us by Dr. Igor Pshenichnov. In CEM03.xx, we use part of a data file with smooth approximations through presently available experimental data, developed for the Moscow INC [70] and have ourselves developed a simple and fast algorithm to simulate unambiguously $d\sigma/d\Omega$ and to choose the corresponding value of Θ for any E_γ, using a single random number ξ uniformly distributed in the interval [0,1] (see details in [19]).

The analysis of experimental data has shown that the channel (8) of two-pion photoproduction proceeds mainly through the decay of the Δ^{++} isobar listed in the last Review of Particle Physics by the Particle Data Group as having the mass $M = 1232$ MeV

$$\begin{aligned} \gamma + p &\rightarrow \Delta^{++} + \pi^- \ , \\ \Delta^{++} &\rightarrow p + \pi^+ \ , \end{aligned} \tag{13}$$

whereas the production cross section of other isobar components $\left(\frac{3}{2}, \frac{3}{2}\right)$ are small and can be neglected. The Dubna INC uses the Lindenbaum-Sternheimer resonance model [71] to simulate the reaction (13). In this model, the mass of the isobar M is determined from the distribution

$$\frac{\mathrm{d}W}{\mathrm{d}M} \sim F(E, M)\sigma(M) \ , \tag{14}$$

where E is the total energy of the system, F is the two-body phase space of the isobar and π^- meson, and σ is the isobar production cross section which is assumed to be equal to the cross section for elastic $\pi^+ p$ scattering.

The c.m. emission angle of the isobar is approximated using Eqs. (11) and (12) with the coefficients a_{nk} listed in Tab. 3 of Ref. [65]; isotropy of the decay of the isobar in its c.m. system is assumed.

In order to calculate the kinematics of the non-resonant part of the reaction (8) and the two remaining three-body channels (9) and (10), the Dubna INC uses the statistical model. The total energies of the two particles (pions) in the c.m. system are determined from the distribution

$$\frac{\mathrm{d}W}{\mathrm{d}E_{\pi_1}\mathrm{d}E_{\pi_2}} \sim (E - E_{\pi_1} - E_{\pi_2})E_{\pi_1}E_{\pi_2}/E \ , \tag{15}$$

and that of the third particle (nucleon, N) from conservation of energy. The actual simulation of such reactions is done as follows: Using a random number ξ, we simulate in the beginning the energy of the first pion using

$$E_{\pi_1} = m_{\pi_1} + \xi(E_{\pi_1}^{max} - m_{\pi_1}),$$

where

$$E_{\pi_1}^{max} = [E^2 + m_{\pi_1}^2 - (m_{\pi_2} + m_N)^2]/2E.$$

Then, we simulate the energy of the second pion E_{π_2} according to Eq. (15) using the Monte-Carlo rejection method. The energy of the nucleon is calculated as $E_N = E - E_{\pi_1} - E_{\pi_2}$, following which we check that the "triangle law" for momenta

$$|p_{\pi_1} - p_{\pi_2}| \leq p_N \leq |p_{\pi_1} + p_{\pi_2}|$$

is fulfilled, otherwise this sampling is rejected and the procedure is repeated. The angles Θ and φ of the pions are sampled assuming an isotropic distribution of particles in the c.m. system,

$$\cos\Theta_{\pi_1} = 2\xi_1 - 1, \qquad \cos\Theta_{\pi_2} = 2\xi_2 - 1, \qquad \varphi_{\pi_1} = 2\pi\xi_3, \qquad \varphi_{\pi_2} = 2\pi\xi_4,$$

and the angles of the nucleon are defined from momentum conservation, $\vec{p}_N = -(\vec{p}_{\pi_1} + \vec{p}_{\pi_2})$. More details on our new approximations for differential elementary cross sections may be found in [18, 19].

The Pauli exclusion principle at the cascade stage of the reaction is handled by assuming that nucleons of the target occupy all the energy levels up to the Fermi energy. Each simulated elastic or inelastic interaction of the projectile (or of a cascade particle) with a nucleon of the target is considered forbidden if the "secondary" nucleons have energies smaller than the Fermi energy. If they do, the trajectory of the particle is traced further from the forbidden point and a new interaction point, a new partner and a new interaction mode are simulated for the traced particle, etc., until the Pauli principle is satisfied or the particle leaves the nucleus.

In this version of the INC, the kinetic energy of the cascade particles is increased or decreased as they move from one of the seven potential regions (zones) to another, but their directions remain unchanged. That is, in our calculations, refraction or reflection of cascade nucleons at potential boundaries is neglected. CEM03.xx allows us to take into account refractions and reflections of cascade nucleons at potential boundaries; for this, one needs to change the value of the parameter **irefrac** from 0 to 1 in the subroutine **initial**. But this option provides somewhat worse overall agreement of calculations with some experimental data, therefore the option of no refractions/reflections was chosen as the default in CEM03.xx.

This INC does not take into account the so-called "trawling" effect [3]. That is, in the beginning of the simulation of each event, the nuclear density distributions for the protons and neutrons of the target are calculated according to Eq. (1) and a subsequent decrease of the nuclear density with the emission of cascade particles is not taken into account. Our detailed analysis of different characteristics of nucleon- and pion-induced reactions for targets from C to Am has shown that this effect may be neglected at incident energies below about 5 GeV in the case of heavy targets like actinides and below about 1 GeV for light targets like carbon. At higher incident energies the progressive decrease of nuclear density with the development of the intranuclear cascade has a strong influence on the calculated characteristics and this effect has to be taken into account [3]. Therefore, in transport codes that use as event generators both CEM03.xx and our high-energy code LAQGSM03.xx [23], we recommend simulating nuclear reactions with CEM03.xx at incident energies up to about 1 GeV for light nuclei like C and up to about 5 GeV for actinide nuclei, and to switch to simulations using LAQGSM03.03, which considers the "trawling" effect (target nucleon depletion during the cascade), at higher energies of transported particles.

An important ingredient of the CEM is the criterion for transition from the intranuclear cascade to the preequilibrium model. In conventional cascade-evaporation models (like ISABEL and Bertini's INC used in MCNPX [55], fast particles are traced down to some minimal energy, the cutoff energy T_{cut} (or one compares the duration of the cascade stage of a reaction with a cutoff time, in "time-like" INC models, such as the Liege INC [68]). This cutoff is usually less than $\simeq 10$ MeV above the Fermi energy, below which particles are considered to be absorbed by the nucleus. The CEM uses a different criterion to decide when a primary particle is considered to have left the cascade.

An effective local optical absorptive potential $W_{opt.\,mod.}(r)$ is defined from the local interaction cross section of the particle, including Pauli-blocking effects. This imaginary potential is compared to one defined by a phenomenological global optical model $W_{opt.\,exp.}(r)$. We characterize the degree of similarity or difference of these imaginary potentials by the parameter

$$\mathcal{P} = \mid (W_{opt.\,mod.} - W_{opt.\,exp.})/W_{opt.\,exp.} \mid . \tag{16}$$

When $\mathcal{P}$ increases above an empirically chosen value, the particle leaves the cascade, and is then considered to be an exciton. From a physical point of view, such a smooth transition from the cascade stage of the reaction seems to be more attractive than the "sharp cut-off" method. In addition, as was shown in Ref. [2], this improves the agreement between the calculated and experimental spectra of secondary nucleons, especially at low incident energies and backward angles of the detected nucleons (see e.g., Figs. 3 and 11 of Ref. [2]). More details about this can be found in [2, 14, 72].

CEM03.xx uses a fixed value $\mathcal{P} = 0.3$ (at incident energies below 100 MeV), just as all its predecessors did. With this value, we find that the cascade stage of the CEM is generally shorter than that in other cascade models. This fact leads to an overestimation of preequilibrium particle emission at incident energies above about 150 MeV, and correspondingly to an underestimation of neutron production from such reactions, as was established in Ref. [14]. In Ref. [14], this problem was solved temporarily in a very rough way by using the transition from the INC to the preequilibrium stage according to Eq. (16) when the incident energy of the projectile is below 150 MeV, and by using the "sharp cut-off" method with a cutoff energy $T_{cut} = 1$ MeV for higher incident energies. This "ad hoc" rough criterion solved the problem of underestimating neutron production at high energies, providing meanwhile a reasonably good description of reactions below 150 MeV. But it provides an unphysical discontinuity in some observables calculated by MCNPX using CEM2k [14] as an event generator, observed but not understood by Broeders and Konobeev [73]. In CEM03.xx, this problem is solved by using a smooth transition from the first criterion to the second one in the energy interval from 75 to 225 MeV, so that no discontinuities are produced in results from CEM03.xx.

Beside the changes to the Dubna INC mentioned above, we also made in the INC a number of other improvements and refinements, such as imposing momentum-energy conservation for each simulated event (the Monte-Carlo algorithm previously used in the CEM provided momentum-energy conservation only statistically, on the average, but not exactly for each simulated event) and using real binding energies for nucleons in the cascade instead of the approximation of a constant separation energy of 7 MeV used in previous versions of the CEM. We have also improved many algorithms used in the Monte-Carlo simulations in many subroutines, decreasing the computing time by up to a factor of 6 for heavy targets, which is very important when performing practical simulations with transport codes like MCNPX or MARS.

Let us mention that in the CEM the initial configuration for the preequilibrium decay (number of excited particles and holes, i.e. excitons $n_0 = p_0 + h_0$, excitation energy E_0^*, linear momentum $\boldsymbol{P}_0$, and angular momentum $\boldsymbol{L}_0$ of the nucleus) differs significantly from that usually postulated in exciton models. Our calculations [2, 74, 75] have shown that the distributions of residual nuclei remaining after the cascade stage of the reaction, i.e. before the preequilibrium emission, with respect to n_0, p_0, h_0, E_0^*, $\boldsymbol{P}_0$, and $\boldsymbol{L}_0$ are rather broad.[1]

[1]Unfortunately, this fact was misunderstood by the authors of the code HETC-3STEP [51]. In spite of the fact that it has been stressed explicitly, and figures with distributions of excited nuclei after the cascade stage of a reaction with respect to the number of excitons and other characteristics were shown in a number of publications (see, e.g., Fig. 5 in Ref. [2], Fig. 1 in Ref. [75], p. 109 in Ref. [74], and p. 706 in Ref. [26]), the authors of Ref. [51] misstated this fact as *"Gudima et al. assumed the state of two particles and one hole at*

2.2. The Coalescence Model

When the cascade stage of a reaction is completed, CEM03.xx uses the coalescence model described in Refs. [76, 77] to "create" high-energy d, t, ^{3}He, and ^{4}He by final-state interactions among emitted cascade nucleons, already outside of the target nucleus. In contrast to most other coalescence models for heavy-ion induced reactions, where complex particle spectra are estimated simply by convolving the measured or calculated inclusive spectra of nucleons with corresponding fitted coefficients (see, e.g., [78] and references therein), CEM03.xx uses in its simulation of particle coalescence real information about all emitted cascade nucleons and does not use integrated spectra. CEM03.xx assumes that all the cascade nucleons having differences in their momenta smaller than p_c and the correct isotopic content form an appropriate composite particle. This means that the formation probability for, e.g. a deuteron is

$$W_d(\vec{p},b) = \int\int d\vec{p}_p d\vec{p}_n \rho^C(\vec{p}_p,b)\rho^C(\vec{p}_n,b)\delta(\vec{p}_p+\vec{p}_n-\vec{p})\Theta(p_c-|\vec{p}_p-\vec{p}_n|), \tag{17}$$

where the particle density in momentum space is related to the one-particle distribution function f by

$$\rho^C(\vec{p},b) = \int d\vec{r} f^C(\vec{r},\vec{p},b). \tag{18}$$

Here, b is the impact parameter for the projectile interacting with the target nucleus and the superscript index C shows that only cascade nucleons are taken into account for the coalescence process. The coalescence radii p_c were fitted for each composite particle in Ref. [76] to describe available data for the reaction Ne+U at 1.04 GeV/nucleon, but the fitted values turned out to be quite universal and were subsequently found to satisfactorily describe high-energy complex-particle production for a variety of reactions induced both by particles and nuclei at incident energies up to about 400 GeV/nucleon, when describing nuclear reactions with the Los Alamos version of the Quark-Gluon String Model (LAQGSM) [23, 36, 79] or with its predecessor, the Quark-Gluon String Model (QGSM) [80]. These parameters are:

$$p_c(d) = 90 \text{ MeV/c}; \qquad p_c(t) = p_c(^3\text{He}) = 108 \text{ MeV/c}; \qquad p_c(^4\text{He}) = 115 \text{ MeV/c}\ . \tag{19}$$

As the INC of CEM03.xx is different from those of LAQGSM or QGSM, it is natural to expect different best values for p_c as well. Our recent studies show that the values of parameters p_c defined by Eq. (19) are also good for CEM03.xx for projectile particles with kinetic energies T_0 lower than 300 MeV and equal to or above 1 GeV. For incident energies in the interval 300 MeV $< T_0 \leq 1$ GeV, a better overall agreement with the available experimental data is obtained by using values of p_c equal to 150, 175, and 175 MeV/c for d, t(^{3}He), and ^{4}He, respectively. These values of p_c are fixed as defaults in CEM03.xx. If several cascade nucleons are chosen to coalesce into composite particles, they are removed from the distributions of nucleons and do not contribute further to such nucleon characteristics as spectra, multiplicities, etc.

2.3. Preequilibrium Reactions

The subsequent preequilibrium interaction stage of nuclear reactions is considered by the CEM in the framework of an extension of the Modified Exciton Model (MEM) [5, 6]. At

---

the beginning $\cdots$ Hence, their assumption is not valid for the wide range of incident energy", claiming this as a weakness of the CEM and a priority of the code HETC-3STEP, where smooth distributions of excited nuclei after the cascade stage of reactions with respect to n_0 are used. This had already been done in the CEM [1, 2].

the preequilibrium stage of a reaction we take into account all possible nuclear transitions changing the number of excitons n with $\Delta n = +2, -2$, and 0, as well as all possible multiple subsequent emissions of n, p, d, t, ^{3}He, and ^{4}He. The corresponding system of master equations describing the behavior of a nucleus at the preequilibrium stage is solved by the Monte-Carlo technique [1, 2].

For a preequilibrium nucleus with excitation energy E and number of excitons $n = p + h$, the partial transition probabilities changing the exciton number by Δn are

$$\lambda_{\Delta n}(p, h, E) = \frac{2\pi}{\hbar} |M_{\Delta n}|^2 \omega_{\Delta n}(p, h, E) \ . \tag{20}$$

The emission rate of a nucleon of the type j into the continuum is estimated according to the detailed balance principle

$$\begin{aligned} \Gamma_j(p, h, E) &= \int_{V_j^c}^{E-B_j} \lambda_c^j(p, h, E, T) dT \ , \\ \lambda_c^j(p, h, E, T) &= \frac{2s_j + 1}{\pi^2 \hbar^3} \mu_j \Re_j(p, h) \frac{\omega(p-1, h, E-B_j-T)}{\omega(p, h, E)} T \sigma_{inv}(T) \ , \end{aligned} \tag{21}$$

where s_j, B_j, V_j^c, and μ_j are the spin, binding energy, Coulomb barrier, and reduced mass of the emitted particle, respectively. The factor $\Re_j(p, h)$ ensures the condition for the exciton chosen to be the particle of type j and can easily be calculated by the Monte-Carlo technique.

Assuming an equidistant level scheme with the single-particle density g, we have the level density of the n-exciton state as [81]

$$\omega(p, h, E) = \frac{g(gE)^{p+h-1}}{p!h!(p+h-1)!} \ . \tag{22}$$

This expression should be substituted into Eq. (21). For the transition rates (20), one needs the number of states taking into account the selection rules for intranuclear exciton-exciton scattering. The appropriate formulae have been derived by Williams [82] and later corrected for the exclusion principle and indistinguishability of identical excitons in Refs. [83, 84]:

$$\begin{aligned} \omega_+(p, h, E) &= \frac{1}{2} g \frac{[gE - \mathcal{A}(p+1, h+1)]^2}{n+1} \left[\frac{gE - \mathcal{A}(p+1, h+1)}{gE - \mathcal{A}(p, h)} \right]^{n-1} \ , \\ \omega_0(p, h, E) &= \frac{1}{2} g \frac{[gE - \mathcal{A}(p, h)]}{n} [p(p-1) + 4ph + h(h-1)] \ , \\ \omega_-(p, h, E) &= \frac{1}{2} g p h (n-2) \ , \end{aligned} \tag{23}$$

where $\mathcal{A}(p, h) = (p^2 + h^2 + p - h)/4 - h/2$. By neglecting the difference of matrix elements with different Δn, $M_+ = M_- = M_0 = M$, we estimate the value of M for a given nuclear state by associating the $\lambda_+(p, h, E)$ transition with the probability for quasi-free scattering of a nucleon above the Fermi level on a nucleon of the target nucleus. Therefore, we have

$$\frac{< \sigma(v_{rel}) v_{rel} >}{V_{int}} = \frac{\pi}{\hbar} |M|^2 \frac{g[gE - \mathcal{A}(p+1, h+1)]}{n+1} \left[\frac{gE - \mathcal{A}(p+1, h+1)}{gE - \mathcal{A}(p, h)} \right]^{n-1} \ . \tag{24}$$

Here, V_{int} is the interaction volume estimated as $V_{int} = \frac{4}{3}\pi(2r_c + \lambda/2\pi)^3$, with the de Broglie wave length $\lambda/2\pi$ corresponding to the relative velocity $v_{rel} = \sqrt{2T_{rel}/m_N}$. A value of the order of the nucleon radius is used for r_c in the CEM: $r_c = 0.6$ fm.

The averaging in the left-hand side of Eq. (24) is carried out over all excited states taking into account the Pauli principle in the approximation

$$< \sigma(v_{rel})v_{rel} > \simeq < \sigma(v_{rel}) >< v_{rel} > \quad . \tag{25}$$

The averaged cross section $< \sigma(v_{rel}) >$ is calculated by the Monte-Carlo simulation method and by introducing a factor η effectively taking into account the Pauli principle exactly as is done in the Fermi-gas model (see, e.g., [85])[2]

$$\sigma(v_{rel}) = \frac{1}{2}[\sigma_{pp}(v_{rel}) + \sigma_{pn}(v_{rel})]\eta(T_F/T) \text{ , where} \tag{26}$$

$$\eta(x) = \begin{cases} 1 - \frac{7}{5}x, & \text{if } x \leq 0.5 \text{ ,} \\ 1 - \frac{7}{5}x + \frac{2}{5}x(2 - \frac{1}{x})^{5/2}, & \text{if } x > 0.5 \text{ .} \end{cases} \tag{27}$$

Here, v_{rel} is the relative velocity of the excited nucleon (exciton) and the target nucleon in units of the speed of light and T is the kinetic energy of the exciton. The free-particle interaction cross sections $\sigma_{pp}(v_{rel})$ and $\sigma_{pn}(v_{rel})$ in Eq. (26) are estimated using the relations suggested by Metropolis et al. [86]

$$\begin{aligned} \sigma_{pp}(v_{rel}) &= \frac{10.63}{v_{rel}^2} - \frac{29.92}{v_{rel}} + 42.9 \text{ ,} \\ \sigma_{pn}(v_{rel}) &= \frac{34.10}{v_{rel}^2} - \frac{82.2}{v_{rel}} + 82.2 \text{ ,} \end{aligned} \tag{28}$$

where the cross sections are given in mb.

The relative kinetic energy of colliding particles necessary to calculate $< v_{rel} >$ and the factor η in Eqs. (26,27) are estimated in the so-called "right-angle collision" approximation [5], i.e. as a sum of the mean kinetic energy of an excited particle (exciton) measured from the bottom of the potential well $T_p = T_F + E/n$ plus the mean kinetic energy of an intranuclear nucleon partner $T_N = 3T_F/5$, that is $T_{rel} = T_p + T_N = 8T_F/5 + E/n$.

Combining (20), (22) and (24), we get finally for the transition rates:

$$\begin{aligned} \lambda_+(p,h,E) &= \frac{< \sigma(v_{rel})v_{rel} >}{V_{int}} \text{ ,} \\ \lambda_0(p,h,E) &= \frac{< \sigma(v_{rel})v_{rel} >}{V_{int}} \frac{n+1}{n} \Big[\frac{gE - \mathcal{A}(p,h)}{gE - \mathcal{A}(p+1,h+1)} \Big]^{n+1} \frac{p(p-1) + 4ph + h(h-1)}{gE - \mathcal{A}(p,h)} \text{ ,} \\ \lambda_-(p,h,E) &= \frac{< \sigma(v_{rel})v_{rel} >}{V_{int}} \Big[\frac{gE - \mathcal{A}(p,h)}{gE - \mathcal{A}(p+1,h+1)} \Big]^{n+1} \frac{ph(n+1)(n-2)}{[gE - \mathcal{A}(p,h)]^2} \text{ .} \end{aligned} \tag{29}$$

CEM considers the possibility of fast d, t, ^{3}He, and ^{4}He emission at the preequilibrium stage of a reaction in addition to the emission of nucleons. We assume that in the course of a reaction p_j excited nucleons (excitons) are able to condense with probability γ_j forming a complex particle which can be emitted during the preequilibrium state. A modification of

[2]Unfortunately, formula (27) as presented in Ref. [2] had some misprints; in the prior publication [1], it was correct.

Eq. (21) for the complex-particle emission rates is described in detail in Refs. [1, 2]. The "condensation" probability γ_j is estimated in those references as the overlap integral of the wave function of independent nucleons with that of the complex particle (cluster)

$$\gamma_j \simeq p_j^3 (V_j/V)^{p_j - 1} = p_j^3 (p_j/A)^{p_j - 1} \ . \tag{30}$$

This is a rather crude estimate. In the usual way the values γ_j are taken from fitting the theoretical preequilibrium spectra to the experimental ones, which gives rise to an additional, as compared to (30), dependence of the factor γ_j on p_j and excitation energy (see, e.g., Refs. [87, 88]), for each considered reaction.

The single-particle density g_j for complex particle states is found in the CEM by assuming the complex particles move freely in a uniform potential well whose depth is equal to the binding energy of this particle in a nucleus [2]

$$g_j(T) = \frac{V(2s_j+1)(2\mu_j)^{3/2}}{4\pi^2\hbar^3}(T+B_j)^{1/2} \ . \tag{31}$$

As we stated previously, this is a crude approximation and it does not provide a good prediction of emission of preequilibrium α particles (see, e.g., [72] and references therein). In CEM03.xx, to improve the description of preequilibrium complex-particle emission, we estimate γ_j by multiplying the estimate provided by Eq. (30) by an empirical coefficient $M_j(A, Z, T_0)$ whose values are fitted to available nucleon-induced experimental complex-particle spectra. We fix the fitted values of $M_j(A, Z, T_0)$ in CEM03.xx and complement them with routines **gambetn** and **gambetp** for their interpolation outside the region covered by our fitting. As shown in one example in Fig. 9 of Appendix 3, after fitting $M_j(A, Z, T_0)$, CEM03.03 describes quite well the measured spectra of all complex particles, providing a much better agreement with experimental data than all its predecessors did.

The CEM predicts forward peaked (in the laboratory system) angular distributions for preequilibrium particles. For instance, CEM03.xx assumes that a nuclear state with a given excitation energy E^* should be specified not only by the exciton number n but also by the momentum direction Ω. Following Ref. [89], the master equation (11) from Ref. [2] can be generalized for this case provided that the angular dependence for the transition rates λ_+, λ_0, and λ_- (Eq. (29)) is factorized. In accordance with Eqs. (24) and (25), in the CEM it is assumed that

$$< \sigma > \rightarrow < \sigma > F(\Omega) \ , \tag{32}$$

where

$$F(\Omega) = \frac{d\sigma^{free}/d\Omega}{\int d\Omega' d\sigma^{free}/d\Omega'} \ . \tag{33}$$

The scattering cross section $d\sigma^{free}/d\Omega$ is assumed to be isotropic in the reference frame of the interacting excitons, thus resulting in an asymmetry in both the nucleus center-of-mass and laboratory frames. The angular distributions of preequilibrium complex particles are assumed [2] to be similar to those for the nucleons in each nuclear state.

This calculational scheme is easily realized by the Monte-Carlo technique. It provides a good description of double differential spectra of preequilibrium nucleons and a not-so-good but still satisfactory description of complex-particle spectra from different types of nuclear reactions at incident energies from tens of MeV to several GeV. For incident energies below about 200 MeV, Kalbach [90] has developed a phenomenological systematics for preequilibrium-particle angular distributions by fitting available measured spectra of nucleons and complex particles. As the Kalbach systematics are based on measured spectra, they describe very well the double-differential spectra of preequilibrium particles and generally provide a better agreement of calculated preequilibrium complex particle spectra with data than does the CEM approach based on Eqs. (32,33). This is why we have incorporated into CEM03.xx the Kalbach systematics [90] to describe angular distributions of both preequilibrium nucleons and complex particles at incident energies up to 210 MeV. At higher energies, we use in CEM03.xx the CEM approach based on Eqs. (32,33).

By "preequilibrium particles" we mean particles which are emitted after the cascade stage of a reaction but before achieving statistical equilibrium at a time t_{eq}, which is fixed by the condition $\lambda_+(n_{eq}, E) = \lambda_-(n_{eq}, E)$ from which we get

$$n_{eq} \simeq \sqrt{2gE} \ . \tag{34}$$

At $t \geq t_{eq}$ (or $n \geq n_{eq}$), the behavior of the remaining excited compound nucleus is described in the framework of both the Weisskopf-Ewing statistical theory of particle evaporation [91] and fission competition according to Bohr-Wheeler theory [92].

The parameter g entering into Eqs. (29) and (34) is related to the level-density parameter of single-particle states $a = \pi^2 g/6$. At the preequilibrium stage, we calculate the level-density parameter a with our own approximation [13] in the form proposed initially by Ignatyuk et al. [93], following the method by Iljinov et al. [94]:

$$a(Z, N, E^*) = \tilde{a}(A) \left\{ 1 + \delta W_{gs}(Z, N) \frac{f(E^* - \Delta)}{E^* - \Delta} \right\} , \tag{35}$$

where

$$\tilde{a}(A) = \alpha A + \beta A^{2/3} B_s \tag{36}$$

is the asymptotic Fermi-gas value of the level density parameter at high excitation energies. Here, B_s is the ratio of the surface area of the nucleus to the surface area of a sphere of the same volume (for the ground state of a nucleus, $B_s \approx 1$), and

$$f(E) = 1 - exp(-\gamma E) \ . \tag{37}$$

E^* is the total excitation energy of the nucleus, related to the "thermal" energy U by: $U = E^* - E_R - \Delta$, where E_R and Δ are the rotational and pairing energies, respectively.

We use the shell correction $\delta W_{gs}(Z, N)$ by Möller et al. [95] and the pairing energy shifts from Möller, Nix, and Kratz [96]. The values of the parameters α, β, and γ were derived in Ref. [13] by fitting the the same data analyzed by Iljinov et al. [94] (we discovered that Iljinov et al. used $11/\sqrt{A}$ for the pairing energies Δ in deriving their level-density systematics instead of the value of $12/\sqrt{A}$ stated in Ref. [94] and we also found several misprints in the nuclear level-density data shown in their Tables. 1 and 2 used in the fit). We find:

$$\alpha = 0.1463, \ \beta = -0.0716, \text{ and } \gamma = 0.0542 \ .$$

As mentioned in Section 2.1, the standard version of the CEM [2] provides an overestimation of preequilibrium particle emission from different p+A and A+A reactions we have analyzed (see more details in [14, 15]). One way to solve this problem suggested in Ref. [14] is to change the criterion for the transition from the cascade stage to the preequilibrium one, as described in Section 2.1. Another easy way suggested in Ref. [14] to shorten the preequilibrium stage of a reaction is to arbitrarily allow only transitions that increase the number of excitons, $\Delta n = +2$, i.e., only allow the evolution of a nucleus toward the compound nucleus. In this case, the time of the equilibration will be shorter and fewer preequilibrium particles will be emitted, leaving more excitation energy for the evaporation. Such a "never-come-back" approach is used by some other exciton models, for instance, by the Multistage Preequilibrium Model (MPM) used in LAHET [97] and by FLUKA [98]. This approach was used in the CEM2k [14] version of the CEM and it allowed us to describe much better the p+A reactions measured at GSI in inverse kinematics at energies around 1 GeV/nucleon. Nevertheless, the "never-come-back" approach seems unphysical, therefore we no longer use it. We now address the problem of emitting fewer preequilibrium particles in the CEM by following Veselský [99]. We assume that the ratio of the number of quasiparticles (excitons) n at each preequilibrium reaction stage to the number of excitons in the equilibrium configuration n_{eq}, corresponding to the same excitation energy, to be a crucial parameter for determining the probability of preequilibrium emission P_{pre}. This probability for a given preequilibrium reaction stage is evaluated using the formula

$$P_{pre}(n/n_{eq}) = 1 - \exp\Big(-\frac{(n/n_{eq} - 1)}{2\sigma^2_{pre}}\Big) \tag{38}$$

for $n \leq n_{eq}$ and equal to zero for $n > n_{eq}$. The basic assumption leading to Eq. (38) is that P_{pre} depends exclusively on the ratio n/n_{eq} as can be deduced from the results of Böhning [100] where the density of particle-hole states is approximately described using a Gaussian centered at n_{eq}. The parameter σ_{pre} is a free parameter and we assume no dependence on excitation energy [99]. Our calculations of several reactions using different values of σ_{pre} show that an overall reasonable agreement with available data can be obtained using $\sigma_{pre} = 0.4$–0.5 (see Fig. 11 in Ref. [15]). In CEM03.xx, we choose the fixed value $\sigma_{pre} = 0.4$ and use Eqs. (34,38) as criteria for the transition from the preequilibrium stage of reactions to evaporation, instead of using the "never-come-back" approach along with Eq. (34), as was done in CEM2k.

2.4. Evaporation

CEM03.xx uses an extension of the Generalized Evaporation Model (GEM) code GEM2 by Furihata [101]–[103] after the preequilibrium stage of reactions to describe evaporation of nucleons, complex particles, and light fragments heavier than ^{4}He (up to ^{28}Mg) from excited compound nuclei and to describe their fission, if the compound nuclei are heavy enough to fission ($Z \geq 65$). The GEM is an extension by Furihata of the Dostrovsky evaporation model [104] as implemented in LAHET [97] to include up to 66 types of particles and fragments that can be evaporated from an excited compound nucleus plus a modification of the version of Atchison's fission model [105, 106] used in LAHET. Many of the parameters were adjusted by Furihata for a better description of fission reactions when using it in conjunction with the extended evaporation model.

A very detailed description of the GEM, together with a large amount of results obtained for many reactions using the GEM coupled either with the Bertini or ISABEL INC models in LAHET may be found in [101, 102]. Therefore, we present here only the main features of the GEM, following mainly [102] and using as well information obtained in private communications with Dr. Furihata.

Furihata did not change in the GEM the general algorithms used in LAHET to simulate evaporation and fission. The decay widths of evaporated particles and fragments are estimated using the classical Weisskopf-Ewing statistical model [91]. In this approach, the decay probability P_j for the emission of a particle j from a parent compound nucleus i with the total kinetic energy in the center-of-mass system between ϵ and $\epsilon + d\epsilon$ is

$$P_j(\epsilon)d\epsilon = g_j\sigma_{inv}(\epsilon)\frac{\rho_d(E-Q-\epsilon)}{\rho_i(E)}\epsilon d\epsilon, \tag{39}$$

where E [MeV] is the excitation energy of the parent nucleus i with mass A_i and charge Z_i, and d denotes a daughter nucleus with mass A_d and charge Z_d produced after the emission of ejectile j with mass A_j and charge Z_j in its ground state. σ_{inv} is the cross section for the inverse reaction, ρ_i and ρ_d are the level densities [MeV]$^{-1}$ of the parent and the daughter nucleus, respectively. $g_j = (2S_j + 1)m_j/\pi^2\hbar^2$, where S_j is the spin and m_j is the reduced mass of the emitted particle j. The Q-value is calculated using the excess mass $M(A, Z)$ as $Q = M(A_j, Z_j) + M(A_d, Z_d) - M(A_i, Z_i)$. In GEM2, four mass tables are used to calculate Q-values, according to the following priorities, where a lower priority table is only used outside the range of validity of the higher priority one: (1) the Audi-Wapstra mass table [107], (2) theoretical masses calculated by Möller et al. [95], (3) theoretical masses calculated by Comay et al. [108], (4) the mass excess calculated using the old Cameron formula [109]. As does LAHET, GEM2 uses Dostrovsky's formula [104] to calculate the inverse cross section σ_{inv} for all emitted particles and fragments

$$\sigma_{inv}(\epsilon) = \sigma_g\alpha\left(1 + \frac{\beta}{\epsilon}\right) \ , \tag{40}$$

which is often written as

$$\sigma_{inv}(\epsilon) = \begin{cases} \sigma_g c_n(1 + b/\epsilon) & \text{for neutrons} \\ \sigma_g c_j(1 - V/\epsilon) & \text{for charged particles} \ , \end{cases}$$

where $\sigma_g = \pi R_b^2$ [fm^2] is the geometrical cross section, and

$$V = k_j Z_j Z_d e^2/R_c \tag{41}$$

is the Coulomb barrier in MeV.

One new ingredient in GEM2 in comparison with LAHET, which considers evaporation of only 6 particles (n, p, d, t, ^{3}He, and ^{4}He), is that Furihata includes the possibility of evaporation of up to 66 types of particles and fragments and incorporates into GEM2 several alternative sets of parameters b, c_j, k_j, R_b, and R_c for each particle type.

The 66 ejectiles considered by GEM2 for evaporation are selected to satisfy the following criteria: (1) isotopes with $Z_j \leq 12$; (2) naturally existing isotopes or isotopes near the stability line; (3) isotopes with half-lives longer than 1 ms. All the 66 ejectiles considered by GEM2 are shown in Table 1.

Table 1. The evaporated particles considered by GEM2

Z_j	Ejectiles						
0	n						
1	p	d	t				
2	^{3}He	^{4}He	^{6}He	^{8}He			
3	^{6}Li	^{7}Li	^{8}Li	^{9}Li			
4	^{7}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be		
5	^{8}B	^{10}B	^{11}B	^{12}B	^{13}B		
6	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C
7	^{12}N	^{13}N	^{14}N	^{15}N	^{16}N	^{17}N	
8	^{14}O	^{15}O	^{16}O	^{17}O	^{18}O	^{19}O	^{20}O
9	^{17}F	^{18}F	^{19}F	^{20}F	^{21}F		
10	^{18}Ne	^{19}Ne	^{20}Ne	^{21}Ne	^{22}Ne	^{23}Ne	^{24}Ne
11	^{21}Na	^{22}Na	^{23}Na	^{24}Na	^{25}Na		
12	^{22}Mg	^{23}Mg	^{24}Mg	^{25}Mg	^{26}Mg	^{27}Mg	^{28}Mg

GEM2 includes several options for the parameter set in expressions (40,41):

1) The "simple" parameter set is given as $c_n = c_j = k_j = 1$, $b = 0$, and $R_b = R_c = r_0(A_j^{1/3} + A_d^{1/3})$ [fm]; users need to input r_0.

2) The "precise" parameter set is used in GEM2 as the default, and we use this set in our present work.

A) For all light ejectiles up to α ($A_j \leq 4$), the parameters determined by Dostrovsky et al. [104] are used in GEM2, namely: $c_n = 0.76 + c_a A_d^{-1/3}$, $b = (b_a A_d^{-2/3} - 0.050)/(0.76 + c_a A_d^{-1/3})$ (and $b = 0$ for $A_d \geq 192$), where $c_a = 1.93$ and $b_a = 1.66$, $c_p = 1 + c$, $c_d = 1 + c/2$, $c_t = 1 + c/3$, $c_{^3He} = c_\alpha = 0$, $k_p = k$, $k_d = k + 0.06$, $k_t = k + 0.12$, $k_{^3He} = k_\alpha - 0.06$, where c, k, and k_α are listed in Table 2 for a set of Z_d. Between the Z_d values listed in Table 2, c, k, and k_α are interpolated linearly.The nuclear distances are given by $R_b = 1.5A^{1/3}$ for neutrons and protons, and $1.5(A_d^{1/3} + A_j^{1/3})$ for d, t, ^{3}He, and α.

Table 2. k, k_α, and c parameters used in GEM2

Z_d	k	k_α	c
≤ 20	0.51	0.81	0.0
30	0.60	0.85	-0.06
40	0.66	0.89	-0.10
≥ 50	0.68	0.93	-0.10

The nuclear distance for the Coulomb barrier is expressed as $R_c = R_d + R_j$, where $R_d = r_0^c A^{1/3}$, $r_0^c = 1.7$, and $R_j = 0$ for neutrons and protons, and $R_j = 1.2$ for d, t, ^{3}He, and ^{4}He. We note that several of these parameters are similar to the original values published by Dostrovsky et al. [104] but not exactly the same. Dostrovsky et al. [104] had $c_a = 2.2$, $b_a = 2.12$, and $r_0^c = 1.5$. Also, for the k, k_α, and c parameters shown in Table 2, they had slightly different values, shown in Table 3.

Table 3. k_p, c_p, k_α, and c_α parameters from Ref. [104]

Z_d	k_p	c_p	k_α	c_α
10	0.42	0.50	0.68	0.10
20	0.58	0.28	0.82	0.10
30	0.68	0.20	0.91	0.10
50	0.77	0.15	0.97	0.08
≥ 70	0.80	0.10	0.98	0.06

B) For fragments heavier than α ($A_j \geq 4$), the "precise" parameters of GEM2 use values by Matsuse et al. [110], namely: $c_j = k = 1$, $R_b = R_0(A_j) + R_0(A_d) + 2.85$ [fm], $R_c = R_0(A_j) + R_0(A_d) + 3.75$ [fm], where $R_0(A) = 1.12A^{1/3} - 0.86A^{-1/3}$.

3) The code GEM2 contains two other options for the parameters of the inverse cross sections.

A) A set of parameters due to Furihata for light ejectiles in combination with Matsuse's parameters for fragments heavier than α. Furihata and Nakamura determined k_j for p, d, t, ^{3}He, and α as follows [103]:

$$k_j = c_1 \log(Z_d) + c_2 \log(A_d) + c_3.$$

The coefficients c_1, c_2, and c_3 for each ejectile are shown in Table 4.

Table 4. c_1, c_2, and c_3 for p, d, t, ^{3}He, and α from [103]

Ejectile	c_1	c_2	c_3
p	0.0615	0.0167	0.3227
d	0.0556	0.0135	0.4067
t	0.0530	0.0134	0.4374
^{3}He	0.0484	0.0122	0.4938
α	0.0468	0.0122	0.5120

When these parameters are chosen in GEM2, the following nuclear radius R is used in the calculation of V and σ_g:

$$R = \begin{cases} 0 & \text{for } A = 1 \ , \\ 1.2 & \text{for } 2 \leq A \leq 4 \ , \\ 2.02 & \text{for } 5 \leq A \leq 6 \ , \\ 2.42 & \text{for } A = 7 \ , \\ 2.83 & \text{for } A = 8 \ , \\ 3.25 & \text{for } A = 9 \ , \\ 1.414A_d^{1/3} + 1 & \text{for } A \geq 10 \ . \end{cases}$$

B) The second new option in GEM2 is to use Furihata's parameters for light ejectiles up to α and the Botvina *et al.* [111] parameterization for inverse cross sections for heavier ejectiles. Botvina et al. [111] found that σ_{inv} can be expressed as

$$\sigma_{inv} = \sigma_g \begin{cases} (1 - V/\epsilon) & \text{for } \epsilon \geq V + 1 \text{ [MeV]}, \\ \exp[\alpha(\epsilon - V - 1)]/(V + 1) & \text{for } \epsilon < V + 1 \text{ [MeV]}, \end{cases} \tag{42}$$

where

$$\alpha = 0.869 + 9.91/Z_j,$$

$$V = \frac{Z_j Z_d}{r_0^b (A_j^{1/3} + A_d^{1/3})},$$

$$r_0^b = 2.173 \frac{1 + 6.103 \times 10^{-3} Z_j Z_d}{1 + 9.443 \times 10^{-3} Z_j Z_d} \text{ [fm]}.$$

The expression of σ_{inv} for $\epsilon < V + 1$ shows the fusion reaction in the sub-barrier region. When using Eq. (42) instead of Eq. (40), the total decay width for a fragment emission can not be calculated analytically. Therefore, the total decay width must be calculated numerically and takes much CPU time.

The total decay width Γ_j is calculated by integrating Eq. (39) with respect to the total kinetic energy ϵ from the Coulomb barrier V up to the maximum possible value, $(E - Q)$. The good feature of Dostrovsky's approximation for the inverse cross sections, Eq. (40), is its simple energy dependence that allows the analytic integration of Eq. (39). By using Eq. (40) for σ_{inv}, the total decay width for the particle emission is

$$\Gamma_j = \frac{g_j \sigma_g \alpha}{\rho_i(E)} \int_V^{E-Q} \epsilon \Big(1 + \frac{\beta}{\epsilon}\Big) \rho_d(E - Q - \epsilon) d\epsilon. \tag{43}$$

The level density $\rho(E)$ is calculated in GEM2 according to the Fermi-gas model using the expression [112]

$$\rho(E) = \frac{\pi}{12} \frac{\exp(2\sqrt{a(E - \delta)})}{a^{1/4}(E - \delta)^{5/4}}, \tag{44}$$

where a is the level density parameter and δ is the pairing energy in MeV. As does LAHET, GEM2 uses the δ values evaluated by Cook et al. [113]. For those values not evaluated by Cook et al., δ's from Gilbert and Cameron [112] are used instead. The simplest option for the level-density parameter in GEM2 is $a = A_d/8$ [MeV^{-1}], but the default is the Gilbert-Cameron-Cook-Ignatyuk (GCCI) parameterization from LAHET [97]:

$$a = \tilde{a} \frac{1 - e^{-u}}{u} + a_I \Big(1 - \frac{1 - e^{-u}}{u}\Big), \tag{45}$$

where $u = 0.05(E - \delta)$, and

$$a_I = (0.1375 - 8.36 \times 10^{-5} A_d) \times A_d,$$

$$\tilde{a} = \begin{cases} A_d/8 & \text{for } Z_d < 9 \text{ or } N_d < 9, \\ A_d(a' + 0.00917S) & \text{for others.} \end{cases}$$

For deformed nuclei with $54 \leq Z_d \leq 78$, $86 \leq Z_d \leq 98$, $86 \leq N_d \leq 122$, or $130 \leq N_d \leq 150$, $a' = 0.12$ while $a' = 0.142$ for other nuclei. The shell corrections S is expressed as a sum of separate contributions from neutrons and protons, i.e. $S = S(Z_d) + S(N_d)$ from [112, 113] and are tabulated in [101].

The level density is calculated using Eq. (44) only for high excitation energies, $E \geq E_x$, where $E_x = U_x + \delta$ and $U_x = 2.5 + 150/A_d$ (all energies are in MeV). At lower excitation energies, the following [112] is used for the level density:

$$\rho(E) = \frac{\pi}{12} \frac{1}{T} \exp((E - E_0)/T), \tag{46}$$

where T is the nuclear temperature defined as $1/T = \sqrt{a/U_x} - 1.5/U_x$. To provide a smooth connection of Eqs. (44) and (46) at $E = E_x$, E_0 is defined as $E_0 = E_x - T(\log T - 0.25 \log a - 1.25 \log U_x + 2\sqrt{aU_x})$.

For $E - Q - V < E_x$, substituting Eq. (46) into Eq. (44) we can calculate the integral analytically, if we neglect the dependence of the level density parameter a on E:

$$\Gamma_j = \frac{\pi g_j \sigma_g \alpha}{12\rho_i(E)} \{I_1(t,t) + (\beta + V) I_0(t)\}, \tag{47}$$

where $I_0(t)$ and $I_1(t, t_x)$ are expressed as

$$\begin{aligned} I_0(t) &= e^{-E_0/T}(e^t - 1), \\ I_1(t, t_x) &= e^{-E_0/T} T\{(t - t_x + 1)e^{t_x} - t - 1\}, \end{aligned}$$

where $t = (E - Q - V)/T$ and $t_x = E_x/T$. For $E - Q - V \geq E_x$, the integral of Eq. (43) cannot be solved analytically because of the denominator in Eq. (44). However, it is approximated as

$$\Gamma_j = \frac{\pi g_j \sigma_g \alpha}{12\rho_i(E)} [I_1(t, t_x) + I_3(s, s_x)e^s + (\beta + V)\{I_0(t_x) - I_2(s, s_x)e^s\}], \tag{48}$$

where $I_2(s, s_x)$ and $I_3(s, s_x)$ are given by

$$I_2(s, s_x) = 2\sqrt{2}\{s^{-3/2} + 1.5s^{-5/2} + 3.75s^{-7/2} - (s_x^{-3/2} + 1.5s_x^{-5/2} + 3.75s_x^{-7/2})e^{s_x - s}\},$$

$$\begin{aligned} I_3(s, s_x) &= (\sqrt{2}a)^{-1}[2s^{-1/2} + 4s^{-3/2} + 13.5s^{-5/2} + 60.0s^{-7/2} + 325.125s^{-9/2} \\ &- \{(s^2 - s_x^2)s_x^{-3/2} + (1.5s^2 + 0.5s_x^2)s_x^{-5/2} + (3.75s^2 + 0.25s_x^2)s_x^{-7/2} + (12.875s^2 \\ &+ 0.625s_x^2)s_x^{-9/2} + (59.0625s^2 + 0.9375s_x^2)s_x^{-11/2} + (324.8s_x^2 + 3.28s_x^2)s_x^{-13/2}\}e^{s_x - s}], \end{aligned}$$

with $s = 2\sqrt{a(E - Q - V - \delta)}$ and $s_x = 2\sqrt{a(E_x - \delta)}$.

The particle type j to be evaporated is selected in GEM2 by the Monte-Carlo method according to the probability distribution calculated as $P_j = \Gamma_j / \sum_j \Gamma_j$, where Γ_j is given by Eqs. (47) or (48). The total kinetic energy ϵ of the emitted particle j and the recoil energy of the daughter nucleus is chosen according to the probability distribution given by Eq. (39). The angular distribution of ejectiles is simulated to be isotropic in the center-of-mass system.

According to Friedman and Lynch [114], it is important to include excited states in the particle emitted via the evaporation process along with evaporation of particles in their ground states, because it greatly enhances the yield of heavy particles. Taking this into consideration, GEM2 includes evaporation of complex particles and light fragments both in the ground states and excited states. An excited state of a fragment is included in calculations if its half-lifetime $T_{1/2}(s)$ satisfies the following condition:

$$\frac{T_{1/2}}{\ln 2} > \frac{\hbar}{\Gamma_j^*}, \tag{49}$$

where Γ_j^* is the decay width of the excited particle (resonance). GEM2 calculates Γ_j^* in the same manner as for a ground-state particle emission. The Q-value for the resonance emission is expressed as $Q^* = Q + E_j^*$, where E_J^* is the excitation energy of the resonance. The spin state of the resonance S_j^* is used in the calculation of g_j, instead of the spin of the ground state S_j.

GEM2 uses the ground state masses m_j for excited states because the difference between the masses is negligible.

Instead of treating a resonance as an independent particle, GEM2 simply enhances the decay width Γ_j of the ground state particle emission as follows:

$$\Gamma_j = \Gamma_j^0 + \sum_n \Gamma_j^n, \tag{50}$$

where Γ_j^0 is the decay width of the ground state particle emission, and Γ_j^n is that of the nth excited state of the particle j emission which satisfies Eq. (49).

The total-kinetic-energy distribution of the excited particles is assumed to be the same as that of the ground-state particle. S_j^*, E_j^*, and $T_{1/2}$ used in GEM2 are extracted from the Evaluated Nuclear Structure Data File (ENSDF) database maintained by the National Nuclear Data Center at Brookhaven National Laboratory [115].

Note that when including evaporation of up to 66 particles in GEM2, its running time increases significantly compared to the case when evaporating only 6 particles, up to ^{4}He. The major particles emitted from an excited nucleus are n, p, d, t, ^{3}He, and ^{4}He. For most cases, the total emission probability of particles heavier than α is negligible compared to those for the emission of light ejectiles. Our detailed study of different reactions (see, e.g., [116] and references therein) shows that if we study only nucleon and complex-particle spectra or only spallation and fission products and are not interested in light fragments, we can consider evaporation of only 6 types of particles in GEM2 and save much time, getting results very close to the ones calculated with the more time consuming "66" option. In CEM03.xx, we have introduced an input parameter called **nevtype** that defines the number of types of particles to be considered at the evaporation stage. The index of each type of particle that can be evaporated corresponds to the particle arrangement in Table 1, with values, e.g., of 1, 2, 3, 4, 5, and 6 for n, p, d, t, ^{3}He, and ^{4}He, with succeeding values up to 66 for ^{28}Mg. All 66 particles that can possibly evaporate are listed in CEM03.xx together with their mass number, charge, and spin values in the **block data bdejc**. For all ten examples of inputs and outputs of CEM03.03 included in Appendices 1 and 2, whose results (when run with much larger numbers of events to improve statistics) are plotted in the figures in Appendix 3, we have performed calculations taking into account only 6 types of evaporated particles (**nevtype = 6**) as well as with the "66" option (**nevtype = 66**) and we provide the corresponding computing time for these examples in the captions to the appropriate figures shown in Appendix 3. The "6" option can be up to several times faster than the "66" option, providing meanwhile almost the same results. Therefore we recommend that users of CEM03.03 use 66 for the value of the input parameter **nevtype** only when they are interested in all fragments heavier than ^{4}He; otherwise, we recommend the default value of 6 for **nevtype**, saving computing time. Alternatively, users may choose intermediate values of **nevtype**, for example 9 if one wants to calculate the production of ^{6}Li, or 14 for modeling the production of ^{9}Be and lighter fragments and nucleons only, while still saving computing time compared to running the code with the maximum value of 66.

2.5. Fission

The fission model used in GEM2 is based on Atchison's model [105, 106] as implemented in LAHET [97], often referred in the literature as the Rutherford Appleton Laboratory (RAL) fission model, which is where Atchison developed it. In GEM2 there are two choices of parameters for the fission model: one of them is the original parameter set by Atchison [105, 106] as implemented in LAHET [97], and the other is a parameter set developed by Furihata [101, 102].

2.5.1. Fission Probability. The Atchison fission model is designed to describe only fission of nuclei with $Z \geq 70$ (we extended it in our CEM03.xx and LAQGSM03.xx codes down to $Z \geq 65$). It assumes that fission competes only with neutron emission, i.e., from the widths Γ_j of n, p, d, t, ^{3}He, and ^{4}He, the RAL code calculates the probability of evaporation of any particle. When a charged particle is selected to be evaporated, no fission competition is taken into account. When a neutron is selected to be evaporated, the code does not actually simulate its evaporation, instead it considers that fission may compete, and chooses either fission or evaporation of a neutron according to the fission probability P_f. This quantity is treated by the RAL code differently for the elements above and below $Z = 89$. The reasons Atchison split the calculation of the fission probability P_f are: (1) there is very little experimental information on fission in the region $Z = 85$ to 88, (2) the marked rise in the fission barrier for nuclei with Z^2/A below about 34 (see Fig. 2 in [106]) together with the disappearance of asymmetric mass splitting, indicates that a change in the character of the fission process occurs. If experimental information were available, a split between regions around $Z^2/A \approx 34$ would be more sensible [106].

1) $65 \leq Z_j \leq 88$. For fissioning nuclei with $65 \leq Z_j \leq 88$, GEM2 uses the original Atchison calculation of the neutron emission width Γ_n and fission width Γ_f to estimate the fission probability as

$$P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} = \frac{1}{1 + \Gamma_n/\Gamma_f}. \tag{51}$$

Atchison uses [105, 106] the Weisskopf and Ewing statistical model [91] with an energy-independent pre-exponential factor for the level density (see Eq. (44)) and Dostrovsky's [104] inverse cross section for neutrons and estimates the neutron width Γ_n as

$$\Gamma_n = 0.352(1.68J_0 + 1.93A_i^{1/3}J_1 + A_i^{2/3}(0.76J_1 - 0.05J_0)), \tag{52}$$

where J_0 and J_1 are functions of the level density parameter a_n and $s_n(= 2\sqrt{a_n(E - Q_n - \delta)})$,

$$J_0 = \frac{(s_n - 1)e^{s_n} + 1}{2a_n},$$

$$J_1 = \frac{(2s_n^2 - 6s_n + 6)e^{s_n} + s_n^2 - 6}{8a_n^2}.$$

Note that the RAL model uses a fixed value for the level density parameter a_n, namely

$$a_n = (A_i - 1)/8, \tag{53}$$

and this approximation is kept in GEM2 when calculating the fission probability according to Eq. (51), although it differs from the GCCI parameterization (45) used in GEM2 to calculate particle evaporation widths. The fission width for nuclei with $65 \leq Z_j \leq 88$ is calculated in the RAL model and in the GEM as

$$\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}, \tag{54}$$

where $s_f = 2\sqrt{a_f(E - B_f - \delta)}$ and the level density parameter in the fission mode a_f is fitted by Atchison to describe the measured Γ_f/Γ_n to be [106]:

$$a_f = a_n\Big(1.08926 + 0.01098(\chi - 31.08551)^2\Big), \tag{55}$$

and $\chi = Z^2/A$. The fission barriers B_f [MeV] are approximated by

$$B_f = Q_n + 321.2 - 16.7\frac{Z_i^2}{A} + 0.218\left(\frac{Z_i^2}{A_i}\right)^2. \tag{56}$$

Note that neither the angular momentum nor the excitation energy of the nucleus are taken into account in finding the fission barriers.

2) $Z_j \geq 89$. For heavy fissioning nuclei with $Z_j \geq 89$ GEM2 follows the RAL model [105, 106] and does not calculate at all the fission width Γ_f and does not use Eq. (51) to estimate the fission probability P_f. Instead, the following semi-empirical expression obtained by Atchison [105, 106] by approximating the experimental values of Γ_n/Γ_f published by Vandenbosch and Huizenga [117] is used to calculate the fission probability:

$$\log(\Gamma_n/\Gamma_f) = C(Z_i)(A_i - A_0(Z_i)), \tag{57}$$

where $C(Z)$ and $A_0(Z)$ are constants depending on the nuclear charge Z only. The values of these constants are those used in the current version of LAHET [97] and are tabulated in Table 5 (note that some adjustments of these values have been done since Atchison's papers [105, 106] were published).

Table 5. $C(Z)$ and $A_0(Z)$ values used in GEM2

Z	$C(Z)$	$A_0(Z)$
89	0.23000	219.40
90	0.23300	226.90
91	0.12225	229.75
92	0.14727	234.04
93	0.13559	238.88
94	0.15735	241.34
95	0.16597	243.04
96	0.17589	245.52
97	0.18018	246.84
98	0.19568	250.18
99	0.16313	254.00
100	0.17123	257.80
101	0.17123	261.30
102	0.17123	264.80
103	0.17123	268.30
104	0.17123	271.80
105	0.17123	275.30
106	0.17123	278.80

In this approach the fission probability P_f is independent of the excitation energy of the fissioning nucleus and its angular momentum.

2.5.2. Mass Distribution. The selection of the mass of the fission fragments depends on whether the fission is symmetric or asymmetric. For a pre-fission nucleus with $Z_i^2/A_i \leq 35$, only symmetric fission is allowed. For $Z_i^2/A_i > 35$, both symmetric and asymmetric fission are allowed, depending on the excitation energy of the fissioning nucleus. No new parameters were determined for asymmetric fission in GEM2.

For nuclei with $Z_i^2/A_i > 35$, whether the fission is symmetric or not is determined by the asymmetric fission probability P_{asy}

$$P_{asy} = \frac{4870e^{-0.36E}}{1 + 4870e^{-0.36E}}. \tag{58}$$

2.5.2.a. Asymmetric fission. For asymmetric fission, the mass of one of the post-fission fragments A_1 is selected from a Gaussian distribution of mean $A_f = 140$ and width $\sigma_M = 6.5$. The mass of the second fragment is $A_2 = A_i - A_1$.

2.5.2.b. Symmetric fission. For symmetric fission, A_1 is selected from the Gaussian distribution of mean $A_f = A_i/2$ and two options for the width σ_M as described below.

The first option for choosing σ_M is the original Atchison approximation:

$$\sigma_M = \begin{cases} 3.97 + 0.425(E - B_f) - 0.00212(E - B_f)^2, \\ 25.27, \end{cases} \tag{59}$$

for $(E - B_f)$ below or above 100 MeV, respectively. In this expression all values are in MeV and the fission barriers B_f are calculated according to Eq. (56) for nuclei with $Z_i \leq 88$. For nuclei with $Z_i > 88$, the expression by Neuzil and Fairhall [118] is used:

$$B_f = C - 0.36(Z_i^2/A_i), \tag{60}$$

where $C = 18.8, 18.1, 18.1,$ and 18.5 [MeV] for odd-odd, even-odd, odd-even, and even-even nuclei, respectively.

The second option in GEM2 for σ_M (used here) was found by Furihata as:

$$\sigma_M = C_3(Z_i^2/A_i)^2 + C_4(Z_i^2/A_i) + C_5(E - B_f) + C_6. \tag{61}$$

The constants $C_3 = 0.122$, $C_4 = -7.77$, $C_5 = 3.32 \times 10^{-2}$, and $C_6 = 134.0$ were obtained by fitting with GEM2 the recent Russian collection of experimental fission-fragment mass distributions [119]. In this expression, the fission barriers B_f by Myers and Swiatecki [120] are used. More details may be found in Ref. [102].

2.5.3. Charge Distribution. The charge distribution of fission fragments is assumed to be a Gaussian distribution of mean Z_f and width σ_Z. Z_f is expressed as

$$Z_f = \frac{Z_i + Z_1' - Z_2'}{2}, \tag{62}$$

where

$$Z_l' = \frac{65.5 A_l}{131 + A_l^{2/3}}, l = 1 \text{ or } 2. \tag{63}$$

The original Atchison model uses $\sigma_Z = 2.0$. An investigation by Furihata [102] suggests that $\sigma_Z = 0.75$ provides a better agreement with data; therefore $\sigma_Z = 0.75$ is used in GEM2 and in our code.

2.5.4. Kinetic Energy Distribution. The kinetic energy of fission fragments [MeV] is determined by a Gaussian distribution with mean ϵ_f and width σ_{ϵ_f}.

The original parameters in the Atchison model are:

$$\epsilon_f = 0.133 Z_i^2/A_i^{1/3} - 11.4,$$
$$\sigma_{\epsilon_f} = 0.084\epsilon_f.$$

Furihata's parameters in the GEM, which we also use, are:

$$\epsilon_f = \begin{cases} 0.131 Z_i^2/A_i^{1/3}, \\ 0.104 Z_i^2/A_i^{1/3} + 24.3, \end{cases} \tag{64}$$

for $Z_i^2/A_i^{1/3} \le 900$ and $900 < Z_i^2/A_i^{1/3} \le 1800$, respectively, according to Rusanov et al. [119]. By fitting the experimental data by Itkis et al. [121], Furihata found the following expression for σ_{ϵ_f}

$$\sigma_{\epsilon_f} = \begin{cases} C_1(Z_i^2/A_i^{1/3} - 1000) + C_2, \\ C_2, \end{cases} \tag{65}$$

for $Z_i^2/A_i^{1/3}$ above and below 1000, respectively, and the values of the fitted constants are $C_1 = 5.70 \times 10^{-4}$ and $C_2 = 86.5$. The experimental data used by Furihata for fitting are the values extrapolated to the nuclear temperature 1.5 MeV by Itkis et al. [121]. More details may be found in [102].

We note that Atchison has also modified his original version using recent data and published [122] improved (and more complicated) parameterizations for many quantities and distributions in his model, but these modifications [122] have not been included either in LAHET or in GEM2.

2.5.5. Modifications to GEM2 in CEM03.xx. First, we fixed several observed uncertainties and small errors in the 2002 version of GEM2 Dr. Furihata kindly sent us. Then, we extended GEM2 to describe fission of lighter nuclei, down to $Z \ge 65$, and modified it [17] so that it provides a good description of fission cross sections when it is used after our INC and preequilibrium models.

If we had merged GEM2 with the INC and preequilibrium-decay modules of CEM03.xx without any modifications, the new code would not describe correctly fission cross sections (and the yields of fission fragments). This is because Atchison fitted the parameters of his RAL fission model when it followed the Bertini INC [123] which differs from ours. In addition, Atchison did not model preequilibrium emission. Therefore, the distributions of fissioning nuclei in A, Z, and excitation energy E^* simulated by Atchison differ significantly from the distributions we get; as a consequence, all the fission characteristics are also different. Furihata used GEM2 coupled either with the Bertini INC [123] or with the ISABEL [124] INC code, which also differs from our INC, and did not include preequilibrium particle emission. Therefore the distributions of fissioning nuclei simulated by Furihata differ from those in our simulations, so the parameters adjusted by Furihata to work well with her INC are not appropriate for us. To get a good description of fission cross sections (and fission-fragment yields) we have modified at least two parameters in GEM2 as used in CEM03.xx (see more details in [15, 16]).

The main parameters that determine the fission cross sections calculated by GEM2 are the level density parameter in the fission channel, a_f (or more exactly, the ratio a_f/a_n as calculated by Eq. (55)) for preactinides, and parameter $C(Z)$ in Eq. (57) for actinides. The sensitivity of results to these parameters is much higher than to either the fission barrier heights used in a calculation or other parameters of the model. Therefore we choose [17] to adjust only these two parameters in our merged code. We do not change the form of systematics (55) and (57) derived by Atchison. We only introduce additional coefficients both to a_f and $C(Z)$, replacing $a_f \rightarrow C_a \times a_f$ in Eq. (55) and $C(Z_i) \rightarrow C_c \times C(Z_i)$ in Eq. (57) and fit C_a and C_c to experimental proton-induced fission cross sections covered by Prokofiev's systematics [125]. No other parameters in GEM2 have been changed. For preactinides, we fit only C_a. The values of C_a found in our fit to Prokofiev's systematics are close to one and vary smoothly with the proton energy and the charge or mass number of the target. This result gives us some confidence in our procedure, and allows us to interpolate the values of C_a for nuclei and incident proton energies not analyzed by Prokofiev. For actinides, as described in [15, 16], we have to fit both C_a and C_c. The values of C_a we find are also very close to one, while the values of C_c are more varied, but both of them change smoothly with the proton energy and Z or A of the target, which again allows us to interpolate them for nuclei and energies outside Prokofiev's systematics.

We fix the fitted values of C_a and C_c in data blocks in our code and use the routines **fitafpa** and **fitafac** to interpolate to nuclei not covered by Prokofiev's systematics. We believe that such a procedure provides a reasonably accurate fission cross section calculation, at least for proton energies and target nuclei not too far from the ones covered by the systematics.

2.6. The Fermi Break-Up Model

After calculating the coalescence stage of a reaction, CEM03.xx moves to the description of the last slow stages of the interaction, namely to preequilibrium decay and evaporation, with a possible competition of fission. But as mentioned above, if the residual nuclei have atomic numbers with $A < 13$, CEM03.xx uses the Fermi break-up model [126] to calculate their further disintegration instead of using the preequilibrium and evaporation models.

All formulas and details of the algorithms used in the version of the Fermi break-up model developed in the former group of Prof. Barashenkov at Joint Institute for Nuclear Research (JINR), Dubna, Russia and released in CEM03.xx may be found in [45]. All the information needed to calculate the break-up of an excited nucleus is its excitation energy U and the mass and charge numbers A and Z. The total energy of the nucleus in the rest frame will be $E = U + M(A, Z)$, where M is the mass of the nucleus. The total probability per unit time for a nucleus to break up into n components in the final state (e.g., a possible residual nucleus, nucleons, deuterons, tritons, alphas, etc.) is given by

$$W(E, n) = (V/\Omega)^{n-1} \rho_n(E), \tag{66}$$

where ρ_n is the density of final states, V is the volume of the decaying system and $\Omega = (2\pi\hbar)^3$ is the normalization volume. The density $\rho_n(E)$ can be defined as a product of three factors:

$$\rho_n(E) = M_n(E) S_n G_n. \tag{67}$$

The first one is the phase space factor defined as

$$M_n(E) = \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} \delta\left(\sum_{b=1}^{n} \vec{p}_b\right) \delta\left(E - \sum_{b=1}^{n} \sqrt{p^2 + m_b^2}\right) \prod_{b=1}^{n} d^3 p_b, \tag{68}$$

where $\vec{p}_b$ are fragment momenta. The second one is the spin factor

$$S_n = \prod_{b=1}^{n} (2 s_b + 1), \tag{69}$$

which gives the number of states with different spin orientations. The last one is the permutation factor

$$G_n = \prod_{j=1}^{k} \frac{1}{n_j!}, \tag{70}$$

which takes into account identical particles in the final state (n_j is the number of components of j-type particles and k is defined by $n = \sum_{j=1}^{k} n_j$). For example, if we have in the final state six particles ($n = 6$) and two of them are alphas, three are nucleons, and one is a deuteron, then $G_6 = 1/(2!3!1!) = 1/12$. For the non-relativistic case, the integration in Eq. (68) can be evaluated analytically (see, e.g., [45]) and the probability for a nucleus to disintegrate into n fragments with masses m_b, where $b = 1, 2, 3, \ldots, n$ is

$$W(E,n) = S_n G_n \left(\frac{V}{\Omega}\right)^{n-1} \left(\frac{1}{\sum_{b=1}^{n} m_b} \prod_{b=1}^{n} m_b\right)^{3/2} \frac{(2\pi)^{3(n-1)/2}}{\Gamma(3(n-1)/2)} E^{(3n-5)/2}, \tag{71}$$

where $\Gamma(x)$ is the gamma function.

The angular distribution of n emitted fragments is assumed to be isotropic in the c.m. system of the disintegrating nucleus and their kinetic energies are calculated from momentum-energy conservation. The Monte-Carlo method is used to randomly select the decay channel according to probabilities defined by Eq. (71). Then, for a given channel, CEM03.xx calculates kinematical quantities for each fragment according to the n-body phase space distribution using Kopylov's method [127]. Generally, CEM03.xx considers formation of fragments only in their ground and those low-lying states which are stable for nucleon emission. However, several unstable fragments with large lifetimes: ^{5}He, ^{5}Li, ^{8}Be, ^{9}B, etc. were considered as well in the version of the Fermi break-up model as incorporated at JINR in a FORTRAN routine used by several transport codes, as described in [45]. (Let us recall here that, as was mentioned above in Section 2, we have addressed and fixed at LANL the problem of production of unstable or/and unphysical fragments in the "03.02" versions of our CEM and LAQGSM codes; CEM03.03 uses the fixed version of the Fermi break-up model, which does not provide unstable or/and unphysical fragments). The randomly chosen channel will be allowed to decay only if the total kinetic energy E_{kin} of all fragments at the moment of break-up is positive, otherwise a new simulation will be performed and a new channel will be selected. The total kinetic energy E_{kin} can be calculated according to the equation:

$$E_{kin} = U + M(A,Z) - E_{Coulomb} - \sum_{b=1}^{n} (m_b + \epsilon_b), \tag{72}$$

where m_b and ϵ_b are masses and excitation energies of fragments, respectively, and $E_{Coulomb}$ is the Coulomb barrier for the given channel. It is approximated by

$$E_{Coulomb} = \frac{3}{5}\frac{e^2}{r_0}\left(1 + \frac{V}{V_0}\right)^{-1/3} \left(\frac{Z^2}{A^{1/3}} - \sum_{b=1}^{n} \frac{Z_b^2}{A_b^{1/3}}\right), \tag{73}$$

where A_b and Z_b are the mass number and the charge of the b-th particle of a given channel, respectively. V_0 is the volume of the system corresponding to normal nuclear density and $V = kV_0$ is the decaying system volume (we assume $k = 1$ in CEM03.xx).

Thus, the Fermi break-up model used here has only one free parameter, V or V_0, the volume of decaying system, which is estimated as follows:

$$V = 4\pi R^3/3 = 4\pi r_0^3 A/3, \tag{74}$$

where we use $r_0 = 1.4$ fm. This parameter is used to calculate the quantity **bl** in the routine **gitab**.

There is no limitation on the number n of fragments a nucleus may break up into in our version of the break-up model, in contrast to implementations in other codes, such as $n \leq 3$ in MCNPX, or $n \leq 7$ in LAHET.

2.7. Total Reaction Cross Sections (Normalization)

CEM03.xx (just like many other INC-based models) calculates the total reaction cross section, σ_{in}, by the Monte-Carlo method using the geometrical cross section, σ_{geom}, and the number of inelastic, N_{in}, and elastic, N_{el}, simulated events, namely: $\sigma_{in} = \sigma_{geom} N_{in}/(N_{in}+N_{el})$. The value of the total reaction cross section calculated this way is printed in the beginning of the CEM03.xx output labeled as *Monte Carlo inelastic cross section*. This approach provides a good agreement with available data for reactions induced by nucleons, pions, and photons at incident energies above about 100 MeV, but is not reliable enough at energies below 100 MeV (see, e.g., Fig. 4 and Ref. [16] and Figs. 4 and 5 in Ref. [19]).

To address this problem, we have incorporated [16] into CEM03.xx the NASA systematics by Tripathi et al. [128] for all incident protons and for neutrons with energies above the maximum in the NASA reaction cross sections, and the Kalbach systematics [129] for neutrons of lower energy. For reactions induced by monochromatic and bremsstrahlung photons, we incorporate into CEM03.xx [19] the recent systematics by Kossov [130]. Details on these systematics together with examples of several total inelastic cross sections calculated with them compared with available experimental data may be found in [16, 19]. Our analysis of many different reactions has shown that at incident energies below about 100 MeV these systematics generally describe the total inelastic cross sections better that the Monte-Carlo method does, and no worse than the Monte-Carlo method at higher energies. Therefore we choose these systematics as the default for normalization of all CEM03.xx results. The total reaction cross sections calculated by these systematics are printed in the CEM03.xx output labeled as *Inelasic cross section used here*. (Of course, users may renormalize all the CEM03.xx results to the Monte-Carlo total reaction cross sections by making a small change to the code in the subroutine **typeout**).

3. Storage of Simulation Results

Although we have extended significantly the variety of characteristics printed in the CEM03.xx output as compared to its predecessors, no predetermined outputs can satisfy the needs of all users. Therefore we provide below the necessary information to help users to modify the output according to their specific needs.

Almost all information about all particles, light fragments, and residual nuclei (there may be two residual nuclei in the case of fission) from every inelastic simulated event is stored in two arrays, **spt(5,150)** and **parz(6,150)**. The second index of both these arrays shows the serial number **k** of a particular particle or nucleus stored in these arrays. These arrays contain physical information only for $1 < k \leq k_{max}$, where k_{max} is the number of all products from a particular inelastic event; all their elements for $k > k_{max}$ are equal to zero. For historical reasons, there is some redundancy in the arrays; for example Θ, T_k, and Z are available from more than one array element. The contents of the arrays **spt(i,k)** and **parz(j,k)** are as follows (all values are in the laboratory system; all energies and masses are in MeV; all angles are in degrees):

1) spt(1,k) = $\sin\Theta$ of particle k
2) spt(2,k) = $\cos\Theta$ of particle k
3) spt(3,k) = T_k, kinetic energy of particle k
4) spt(4,k) = electric charge (Z) of particle k
5) spt(5,k) = rest mass of particle k

1) parz(1,k) = particle type (index), defined as:
   1 = n
   2 = p
   3 = d
   4 = t
   5 = ^{3}He
   6 = ^{4}He
   7 = π^-
   8 = π^0
   9 = π^+
   1000Z+N = A + 999Z, for products heavier than ^{4}He
2) parz(2,k) = T_k, kinetic energy of particle k
3) parz(3,k) = Θ of particle k
4) parz(4,k) = φ of particle k
5) parz(5,k) = reaction mechanism type (index), as following:
   if < 100, the "k" particle was emitted at the INC stage of reaction; the value stored here is equal to the number of successive interaction acts n_c before emission of particle k (see more details in [26])
   = 100 for preequilibrium emission
   = 200 for particles produced via coalescence
   = 1000 for evaporation from spallation residue (and for residue itself)
   = 1500 for Fermi breakup
   = 2000 for evaporation from fission product (and for fragments themselves)
6) parz(6,k) = electric charge of particle k.

The code does not store the value of k_{max} for each simulated event. To retrieve information about the products from an inelastic event, users should read (in **vlobd**) either array in a loop over k from 1 to 150 looking, e.g., at the mass of products stored in **spt(5,k)** until they get for $k = (k_{max} + 1)$ a zero value, indicating that there are no more products from this event, thereby determining k_{max}.

CEM03.xx does not describe emission of γ's from residual nuclei with an excitation energy below the threshold of particle evaporation, i.e. a few MeV. (It neglects also emission of γ's with higher energy, as a competitor to evaporation and preequilibrium-particle emission, since the cross sections of such processes are insignificant compared to those of particle emission.) When using CEM03.xx as an event generator in a transport code, it should be supplemented by a module with the same function as the **PHT** code from LAHET [97], which can describe the cooling of such excited nuclei via γ emission. For this, one needs to know the excitation energy of all residual nuclei provided by CEM03.xx. (CEM03.03 was incorporated in just this way into the LANL transport codes MCNP6 [54] and MCNPX [55].)

Note that in the case of Fermi break-up, we have no excited residual nuclei; it is assumed that all fragments are already in their ground states (unstable fragments are allowed to decay before filling the arrays **spt** and **parz**. For such events, we do not have to look for a residual nucleus to deposit its excitation energy via γ-emission. To know if this is the case, we have to look at the value of the parameter **fusion** stored in the common block: **common /dele/ sfu, wf, fusion, sigfw**. If **fusion = 0**, this is an event that ended with Fermi break-up and we have no excited residual nuclei.

If **fusion = -1**, this is an event without Fermi break-up and without fission and we have only one residual nucleus. Its excitation energy, **ut** (in MeV), is stored in the common block: **common /bl1003/ ut, at, zt**.

If **fusion = +1**, this is an event that ended with fission, so that we have two excited residual nuclei. Their excitation energy (in MeV) are equal to **ex12(1)** and **ex12(2)**, their mass and charge numbers are equal to **af12(1)** and **af12(2)**, and **zf12(1)** and **zf12(2)**, respectively, and their kinetic energy (in MeV) are equal to **tf12(1)** and **tf12(2)**, correspondingly. All this information is stored in the common block: **common /ifiss/ af12(2), zf12(2), tf12(2), ex12(2), bf12(2,3), ifiss**. In the case of fission, the parameter **ifiss** has a values of **1** (**ifiss = 0** for events without fission); its value can be also used to determine if fission occurred in a particular event, in addition to checking the parameter **fusion**.

Unfortunately, GEM2 as used in CEM03.xx does not consider at all the angular momenta of evaporated particles, the residual nucleus, and fission fragments. This is why the code does not provide values of angular momenta for the final reaction products. This is one problem we plan to address in the next version of CEM. We do calculate angular momenta of excited nuclei after the cascade and preequilibrium stages of reactions. After the cascade stage, their values (in units of $\hbar$), $L_x = amnucl(1)$, $L_y = amnucl(2)$, and $L_z = amnucl(3)$ are provided as output of the **subroutine cascad (enext, atwght, charge, pnucl, amnucl, kstart, obr, nel)**. After the preequilibrium stage, their values $L_x = angmom(1)$, $L_y = angmom(2)$, and $L_z = angmom(3)$ are stored in the common block: **common /resid/ angmom(3), v(3), remn**. These values are used to build several distributions printed in the CEM03.xx output. They are presently of only "academic" interest to study nuclear reactions but are not ready for applications, as GEM2 does not consider angular momenta and CEM03.xx does not provide angular momenta for the final reaction products.

With this information and our routines **vlobd**, **resdist**, **opandis**, and **disnmul** as examples of how to build the histograms of needed characteristics and our routines **prinp** and **typeout** that write them into our output file, users should be able to write their own customized output tables.

4. Input File

CEM03.xx has four data files: **mass.tbl, level.tbl, gamman.tbl, and level.tbl**, which should not be changed by users. It uses one user-specified input file called **cem03.inp** that must be prepared to define a calculation. It has 25 obligatory lines that describe the reaction to be calculated and the desired format of the output, and can contain also up to 10 lines of text with comments to be printed near the beginning of the output file.

4.1. 1st Input Line

This line defines the name of an auxiliary output file where some diagnostic information is printed (no results of calculations are stored in this file; the information printed in it is very useful if we encounter an unexpected problem in calculation of a specific reaction, like a “bug”). This name may contain up to 30 characters.

4.2. 2nd Input Line

This line defines the name for the CEM03.03 output file, again with up to 30 characters.

4.3. 3rd to 5th Input Lines

The 3rd line defines the projectile. Use prot for protons, neut for neutrons, pipl for π^+, pimi for π^-, pize for π^0, gamm for monochromatic γ's, and gamb for bremsstrahlung γ's. The 4th and 5th lines continue the description of the line 3 input, which is too long to fit entirely on the 3rd line.

4.4. 6th Input Line

This line defines the projectile kinetic energy in MeV, t0mev, for the case where we need to calculate only one energy and the reaction is not induced by bremsstrahlung γ's. When we need to calculate a reaction at several energies (with a step defined by the 10th line and the final energy by the 11th line), t0mev is the initial energy. For reactions induced by bremsstrahlung (**only**), we recommend using 30.0 on this line; it is the value of E_{min}, the minimum energy of the bremsstrahlung γ spectrum to be considered in calculations (above the GDR region), as described in [19].

4.5. 7th Input Line

This line defines the mass number A of the target nucleus.

4.6. 8th Input Line

This line defines the atomic number Z of the target nucleus.

4.7. 9th Input Line

This line defines the number of inelastic events to be simulated for this particular case. The appropriate value for this number depends on the characteristics of a reaction in which we are interested, as well as on the target and projectile: To calculate only fission cross sections of actinides or the mean multiplicities of nucleons from any reaction, 5000 inelastic events would be more than enough. To get double differential spectra of particles with small energy and angle bins, we may need to simulate 1,000,000 inelastic events. To have satisfactory statistics for the cross sections for production of isotopes in regions between spallation and fission and between fission and fragmentation (whose yields are very small) and for their mean energies and angles of emission, we may need to simulate 10,000,000 or even more inelastic events. The 10 examples shown in Appendix 3 may give guidance on choosing this number for different reactions.

4.8. 10th Input Line

This line defines the step of the projectile kinetic energy in MeV for calculating several incident energies in a single run. For only one incident energy, use a negative number, for example -5.0 for this parameter.

4.9. 11th Input Line

This line defines the maximum (final) kinetic energy of the projectile in MeV when we calculate a reaction at several energies, with a step defined on line 10 and the initial energy on line 6. The number must be greater than t0mev in order to calculate a single energy. Alternatively, for reactions induced by bremsstrahlung photons only, this parameter defines the end-point (maximum) energy in MeV of the bremsstrahlung γ spectrum, usually denoted in the literature as E_0; see details on bremsstrahlung reactions in [19] and in our Example 10 below.

Useful Hints:

When we need to calculate only one incident energy, e.g., 100 MeV, we suggest using for the t0mev parameter on the 6th line the value 100.0, for the parameter dt0 on the 10th line, any negative number, like -5.0, and for the parameter t0max on this line, any number bigger than 100.0, e.g., 5000.0.

If we need to calculate a reaction at three incident energies, e.g., 100, 200, and 300 MeV, use for t0mev on the 6th line the value 100.0, for the parameter dt0 on the 10th line, use the value 100.0, and for t0max on this line, use the values 300.5: The code will run in a loop at 100, 200, and 300 MeV, and will stop after 300 MeV, as with the incident energy step of 100 MeV the next incident energy would be 400 MeV, which is higher than 300.5 MeV given by the t0max on this line, so the code will stop.

4.10. 12th Input Line

This line defines the step-size $\Delta\Theta$ in degrees in the ejectile angular spectra $d\sigma/d\Omega$ [mb/sr]. It is used only when we calculate $d\sigma/d\Omega$, which is selected by the input parameter mang defined on the 18th line having the value 1 or 2.

4.11. 13th Input Line

This line defines whether or not we wish to calculate the angle-integrated energy spectra of ejectiles $d\sigma/dT$ in mb/MeV. Use 0 for the parameter mspec on this line to not calculate the energy spectra, and 1 to calculate them. When we use mspec = 1, the code provides $d\sigma/dT$ for particles produced by all nuclear-reaction mechanisms considered in CEM03.03 labeled as Total, as well as their components from particles emitted at the intranuclear cascade (or produced via coalescence, in the case of complex particles), preequilibrium, and evaporation stages of reactions labeled as Cascade, Precompound, and Total Evaporation, respectively. Particles produced via Fermi break-up are included into the Total Evaporation component; in case of evaporation from heavy nuclei that fission, this component includes particles evaporated both before fission (often called in the literature "pre-fission") and evaporated from fission fragments after fission (called in the literature "post-fission"). At the end of each spectrum, its integral over the entire energy range (i.e., particle "yield" in mb) is provided, labeled as Integrated.

There is an additional option for this parameter, namely having it equal to 2 instead of 1, to study in more detail fission reactions: If we choose the value 2 for mspec, the code will provide energy spectra of ejectiles only from events that do fission (particles from events of this reaction that do not fission will be not included into $d\sigma/dT$ calculated with the option mspec = 2) and the normalization of spectra is made to the fissioning events only and not to the total number of simulated events as is done for mspec = 1. These spectra do not represent the spectra of all emitted particles and they can not be compared directly with the measured spectra that include all particles produced from events both with and without fission. This option **is** useful for comparing to coincidence experiments, where particles are measured in coincidence with fission fragments.

In addition to $d\sigma/dT$ in mb/MeV, the option mspec = 2 provides also spectra of particles normalized to one (i.e. probability spectra), often used in the literature when studying fission induced by low energy projectiles. The option mspec = 2 provides separately "pre-fission" and "post-fission" components of particle spectra labeled as Prefission and Fission Fragments, in addition to the Total, Cascade, Precompound, and Total Evaporation components of the spectra.

4.12. 14th Input Line

This line defines whether or not we wish to calculate secondary-particle multiplicities, yields (in mb), and mean kinetic energies (in MeV). If we use 0 for the parameter mpyld on this line, these characteristics will not be calculated. When mpyld = 1, these characteristics will be calculated and printed in a table near the beginning of the output. This table contains the total (labeled as T) mean multiplicity, yield, and kinetic energy of n, p, d, t, ^{3}He, ^{4}He, π^-, π^0, and π^+, when these values are non-zero, as well as their components from cascade, preequilibrium, evaporation from events without fission (spallation), evaporation events that will fission just before fission, evaporation from fission fragments, the sum of all evaporated particles, and from coalescence, labeled as C, P, Sp, Pf, F, E, and Co, respectively. Particles produced via Fermi Break-up are included in "evaporation" (E). As in the case of the parameter mspec defined on the 13th line, there is an additional option for this parameter, mpyld = 2, to study in more detail fission. In this case, only events with fission will be considered and the mean multiplicities, yields, and kinetic energies of particles produced only in fission events will be included in this table; their normalization is done to the fission events only. As mentioned above about particle spectra, these characteristics obtained with the option mpyld = 2 can be compared directly only with models or data from coincidence measurements which select fission reactions.

4.13. 15th Input Line

This line defines whether or not we wish to calculate cross sections of 192 possible specific "channels" of reactions that contribute to the production of final isotopes. Knowledge of excitation functions for such "channels" are of mainly "academic" interest rather than for applications, as it splits the contributions to the production of a specific final isotope into different reaction channels. The γ-spectrometry method frequently used to measure nuclide production cross sections from, let us say, a photonuclear reaction on a target [Z,A], provides us only the cross section (yield) of a final isotope, e.g., [(Z-y),(A-x-y)] considering it to be produced via a (γ,xnyp) reaction, without any information about the emitted x neutrons and y protons; have they been emitted as independent nucleons or contained in emitted complex particles? The option mchy = 1 of CEM03.03 defined on this line helps us to address this question, as it provides cross sections for different possible "channels" of a reaction that lead to the same final product nuclide. The option mchy = 1 requires significant additional computing time, so we recommend using it only when the contributions to the production of final isotopes from different processes need to be studied in detail. When not needed, use the faster option mchy = 0, in order to ignore such "channel" cross sections.

4.14. 16th Input Line

This line defines whether or not we wish to calculate cross sections ("yields") in mb of all nuclide products. The option misy = 0 does not provide such yields.

With the option misy = 1, CEM03.03 calculates yields of all isotopes produced in a reaction, as well as the integrated mass and charge yields in mb and the mass and charge distributions of their mean kinetic energies and their variances in MeV. In all cases, lines with all zero values are not written to the output file.

The option misy = 2 provides the same as misy = 1, plus:

it provides also yields of all nuclei, mass and charge distributions of cross sections and of mean kinetic energy of products emitted separately in the forward and backward directions in the laboratory system;

the average kinetic energy in MeV of all products;

mass yield and mean and variance of the laboratory emission angle in degrees as functions of the product mass number;

mean and variance of the z-velocity (parallel to the projectile beam) of all products in units of v/c and the ratio of the mass yields of products emitted in the forward direction in the laboratory system to those for the backward direction (the F/B ratio) and its variance as functions of product mass numbers;

similar distributions as functions of the atomic number of the products.

Finally, the most detailed option misy = 3 provides the same as misy = 2, plus:

mass distributions of excited nuclei after the cascade and preequilibrium stages of a reaction and distributions at the beginning of the evaporation stage of nuclei that will not fission, of ones that will fission, and of all nuclei just prior to fission, after any possible prefission evaporation;

similar distributions of nuclei as functions of their atomic number;

excitation energy distributions in 1/MeV of nuclei after the cascade and preequilibrium stages and distributions at the beginning of the evaporation stage of nuclei that will not fission, of ones that will fission, and of all nuclei just prior to fission;

similar distributions for linear momentum of nuclei in 1/MeV/c;

similar distributions for angular momentum of nuclei in $1/\hbar$;

distributions of fission-fragment opening angles in the laboratory system in 1/degrees in different bins of neutron multiplicity $< n >$, namely, for $< n >= 0-5$, $< n >= 6-8$, $< n >= 9-12$, $< n >= 13-15$, $< n >= 16-19$, and $< n >\geq 20$, respectively;

neutron-multiplicity probabilities for all events, as well as for the emission of neutrons only during the cascade and preequilibrium stages of reaction, and for evaporation from events without fission (labeled in the output as Evap. res., from evaporation before fission for events that will fission (labeled in the output as Pre-fiss, and from evaporation from fission fragments after fission (labeled in the output as Post-fiss).

At the end of tables with these distributions, the mean values (labeled as $<$ ... $>$), their standard deviations (labeled as St dv), and the corresponding normalization factor (labeled as norm.) are printed in the output, respectively.

4.15. 17th Input Line

The parameter mdubl on this line defines whether or not to calculate double-differential spectra of ejectiles $d^2\sigma/(dTd\Omega)$ in mb/(MeV sr). Use for the parameter mdubl values of 0, 1, or 2 to not calculate, to calculate, or to calculate only for fission events $d^2\sigma/(dTd\Omega)$ of ejectiles, in the same manner as described above for the parameter mspec defined on the 13th line.

4.16. 18th Input Line

The parameter mang on this line defines whether or not to calculate energy-integrated angular spectra of ejectiles $d\sigma/d\Omega$ in mb/sr. Use for the parameter mang values of 0, 1, or 2 to not calculate, to calculate, or to calculate only for fission events $d\sigma/d\Omega$ of ejectiles, in the same manner as described above for the parameter mspec defined on the 13th line.

4.17. 19th Input Line

The parameters ipar1 and ipar2 on this line define the range of the ejectile types for calculations of spectra $d\sigma/dT$, $d\sigma/d\Omega$, and $d^2\sigma/(dTd\Omega)$, with the notation of the particle "type" (ID) as described above: 1, 2, 3, 4, 5, 6, 7, 8, and 9 for n, p, d, t, ^{3}He, ^{4}He, π^-, π^0, and π^+, respectively. Note that the code does not allow us to calculate electively spectra of only several particles when their ID are not ordered: e.g., if we need spectra of only n, d, and π^+, we will have to calculate in a loop spectra of all 9 types of particles, using ipar1 = 1 and ipar1 = 9. To calculate spectra (and multiplicities) of fragments heavier than ^{4}He, users will have to modify the writing to the output file for themselves.

4.18. 20th Input Line

This line defines up to 10 angle bins $\Theta(j)$ from $\Theta_1(j)$ to $\Theta_2(j)$ in degrees for double-differential spectra calculations (when mdubl = 1). The code calculates in a loop either 10 spectra starting with $j = 1$ to $j = 10$, or until a value of $\Theta_1(j)$ read from this line is negative. If we need, e.g., $d^2\sigma/(dTd\Omega)$ for only two angles ($\Theta(1) < \Theta(2)$), define on this line the corresponding values of $\Theta_1(1)$, $\Theta_2(1)$, and $\Theta_1(2)$, $\Theta_2(2)$, and use any negative number for $\Theta_1(3)$, like -5.0, then include values for the rest of $\Theta_1(j)$, $\Theta_2(j)$, up to $j = 10$ as well, since the code expects to encounter all 20 values.

4.19. 21st Input Line

This line defines energy bins $\Delta T(j)$ for four energy regions j, from $T_1(j)$ to $T_2(j)$ $(j = 1, 4)$ in MeV for angle-integrated energy spectra $d\sigma/dT$ and double-differential spectra $d^2\sigma/(dTd\Omega)$ calculations (when mspec $\geq$ 1 or/and mdubl $\geq$ 1). Take care that the whole possible energy region is covered by the four energy regions chosen on this line, so that $T_2(1) = T_1(2)$, $T_2(2) = T_1(3)$, and $T_2(3) = T_1(4)$, as is done in our examples of inputs shown in Appendix 1. It is also important that the value of $T_2(4)$ be as large as the maximum energy particle to be encountered.

4.20. 22nd Input Line

The parameter nevtype on this line defines the number of up to 66 different types of particles to be possibly evaporated, as described above in Section 2.4. We recommend using for the parameter nevtype on this line values in the range 7–66 only when fragments heavier than ^{4}He, need to be considered; otherwise, we suggest using a default value of 6, saving much computing time. See more details at the end of Section 2.4.

4.21. 23rd Input Line

The parameter ityp on this line defines the version of the random-number generator to be used in simulations, as defined by the first seven "indices" in Table 1 of Ref. [62]. See also the comments in the randmc.f source file. Note that the final CEM03.03 results calculated with good statistics should not depend on this parameter, so a user could always use the default value of 1 for it. Rerunning a particular simulation with a different value of ityp can provide an independent estimate of statistical uncertainties.

4.22. 24rd Input Line

The parameter nh on this line defines the number of up to 10 lines of commentary text to be printed in the beginning of the output as a header describing the given calculation. It could be zero, if users do not need to have any comments in their output.

4.23. Input Lines from 24 to 34

Here, users put up to 10 lines of commentary text to be printed in the beginning of the output as a header, as described above (up to 72 characters per line).

4.24. Input lines from 24 + nh + 1 to ...

All lines from 3 to 24 + nh may be repeated (with appropriately changed input values) as many times as desired in order to study other energy ranges, target isotopes, projectiles, etc.

4.25. The Last Input Line

On the last line of the input should be: stop.

5. Output File

The CEM03.03 output has plenty of captions and descriptions of all quantities printed, therefore we hope that users will have few problems in understanding it, given the information in the previous Section. We mention here only a few points about the output.

In the beginning of the output, all CEM03.03 input parameters and approximations for the level-density parameters used at the preequilibrium stage of the reaction are listed.

Then the total reaction cross section is listed, as described in Section 2.7.

The total number of inelastic and elastic simulated events are printed. Note that the elastic cross section printed after that is only to give users an idea about its order of magnitude: CEM03.03, like many other INC-based models does not pretend to describe reliably elastic cross sections.

Following this are several tables with statistical information about the mean values of the excitation energy, charge, mass, and angular momentum of nuclei after the cascade and preequilibrium stages of reactions, as well as similar distributions (plus a little more) for fissioning nuclei. Possible negative values for the minimum excitation energy of nuclei after the INC labeled as E*min may occur for some reactions. This does not indicate that CEM03.03 met a problem in calculating that specific reaction or something was wrong. A negative "excitation energy" may appear in occasional cases at the beginning of the preequilibrium stage of a reaction, when the real excitation energy of a nucleus after the INC is positive but very small. We subtract from it at the preequilibrium stage the pairing energy and the rotational energy (which are ignored by the classical INC). These rare cases are handled internally by counting them the same as any other case exiting from the cascade with an excitation energy less than a particle binding energy (listed as a residual nucleus with only cascade particles in the particle arrays **spt** and **parz**).

Following these tables, the fission probability (labeled as Fissility) and the fission cross section in mb, if the target was heavy enough to fission, are presented. CEM03.03 calculates the fission probability and cross section in two different ways: by the direct Monte-Carlo method and using the statistical weight-function method (see details in [9]), and results from both methods are printed in the output. All the yields of all products are calculated in CEM03.03 using the direct Monte-Carlo method, using the fission cross section calculated by this method. Therefore, we suggest that users use the fission probability and cross section calculated by the direct Monte-Carlo method, if the statistics of the calculation are high enough so that the fission cross section provided by the Monte-Carlo method is not too small, and greater than its statistical error printed in the output. At low incident energies, for reactions on light preactinide nuclei, the fission cross sections calculated by the Monte-Carlo method may be too small (or even zero), with big statistical errors. In such cases, users should instead use the fission probabilities and cross sections calculated by the statistical weight-function method.

We would like to emphasize that all results provided by CEM03.03 for reactions induced by bremsstrahlung γ's are normalized to the so-called "equivalent γ quanta", as is usually done in the literature (see details on bremsstrahlung reactions in [19]). This point is mentioned in the CEM03.03 output, but the situation is different from all other types of reactions considered by the code, so we wish to again remind users about this. The output and the figures for Example 10 in the Appendices illustrate this difference.

Finally, for the input parameters mspec, mpyld, mdubl, and mang having the value 2 instead of 1, the spectra, particle multiplicities and the mean kinetic energies printed in the output are for events with fission only but not for all simulated events.

Acknowledgments

The authors of this Manual and all co-authors of the CEM03.xx codes are grateful to Dr. Shiori Furihata for providing to us her Generalized Evaporation/fission Model code GEM2 which we have incorporated into CEM03.xx, several useful discussions, and allowing us to use GEM2 in our codes and to distribute it further to other users without needing further permission. We thank Dr. Helder Duarte for providing us with numerical values of experimental cross sections from his collection, useful discussions, and help. We thank Dr. Kumataro Ukai for providing us with numerical values of single-pion photoproduction cross sections from their compilation [131]. We thank Prof. Koh Sakamoto and Drs. Hiroshi Matsumura, Hiromitsu Haba, and Yasuji Oura for providing us with their publications and numerical tables of their measured data, as well as for useful discussions, help in creating several figures for us, and their interest in our modeling. We thank Dr. Igor Pshenichnov for sending us the $\gamma - p$ and $\gamma - n$ event generators from their Moscow photonuclear reaction INC [70]; we use a small portion of a large data file developed for this code in CEM03.xx.

We thank Drs. Arjan Koning, Nathalie Marie-Nourry, Valentin Blideanu, Alain Letourneau, Yury Titarenko, Vechaslav Batyaev, Vitaly Pronskikh, Carmen Villagrasa-Canton, Alexander Prokofiev, Anatoly Ignatyuk, and Satoshi Chiba for providing us with tabulated values of many of their measurements and experimental data by other authors from their collections, which we have used while developing CEM03.xx.

We thank Dr. Forrest Brown for providing to us his MCNP5 random number generator and allowing us to use it in our codes and to distribute it further to other users without needing further permission.

Last but not least, we express our gratitude to many colleagues, in particular Drs. Mark Chadwick, Tony Gabriel, Franz Gallmeier, Tim Goorley, Gerry Hale, Alexandra Heath, Robert Little, Marcus Mendenhall, Igor Moskalenko, Jerry Nolen, Richard Olsher, Jerry Peterson, Laurie Waters, Robert Webster, and Robert Weller for useful discussions, interest in and support of our work.

This work was carried out under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396.

We ask users of CEM03.03 to contact us (specifically, SGM and AJS) using the E-mail addresses provided on the first page in case of questions on our code. We thank them in advance for comments and information about possible problems in using the code or “bugs” they will find.

References

[1] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Cascade-Exciton Model of Nuclear Reactions: Model Formulation,” JINR Communication P2-80-774, Dubna (1980); “Cascade-Exciton Model of Nuclear Reactions: Comparison with Experiment,” JINR Communication P2-80-777, Dubna (1980).

[2] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, “Cascade-Exciton Model of Nuclear Reactions,” Nucl. Phys. **A401** (1983) 329–361.

[3] V. S. Barashenkov and V. D. Toneev, *Interaction of High Energy Particle and Nuclei with Atomic Nuclei*, Atomizdat, Moscow (1972).

[4] V. S. Barashenkov, A. S. Iljinov, N. M. Sobolevskii, and V. D. Toneev, "Interaction of Particles and Nuclei of High and Ultrahigh Energy with Nuclei," Usp. Fiz. Nauk **109**, (1973) 91–136 [Sov. Phys. Usp. **16** (1973) 31–52].

[5] K. K. Gudima, G. A. Ososkov, and V. D. Toneev, "Model for Pre-Equilibrium Decay of Excited Nuclei," Yad. Fiz. **21** (1975) 260–272 [Sov. J. Nucl. Phys. **21** (1975) 138–143].

[6] S. G. Mashnik and V. D. Toneev, "MODEX—the Program for Calculation of the Energy Spectra of Particles Emitted in the Reactions of Pre-Equilibrium and Equilibrium Statistical Decays," JINR Communication P4-8417, Dubna (1974).

[7] T. Gabriel, G. Maino, and S. G. Mashnik, "Analysis of Intermediate Energy Photonuclear Reactions," JINR Preprint E2-94-424, Dubna (1994); Proc. XII Int. Sem. on High Energy Phys. Problems *Relativistic Nuclear Physics & Quantum Chromodynamics*, Dubna, Russia, September 12–17, 1994, Eds. A. M. Baldin and V. V. Burov, Dubna, JINR Publish Department, 1997, JINR E1,2-97-79, pp. 309–318.

[8] S. G. Mashnik, "Cascade-Exciton Model Analysis of Excitation Functions for Proton-Induced Reactions at Low and Intermediate Energies, Izv. RAN, Ser. Fiz. **60** (1996) 73–84 [Bull. of the Russian Acad. Sci., Physics, **60** (1996) 58–67].

[9] S. G. Mashnik, "User Manual for the Code CEM95," (1995), Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia; OECD Nuclear Energy Agency Data Bank, Le Seine Saint-Germain 12, Boulevard des Iles, F-92130 Issy-les-Moulineax, Paris, France http://www.nea.fr/abs/html/iaea1247.html;
Radiation Safety Information Computational Center (RSICC), Oak Ridge, USA, http://www-rsicc.ornl.gov/codes/psr/psr3/psr-357.html.

[10] M. Blann, H. Gruppelar, P. Nagel, and J. Rodens, *International Code Comparison for Intermediate Energy Nuclear Data*, NEA OECD, Paris (1994).

[11] P. Nagel, J. Rodens, M. Blann, and H. Gruppelar, "Intermediate Energy Nuclear Reaction Code Intercomparison: Application to Transmutation of Long-Lived Reactor Wastes," Nucl. Sci. Eng. **119** (1995) 97–107.

[12] S. G. Mashnik and A. J. Sierk, "Improved Cascade-Exciton Model of Nuclear Reactions," LANL Report LA-UR-98-5999 (1998); E-print: nucl-th/9812069; Proc. SARE-4, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel (ORNL, 1999), pp. 29–51.

[13] A. J. Sierk and S. G. Mashnik, "Modeling Fission in the Cascade-Exciton Model," LANL Report LA-UR-98-5998 (1998); E-print: nucl-th/9812070; Proc. SARE-4, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel (ORNL, 1999), pp. 53–67.

[14] S. G. Mashnik and A. J. Sierk, "CEM2k—Recent Developments in CEM," Proc. AccApp00, November 12–16, 2000, Washington, DC (USA), American Nuclear Society, La Grange Park, IL, 2001, pp. 328–341; E-print: nucl-th/0011064.

[15] S. G. Mashnik, K. K. Gudima, and A. J. Sierk, "Merging the CEM2k and LAQGSM Codes with GEM2 to Describe Fission and Light-Fragment Production," LANL Report LA-UR-03-2261, Los Alamos (2003); E-print: nucl-th/0304012; Proc. SATIF-6, April 10–12, 2002, Stanford Linear Accelerator Center, CA 94025, USA, (NEA/OECD, Paris, France, 2004), pp. 337–366.

[16] Stepan G. Mashnik, Arnold J. Sierk, and Konstantin K. Gudima, "Complex Particle and Light Fragment Emission in the Cascade-Exciton Model of Nuclear Reactions," LANL Report LA-UR-02-5185, Los Alamos (2002); E-print: nucl-th/0208048.

[17] M. Baznat, K. Gudima, and S. Mashnik, "Proton-Induced Fission Cross Section Calculation with the LANL Codes CEM2k+GEM2 and LAQGSM+GEM2," LANL Report LA-UR-03-3750, Los Alamos (2003); Proc. AccApp03, San Diego, California, June 1–5, 2003, (ANS, La Grange Park, IL 60526, USA, 2004), pp. 976–985; E-print: nucl-th/0307014.

[18] S. G. Mashnik, K. K. Gudima, A. J. Sierk, and R. E. Prael, "Improved Intranuclear Cascade Models for the Codes CEM2k and LAQGSM," LA-UR-05-0711, Los Alamos (2005); E-print: nucl-th/0502019; Proc. ND2004, September 26–October 1, 2004, Santa Fe, NM, USA, edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou, (AIP Conference Proceedings, Volume 769, Melville, New York, 2005), pp. 1188–1192.

[19] S. G. Mashnik, M. I. Baznat, K. K. Gudima, A. J. Sierk, and R. E. Prael, "Extension of the CEM2k and LAQGSM Codes to Describe Photo-Nuclear Reactions," LANL Report LA-UR-05-2013, Los Alamos (2005), E-print: nucl-th/0503061; "CEM03 and LAQGSM03: Extension of the CEM2k+GEM2 and LAQGSM Codes to Describe Photo-Nuclear Reactions at Intermediate Energies (30 MeV to 1.5 GeV)," J. Nucl. Radiochem. Sci. **6** (2005) A1–A19; http://www.radiochem.org/j-online.html.

[20] S. G. Mashnik, K. K. Gudima, M. I. Baznat, A. J. Sierk, R. E. Prael, and N. V. Mokhov, "CEM03.01 and LAQGSM03.01 Versions of the Improved Cascade-Exciton Model (CEM) and Los Alamos Quark-Gluon String Model (LAQGSM) Codes," LANL Research Note X-5-RN (U) 05-11, LA-UR-05-2686 (2005).

[21] Stepan G. Mashnik, Konstantin K. Gudima, Arnold J. Sierk, Mircea I. Baznat, and Nikolai V. Mokhov, "CEM03.01 User Manual," LANL Report LA-UR-05-7321, Los Alamos (2005); RSICC Code Package PSR-532; http://www-rsicc.ornl.gov/codes/psr/psr5/psr532.html; http://www.nea.fr/abs/html/psr-0532.html.

[22] S. G. Mashnik, R. E. Prael, and K. K. Gudima, "Implementation of CEM03.01 into MCNP6 and its Verification and Validation Running through MCNP6. CEM03.02 Upgrade," LANL Research Note X-3-RN(U)-07-03, LANL Report LA-UR-06-8652, Los Alamos (2007).

[23] S. G. Mashnik, K. K. Gudima, R. E. Prael, A. J. Sierk, M. I. Baznat, and N. V. Mokhov, "CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes," Invited lectures presented at the Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions, February 4–8, 2008, ICTP, Trieste, Italy, LA-UR-08-2931, Los Alamos (2008); E-print: arXiv:0805.0751 [nucl-th].

[24] K. K. Gudima, M. I. Baznat, S. G. Mashnik, and A. J. Sierk, "Benchmarking the CEM03.03 Event Generator," LANL Report LA-UR-09-03047, Los Alamos (2009), presentation at the International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators (AccApp'09), 4-8 May 2009, IAEA, Vienna, Austria, http://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/presentations/SM-SR-07.pdf; M. I. Baznat, K. K. Gudima, S. G. Mashnik, and A. J. Sierk, "Complex particle production by CEM03.03," LANL Report LA-UR-09-03046, Los Alamos (2009), poster presented at the International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators (AccApp'09), 4-8 May 2009, IAEA, Vienna, Austria; http://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/papers/sm_sr-07.pdf; http://nds121.iaea.org/alberto/mediawiki-1.6.10/images/6/62/LA-UR-09-03046.pdf.

[25] M. G. Gornov, Yu. B. Gurov, A. L. Iljin, S. G. Mashnik, P. V. Morokhov, V. A. Pechkurov, M. A. Polikarpov, V. I. Saveliev, F. M. Sergeev, S. A. Smirnov, A. A. Khomutov, B. A. Chernyshev, R. R. Shafigullin, and A. V. Shishkov, "Emission of Protons on Absorption of Stopped Negative Pions by *Be*, *C*, *Si*, *Cu*, and *Ge* Nuclei," Yad. Fiz. **47** (1988) 959–967 [Sov. J. Nucl. Phys. **47** (1988) 612–617]; "Emission of Composite Particles in the Absorption of Stopped Negative Pions by Nuclei of *Be*, *C*, *Si*, *Cu*, and *Ge*," Yad. Fiz. **47** (1988) 1193–1200 [Sov. J. Nucl. Phys. **47** (1988) 760–764]; http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6721591&query_id=0.

[26] S. G. Mashnik, "Neutron-Induced Particle Production in the Cumulative and Noncumulative Regions at Intermediate Energies," Nucl. Phys. **A568** (1994) 703–726.

[27] S. G. Mashnik, R. J. Peterson, A. J. Sierk, and M. R. Braunstein. "Pion-Induced Transport of π Mesons in Nuclei," Phys. Rev. C **61** (2000) 034601.

[28] R. J. Peterson, S. de Barros, H. Schechter, A. G. DaSilva, J. C. Suita, and S. G. Mashnik, "Fission Probabilities Across the π-Nucleon Delta Resonance," Euro. Phys. J. A **10** (2001) 69–71; A. V. Prokofiev, S. G. Mashnik, and A. J. Sierk, "Cascade-Exciton Model Analysis of Nucleon-Induced Fission Cross Sections of Lead and Bismuth at Energies from 45 to 500 MeV," Nucl. Sci. Eng. **131** (1999) 78–95.

[29] Yu. E. Titarenko, O. V. Shvedov, V. F. Batyaev, E. I. Karpikhin, V. M. Zhivun, A. B. Koldobsky, R. D. Mulambetov, S. V. Kvasova, A. N. Sosnin, S. G. Mashnik, R. E. Prael, A. J. Sierk, T. A. Gabriel, M. Saito, and H. Yasuda, "Cross Sections for Nuclide Production in 1 GeV Proton-Irradiated ^{208}Pb," Phys. Rev. C **65** (2002) 064610.

[30] K. A. Van Riper, S. G. Mashnik, and W. B. Wilson, "A Computer Study of Radionuclide Production in High Power Accelerators for Medical and Industrial Applications," Nucl. Instr. Meth. A **463** (2001) 576–585.

[31] S. G. Mashnik, K. K. Gudima, I. V. Moskalenko, R. E. Prael, and A. J. Sierk, "CEM2k and LAQGSM as Event Generators for Space-Radiation-Shielding and Cosmic-Ray-Propagation Applications," Advances in Space Research **34** (2004) 1288–1296.

[32] Yu. E. Titarenko, V. F. Batyaev, A. Yu. Titarenko, M. A. Butko, K. V. Pavlov, S. N. Florya, R. S. Tikhonov, S. G. Mashnik, A. V. Ignatyuk, N. N. Titarenko, W. Gudowski, M. Těšínský, C.-M. L. Persson, H. Ait Abderrahim, H. Kumawat, and H. Duarte, "Cross-sections for nuclide production in ^{56}Fe target irradiated by 300, 500, 750, 1000, 1500, and

2600 MeV protons compared with data on hydrogen target irradiation by 300, 500, 750, 1000, and 1500 MeV/nucleon ^{56}Fe ions," LANL Report LA-UR-08-2219, Los Alamos (2008); arXiv:0804.1260; Phys. Rev. C **78**, 034615 (2008).

[33] S. R. Elliott, V. E. Guiseppe, B. H. LaRoque R. Johnson, and S. G. Mashnik, "Fast-Neutron Activation of Long-Lived Isotopes in Enriched Ge," LANL Report LA-UR-09-06838, Los Alamos (2009); arXiv:0912.3748; Phys. Rev. C **82**, 054610 (2010).

[34] Yu. E. Titarenko, V. F. Batyaev, A. Yu. Titarenko, M. A. Butko, K. V. Pavlov, S. N. Florya, R. S. Tikhonov, V. M. Zhivun, A. V. Ignatyuk, S. G. Mashnik, S. Leray, A. Boudard, J. Cugnon, D. Mancusi, Y. Yariv, K. Nishihara, N. Matsuda, H. Kumawat, G. Mank, and W. Gudowski, "Measurement and Simulation of the Cross Sections for Nuclide Production in nat-W and 181-Ta Targets Irradiated with 0.04- to 2.6-GeV Protons," Yadernaya Fizika **74**, 574–595 (2011); Physics of Atomic Nuclei **74**, 551–572 (2011).

[35] Yu. E. Titarenko, V. F. Batyaev, M. A. Butko, D. V. Dikarev, S. N. Florya, K. V. Pavlov, A. Yu. Titarenko, R. S. Tikhonov, V. M. Zhivun, A. V. Ignatyuk, S. G. Mashnik, A. Boudard, S. Leray, J.-C. David, J. Cugnon, D. Mancusi, Y. Yariv, H. Kumawat, K. Nishihara, N. Matsuda, G. Mank, and W. Gudowski, "Verification of high-energy transport codes on the basis of activation data," LANL Report LA-UR-11-02704, Los Alamos (2011), arXiv:1106.0054; Phys. Rev. C **84**, 064612 (2011).

[36] Stepan G. Mashnik, "Validation and Verification of MCNP6 Against Intermediate and High-Energy Experimental Data and Results by Other Codes," LANL Report LA-UR-10-07847, Los Alamos (2010); arXiv:1011.4978; Eur. Phys. J. Plus **126**: 49 (2011).

[37] C. Y. Fu, T. A. Gabriel, and R. A. Lillie, "PICA95: an Intranuclear-Cascade Code for 25 MeV to 3.5 GeV Photon-Induced Nuclear Reactions," Proc. 3rd Specialists Meeting on Shielding Aspects of Accelerators, Targets and Irradiation Facilities (SATIF-3), Tohoku University, Sendai, Japan, May 12–13, 1997, NEA/OECD, 1998, pp. 49–60; http://www.osti.gov/bridge/product.biblio.jsp?osti_id=474922.

[38] T. Sato, K. Shin, S. Ban, T. A. Gabriel, C. Y. Fu, and H. S. Lee, "PICA3, an Updated Code of Photo-Nuclear Cascade Evaporation Code PICA95, and Its Benchmark Experiments," Proc. MC2000, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távora, and P. Vaz, Springer, Berlin, (2001), pp. 1139–1144.

[39] A. V. Ignatyuk, N. T. Kulagin, V. P. Lunev, and K.-H. Schmidt, "Analysis of Spallation Residues within the Intranuclear Cascade Model," Proc. XV Workshop on Physics of Nuclear Fission, Obninsk, 3–6 October, 2000, www-w2k.gsi.de/charms/Preprints/Obninsk2000/Cascado-v7.pdf.

[40] A. V. Ignatyuk, N. T. Kulagin, V. P. Lunev, Yu. N. Shubin, N. N. Titarenko, V. F. Batyaev, Yu. E. Titarenko, and V. M. Zhivun, "Analysis of Spallation and Fission Residues for Separated Lead Isotopes Irradiated by Protons at Energies 0.15, 1.0, and 2.6 GeV," Proc. ND2004, September 26–October 1, 2004, Santa Fe, NM, USA, edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou, (AIP Conference Proceedings, Volume 769, Melville, New York, 2005), pp. 1307–1312.

[41] S. Yavshits, G. Boykov, V. Ippolitov, S. Pakhomov, and O. Grudzwvich, "Multiconfiguration Fission Cross Sections at Transitional Energy Region 20–200 MeV," Voprosy Atomnoj Nauki i Tekhniki, seriya Yadernye Konstanty (Nuclear Constants) **1** (2000) 62–70 (in Russian), translated to Engish in Report INDC(CCP)-430 (2001), pp. 83–94, http://www.ippe.obninsk.ru/podr/cjd/vant/00-1/1-07.pdf.

[42] Zs. Schram, Gy. Kluge, and K. Sailer, "Exciton Cascade Model for Fast Neutron Reactions," International Atomic Energy Agency Report INDC(HUN)-023/L, Vienna, Austria, June 1987.

[43] T. Nishida, Y. Nakahara, and T. Tsutsui, "Development of a Nuclear Spallation Simulation Code Calculation of Primary Spallation Products," *JAERI-M-86-116* (1986) T. Nishida, Y. Nakahara, and T. Tsutsui, "Analysis of the Mass Formula Dependence of the Spallation Product Distribution," JAERI-M-87-088 (1987); T. Nishida, H. Takada, and Y. Nakahara, "NUCLEUS," Proc. Int. Conf. on Nuclear Data for Science and Technology, Jülich, Germany, May 13–17, 1991, Ed. S. M. Qaim, Springer-Verlag, Berlin (1992), pp. 152–157; H. Takada, Y. Nakahara, T. Nishida, K. Ishibashi, and N. Yoshizawa, "Microscopic Cross Section Calculations with NUCLEUS and HETC-3STEP," pp. 121–136 in Ref. [10].

[44] V. S. Barashenkov, Le Van Ngok, L. G. Levchuk, Zh. Zh. Musul'manbekov, A. N. Sosnin, V. D. Toneev and S. Yu. Shmakov, "Cascade Program Complex for Monte-Carlo Simulation of Nuclear Processes Initiated by High Energy Particles and Nuclei in Gaseous and Condensed Matter," JINR Report R2-85-173, Dubna (1985).

[45] Nikolai Amelin, "Physics and Algorithms of the Hadronic Monte-Carlo Event Generators. Notes for a Developer," CERN/IT/ASD Report CERN/IT/99/6, Geneva, Switzerland and JINR/LHE, Dubna, Russia; **Geant4 User's Documents, Physics Reference Manual**, December 8, 1998, http://wwwinfo.cern.ch/asd/geant/geant4_public/G4UsersDocuments/Overview/html/index.html/.

[46] V. Lara, "Object-Oriented Approach to Preequilibrium and Equilibrium Decays in Geant4," Proc. MC2000, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távora, and P. Vaz, Springer, Berlin, (2001), pp. 1039–1044; Vichente Lara and Johannes Peter Wellisch, "Preequilibrium and Equilibrium Decays in Geant4," chep2000.pd.infn.it/short_p/spa_a096.pdf; more references and many details on GEANT4 may be found at the Web page http://wwwasd.web.cern.ch/wwwasd/geant4/geant4.html; Jose Manuel Quesada, Vladimr Ivanchenko, Anton Ivanchenko, Manuel Antonio Cortes-Giraldo, Gunter Folger, Alex Howard, and Dennis Wright on behalf of the Geant4 Hadronic Working Group, "Recent Developments in Pre-Equilibrium And De-Excitation Models in GEANT4," Prog. Nucl. Sci. Technol. **2** (2011) 936–941.

[47] N. M. Sobolevsky, "The SHIELD Code (Version 1996.hadr.0) Short User's Manual," CCC-667 SHIELD, RSICC Computer Code Collection, ORNL, 1998; A. V. Dementyev and N. M. Sobolevsky, "SHIELD—Universal Monte Carlo Hadron Transport Code: Scope and Applications," Radiation Measurements **30** (1999) 553–557; more references and many details on SHIELD may be

found at the Web pages http://www.nea.fr/abs/html/iaea1287.html; http://www-rsicc.ornl.gov/codes/ccc/ccc6/ccc-667.html.

[48] I. I. Degtyarev, A. E. Lokhovitskii, M. A. Maslov, I. A. Yazynin, V. I. Belyakov-Bodin, and A. I. Blokhin, "RTS&T Main Features," Proc. Fourth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Hyatt Regency, Knoxville, TN, September 13–16, 1998, edited by Tony A. Gabriel, ORNL, 1999, pp. 141–149; I. I. Degtyarev, O. A. Liashenko, I. A. Yazynin, V. I. Belyakov-Bodin, and A. I. Blokhin, "Calculational Estimations of Neutron Yield From ADS Targets," Proc. of the 2001 Particle Accelerator Conference, Chicago, USA, Voprosy Atomnoi Nauki i Tekhniki **01-1** (2001) 2796–2798, www.ippe.obninsk.ru/podr/cjd/vant/01-1/2-03.pdf.

[49] S. E. Chigrinov, A. I. Kievitskaia, I. L. Rakhno, and C. K. Rutkovskaia, "The Code SONET to Calculate Accelerator Driven System Performance," Proc. Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTT'99), Praha, Czech Republic, June 7–11, 1999, paper Mo-O-C12 on the Conference CD-ROM and Web page http://fjfi.cvut.cz/con_adtt99.

[50] C. Y. Fu and T. A. Gabriel, "CALOR As A Single Code Including A Modular Version of HETC," Proc. Fourth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Hyatt Regency, Knoxville, TN, September 13–16, 1998, ORNL, 1999, pp. 23–27, http://www.osti.gov/bridge/product.biblio.jsp?osti_id=1769; T. A. Gabriel and L. A. Carlson, "Charged and Neutral Particle Transport Methods and Applications: The CALOR Code System," Proc. Joint Int. Conf. on Mathematical Methods and Supercomputing for Nuclear Applications, Satatoga Springs, NY, Oct. 6–10, 1997, http://www.osti.gov/bridge/product.biblio.jsp?osti_id=527544.

[51] N. Yoshizawa, K. Ishibashi, and H. Takada, "Development of High Energy Transport Code HETC-3STEP Applicable to the Nuclear Reaction with Incident Energies above 20 MeV," J. Nucl. Sci. Techn. **32** (1995) 601-607; H. Takada, Y. Nakahara, T. Nishida, K. Ishibashi, and N. Yoshizawa, "Microscopic Cross Section Calculations with NUCLEUS and HETC-3STEP," pp. 121–136 in Ref. [10].

[52] V. S. Barashenkov, A. Yu. Konobeev, Yu. A. Korovin, and V. N. Sosnin, "CASCADE/INPE Code System," Atomnaya Energiya **87** (1999) 283–286 [Atomic Evergy **87** (1999) 742–744].

[53] A. V. Sannikov and E. N. Savitskaya, "Physics of the HADRON Code: Recent Status and Comparison with Experiment," Nucl. Instr. Meth. A **450** (2000) 127–137.

[54] T. Goorley, M. James, T. Booth, F. Brown, J. Bull, L. J. Cox, J. Durkee, J. Elson, M. Fensin, R. A. Forster, J. Hendricks, H. G. Hughes, R. Johns, B. Kiedrowski, R. Martz, S. Mashnik, G. McKinney, D. Pelowitz, R. Prael, J. Sweezy, L. Waters, T. Wilcox, and T. Zukaitis, "Initial MCNP6 Release Overview" LANL Report LA-UR-11-05198, Los Alamos (2011), to be published in *Nuclear Technology* (2012).

[55] Denise B. Pelowitz, Joe W. Durkee, Jay S. Elson, Michael L. Fensin, John S. Hendricks, Michael R. James, Russell C. Johns, Gregg W. McKinney, Stepan G. Mashnik, Jerome M. Verbeke, Laurie S. Waters, Trevor A. Wilcox, "MCNPX 2.7.0 Extensions," LANL

Report LA-UR-11-02295, Los Alamos, April 2011; more references and many details on MCNPX may be found at the Web page http://mcnpx.lanl.gov/.

[56] N. V. Mokhov, K. K. Gudima, C. C. James, M. A. Kostin, S. G. Mashnik, E. Ng, J.-F. Ostiguy, I. L. Rakhno, A. J. Sierk, S. I. Striganov, "Recent Enhancements to the MARS15 Code," Radiation Protection Dosimetry, 2005, vol. 116, No. 104, pp. 99-103; LA-UR-04-3047, Los Alamos (2004); E-print: nucl-th/0404084; more recent references and many useful details on MARS may be found at the Web page http://www-ap.fnal.gov/MARS/.

[57] R. A. Weller, M. H. Mendenhall, R. A. Reed, R. D. Schrimpf, M. K. Warren, B. D. Sierawski, and L. W. Massengill, "Monte Carlo Simulation of Single Event Effects," IEEE Transactions on Nuclear Science, **57**, 1726–1746 (2010).

[58] S. G. Mashnik, A. J. Sierk, K. A. Van Riper, and W. B. Wilson, "Production and Validation of Isotope Production Cross Section Libraries for Neutrons and Protons to 1.7 GeV," LANL Report LA-UR-98-6000 (1998); Eprint: **nucl-th/9812071**; Proc. Forth Int. Workshop on Simulating Accelerator Radiation Environments (SARE-4), Hyatt Regency, Knoxville, TN, September 13-16, 1998 ORNL, 1999, pp. 151-162 (our T-16 Library "T-16 Lib" is updated permanently when new experimental data became available to us).

[59] S. G. Mashnik, K. K. Gudima, N. V. Mokhov, and R. E. Prael, "LAQGSM03.03 Upgrade and Its Validation," LANL Report LA-UR-07-6198, Los Alamos (2007); E-print: arXiv:0709.173.

[60] *Benchmark of Spallation Models* organized at the International Atomic Energy Agency during 2008-2009 by Detlef Filges, Sylvie Leray, Jean-Christophe David, Gunter Mank, Yair Yariv, Alberto Mengoni, Alexander Stanculescu, Mayeen Khandaker, and Naohiko Otsuka, IAEA Vienna, Austria, http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page.

[61] Stepan G. Mashnik, Arnold J. Sierk, and Richard E. Prael, "MCNP6 Fission Cross Section Calculations at Intermediate and High Energies," LANL Report LA-UR-12-00228, Los Alamos (2012).

[62] Forrest B. Brown and Yasunobu Nagaya, "The MCNP5 Random Number Generator," LANL Report LA-UR-02-3782, Los Alamos (2002); Trans. Am. Nucl. Soc. **87** (2002) 230.

[63] Yasunobu Nagaya and Forrest B. Brown, "Testing MCNP Random Number Generators," LANL Report LA-UR-11-04858, Los Alamos (2011).

[64] K. K. Gudima, A. S. Iljinov, and V. D. Toneev, "A Cascade Model for Photonuclear Reactions," Communication JINR P2-4661, Dubna (1969).

[65] V. S. Barashenkov, F. G. Geregi, A. S. Iljinov, G. G. Jonsson, and V. D. Toneev, "A Cascade-Evaporation Model for Photonuclear Reactions," Nucl. Phys. **A231** (1974) 462–476.

[66] J. S. Levinger, "The High Energy Nuclear Photoeffect," Phys. Rev. **84** (1951) 43–51; *Nuclear Photo-Disintegration* (Oxford University Press, 1960); Phys. Lett. B **82**, (1979) 181–182.

[67] W. O. Lock and D. F. Measday, *Intermediate Energy Nuclear Physics*, London, Methuen; [Distributed in the U.S.A. by Barnes and Noble, 1970].

[68] J. Cugnon, C. Volant, and S. Vuillier, "Improved Intranuclear Cascade Model for Nucleon-Nucleus Interactions," Nucl. Phys. **A620** (1997) 475–509; Th. Aoust and J. Cugnon, "Effects of Isospin and Energy Dependences of the Nuclear Mean Field in Spallation Reactions," Eur. Phys. J. A **21** (2004) 79–85.

[69] Helder Duarte, "An Intranuclear Cascade Model for High Energy Transport Codes," Proc. Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications (ADTT'99), Praha, Czech Republic, June 7–11, 1999, paper Mo–O–C17 on the Conference CD–ROM and Web page http://fjfi.cvut.cz/con_adtt99; "Particle Production in Nucleon Induced Reactions Above 14 MeV with an Intranuclear Cascade Model," Phys. Rev. C **75** (2007) 024611.

[70] A. S. Iljinov, I. A. Pshenichnov, N. Bianchi, E. De Sanctis, V. Muccifora, M. Mirazita, and P. Rossi, "Extension of the Intranuclear Cascade Model for Photonuclear Reactions at Energies up to 10 GeV," Nucl. Phys. **A616** (1997) 575–605.

[71] S. J. Lindenbaum and R. M. Sternheimer, "Isobaric Nucleon Model for Pion Production in Nucleon-Nucleon Collisions," Phys. Rev. **105** (1957) 1874–1899.

[72] S. G. Mashnik, A. J. Sierk, O. Bersillon, and T. Gabriel, "Cascade-Exciton Model Detailed Analysis of Proton Spallation at Energies from 10 MeV to 5 GeV," LANL Report LA-UR-97-2905 (1997); http://t2.lanl.gov/publications/publications.html.

[73] C. H. M. Broeders and A. Yu. Konobeev, "Evaluation of He-4 Production Cross-Section for Tantalum, Tungsten and Gold Irradiated with Neutrons and Protons at the Energies up to 1 GeV," Nucl. Instr. Meth. B **234** (2005) 387–411.

[74] S. G. Mashnik, "Physics of the CEM92M Code," pp. 107–120 in [10].

[75] K. K. Gudima, S. G. Mashnik, and V. D. Toneev, "Preequilibrium Emission in Hadron-Nuclear Reactions at $T_0 < 1$–2 GeV," Proc. Europhysics Topical Conference June 21–25, 1982, Smollenice, Neutron Induced Reactions. Physics and Applications **10** (1982) 347–351.

[76] V. D. Toneev and K. K. Gudima, "Particle Emission in Light and Heavy-Ion Reactions," Nucl. Phys. **A400** (1983) 173c–190c.

[77] K. K. Gudima, G. Röpke, H. Schulz, and V. D. Toneev, "The Coalescence Model and Pauli Quenching in High-Energy Heavy-Ion Collisions," Joint Institute for Nuclear Research Preprint JINR-E2-83-101, Dubna (1983); H. Schulz, G. Röpke, K. K. Gudima, and V. D. Toneev, "The Coalescence Phenomenon and the Pauli Quenching in High-Energy Heavy-Ion Collisions," Phys. Lett. B **124** (1983) 458–460.

[78] Joseph I. Kapusta, "Mechanisms for Deuteron Production in Relativistic Nuclear Collisions," Phys. Rev. C **21** (1980) 1301–1310.

[79] Konstantin K. Gudima, Stepan G. Mashnik, and Arnold J. Sierk, "User Manual for the code LAQGSM," LANL Report LA-UR-01-6804; http://lib-www.lanl.gov/la-pubs/00818645.pdf.

[80] N. S. Amelin, K. K. Gudima, and V. D. Toneev, “The Quark-Gluon String Model and Ultrarelativistic Heavy-Ion Collisions,” Yad. Fiz. **51** (1990) 512–523 [Sov. J. Nucl. Phys. **51** (1990) 327–333]; N. S. Amelin, K. K. Gudima, and V. D. Toneev, “Further Development of the Model of Quark-Gluon Strings for the Description of High-Energy Collisions with a Target Nucleus,” Yad. Fiz. **52** (1990) 272–282 [Sov. J. Nucl. Phys. **52** (1990) 172–178].

[81] T. Ericson, “The Statistical Model and Nuclear Level Densities,” Adv. in Physics **9** (1960) 425–511.

[82] F. C. Williams Jr., “Intermediate State Transition Rates in the Griffin Model,” Phys. Lett. B **31** (1970) 184–186.

[83] F. C. Williams Jr., “Particle-Hole State Density in the Uniform Spacing Model,” Nucl. Phys. **A161** (1971) 231–240.

[84] I. Ribansky, P. Oblozinsky, and E. Betak, “Pre-Equilibrium Decay and the Exciton Model,” Nucl. Phys. **A205** (1973) 545–560.

[85] K. Kikuchi and M. Kawai, *Nuclear Matter and Nuclear Reactions*, North-Holland, Amsterdam (1968).

[86] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, “Monte Carlo Calculations on Intranuclear Cascades. I. Low-Energy Studies,” Phys. Rev. **110** (1958) 185–203.

[87] E. Betak, “Complex Particle Emission in the Exciton Model of Nuclear Reactions,” Acta Phys. Slov. **26** (1976) 21–24.

[88] J. R. Wu and C. C. Chang, “Complex-Particle Emission in the Pre-Equilibrium Exciton Model,” Phys. Rev. C **17** (1978) 1540–1549.

[89] G. Mantzouranis, H. A. Weidenmüller, and D. Agassi, “Generalized Exciton Model for the Description of Preequilibrium Angular Distributions,” Z. Phys. A **276** (1976) 145–154.

[90] C. Kalbach, “Systematics of Continuum Angular Distributions: Extensions to Higher Energies,” Phys. Rev. C **37** (1988) 2350–2370.

[91] V. F. Weisskopf and D. H. Ewing, “On the Yield of Nuclear Reactions with Heavy Elements,” Phys. Rev. **57** (1940) 472–483.

[92] N. Bohr and J. A. Wheeler, “The Mechanism of Nuclear Fission,” Phys. Rev. **56** (1939) 426–450.

[93] A. V. Ignatyuk, G. N. Smirenkin, and A. S. Tishin, “Phenomenological Description of the Energy Dependence of the Level Density Parameter,” Yad. Fiz. **21** (1975) 485–490 [Sov. J. Nucl. Phys. **21** (1975) 255–257]; A. V. Ignatyuk, M. G. Itkis, V. N. Okolovich, G. N. Smirenkin, and A. S. Tishin, “Fission of Pre-Actinide Nuclei. Excitation Functions for the (α, f) Reactions,” Yad. Fiz. **21** (1975) 1185–1205 Sov. J. Nucl. Phys. **21** (1975) 612–621].

[94] A. S. Iljinov, M. V. Mebel, N. Bianchi, E. De Sanctis, C. Guaraldo, V. Lucherini, V. Muccifora, E. Polli, A. R. Reolon, and P. Rossi, "Phenomenological Statistical Analysis of Level Densities, Decay Width and Lifetimes of Excited Nuclei," Nucl. Phys. **A543** (1992) 517–557.

[95] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, "Nuclear Ground-States Masses and Deformations," Atomic Data and Nuclear Data Tables, **59** (1995) 185–381.

[96] P. Möller, J. R. Nix, and K.-L. Kratz, "Nuclear Properties for Astrophysical and Radioactive-Ion-Beam Application," Atomic Data and Nuclear Data Tables, **66** (1997) 131–343.

[97] R. E. Prael and H. Lichtenstein, "User guide to LCS: The LAHET Code System," LANL Report No. LA-UR-89-3014, Los Alamos (1989).

[98] A. Ferrari, J. Ranft, S. Roesler, and P. R. Sala, "Cascade Particles, Nuclear Evaporation, and Residual Nuclei in High Energy Hadron-Nucleus Interactions," Z. Phys. C **70** (1996) 413–426.

[99] M. Veselský, "Production Mechanism of Hot Nuclei in Violent Collisions in the Fermi Energy Domain," Nucl Phys. **A705** (2002) 193–222; M. Veselský, Š. Šáro, F. P. Heßberger, V. Ninov, S. Hofmann, and D. Ackermann, "Production of Fast Evaporation Residues by the Reaction ^{20}Ne + ^{208}Pb at Projectile Energies of 8.6, 11.4 and 14.9 A MeV," Z. Phys. A **356** (1997) 403–410.

[100] M. Böhning, "Density of Particle-hole States in the Equidistant-Spacing Model," Nucl. Phys. **A152** (1970) 529–546.

[101] S. Furihata, "Statistical Analysis of Light Fragment Production from Medium Energy Proton-Induced Reactions," Nucl. Instr. Meth. B **171** (2000) 252–258; "The Gem Code—the Generalized Evaporation Model and the Fission Model," Proc. MC2000, Lisbon, Portugal, 2000, edited by A. Kling, F. J. C. Barão, M. Nakagawa, L. Távora, and P. Vaz, Springer, Berlin, (2001), pp. 1045–1050; "The Gem Code Version 2 Users Manual," Mitsubishi Research Institute, Inc., Tokyo, Japan (November 8, 2001).

[102] S. Furihata, K. Niita, S. Meigo, Y. Ikeda, and F. Maekawa, "The Gem Code—a Simulation Program for the Evaporation and Fission Process of an Excited Nucleus," JAERI-Data/Code 2001-015, JAERI, Tokai-mura, Naka-gam, Ibaraki-ken, Japan (2001).

[103] Shiori Furihata, *Development of a Generalized Evaporation Model and Study of Residual Nuclei Production*, Ph.D. thesis, Tohoku University, March, 2003; S. Furihata and T. Nakamura, "Calculation of Nuclide Production from Proton Induced Reactions on Heavy Targets with INC/GEM," J. Nucl. Sci. Technol. Suppl. **2** (2002) 758–761.

[104] I. Dostrovsky, Z. Frankel, and G. Friedlander, "Monte Carlo Calculations of Nuclear Evaporation Processes. III. Application to Low-Energy Reactions," Phys. Rev. **116** (1959) 683–702.

[105] F. Atchison, "Spallation and Fission in Heavy Metal Nuclei under Medium Energy Proton Bombardment," in Proc. Meeting on Targets for Neutron Beam Spallation Source, Julich,

June 11–12, 1979, pp. 17–46, G. S. Bauer, Ed., Jul-Conf-34, Kernforschungsanlage Julich GmbH, Germany (1980).

[106] F. Atchison, "A Treatment of Fission for HETC," in Intermediate Energy Nuclear Data: Models and Codes, pp. 199–218, Proc. of a Specialists's Meeting, May 30–June 1, 1994, Issy-Les-Moulineaux, France, OECD, Paris, France (1994).

[107] G. Audi and A. H. Wapstra, "The 1995 Update to the Atomic Mass Evaluation," Nucl. Phys. **A595** (1995) 409–480.

[108] P. E. Haustein, "An Overview of the 1986–1987 Atomic Mass Predictions," Atomic Data and Nuclear Data Tables **39** (1988) 185–393.

[109] A. G. W. Cameron, "A Revised Semiempirical Atomic Mass Formula," Can. J. Phys. **35** (1957) 1021–1032.

[110] T. Matsuse, A. Arima, and S. M. Lee, "Critical Distance in Fusion Reactions," Phys. Rev. C **26** (1982) 2338–2341.

[111] A. S. Botvina, A. S. Iljinov, I. N. Mishustin, J. P. Bondorf, R. Donangelo, and K. Snappen, "Statistical Simulation of the Break-up of Highly Excited Nuclei," Nucl. Phys. **A475** (1987) 663–686.

[112] A. Gilbert and A. G. W. Cameron, "A Composite Nuclear-Level Density Formula with Shell Corrections," Can. J. Phys. **43** (1965) 1446–1496.

[113] J. L. Cook, H. Ferguson, and A. R. del Musgrove, "Nuclear Level Densities in Intermediate and Heavy Nuclei," Australian Journal of Physics **20** (1967) 477–487.

[114] W. A. Friedman and W. G. Lynch, "Statistical Formalism for Particle Emission," Phys. Rev. C **28** (1983) 16–23.

[115] The Evaluated Nuclear Structure Data File (ENSDF) maintained by the National Nuclear Data Center (NNDC), Brookhaven National Laboratory, http://www.nndc.bnl.gov/.

[116] S. G. Mashnik, K. K. Gudima, R. E. Prael, and A. J. Sierk, "Analysis of the GSI A+p and A+A Spallation, Fission, and Fragmentation Measurements with the LANL CEM2k and LAQGSM Codes," in Proc. TRAMU@GSI, Darmstadt, Germany, 2003, Eds. A. Kelic and K.-H. Schmidt, ISBN 3-00-012276-1, http://ww-wnt.gsi.de/tramu; E-print: nucl-th/0404018.

[117] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission*, Academic Press, New York (1973).

[118] E. F. Neuzil and A. W. Fairhall, "Fission Product Yields in Helium Ion-Induced Fission of Au^{197}, Pb^{204}, and Pb^{206} Targets," Phys. Rev. **129** (1963) 2705–2710.

[119] A. Ya. Rusanov, M. G. Itkis, and V. N. Okolovich, "Features of Mass Distributions of Hot Rotating Nuclei," Yad. Fiz. **60** (1997) 773–803 [Phys. At. Nucl. **60** (1997) 683–712]; M. G. Itkis, Yu. A. Muzychka, Yu. Ts. Oganesyan, V. N. Okolovich, V. V. Pashkevich, A. Ya. Rusanov, V. S. Salamatin, G. N. Smirenkin, and G. G. Chubaryan, "Fission of Excited Nuclei with Z^2/A =20–33: Mass-Energy Distributions of Fragments, Angular Momentum, and Liquid-Drop Model," Yad. Fiz. **58 (1995)** 2140–2165 [Phys. At. Nucl. **58** (1995) 2026–2051].

[120] W. D. Myers and W. J. Swiatecki, "Thomas-Fermi Fission Barriers," Phys. Rev. C **60** (1999) 014606.

[121] M. G. Itkis, S. M. Luk'yanov, V. N. Okolovich, Yu. E. Penionzhkevich, A. Ya. Rusanov, V. S. Salamatin, G. N. Smirenkin, and G. G. Chubaryan, "Experimental Study of the Mass and Energy Distributions of Fragments from Fission," Ya. Fiz. **52** (1990) 23–35 [Sov. J. Nucl. Phys. **52** (1990) 15–22].

[122] F. Atchison, "A Revised Calculational Model for Fission," Paul Scherrer Insititut Report No. 98-12, Villigen PSI (1998); F. Atchison, "A treatment of medium-energy particle induced fission for spallation-systems' calculations," Nucl. Instrum. Meth. B **259**, 909–932 (2007).

[123] H. W. Bertini, "Low-Energy Intranuclear Cascade Calculation," Phys. Rev. **131** (1963) 1801–1871; "Intranuclear Cascade Calculation of the Secondary Nucleon Spectra from Nucleon-Nucleus Interactions in the Energy Range 340 to 2900 MeV and Comparison with Experiment," Phys. Rev. **188** (1969) 1711–1730.

[124] Y. Yariv and Z. Frankel, "Intranuclear Cascade Calculation of High-Energy Heavy-Ion Interactions," Phys. Rev. C **20** (1979) 2227–2243; "Inclusive Cascade Calculation of High Energy Heavy Ion Collisions: Effect of Interactions between Cascade Particles," Phys. Rev. C **24 (1981)** 488–494.

[125] A. V. Prokofiev, "Compilation and Systematics of Proton-Induced Fission Cross-Section Data," Nucl. Instr. Meth. A **463** (2001) 557–575; A. V. Prokofiev, S. G. Mashnik, and W. B. Wilson, "Systematics of Proton-Induced Fission Cross Sections for Intermediate Energy Applications," LANL Report LA-UR-02-5837, Los Alamos, 2002, E-print: nucl-th/0210071.

[126] E. Fermi, "High Energy Nuclear Events", Prog. Theor. Phys. **5** (1950) 570–583.

[127] G. I. Kopylov, *Principles of Resonance Kinematics*, Moscow, Nauka (1970) [in Russian].

[128] R. K. Tripathi, F. A. Cucinotta, and J. W. Wilson, "Accurate Universal Parameterization of Absorption Cross Sections," Nucl. Instr. Meth. B **117 (1996)** 347–349.

[129] C. Kalbach, "Towards a Global Exciton Model; Lessons at 14 MeV," J. Phys. G **24 (1998)** 847–866.

[130] M. V. Kossov, "Approximation of Photonuclear Interaction Cross-Sections," Eur. Phys. J. A **14** (2002) 377–392.

[131] K. Ukai and T. Nakamura, "Data Compilation of Single Pion Photoproduction Below 2 GeV", INS-T-550, March 1997, Inst. for Nucl. Study, University of Tokyo, and private communication from K. Ukai to SGM (1997).

[132] G. Roy, L. Greeniaus, G. A. Moss, D. A. Hutcheon, R. Liljestrand, R. M. Woloshyn, D. H. Boal, A. W. Stetz, K. Aniol, A. Willis, N. Willis, and R. McCamis, "Inclusive Scattering of Protons on Helium, Nickel, and Tantalum at 500 MeV," Phys. Rev. C **23** (1981) 16711–1678.

[133] J. Ouyang, *Quasi-Free Pion Single Charge Exchange*, Ph.D. thesis U. of Colorado (LANL Report No. LA-12457-T, UC-413, 1992).

[134] Melynda Louise Brooks, *Neutron Induced Pion Production on C, Al, Cu, and W at Neutron Energies of 200–600 MeV*, Ph.D. thesis, U. of New Mexico, (LA-12210-T, UC-910, Oct., 1991, Los Alamos); M. L. Brooks, B. Bassalleck, B. D. Dieterle, R. A. Reeder, D. M. Lee, J. A. McGill, M. E. Schillaci, R. A. Ristinen, and W. R. Smythe, "Neutron Induced Pion Production on C, Al, Cu, and W at 200–600 MeV," Phys. Rev. C **45** (1992) 2343–2354.

[135] T. Nakamoto, K. Ishibashi, N. Matsufuji, N. Shigyo, K. Maehata, H. Arima, S. Meigo, H. Takada, S. Chiba, and M. Numajiri, "Experimental Neutron-Production Double-Differential Cross Section for the Nuclear Reaction by 1.5 GeV π^+ Mesons Incident on Iron," J. Nucl. Sci. and Techn. **34** (1997) 860–862.

[136] P. Staples, N. W. Hill, and P. W. Lisowski, "Fission Cross Section Ratios of ^{nat}Pb and ^{209}Bi Relative to ^{235}U for Neutron Energies from Threshold to 400 MeV," Bull. Am. Phys. Soc., **40** (1995) 962; Parrish Staples and Kevin Morley, "Neutron-Induced Fission Cross-Section Reactions for ^{239}Pu, ^{240}Pu, ^{242}Pu, and ^{244}Pu Relative to ^{235}U from 0.5 to 400 MeV," Nucl. Sci. Eng. **129** (1998) 149–163, and private communication from P. Staples to T-2, LANL, 1996.

[137] A. V. Prokofiev, P.-U. Renberg, and N. Olson, "Measurement of Neutron-Induced Fission Cross Sections for ^{nat}Pb, ^{208}Pb, ^{197}Au, ^{nat}W, and ^{181}Ta in the Intermediate Energy Region," Uppsala University Neutron Physics Report UU-NF 01#6 (March 2001).

[138] A. N. Smirnov, V. P. Eismont, N. P. Filatov, J. Blumgren, H. Condé, A. V. Prokofiev, P.-U. Renberg, and N. Olsson, "Measurements of Neutron-Induced Fission Cross Sections for ^{209}Bi, ^{nat}Pb, ^{208}Pb, ^{197}Au, ^{nat}W, and ^{181}Ta in the Intermediate Energy Region," Phys. Rev. C **70** (2004) 054603.

[139] A. Guertin, N. Marie, S. Auduc, V. Blideanu, Th. Delbar, P. Eudes, Y. Foucher, F. Haddad, T. Kirchner, Ch. Le Brun, C. Lebrun, F. R. Lecolley, J. F. Lecolley, X. Ledoux, F. Lefèbvres, T. Lefort, M. Louvel, A. Ninane, Y. Patin, Ph. Pras, G. Rivière, and C. Varignon, "Neutron and Light-Charged-Particle Productions in Proton-Induced Reactions on ^{208}Pb at 62.9 MeV," Eur. Phys. J. **A23** (2005) 49–60.

[140] F. Rejmund, B. Mustapha, P. Armbruster, J. Benlliure, M. Bernas, A. Boudard, J. P. Dufour, T. Enqvist, R. Legrain, S. Leray, K.-H. Schmidt, C. Stéphan, J. Taieb, L. Tassan-Got, and C. Volant, "Measurement of Isotopic Cross Sections of Spallation Residues in 800 A MeV ^{197}Au + p Collisions," Nucl. Phys. **A683** (2001) 540–565; J. Benlliure, P. Armbruster, M. Bernas, A. Boudard, J. P. Dufour, T. Enqvist, R. Legrain, S. Leray, B. Mustapha, F. Rejmund, K.-H. Schmidt, C. Stéphan, L. Tassan-Got, and C. Volant, "Isotopic Production Cross Sections of Fission Residues in ^{197}Au-on-Proton Collisions at 800 A MeV," Nucl. Phys. **A683** (2001) 513–539.

[141] Carmen Villagrasa-Canton, "Etude de la production des noyaux résiduels dans la réaction de spallation Fe + p à 5 énergies (300–1500 MeV/A) et application au calcul de dommage sur une fenêtre de système hybride," PhD Thesis, Universite de Paris XI Orsay, December

5, 2003, http://www-w2k.gsi.de/charms/theses.htm, and private communication from Dr. Villagrasa to SGM, March 11, 2004.

[142] Paolo Napolitani, "New Findings on the Onset of Thermal Disassembly in Spallation Reactions," PhD Thesis, University Paris XI Orsay, IPNO-T-04-14, September 24, 2004; P. Napolitani, K.-H. Schmidt, A. S. Botvina, F. Rejmund, L. Tassan-Got, and C. Villagrasa, "High-Resolution Velocity Measurements on Fully Identified Light Nuclides Produced in ^{56}Fe + Hydrogen and ^{56}Fe + Titanium Systems," Phys. Rev. C **70** (2004) 054607.

[143] R. A. Schumacher, G. S. Adams, D. R. Ingham, J. L. Matthews, W. W. Sapp, R. S. Turley, R. O. Owens, and B. L. Roberts, "Cu(γ, p)X Reaction at $E_\gamma = 150$ and 300 MeV," Phys. Rev. C **25** (1982) 2269–2277.

[144] Koh Sakamoto, "Radiochemical Study on Photonuclear Reactions of Complex Nuclei at Intermediate Energies," J. Nucl. Radiochem. Sci. **4** (2003) A9–A31; http://www.radiochem.org/j-online.html.

Appendix 1

CEM03.03 Input Example 1

```
p500Ni6.inf                    /File name for diagnostic output. (<31 char.)
p500Ni6.res                    /File name for results of calculation. (<31 char.)
prot    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
500.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
58.    /anucl/  target mass number
28.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-20.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
500.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
60.0 70.0 85.0 95.0 115.0 125.0 155.0 165.0 -5.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 22. 1. 22. 100. 3. 100. 500. 10. 500. 5000. 200. /tmin, tmax, dt, j=1-4/
6      /nevtype/ number of evaporated particle types (see table in bldatgem.f).
1       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
1       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 1: Proton spectra from 500 MeV p + Ni58; 10,000 events.
stop
```

CEM03.03 Input Example 2

```
pim500Cu.inf                   /File name for diagnostic output. (<31 char.)
pim500Cu.res                    /File name for results of calculation. (<31 char.)
pimi    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
500.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
64.    /anucl/  target mass number
29.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-20.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
500.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
1      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
8 8  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 45.0 55.0 65.0 75.0 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 10. 500. 600. 10. 600. 700. 10. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6      /nevtype/ number of evaporated particle types (see table in bldatgem.f).
2       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
1       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 2: pi0 spectra from 500 MeV pi- + Cu64; 10,000 events.
stop
```

CEM03.03 Input Example 3

```
n562Cu.inf                        /File name for diagnostic output. (<31 char.)
n562Cu.res                        /File name for results of calculation. (<31 char.)
neut    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
562.5  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
64.    /anucl/  target mass number
29.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-10.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
600.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
9 9  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 55.0 65.0 75.0 85.0 115.0 125.0 -5.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 20. 500. 600. 20. 600. 700. 20. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
4       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
1       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 3: pi+ spectra from 562.5 MeV n + Cu64; 10,000 events.
stop
```

CEM03.03 Input Example 4

```
pip1_5Fe.inf                   /File name for diagnostic output. (<31 char.)
pip1_5Fe.res                   /File name for results of calculation. (<31 char.)
pipl    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
1500.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
56.    /anucl/  target mass number
26.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-10.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
1600.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
1 1  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 85.0 95.0 145.0 155.0 -15.0 125.0 -5.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 10. 1. 10. 100. 10. 100. 1500. 100. 1500. 5000. 200. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
3       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
1       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 4: Neutron spectra from 1.5 GeV pi+ + Fe56; 10,000 events.
stop
```

CEM03.03 Input Example 5

```
nAu6.inf                        /File name for diagnostic output. (<31 char.)
nAu6.res                        /File name for results of calculation. (<31 char.)
neut    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
30.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
197.    /anucl/  target mass number
79.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
10.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
300.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
0      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 45.0 55.0 65.0 75.0 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 10. 500. 600. 10. 600. 700. 10. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
2       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
2       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 5: Fission cross section of Au197 bombarded with
neutrons from 30 to 300 MeV with a step of 10 MeV; 10,000 events.
stop
```

CEM03.03 Input Example 6

```
p62_9Pb6.inf                  /File name for diagnostic output. (<31 char.)
p62_9Pb6.res                  /File name for results of calculation. (<31 char.)
prot    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
62.9  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
208.    /anucl/  target mass number
82.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-10.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
200.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
1      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
1      /mang/   (0/1,2) if angular distributions (are not/are) needed
1 6  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
22.5 27.5 52.5 57.5 72.5 77.5 92.5 97.5 112.5 117.5 152.5 157.5 -5.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 22. 1. 22. 120. 2. 120. 400. 10. 400. 1000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
6       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
2       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 6: Energy, angular, and double-differential spectra
of n to He from 62.9 MeV p  + Pb208;  100,000 events;
stop
```

CEM03.03 Input Example 7

```
p800Au6.inf                    /File name for diagnostic output. (<31 char.)
p800Au6.res                    /File name for results of calculation. (<31 char.)
prot    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
800.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
197.    /anucl/  target mass number
79.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-20.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
1000.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
1      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
0      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 45.0 55.0 65.0 75.0 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 10. 500. 600. 10. 600. 700. 10. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
7       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
2       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 7: xsec and kinetic energy of all products measured
at GSI in inverse kinematics for 800 MeV p + Au197; 10,000 events.
stop
```

CEM03.03 Input Example 8

```
p1000Fe6.inf                   /File name for diagnostic output. (<31 char.)
p1000Fe6.res                   /File name for results of calculation. (<31 char.)
prot    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
1000.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
56.    /anucl/  target mass number
26.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-20.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
1000.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,3) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
3      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
0      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 45.0 55.0 65.0 75.0 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 10. 500. 600. 10. 600. 700. 10. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
5       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
3       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 8: Yields, mean kinetic energy, angles of emission,
and much more (the most complete output) of all products measured
at GSI in inverse kinematics for 1000 MeV p + Fe56; 10,000 events.
stop
```

CEM03.03 Input Example 9

```
g300Cu.inf                    /File name for diagnostic output. (<31 char.)
g300Cu.res                    /File name for results of calculation. (<31 char.)
gamm    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
300.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
64.    /anucl/  target mass number
29.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-5.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
300.5  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
0      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
1      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
42.5 47.5 87.5 92.5 132.5 137.5 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 22. 1. 22. 120. 2. 120. 400. 10. 400. 1000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
3       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
2       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 9: Proton spectra from monochromatic 300 MeV gamma + 64Cu;
10,000 events.
stop
```

CEM03.03 Input Example 10

```
b1000Au6.inf                  /File name for diagnostic output. (<31 char.)
b1000Au6.res                  /File name for results of calculation. (<31 char.)
gamb    /pname/ projectile particle name:
              prot - proton, neut - neutron, pipl - pi+, pimi - pi-, pize - pi0,
              gamm - gamma with fixed energy, gamb - bremss. gamma, stop - no more calc.
30.0  /t0mev/  minimum (initial) projectile kinetic energy in MeV; [tgmin for gamb]
197.    /anucl/  target mass number
79.    /znucl/  target atomic number
10000  /limc/   total number of inelastic events, normally 2000-500000
-20.    /dt0/    projectile kinetic energy step-size in MeV [Only 1 energy if <0.]
1000.0  /t0max/  maximum (final) projectile kinetic energy in MeV, [tgmax for gamb]
10.    /dteta/  step-size (degrees) in ejectile angular distributions [mang > 0]
0      /mspec/  (0/1,2) if ejectile energy spectra (are not/are) needed
1      /mpyld/  (0/1,2) if particle yield tables (are not/are) needed
0      /mchy/   (0/1) if particle channel yields (are not/are) needed
3      /misy/   (0/1,2,3) if isotope yields (are not/are) needed
0      /mdubl/  (0/1,2) if double differential spectra (are not/are) needed
0      /mang/   (0/1,2) if angular distributions (are not/are) needed
2 2  /ipar1,ipar2/ range of ejectile types for spectrum calcs. [Below, ang. bins for mdubl > 0]
25.0 35.0 45.0 55.0 65.0 75.0 -55.0 165.0 55.0 65.0 75.0 85.0 95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0
0. 500. 10. 500. 600. 10. 600. 700. 10. 700. 5000. 20. /tmin, tmax, dt, j=1-4/
6     /nevtype/ number of evaporated particle types (see table in bldatgem.f).
3       /ityp/   Version of the random no. generator used; 1-7 OK; default 1
4       /nh/     Lines of text (<11) to be read in; printed on results file (line 2).
Example No. 10: Yields, mean kinetic energy, emission angles,
neutron multiplicities, Forward/Backward ratios, and much more
(the most complete output) of all products from E_max = 1000 MeV
bremsstrahlung gammas + 197Au; 10,000 events.
stop
```

Appendix 2

To save space, parts of long tables shown in all 10 examples of the CEM03.03 output are deleted and replaced here with dashed lines, keeping only the first two and the last two lines of each table. We also deleted the Copyright Notice and the information about the level-density parameter used in the preequilibrium calculations in all examples except the first one.

CEM03.03 Output Example 1


```
          The primary authors of CEM03.03 are: S. G. Mashnik (LANL),
     K. K. Gudima (IAP), and A. J. Sierk (LANL); with important contributions
     from R. E. Prael (LANL), M. I. Baznat (IAP), and N. V. Mokhov (Fermilab).
     (IAP = Institute of Applied Physics, Academy of Science of Moldova.)

 -----------------------------------------------------------------------------

 Wed Feb  1 10:54:48 2012

Example No. 1: Proton spectra from 500 MeV p + Ni58; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9383 0.5000   58.  28.  1  1   10000   1

 dt0 =  -20.0, t0max =  500.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     0     1     0     2     2

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  60.0  70.0  85.0  95.0 115.0 125.0 155.0 165.0  -5.0  65.0  75.0  85.0

    Theta7      Theta8      Theta9     Theta10
  95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0  22.0  1.00  22.0 100.0  3.00  100.  500.  10.0  500. 5000.  200.

 lim =     100000 .

 Geometrical cross section = 1387.69 mb.
 Calculation takes into account fission and evaporation processes
 using Furihata-s GEM2 code.
 The following level density parameters were used in
 the preequilibrium part of this calculation:
 a(Z,N,E) was calculated with Moller, Nix, Myers & Swiatecki microscopic
 corrections; [Atomic Data Nucl. Data Tables, 59, 185 (1995)];
 Level density is from a shifted Fermi-gas formula, with the shift given by
  0, delta-p, delta-n, or delta-p + delta-n, for odd-odd; odd-n, even-p;
 odd-p, even-n; and even-even nuclei, respectively for the compound
 nucleus, and similarly using deltaM-p and deltaM-n for the saddle point.
 delta-n and delta-p are tabulated by Moller, Nix & Kratz and
 deltaM-n and deltaM-p are 4.80 MeV * Bs * {1/N**(1/3) or 1/Z**(1/3)}.
 Bs is the surface area of the saddle-point shape with respect to a sphere.

   Inelastic cross section used here =  684.39 mb
```

```
Monte Carlo inelastic cross section =  700.61 mb

    Wed Feb  1 10:54:48 2012

               500.0 MeV (Z =  1, A = 1) + (Z = 28., A =  58.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     9807,

Reaction cross section =  684.39 mb, Elastic cross section =  671.18 mb.

 The mean excitation energy, charge, mass, and angular momentum
 of the    10000 nuclei after the
 cascade and before preequilibrium decay are:
 E*av =  84.4 +/- 74.1 MeV;  E*min =  -3.4;  E*max = 459.1
  Zav =  27.2 +/-  1.1;       Zmin =  21.;    Zmax =  30.
  Aav =  55.8 +/-  1.6;       Amin =  49.;    Amax =  58.
  Lav =   5.3 +/-  3.4 h-bar; Lmin =   0.;    Lmax =  22.

 The mean charge, mass, and angular momentum
 of the     526 residual nuclei with less than
 3 MeV of excitation energy after the cascade are:
  Zav =  28.1 +/-  0.2;       Zmin =  28.;   Zmax =  29.
  Aav =  57.1 +/-  0.4;       Amin =  55.;   Amax =  58.
  Lav =   2.4 +/-  1.6 h-bar; Lmin =   0.;   Lmax =  10.

 The mean excitation energy, charge, mass, and angular momentum
 of the    9474 nuclei after preequilibrium
 decay and before the start of statistical decay are:
 E*av =  72.5 +/-  62.0 MeV; E*min =   0.8;  E*max = 444.7
  Zav =  26.7 +/-  1.3;       Zmin =  18.;   Zmax =  30.
  Aav =  55.0 +/-  2.3;       Amin =  42.;   Amax =  58.
  Lav =   6.1 +/-  4.2 h-bar; Lmin =   0.;   Lmax =  34.

 The mean kinetic energy, charge, mass, and angular momentum
 of the   10000 residual nuclei are:
 Ekav =   2.6 +/-  3.4 MeV;  Ekmin =  0.0;  Ekmax =  41.7
  Zav =  23.7 +/-  3.4;       Zmin =   9.;   Zmax =  29.
  Aav =  49.5 +/-  6.8;       Amin =  18.;   Amax =  58.
  Lav =   5.9 +/-  4.2 h-bar; Lmin =   0.;   Lmax =  34.

Number of coalesced d, t, He3, He4 =     2371     423     364     159

Mean multiplicities, yields, and mean energies of ejected particles:
(Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
Sp - from spallation residues, Pf - from nuclei before fission,
F - from fission fragments, E - total evaporation = Sp + Pf + F,
Co - Coalescence from cascade;
Values which are identically zero are not printed.

Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
*****************************************************************
T  n     2.4439 +/- 0.0156    1672.582 +/-  10.699     55.04
C  n     1.0507 +/- 0.0103     719.089 +/-   7.015    120.68
P  n     0.1001 +/- 0.0032      68.507 +/-   2.165     17.56
Sp n     1.2931 +/- 0.0114     884.985 +/-   7.783      4.61
E  n     1.2931 +/- 0.0114     884.985 +/-   7.783      4.61
*****************************************************************
T  p     3.4956 +/- 0.0187    2392.355 +/-  12.796     66.35
C  p     1.4094 +/- 0.0119     964.580 +/-   8.125    151.94
P  p     0.1493 +/- 0.0039     102.180 +/-   2.644     19.94
Sp p     1.9369 +/- 0.0139    1325.596 +/-   9.525      7.65
E  p     1.9369 +/- 0.0139    1325.596 +/-   9.525      7.65
*****************************************************************
T  d     0.5766 +/- 0.0076     394.620 +/-   5.197     31.13
P  d     0.0884 +/- 0.0030      60.500 +/-   2.035     22.84
Sp d     0.2511 +/- 0.0050     171.850 +/-   3.429      9.71
E  d     0.2511 +/- 0.0050     171.850 +/-   3.429      9.71
Co d     0.2371 +/- 0.0049     162.269 +/-   3.332     56.91
*****************************************************************
T  t     0.1015 +/- 0.0032      69.466 +/-   2.180     24.01
P  t     0.0250 +/- 0.0016      17.110 +/-   1.082     27.67
Sp t     0.0342 +/- 0.0018      23.406 +/-   1.266     10.44
E  t     0.0342 +/- 0.0018      23.406 +/-   1.266     10.44
Co t     0.0423 +/- 0.0021      28.950 +/-   1.408     32.81
*****************************************************************
T He3    0.1114 +/- 0.0033      76.241 +/-   2.284     26.77
P He3    0.0288 +/- 0.0017      19.710 +/-   1.161     30.48
SpHe3    0.0462 +/- 0.0021      31.619 +/-   1.471     13.61
E He3    0.0462 +/- 0.0021      31.619 +/-   1.471     13.61
CoHe3    0.0364 +/- 0.0019      24.912 +/-   1.306     40.53
*****************************************************************
T He4    0.4321 +/- 0.0066     295.725 +/-   4.499     14.08
P He4    0.0233 +/- 0.0015      15.946 +/-   1.045     40.15
SpHe4    0.3929 +/- 0.0063     268.897 +/-   4.290     11.91
E He4    0.3929 +/- 0.0063     268.897 +/-   4.290     11.91
CoHe4    0.0159 +/- 0.0013      10.882 +/-   0.863     29.37
*****************************************************************
pi-      0.0214 +/- 0.0015      14.646 +/-   1.001     49.69
pi0      0.0591 +/- 0.0024      40.447 +/-   1.664     55.57
pi+      0.0439 +/- 0.0021      30.045 +/-   1.434     50.98
*****************************************************************

**********************************  protons   ********************************

Double differential cross sections [mb/MeV/sr];
```

```
Lab. angle =  60.0 to  70.0 degrees.

   Tp  [MeV]          Total               Cascade              Precompound       Total Evaporation
   1.0-   2.0  6.895E-02 +/- 6.89E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 6.895E-02 +/- 6.89E-02
   2.0-   3.0  2.068E+00 +/- 3.78E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.068E+00 +/- 3.78E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 290.0- 300.0  6.895E-03 +/- 6.89E-03 6.895E-03 +/- 6.89E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 300.0- 310.0  6.895E-03 +/- 6.89E-03 6.895E-03 +/- 6.89E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   2.155E+02 +/- 3.85E+00 9.680E+01 +/- 2.58E+00 9.653E+00 +/- 8.16E-01 1.090E+02 +/- 2.74E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  85.0 to  95.0 degrees.

   Tp  [MeV]          Total               Cascade              Precompound       Total Evaporation
   1.0-   2.0  4.374E-01 +/- 1.65E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.374E-01 +/- 1.65E-01
   2.0-   3.0  2.562E+00 +/- 4.00E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.562E+00 +/- 4.00E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 220.0- 230.0  6.249E-03 +/- 6.25E-03 6.249E-03 +/- 6.25E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 230.0- 240.0  6.249E-03 +/- 6.25E-03 6.249E-03 +/- 6.25E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   1.521E+02 +/- 3.08E+00 3.868E+01 +/- 1.55E+00 8.186E+00 +/- 7.15E-01 1.052E+02 +/- 2.56E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle = 115.0 to 125.0 degrees.

   Tp  [MeV]          Total               Cascade              Precompound       Total Evaporation
   1.0-   2.0  2.886E-01 +/- 1.44E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.886E-01 +/- 1.44E-01
   2.0-   3.0  4.113E+00 +/- 5.45E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.113E+00 +/- 5.45E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 140.0- 150.0  1.443E-02 +/- 1.02E-02 1.443E-02 +/- 1.02E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 150.0- 160.0  7.216E-03 +/- 7.22E-03 7.216E-03 +/- 7.22E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   1.123E+02 +/- 2.85E+00 1.306E+01 +/- 9.71E-01 6.133E+00 +/- 6.65E-01 9.308E+01 +/- 2.59E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle = 155.0 to 165.0 degrees.

   Tp  [MeV]          Total               Cascade              Precompound       Total Evaporation
   1.0-   2.0  5.481E-01 +/- 3.16E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 5.481E-01 +/- 3.16E-01
   2.0-   3.0  6.212E+00 +/- 1.07E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 6.212E+00 +/- 1.07E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 120.0- 130.0  1.827E-02 +/- 1.83E-02 1.827E-02 +/- 1.83E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 130.0- 140.0  1.827E-02 +/- 1.83E-02 1.827E-02 +/- 1.83E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   1.063E+02 +/- 4.41E+00 8.222E+00 +/- 1.23E+00 2.375E+00 +/- 6.59E-01 9.574E+01 +/- 4.18E+00

Elapsed cpu time  =  0. min and  4.440 sec.
```

CEM03.03 Output Example 2

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:55:24 2012

Example No. 2: pi0 spectra from 500 MeV pi- + Cu64; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.1396 0.5000   64.  29. -1  0   10000   1

 dt0 =  -20.0, t0max =  500.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    1     1     0     0     1     0     8     8

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  25.0  35.0  45.0  55.0  65.0  75.0 -55.0 165.0  55.0  65.0  75.0  85.0

    Theta7      Theta8      Theta9     Theta10
  95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0 500.0 10.00 500.0 600.0 10.00  600.  700.  10.0  700. 5000.   20.

 lim =     100000 .

 Geometrical cross section = 1445.99 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here =  667.09 mb
 Monte Carlo inelastic cross section =  667.09 mb

     Wed Feb  1 10:55:24 2012

              500.0 MeV (Z = -1, A = 0) + (Z = 29., A =  64.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =    11676,

 Reaction cross section =  667.09 mb, Elastic cross section =  778.90 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av = 104.5 +/- 91.2 MeV;  E*min =  -3.7;  E*max = 525.5
   Zav =  27.7 +/-  1.2;       Zmin =  21.;    Zmax =  30.
   Aav =  60.8 +/-  2.4;       Amin =  52.;    Amax =  64.
   Lav =   5.1 +/-  3.1 h-bar; Lmin =   0.;    Lmax =  23.

  The mean charge, mass, and angular momentum
  of the     465 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  28.9 +/-  0.3;       Zmin =  27.;   Zmax =  29.
   Aav =  62.9 +/-  0.5;       Amin =  59.;   Amax =  64.
   Lav =   2.5 +/-  1.5 h-bar; Lmin =   0.;   Lmax =  11.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9535 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  90.7 +/-  79.7 MeV; E*min =   0.4;  E*max = 523.5
   Zav =  27.2 +/-  1.6;       Zmin =  19.;   Zmax =  30.
   Aav =  59.9 +/-  3.1;       Amin =  45.;   Amax =  64.
   Lav =   6.2 +/-  4.1 h-bar; Lmin =   0.;   Lmax =  39.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   2.4 +/-  3.1 MeV;  Ekmin =  0.0;  Ekmax =  29.4
   Zav =  24.7 +/-  3.8;       Zmin =   8.;   Zmax =  29.
   Aav =  53.2 +/-  8.5;       Amin =  16.;   Amax =  64.
   Lav =   6.0 +/-  4.1 h-bar; Lmin =   0.;   Lmax =  39.

 Number of coalesced d, t, He3, He4 =     2275     674     151     161

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     4.9853 +/- 0.0223    3325.656 +/-  14.895     27.27
 C  n     1.9559 +/- 0.0140    1304.766 +/-   9.330     60.84
 P  n     0.1723 +/- 0.0042     114.940 +/-   2.769     18.00
 Sp n     2.8571 +/- 0.0169    1905.950 +/-  11.276      4.84
 E  n     2.8571 +/- 0.0169    1905.950 +/-  11.276      4.84
 *****************************************************************
 T  p     1.8209 +/- 0.0135    1214.709 +/-   9.002     30.42
 C  p     0.4589 +/- 0.0068     306.129 +/-   4.519     92.48
 P  p     0.1112 +/- 0.0033      74.181 +/-   2.225     22.11
```

```
Sp p     1.2508 +/- 0.0112     834.399 +/-   7.461      8.40
E  p     1.2508 +/- 0.0112     834.399 +/-   7.461      8.40
*****************************************************************
T  d     0.6753 +/- 0.0082     450.487 +/-   5.482     24.57
P  d     0.0965 +/- 0.0031      64.374 +/-   2.072     24.00
Sp d     0.3543 +/- 0.0060     236.351 +/-   3.971     10.22
E  d     0.3543 +/- 0.0060     236.351 +/-   3.971     10.22
Co d     0.2245 +/- 0.0047     149.762 +/-   3.161     47.46
*****************************************************************
T  t     0.1886 +/- 0.0043     125.814 +/-   2.897     22.88
P  t     0.0436 +/- 0.0021      29.085 +/-   1.393     30.52
Sp t     0.0793 +/- 0.0028      52.900 +/-   1.879     10.59
E  t     0.0793 +/- 0.0028      52.900 +/-   1.879     10.59
Co t     0.0657 +/- 0.0026      43.828 +/-   1.710     32.64
*****************************************************************
T He3    0.0831 +/- 0.0029      55.435 +/-   1.923     24.21
P He3    0.0291 +/- 0.0017      19.412 +/-   1.138     30.80
SpHe3    0.0393 +/- 0.0020      26.217 +/-   1.322     14.42
E He3    0.0393 +/- 0.0020      26.217 +/-   1.322     14.42
CoHe3    0.0147 +/- 0.0012       9.806 +/-   0.809     37.33
*****************************************************************
T He4    0.4460 +/- 0.0067     297.523 +/-   4.455     14.22
P He4    0.0254 +/- 0.0016      16.944 +/-   1.063     38.67
SpHe4    0.4047 +/- 0.0064     269.972 +/-   4.244     12.28
E He4    0.4047 +/- 0.0064     269.972 +/-   4.244     12.28
CoHe4    0.0159 +/- 0.0013      10.607 +/-   0.841     24.52
*****************************************************************
pi-      0.5456 +/- 0.0074     363.966 +/-   4.927    281.44
pi0      0.2766 +/- 0.0053     184.518 +/-   3.508    152.66
pi+      0.0602 +/- 0.0025      40.159 +/-   1.637     78.51
*****************************************************************

********************************** neut pions ********************************

-------------------------- Energy Spectrum [mb/MeV] -------------------------
    Energy spectrum from   0.0 to  570.0 MeV (zero values suppressed).

   Tpi0[MeV]      Total = Cascade
   0.0-  10.0  8.072E-01 +/- 7.34E-02
  10.0-  20.0  1.181E+00 +/- 8.88E-02
- - - - - - - - - - - - - - - - - - -
 480.0- 490.0  1.868E-01 +/- 3.53E-02
 490.0- 500.0  2.001E-02 +/- 1.16E-02

 Integrated:   1.845E+02 +/- 3.51E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  25.0 to  35.0 degrees.

   Tpi0[MeV]      Total = Cascade
  10.0-  20.0  8.527E-02 +/- 3.22E-02
  20.0-  30.0  7.309E-02 +/- 2.98E-02
- - - - - - - - - - - - - - - - - - -
 470.0- 480.0  1.096E-01 +/- 3.65E-02
 480.0- 490.0  3.655E-02 +/- 2.11E-02

 Integrated:   3.119E+01 +/- 1.95E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  45.0 to  55.0 degrees.

   Tpi0[MeV]      Total = Cascade
   0.0-  10.0  5.566E-02 +/- 2.10E-02
  10.0-  20.0  7.156E-02 +/- 2.39E-02
- - - - - - - - - - - - - - - - - - -
 440.0- 450.0  1.590E-02 +/- 1.12E-02
 460.0- 470.0  7.951E-03 +/- 7.95E-03

 Integrated:   1.558E+01 +/- 1.11E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  65.0 to  75.0 degrees.

   Tpi0[MeV]      Total = Cascade
   0.0-  10.0  7.130E-02 +/- 2.15E-02
  10.0-  20.0  9.723E-02 +/- 2.51E-02
- - - - - - - - - - - - - - - - - - -
 410.0- 420.0  6.482E-03 +/- 6.48E-03
 420.0- 430.0  6.482E-03 +/- 6.48E-03

 Integrated:   1.458E+01 +/- 9.72E-01

Elapsed cpu time  =  0. min and  5.228 sec.
```

CEM03.03 Output Example 3

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:49:14 2012

Example No. 3: pi+ spectra from 562.5 MeV n + Cu64; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9396 0.5625   64.  29.  0  1   10000   1

 dt0 =  -10.0, t0max =  600.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     0     1     0     9     9

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  25.0  35.0  55.0  65.0  75.0  85.0 115.0 125.0  -5.0  65.0  75.0  85.0

    Theta7      Theta8      Theta9     Theta10
  95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0 500.0 20.00 500.0 600.0 20.00  600.  700.  20.0  700. 5000.   20.

 lim =     100000 .

 Geometrical cross section = 1445.99 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here =  807.64 mb
 Monte Carlo inelastic cross section =  759.57 mb

     Wed Feb  1 10:49:14 2012

               562.5 MeV (Z =  0, A = 1) + (Z = 29., A =  64.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =     9037,

 Reaction cross section =  807.64 mb, Elastic cross section =  729.86 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av =  94.2 +/- 79.6 MeV;  E*min =  -2.2;  E*max = 491.0
   Zav =  28.0 +/-  1.0;       Zmin =  23.;    Zmax =  30.
   Aav =  61.3 +/-  1.9;       Amin =  52.;    Amax =  65.
   Lav =   5.8 +/-  3.7 h-bar; Lmin =   0.;    Lmax =  25.

  The mean charge, mass, and angular momentum
  of the     460 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  29.0 +/-  0.0;       Zmin =  28.;   Zmax =  29.
   Aav =  63.0 +/-  0.3;       Amin =  60.;   Amax =  64.
   Lav =   2.3 +/-  1.3 h-bar; Lmin =   0.;   Lmax =   8.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9539 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  80.8 +/-  68.3 MeV; E*min =   0.2;  E*max = 480.2
   Zav =  27.6 +/-  1.3;       Zmin =  21.;   Zmax =  30.
   Aav =  60.4 +/-  2.6;       Amin =  47.;   Amax =  65.
   Lav =   6.6 +/-  4.4 h-bar; Lmin =   0.;   Lmax =  32.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   2.6 +/-  3.6 MeV;  Ekmin =  0.0;  Ekmax =  42.0
   Zav =  25.3 +/-  3.2;       Zmin =  11.;   Zmax =  30.
   Aav =  54.4 +/-  7.2;       Amin =  24.;   Amax =  64.
   Lav =   6.4 +/-  4.4 h-bar; Lmin =   0.;   Lmax =  32.

 Number of coalesced d, t, He3, He4 =     2439     642     189     169

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     4.9561 +/- 0.0223    4002.731 +/-  17.980     59.51
 C  n     2.2003 +/- 0.0148    1777.044 +/-  11.980    127.55
 P  n     0.1585 +/- 0.0040     128.010 +/-   3.215     17.19
 Sp n     2.5973 +/- 0.0161    2097.676 +/-  13.016      4.45
 E  n     2.5973 +/- 0.0161    2097.676 +/-  13.016      4.45
 *****************************************************************
 T  p     2.0272 +/- 0.0142    1637.242 +/-  11.499     53.37
 C  p     0.6935 +/- 0.0083     560.096 +/-   6.726    138.41
 P  p     0.1168 +/- 0.0034      94.332 +/-   2.760     20.76
```

```
Sp p     1.2169 +/- 0.0110     982.814 +/-   8.909      8.04
E  p     1.2169 +/- 0.0110     982.814 +/-   8.909      8.04
*****************************************************************
T  d     0.6273 +/- 0.0079     506.631 +/-   6.397     32.05
P  d     0.0962 +/- 0.0031      77.695 +/-   2.505     23.06
Sp d     0.2875 +/- 0.0054     232.196 +/-   4.330     10.04
E  d     0.2875 +/- 0.0054     232.196 +/-   4.330     10.04
Co d     0.2436 +/- 0.0049     196.740 +/-   3.986     61.58
*****************************************************************
T  t     0.1579 +/- 0.0040     127.526 +/-   3.209     24.01
P  t     0.0369 +/- 0.0019      29.802 +/-   1.551     25.78
Sp t     0.0570 +/- 0.0024      46.035 +/-   1.928     10.59
E  t     0.0570 +/- 0.0024      46.035 +/-   1.928     10.59
Co t     0.0640 +/- 0.0025      51.689 +/-   2.043     34.94
*****************************************************************
T He3    0.0769 +/- 0.0028      62.107 +/-   2.240     27.51
P He3    0.0268 +/- 0.0016      21.645 +/-   1.322     28.80
SpHe3    0.0312 +/- 0.0018      25.198 +/-   1.427     14.44
E He3    0.0312 +/- 0.0018      25.198 +/-   1.427     14.44
CoHe3    0.0189 +/- 0.0014      15.264 +/-   1.110     47.24
*****************************************************************
T He4    0.4096 +/- 0.0064     330.808 +/-   5.169     14.61
P He4    0.0235 +/- 0.0015      18.979 +/-   1.238     38.69
SpHe4    0.3692 +/- 0.0061     298.180 +/-   4.907     12.50
E He4    0.3692 +/- 0.0061     298.180 +/-   4.907     12.50
CoHe4    0.0169 +/- 0.0013      13.649 +/-   1.050     27.08
*****************************************************************
pi-      0.0908 +/- 0.0030      73.333 +/-   2.434     67.85
pi0      0.0869 +/- 0.0029      70.184 +/-   2.381     64.14
pi+      0.0162 +/- 0.0013      13.084 +/-   1.028     56.27
*****************************************************************

********************************** pos. pions ********************************

Double differential cross sections [mb/MeV/sr];
Lab. angle =  25.0 to  35.0 degrees.

   Tpi+[MeV]      Total = Cascade
  40.0-  60.0  7.374E-03 +/- 7.37E-03
 100.0- 120.0  7.374E-03 +/- 7.37E-03
- - - - - - - - - - - - - - - - - - - -
 180.0- 200.0  1.475E-02 +/- 1.04E-02
 220.0- 240.0  7.374E-03 +/- 7.37E-03

 Integrated:   1.180E+00 +/- 4.17E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  55.0 to  65.0 degrees.

   Tpi+[MeV]      Total = Cascade
   0.0-  20.0  1.703E-02 +/- 8.51E-03
  20.0-  40.0  1.277E-02 +/- 7.37E-03
  40.0-  60.0  1.277E-02 +/- 7.37E-03
 100.0- 120.0  4.257E-03 +/- 4.26E-03

 Integrated:   9.366E-01 +/- 2.82E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  75.0 to  85.0 degrees.

   Tpi+[MeV]      Total = Cascade
   0.0-  20.0  1.123E-02 +/- 6.48E-03
  20.0-  40.0  1.123E-02 +/- 6.48E-03
- - - - - - - - - - - - - - - - - - - -
 120.0- 140.0  3.744E-03 +/- 3.74E-03
 140.0- 160.0  3.744E-03 +/- 3.74E-03

 Integrated:   9.734E-01 +/- 2.70E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle = 115.0 to 125.0 degrees.

   Tpi+[MeV]      Total = Cascade
   0.0-  20.0  2.980E-02 +/- 1.13E-02
  20.0-  40.0  1.277E-02 +/- 7.37E-03
  40.0-  60.0  8.515E-03 +/- 6.02E-03

 Integrated:   1.022E+00 +/- 2.95E-01

Elapsed cpu time  =  0. min and  4.865 sec.
```

CEM03.03 Output Example 4

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:55:39 2012

Example No. 4: Neutron spectra from 1.5 GeV pi+ + Fe56; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.1396 1.5000   56.  26.  1  0   10000   1

 dt0 =  -10.0, t0max = 1600.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     0     1     0     1     1

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  25.0  35.0  85.0  95.0 145.0 155.0 -15.0 125.0  -5.0  65.0  75.0  85.0

    Theta7      Theta8      Theta9     Theta10
  95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0  10.0  1.00  10.0 100.0 10.00  100. 1500. 100.0 1500. 5000.  200.

 lim =     100000 .

 Geometrical cross section = 1367.65 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here =  678.77 mb
 Monte Carlo inelastic cross section =  678.77 mb

     Wed Feb  1 10:55:39 2012

              1500.0 MeV (Z =  1, A = 0) + (Z = 26., A =  56.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =    10149,

 Reaction cross section =  678.77 mb, Elastic cross section =  688.88 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av = 214.9 +/-167.5 MeV;  E*min =  -3.5;  E*max = 967.8
   Zav =  23.9 +/-  1.9;       Zmin =  15.;    Zmax =  29.
   Aav =  50.2 +/-  4.1;       Amin =  35.;    Amax =  56.
   Lav =   7.1 +/-  4.5 h-bar; Lmin =   0.;    Lmax =  28.

 The program called Fermi breakup      620 times.

  The mean charge, mass, and angular momentum
  of the     172 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  26.0 +/-  0.2;       Zmin =  26.;   Zmax =  27.
   Aav =  55.1 +/-  0.5;       Amin =  52.;   Amax =  56.
   Lav =   2.5 +/-  1.6 h-bar; Lmin =   0.;   Lmax =  10.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9828 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av = 192.0 +/- 161.7 MeV; E*min =   0.1;  E*max = 963.4
   Zav =  23.4 +/-  2.1;       Zmin =  14.;   Zmax =  29.
   Aav =  49.1 +/-  4.5;       Amin =  32.;   Amax =  56.
   Lav =   8.2 +/-  5.3 h-bar; Lmin =   0.;   Lmax =  33.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   5.2 +/-  6.5 MeV;  Ekmin =  0.0;  Ekmax =  70.7
   Zav =  17.8 +/-  5.7;       Zmin =   6.;   Zmax =  27.
   Aav =  37.6 +/- 12.3;       Amin =  13.;   Amax =  56.
   Lav =   8.1 +/-  5.3 h-bar; Lmin =   0.;   Lmax =  33.

 Number of coalesced d, t, He3, He4 =     3844     681     360     217

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     6.0981 +/- 0.0247    4139.208 +/-  16.762     43.37
 C  n     2.5730 +/- 0.0160    1746.476 +/-  10.888     90.67
 P  n     0.1377 +/- 0.0037      93.467 +/-   2.519     22.04
 Sp n     3.3874 +/- 0.0184    2299.266 +/-  12.493      8.31
 E  n     3.3874 +/- 0.0184    2299.266 +/-  12.493      8.31
 *****************************************************************
```

```
T  p     5.0712 +/- 0.0225    3442.179 +/-  15.285     56.71
C  p     2.0809 +/- 0.0144    1412.453 +/-   9.791    120.52
P  p     0.1391 +/- 0.0037      94.417 +/-   2.532     24.84
Sp p     2.8512 +/- 0.0169    1935.309 +/-  11.461     11.70
E  p     2.8512 +/- 0.0169    1935.309 +/-  11.461     11.70
*****************************************************************
T  d     1.7013 +/- 0.0130    1154.792 +/-   8.853     22.21
P  d     0.1097 +/- 0.0033      74.461 +/-   2.248     26.40
Sp d     1.2169 +/- 0.0110     825.995 +/-   7.488     13.64
E  d     1.2169 +/- 0.0110     825.995 +/-   7.488     13.64
Co d     0.3747 +/- 0.0061     254.335 +/-   4.155     48.84
*****************************************************************
T  t     0.3541 +/- 0.0060     240.352 +/-   4.039     19.70
P  t     0.0496 +/- 0.0022      33.667 +/-   1.512     33.61
Sp t     0.2377 +/- 0.0049     161.344 +/-   3.309     13.49
E  t     0.2377 +/- 0.0049     161.344 +/-   3.309     13.49
Co t     0.0668 +/- 0.0026      45.342 +/-   1.754     31.47
*****************************************************************
T He3    0.3383 +/- 0.0058     229.628 +/-   3.948     22.33
P He3    0.0533 +/- 0.0023      36.178 +/-   1.567     35.83
SpHe3    0.2499 +/- 0.0050     169.625 +/-   3.393     17.09
E He3    0.2499 +/- 0.0050     169.625 +/-   3.393     17.09
CoHe3    0.0351 +/- 0.0019      23.825 +/-   1.272     39.15
*****************************************************************
T He4    0.9033 +/- 0.0095     613.133 +/-   6.451     14.59
P He4    0.0470 +/- 0.0022      31.902 +/-   1.472     48.55
SpHe4    0.8353 +/- 0.0091     566.977 +/-   6.204     12.38
E He4    0.8353 +/- 0.0091     566.977 +/-   6.204     12.38
CoHe4    0.0210 +/- 0.0014      14.254 +/-   0.984     26.27
*****************************************************************
pi-      0.3448 +/- 0.0059     234.040 +/-   3.986    218.77
pi0      0.6841 +/- 0.0083     464.347 +/-   5.614    235.69
pi+      0.7787 +/- 0.0088     528.558 +/-   5.990    463.33
*****************************************************************

**********************************  neutrons  ********************************

Double differential cross sections [mb/MeV/sr];
Lab. angle =  25.0 to  35.0 degrees.

   Tn  [MeV]          Total                Cascade               Precompound        Total Evaporation
   0.0-   1.0  1.463E+01 +/- 1.35E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.463E+01 +/- 1.35E+00
   1.0-   2.0  2.157E+01 +/- 1.64E+00 3.842E+00 +/- 6.90E-01 0.000E+00 +/- 0.00E+00 1.772E+01 +/- 1.48E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 900.0-1000.0  9.916E-03 +/- 3.51E-03 9.916E-03 +/- 3.51E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
1000.0-1100.0  2.479E-03 +/- 1.75E-03 2.479E-03 +/- 1.75E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   5.045E+02 +/- 7.91E+00 2.716E+02 +/- 5.80E+00 8.553E+00 +/- 1.03E+00 2.243E+02 +/- 5.27E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  85.0 to  95.0 degrees.

   Tn  [MeV]          Total                Cascade               Precompound        Total Evaporation
   0.0-   1.0  1.407E+01 +/- 9.34E-01 0.000E+00 +/- 0.00E+00 6.198E-02 +/- 6.20E-02 1.401E+01 +/- 9.32E-01
   1.0-   2.0  2.262E+01 +/- 1.18E+00 3.842E+00 +/- 4.88E-01 1.240E-01 +/- 8.76E-02 1.865E+01 +/- 1.08E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 200.0- 300.0  2.541E-02 +/- 3.97E-03 2.541E-02 +/- 3.97E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 400.0- 500.0  6.198E-04 +/- 6.20E-04 6.198E-04 +/- 6.20E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   2.974E+02 +/- 4.29E+00 1.147E+02 +/- 2.67E+00 7.003E+00 +/- 6.59E-01 1.757E+02 +/- 3.30E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle = 145.0 to 155.0 degrees.

   Tn  [MeV]          Total                Cascade               Precompound        Total Evaporation
   0.0-   1.0  1.240E+01 +/- 1.24E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.240E+01 +/- 1.24E+00
   1.0-   2.0  1.958E+01 +/- 1.56E+00 2.479E+00 +/- 5.54E-01 2.479E-01 +/- 1.75E-01 1.686E+01 +/- 1.45E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 200.0- 300.0  3.719E-03 +/- 2.15E-03 3.719E-03 +/- 2.15E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 300.0- 400.0  1.240E-03 +/- 1.24E-03 1.240E-03 +/- 1.24E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   2.372E+02 +/- 5.42E+00 7.425E+01 +/- 3.03E+00 4.710E+00 +/- 7.64E-01 1.583E+02 +/- 4.43E+00

The program called Fermi breakup      620 times.

Elapsed cpu time  =  0. min and  8.309 sec.
```

CEM03.03 Output Example 5

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:49:23 2012

Example No. 5: Fission cross section of Au197 bombarded with
neutrons from 30 to 300 MeV with a step of 10 MeV; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9396 0.0300  197.  79.  0  1   10000   1

 dt0 =   10.0, t0max =  300.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     0     0     0     2     2

 r0m =  1.2, & cevap = 12.0.

 lim =     100000 .

 Geometrical cross section = 2394.46 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here = 2333.73 mb
 Monte Carlo inelastic cross section = 1647.94 mb

     Wed Feb  1 10:49:23 2012

                 30.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =     4530,

 Reaction cross section = 2333.73 mb, Elastic cross section = 1057.18 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av =  34.9 +/-  5.0 MeV;  E*min =  -0.1;  E*max =  36.3
   Zav =  79.0 +/-  0.0;       Zmin =  78.;    Zmax =  79.
   Aav = 197.9 +/-  0.3;       Amin = 195.;    Amax = 198.
   Lav =   6.2 +/-  2.4 h-bar; Lmin =   0.;    Lmax =  11.

  The mean charge, mass, and angular momentum
  of the      34 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  79.0 +/-  0.0;       Zmin =  79.;   Zmax =  79.
   Aav = 196.2 +/-  0.5;       Amin = 195.;   Amax = 197.
   Lav =   3.0 +/-  1.4 h-bar; Lmin =   1.;   Lmax =   6.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9965 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  28.2 +/-  10.4 MeV; E*min =   0.1;  E*max =  36.2
   Zav =  79.0 +/-  0.2;       Zmin =  77.;   Zmax =  79.
   Aav = 197.6 +/-  0.6;       Amin = 193.;   Amax = 198.
   Lav =   6.5 +/-  2.7 h-bar; Lmin =   0.;   Lmax =  20.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   0.2 +/-  0.1 MeV;  Ekmin =  0.0;  Ekmax =   1.2
   Zav =  78.9 +/-  0.2;       Zmin =  77.;   Zmax =  79.
   Aav = 194.8 +/-  0.8;       Amin = 192.;   Amax = 197.
   Lav =   6.5 +/-  2.7 h-bar; Lmin =   0.;   Lmax =  20.

               Statistical Weight Functions Method:
 Fissility =  0.0000,
 Fission cross section = 1.35863E-02 mb.

 Number of coalesced d, t, He3, He4 =       1       0       0       0

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities          Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     3.1473 +/- 0.0177    7344.961 +/-  41.402      2.64
 C  n     0.0758 +/- 0.0028     176.897 +/-   6.425      9.24
 P  n     0.3028 +/- 0.0055     706.655 +/-  12.842     10.63
 Sp n     2.7687 +/- 0.0166    6461.409 +/-  38.832      1.59
 E  n     2.7687 +/- 0.0166    6461.409 +/-  38.832      1.59
 *****************************************************************
 T  p     0.0333 +/- 0.0018      77.713 +/-   4.259     17.02
 C  p     0.0005 +/- 0.0002       1.167 +/-   0.522     12.41
 P  p     0.0325 +/- 0.0018      75.846 +/-   4.207     17.16
 Sp p     0.0003 +/- 0.0002       0.700 +/-   0.404      9.15
 E  p     0.0003 +/- 0.0002       0.700 +/-   0.404      9.15
 *****************************************************************
 T  d     0.0092 +/- 0.0010      21.470 +/-   2.238     17.60
 P  d     0.0091 +/- 0.0010      21.237 +/-   2.226     17.72
```

```
Co d     0.0001 +/- 0.0001       0.233 +/-   0.233      6.90
*****************************************************************
T  t     0.0023 +/- 0.0005       5.368 +/-   1.119     13.92
P  t     0.0022 +/- 0.0005       5.134 +/-   1.095     14.09
Sp t     0.0001 +/- 0.0001       0.233 +/-   0.233     10.11
E  t     0.0001 +/- 0.0001       0.233 +/-   0.233     10.11
*****************************************************************
T He4    0.0028 +/- 0.0005       6.534 +/-   1.235     23.84
P He4    0.0023 +/- 0.0005       5.368 +/-   1.119     24.64
SpHe4    0.0005 +/- 0.0002       1.167 +/-   0.522     20.16
E He4    0.0005 +/- 0.0002       1.167 +/-   0.522     20.16
*****************************************************************

Geometrical cross section = 2394.46 mb.

  Inelastic cross section used here = 2222.93 mb
Monte Carlo inelastic cross section = 1636.01 mb

    Wed Feb  1 10:49:33 2012

                40.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     4636,

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

The mean total fission product kinetic energy after neutron emission is 138.49 MeV.

              Direct Monte Carlo Simulation Method:
Fissility =  0.0002 +/-  0.0001,
Fission cross section = 4.44586E-01 +/- 3.14E-01 mb.

              Statistical Weight Functions Method:
Fissility =  0.0000,
Fission cross section = 8.69020E-02 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                50.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     5051,

Reaction cross section = 2135.39 mb, Elastic cross section = 1078.58 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

              Statistical Weight Functions Method:
Fissility =  0.0001,
Fission cross section = 1.95606E-01 mb.

 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                60.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     5308,

Reaction cross section = 2066.02 mb, Elastic cross section = 1096.64 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

The mean total fission product kinetic energy after neutron emission is 139.48 MeV.

              Direct Monte Carlo Simulation Method:
Fissility =  0.0003 +/-  0.0002,
Fission cross section = 6.19806E-01 +/- 3.58E-01 mb.

              Statistical Weight Functions Method:
Fissility =  0.0002,
Fission cross section = 4.26275E-01 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

               290.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     6491,

Reaction cross section = 1766.57 mb, Elastic cross section = 1146.68 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

The mean total fission product kinetic energy after neutron emission is 130.08 MeV.

              Direct Monte Carlo Simulation Method:
Fissility =  0.0132 +/-  0.0011,
Fission cross section = 2.33187E+01 +/- 2.03E+00 mb.

              Statistical Weight Functions Method:
Fissility =  0.0130,
```

```
Fission cross section = 2.30023E+01 mb.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

              300.0 MeV (Z =  0, A = 1) + (Z = 79., A = 197.)

Number of inelastic interactions =    10000,
Number of elastic interactions   =     6420,

Reaction cross section = 1767.01 mb, Elastic cross section = 1134.42 mb.

 The mean excitation energy, charge, mass, and angular momentum
 of the    10000 nuclei after the
 cascade and before preequilibrium decay are:
 E*av = 100.8 +/- 67.9 MeV;  E*min =  -0.4;  E*max = 304.4
  Zav =  78.6 +/-  0.6;       Zmin =  76.;    Zmax =  80.
  Aav = 195.0 +/-  1.3;       Amin = 190.;    Amax = 198.
  Lav =   8.2 +/-  4.7 h-bar; Lmin =   0.;    Lmax =  33.

 The mean charge, mass, and angular momentum
 of the     292 residual nuclei with less than
 3 MeV of excitation energy after the cascade are:
  Zav =  79.0 +/-  0.0;       Zmin =  79.;   Zmax =  79.
  Aav = 196.0 +/-  0.4;       Amin = 195.;   Amax = 197.
  Lav =   3.3 +/-  1.8 h-bar; Lmin =   0.;   Lmax =   9.

 The mean excitation energy, charge, mass, and angular momentum
 of the    9707 nuclei after preequilibrium
 decay and before the start of statistical decay are:
 E*av =  81.8 +/-  54.2 MeV; E*min =   0.5;  E*max = 293.6
  Zav =  78.2 +/-  0.9;       Zmin =  73.;   Zmax =  80.
  Aav = 194.0 +/-  2.0;       Amin = 184.;   Amax = 198.
  Lav =   9.4 +/-  5.5 h-bar; Lmin =   0.;   Lmax =  41.

 The mean kinetic energy, charge, mass, and angular momentum
 of the    9825 residual nuclei are:
 Ekav =   0.8 +/-  0.9 MeV;  Ekmin =  0.0;  Ekmax =   8.0
  Zav =  77.8 +/-  1.2;       Zmin =  71.;   Zmax =  80.
  Aav = 186.8 +/-  6.0;       Amin = 166.;   Amax = 197.
  Lav =   9.1 +/-  5.5 h-bar; Lmin =   0.;   Lmax =  41.

 The mean excitation energy, charge, mass, angular momentum, and
 fission barrier height of the     175 fissioning nuclei are:
 E*av = 140.8 +/- 43.9 MeV; E*min =  40.3; E*max =  282.0
  Zav =  78.3 +/- 0.8;        Zmin =  74.;  Zmax =  80.
  Aav = 190.3 +/- 3.2;        Amin = 179.;  Amax = 196.
  Lav =  11.6 +/- 5.1 h-bar;  Lmin =   1.;  Lmax =  30.
 Bfav =  18.3 +/- 1.4 MeV;   Bfmin = 14.3; Bfmax = 22.2

The mean total fission product kinetic energy after neutron emission is 127.84 MeV.

             Direct Monte Carlo Simulation Method:
Fissility =  0.0175 +/-  0.0013,
Fission cross section = 3.09227E+01 +/- 2.34E+00 mb.

             Statistical Weight Functions Method:
Fissility =  0.0147,
Fission cross section = 2.59347E+01 mb.

Number of coalesced d, t, He3, He4 =     1064     369      30      30

Mean multiplicities, yields, and mean energies of ejected particles:
(Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
Sp - from spallation residues, Pf - from nuclei before fission,
F - from fission fragments, E - total evaporation = Sp + Pf + F,
Co - Coalescence from cascade;
Values which are identically zero are not printed.

Part.     Multiplicities          Yields [mb]     <TKE> [MeV]
*****************************************************************
T  n     9.4214 +/- 0.0307   16647.712 +/-  54.237     17.93
C  n     2.4302 +/- 0.0156    4294.189 +/-  27.546     59.32
P  n     0.4444 +/- 0.0067     785.259 +/-  11.779     15.55
Sp n     6.3099 +/- 0.0251   11149.659 +/-  44.386      2.69
Pf n     0.0425 +/- 0.0021      75.098 +/-   3.643      4.47
F  n     0.1944 +/- 0.0044     343.507 +/-   7.791      3.73
E  n     6.5468 +/- 0.0256   11568.264 +/-  45.212      2.73
*****************************************************************
T  p     0.6631 +/- 0.0081    1171.705 +/-  14.389     53.23
C  p     0.2654 +/- 0.0052     468.965 +/-   9.103    107.15
P  p     0.1789 +/- 0.0042     316.118 +/-   7.474     24.72
Sp p     0.2136 +/- 0.0046     377.433 +/-   8.167     11.18
Pf p     0.0020 +/- 0.0004       3.534 +/-   0.790     11.65
F  p     0.0032 +/- 0.0006       5.654 +/-   1.000      7.91
E  p     0.2188 +/- 0.0047     386.622 +/-   8.265     11.14
*****************************************************************
T  d     0.2507 +/- 0.0050     442.990 +/-   8.847     28.52
P  d     0.0919 +/- 0.0030     162.388 +/-   5.357     26.02
Sp d     0.0507 +/- 0.0023      89.587 +/-   3.979     11.73
Pf d     0.0011 +/- 0.0003       1.944 +/-   0.586     13.07
F  d     0.0006 +/- 0.0002       1.060 +/-   0.433      9.95
E  d     0.0524 +/- 0.0023      92.591 +/-   4.045     11.74
Co d     0.1064 +/- 0.0033     188.010 +/-   5.764     38.94
*****************************************************************
T  t     0.0847 +/- 0.0029     149.666 +/-   5.143     22.94
P  t     0.0234 +/- 0.0015      41.348 +/-   2.703     29.50
```

```
Sp t     0.0238 +/- 0.0015      42.055 +/-   2.726      12.57
Pf t     0.0006 +/- 0.0002       1.060 +/-   0.433      14.04
E  t     0.0244 +/- 0.0016      43.115 +/-   2.760      12.60
Co t     0.0369 +/- 0.0019      65.203 +/-   3.394      25.61
*****************************************************************
T He3    0.0127 +/- 0.0011      22.441 +/-   1.991      35.92
P He3    0.0093 +/- 0.0010      16.433 +/-   1.704      38.94
SpHe3    0.0004 +/- 0.0002       0.707 +/-   0.353      22.18
E He3    0.0004 +/- 0.0002       0.707 +/-   0.353      22.18
CoHe3    0.0030 +/- 0.0005       5.301 +/-   0.968      28.39
*****************************************************************
T He4    0.1056 +/- 0.0032     186.596 +/-   5.742      23.11
P He4    0.0055 +/- 0.0007       9.719 +/-   1.310      40.19
SpHe4    0.0951 +/- 0.0031     168.043 +/-   5.449      22.21
PfHe4    0.0007 +/- 0.0003       1.237 +/-   0.468      22.32
F He4    0.0013 +/- 0.0004       2.297 +/-   0.637      17.04
E He4    0.0971 +/- 0.0031     171.577 +/-   5.506      22.14
CoHe4    0.0030 +/- 0.0005       5.301 +/-   0.968      23.01
*****************************************************************
pi-      0.0098 +/- 0.0010      17.317 +/-   1.749      35.23
pi0      0.0036 +/- 0.0006       6.361 +/-   1.060      30.35
*****************************************************************

Elapsed cpu time  =  2. min and 49.225 sec.
```

CEM03.03 Output Example 6

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:55:00 2012

Example No. 6: Energy, angular, and double-differential spectra
of n to He from 62.9 MeV p  + Pb208;  100,000 events;
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9383 0.0629  208.  82.  1  1   10000   1

 dt0 =  -10.0, t0max =  200.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    1     1     0     0     1     1     1     6

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  22.5  27.5  52.5  57.5  72.5  77.5  92.5  97.5 112.5 117.5 152.5 157.5

    Theta7      Theta8      Theta9     Theta10
  -5.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0  22.0  1.00  22.0 120.0  2.00  120.  400.  10.0  400. 1000.   20.

 lim =     100000 .

 Geometrical cross section = 2457.28 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here = 1962.23 mb
 Monte Carlo inelastic cross section = 1638.74 mb

     Wed Feb  1 10:55:00 2012

                 62.9 MeV (Z =  1, A = 1) + (Z = 82., A = 208.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =     4995,

 Reaction cross section = 1962.23 mb, Elastic cross section =  980.14 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av =  47.9 +/- 21.9 MeV;  E*min =  -1.6;  E*max =  65.5
   Zav =  82.8 +/-  0.4;       Zmin =  81.;    Zmax =  83.
   Aav = 208.5 +/-  0.6;       Amin = 206.;    Amax = 209.
   Lav =   6.6 +/-  3.1 h-bar; Lmin =   0.;    Lmax =  16.

  The mean charge, mass, and angular momentum
  of the     363 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  82.3 +/-  0.4;       Zmin =  82.;   Zmax =  83.
   Aav = 207.5 +/-  0.5;       Amin = 206.;   Amax = 208.
   Lav =   3.2 +/-  2.0 h-bar; Lmin =   0.;   Lmax =  10.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9636 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  33.8 +/-  18.9 MeV; E*min =   0.1;  E*max =  65.1
   Zav =  82.5 +/-  0.6;       Zmin =  80.;   Zmax =  83.
   Aav = 207.8 +/-  0.8;       Amin = 203.;   Amax = 209.
   Lav =   7.7 +/-  3.9 h-bar; Lmin =   0.;   Lmax =  28.

  The mean kinetic energy, charge, mass, and angular momentum
  of the    9943 residual nuclei are:
  Ekav =   0.3 +/-  0.2 MeV;  Ekmin =  0.0;  Ekmax =   2.1
   Zav =  82.5 +/-  0.6;       Zmin =  80.;   Zmax =  83.
   Aav = 204.8 +/-  1.6;       Amin = 200.;   Amax = 208.
   Lav =   7.5 +/-  4.0 h-bar; Lmin =   0.;   Lmax =  28.

  The mean excitation energy, charge, mass, angular momentum, and
  fission barrier height of the      57 fissioning nuclei are:
  E*av =  56.8 +/-  8.5 MeV; E*min =  34.3; E*max =   65.1
   Zav =  83.0 +/- 0.0;        Zmin =  83.;  Zmax =  83.
   Aav = 208.2 +/- 0.8;        Amin = 206.;  Amax = 209.
   Lav =   7.9 +/- 2.9 h-bar;  Lmin =   1.;  Lmax =  14.
  Bfav =  23.6 +/- 0.2 MeV;   Bfmin = 23.3; Bfmax = 23.9

 The mean total fission product kinetic energy after neutron emission is 140.36 MeV.

              Direct Monte Carlo Simulation Method:
 Fissility =  0.0057 +/-  0.0008,
 Fission cross section = 1.11847E+01 +/- 1.48E+00 mb.

              Statistical Weight Functions Method:
 Fissility =  0.0052,
 Fission cross section = 1.01828E+01 mb.

 Number of coalesced d, t, He3, He4 =      27      0      0      0
```

```
Mean multiplicities, yields, and mean energies of ejected particles:
(Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
Sp - from spallation residues, Pf - from nuclei before fission,
F - from fission fragments, E - total evaporation = Sp + Pf + F,
Co - Coalescence from cascade;
Values which are identically zero are not printed.

Part.     Multiplicities          Yields [mb]     <TKE> [MeV]
*****************************************************************
T  n     3.6353 +/- 0.0191    7133.305 +/-  37.413      4.64
C  n     0.2867 +/- 0.0054     562.572 +/-  10.507     21.87
P  n     0.2982 +/- 0.0055     585.138 +/-  10.715     14.77
Sp n     3.0175 +/- 0.0174    5921.037 +/-  34.086      2.02
Pf n     0.0030 +/- 0.0005       5.887 +/-   1.075      2.11
F  n     0.0299 +/- 0.0017      58.671 +/-   3.393      2.26
E  n     3.0504 +/- 0.0175    5985.595 +/-  34.271      2.02
*****************************************************************
T  p     0.4624 +/- 0.0068     907.336 +/-  13.343     29.61
C  p     0.2436 +/- 0.0049     478.000 +/-   9.685     32.60
P  p     0.2100 +/- 0.0046     412.069 +/-   8.992     26.94
Sp p     0.0088 +/- 0.0009      17.268 +/-   1.841     10.66
E  p     0.0088 +/- 0.0009      17.268 +/-   1.841     10.66
*****************************************************************
T  d     0.0409 +/- 0.0020      80.255 +/-   3.968     26.14
P  d     0.0378 +/- 0.0019      74.172 +/-   3.815     26.84
Sp d     0.0004 +/- 0.0002       0.785 +/-   0.392     11.65
E  d     0.0004 +/- 0.0002       0.785 +/-   0.392     11.65
Co d     0.0027 +/- 0.0005       5.298 +/-   1.020     18.53
*****************************************************************
T  t     0.0127 +/- 0.0011      24.920 +/-   2.211     23.22
P  t     0.0126 +/- 0.0011      24.724 +/-   2.203     23.32
Sp t     0.0001 +/- 0.0001       0.196 +/-   0.196     10.90
E  t     0.0001 +/- 0.0001       0.196 +/-   0.196     10.90
*****************************************************************
T He3    0.0016 +/- 0.0004       3.140 +/-   0.785     32.92
P He3    0.0016 +/- 0.0004       3.140 +/-   0.785     32.92
*****************************************************************
T He4    0.0074 +/- 0.0009      14.521 +/-   1.688     31.27
P He4    0.0062 +/- 0.0008      12.166 +/-   1.545     33.12
SpHe4    0.0012 +/- 0.0003       2.355 +/-   0.680     21.72
E He4    0.0012 +/- 0.0003       2.355 +/-   0.680     21.72
*****************************************************************

**********************************  neutrons  ********************************

--------------------------- Energy Spectrum [mb/MeV] --------------------------
    Energy spectrum from   0.0 to   64.0 MeV (zero values suppressed).

   Tn  [MeV]           Total                 Cascade               Precompound        Total Evaporation
   0.0-   1.0  1.833E+03 +/- 1.90E+01 0.000E+00 +/- 0.00E+00 9.026E+00 +/- 1.33E+00 1.824E+03 +/- 1.89E+01
   1.0-   2.0  1.847E+03 +/- 1.90E+01 2.374E+01 +/- 2.16E+00 1.923E+01 +/- 1.94E+00 1.804E+03 +/- 1.88E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  56.0-  58.0  5.396E+00 +/- 7.28E-01 5.004E+00 +/- 7.01E-01 3.924E-01 +/- 1.96E-01 0.000E+00 +/- 0.00E+00
  58.0-  60.0  3.532E+00 +/- 5.89E-01 3.532E+00 +/- 5.89E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   7.133E+03 +/- 3.74E+01 5.626E+02 +/- 1.05E+01 5.851E+02 +/- 1.07E+01 5.986E+03 +/- 3.43E+01

----------------Normalized Energy Probability Spectrum [1/MeV] ----------------
    Energy spectrum from   0.0 to   64.0 MeV (zero values suppressed).

   Tn  [MeV]           Total                 Cascade               Precompound        Total Evaporation
   0.0-   1.0  2.570E-01 +/- 2.66E-03 0.000E+00 +/- 0.00E+00 1.265E-03 +/- 1.87E-04 2.557E-01 +/- 2.65E-03
   1.0-   2.0  2.590E-01 +/- 2.67E-03 3.328E-03 +/- 3.03E-04 2.696E-03 +/- 2.72E-04 2.529E-01 +/- 2.64E-03
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  56.0-  58.0  7.565E-04 +/- 1.02E-04 7.015E-04 +/- 9.82E-05 5.502E-05 +/- 2.75E-05 0.000E+00 +/- 0.00E+00
  58.0-  60.0  4.951E-04 +/- 8.25E-05 4.951E-04 +/- 8.25E-05 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   1.000E+00 +/- 5.24E-03 7.887E-02 +/- 1.47E-03 8.203E-02 +/- 1.50E-03 8.391E-01 +/- 4.80E-03

----------------------- Angular Distributions [mb/sr] -----------------------

 Ang.n          Total                Cascade              Precompound        Total Evaporation
 [deg.]
   5.0   6.845E+02 +/- 3.75E+01 8.223E+01 +/- 1.30E+01 1.089E+02 +/- 1.50E+01 4.934E+02 +/- 3.18E+01
  15.0   7.691E+02 +/- 2.31E+01 1.405E+02 +/- 9.86E+00 1.059E+02 +/- 8.56E+00 5.226E+02 +/- 1.90E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 165.0   4.853E+02 +/- 1.83E+01 6.922E-01 +/- 6.92E-01 2.077E+01 +/- 3.79E+00 4.638E+02 +/- 1.79E+01
 175.0   4.872E+02 +/- 3.16E+01 0.000E+00 +/- 0.00E+00 1.233E+01 +/- 5.04E+00 4.749E+02 +/- 3.12E+01

Integ.   7.133E+03 +/- 3.74E+01 5.626E+02 +/- 1.05E+01 5.851E+02 +/- 1.07E+01 5.986E+03 +/- 3.43E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  22.5 to  27.5 degrees.

   Tn  [MeV]           Total                 Cascade               Precompound        Total Evaporation
   0.0-   1.0  1.262E+02 +/- 1.03E+01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.262E+02 +/- 1.03E+01
   1.0-   2.0  1.457E+02 +/- 1.11E+01 5.929E+00 +/- 2.24E+00 1.694E+00 +/- 1.20E+00 1.381E+02 +/- 1.08E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  56.0-  58.0  4.235E+00 +/- 1.34E+00 4.235E+00 +/- 1.34E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
  58.0-  60.0  1.271E+00 +/- 7.34E-01 1.271E+00 +/- 7.34E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   7.573E+02 +/- 2.53E+01 1.762E+02 +/- 1.22E+01 8.809E+01 +/- 8.64E+00 4.930E+02 +/- 2.04E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  52.5 to  57.5 degrees.
```

```
   Tn  [MeV]           Total               Cascade               Precompound       Total Evaporation
   0.0-   1.0  1.403E+02 +/- 7.83E+00 0.000E+00 +/- 0.00E+00 8.740E-01 +/- 6.18E-01 1.394E+02 +/- 7.81E+00
   1.0-   2.0  1.385E+02 +/- 7.78E+00 3.059E+00 +/- 1.16E+00 2.185E+00 +/- 9.77E-01 1.333E+02 +/- 7.63E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  54.0-  56.0  8.740E-01 +/- 4.37E-01 8.740E-01 +/- 4.37E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
  56.0-  58.0  2.185E-01 +/- 2.19E-01 2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   6.241E+02 +/- 1.65E+01 7.997E+01 +/- 5.91E+00 7.254E+01 +/- 5.63E+00 4.715E+02 +/- 1.44E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  72.5 to  77.5 degrees.

   Tn  [MeV]           Total               Cascade               Precompound       Total Evaporation
   0.0-   1.0  1.583E+02 +/- 7.66E+00 0.000E+00 +/- 0.00E+00 3.706E-01 +/- 3.71E-01 1.579E+02 +/- 7.65E+00
   1.0-   2.0  1.523E+02 +/- 7.51E+00 1.853E+00 +/- 8.29E-01 1.482E+00 +/- 7.41E-01 1.490E+02 +/- 7.43E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  48.0-  50.0  1.853E-01 +/- 1.85E-01 1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
  54.0-  56.0  1.853E-01 +/- 1.85E-01 1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   5.841E+02 +/- 1.47E+01 4.373E+01 +/- 4.03E+00 4.744E+01 +/- 4.19E+00 4.929E+02 +/- 1.35E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  92.5 to  97.5 degrees.

   Tn  [MeV]           Total               Cascade               Precompound       Total Evaporation
   0.0-   1.0  1.445E+02 +/- 7.20E+00 0.000E+00 +/- 0.00E+00 7.187E-01 +/- 5.08E-01 1.437E+02 +/- 7.19E+00
   1.0-   2.0  1.520E+02 +/- 7.39E+00 1.797E+00 +/- 8.04E-01 1.437E+00 +/- 7.19E-01 1.488E+02 +/- 7.31E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  34.0-  36.0  3.593E-01 +/- 2.54E-01 0.000E+00 +/- 0.00E+00 3.593E-01 +/- 2.54E-01 0.000E+00 +/- 0.00E+00
  38.0-  40.0  1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00 1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00

 Integrated:   5.365E+02 +/- 1.39E+01 1.725E+01 +/- 2.49E+00 3.450E+01 +/- 3.52E+00 4.848E+02 +/- 1.32E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle = 112.5 to 117.5 degrees.

   Tn  [MeV]           Total               Cascade               Precompound       Total Evaporation
   0.0-   1.0  1.540E+02 +/- 7.80E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.540E+02 +/- 7.80E+00
   1.0-   2.0  1.544E+02 +/- 7.81E+00 1.580E+00 +/- 7.90E-01 2.370E+00 +/- 9.68E-01 1.505E+02 +/- 7.71E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  30.0-  32.0  1.975E-01 +/- 1.97E-01 0.000E+00 +/- 0.00E+00 1.975E-01 +/- 1.97E-01 0.000E+00 +/- 0.00E+00
  34.0-  36.0  3.950E-01 +/- 2.79E-01 0.000E+00 +/- 0.00E+00 3.950E-01 +/- 2.79E-01 0.000E+00 +/- 0.00E+00

 Integrated:   5.159E+02 +/- 1.43E+01 7.900E+00 +/- 1.77E+00 2.686E+01 +/- 3.26E+00 4.811E+02 +/- 1.38E+01

Double differential cross sections [mb/MeV/sr];
Lab. angle = 152.5 to 157.5 degrees.

   Tn  [MeV]           Total               Cascade               Precompound       Total Evaporation
   0.0-   1.0  1.423E+02 +/- 1.10E+01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.423E+02 +/- 1.10E+01
   1.0-   2.0  1.482E+02 +/- 1.12E+01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.482E+02 +/- 1.12E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  22.0-  24.0  8.471E-01 +/- 5.99E-01 0.000E+00 +/- 0.00E+00 8.471E-01 +/- 5.99E-01 0.000E+00 +/- 0.00E+00
  24.0-  26.0  4.235E-01 +/- 4.24E-01 0.000E+00 +/- 0.00E+00 4.235E-01 +/- 4.24E-01 0.000E+00 +/- 0.00E+00

 Integrated:   4.727E+02 +/- 2.00E+01 0.000E+00 +/- 0.00E+00 1.525E+01 +/- 3.59E+00 4.574E+02 +/- 1.97E+01

**********************************  protons   ********************************

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


**********************************   alphas   ********************************

-------------------------- Energy Spectrum [mb/MeV] --------------------------
    Energy spectrum from   0.0 to   64.0 MeV (zero values suppressed).

   THe4[MeV]          Total              Coalescence           Precompound        Total Evaporation
  19.0-  20.0  3.924E-01 +/- 2.78E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 3.924E-01 +/- 2.78E-01
  20.0-  21.0  7.849E-01 +/- 3.92E-01 0.000E+00 +/- 0.00E+00 1.962E-01 +/- 1.96E-01 5.887E-01 +/- 3.40E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  54.0-  56.0  9.811E-02 +/- 9.81E-02 0.000E+00 +/- 0.00E+00 9.811E-02 +/- 9.81E-02 0.000E+00 +/- 0.00E+00
  56.0-  58.0  9.811E-02 +/- 9.81E-02 0.000E+00 +/- 0.00E+00 9.811E-02 +/- 9.81E-02 0.000E+00 +/- 0.00E+00

 Integrated:   1.452E+01 +/- 1.69E+00 0.000E+00 +/- 0.00E+00 1.217E+01 +/- 1.55E+00 2.355E+00 +/- 6.80E-01

----------------------- Angular Distributions [mb/sr] -----------------------

 Ang.He4        Total              Coalescence            Precompound        Total Evaporation
 [deg.]
  15.0   2.769E+00 +/- 1.38E+00 0.000E+00 +/- 0.00E+00 2.769E+00 +/- 1.38E+00 0.000E+00 +/- 0.00E+00
  25.0   2.544E+00 +/- 1.04E+00 0.000E+00 +/- 0.00E+00 2.544E+00 +/- 1.04E+00 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 165.0   6.922E-01 +/- 6.92E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 6.922E-01 +/- 6.92E-01
 175.0   2.056E+00 +/- 2.06E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.056E+00 +/- 2.06E+00

Integ.   1.452E+01 +/- 1.69E+00 0.000E+00 +/- 0.00E+00 1.217E+01 +/- 1.55E+00 2.355E+00 +/- 6.80E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  22.5 to  27.5 degrees.
```

```
   THe4[MeV]          Total               Coalescence           Precompound        Total Evaporation
  26.0-  28.0  4.235E-01 +/- 4.24E-01 0.000E+00 +/- 0.00E+00 4.235E-01 +/- 4.24E-01 0.000E+00 +/- 0.00E+00

 Integrated:   8.471E-01 +/- 8.47E-01 0.000E+00 +/- 0.00E+00 8.471E-01 +/- 8.47E-01 0.000E+00 +/- 0.00E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  52.5 to  57.5 degrees.

   THe4[MeV]          Total               Coalescence           Precompound        Total Evaporation
  22.0-  24.0  2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00 2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00
  24.0-  26.0  2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00 2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00
  26.0-  28.0  2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00 2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00
  30.0-  32.0  2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00 2.185E-01 +/- 2.19E-01 0.000E+00 +/- 0.00E+00

 Integrated:   1.748E+00 +/- 8.74E-01 0.000E+00 +/- 0.00E+00 1.748E+00 +/- 8.74E-01 0.000E+00 +/- 0.00E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  72.5 to  77.5 degrees.

   THe4[MeV]          Total               Coalescence           Precompound        Total Evaporation
  26.0-  28.0  1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00 1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00
  36.0-  38.0  1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00 1.853E-01 +/- 1.85E-01 0.000E+00 +/- 0.00E+00

 Integrated:   7.412E-01 +/- 5.24E-01 0.000E+00 +/- 0.00E+00 7.412E-01 +/- 5.24E-01 0.000E+00 +/- 0.00E+00

Double differential cross sections [mb/MeV/sr];
Lab. angle =  92.5 to  97.5 degrees.

   THe4[MeV]          Total               Coalescence           Precompound        Total Evaporation
  22.0-  24.0  1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00 1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00
  24.0-  26.0  1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00 1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00
  30.0-  32.0  1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00 1.797E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00

 Integrated:   1.078E+00 +/- 6.22E-01 0.000E+00 +/- 0.00E+00 1.078E+00 +/- 6.22E-01 0.000E+00 +/- 0.00E+00

Elapsed cpu time  =  0. min and  5.669 sec.
```

CEM03.03 Output Example 7

```
 -----------------------------------------------------------------------------

 Wed Feb  1 10:55:15 2012

Example No. 7: xsec and kinetic energy of all products measured
at GSI in inverse kinematics for 800 MeV p + Au197; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9383 0.8000  197.  79.  1  1   10000   1

 dt0 =  -20.0, t0max = 1000.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     1     0     0     2     2

 r0m =  1.2, & cevap = 12.0.

 lim =     100000 .

 Geometrical cross section = 2394.46 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here = 1629.65 mb
 Monte Carlo inelastic cross section = 1590.37 mb

     Wed Feb  1 10:55:15 2012

              800.0 MeV (Z =  1, A = 1) + (Z = 79., A = 197.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =     5056,

 Reaction cross section = 1629.65 mb, Elastic cross section =  823.95 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av = 226.4 +/-150.4 MeV;  E*min =  -1.1;  E*max = 717.9
   Zav =  78.6 +/-  1.1;       Zmin =  73.;    Zmax =  82.
   Aav = 192.7 +/-  2.6;       Amin = 182.;    Amax = 198.
   Lav =  12.7 +/-  7.5 h-bar; Lmin =   0.;    Lmax =  46.

  The mean charge, mass, and angular momentum
  of the     165 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  79.2 +/-  0.4;       Zmin =  79.;   Zmax =  80.
   Aav = 196.1 +/-  0.4;       Amin = 194.;   Amax = 197.
   Lav =   3.5 +/-  2.2 h-bar; Lmin =   0.;   Lmax =  13.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9835 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av = 181.2 +/- 128.5 MeV; E*min =   1.0;  E*max = 683.9
   Zav =  77.7 +/-  1.7;       Zmin =  69.;   Zmax =  81.
   Aav = 190.6 +/-  4.2;       Amin = 172.;   Amax = 197.
   Lav =  14.8 +/-  9.0 h-bar; Lmin =   0.;   Lmax =  66.

  The mean kinetic energy, charge, mass, and angular momentum
  of the    9566 residual nuclei are:
  Ekav =   2.1 +/-  2.6 MeV;  Ekmin =  0.0;  Ekmax =  23.6
   Zav =  74.9 +/-  3.9;       Zmin =  60.;   Zmax =  81.
   Aav = 175.8 +/- 13.3;       Amin = 132.;   Amax = 197.
   Lav =  14.5 +/-  9.1 h-bar; Lmin =   0.;   Lmax =  66.

  The mean excitation energy, charge, mass, angular momentum, and
  fission barrier height of the     434 fissioning nuclei are:
  E*av = 254.1 +/-102.0 MeV; E*min =  48.9; E*max =  551.3
   Zav =  76.9 +/- 2.4;        Zmin =  66.;  Zmax =  81.
   Aav = 184.0 +/- 6.3;        Amin = 160.;  Amax = 196.
   Lav =  17.7 +/- 8.2 h-bar;  Lmin =   2.;  Lmax =  51.
  Bfav =  15.9 +/- 2.8 MeV;   Bfmin =  8.3; Bfmax = 25.7

 The mean total fission product kinetic energy after neutron emission is 121.75 MeV.

             Direct Monte Carlo Simulation Method:
 Fissility =  0.0434 +/-  0.0021,
 Fission cross section = 7.07268E+01 +/- 3.39E+00 mb.

             Statistical Weight Functions Method:
 Fissility =  0.0418,
 Fission cross section = 6.81368E+01 mb.

 Number of coalesced d, t, He3, He4 =     3566    1169     221     235

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
```

```
 T  n    14.4065 +/- 0.0380   23477.537 +/-  61.855     20.72
 C  n     3.1900 +/- 0.0179    5198.580 +/-  29.106     76.92
 P  n     0.5990 +/- 0.0077     976.160 +/-  12.613     19.31
 Sp n     9.8640 +/- 0.0314   16074.857 +/-  51.182      3.82
 Pf n     0.1216 +/- 0.0035     198.165 +/-   5.683      6.80
 F  n     0.6319 +/- 0.0079    1029.775 +/-  12.954      4.83
 E  n    10.6175 +/- 0.0326   17302.797 +/-  53.101      3.92
 *****************************************************************
 T  p     2.3550 +/- 0.0153    3837.823 +/-  25.009     80.49
 C  p     0.8762 +/- 0.0094    1427.898 +/-  15.254    189.69
 P  p     0.3430 +/- 0.0059     558.970 +/-   9.544     28.11
 Sp p     1.0578 +/- 0.0103    1723.843 +/-  16.761     12.15
 Pf p     0.0179 +/- 0.0013      29.171 +/-   2.180     14.39
 F  p     0.0601 +/- 0.0025      97.942 +/-   3.995      9.75
 E  p     1.1358 +/- 0.0107    1850.955 +/-  17.368     12.06
 *****************************************************************
 T  d     1.0705 +/- 0.0103    1744.539 +/-  16.861     36.49
 P  d     0.2514 +/- 0.0050     409.694 +/-   8.171     31.55
 Sp d     0.4316 +/- 0.0066     703.356 +/-  10.706     13.31
 Pf d     0.0136 +/- 0.0012      22.163 +/-   1.900     14.79
 F  d     0.0182 +/- 0.0013      29.660 +/-   2.199     11.71
 E  d     0.4634 +/- 0.0068     755.179 +/-  11.094     13.29
 Co d     0.3557 +/- 0.0060     579.666 +/-   9.719     70.19
 *****************************************************************
 T  t     0.3894 +/- 0.0062     634.585 +/-  10.169     27.60
 P  t     0.0802 +/- 0.0028     130.698 +/-   4.615     36.83
 Sp t     0.1773 +/- 0.0042     288.937 +/-   6.862     14.13
 Pf t     0.0065 +/- 0.0008      10.593 +/-   1.314     14.93
 F  t     0.0087 +/- 0.0009      14.178 +/-   1.520     13.03
 E  t     0.1925 +/- 0.0044     313.707 +/-   7.150     14.11
 Co t     0.1167 +/- 0.0034     190.180 +/-   5.567     43.50
 *****************************************************************
 T He3    0.0965 +/- 0.0031     157.261 +/-   5.062     44.27
 P He3    0.0555 +/- 0.0024      90.446 +/-   3.839     44.17
 SpHe3    0.0173 +/- 0.0013      28.193 +/-   2.143     23.59
 PfHe3    0.0007 +/- 0.0003       1.141 +/-   0.431     25.34
 F He3    0.0009 +/- 0.0003       1.467 +/-   0.489     21.30
 E He3    0.0189 +/- 0.0014      30.800 +/-   2.240     23.55
 CoHe3    0.0221 +/- 0.0015      36.015 +/-   2.423     62.24
 *****************************************************************
 T He4    0.5945 +/- 0.0077     968.826 +/-  12.565     25.38
 P He4    0.0343 +/- 0.0019      55.897 +/-   3.018     54.99
 SpHe4    0.5015 +/- 0.0071     817.269 +/-  11.541     23.24
 PfHe4    0.0085 +/- 0.0009      13.852 +/-   1.502     25.69
 F He4    0.0269 +/- 0.0016      43.838 +/-   2.673     17.93
 E He4    0.5369 +/- 0.0073     874.959 +/-  11.941     23.01
 CoHe4    0.0233 +/- 0.0015      37.971 +/-   2.488     36.26
 *****************************************************************
 pi-      0.1051 +/- 0.0032     171.276 +/-   5.283     72.42
 pi0      0.1857 +/- 0.0043     302.626 +/-   7.023     84.07
 pi+      0.0870 +/- 0.0029     141.779 +/-   4.807    115.45
 *****************************************************************

 *************** Nuclide yields [mb]  (zero values suppressed) *****************

               Z =  81.                Z =  80.                Z =  79.
 A = 197 0.000E+00 +/- 0.00E+00 5.541E+00 +/- 9.50E-01 4.889E+00 +/- 8.93E-01
 A = 196 0.000E+00 +/- 0.00E+00 8.800E+00 +/- 1.20E+00 3.748E+01 +/- 2.47E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 182 0.000E+00 +/- 0.00E+00 1.630E-01 +/- 1.63E-01 0.000E+00 +/- 0.00E+00
 S =  16 8.148E-01 +/- 3.64E-01 7.692E+01 +/- 3.54E+00 1.974E+02 +/- 5.67E+00

               Z =  78.                Z =  77.                Z =  76.
 A = 196 3.259E-01 +/- 2.30E-01 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A = 195 1.124E+01 +/- 1.35E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 168 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.889E-01 +/- 2.82E-01
 S =  29 2.537E+02 +/- 6.43E+00 1.371E+02 +/- 4.73E+00 1.657E+02 +/- 5.20E+00

               Z =  75.                Z =  74.                Z =  73.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

               Z =   9.                Z =   8.                Z =   7.
 A =  14 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.630E-01 +/- 1.63E-01
 S =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.630E-01 +/- 1.63E-01

               Z =   3.                Z =   2.                Z =   1.
 A =   4 0.000E+00 +/- 0.00E+00 9.688E+02 +/- 1.26E+01 0.000E+00 +/- 0.00E+00
 A =   3 0.000E+00 +/- 0.00E+00 1.573E+02 +/- 5.06E+00 6.346E+02 +/- 1.02E+01
 A =   2 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.745E+03 +/- 1.69E+01
 A =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 3.838E+03 +/- 2.50E+01
 S =   4 0.000E+00 +/- 0.00E+00 1.126E+03 +/- 1.35E+01 6.217E+03 +/- 3.18E+01

               Z =   0.
 A =   1 2.348E+04 +/- 6.19E+01
 S =   1 2.348E+04 +/- 6.19E+01

 End of nuclide yields.

Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei:
```

```
 A = 197 1.043E+01 +/- 1.30E+00  1.227E-01 +/- 1.28E-01
 A = 196 4.661E+01 +/- 2.76E+00  7.283E-02 +/- 9.35E-02
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 2.732E+04 +/- 6.67E+01  2.912E+01 +/- 8.56E+01
 S = 156 3.252E+04 +/- 7.28E+01  2.829E+01 +/- 7.98E+01

Charge yield [mb] and the mean and variance of the  kinetic energy [MeV]
 of residual nuclei:
 Z = 81 8.148E-01 +/- 3.64E-01  6.399E-01 +/- 4.53E-01
 Z = 80 7.692E+01 +/- 3.54E+00  4.428E-01 +/- 4.24E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 2.348E+04 +/- 6.19E+01  2.072E+01 +/- 6.90E+01
 S = 69 3.252E+04 +/- 7.28E+01  2.829E+01 +/- 7.98E+01

 Elapsed cpu time  =  0. min and  8.608 sec.
```

CEM03.03 Output Example 8

```
 -----------------------------------------------------------------------------

 Wed Feb  1 10:54:39 2012

Example No. 8: Yields, mean kinetic energy, angles of emission,
and much more (the most complete output) of all products measured
at GSI in inverse kinematics for 1000 MeV p + Fe56; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.9383 1.0000   56.  26.  1  1   10000   1

 dt0 =  -20.0, t0max = 1000.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     3     0     0     2     2

 r0m =  1.2, & cevap = 12.0.

 lim =     100000 .

 Geometrical cross section = 1367.65 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here =  735.39 mb
 Monte Carlo inelastic cross section =  744.87 mb

     Wed Feb  1 10:54:39 2012

              1000.0 MeV (Z =  1, A = 1) + (Z = 26., A =  56.)

 Number of inelastic interactions =    10000,
 Number of elastic interactions   =     8361,

 Reaction cross section =  735.39 mb, Elastic cross section =  614.86 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av = 148.9 +/-119.9 MeV;  E*min =  -3.0;  E*max = 707.8
   Zav =  24.7 +/-  1.4;       Zmin =  18.;    Zmax =  28.
   Aav =  52.1 +/-  2.8;       Amin =  40.;    Amax =  56.
   Lav =   6.6 +/-  4.3 h-bar; Lmin =   0.;    Lmax =  33.

 The program called Fermi breakup       46 times.

  The mean charge, mass, and angular momentum
  of the     319 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  26.1 +/-  0.3;       Zmin =  26.;   Zmax =  27.
   Aav =  55.1 +/-  0.4;       Amin =  54.;   Amax =  56.
   Lav =   2.2 +/-  1.3 h-bar; Lmin =   0.;   Lmax =   7.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9681 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av = 128.7 +/- 108.8 MeV; E*min =   1.3;  E*max = 689.5
   Zav =  24.1 +/-  1.8;       Zmin =  16.;   Zmax =  28.
   Aav =  51.0 +/-  3.4;       Amin =  35.;   Amax =  56.
   Lav =   7.7 +/-  5.1 h-bar; Lmin =   0.;   Lmax =  33.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   4.4 +/-  5.7 MeV;  Ekmin =  0.0;  Ekmax =  52.6
   Zav =  19.8 +/-  4.8;       Zmin =   6.;   Zmax =  27.
   Aav =  41.7 +/- 10.4;       Amin =  13.;   Amax =  56.
   Lav =   7.5 +/-  5.1 h-bar; Lmin =   0.;   Lmax =  33.

 Number of coalesced d, t, He3, He4 =     4275     847     493     490

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     4.7164 +/- 0.0217    3468.374 +/-  15.971     66.38
 C  n     1.8841 +/- 0.0137    1385.541 +/-  10.094    155.67
 P  n     0.1444 +/- 0.0038     106.190 +/-   2.794     20.23
 Sp n     2.6879 +/- 0.0164    1976.644 +/-  12.057      6.27
 E  n     2.6879 +/- 0.0164    1976.644 +/-  12.057      6.27
 *****************************************************************
 T  p     3.8522 +/- 0.0196    2832.854 +/-  14.433     85.07
 C  p     1.5569 +/- 0.0125    1144.922 +/-   9.176    195.22
 P  p     0.1437 +/- 0.0038     105.675 +/-   2.788     23.69
 Sp p     2.1516 +/- 0.0147    1582.256 +/-  10.787      9.46
 E  p     2.1516 +/- 0.0147    1582.256 +/-  10.787      9.46
 *****************************************************************
 T  d     1.2450 +/- 0.0112     915.556 +/-   8.205     35.69
 P  d     0.1151 +/- 0.0034      84.643 +/-   2.495     26.83
 Sp d     0.7037 +/- 0.0084     517.491 +/-   6.169     11.68
```

```
 E  d     0.7037 +/- 0.0084     517.491 +/-   6.169     11.68
 Co d     0.4262 +/- 0.0065     313.422 +/-   4.801     77.74
 *****************************************************************
 T  t     0.2611 +/- 0.0051     192.009 +/-   3.758     25.40
 P  t     0.0443 +/- 0.0021      32.578 +/-   1.548     30.68
 Sp t     0.1323 +/- 0.0036      97.292 +/-   2.675     11.72
 E  t     0.1323 +/- 0.0036      97.292 +/-   2.675     11.72
 Co t     0.0845 +/- 0.0029      62.140 +/-   2.138     44.04
 *****************************************************************
 T He3    0.2164 +/- 0.0047     159.138 +/-   3.421     29.46
 P He3    0.0474 +/- 0.0022      34.857 +/-   1.601     34.40
 SpHe3    0.1198 +/- 0.0035      88.099 +/-   2.545     15.67
 E He3    0.1198 +/- 0.0035      88.099 +/-   2.545     15.67
 CoHe3    0.0492 +/- 0.0022      36.181 +/-   1.631     58.26
 *****************************************************************
 T He4    0.7308 +/- 0.0085     537.420 +/-   6.287     15.18
 P He4    0.0419 +/- 0.0020      30.813 +/-   1.505     43.49
 SpHe4    0.6400 +/- 0.0080     470.647 +/-   5.883     12.11
 E He4    0.6400 +/- 0.0080     470.647 +/-   5.883     12.11
 CoHe4    0.0489 +/- 0.0022      35.960 +/-   1.626     30.99
 *****************************************************************
 pi-      0.1301 +/- 0.0036      95.674 +/-   2.652    108.73
 pi0      0.2637 +/- 0.0051     193.921 +/-   3.776    115.41
 pi+      0.1871 +/- 0.0043     137.591 +/-   3.181    157.10
 *****************************************************************

 *************** Nuclide yields [mb]  (zero values suppressed) *****************

                Z =  28.               Z =  27.               Z =  26.
 A =  56 0.000E+00 +/- 0.00E+00 3.824E+00 +/- 5.30E-01 4.927E+00 +/- 6.02E-01
 A =  55 0.000E+00 +/- 0.00E+00 1.691E+00 +/- 3.53E-01 3.250E+01 +/- 1.55E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =  52 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.030E+00 +/- 2.75E-01
 S =   5 0.000E+00 +/- 0.00E+00 5.883E+00 +/- 6.58E-01 5.817E+01 +/- 2.07E+00

                Z =  25.               Z =  24.               Z =  23.
 A =  55 1.633E+01 +/- 1.10E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A =  54 1.302E+01 +/- 9.78E-01 4.412E-01 +/- 1.80E-01 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =  46 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.030E+00 +/- 2.75E-01
 S =  10 7.619E+01 +/- 2.37E+00 7.802E+01 +/- 2.40E+00 5.045E+01 +/- 1.93E+00

                Z =  22.               Z =  21.               Z =  20.
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                Z =   4.               Z =   3.               Z =   2.
 A =   7 7.354E-02 +/- 7.35E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A =   6 0.000E+00 +/- 0.00E+00 2.206E-01 +/- 1.27E-01 0.000E+00 +/- 0.00E+00
 A =   4 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 5.374E+02 +/- 6.29E+00
 A =   3 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.591E+02 +/- 3.42E+00
 S =   4 7.354E-02 +/- 7.35E-02 2.206E-01 +/- 1.27E-01 6.966E+02 +/- 7.16E+00

                Z =   1.               Z =   0.
 A =   3 1.920E+02 +/- 3.76E+00 0.000E+00 +/- 0.00E+00
 A =   2 9.156E+02 +/- 8.21E+00 0.000E+00 +/- 0.00E+00
 A =   1 2.833E+03 +/- 1.44E+01 3.468E+03 +/- 1.60E+01
 S =   3 3.940E+03 +/- 1.70E+01 3.468E+03 +/- 1.60E+01

 End of nuclide yields.

Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei:
 A =  56 8.751E+00 +/- 8.02E-01  3.434E-01 +/- 3.79E-01
 A =  55 5.052E+01 +/- 1.93E+00  2.156E-01 +/- 3.13E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 6.301E+03 +/- 2.15E+01  7.478E+01 +/- 1.62E+02
 S =  53 8.840E+03 +/- 2.55E+01  5.937E+01 +/- 1.41E+02

Charge yield [mb] and the mean and variance of the  kinetic energy [MeV]
 of residual nuclei:
 Z = 27 5.883E+00 +/- 6.58E-01  4.566E-01 +/- 3.71E-01
 Z = 26 5.817E+01 +/- 2.07E+00  3.842E-01 +/- 5.73E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 3.468E+03 +/- 1.60E+01  6.638E+01 +/- 1.53E+02
 S = 28 8.840E+03 +/- 2.55E+01  5.937E+01 +/- 1.41E+02

 ********** Nuclide yields [mb] in forward direction (theta_lab < 90) **********
           (zero values suppressed)

                Z =  28.               Z =  27.               Z =  26.
 A =  56 0.000E+00 +/- 0.00E+00 3.824E+00 +/- 5.30E-01 4.927E+00 +/- 6.02E-01
 A =  55 0.000E+00 +/- 0.00E+00 1.103E+00 +/- 2.85E-01 1.912E+01 +/- 1.19E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =  52 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 8.089E-01 +/- 2.44E-01
 S =   5 0.000E+00 +/- 0.00E+00 5.148E+00 +/- 6.15E-01 3.765E+01 +/- 1.66E+00

                Z =  25.               Z =  24.               Z =  23.
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
                Z =   4.               Z =   3.               Z =   2.
 A =   7 7.354E-02 +/- 7.35E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A =   6 0.000E+00 +/- 0.00E+00 1.471E-01 +/- 1.04E-01 0.000E+00 +/- 0.00E+00
 A =   4 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 3.214E+02 +/- 4.86E+00
 A =   3 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.057E+02 +/- 2.79E+00
 S =   4 7.354E-02 +/- 7.35E-02 1.471E-01 +/- 1.04E-01 4.272E+02 +/- 5.60E+00

                Z =   1.               Z =   0.
 A =   3 1.293E+02 +/- 3.08E+00 0.000E+00 +/- 0.00E+00
 A =   2 5.944E+02 +/- 6.61E+00 0.000E+00 +/- 0.00E+00
 A =   1 1.892E+03 +/- 1.18E+01 2.264E+03 +/- 1.29E+01
 S =   3 2.616E+03 +/- 1.39E+01 2.264E+03 +/- 1.29E+01

 End of nuclide yields (forward direction).

 Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the forward direction:
 A =  56 8.751E+00 +/- 8.02E-01  3.434E-01 +/- 3.79E-01
 A =  55 3.015E+01 +/- 1.49E+00  2.417E-01 +/- 2.89E-01
 - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 4.157E+03 +/- 1.75E+01  1.050E+02 +/- 1.92E+02
 S =  53 5.870E+03 +/- 2.08E+01  8.170E+01 +/- 1.67E+02

Charge yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the forward direction:
 Z = 27 5.148E+00 +/- 6.15E-01  4.243E-01 +/- 7.18E-01
 Z = 26 3.765E+01 +/- 1.66E+00  4.450E-01 +/- 1.07E+00
 - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 2.264E+03 +/- 1.29E+01  9.405E+01 +/- 9.16E+01
 S = 28 5.870E+03 +/- 2.08E+01  8.170E+01 +/- 1.67E+02

 ********** Nuclide yields [mb] in backward direction (theta_lab > 90) *********
           (zero values suppressed)

                Z =  28.               Z =  27.               Z =  26.
 A =  55 0.000E+00 +/- 0.00E+00 5.883E-01 +/- 2.08E-01 1.338E+01 +/- 9.92E-01
 A =  54 0.000E+00 +/- 0.00E+00 1.471E-01 +/- 1.04E-01 5.736E+00 +/- 6.49E-01
 A =  53 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.177E+00 +/- 2.94E-01
 A =  52 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.206E-01 +/- 1.27E-01
 S =   4 0.000E+00 +/- 0.00E+00 7.354E-01 +/- 2.33E-01 2.052E+01 +/- 1.23E+00

                Z =  25.               Z =  24.               Z =  23.
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                Z =   4.               Z =   3.               Z =   2.
 A =   6 0.000E+00 +/- 0.00E+00 7.354E-02 +/- 7.35E-02 0.000E+00 +/- 0.00E+00
 A =   4 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.160E+02 +/- 3.99E+00
 A =   3 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 5.339E+01 +/- 1.98E+00
 S =   3 0.000E+00 +/- 0.00E+00 7.354E-02 +/- 7.35E-02 2.694E+02 +/- 4.45E+00

                Z =   1.               Z =   0.
 A =   3 6.273E+01 +/- 2.15E+00 0.000E+00 +/- 0.00E+00
 A =   2 3.211E+02 +/- 4.86E+00 0.000E+00 +/- 0.00E+00
 A =   1 9.406E+02 +/- 8.32E+00 1.204E+03 +/- 9.41E+00
 S =   3 1.324E+03 +/- 9.87E+00 1.204E+03 +/- 9.41E+00

 End of nuclide yields (backward direction).

 Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the backward direction:
 A =  55 2.037E+01 +/- 1.22E+00  1.769E-01 +/- 3.41E-01
 A =  54 1.052E+01 +/- 8.79E-01  4.401E-01 +/- 5.32E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 2.145E+03 +/- 1.26E+01  1.615E+01 +/- 2.71E+01
 S =  50 2.970E+03 +/- 1.48E+01  1.524E+01 +/- 2.47E+01

 Charge yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the backward direction:
 Z = 27 7.354E-01 +/- 2.33E-01  6.830E-01 +/- 4.85E-01
 Z = 26 2.052E+01 +/- 1.23E+00  2.728E-01 +/- 4.29E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 1.204E+03 +/- 9.41E+00  1.435E+01 +/- 2.58E+01
 S = 27 2.970E+03 +/- 1.48E+01  1.524E+01 +/- 2.47E+01

******** Nuclide average kinetic energies [MeV] (zero yield suppressed) ********

                Z =  28.               Z =  27.               Z =  26.
 A =  56 0.000E+00 +/- 0.00E+00 4.148E-01 +/- 3.61E-01 2.879E-01 +/- 3.84E-01
 A =  55 0.000E+00 +/- 0.00E+00 4.777E-01 +/- 3.17E-01 2.224E-01 +/- 3.00E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =  52 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.539E+00 +/- 1.76E+00
 S =   5 0.000E+00 +/- 0.00E+00 4.566E-01 +/- 3.71E-01 3.842E-01 +/- 5.73E-01

                Z =  25.               Z =  24.               Z =  23.
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                Z =   4.               Z =   3.               Z =   2.
```

```
 A =   7 9.753E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A =   6 0.000E+00 +/- 0.00E+00 1.124E+01 +/- 9.67E+00 0.000E+00 +/- 0.00E+00
 A =   4 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.518E+01 +/- 1.42E+01
 A =   3 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.946E+01 +/- 3.82E+01
 S =   4 9.753E+00 +/- 0.00E+00 1.124E+01 +/- 9.67E+00 1.844E+01 +/- 2.29E+01

                Z =   1.              Z =   0.
 A =   3 2.540E+01 +/- 3.40E+01 0.000E+00 +/- 0.00E+00
 A =   2 3.569E+01 +/- 6.31E+01 0.000E+00 +/- 0.00E+00
 A =   1 8.507E+01 +/- 1.71E+02 6.638E+01 +/- 1.53E+02
 S =   3 7.069E+01 +/- 1.50E+02 6.638E+01 +/- 1.53E+02

 End of nuclide average kinetic energies.

 Mass yield [mb] and the mean and variance of the emission angle [deg.]
 of residual nuclei:
 A =  56  8.751E+00 +/- 8.02E-01   8.315E+01 +/- 1.74E+00
 A =  55  5.052E+01 +/- 1.93E+00   8.380E+01 +/- 3.26E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1  6.301E+03 +/- 2.15E+01   7.365E+01 +/- 4.04E+01
 S =  53  8.840E+03 +/- 2.55E+01   7.382E+01 +/- 3.97E+01

 The mean and variance of the z velocity [v/c] of residual nuclei,
 and the forward/backward ratio:
 A =  56  4.003E-04 +/- 2.63E-04   1.000E+00 +/- 0.00E+00
 A =  55  3.056E-04 +/- 1.09E-03   1.480E+00 +/- 1.62E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1  1.106E-01 +/- 2.25E-01   1.938E+00 +/- 1.95E-02
 S =  53  8.698E-02 +/- 1.99E-01   1.977E+00 +/- 1.68E-02

 Charge yield [mb] and the mean and variance of the emission angle [deg.]
 of residual nuclei:
 Z = 27  5.883E+00 +/- 6.58E-01   8.332E+01 +/- 1.23E+01
 Z = 26  5.817E+01 +/- 2.07E+00   8.288E+01 +/- 3.12E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0  3.468E+03 +/- 1.60E+01   7.434E+01 +/- 4.04E+01
 S = 28  8.840E+03 +/- 2.55E+01   7.382E+01 +/- 3.97E+01

 The mean and variance of the z velocity [v/c] of residual nuclei,
 and the forward/backward ratio:
 Z = 27  3.928E-04 +/- 1.01E-03   4.348E+00 +/- 2.46E+00
 Z = 26  5.406E-04 +/- 1.56E-03   2.993E+00 +/- 5.41E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0  1.000E-01 +/- 2.16E-01   1.232E+01 +/- 3.27E-02
 S = 28  8.698E-02 +/- 1.99E-01   1.977E+00 +/- 1.68E-02

                  Mass distributions of nuclei:
                                    at start of evap, which:  just prior to
           after cascade after preeq   evap. only    fission      fission
   A =  56    3.910E-02    3.160E-02    3.160E-02    0.000E+00    0.000E+00
   A =  55    1.908E-01    1.468E-01    1.468E-01    0.000E+00    0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   A =  35    0.000E+00    1.000E-04    1.000E-04    0.000E+00    0.000E+00
    <A> =     5.202E+01    5.102E+01    5.102E+01    0.000E+00    0.000E+00
St Dv A =     2.745E+00    3.445E+00    3.445E+00    0.000E+00    0.000E+00
   norm =     1.000E+00    1.000E+00    1.000E+00    0.000E+00    0.000E+00

                  Charge distributions of nuclei:
                                    at start of evap, which:  just prior to
           after cascade after preeq   evap. only    fission      fission
   Z =  28    1.900E-03    1.600E-03    1.600E-03    0.000E+00    0.000E+00
   Z =  27    5.630E-02    4.010E-02    4.010E-02    0.000E+00    0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   Z =  16    0.000E+00    3.000E-04    3.000E-04    0.000E+00    0.000E+00
    <Z> =     2.463E+01    2.413E+01    2.413E+01    0.000E+00    0.000E+00
St Dv Z =     1.445E+00    1.779E+00    1.779E+00    0.000E+00    0.000E+00
   norm =     1.000E+00    1.000E+00    1.000E+00    0.000E+00    0.000E+00

          Excitation energy distributions [1/MeV] of nuclei:
                                      at start of evap, which:  just prior to
    E*(MeV)   after cascade after preeq   evap. only    fission      fission
    0.-  10.    4.380E-03    5.010E-03    5.010E-03    0.000E+00    0.000E+00
   10.-  20.    3.630E-03    5.070E-03    5.070E-03    0.000E+00    0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  680.- 690.    1.000E-05    1.000E-05    1.000E-05    0.000E+00    0.000E+00
     <E*> =     1.496E+02    1.286E+02    1.286E+02    0.000E+00    0.000E+00
St dev E* =     1.151E+02    1.086E+02    1.086E+02    0.000E+00    0.000E+00
     norm =     1.000E+00    1.000E+00    1.000E+00    0.000E+00    0.000E+00

          Linear momentum distributions [1/MeV/c] of nuclei:
                                      at start of evap, which:  just prior to
    P(MeV/c)  after cascade after preeq   evap. only    fission      fission
    0.-  20.    4.000E-05    4.500E-05    4.500E-05    0.000E+00    0.000E+00
   20.-  40.    3.050E-04    3.100E-04    3.100E-04    0.000E+00    0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 1940.-1960.    1.000E-05    1.000E-05    1.000E-05    0.000E+00    0.000E+00
      <P> =     5.097E+02    5.052E+02    5.052E+02    0.000E+00    0.000E+00
 St dev P =     3.426E+02    3.376E+02    3.376E+02    0.000E+00    0.000E+00
     norm =     1.000E+00    1.000E+00    1.000E+00    0.000E+00    0.000E+00

              Angular momentum distributions [1/hbar] of nuclei:
                                   at start of evap, which:  just prior to
      L     after cascade after preeq   evap. only    fission      fission
   0.-  1.    4.300E-03    3.800E-03    3.800E-03    0.000E+00    0.000E+00
   1.-  2.    4.780E-02    4.010E-02    4.010E-02    0.000E+00    0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
  33.- 34.    1.000E-04    2.000E-04    2.000E-04    0.000E+00    0.000E+00
    <L> =     6.771E+00    7.700E+00    7.700E+00    0.000E+00    0.000E+00
St dv L =     4.291E+00    5.092E+00    5.092E+00    0.000E+00    0.000E+00
   norm =     1.000E+00    1.000E+00    1.000E+00    0.000E+00    0.000E+00

                    Neutron-multiplicity probability:

     Nn      Total      Cascade    Preequil.   Evap. res.  Pre-fiss.   Post-fiss.
      0    3.250E-02   1.602E-01   8.701E-01   1.393E-01   0.000E+00   0.000E+00
      1    8.940E-02   3.230E-01   1.167E-01   1.943E-01   0.000E+00   0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
     15    1.000E-04   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
    <n> =  4.716E+00   1.884E+00   1.444E-01   2.688E+00   0.000E+00   0.000E+00
St dv n =  2.695E+00   1.500E+00   3.939E-01   2.069E+00   0.000E+00   0.000E+00
   norm =  1.000E+00   1.000E+00   1.000E+00   1.000E+00   0.000E+00   0.000E+00


 The program called Fermi breakup       46 times.

 Elapsed cpu time  =  0. min and  6.201 sec.
```

CEM03.03 Output Example 9

```
 ----------------------------------------------------------------------------

 Wed Feb  1 10:49:05 2012

Example No. 9: Proton spectra from monochromatic 300 MeV gamma + 64Cu;
10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.0000 0.3000   64.  29.  0  0   10000   1

 dt0 =   -5.0, t0max =  300.5, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     0     1     0     2     2

 r0m =  1.2, & cevap = 12.0.

    Theta1      Theta2      Theta3      Theta4      Theta5      Theta6
  42.5  47.5  87.5  92.5 132.5 137.5 -55.0 165.0  55.0  65.0  75.0  85.0

    Theta7      Theta8      Theta9     Theta10
  95.0 105.0 115.0 125.0 135.0 145.0 155.0 165.0


 Tmin, Tmax, dT{1};Tmin, Tmax, dT{2};Tmin, Tmax, dT{3};Tmin, Tmax, dT{4}.
   0.0  22.0  1.00  22.0 120.0  2.00  120.  400.  10.0  400. 1000.   20.

 lim =    6000000 .

 Geometrical cross section = 1445.99 mb.
- - - - - - - - - - - - - - - - - - - - - - - - -
   Inelastic cross section used here =   26.58 mb
 Monte Carlo inelastic cross section =   28.02 mb

     Wed Feb  1 10:49:06 2012

               300.0 MeV (Z =  0, A = 0) + (Z = 29., A =  64.)

 Number of inelastic interactions =        10000,
 Number of elastic interactions   =       505970,

 Reaction cross section =   26.58 mb, Elastic cross section = 1344.95 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av =  86.6 +/- 52.5 MeV;  E*min =   1.3;  E*max = 299.2
   Zav =  28.3 +/-  0.9;       Zmin =  24.;    Zmax =  30.
   Aav =  61.8 +/-  1.4;       Amin =  56.;    Amax =  64.
   Lav =   4.3 +/-  2.5 h-bar; Lmin =   0.;    Lmax =  17.

  The mean charge, mass, and angular momentum
  of the      13 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  28.0 +/-  0.0;       Zmin =  28.;   Zmax =  28.
   Aav =  62.0 +/-  0.0;       Amin =  62.;   Amax =  62.
   Lav =   3.6 +/-  1.5 h-bar; Lmin =   2.;   Lmax =   7.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9986 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  66.1 +/-  44.2 MeV; E*min =   0.7;  E*max = 298.3
   Zav =  27.8 +/-  1.1;       Zmin =  22.;   Zmax =  30.
   Aav =  60.9 +/-  2.0;       Amin =  51.;   Amax =  64.
   Lav =   5.4 +/-  3.4 h-bar; Lmin =   0.;   Lmax =  35.

  The mean kinetic energy, charge, mass, and angular momentum
  of the   10000 residual nuclei are:
  Ekav =   1.7 +/-  1.8 MeV;  Ekmin =  0.0;  Ekmax =  18.5
   Zav =  25.9 +/-  2.1;       Zmin =  15.;   Zmax =  30.
   Aav =  55.5 +/-  4.7;       Amin =  33.;   Amax =  63.
   Lav =   5.4 +/-  3.4 h-bar; Lmin =   0.;   Lmax =  35.

 Number of coalesced d, t, He3, He4 =      758      95      13       4

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
 Sp - from spallation residues, Pf - from nuclei before fission,
 F - from fission fragments, E - total evaporation = Sp + Pf + F,
 Co - Coalescence from cascade;
 Values which are identically zero are not printed.

 Part.     Multiplicities           Yields [mb]     <TKE> [MeV]
 *****************************************************************
 T  n     4.1051 +/- 0.0203     109.120 +/-   0.539     18.40
 C  n     1.3358 +/- 0.0116      35.508 +/-   0.307     46.23
 P  n     0.2486 +/- 0.0050       6.608 +/-   0.133     17.15
 Sp n     2.5207 +/- 0.0159      67.004 +/-   0.422      3.79
 E  n     2.5207 +/- 0.0159      67.004 +/-   0.422      3.79
 *****************************************************************
 T  p     1.9716 +/- 0.0140      52.408 +/-   0.373     29.11
```

```
C  p    0.7029 +/- 0.0084      18.684 +/-   0.223     64.50
P  p    0.1849 +/- 0.0043       4.915 +/-   0.114     21.64
Sp p    1.0838 +/- 0.0104      28.809 +/-   0.277      7.43
E  p    1.0838 +/- 0.0104      28.809 +/-   0.277      7.43
*****************************************************************
T  d    0.3705 +/- 0.0061       9.848 +/-   0.162     16.76
P  d    0.1206 +/- 0.0035       3.206 +/-   0.092     23.68
Sp d    0.1742 +/- 0.0042       4.631 +/-   0.111      8.99
E  d    0.1742 +/- 0.0042       4.631 +/-   0.111      8.99
Co d    0.0757 +/- 0.0028       2.012 +/-   0.073     23.61
*****************************************************************
T  t    0.0705 +/- 0.0027       1.874 +/-   0.071     17.86
P  t    0.0320 +/- 0.0018       0.851 +/-   0.048     25.79
Sp t    0.0290 +/- 0.0017       0.771 +/-   0.045      9.23
E  t    0.0290 +/- 0.0017       0.771 +/-   0.045      9.23
Co t    0.0095 +/- 0.0010       0.253 +/-   0.026     17.50
*****************************************************************
T He3   0.0357 +/- 0.0019       0.949 +/-   0.050     23.34
P He3   0.0217 +/- 0.0015       0.577 +/-   0.039     29.28
SpHe3   0.0127 +/- 0.0011       0.338 +/-   0.030     12.94
E He3   0.0127 +/- 0.0011       0.338 +/-   0.030     12.94
CoHe3   0.0013 +/- 0.0004       0.035 +/-   0.010     25.82
*****************************************************************
T He4   0.3421 +/- 0.0058       9.094 +/-   0.155     13.38
P He4   0.0162 +/- 0.0013       0.431 +/-   0.034     38.47
SpHe4   0.3255 +/- 0.0057       8.652 +/-   0.152     12.12
E He4   0.3255 +/- 0.0057       8.652 +/-   0.152     12.12
CoHe4   0.0004 +/- 0.0002       0.011 +/-   0.005     18.83
*****************************************************************
pi-     0.1220 +/- 0.0035       3.243 +/-   0.093     55.35
pi0     0.2211 +/- 0.0047       5.877 +/-   0.125     58.90
pi+     0.0802 +/- 0.0028       2.132 +/-   0.075     48.01
*****************************************************************

************************************  protons   ********************************

Double differential cross sections [mb/MeV/sr];
Lab. angle =  42.5 to  47.5 degrees.

   Tp  [MeV]           Total                 Cascade              Precompound        Total Evaporation
   3.0-   4.0  1.509E-01 +/- 3.22E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.509E-01 +/- 3.22E-02
   4.0-   5.0  4.389E-01 +/- 5.49E-02 6.858E-03 +/- 6.86E-03 6.858E-03 +/- 6.86E-03 4.252E-01 +/- 5.40E-02
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 220.0- 230.0  1.372E-03 +/- 9.70E-04 1.372E-03 +/- 9.70E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 230.0- 240.0  6.858E-04 +/- 6.86E-04 6.858E-04 +/- 6.86E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   5.219E+00 +/- 1.89E-01 2.188E+00 +/- 1.22E-01 5.212E-01 +/- 5.98E-02 2.510E+00 +/- 1.31E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle =  87.5 to  92.5 degrees.

   Tp  [MeV]           Total                 Cascade              Precompound        Total Evaporation
   2.0-   3.0  1.940E-02 +/- 9.70E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.940E-02 +/- 9.70E-03
   3.0-   4.0  2.861E-01 +/- 3.72E-02 0.000E+00 +/- 0.00E+00 4.849E-03 +/- 4.85E-03 2.813E-01 +/- 3.69E-02
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 170.0- 180.0  4.849E-04 +/- 4.85E-04 4.849E-04 +/- 4.85E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 180.0- 190.0  4.849E-04 +/- 4.85E-04 4.849E-04 +/- 4.85E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   3.884E+00 +/- 1.37E-01 1.014E+00 +/- 7.01E-02 3.686E-01 +/- 4.23E-02 2.502E+00 +/- 1.10E-01

Double differential cross sections [mb/MeV/sr];
Lab. angle = 132.5 to 137.5 degrees.

   Tp  [MeV]           Total                 Cascade              Precompound        Total Evaporation
   2.0-   3.0  3.429E-02 +/- 1.53E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 3.429E-02 +/- 1.53E-02
   3.0-   4.0  3.223E-01 +/- 4.70E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 3.223E-01 +/- 4.70E-02
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 130.0- 140.0  2.743E-03 +/- 1.37E-03 2.743E-03 +/- 1.37E-03 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 140.0- 150.0  6.858E-04 +/- 6.86E-04 6.858E-04 +/- 6.86E-04 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00

 Integrated:   3.381E+00 +/- 1.52E-01 8.710E-01 +/- 7.73E-02 3.018E-01 +/- 4.55E-02 2.208E+00 +/- 1.23E-01

Elapsed cpu time  =  0. min and 16.136 sec.
```

CEM03.03 Output Example 10

```
 ------------------------------------------------------------------------------

 Wed Feb  1 10:48:33 2012

Example No. 10: Yields, mean kinetic energy, emission angles,
neutron multiplicities, Forward/Backward ratios, and much more
(the most complete output) of all products from E_max = 1000 MeV
bremsstrahlung gammas + 197Au; 10,000 events.
 Number of types of evaporated particles =  6

    M      T0     A    Z   Q  B   limc   idel
 0.0000 0.4595  197.  79.  0  0   10000   1

 dt0 =  -20.0, t0max = 1000.0, dteta = 10.0

  mspec mpyld  mchy  misy mdubl mang  ipar1 ipar2
    0     1     0     3     0     0     2     2

 r0m =  1.2, & cevap = 12.0.

 lim =    6000000 .

 Geometrical cross section = 2394.46 mb.
- - - - - - - - - - - - - - - - - - - - - - - - - -
  Number of equivalent gamma quanta =  3.220898E-01
  Inelasic cross section per eqqv   =  1.389253E+02
  Averaged absorption cross section =  4.474643E+01
  Results are normalized to eqqv.

   Inelastic cross section used here =  138.93 mb
 Monte Carlo inelastic cross section =   35.37 mb

     Wed Feb  1 10:48:33 2012

                459.5 MeV (Z =  0, A = 0) + (Z = 79., A = 197.)

 Number of inelastic interactions =        10000,
 Number of elastic interactions   =       666883,

 Reaction cross section =  138.93 mb, Elastic cross section = 9264.69 mb.

  The mean excitation energy, charge, mass, and angular momentum
  of the    10000 nuclei after the
  cascade and before preequilibrium decay are:
  E*av = 126.4 +/-104.9 MeV;  E*min =   1.2;  E*max = 789.4
   Zav =  78.6 +/-  0.8;       Zmin =  73.;    Zmax =  81.
   Aav = 194.7 +/-  2.2;       Amin = 182.;    Amax = 197.
   Lav =   6.0 +/-  4.6 h-bar; Lmin =   0.;    Lmax =  40.

  The mean charge, mass, and angular momentum
  of the       2 residual nuclei with less than
  3 MeV of excitation energy after the cascade are:
   Zav =  79.0 +/-  0.0;       Zmin =  79.;   Zmax =  79.
   Aav = 196.0 +/-  0.0;       Amin = 196.;   Amax = 196.
   Lav =   3.5 +/-  2.5 h-bar; Lmin =   1.;   Lmax =   6.

  The mean excitation energy, charge, mass, and angular momentum
  of the    9998 nuclei after preequilibrium
  decay and before the start of statistical decay are:
  E*av =  92.9 +/-  87.4 MeV; E*min =   0.2;  E*max = 713.4
   Zav =  78.1 +/-  1.2;       Zmin =  70.;   Zmax =  81.
   Aav = 193.5 +/-  3.2;       Amin = 175.;   Amax = 197.
   Lav =   8.1 +/-  6.0 h-bar; Lmin =   0.;   Lmax =  61.

  The mean kinetic energy, charge, mass, and angular momentum
  of the    9799 residual nuclei are:
  Ekav =   0.6 +/-  1.1 MeV;  Ekmin =  0.0;  Ekmax =  21.9
   Zav =  77.3 +/-  2.5;       Zmin =  60.;   Zmax =  81.
   Aav = 185.3 +/-  9.4;       Amin = 134.;   Amax = 196.
   Lav =   8.0 +/-  6.0 h-bar; Lmin =   0.;   Lmax =  61.

  The mean excitation energy, charge, mass, angular momentum, and
  fission barrier height of the     201 fissioning nuclei are:
  E*av = 203.9 +/- 96.6 MeV; E*min =  46.2; E*max =  487.2
   Zav =  77.0 +/- 2.5;        Zmin =  68.;  Zmax =  81.
   Aav = 186.8 +/- 6.6;        Amin = 165.;  Amax = 196.
   Lav =  10.8 +/- 7.1 h-bar;  Lmin =   1.;  Lmax =  40.
  Bfav =  18.4 +/- 2.2 MeV;   Bfmin = 12.7; Bfmax = 24.8

 The mean total fission product kinetic energy after neutron emission is 122.90 MeV.

              Direct Monte Carlo Simulation Method:
 Fissility =  0.0201 +/-  0.0014,
 Fission cross section = 2.79240E+00 +/- 1.97E-01 mb.

              Statistical Weight Functions Method:
 Fissility =  0.0170,
 Fission cross section = 2.36377E+00 mb.

 Number of coalesced d, t, He3, He4 =     1051     333      49      40

 Mean multiplicities, yields, and mean energies of ejected particles:
 (Notation: T - all production mechanisms, C - cascade, P - pre-equilibrium,
```

```
Sp - from spallation residues, Pf - from nuclei before fission,
F - from fission fragments, E - total evaporation = Sp + Pf + F,
Co - Coalescence from cascade;
Values which are identically zero are not printed.

Part.     Multiplicities          Yields [mb]     <TKE> [MeV]
*****************************************************************
T  n     9.1639 +/- 0.0303    1273.098 +/-   4.206     10.78
C  n     1.6086 +/- 0.0127     223.475 +/-   1.762     41.52
P  n     0.5664 +/- 0.0075      78.687 +/-   1.046     19.26
Sp n     6.6590 +/- 0.0258     925.104 +/-   3.585      2.93
Pf n     0.0553 +/- 0.0024       7.683 +/-   0.327      6.19
F  n     0.2746 +/- 0.0052      38.149 +/-   0.728      4.37
E  n     6.9889 +/- 0.0264     970.935 +/-   3.673      3.01
*****************************************************************
T  p     0.9682 +/- 0.0098     134.507 +/-   1.367     44.12
C  p     0.3384 +/- 0.0058      47.012 +/-   0.808     88.78
P  p     0.2918 +/- 0.0054      40.538 +/-   0.750     29.83
Sp p     0.3186 +/- 0.0056      44.262 +/-   0.784     11.81
Pf p     0.0048 +/- 0.0007       0.667 +/-   0.096     14.54
F  p     0.0146 +/- 0.0012       2.028 +/-   0.168      9.23
E  p     0.3380 +/- 0.0058      46.957 +/-   0.808     11.74
*****************************************************************
T  d     0.3494 +/- 0.0059      48.541 +/-   0.821     28.84
P  d     0.1196 +/- 0.0035      16.615 +/-   0.480     31.04
Sp d     0.1179 +/- 0.0034      16.379 +/-   0.477     12.92
Pf d     0.0042 +/- 0.0006       0.583 +/-   0.090     15.72
F  d     0.0036 +/- 0.0006       0.500 +/-   0.083     11.02
E  d     0.1257 +/- 0.0035      17.463 +/-   0.493     12.95
Co d     0.1041 +/- 0.0032      14.462 +/-   0.448     45.50
*****************************************************************
T  t     0.1152 +/- 0.0034      16.004 +/-   0.472     22.79
P  t     0.0284 +/- 0.0017       3.945 +/-   0.234     33.13
Sp t     0.0509 +/- 0.0023       7.071 +/-   0.313     13.67
Pf t     0.0015 +/- 0.0004       0.208 +/-   0.054     13.99
F  t     0.0016 +/- 0.0004       0.222 +/-   0.056     12.18
E  t     0.0540 +/- 0.0023       7.502 +/-   0.323     13.63
Co t     0.0328 +/- 0.0018       4.557 +/-   0.252     28.91
*****************************************************************
T He3    0.0261 +/- 0.0016       3.626 +/-   0.224     42.07
P He3    0.0168 +/- 0.0013       2.334 +/-   0.180     47.29
SpHe3    0.0042 +/- 0.0006       0.583 +/-   0.090     23.53
PfHe3    0.0001 +/- 0.0001       0.014 +/-   0.014     25.09
F He3    0.0001 +/- 0.0001       0.014 +/-   0.014     13.66
E He3    0.0044 +/- 0.0007       0.611 +/-   0.092     23.34
CoHe3    0.0049 +/- 0.0007       0.681 +/-   0.097     40.97
*****************************************************************
T He4    0.1774 +/- 0.0042      24.645 +/-   0.585     24.18
P He4    0.0074 +/- 0.0009       1.028 +/-   0.120     56.90
SpHe4    0.1568 +/- 0.0040      21.783 +/-   0.550     22.73
PfHe4    0.0041 +/- 0.0006       0.570 +/-   0.089     25.74
F He4    0.0051 +/- 0.0007       0.709 +/-   0.099     17.39
E He4    0.1660 +/- 0.0041      23.062 +/-   0.566     22.64
CoHe4    0.0040 +/- 0.0006       0.556 +/-   0.088     27.64
*****************************************************************
pi-      0.1199 +/- 0.0035      16.657 +/-   0.481    100.65
pi0      0.1332 +/- 0.0036      18.505 +/-   0.507     89.72
pi+      0.0513 +/- 0.0023       7.127 +/-   0.315    130.85
*****************************************************************

*************** Nuclide yields [mb]  (zero values suppressed) *****************

               Z =  81.              Z =  80.              Z =  79.
A = 196 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.446E-01 +/- 7.86E-02
A = 195 0.000E+00 +/- 0.00E+00 1.667E-01 +/- 4.81E-02 2.987E+00 +/- 2.04E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
A = 183 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02 1.389E-02 +/- 1.39E-02
S =  14 1.389E-02 +/- 1.39E-02 3.779E+00 +/- 2.29E-01 4.232E+01 +/- 7.67E-01

               Z =  78.              Z =  77.              Z =  76.
A = 196 2.362E-01 +/- 5.73E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
A = 195 1.320E+00 +/- 1.35E-01 1.389E-02 +/- 1.39E-02 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
A = 169 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02
S =  28 4.303E+01 +/- 7.73E-01 1.595E+01 +/- 4.71E-01 1.136E+01 +/- 3.97E-01

               Z =  75.              Z =  74.              Z =  73.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

               Z =   3.              Z =   2.              Z =   1.
A =   4 0.000E+00 +/- 0.00E+00 2.465E+01 +/- 5.85E-01 0.000E+00 +/- 0.00E+00
A =   3 0.000E+00 +/- 0.00E+00 3.626E+00 +/- 2.24E-01 1.600E+01 +/- 4.72E-01
A =   2 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.854E+01 +/- 8.21E-01
A =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.345E+02 +/- 1.37E+00
S =   4 0.000E+00 +/- 0.00E+00 2.827E+01 +/- 6.27E-01 1.991E+02 +/- 1.66E+00

               Z =   0.
A =   1 1.273E+03 +/- 4.21E+00
S =   1 1.273E+03 +/- 4.21E+00

End of nuclide yields.
```

```
Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei:
 A = 196 6.807E-01 +/- 9.72E-02  1.629E-01 +/- 9.21E-02
 A = 195 4.487E+00 +/- 2.50E-01  1.524E-01 +/- 1.40E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 1.408E+03 +/- 4.42E+00  1.396E+01 +/- 3.41E+01
 S = 140 1.642E+03 +/- 4.78E+00  1.376E+01 +/- 3.26E+01

Charge yield [mb] and the mean and variance of the  kinetic energy [MeV]
 of residual nuclei:
 Z = 81 1.389E-02 +/- 1.39E-02  2.362E-01 +/- 0.00E+00
 Z = 80 3.779E+00 +/- 2.29E-01  3.332E-01 +/- 3.29E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 1.273E+03 +/- 4.21E+00  1.078E+01 +/- 2.84E+01
 S = 61 1.642E+03 +/- 4.78E+00  1.376E+01 +/- 3.26E+01

 ********** Nuclide yields [mb] in forward direction (theta_lab < 90) **********
           (zero values suppressed)

                Z =  81.               Z =  80.               Z =  79.
 A = 196 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.806E-01 +/- 5.01E-02
 A = 195 0.000E+00 +/- 0.00E+00 1.667E-01 +/- 4.81E-02 1.514E+00 +/- 1.45E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 183 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02 1.389E-02 +/- 1.39E-02
 S =  14 1.389E-02 +/- 1.39E-02 3.459E+00 +/- 2.19E-01 2.613E+01 +/- 6.03E-01

                Z =  78.               Z =  77.               Z =  76.
 A = 196 4.168E-02 +/- 2.41E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A = 195 4.862E-01 +/- 8.22E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 169 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02
 S =  27 2.455E+01 +/- 5.84E-01 9.878E+00 +/- 3.70E-01 7.669E+00 +/- 3.26E-01

                Z =  75.               Z =  74.               Z =  73.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

                Z =   3.               Z =   2.               Z =   1.
 A =   4 0.000E+00 +/- 0.00E+00 1.285E+01 +/- 4.23E-01 0.000E+00 +/- 0.00E+00
 A =   3 0.000E+00 +/- 0.00E+00 2.112E+00 +/- 1.71E-01 9.544E+00 +/- 3.64E-01
 A =   2 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.824E+01 +/- 6.26E-01
 A =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 8.391E+01 +/- 1.08E+00
 S =   4 0.000E+00 +/- 0.00E+00 1.496E+01 +/- 4.56E-01 1.217E+02 +/- 1.30E+00

                Z =   0.
 A =   1 6.777E+02 +/- 3.07E+00
 S =   1 6.777E+02 +/- 3.07E+00

 End of nuclide yields (forward direction).

 Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the forward direction:
 A = 196 2.223E-01 +/- 5.56E-02  2.082E-01 +/- 1.25E-01
 A = 195 2.167E+00 +/- 1.74E-01  1.471E-01 +/- 1.28E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 7.616E+02 +/- 3.25E+00  1.770E+01 +/- 4.20E+01
 S = 125 9.031E+02 +/- 3.54E+00  1.693E+01 +/- 3.97E+01

Charge yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the forward direction:
 Z = 81 1.389E-02 +/- 1.39E-02  2.362E-01 +/- 4.25E-01
 Z = 80 3.459E+00 +/- 2.19E-01  3.408E-01 +/- 7.41E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 6.777E+02 +/- 3.07E+00  1.329E+01 +/- 8.47E+00
 S = 54 9.031E+02 +/- 3.54E+00  1.693E+01 +/- 3.97E+01

 ********** Nuclide yields [mb] in backward direction (theta_lab > 90) *********
           (zero values suppressed)

                Z =  81.               Z =  80.               Z =  79.
 A = 196 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.640E-01 +/- 6.06E-02
 A = 195 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.473E+00 +/- 1.43E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 184 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02 1.389E-02 +/- 1.39E-02
 S =  13 0.000E+00 +/- 0.00E+00 3.195E-01 +/- 6.66E-02 1.618E+01 +/- 4.74E-01

                Z =  78.               Z =  77.               Z =  76.
 A = 196 1.945E-01 +/- 5.20E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A = 195 8.336E-01 +/- 1.08E-01 1.389E-02 +/- 1.39E-02 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 170 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.389E-02 +/- 1.39E-02
 S =  26 1.848E+01 +/- 5.07E-01 6.071E+00 +/- 2.90E-01 3.695E+00 +/- 2.27E-01

                Z =  75.               Z =  74.               Z =  73.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

```
               Z =   3.               Z =   2.               Z =   1.
 A =   4 0.000E+00 +/- 0.00E+00 1.179E+01 +/- 4.05E-01 0.000E+00 +/- 0.00E+00
 A =   3 0.000E+00 +/- 0.00E+00 1.514E+00 +/- 1.45E-01 6.460E+00 +/- 3.00E-01
 A =   2 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.030E+01 +/- 5.31E-01
 A =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 5.060E+01 +/- 8.38E-01
 S =   4 0.000E+00 +/- 0.00E+00 1.331E+01 +/- 4.30E-01 7.735E+01 +/- 1.04E+00

               Z =   0.
 A =   1 5.954E+02 +/- 2.88E+00
 S =   1 5.954E+02 +/- 2.88E+00

 End of nuclide yields (backward direction).

 Mass yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the backward direction:
 A = 196 4.585E-01 +/- 7.98E-02  1.409E-01 +/- 5.97E-02
 A = 195 2.320E+00 +/- 1.80E-01  1.574E-01 +/- 1.50E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1 6.460E+02 +/- 3.00E+00  9.552E+00 +/- 2.02E+01
 S = 123 7.390E+02 +/- 3.20E+00  9.892E+00 +/- 2.00E+01

 Charge yield [mb] and the mean and variance of the kinetic energy [MeV]
 of residual nuclei in the backward direction:
 Z = 80 3.195E-01 +/- 6.66E-02  2.509E-01 +/- 2.70E-01
 Z = 79 1.618E+01 +/- 4.74E-01  1.447E-01 +/- 1.72E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0 5.954E+02 +/- 2.88E+00  7.918E+00 +/- 1.80E+01
 S = 56 7.390E+02 +/- 3.20E+00  9.892E+00 +/- 2.00E+01

******** Nuclide average kinetic energies [MeV] (zero yield suppressed) ********

               Z =  81.               Z =  80.               Z =  79.
 A = 196 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 1.705E-01 +/- 1.03E-01
 A = 195 0.000E+00 +/- 0.00E+00 2.419E-01 +/- 2.74E-01 1.210E-01 +/- 8.70E-02
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 183 0.000E+00 +/- 0.00E+00 2.226E-01 +/- 0.00E+00 2.385E+00 +/- 0.00E+00
 S =  14 2.362E-01 +/- 0.00E+00 3.332E-01 +/- 3.29E-01 1.754E-01 +/- 2.32E-01

               Z =  78.               Z =  77.               Z =  76.
 A = 196 1.484E-01 +/- 6.31E-02 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
 A = 195 2.103E-01 +/- 1.81E-01 3.451E-01 +/- 0.00E+00 0.000E+00 +/- 0.00E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A = 169 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.814E+00 +/- 0.00E+00
 S =  28 4.145E-01 +/- 4.36E-01 7.161E-01 +/- 6.47E-01 9.505E-01 +/- 8.63E-01

               Z =  75.               Z =  74.               Z =  73.

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

               Z =   3.               Z =   2.               Z =   1.
 A =   4 0.000E+00 +/- 0.00E+00 2.418E+01 +/- 9.69E+00 0.000E+00 +/- 0.00E+00
 A =   3 0.000E+00 +/- 0.00E+00 4.207E+01 +/- 2.47E+01 2.279E+01 +/- 1.96E+01
 A =   2 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 2.884E+01 +/- 2.93E+01
 A =   1 0.000E+00 +/- 0.00E+00 0.000E+00 +/- 0.00E+00 4.412E+01 +/- 5.92E+01
 S =   4 0.000E+00 +/- 0.00E+00 2.648E+01 +/- 1.40E+01 3.868E+01 +/- 5.17E+01

               Z =   0.
 A =   1 1.078E+01 +/- 2.84E+01
 S =   1 1.078E+01 +/- 2.84E+01

 End of nuclide average kinetic energies.

 Mass yield [mb] and the mean and variance of the emission angle [deg.]
 of residual nuclei:
 A = 196  6.807E-01 +/- 9.72E-02   9.892E+01 +/- 4.05E+01
 A = 195  4.487E+00 +/- 2.50E-01   9.217E+01 +/- 4.52E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1  1.408E+03 +/- 4.42E+00   8.597E+01 +/- 4.01E+01
 S = 140  1.642E+03 +/- 4.78E+00   8.516E+01 +/- 4.02E+01

 The mean and variance of the z velocity [v/c] of residual nuclei,
 and the forward/backward ratio:
 A = 196 -9.863E-05 +/- 8.57E-04   4.848E-01 +/- 2.06E-01
 A = 195 -3.324E-05 +/- 8.47E-04   9.341E-01 +/- 1.47E-01
- - - - - - - - - - - - - - - - - - - - - - - - - - - -
 A =   1  1.708E-02 +/- 1.04E-01   1.179E+00 +/- 1.05E-02
 S = 140  1.571E-02 +/- 9.91E-02   1.222E+00 +/- 1.01E-02

 Charge yield [mb] and the mean and variance of the emission angle [deg.]
 of residual nuclei:
 Z = 81  1.389E-02 +/- 1.39E-02   3.843E+01 +/- 0.00E+00
 Z = 80  3.779E+00 +/- 2.29E-01   4.682E+01 +/- 3.04E+01
- - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0  1.273E+03 +/- 4.21E+00   8.689E+01 +/- 3.98E+01
 S = 61  1.642E+03 +/- 4.78E+00   8.516E+01 +/- 4.02E+01

 The mean and variance of the z velocity [v/c] of residual nuclei,
 and the forward/backward ratio:
 Z = 81  1.283E-03 +/- 0.00E+00   1.000E+00 +/- 0.00E+00
 Z = 80  1.127E-03 +/- 8.82E-04   1.471E+01 +/- 7.72E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - -
 Z =  0  1.170E-02 +/- 9.07E-02   1.910E+00 +/- 5.65E-03
```

```
 S = 61  1.571E-02 +/- 9.91E-02   1.222E+00 +/- 1.01E-02

                  Mass distributions of nuclei:
                                   at start of evap, which:  just prior to
           after cascade after preeq   evap. only    fission     fission
   A = 197    2.070E-01   8.720E-02   8.710E-02   1.000E-04   0.000E+00
   A = 196    2.637E-01   2.248E-01   2.236E-01   1.200E-03   4.000E-04
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   A = 165    0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.000E-04
    <A> =     1.947E+02   1.935E+02   1.935E+02   1.912E+02   1.868E+02
St Dv A =     2.205E+00   3.212E+00   3.187E+00   3.606E+00   6.608E+00
   norm =     1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02

                  Charge distributions of nuclei:
                                   at start of evap, which:  just prior to
           after cascade after preeq   evap. only    fission     fission
   Z =  81    1.100E-03   4.000E-04   3.000E-04   1.000E-04   1.000E-04
   Z =  80    5.090E-02   3.660E-02   3.490E-02   1.700E-03   1.400E-03
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
   Z =  68    0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.000E-04
    <Z> =     7.858E+01   7.809E+01   7.809E+01   7.790E+01   7.696E+01
St Dv Z =     7.861E-01   1.235E+00   1.227E+00   1.558E+00   7.646E+01
   norm =     1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02

          Excitation energy distributions [1/MeV] of nuclei:
                                     at start of evap, which:  just prior to
    E*(MeV)   after cascade after preeq   evap. only    fission     fission
    0.-  10.    3.400E-04   2.370E-03   2.370E-03   0.000E+00   0.000E+00
   10.-  20.    2.210E-03   6.260E-03   6.260E-03   0.000E+00   0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  780.- 790.    1.000E-05   0.000E+00   0.000E+00   0.000E+00   0.000E+00
     <E*> =     1.260E+02   9.288E+01   8.946E+01   2.593E+02   2.039E+02
St dev E* =     1.045E+02   8.738E+01   8.321E+01   1.186E+02   9.656E+01
     norm =     1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02

          Linear momentum distributions [1/MeV/c] of nuclei:
                                     at start of evap, which:  just prior to
    P(MeV/c)  after cascade after preeq   evap. only    fission     fission
    0.-  10.    1.000E-05   0.000E+00   0.000E+00   0.000E+00   0.000E+00
   10.-  20.    4.000E-05   5.000E-05   5.000E-05   0.000E+00   0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 2070.-2080.    0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.000E-05
      <P> =     2.999E+02   3.357E+02   3.318E+02   5.253E+02   5.774E+02
 St dev P =     2.208E+02   2.254E+02   2.229E+02   2.644E+02   2.924E+02
     norm =     1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02

              Angular momentum distributions [1/hbar] of nuclei:
                                    at start of evap, which:  just prior to
      L    after cascade after preeq   evap. only    fission     fission
   0.-  1.    2.420E-02   1.340E-02   1.340E-02   0.000E+00   0.000E+00
   1.-  2.    1.379E-01   8.070E-02   8.050E-02   2.000E-04   2.000E-04
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  61.- 62.    0.000E+00   1.000E-04   1.000E-04   0.000E+00   0.000E+00
    <L> =     5.997E+00   8.098E+00   8.043E+00   1.082E+01   1.082E+01
St dv L =     4.626E+00   6.045E+00   6.008E+00   7.133E+00   7.133E+00
   norm =     1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02

   Distribution of fission-fragment opening angles [1/deg.] (lab.sys.) in different
                             bins of neutron multiplicity:
 theta(deg.) All events  n = 0-5   n = 6-8  n = 9-12  n = 13-15 n = 16-19   n > 20
 140. - 141.  4.975E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.975E-03
 148. - 149.  4.975E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.975E-03
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
 179. - 180.  1.493E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 4.975E-03 9.950E-03
    <thet> =  1.706E+02 0.000E+00 1.760E+02 1.735E+02 1.738E+02 1.721E+02 1.688E+02
St dv thet =  6.315E+00 0.000E+00 0.000E+00 3.038E+00 3.017E+00 3.840E+00 7.377E+00
     norm. =  1.000E+00 0.000E+00 4.975E-03 6.468E-02 1.294E-01 2.488E-01 5.522E-01


                     Neutron-multiplicity probability:

     Nn      Total     Cascade     Preequil.   Evap. res.  Pre-fiss.   Post-fiss.
      0    2.500E-03   2.878E-01   5.879E-01   1.340E-02   5.200E-03   0.000E+00
      1    1.400E-02   3.172E-01   2.960E-01   4.520E-02   3.800E-03   0.000E+00
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
     37    1.000E-04   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
   <n> =   9.164E+00   1.609E+00   5.664E-01   6.796E+00   2.751E+00   1.366E+01
St dv n =  5.816E+00   1.704E+00   8.036E-01   4.392E+00   2.830E+00   4.707E+00
   norm =  1.000E+00   1.000E+00   1.000E+00   9.799E-01   2.010E-02   2.010E-02


 Elapsed cpu time  =  0. min and 23.331 sec.
```

Appendix 3

Example 1

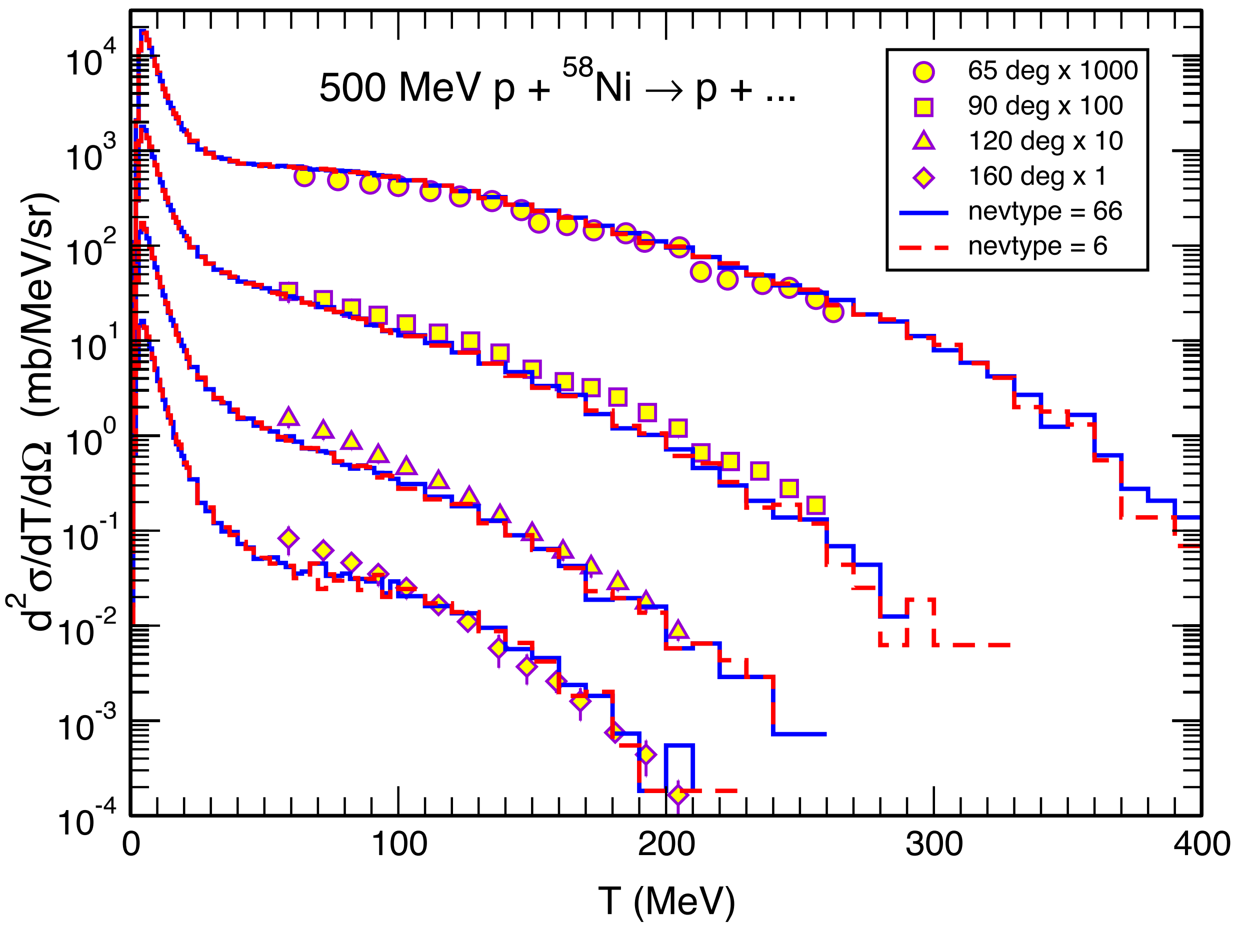

Figure 4: Experimental proton spectra from 500 MeV p + Ni [132] compared with CEM03.03 results obtained using the input shown in Example 1 of Appendix 1 (the corresponding output is shown in Example 1 of Appendix 2). In contrast to the input file shown in Appendix 1, the results shown in this figure are for one million simulated inelastic events (**limc=1000000**). The option considering 66 types of possible evaporated particles (**nevtype=66**) requires 18 min 34 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 6 min 51 sec, providing almost the same results.

Example 2

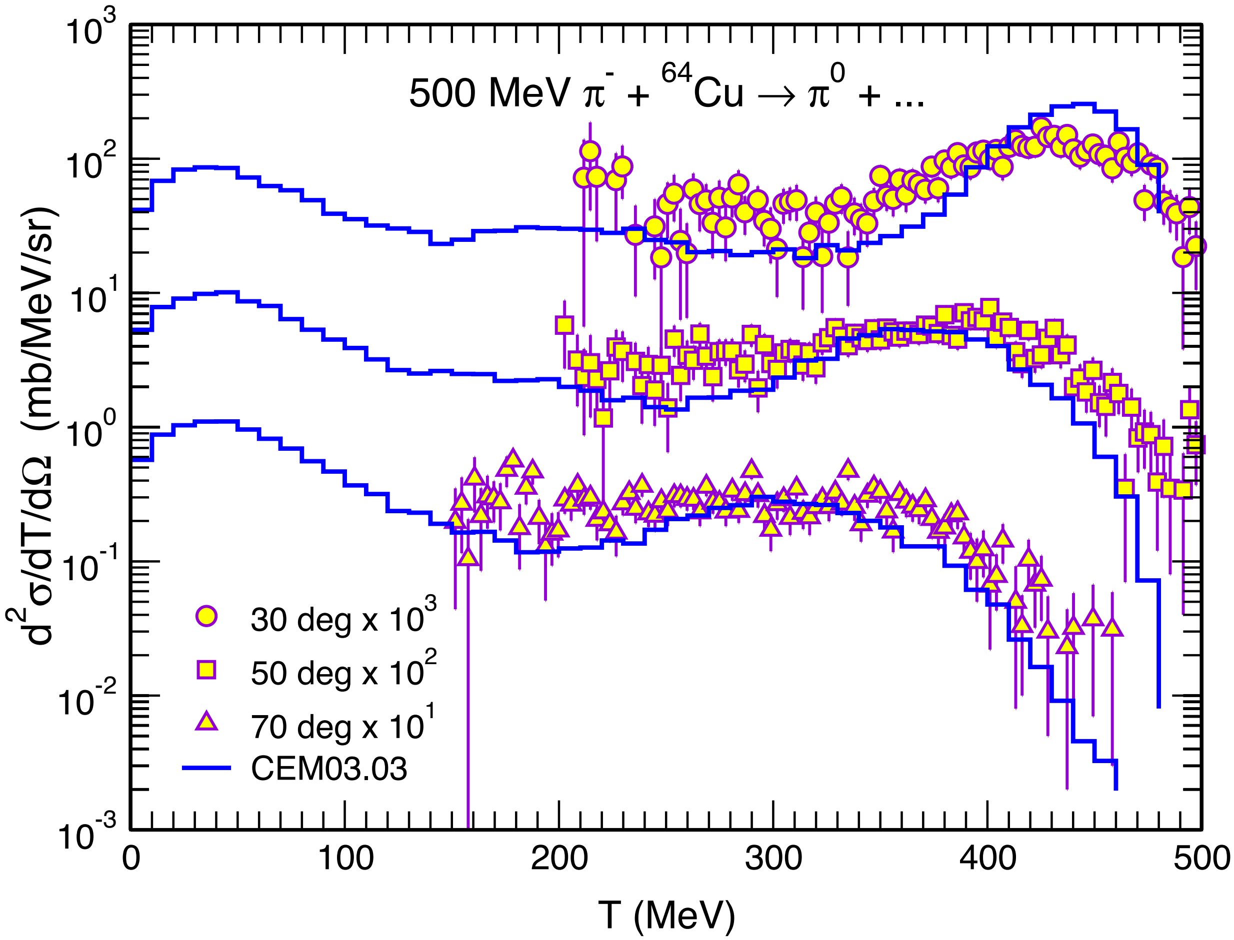

Figure 5: Experimental π^0 spectra from 500 MeV π^- + Cu [133, 27] compared with CEM03.03 results obtained using the input shown in Example 2 of Appendix 1 (the corresponding output is shown in Example 2 of Appendix 2). In contrast to the input file shown in Appendix 1, the results shown in this figure are for one million simulated inelastic events (**limc=1000000**). As pions are produced by CEM03.03 only at the INC stage of reactions, calculated pion spectra do not depend on the value of **nevtype**; this calculation was done using only the **nevtype=6** option in the input and it took 8 min 11 sec on an UltraSPARC 1.3 GHz Sunstation.

Example 3

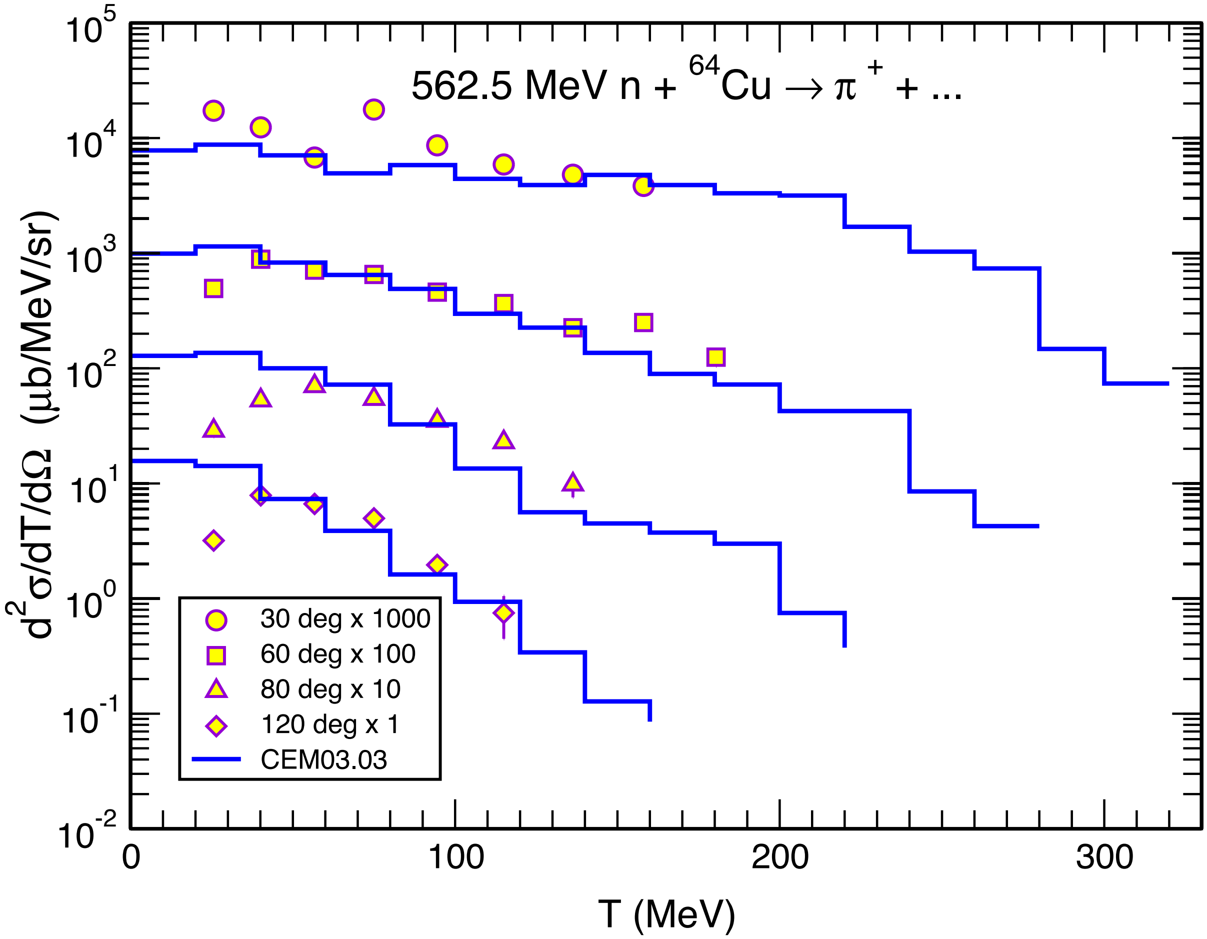

Figure 6: Experimental π^+ spectra from 562.5 MeV n + Cu [134] compared with CEM03.03 results obtained using the input shown in Example 3 of Appendix 1 (the corresponding output is shown in Example 3 of Appendix 2). In contrast to the input file shown in Appendix 1, the results shown in this figure are for one million simulated inelastic events (**limc=1000000**). This calculation was done using only the **nevtype=6** option in the input, for the same reason as discussed for Example 2, and it took 7 min 33 sec on an UltraSPARC 1.3 GHz Sunstation.

Example 4

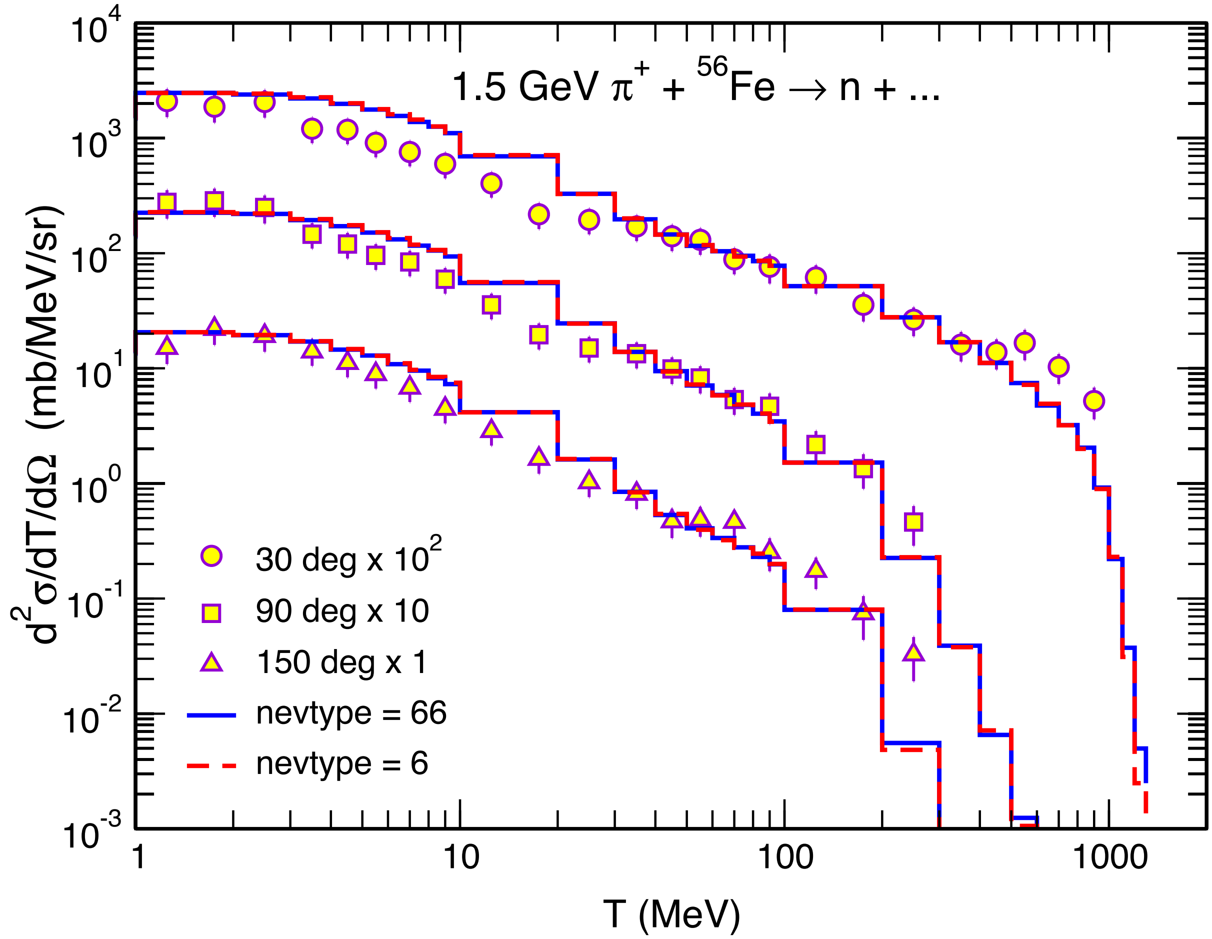

Figure 7: Experimental neutron spectra from 1.5 GeV π^+ + Fe [135] compared with CEM03.03 results obtained using the input shown in Example 4 of Appendix 1 (the corresponding output is shown in Example 4 of Appendix 2). In contrast to the input file shown in Appendix 1, the results shown in this figure are for one million simulated inelastic events (**limc=1000000**). The **nevtype=66** option requires 38 min 17 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 13 min 9 sec, providing almost the same results.

Example 5

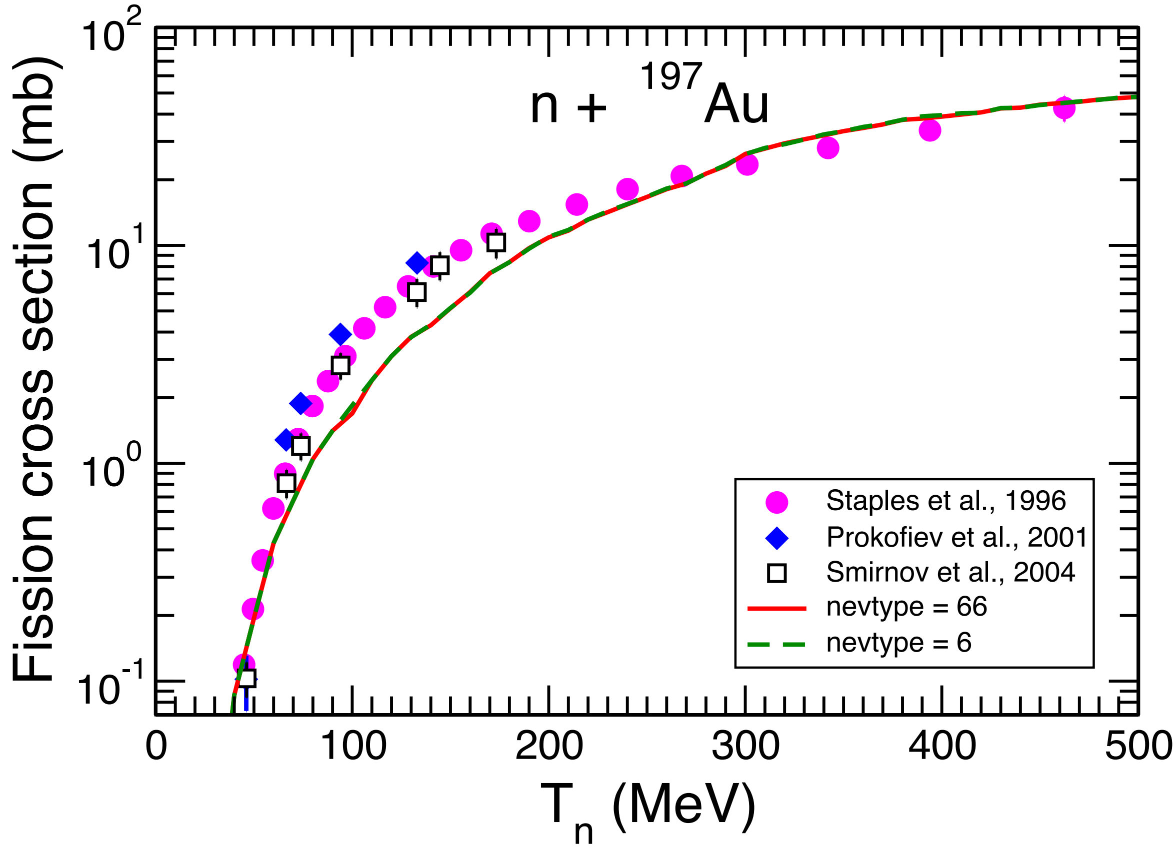

Figure 8: Experimental neutron-induced fission cross section of ^{197}Au [136]–[138] compared with CEM03.03 results obtained using the input shown in Example 5 of Appendix 1 (the corresponding output is shown in Example 5 of Appendix 2). The results shown in this figure are the **Direct Monte Carlo Simulation Method** fission cross sections from the CEM03.03 output. These calculations were done at neutron energies from 30 MeV (**t0mev=30.0**) to 500 MeV (**t0max=500.5**) with a step of 10 MeV (**dt0=10.0**) and, in contrast to the input file shown in Appendix 1, use 100000 simulated inelastic events for each energy point (**limc=100000**). The **nevtype=66** option requires 1 hr 34 min 11 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 43 min 29 sec, providing almost the same results.

Example 6

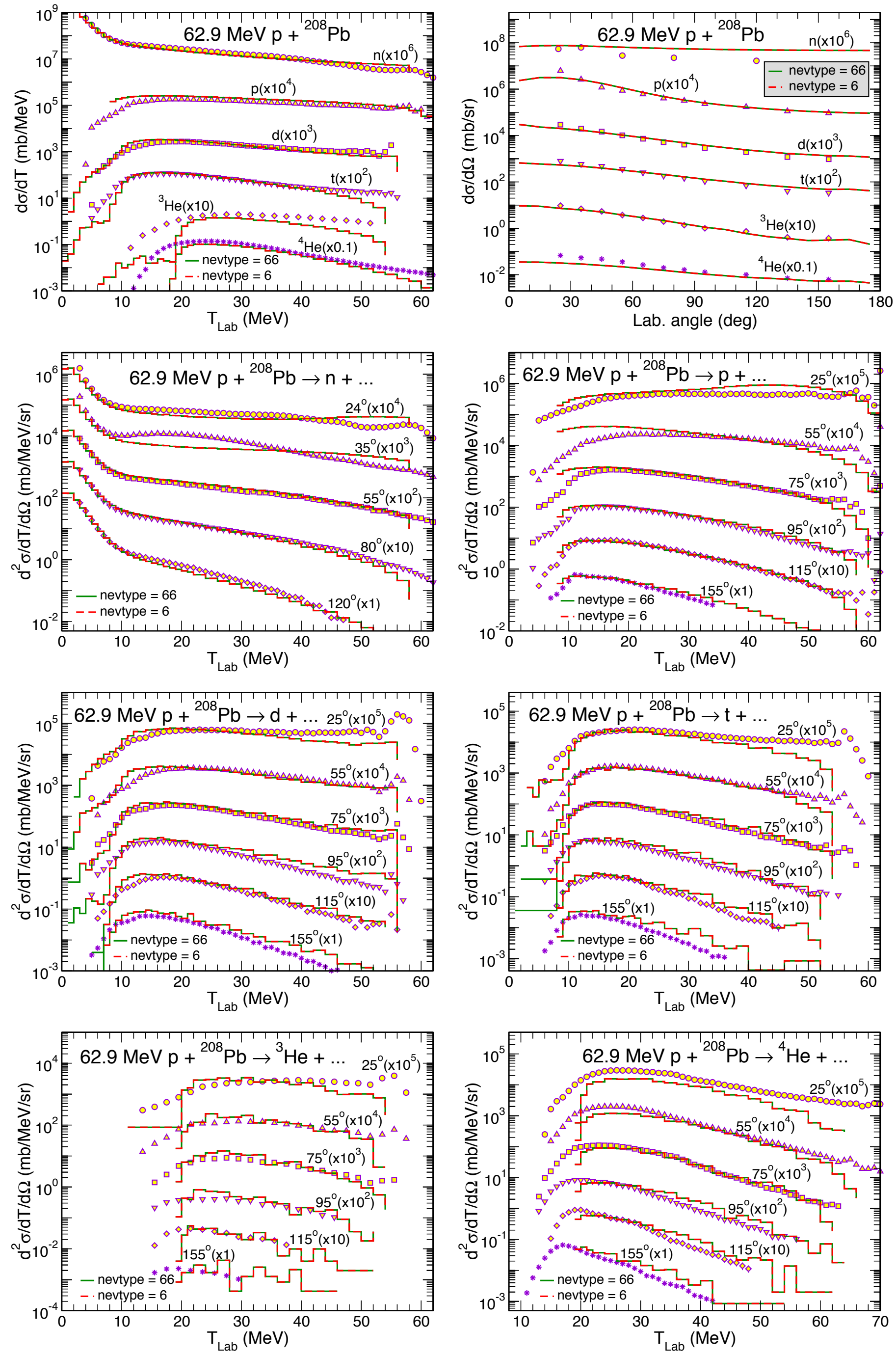

Figure 9: Experimental angle-integrated energy spectra (upper left plot), energy-integrated angular distributions (upper right plot), and double-differential spectra of nucleons and complex particles [139] compared with CEM03.03 results obtained using the input shown in Example 6 of Appendix 1 (the corresponding output is shown in Example 6 of Appendix 2). In contrast to the input file shown in Appendix 1, the results shown in this figure are for ten million simulated inelastic events (**limc=10000000**). The **nevtype=66** option requires 1 hr 51 min 8 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 1 hr 26 min 20 sec, providing practically the same results, indistinguishable within the scale of this figure.

Example 7

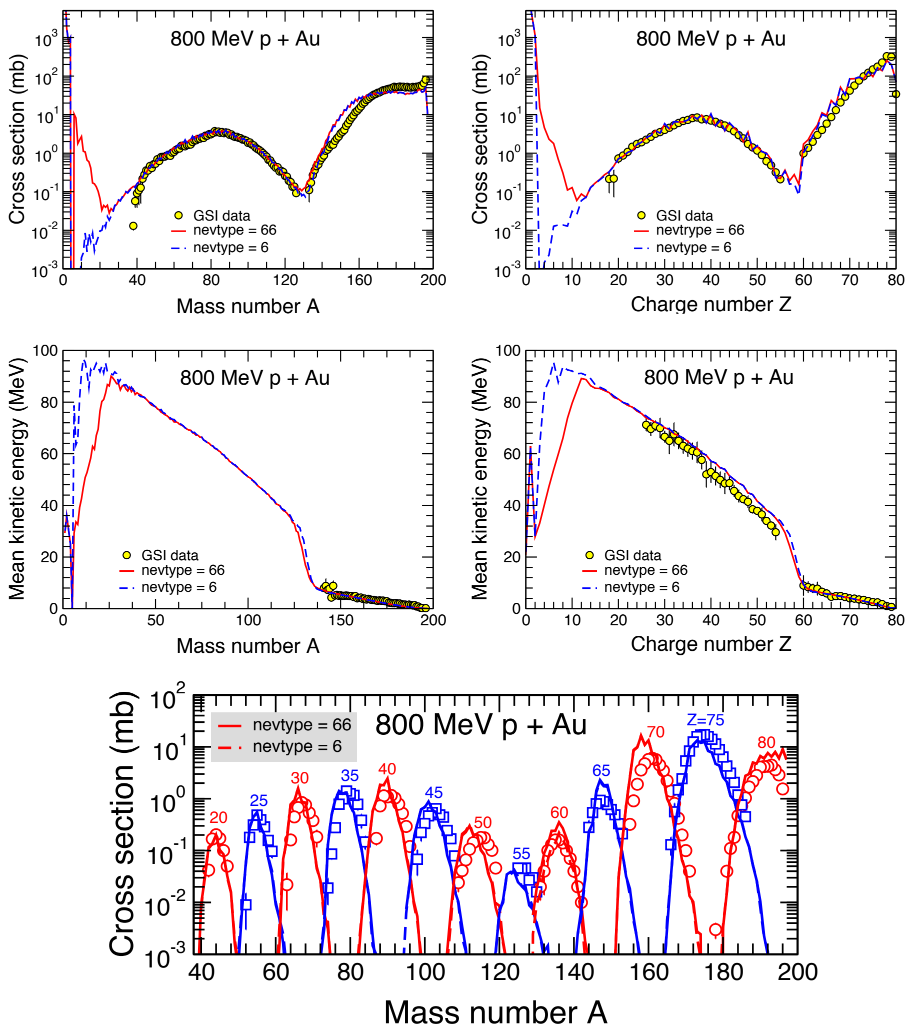

Figure 10: The measured [140] mass and charge distributions of the product yields from the reaction 800 MeV/A ^{197}Au+p and of the mean kinetic energy of these products, and the mass distributions of the cross sections for the production of thirteen elements with the charge Z from 20 to 80 (open symbols) compared with CEM03.03 results obtained using the input shown in Example 7 of Appendix 1 (the corresponding output is shown in Example 7 of Appendix 2). In contrast to the input file from Appendix 1, the results shown in this figure are for ten million simulated inelastic events (**limc=10000000**). The **nevtype=66** option requires 9 hr 7 min 23 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 2 hr 14 min 45 sec, providing almost the same results for the spallation and fission products. The fragment ($2 < Z < 13$, $6 < A < 29$) results are very different, therefore we need to use the option **nevtype=66** when we are interested in fragment production.

Example 8

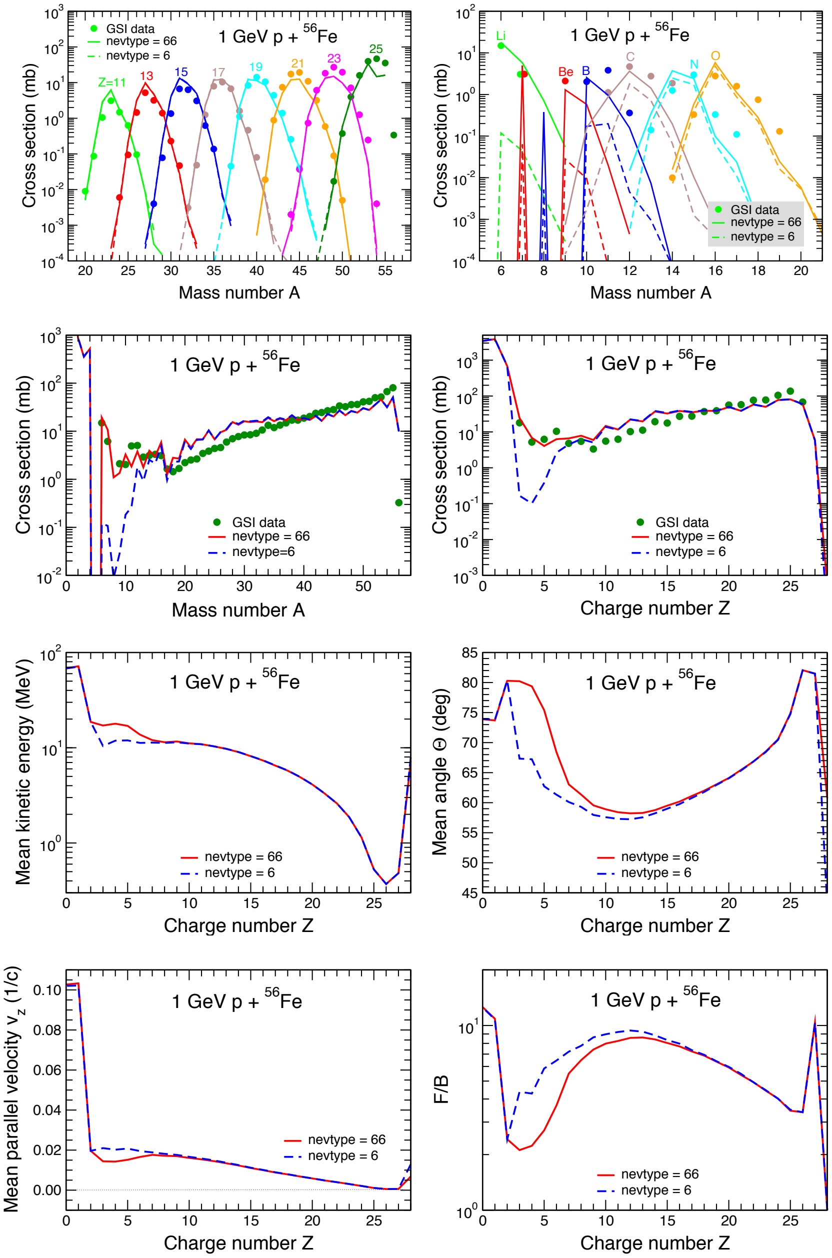

Figure 11: Experimental mass distributions of the yields of eight isotopes from Na to Mn [141] and of all light fragments from Li to O [142] from the reaction 1 GeV/A ^{56}Fe+p and the mass number- and charge-distributions of the product yield compared with CEM03.03 results obtained using the input shown in Example 8 of Appendix 1 (the corresponding output is shown in Example 8 of Appendix 2). Predictions of CEM03.03 for the mean kinetic energy, mean production angle Θ, mean parallel velocity v_z, and of the F/B ratio of the forward product cross sections to the backward ones of all isotopes in the laboratory system are given as well. In contrast to the input file from Appendix 1, the results shown in this figure are for ten million simulated inelastic events (**limc=10000000**). The **nevtype=66** option requires 4 hr 57 min 52 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 1 hr 38 min 23 sec, providing almost the same results for the spallation products. The yields of light fragments, especially of Li and Be, differ by several orders of magnitude, therefore we need to use the option **nevtype** $>$ **6** when we are interested in light-fragment production.

Example 9

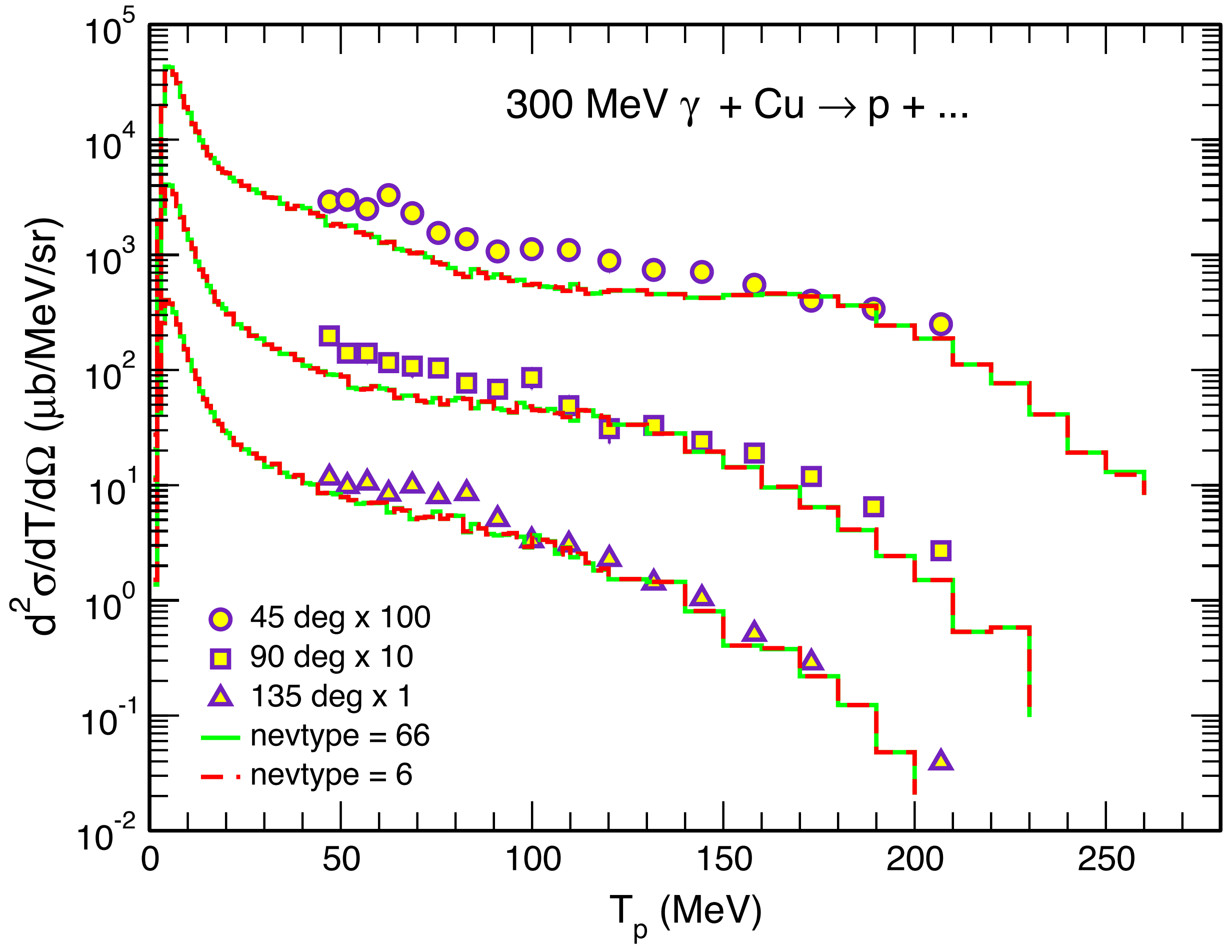

Figure 12: Proton spectra at 45°, 90°, and 135° from the reaction 300 MeV γ + Cu. Symbols are experimental data from [143] and histograms are CEM03.03 results obtained using the input shown in Example 9 of Appendix 1 (the corresponding output is shown in Example 9 of Appendix 2). In contrast to the input file from Appendix 1, the results shown in this figure are for one million simulated inelastic events (**limc=1000000**). The **nevtype=66** option requires 35 min 18 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 26 min 23 sec, providing almost the same results.

Example 10

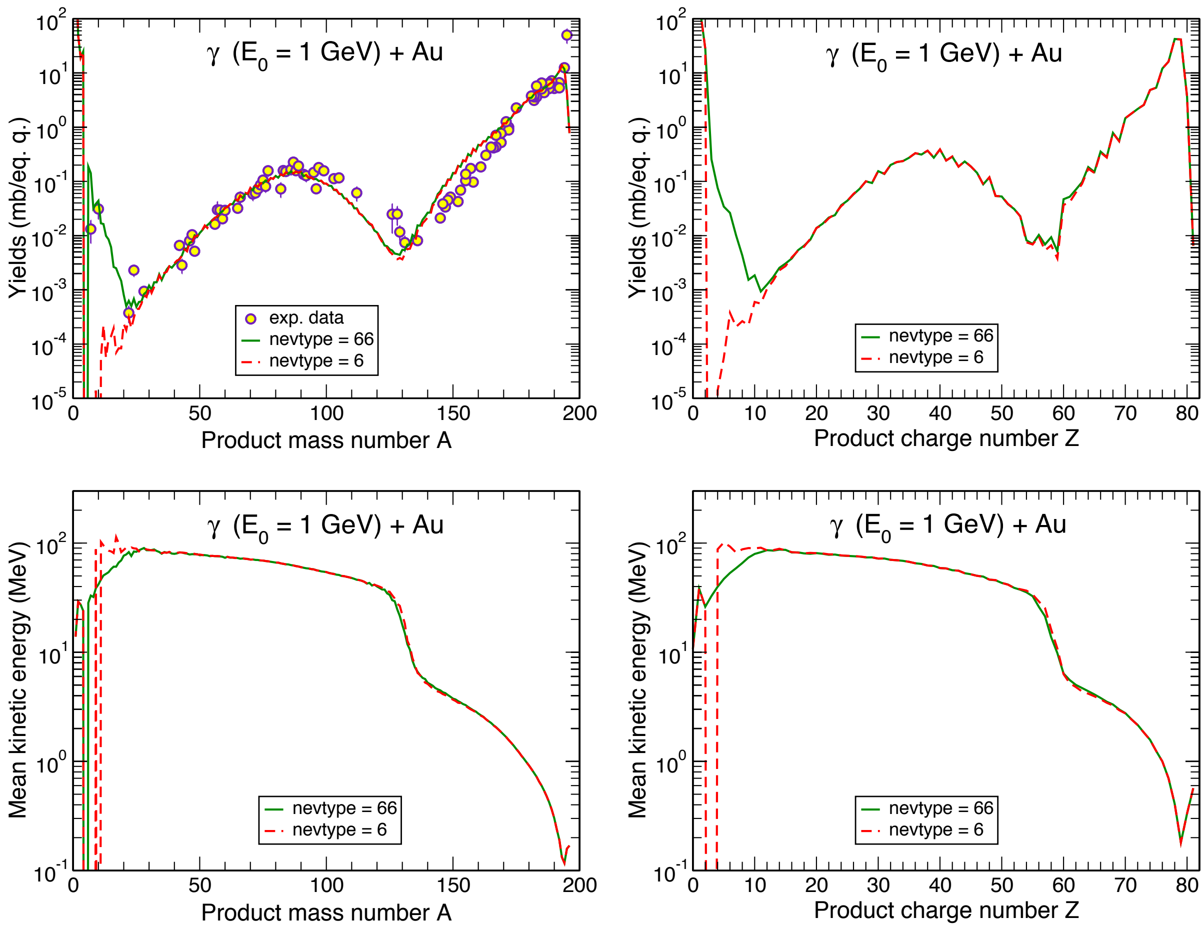

Figure 13: Results from CEM03.03 for the product yield of all isotopes and of their mean laboratory kinetic energy as functions of the product mass-number A and charge Z from interactions of bremsstrahlung gammas with a maximum energy of 1 GeV with Au. In contrast to the input file from Appendix 1, whose output we show in Example 10 of Appendix 2, we use ten million simulated inelastic events (**limc=10000000**). The **nevtype=66** option requires 8 hr 58 min 58 sec of computing time on an UltraSPARC 1.3 GHz Sunstation, while the **nevtype=6** option requires only 6 hr 17 min 31 sec, providing almost the same results for the spallation and fission products but underestimating the yields of light fragments by more than two orders of magnitude. The experimental cross sections shown for comparison by circles are from the review [144] and their tabulated values were kindly sent us by by Dr. Hiroshi Matsumura.