

LA-UR-10-07847

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*Title:* Validation and Verification of MCNP6 Against  
Intermediate and High-Energy Experimental Data  
and Results by Other Codes

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*Intended for:* Invited talk presented at the Int. Conf. on Math. and Comput.  
Meth. Applied to Nucl. Science and Engineering (MC 2011),  
Rio de Janeiro, Brazil, May 8-12, 2011; arXiv:1011.4978;  
published by invitation in Eur. Phys. J. Plus (2011) 126: 49;  
The final publication is available at [www.epj.org](http://www.epj.org)

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Eur. Phys. J. Plus (2011) **126**: 49

DOI: 10.1140/epjp/i2011-11049-1

## Validation and verification of MCNP6 against intermediate and high-energy experimental data and results by other codes

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# Validation and verification of MCNP6 against intermediate and high-energy experimental data and results by other codes

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Received: 2 February 2011 / Revised: 31 March 2011

Published online: 24 May 2011 – © Società Italiana di Fisica / Springer-Verlag 2011

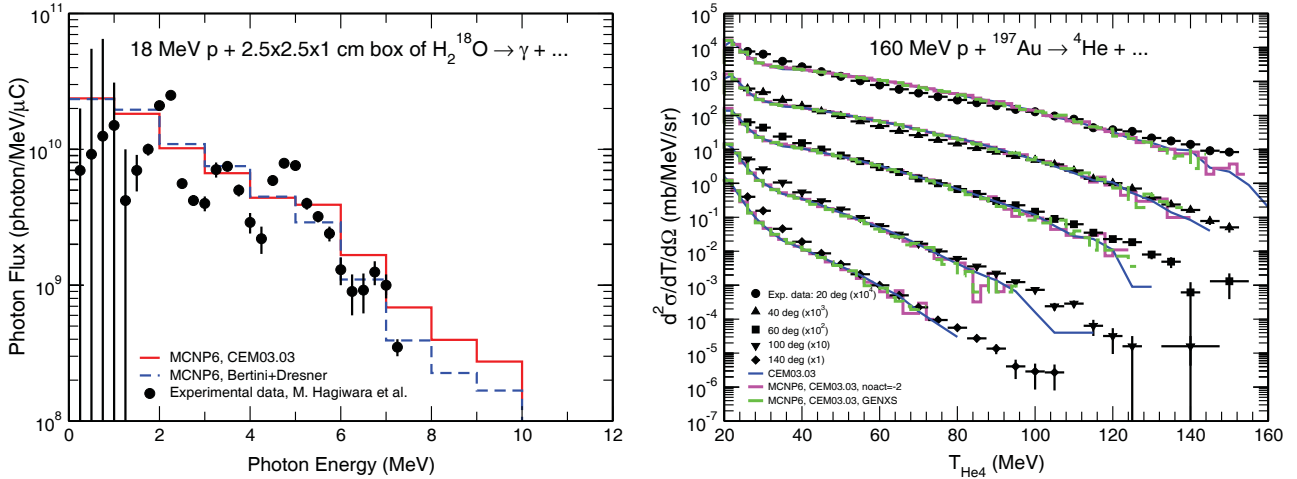
**Abstract.** MCNP6, the latest and most advanced LANL transport code representing a recent merger of MCNP5 and MCNPX, has been Validated and Verified (V&V) against a variety of intermediate and high-energy experimental data and against results by different versions of MCNPX and other codes. In the present work, we V&V MCNP6 using mainly the latest modifications of the Cascade-Exciton Model (CEM) and of the Los Alamos version of the Quark-Gluon String Model (LAQGSM) event generators CEM03.03 and LAQGSM03.03. We found that MCNP6 describes reasonably well various reactions induced by particles and nuclei at incident energies from 18 MeV to about 1 TeV per nucleon measured on thin and thick targets and agrees very well with similar results obtained with MCNPX and calculations by CEM03.03, LAQGSM03.03 (03.01), INCL4 + ABLA, and Bertini INC + Dresner evaporation, EPAX, ABRABLA, HIPSE, and AMD, used as stand-alone codes. Most of several computational bugs and more serious physics problems observed in MCNP6/X during our V&V have been fixed; we continue our work to solve all the known problems before MCNP6 is distributed to the public.

## 1 Introduction

During the past several years, a major effort has been undertaken at the Los Alamos National Laboratory (LANL) to develop the transport code MCNP6 [1,2], the latest and most advanced Los Alamos transport code representing a merger of MCNP5 [3] and MCNPX [4]. The work on MCNP6 is not yet completed; we continue to solve the observed problems in the current version of MCNP6 and to develop and further improve it, with a plan to make it available officially to the users via RSICC at Oak Ridge, TN, USA, during 2011. Before distributing MCNP6 to the public, we must test and validate it on as many test problems as possible, using reliable experimental data. Extensive Validation and Verification (V&V) of our low-energy transport code MCNP5 has been performed and published for many different test problems involving interactions of neutrons, photons, and electrons with thick and thin targets, therefore V&V of MCNP6 for such problems is important but not very critical. On the other hand, our high-energy transport code, MCNPX, was not tested against experimental data so extensively, especially for high-energy processes induced by protons, and heavy ions. More important, MCNP6 uses the latest modifications of the Cascade-Exciton Model (CEM) and of the Los Alamos version of the Quark-Gluon String Model (LAQGSM) event generators CEM03.03 and LAQGSM03.03 [5], and they were not tested extensively in MCNPX. This is why it is necessary to V&V MCNP6 at intermediate and high energies, to test how CEM03.03 and LAQGSM03.03 work in MCNP6 and to make sure that the latter properly transports energetic particles and nuclei through the matter.

A description of different versions of our CEM and LAQGSM event generators with many useful references may be found in our recent lecture [5]. Let us recall here only their main assumptions. The basic version of both our CEM and LAQGSM event generators is the so-called “03.01” version, namely CEM03.01 and LAQGSM03.01. CEM describes reactions induced by nucleons, pions, and photons at energies below  $\sim 5$  GeV. LAQGSM describes reactions induced by almost all elementary particles as well as by heavy ions at incident energies up to  $\sim 1$  TeV/nucleon. However, our numerous tests show that CEM provides a little better agreement than LAQGSM with experimental data for reactions induced by p, n,  $\pi$ , and  $\gamma$  at energies below several GeV, therefore we recommend using CEM in MCNP6 to describe such reaction at energies below  $\sim 3.5$  GeV, and using LAQGSM at higher energies and for projectiles not allowed by CEM.

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**Fig. 1.** Comparison of the measured [10] energy spectra of prompt  $\gamma$ -rays from a thick  $\text{H}_2^{18}\text{O}$  target bombarded with 18 MeV protons with our MCNP6 results using the CEM03.03 [5] and the Bertini INC [11] + Multistage Pre-equilibrium Model (MPM) [12] + Dresner evaporation [13] event generators (left plot) and experimental [14] double-differential spectra of  $^4\text{He}$  at 20, 40, 60, 100, and 140 degrees from interactions of 160 MeV protons with a thin  $^{197}\text{Au}$  target compared with calculations by CEM03.03 as presented at the recent International Benchmark of Spallation Models [15] and with our current results by MCNP6 using CEM03.03 (right plot), as indicated.

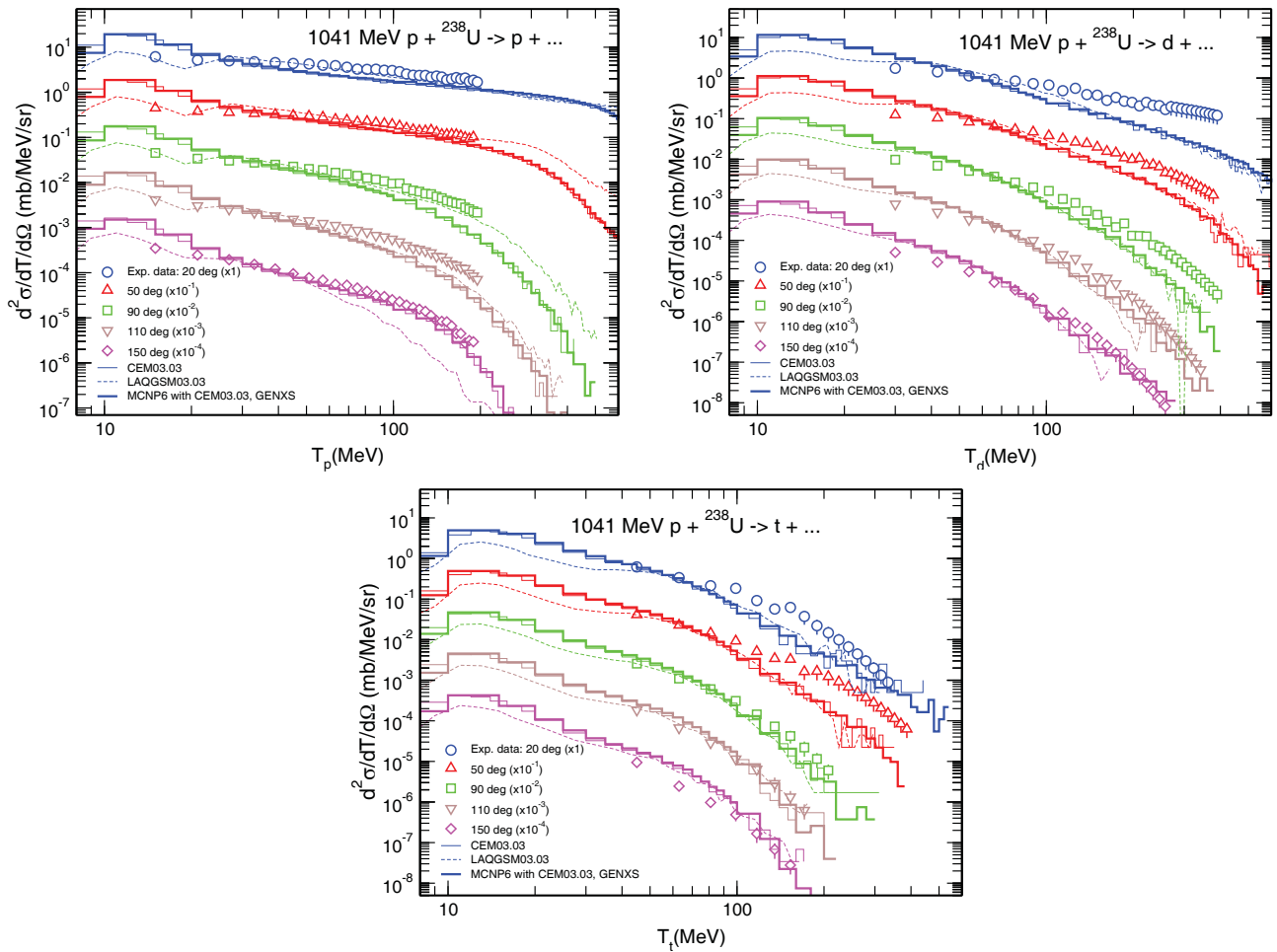
Both CEM and LAQGSM assume that nuclear reactions occur generally in three stages. The first stage is the IntraNuclear Cascade (INC), completely different in CEM and LAQGSM, in which primary particles can be re-scattered and produce secondary particles several times prior to the absorption by, or escape from the nucleus. When the cascade stage of a reaction is complete, CEM03.01 uses the coalescence model to “create” high-energy  $d$ ,  $t$ ,  $^3\text{He}$ , and  $^4\text{He}$  via final-state interactions among emitted cascade nucleons, already outside of the target. The subsequent relaxation of the nuclear excitation is treated in terms of an improved version of the modified exciton model of pre-equilibrium decay followed by the equilibrium evaporation/fission stage of the reaction. But if the residual nuclei after the INC have atomic numbers with  $A < 13$ , CEM and LAQGSM use the Fermi breakup model to calculate their further disintegration instead of using the pre-equilibrium and evaporation models.

The main difference of the following, so-called “03.02” versions of CEM and LAQGSM from the basic “03.01” versions is that the latter use the Fermi breakup model to calculate the disintegration of light nuclei instead of using the pre-equilibrium and evaporation models only after the INC, when  $A < 13$ . It does not use the Fermi breakup model at the pre-equilibrium, evaporation, and fission stages, when, due to emission of pre-equilibrium particles or due to evaporation or to a very asymmetric fission, we get an excited nucleus or a fission fragment with  $A < 13$ . This problem was solved in the 03.02 versions of CEM and LAQGSM, where the Fermi breakup model is used also during the pre-equilibrium and evaporation stages of a reaction, when we get an excited nucleus with  $A < 13$ . Finally, the latest, 03.03 versions of our codes do not produce any unstable products via very asymmetric fission, allowed in very, very rare cases by the previous versions, and have several bugs fixed that were observed in the previous versions. More details and useful references on CEM and LAQGSM may be found in ref. [5].

## 2 Validation and verification of MCNP6

In the present work, we present only a small part of our recent extensive V&V of MCNP6 [6,7] using as event generators mostly CEM03.03 and LAQGSM03.03. For convenience, we start with the V&V of MCNP6 using CEM, followed by the results using LAQGSM.

Before presenting our results, let us mention that the easiest way to calculate (in MCNP6) spectra of secondary particles and cross-section of products from a thin target is to use either the `noact=-2` option on the LCA card of the MCNP6 input file, or the special `GENXS` option of MCNP6. The first option (`noact=-2`) was developed for the MCNPX code and is described in detail in sect. 5.4.6.1 of the MCNPX Manual [8]; it migrated later to MCNP6 exactly as was done in MCNPX [8]. The second option (`GENXS`) was developed by R. Prael especially for MCNP6 and is described in detail in ref. [9]. Both these documents [8,9] will be included in the package to be distributed to the MCNP6 users. The two MCNP6 Primers [6,7] show examples of MCNP6 input files with both these options. Below, in cases of test problems with thin targets, we show examples of using either the first or the second option (or both of them, as shown in fig. 1).



**Fig. 2.** Experimental [16] double-differential spectra of protons, deuterons, and tritons at 20°, 50°, 90°, 110°, and 150° from interactions of 1.041 GeV protons with a thin  $^{238}\text{U}$  target compared with calculations by CEM03.03 and LAQGSM03.03 used as stand-alone codes and with current results by MCNP6 using the CEM03.03 event generator, as indicated.

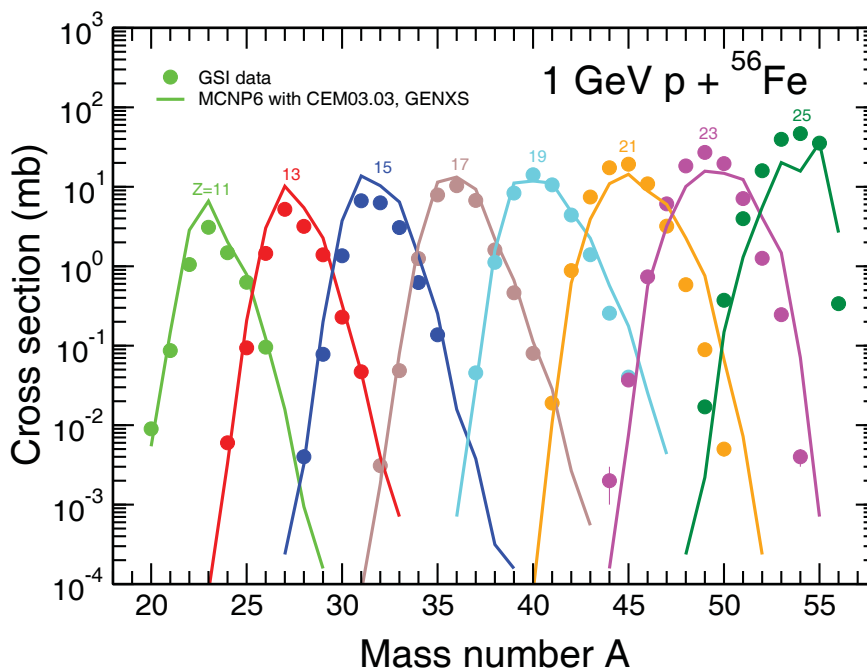
## 2.1 CEM test problems

Let us start our presentation of the V&V of MCNP6 using CEM with a test problem at a very low energy of 18 MeV, namely the energy spectra of prompt  $\gamma$ -rays from a thick  $\text{H}_2^{18}\text{O}$  target bombarded with 18 MeV protons. This problem is of interest for positron emission tomography (PET), as  $^{18}\text{F}$  used in PET is usually produced via the  $^{18}\text{O}(p,n)^{18}\text{F}$  reaction and energy spectrum and angular distribution of neutrons and photons produced in this reaction should be estimated for radiation safety and clearance of the production facility [10]. Generally, at energies below 150 MeV, MCNP6 uses data libraries instead of event generators. But in cases when we do not have any data libraries for a particular isotope, MCNP6 must use an event generator, therefore it is necessary to test how well CEM works in MCNP6 even at such low energies.

As one can see from the left plot of fig. 1, MCNP6 with CEM03.03 describes well the recently measured [10] spectrum of prompt  $\gamma$ -ray from this reaction and agrees reasonably with similar results obtained using the Bertini INC [11] + Multistage Pre-equilibrium Model (MPM) [12] + Dresner evaporation [13] event generator.

The right plot in fig. 1 shows examples of  $^4\text{He}$  spectra emitted from the 160 MeV  $p + ^{197}\text{Au}$  reaction at five angles as calculated by MCNP6 using CEM03.03 compared with experimental data [14] and with results by CEM03.03 used as a stand-alone code as presented at the recent International Benchmark of Spallation Models [15]. Such reactions are of interest for many applications where gas production is important and should be properly accounted; we see that MCNP6 using CEM03.03 describes them very well.

Figure 2 shows examples of  $p$ ,  $d$ , and  $t$  spectra from the 1041 MeV  $p + ^{238}\text{U}$  reaction calculated by MCNP6 using CEM03.03 compared with experimental data [16] and results by CEM03.03 and LAQGSM03.3 used as stand-alone



**Fig. 3.** The measured [17] cross-sections for the production of elements with the charge  $Z$  equal to 11, 13, 15, 17, 19, 21, 23, and 25 (filled color circles) from the reaction  $1 \text{ GeV}/A \text{ } ^{56}\text{Fe} + p$  compared with results MCNP6 using the CEM03.03 event generator, as indicated.

codes. Such reactions are of interest for several applications, especially the cases when gas production must be properly accounted; we see that MCNP6 describes them well.

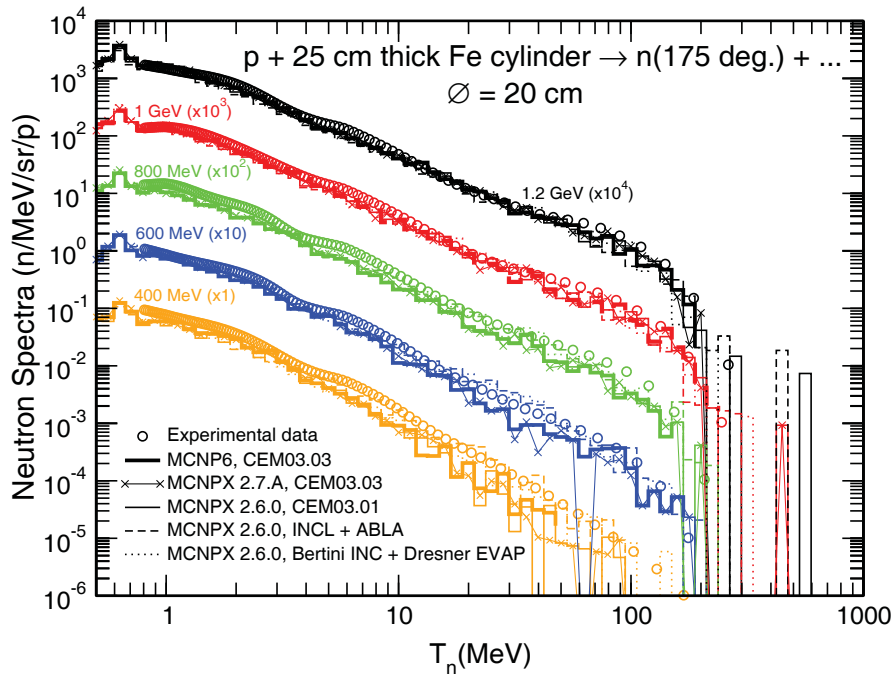
Figure 3 shows examples of yields of eight elements produced from the reaction of  $1 \text{ GeV}/\text{nucleon } ^{56}\text{Fe} + p$  calculated with MCNP6 using CEM03.03 compared with recent GSI measurements [17]. Such reactions are of interest for many technical applications using iron as a construction material, and we see that MCNP6 using CEM03.03 describes them well.

Figure 4 shows backward-angle spectra of neutrons from a thick Fe cylinder bombarded by protons of 400, 600, 800, 1000, and 1200 MeV calculated by MCNP6 using the CEM03.03 event generator compared with experimental data [18] and results by MCNPX 2.7.A [19] using the CEM03.03, and by the 2.6.0 version of MCNPX [8] using the CEM03.01, Bertini INC [11] followed by MPM [12] and the Dresner evaporation [13], as well as using the INCL+ABLA [20,21] event generators. Such processes are of interest to shielding applications in predicting personnel radiation exposure from backward fluxes, to test how the event generators work in this “difficult” kinematics region, and to study the mechanisms of cumulative particle production (an academic problem under investigation for about four decades but still with many open questions). We see that MCNP6 results agree very well with the measured data and calculations by other codes. Very similar results were obtained recently also for a thick Pb target [22].

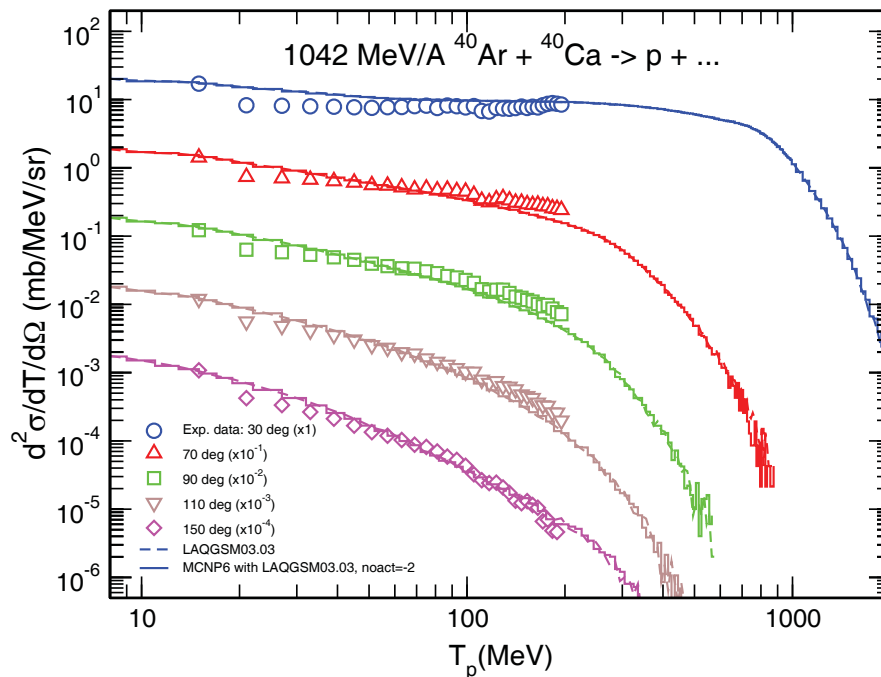
## 2.2 LAQGSM test problems

Now, let us present several results on V&V of MCNP6 using LAQGSM. Figure 5 shows measured [16] double-differential spectra of protons at  $30^\circ$ ,  $70^\circ$ ,  $90^\circ$ ,  $110^\circ$ , and  $150^\circ$  from interaction of a  $1042 \text{ MeV}/\text{nucleon } ^{40}\text{Ar}$  beam with a thin  $^{40}\text{Ca}$  target compared with results by MCNP6 using LAQGSM03.03 and by LAQGSM03.03 used as a stand-alone code. This V&V problem tests the applicability of MCNP6 to calculate production of protons from intermediate energy heavy-ion induced reactions for different NASA (shielding for missions in space), medical (cancer treatment with heavy ions), FRIB (Facility for Rare Isotope Beams), and for several other U.S. DOE applications; we see that MCNP6 describes such reactions very well.

In fig. 6, we test the capability of MCNP6 to describe spectra of complex particles from reactions induced by heavy ions at intermediate energies. Namely, we compare the experimental [16,23] double-differential spectra of  $d$ ,  $t$ ,  $^3\text{He}$ , and  $^4\text{He}$  from thin  $^{64}\text{Cu}$  and  $^{238}\text{U}$  targets bombarded with  $^{20}\text{Ne}$  beams of several energies compared with the results by MCNP6 using the LAQGSM03.03 event generator and by LAQGSM03.03 used as a stand-alone code. The interest in such types of reactions is very similar to the one listed above regarding fig. 5. In addition, we would like to note that light charged particles, *i.e.*,  $p$ ,  $d$ ,  $t$ ,  $^3\text{He}$ , and  $^4\text{He}$  from any reactions are of a major concern for material damage,

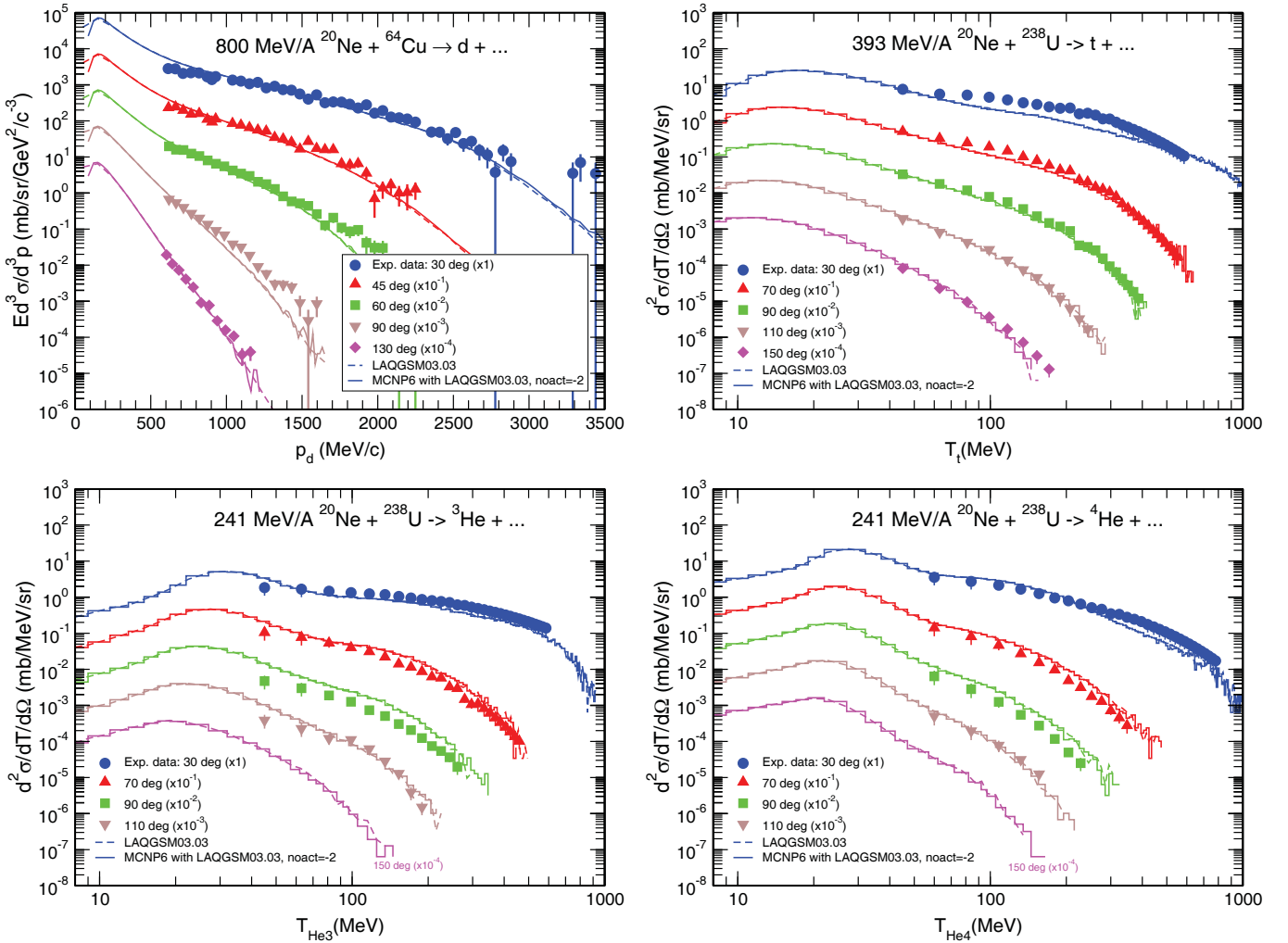


**Fig. 4.** Experimental [18] neutron spectra at 175 degrees (symbols) from a thick Fe cylinder bombarded with 400, 600, 800, 1000, and 1200 MeV protons compared with the results by MCNP6 using the CEM03.03 event generator, by MCNPX 2.7.A [19] using the CEM03.03 event generator, and by the 2.6.0 version of MCNPX [8] using the CEM03.01, Bertini INC [11] followed by the Multistage Pre-equilibrium Model (MPM) [12] and the evaporation model described with the Dresner code EVAP [13], and by the INCL+ABLA [20,21] event generators, as indicated in legend.



**Fig. 5.** Experimental [16] proton spectra at 30, 70, 90, 110, and 150 degrees (symbols) from a thin  $^{40}\text{Ca}$  target bombarded with a 1042 MeV/nucleon  $^{40}\text{Ar}$  beam compared with the results by LAQGSM03.03 used as a stand-alone code and by MCNP6 using the LAQGSM03.03 event generator, as indicated.





**Fig. 6.** Experimental [16, 23] double-differential spectra of deuterons, tritons,  $^3\text{He}$ , and  $^4\text{He}$  at five different angles (symbols) from thin  $^{64}\text{Cu}$  and  $^{238}\text{U}$  targets bombarded with  $^{20}\text{Ne}$  beams of listed energies compared with the results by LAQGSM03.03 used as a stand-alone code and by MCNP6 using the LAQGSM03.03 event generator, as indicated (no  $^3\text{He}$  and  $^4\text{He}$  measured data are available at  $150^\circ$ , so we present for this angle only our predictions).

as helium can cause swelling in structure materials; tritium is often an issue from a radioprotection point of view. We see that MCNP6 describes such reactions very well.

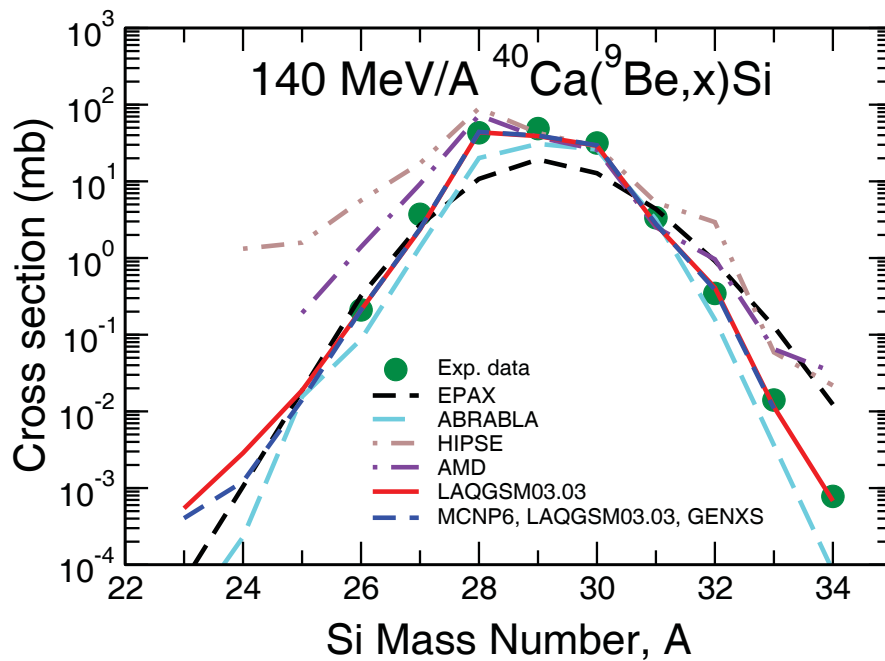
Figure 7 presents experimental [24] yields of the Si ions from the 140 MeV/nucleon  $^{40}\text{Ca} + ^9\text{Be}$  reaction compared with the results by MCNP6 using the LAQGSM03.03 and by LAQGSM03.03 used as a stand-alone code, as well as the results by EPAX [25], ABRABLA [26], HIPSE [27], and AMD [28] from [24]. Such reactions are of interest for FRIB (a modification and continuation of the former Rare Isotope Accelerator (RIA) project) and the measurements [24] were performed especially to support RIA. We see that MCNP6 describes these measurements very well and is not worse than other models. We obtained similar results for many other reactions measured for FRIB/RIA at the National Superconducting Cyclotron Laboratory (NSCL) in East Lansing, MI, USA, allowing us to conclude that MCNP6 can be a useful and reliable tool for FRIB simulations.

### 2.3 Some physics problems and bugs fixes

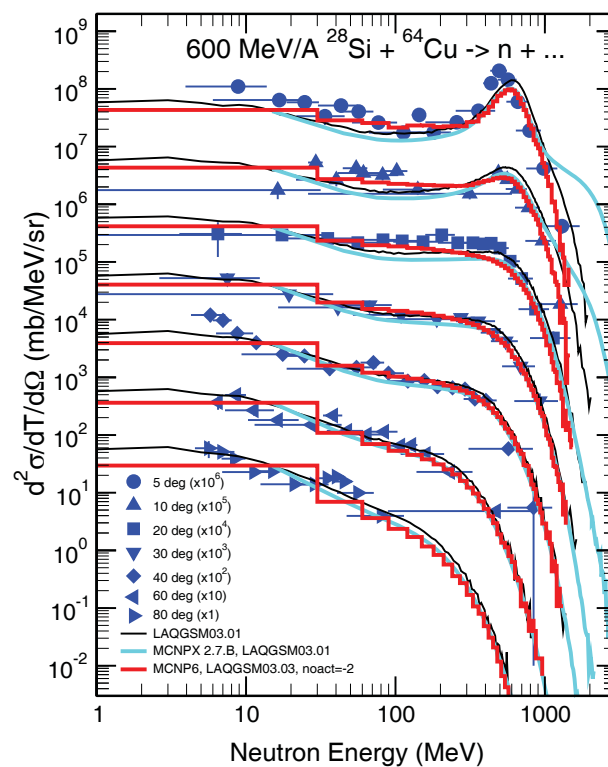
Naturally, during our extensive V&V work of MCNP6, we discovered some bugs and more serious physics problems in MCNP6 or/and in MCNPX. Most of them have been fixed; we continue our work to solve all the observed problems before MCNP6 is distributed to the public. Let us present below only two examples.

Figure 8 shows the experimental [29] spectra of neutrons at  $5^\circ$ ,  $10^\circ$ ,  $20^\circ$ ,  $30^\circ$ ,  $40^\circ$ ,  $60^\circ$ , and  $80^\circ$  from a relatively thin Cu target bombarded with a 600 MeV/nucleon  $^{28}\text{Si}$  beam compared with the results by MCNP6 using LAQGSM03.03 used as a stand-alone code, as well as with the calculations by MCNPX 2.7.B [30] using LAQGSM03.01.

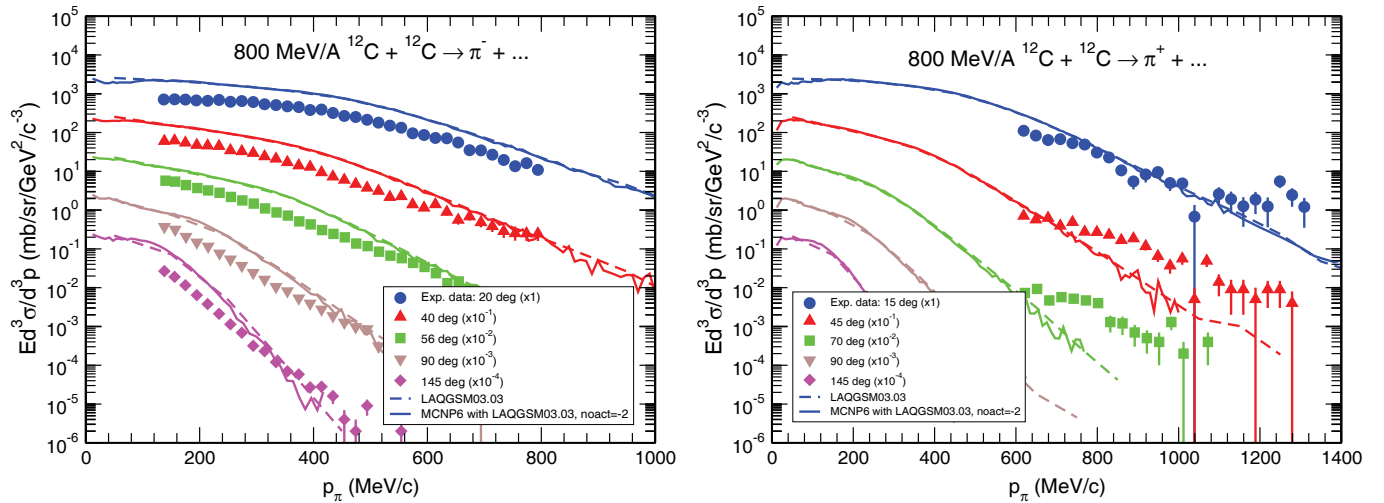




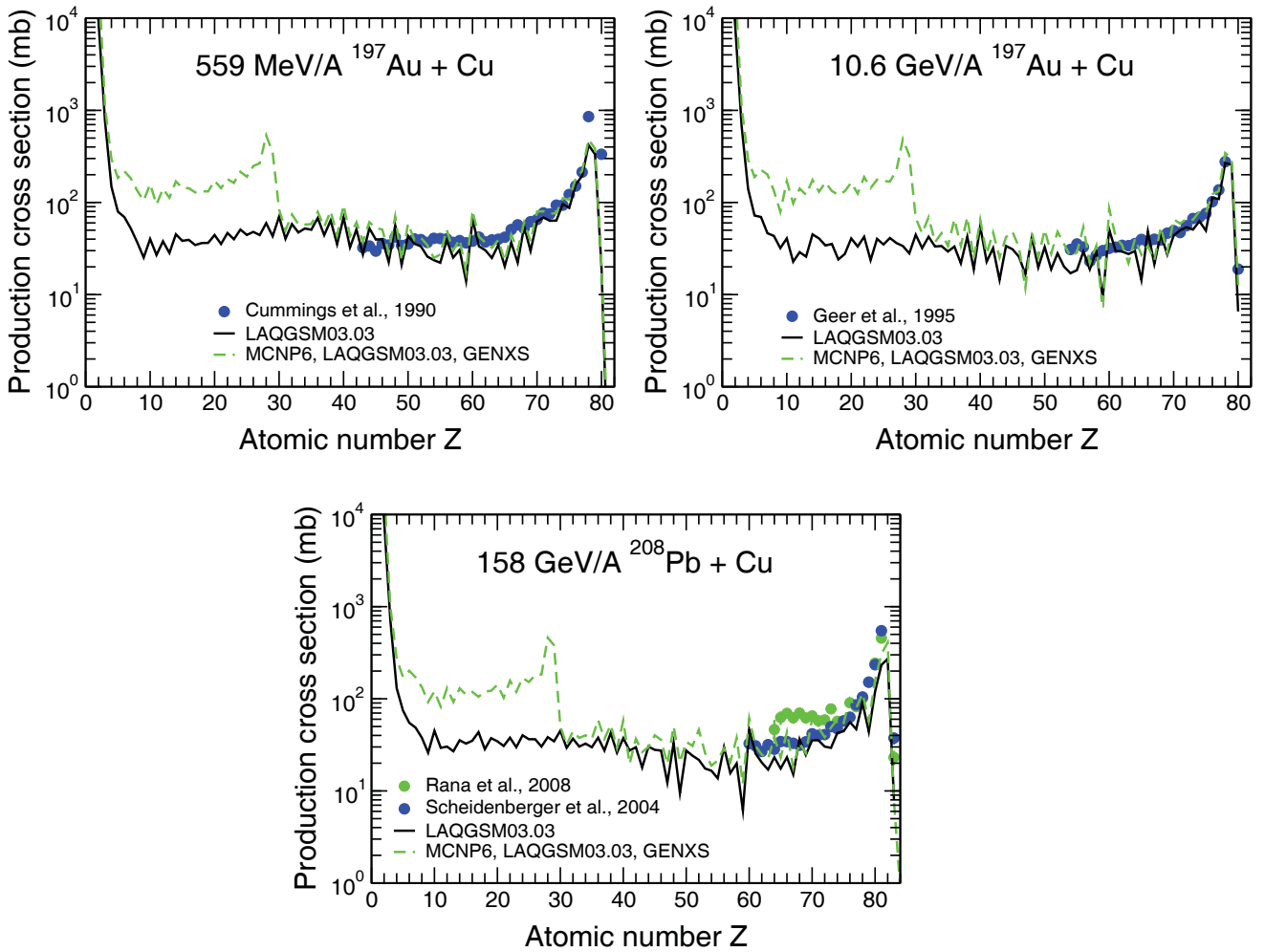
**Fig. 7.** Experimental [24] mass number distribution of the Si ions yield (green filled circles) from the 140 MeV/A  $^{40}\text{Ca} + ^9\text{Be}$  reaction compared with the results by EPAX [25], ABRABLA [26], HIPSE [27], and AMD [28] from [24], as well as with the predictions by LAQGSM03.03 used as a stand-alone code and by MCNP6 using the LAQGSM03.03 event generator, as indicated.



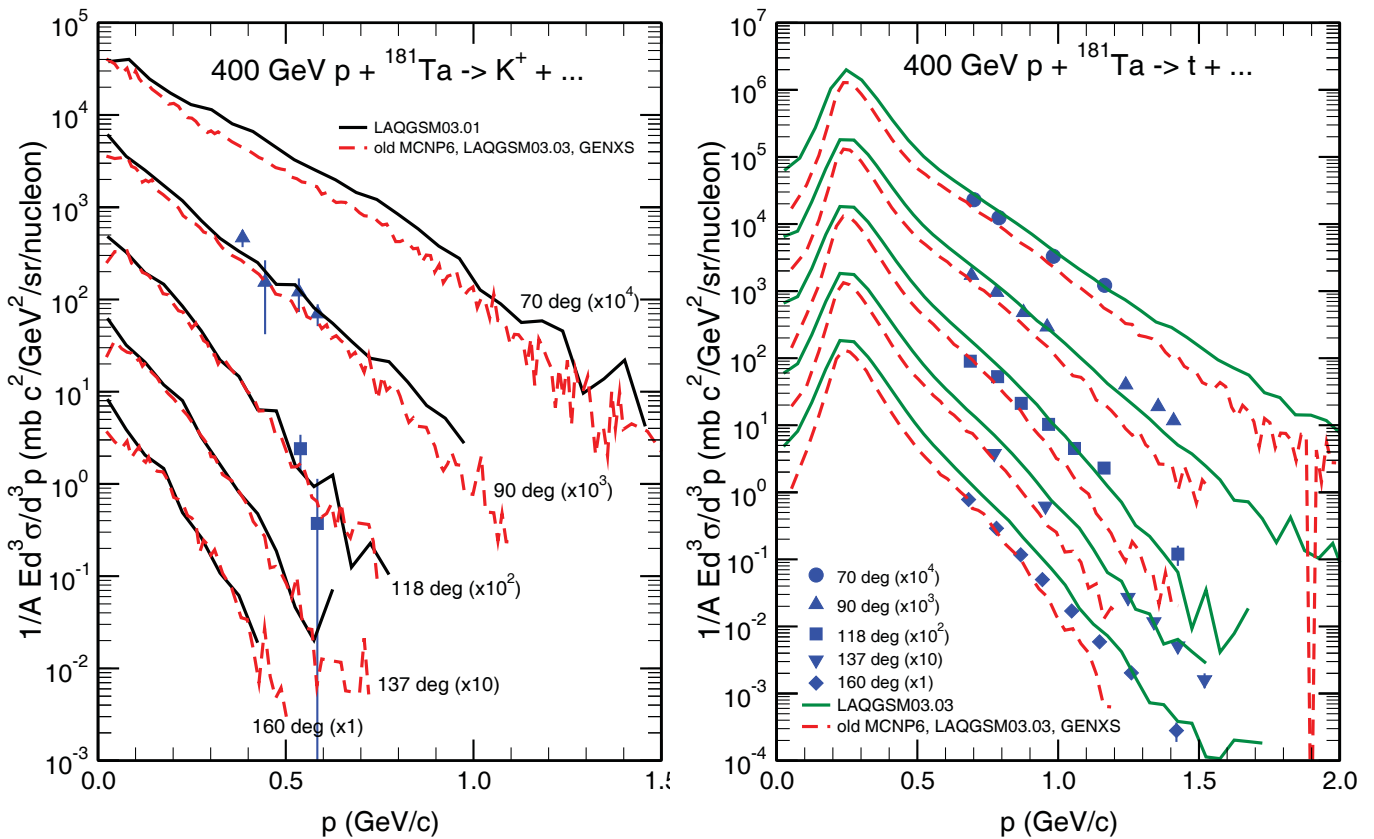
**Fig. 8.** Experimental [29] neutron spectra at 5°, 10°, 20°, 30°, 40°, 60°, and 80° from the 600 MeV/A  $^{28}\text{Si} + \text{Cu}$  reaction compared with the results by LAQGSM03.01 used as a stand-alone code, and with our MCNP6 results using LAQGSM03.03, as well as with the results by MCNPX 2.7.B [30] obtained by I. Remeč at ORNL using LAQGSM03.01, as indicated.



**Fig. 9.** Experimental [23] invariant  $\pi^-$  and  $\pi^+$  spectra at five different angles (symbols) from a thin C target bombarded with an 800 MeV/nucleon  $^{12}\text{C}$  beam compared with the results by LAQGSM03.03 used as a stand-alone code and by MCNP6 using the LAQGSM03.03 event generator, as indicated (no  $\pi^+$  measured data are available at 90 and 145 degrees, so we present for this angle only our predictions).



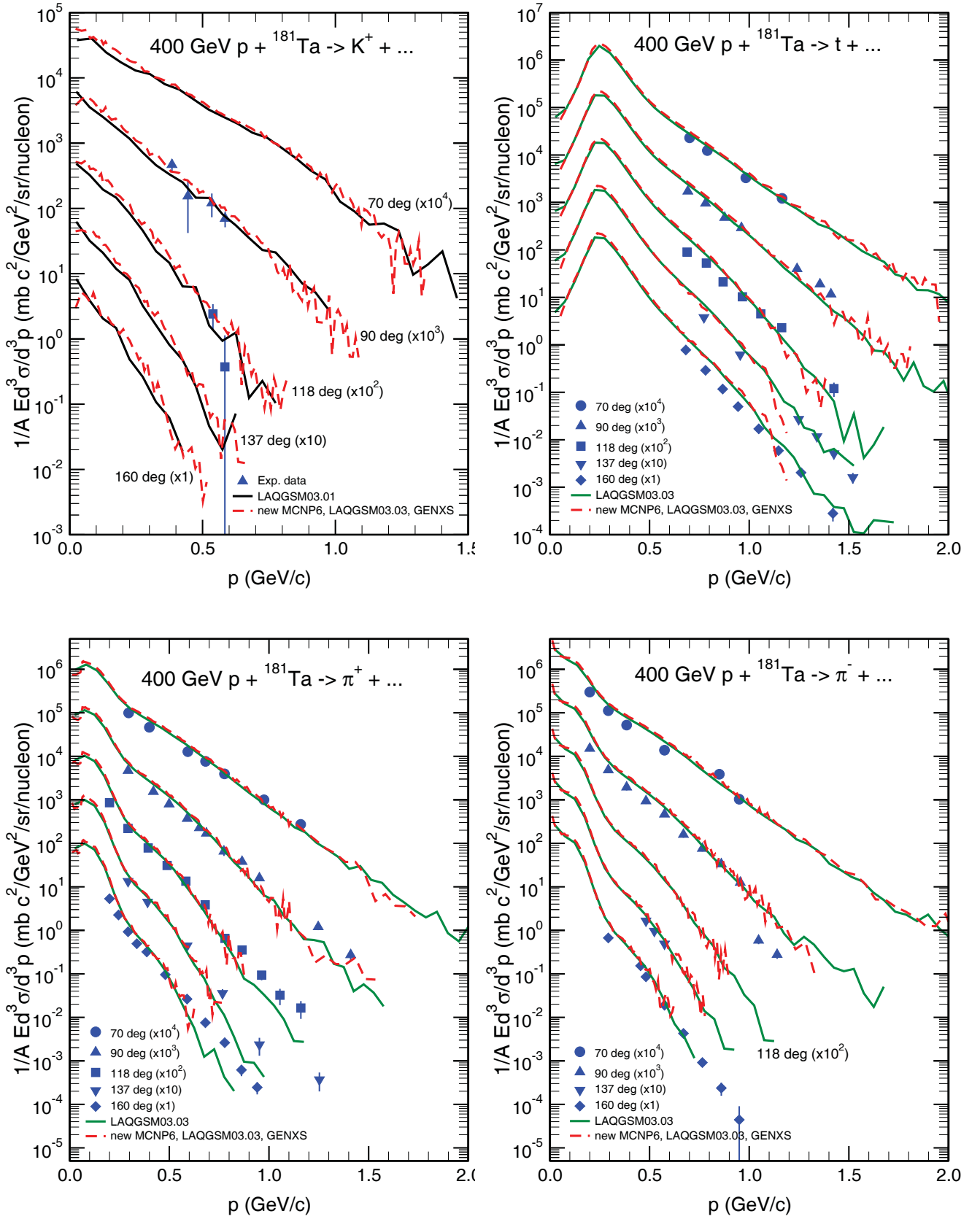
**Fig. 10.** Experimental [31–34] charge distributions of product yields (color filled circles) from 559 MeV/A  $^{197}\text{Au} + \text{Cu}$ , 10.6 GeV/A  $^{197}\text{Au} + \text{Cu}$ , and 158 GeV/A  $^{208}\text{Pb} + \text{Cu}$  reactions compared with the results by LAQGSM03.03 used as a stand-alone code and by MCNP6 using the LAQGSM03.03 event generator, as indicated.



**Fig. 11.** Experimental [35,36] invariant spectra of  $K^+$  and  $t$  from the reaction  $400 \text{ GeV } p + {}^{181}\text{Ta} \rightarrow K^+ + \dots$  (symbols) compared with the results by a preliminary, still under development, version (see text) of MCNP6 using LAQGSM03.03 (red dashed lines), with the calculations by LAQGSM03.03 used as a stand-alone code, and with our 2005 results by LAQGSM03.01 from ref. [37], as indicated. Similar results are obtained also for the measured  $p$ ,  $d$ ,  ${}^3\text{He}$ ,  ${}^4\text{He}$ ,  $K^-$ , and antiproton spectra from  ${}^{181}\text{Ta}$ , as well as for all measured spectra from C, Al, and Cu (see [35,36] and references therein and our LAQGSM03.01 results in refs. [37,38]).

I. Remec of ORNL, who kindly sent us these (and many other) MCNPX 2.7.B results called our attention to a problem he observed in the MCNPX 2.7.B for neutron spectra at forward angles. For unknown reasons, MCNPX 2.7.B using LAQGSM03.01 strongly overestimates the neutron spectra at forward angles (see the cyan lines in fig. 8), while LAQGSM03.01, used as a stand-alone code, describes such spectra very well (see the black lines in fig. 8). A special investigation by M. James of the LANL D-5 Group has identified a previously unobserved error in the implementation of LAQGSM03.01 in MCNPX, which caused that problem. This implementation error was fixed by M. James in a very recent version of MCNPX by replacing completely the relatively old LAQGSM03.01 with the latest version LAQGSM03.03. Such a replacement was also done in MCNP6 by R. Prael. As we can see from fig. 8, the current version of MCNP6 describes these measured neutron spectra very well, just as LAQGSM03.03 and LAQGSM03.01 do as stand-alone codes.

Figure 9 shows an example of another problem solved recently in MCNP6. For historical reasons, the initial version of MCNP6 would “tally” (*i.e.*, would count, and provide results in the output file) particles together with antiparticles from any nuclear reactions, as would MCNPX and MCNP5. This was needed and very useful for some of our applications. But for other applications, especially at high energies, this feature is not convenient at all, as it does not allow users to easily get separate results for particles and antiparticles. This issue was corrected recently in MCNP6 by G. Hughes (in the latest versions of MCNPX, MCNPX 2.7.D and MCNPX 2.7.E, this problem was also addressed, but in a different way). As we see from fig. 9, the current version of MCNP6 is able to calculate without problems separate spectra of  $\pi^+$  and  $\pi^-$  from nuclear reactions. In this particular example, we compare the experimental [23] spectra of  $\pi^+$  and  $\pi^-$  from a thin C target bombarded with a 800 MeV/nucleon  ${}^{12}\text{C}$  with the results by MCNP6 using LAQGSM03.03 and with calculations by LAQGSM03.03 used as a stand-alone code. We see a very good agreement between the results by MCNP6 and by LAQGSM03.03 used as a stand-alone code, and a worse, especially for  $\pi^+$ , but still a reasonable agreement with the experimental data.



**Fig. 12.** Experimental [35,36] invariant spectra of  $K^+$ ,  $t$ ,  $\pi^+$ , and  $\pi^-$  from the reaction  $400 \text{ GeV } p + {}^{181}\text{Ta}$  (symbols) compared with the results by the latest version (see text) of MCNP6 using LAQGSM03.03 (red dashed lines), with the calculations by LAQGSM03.03 used as a stand-alone code, and with our 2005 results by LAQGSM03.01 from ref. [37], as indicated.

## 2.4 Reactions at ultrarelativistic energies

Finally, let us present in figs. 10 and 11 two examples of reactions at ultrarelativistic energies. Figure 10 shows a test of the capability of MCNP6 to describe the same (almost) heavy-ion induced reaction in a very large range of incident energies, namely it provides a comparison of the experimental [31–34] charge distributions of product yields from 559 MeV/nucleon  $^{197}\text{Au} + \text{Cu}$ , 10.6 GeV/nucleon  $^{197}\text{Au} + \text{Cu}$ , and from a very similar but at an ultrarelativistic energy of 158 GeV/nucleon  $^{208}\text{Pb} + \text{Cu}$  reaction compared with the results by MCNP6 using the LAQGSM03.03 event generator and by LAQGSM03.03 used as a stand-alone code. Such capabilities of MCNP6 are needed for astrophysical applications, particularly for problems of propagation of cosmic rays through matter. Let us note that the MCNP6 results shown in fig. 10 represent cross-sections of the products from both the projectile and target nuclei, while the LAQGSM03.03 used as stand-alone calculated only fragmentation products from the bombarding nuclei. This is why we see a good agreement between the MCNP6 and LAQGSM03.03 results and the measured projectile fragmentation cross-sections (*i.e.*, for products heavier than Cu), and a much higher MCNP6 yield of products lighter than Cu than the one calculated by LAQGSM03.03 from only the projectiles.

In the end, we would like to present an example of our work still in progress. Namely, fig. 11 shows a comparison of experimental [35,36] invariant spectra of  $K^+$  and  $t$  from the ultrarelativistic reaction 400 GeV  $p + ^{181}\text{Ta}$  compared with our preliminary results by MCNP6 using LAQGSM03.03 and with the calculations by LAQGSM03.03 used as a stand-alone code, as well as with our 2005 results by LAQGSM03.01 from ref. [37]. Similar preliminary results are obtained also for the measured  $p$ ,  $d$ ,  $^3\text{He}$ ,  $^4\text{He}$ ,  $K^-$ , and antiproton spectra from  $^{181}\text{Ta}$ , as well as for all measured spectra from C, Al, and Cu (see [35,36] and references therein and our LAQGSM03.01 results presented in refs. [37,38]). In addition to astrophysical applications, such reactions are of great academic interest in studying the production of the so-called “cumulative particles”, *i.e.*, energetic particles at backward angles in the kinematic region forbidden in the interactions of the projectile with free stationary nucleons of the target nucleus. It is believed that cumulative particles contain information needed for the study of the high-momentum component of nuclear wave functions, or of collective phenomena in nuclei, or of quark and gluon degrees of freedom. We see that our preliminary results by MCNP6 differ a little from the results obtained with the LAQGSM03.03 used as a stand-alone code, requiring more work on MCNP6. But the agreement with the experimental data is reasonably good, especially when considering that, to the best of our knowledge, these “cumulative” particle spectra, measured at the Fermi National Accelerator Laboratory three decades ago, were described simultaneously within a single approach and without using any “exotic” nuclear-reaction mechanisms for the first time in 2005 by our LAQGSM03.01 [37,38] and here, with MCNP6 using LAQGSM03.03.

Let us mention here that the results presented in fig. 11 correspond to the status of MCNP6 as of November 2010, when the first draft of the current work was written for the presentation at the M&C2011 conference [39] (this is why we have labeled those results in the legend of fig. 11 as “old MCNP6”). Thereafter, a bug was found in the high-energy portion of MCNP6 and was fixed by R. Prael. As can be seen from the upper row of fig. 12, the current version of MCNP6 provides spectra (we label in the legend of fig. 12 the results by the latest version of MCNP6 as “new MCNP6”) for these reactions and is in good agreement with the results obtained when LAQGSM03.03 is used as a stand-alone code. The lower row of fig. 12 is related to the problem of MCNP6 tallying particles separately from antiparticles, as discussed in sect. 2.3. We see that the current version of MCNP6, where this problem was solved by G. Hughes as discussed above, is able to describe spectra of  $\pi^+$  separately from those of  $\pi^-$ ; that was not possible in the initial version of MCNP6 and in early versions of MCNPX. We can see a very good agreement of the measured spectra of “cumulative pions” from this reaction with our calculations.

## 3 Conclusion

MCNP6, the latest and most advanced LANL transport code representing a recent merger of MCNP5 and MCNPX, has been validated and verified against a variety of intermediate and high-energy experimental data and against calculations by different versions of MCNPX and results by several other codes. In the present work, MCNP6 was tested using mainly the latest modifications of the Cascade-Exciton Model (CEM) and of the Los Alamos version of the Quark-Gluon String Model (LAQGSM) event generators CEM03.03 and LAQGSM03.03. We found that MCNP6 describes reasonably well various reactions induced by particles and heavy ions at incident energies from 18 MeV to about 1 TeV/nucleon measured on both thin and thick targets and agrees very well with similar results obtained with MCNPX and calculations by other codes. Most of several computational bugs and more serious physics problems observed in MCNP6/X during our V&V have been fixed. We continue our work to solve all the known problems before the official distribution of MCNP6 to the public via RSICC at Oak Ridge, TN, USA planned for the middle of 2011. From the current V&V, we can conclude that MCNP6 is a reliable and useful transport code for different applications involving reactions induced by almost all types of elementary particles and heavy ions, in a very broad range of incident energies.



I am grateful to my LANL colleagues, Drs. F. Brown, J. Bull, T. Goorley, G. Hughes, M. James, R. Martz, R. Prael, A. Sierk, and L. Waters as well as to F. Gallmeier and W. Lu of ORNL, Oak Ridge, TN, USA, and to K. Gudima of the Academy of Science of Moldova, for useful discussions, help, and/or for correcting some of the MCNP6/X bugs I have detected during the current V&V work. I thank Drs. V. Belyakov-Bodin, M. Hagiwara, Y. Miake, S. Nagamiya, P. Napolitani, M. Nortier, Y. Uozumi, and J. Weidner for sending me their publications and/or files with numerical values of their experimental data I used in my V&V work. It is a pleasure to acknowledge Drs. F. Gallmeier, M. Hagiwara, A. Krassa, W. Lu, M. Majerle, and I. Remec for sending me their MCNPX calculations included in my comparisons. 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 with funding from the Defense Threat Reduction Agency (DTRA).

## References

1. H.G. Hughes *et al.*, *Recent Developments in MCNP and MCNPX*, LANL report LA-UR-08-01065 (2008).
2. J.T. Goorley, *Eolus L2: MCNP MCNPX merger (U)*, LANL report LA-UR-09-06034 (2009).
3. X-5 Monte Carlo Team, *MCNP - A General Monte Carlo N-Particle Transport Code, Version 5, Volume I: Overview and Theory*, LANL report LA-UR-03-1987 (2008).
4. L.S. Waters (Editor), *MCNPX User's Manual, Version 2.3.0*, LANL report LA-UR-02-2607 (2002); see more references on MCNPX at: <http://mcnp.lanl.gov/>.
5. S.G. Mashnik *et al.*, *CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX, and MARS15 Transport Codes*, LANL report LA-UR-08-2931 (2008); E-print: arXiv:0805.0751.
6. S.G. Mashnik, *Validation and Verification of MCNP6 against High-Energy Experimental Data and Calculations by other Codes. I. The CEM Testing Primer*, LANL report LA-UR 11-xxxxx (2011).
7. S.G. Mashnik, *Validation and Verification of MCNP6 against High-Energy Experimental Data and Calculations by other Codes. II. The LAQGSM Testing Primer*, LANL report LA-UR 11-xxxxx (2011).
8. D.B. Pelowitz (Editor), *MCNPX User's Manual, Version 2.6.0*, LANL report LA-CP-07-1473 (2008).
9. R.E. Prael, *Tally Edits for the MCNP6 GENXS Option*, LANL Research Note X-5-RN(U) 04-41 (2004).
10. M. Hagiwara *et al.*, *Spectrum Measurement of Neutrons and Gamma-rays from Thick H218O Target Bombarded with 18 MeV Protons*, in *Proceedings of the International Conference on Nuclear Data for Science and Technology (ND2010)*, Jeju Island, Korea, April 26-30, 2010, in press.
11. H.W. Bertini, *Phys. Rev.* **131**, 1801 (1963).
12. R.E. Prael, M. Bozoian, *Adaptation of the Multistage Preequilibrium Model for the Monte Carlo Method*, LANL report LA-UR-88-3238 (1988).
13. L. Dresner, *EVAP - A Fortran Program for Calculation the Evaporation of Various Particles from Excited Compound Nuclei*, Oak Ridge National Laboratory report ORNL-TM-196 (1962).
14. A.A. Cowley *et al.*, *Phys. Rev. C* **54**, 778 (1996).
15. *Benchmark of Spallation Models* organized at the International Atomic Energy Agency during 2008-2009, [http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main\\_Page](http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Main_Page).
16. A. Sandoval *et al.*, *Phys. Rev. C* **21**, 1321 (1980).
17. C. Villagrasa-Canton *et al.*, *Phys. Rev. C* **75**, 044603 (2007).
18. I.L. Azhgirey *et al.*, *Nucl. Instrum. Methods B* **267**, 3601 (2009).
19. D.B. Pelowitz *et al.*, *MCNPX 2.7.A Extensions*, LANL report LA-UR-08-07182 (2008).
20. A. Boudard *et al.*, *Phys. Rev. C* **66**, 044615 (2002).
21. A.R. Junghans *et al.*, *Nucl. Phys. A* **629**, 635 (1998).
22. I.L. Azhgirey *et al.*, *Nucl. Instrum. Methods B* **268**, 3426 (2010).
23. S. Nagamiya *et al.*, *Phys. Rev. C* **24**, 971 (1981).
24. M. Mocko, *Rare Isotope Production*, PhD thesis, Michigan State University (2006), [http://groups.nsl.msu.edu/nsl\\_library/Thesis/index.htm](http://groups.nsl.msu.edu/nsl_library/Thesis/index.htm).
25. K. Summerer, B. Blank, *Phys. Rev. C* **61**, 034607 (2000).
26. J.-J. Gaimard, K.-H. Schmidt, *Nucl. Phys. A* **531**, 709 (1991).
27. D. Lacroix *et al.*, *Phys. Rev. C* **69**, 054604 (2004).
28. A. Ono, H. Horiuchi, *Prog. Part. Nucl. Phys.* **53**, 501 (2004).
29. L. Heilbronn *et al.*, *Nucl. Sci. Eng.* **157**, 142 (2007).
30. D.B. Pelowitz *et al.*, *MCNPX 2.7.B Extensions*, LANL report LA-UR-09-04150 (2009).
31. J.R. Cummings *et al.*, *Phys. Rev. C* **42**, 2508 (1990).
32. L.Y. Geer *et al.*, *Phys. Rev. C* **52**, 334 (1995).
33. C. Scheidenberger *et al.*, *Phys. Rev. C* **70**, 014902 (2004).
34. M.A. Rana, S. Manzoor, *Rad. Measur.* **43**, 1383 (2008).
35. N.A. Nikiforov *et al.*, *Phys. Rev. C* **22**, 700 (1980).
36. S. Frankel *et al.*, *Phys. Rev. C* **20**, 2257 (1979).
37. S.G. Mashnik *et al.*, *J. Phys.: Conf. Ser.* **41**, 340 (2006) arXiv:nucl-th/0510070.
38. S.G. Mashnik *et al.*, *Overview and Validation of the CEM03.01 and LAQGSM03.01 Event Generators for MCNP6, MCNPX, and MARS15*, presentation at the *Hadronic Shower Simulation Workshop (HSSW06)*, FNAL, Batavia, IL, USA, September 6-8, 2006, <http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=3734>.
39. S. Mashnik, arXiv:1011.4978.