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Title: MCNP6 Fission Cross Section Calculation at Intermediate and High Energies

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MCNP6 Fission Cross Section Calculation at Intermediate and High Energies

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2. Fission Cross Section Calculation by CEM and LAQGSM
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Many people participated in development of the Cascade-Exciton Model (CEM) and Los Alamos version of the Quark-Gluon String Model (LAQGSM) over their almost 40-year history.

The current contributors are:

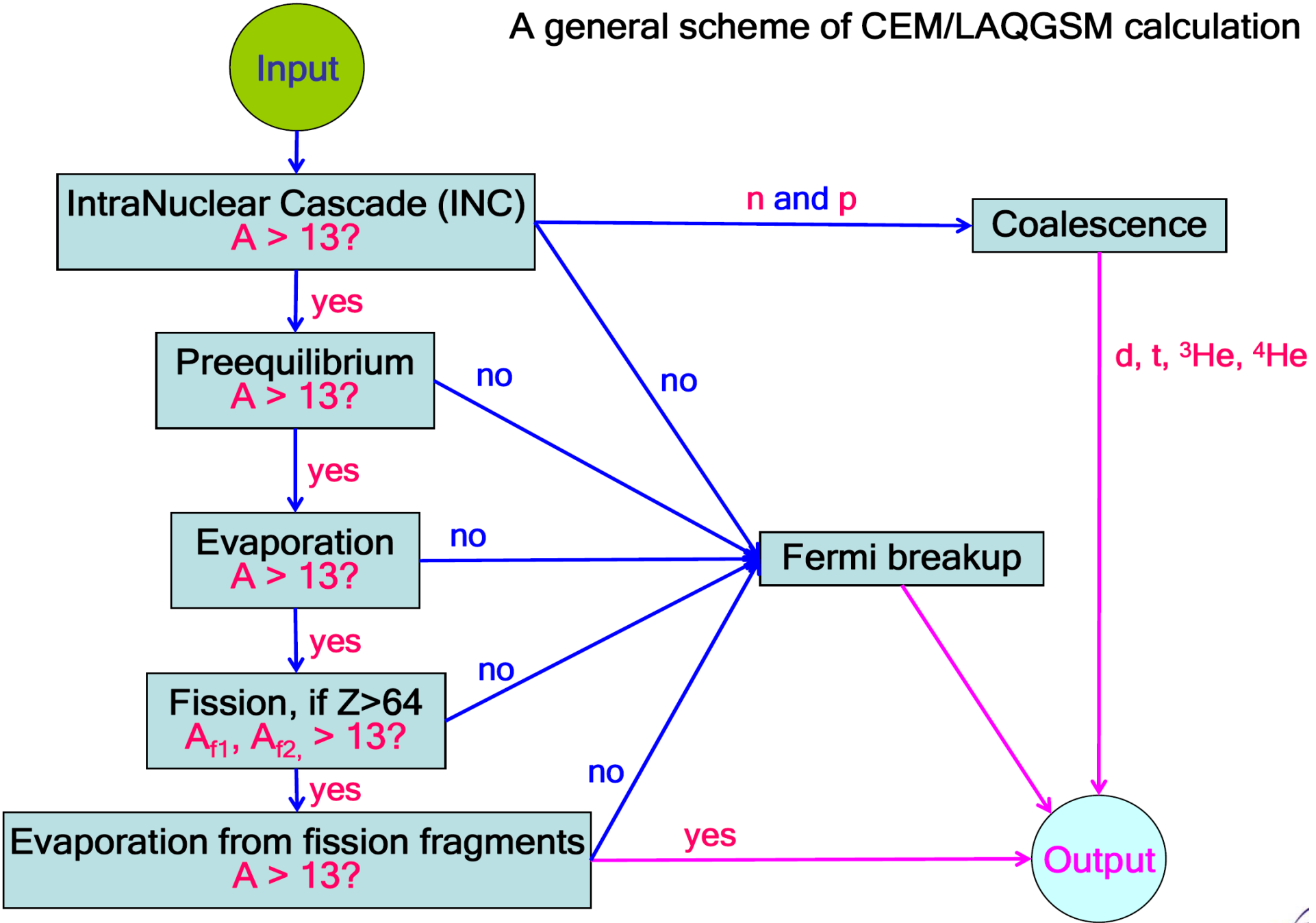
S. G. Mashnik, K. K. Gudima, A. J. Sierk,

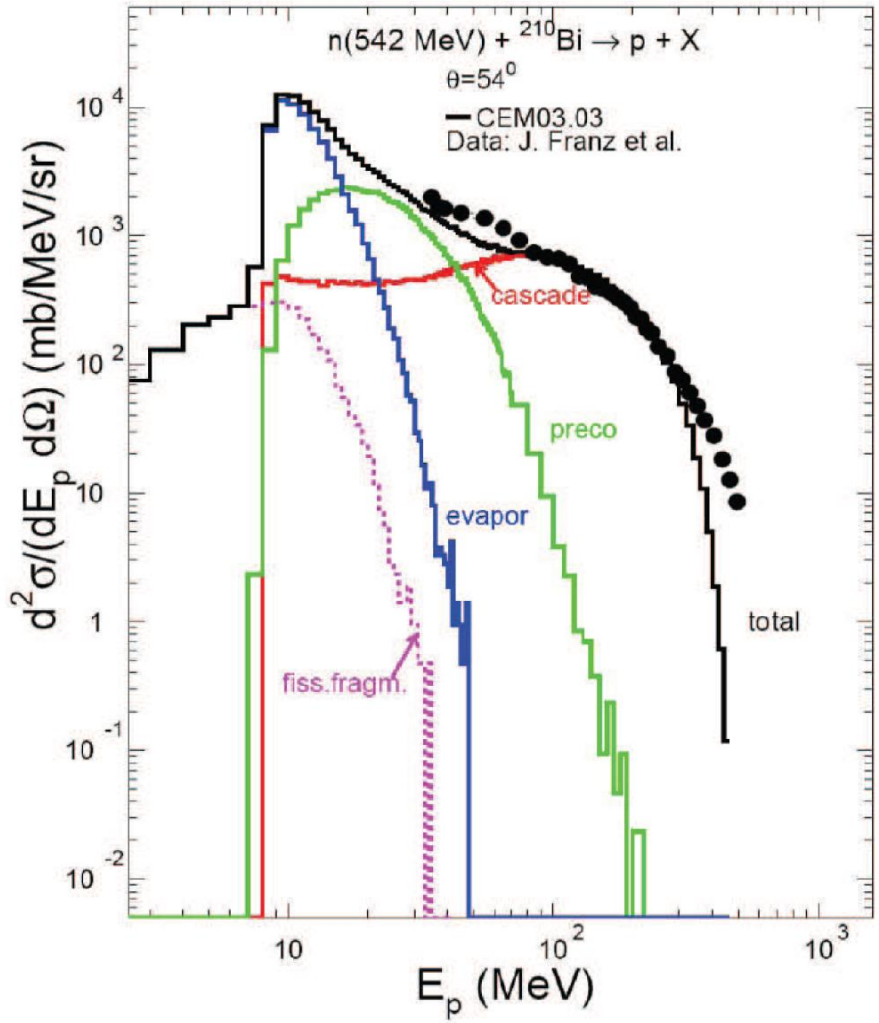
M. I. Baznat, R. E. Prael, N. V. Mokhov.

A recent lecture with many references on our work may be found in:

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*, 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.

A general scheme of CEM/LAQGSM calculation





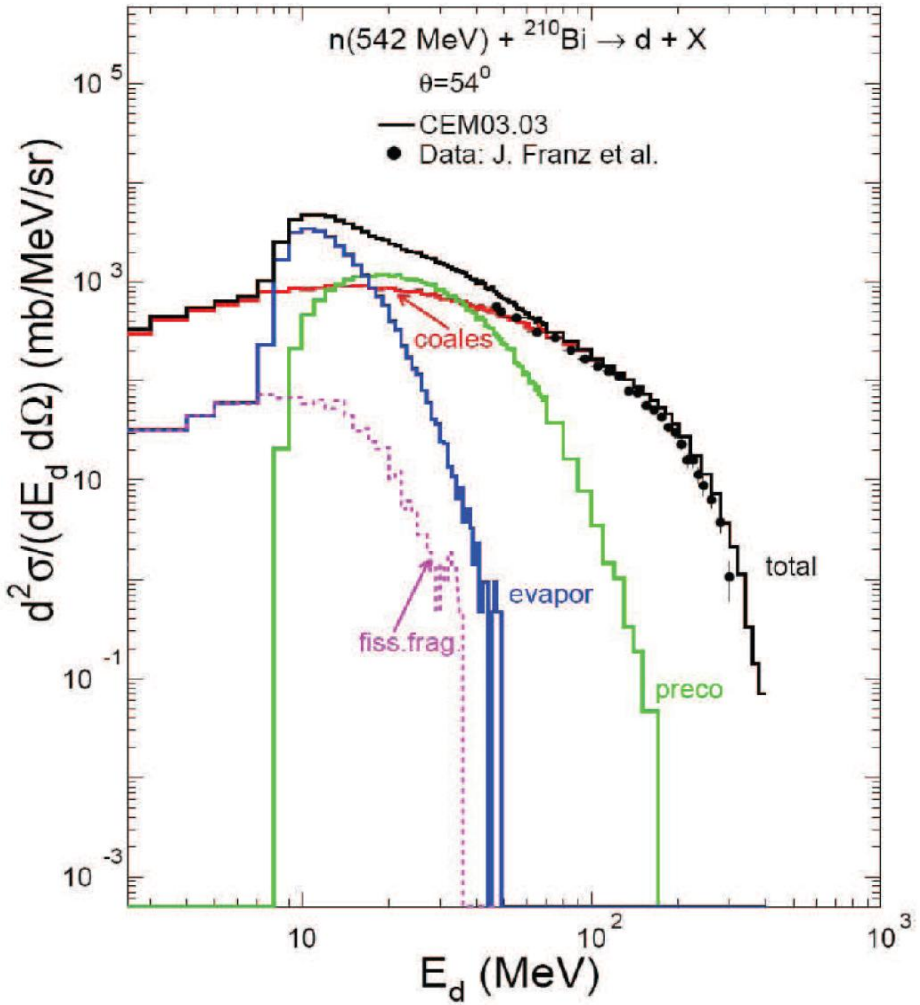


Figure 4: Experimental double-differential spectra of protons and deuterons at 54 degrees from 542 MeV n + Bi (black circles) [13] compared with our results by CEM03.03 (histograms) presented at the Benchmark [10]. Contributions from intra-nuclear cascade, preequilibrium, evaporation before or without fission, coalescence, and evaporation from fission fragments to the total spectra (black histograms) are shown by different colors, as indicated.

CEM03.03 and LAQGSM03.03 use a modification of GEM2 by S. Furihata (NIM B171 (2000) 252) to calculate fission cross sections and evaporation of particles and light fragments. For 65<Z<88, we have:

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

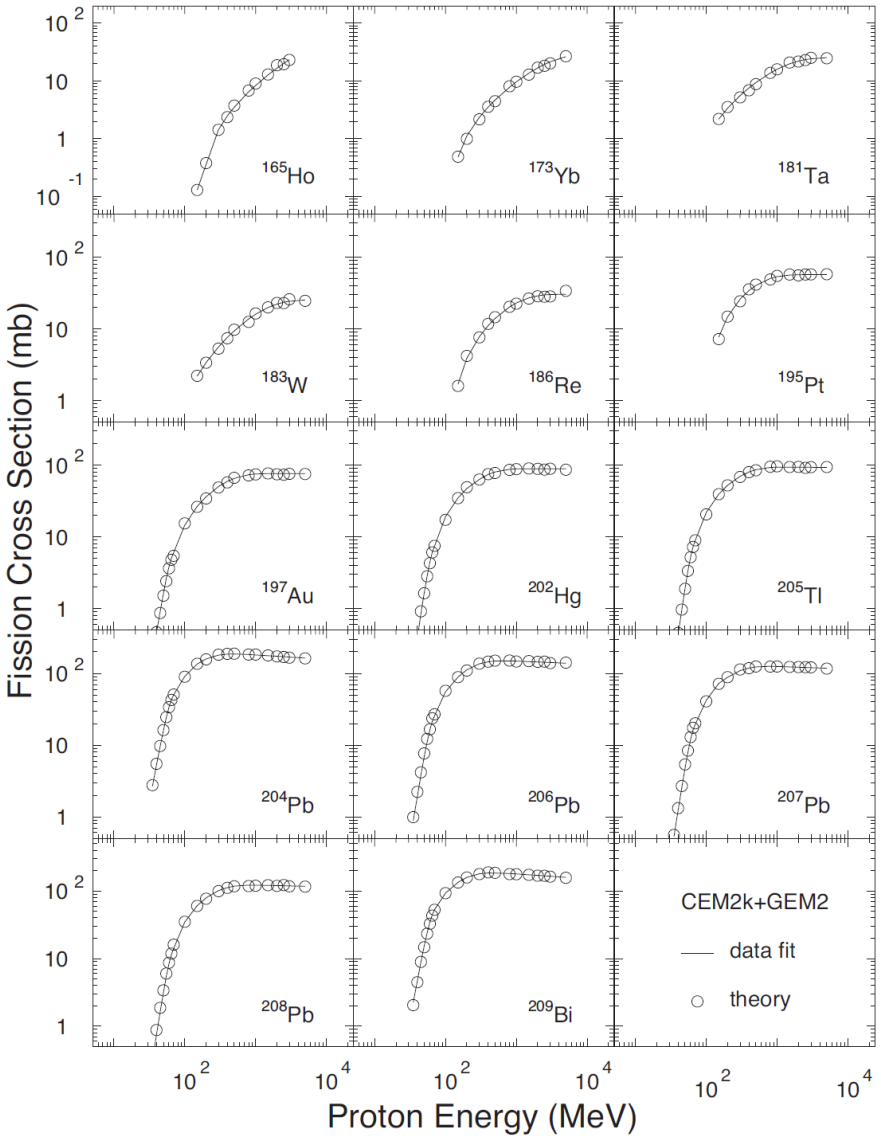
$$\Gamma_n = 0.352(1.68J_0 + 1.93A_i^{1/3}J_1 + A_i^{2/3}(0.76J_1 - 0.05J_0))$$

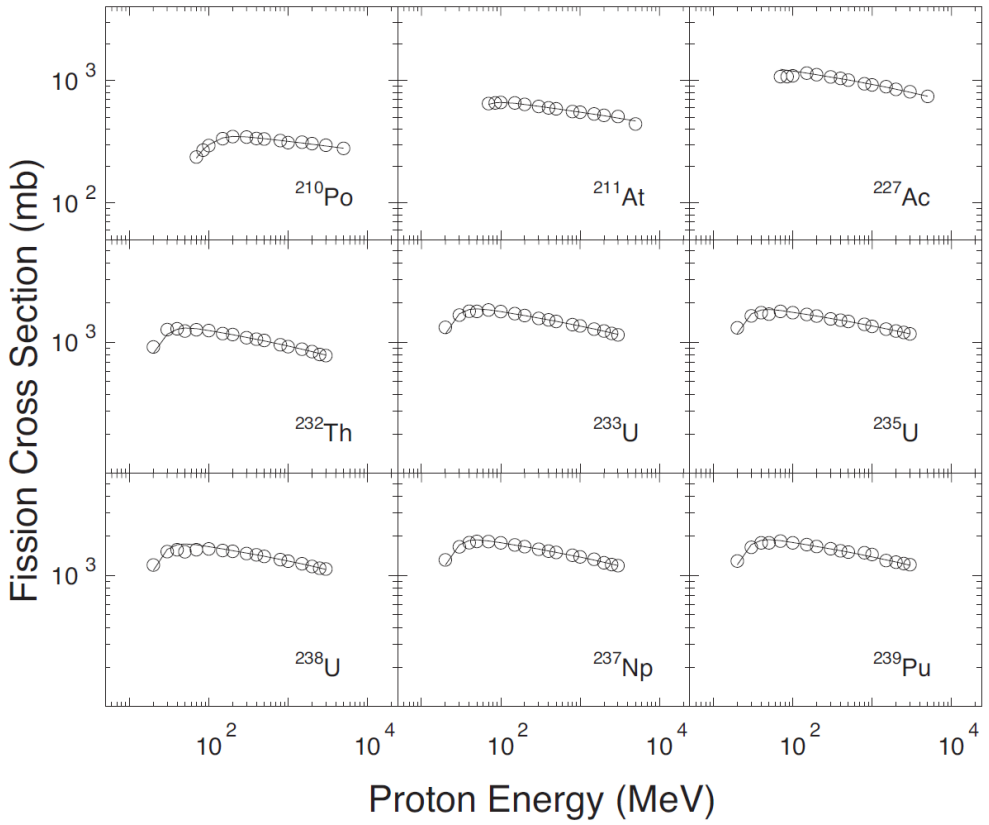
$$\Gamma_f = \frac{(s_f - 1)e^{s_f} + 1}{a_f}$$

$$s_f = 2\sqrt{a_f(E - B_f - \delta)}$$

$$a_f = a_n\left(1.08926 + 0.01098(\chi - 31.08551)^2\right)$$

After fitting a_f/a_n for CEM and LAQGSM in the modified GEM2 (M. Baznat, K. Gudima, S. Mashnik, Proc. AccApp'03, LA-UR-03-3750; arXiv:nucl-th/0307014), we got:





This is the reason why we did not test until recently how MCNP6 calculates fission cross sections while using CEM and LAQGSM

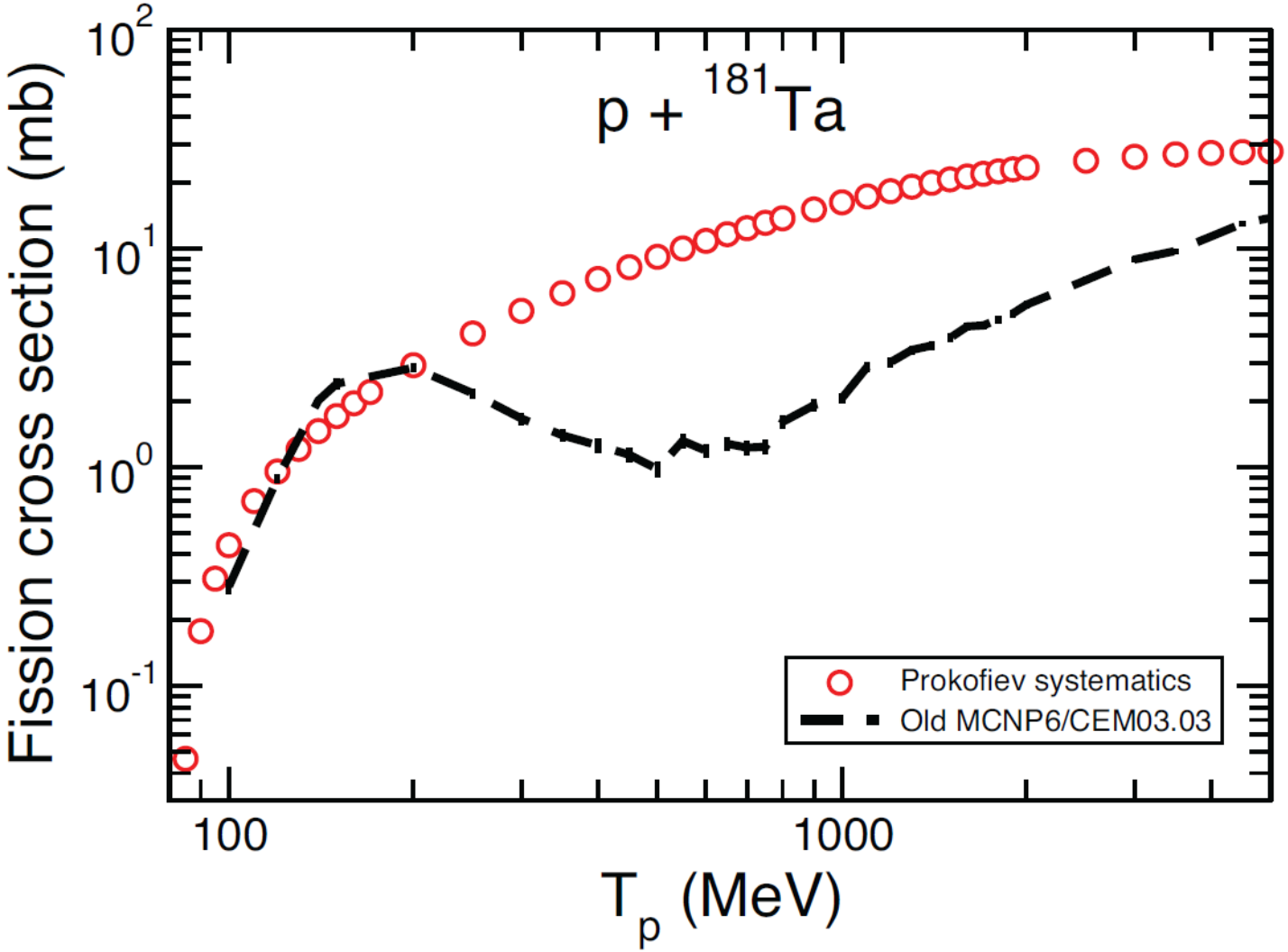


Figure 4: Comparison of Prokofiev systematics [25] of experimental (p,f) cross sections of ^{181}Ta nuclei (red circles) with our old MCNP6 calculations (black dashed lines) using the CEM03.03 event generator before we found and fixed the error (see text for details). CEM03.03 used as a stand alone code provides results which practically coincide with those by MCNP6.

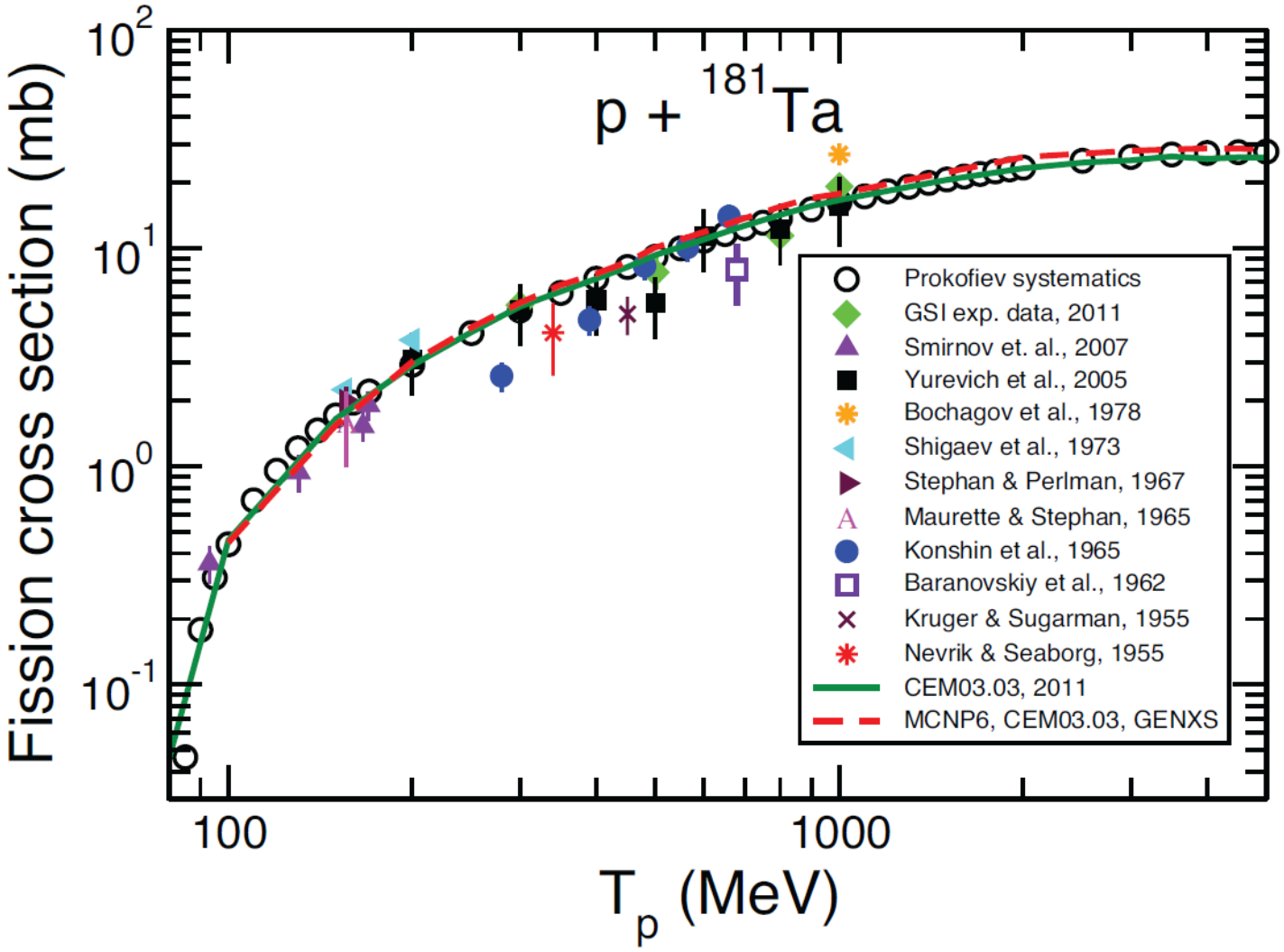


Figure 5: Prokofiev systematics [25] (open circles) and experimental proton-induced fission cross section of ^{181}Ta [33]–[43] (symbols) compared with corrected CEM03.03 results and with calculations by the updated MCNP6 using the CEM03.03 event generator (red dashed line), as indicated.

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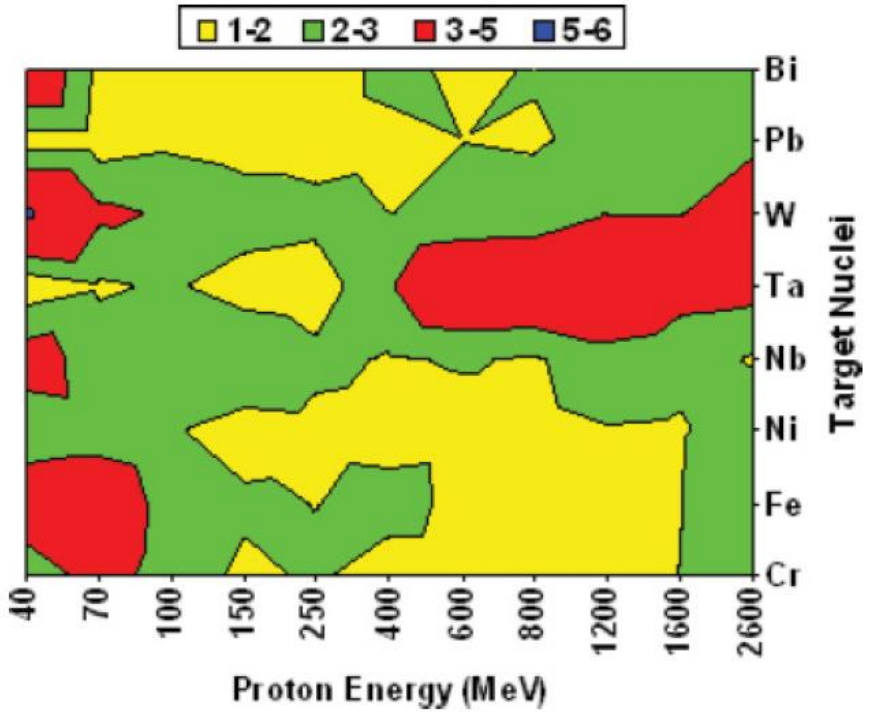
Verification of high-energy transport codes on the basis of activation data

Yu. E. Titarenko,[1] V. F. Batyaev,[1] M. A. Butko,[1] D. V. Dikarev,[1] S. N. Florya,[1] K. V. Pavlov,[1] A. Yu. Titarenko,[1] R. S. Tikhonov,[1] V. M. Zhivun,[1] A. V. Ignatyuk,[2] S. G. Mashnik,[3] A. Boudard,[4] S. Leray,[4] J.-C. David,[4] J. Cugnon,[5] D. Mancusi,[5] Y. Yariv,[6] H. Kumawat,[7] K. Nishihara,[8] N. Matsuda,[8] G. Mank,[9] and W. Gudowski[10]



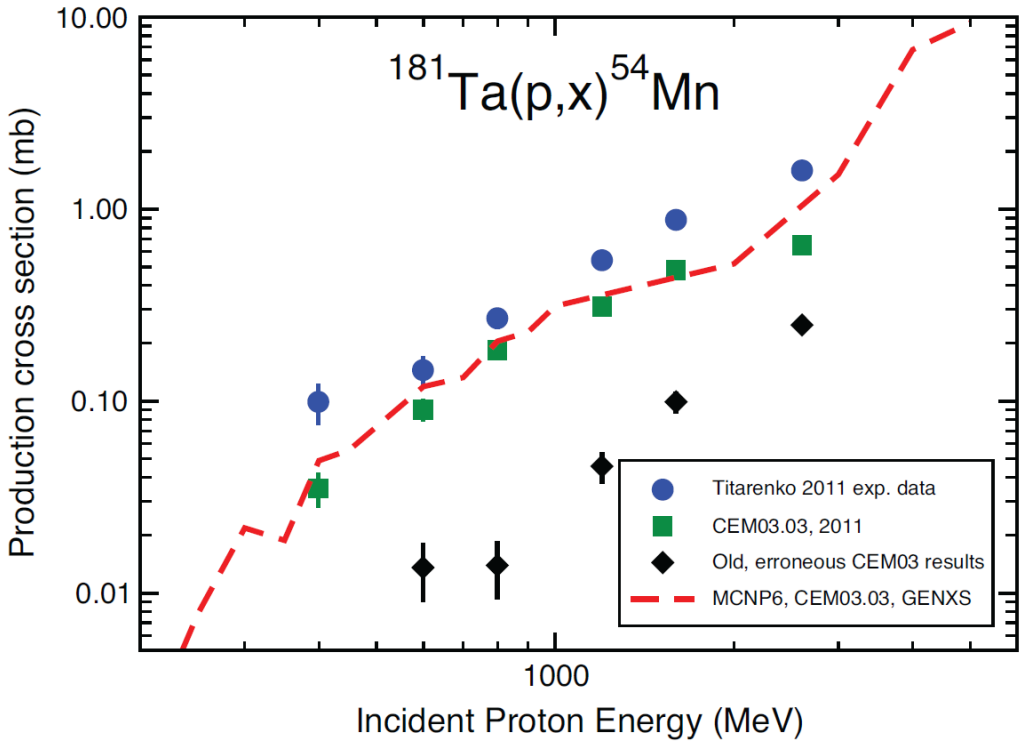
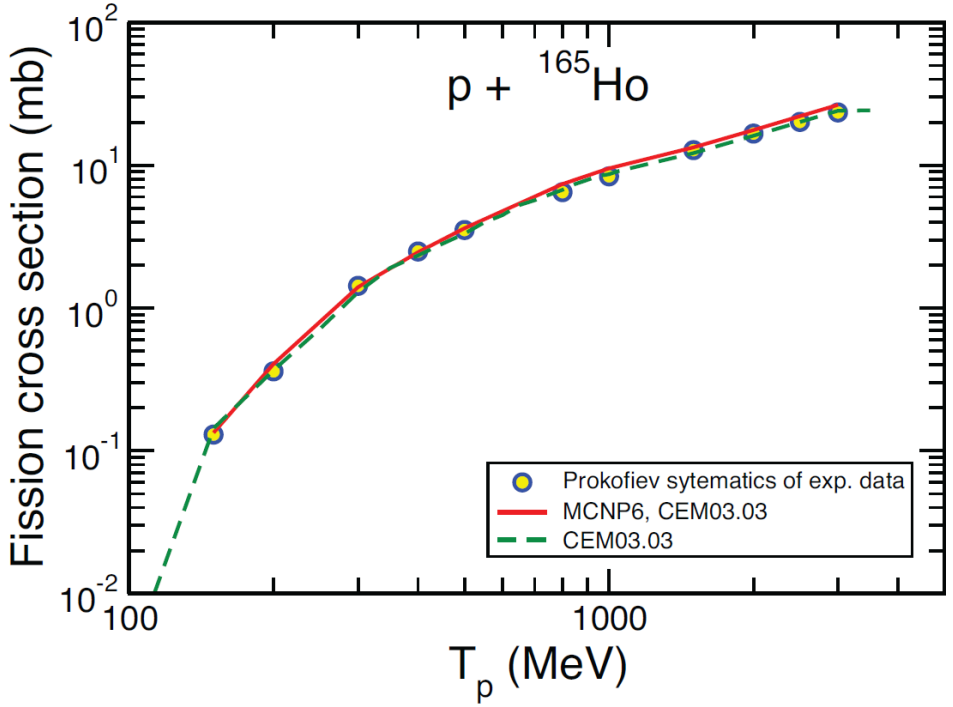
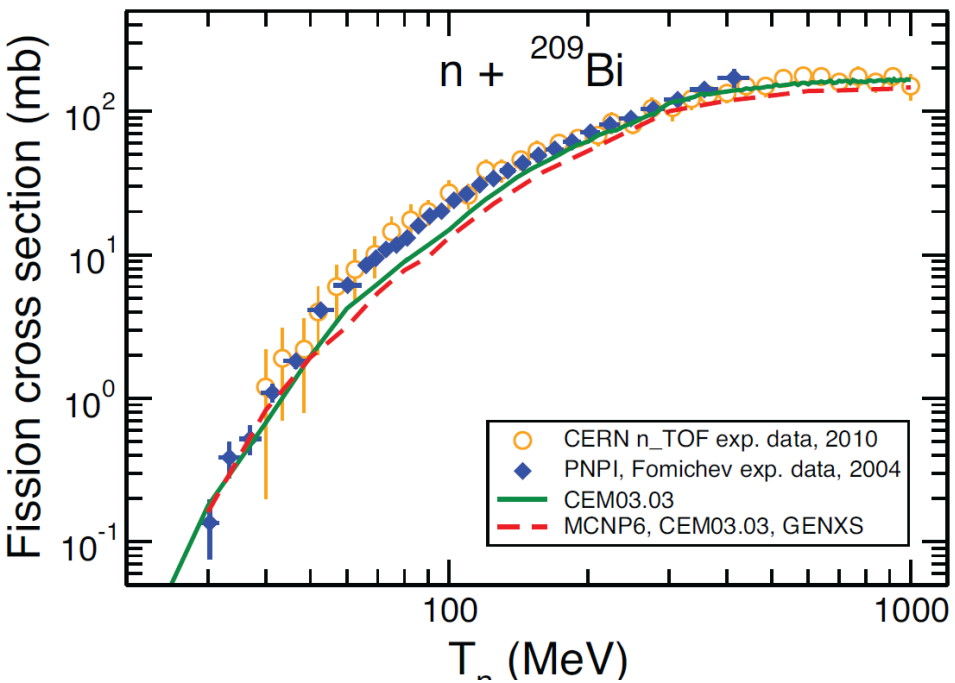
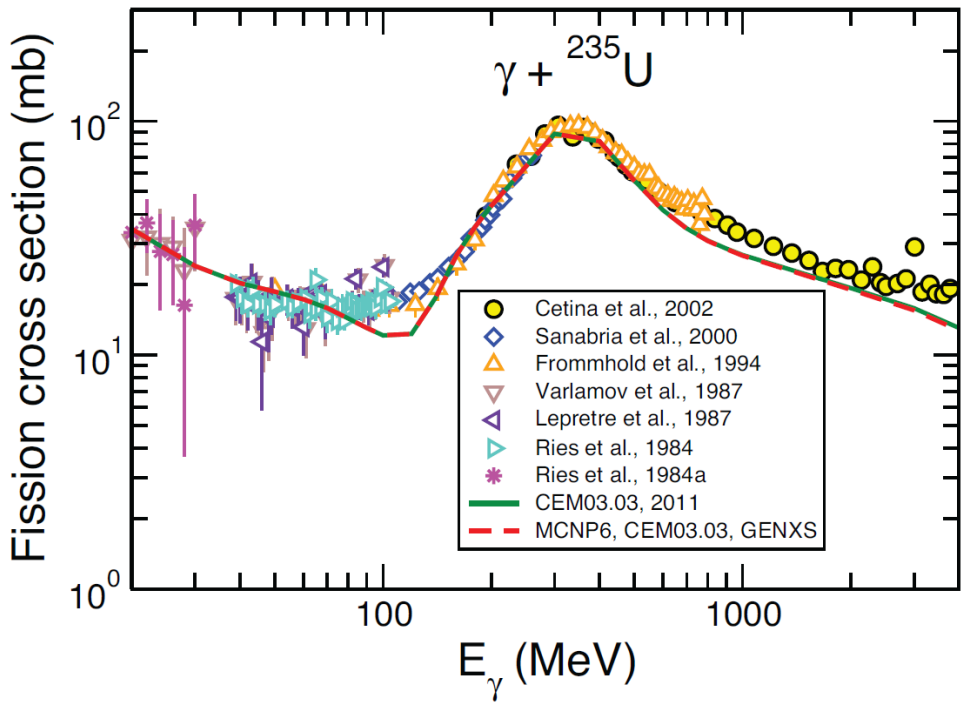
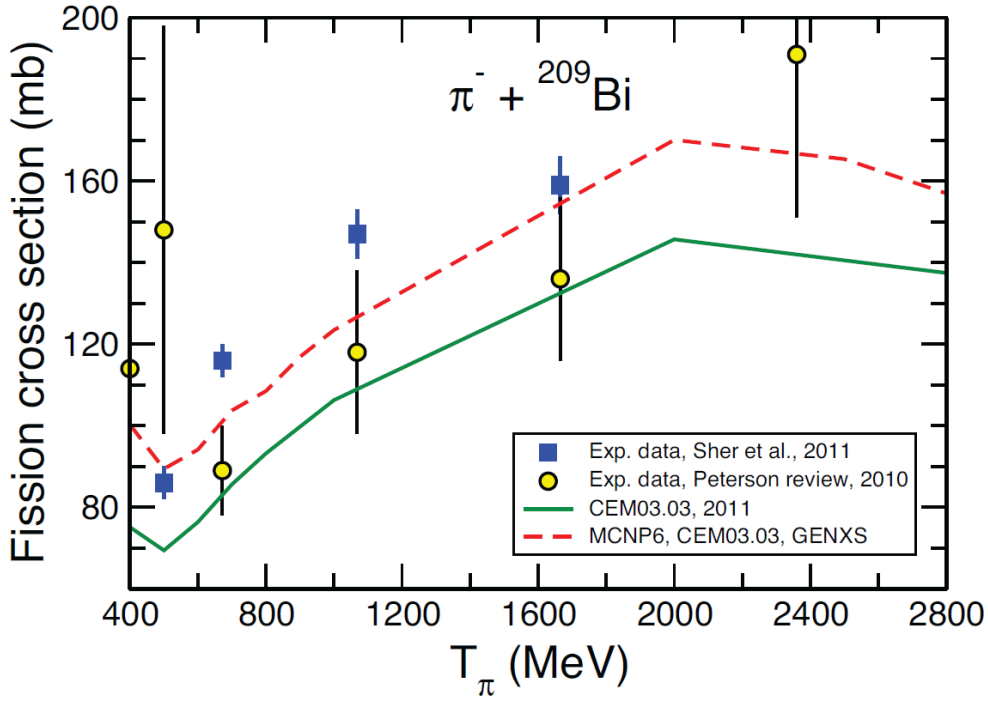


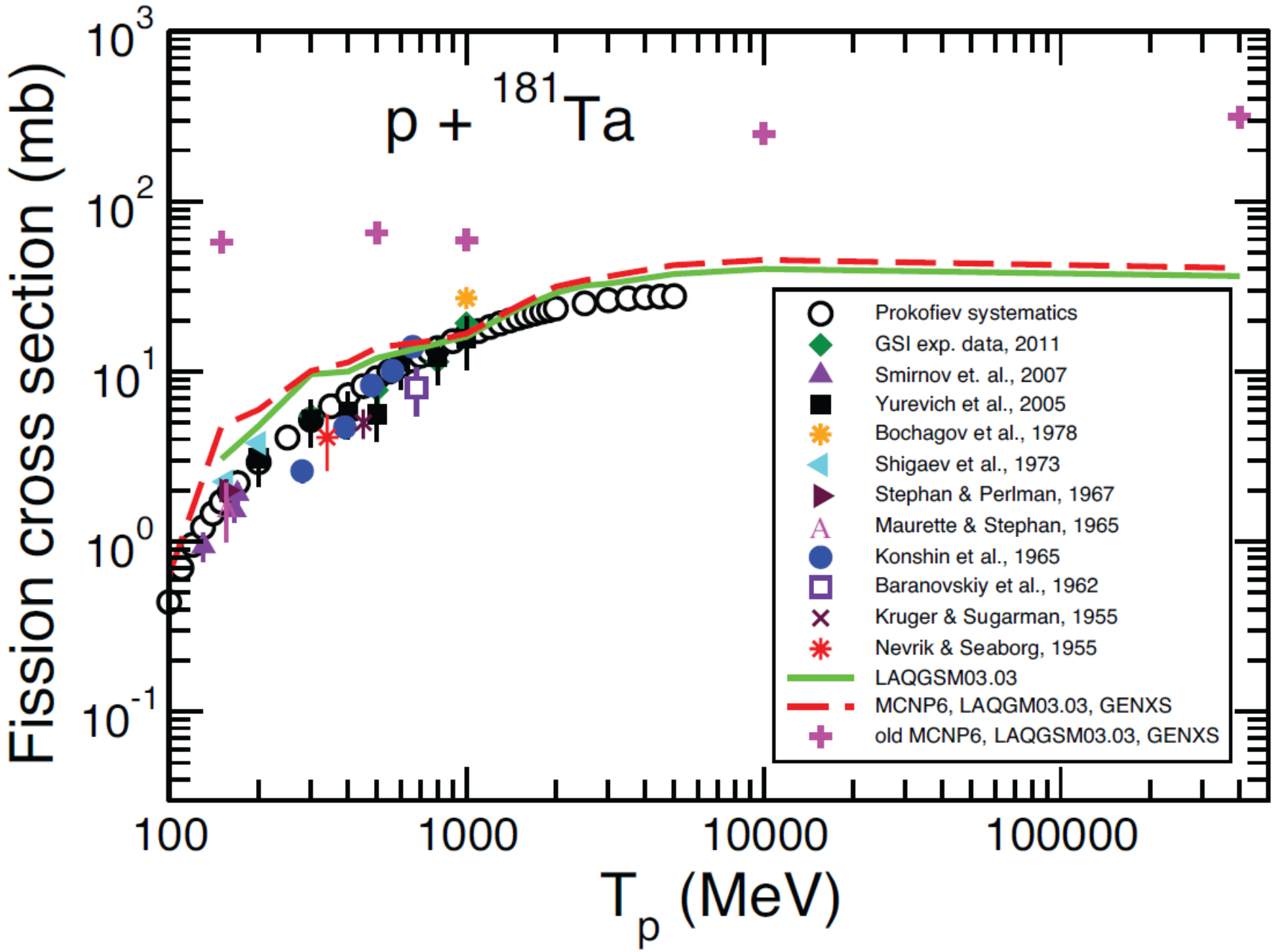
FIG. 14. (Color online) The same as in Fig. 12, but for the CEM03.02 code.


p + 165Ho
Fission cross section (mb)
Tp (MeV)
Prokofiev sytematics of exp. data
MCNP6, CEM03.03
CEM03.03


n + 209Bi
Fission cross section (mb)
CERN n_TOF exp. data, 2010
PNPI, Fomichev exp. data, 2004
CEM03.03
MCNP6, CEM03.03, GENXS


γ + 235U
Fission cross section (mb)
Eγ (MeV)
Cetina et al., 2002
Sanabria et al., 2000
Frommhold et al., 1994
Varlamov et al., 1987
Lepretre et al., 1987
Ries et al., 1984
Ries et al., 1984a
CEM03.03, 2011
MCNP6, CEM03.03, GENXS


π- + 209Bi
Fission cross section (mb)
Tπ (MeV)
Exp. data, Sher et al., 2011
Exp. data, Peterson review, 2010
CEM03.03, 2011
MCNP6, CEM03.03, GENXS


p + 181Ta
Fission cross section (mb)
10^3
10^2
10^1
10^0
10^{-1}
100
1000
10000
100000
T_p (MeV)
Prokofiev systematics
GSI exp. data, 2011
Smirnov et. al., 2007
Yurevich et al., 2005
Bochagov et al., 1978
Shigaev et al., 1973
Stephan & Perlman, 1967
Maurette & Stephan, 1965
Konshin et al., 1965
Baranovskiy et al., 1962
Kruger & Sugarman, 1955
Nevrik & Seaborg, 1955
LAQGSM03.03
MCNP6, LAQGM03.03, GENXS
old MCNP6, LAQGSM03.03, GENXS

Summary

- MCNP6 has been Validated and Verified (V&V) against intermediate- and high-energy fission-cross-section experimental data.
- A previously unobserved error in the calculation of fission cross sections of ^{181}Ta and other nearby target nuclei by the CEM03.03 event generator in MCNP6 and a technical "bug" in the calculation of fission cross sections with the GENXS option of MCNP6 while using the LAQGSM03.03 event generator were detected during our current V&V work.
- After fixing both these problems, we find that MCNP6 using the CEM03.03 and LAQGSM03.03 event generators calculates fission cross sections 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) at incident energies from several tens of MeV to about 1 TeV.