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at Intermediate and High Energies

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MCNP6 Fission Cross Section Calculations
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Abstract

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.

1. Introduction

Monte-Carlo transport codes like MCNP6 [1] and MCNPX [2] are used in various applications involving fission reactions at low, but also at intermediate and high energies. It is critical for many problems that transport codes describe such reactions as well as possible, therefore the codes are often validated and verified against available experimental data and calculations by other models (see, e.g., the recent work [3]–[5]). However, for nuclear reactions involving fission, generally the transport codes are only tested for how well they describe the fission-fragment yields, and the emission of particles from them (spectra and multiplicities, both "prompt" and "delayed"). Calculation of fission cross sections themselves by the transport codes is usually not tested, as it is assumed that data libraries used by the transport codes at energies below 150 MeV must provide reliable fission cross sections, as should the event generators used at higher energies, where/when data libraries are not available. This work shows that this assumption is too optimistic, as some event generators have problems describing well some fission cross sections. In such cases, all the characteristics of the corresponding fission reactions calculated by the transport codes, like the yields of fission fragments, spectra and multiplicities of neutrons and other particles, both "prompt" and "delayed" would also not be reliable. To assess this situation, we test how MCNP6 calculates fission cross sections using the Cascade-Exciton Model (CEM) and the Los Alamos version of the Quark-Gluon String Model (LAQGSM) as realized in the event generators CEM03.03 and LAQGSM03.03, respectively, for reactions induced by nucleons, pions, and photons at incident energies from several tens of MeV to about 1 TeV.

A comprehensive description of the CEM03.03 and LAQGSM03.03 event generators can be found in our recent Lecture [6] and references therein. Therefore, we present only a brief summary of how CEM03.03 and LAQGSM03.03 calculate fission cross sections, needed to better

understand our results presented later.

2. Calculation of fission cross sections with CEM03.03 and LAQGSM03.03

Initially, CEM [7], LAQGSM [8] and its precursor, the Quark-Gluon String Model (QGSM) [9], did not have a fission model. All of them use different modifications of the Weisskopf and Ewing statistical model [10] to calculate the fission cross section (see details, e.g., in [11]–[13]) needed to account for the competition between evaporation and fission in their Monte-Carlo simulations. So they did not describe production of fission fragments or of light fragments heavier than ^{4}He and their further de-excitation. To address this, we investigated several fission models that could be merged with CEM and LAQGSM (see details, e.g., in [14]). We chose the Generalized Evaporation Model as implemented in the code GEM2 by Furihata [15] as the best universal model available to us at that time, able to predict reasonably well fission fragments from arbitrary reactions, when merged with our CEM and LAQGSM codes [16, 17].

GEM2 is an extension by Furihata of the Dostrovsky et al. [18] evaporation model as implemented in LAHET [19] 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 [20] used in LAHET. It was found [14, 16] that if we were to merge GEM2 with the latest version of the CEM we had at that time, CEM2k [21], or with LAQGSM [8], without any modifications, the new code would not describe correctly the fission cross sections. This is because Atchison fitted the parameters of his fission model when it was coupled with the Bertini Intra-Nuclear Cascade (INC) [22] which differs from our INC, and did not model preequilibrium emission. Therefore, the distributions of fissioning nuclei in A, Z, and excitation energy E^* simulated by Atchison differ significantly of the distributions we get; as a consequence, all the fission characteristics are also different. Similarly, Furihata used GEM2 coupled either with the Bertini INC [22] or with the ISABEL [23] INC code, which also differs from our INC, and also did not include preequilibrium particle emission. Thus the parameters adjusted by Furihata to work the best with her INC will not work for ours. To get a good description of fission cross sections (and fission-fragment yields) we had to modify at least two parameters in GEM2 (see details in [14, 16]). This problem was solved both for CEM2k+GEM2 and LAQGSM+GEM2 in the work [17].

A comprehensive description of GEM2 was published by Furihata [15], some details may be found in our papers [14, 16], therefore we recall here only how fission cross sections are calculated by GEM2, to show how we modify them for ^{181}Ta and other nearby target nuclei. The fission model used in GEM2 is based on Atchison's model [20], often referred in the literature as the Rutherford Appleton Laboratory (RAL) model, which is where Atchison developed it. There are two choices of parameters for the fission model: one of them is the original parameter set by Atchison [20] as implemented in LAHET [19], and the other is a parameter set evaluated by Furihata [15], used here as a default of GEM2.

The Atchison fission model is designed to only describe fission of nuclei with $Z \geq 70$ (we extended it in our 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,

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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 $Z = 89$.

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

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

Atchison uses [20] the Weisskopf and Ewing statistical model [10] with an energy-independent pre-exponential factor for the level density and Dostrovsky's [18] inverse cross section for neutrons and estimates the neutron width Γ_n as

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

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

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

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

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

$$a_n = (A_i - 1)/8.$$

The fission width for nuclei with $Z_j \leq 88$ is calculated in the RAL model and in GEM2 as

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

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 as

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

and $\chi = Z^2/A$.

2) $Z_j \geq 89$. For heavy fissioning nuclei with $Z_j \geq 89$ GEM2 follows the RAL model and does not calculate at all the fission width Γ_f and does not use Eq. (1) to estimate the fission probability P_f. Instead, the following semi-empirical expression obtained by Atchison by approximating the experimental values of Γ_n/Γ_f published by Vandenbosch and Huizenga [24] is used to calculate the fission probability:

$$\log(\Gamma_n/\Gamma_f) = C(Z_i)(A_i - A_0(Z_i)), \tag{3}$$

where $C(Z)$ and $A_0(Z)$ are constants dependent on the nuclear charge Z only. The values of these constants are those used in the current version of LAHET [19] and are tabulated in Table 1 (note that some adjustments of these values have been done since Atchison's papers [20] were published).

Table 1. $C(Z)$ 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

When we modified the GEM2 parameters in Ref. [17] so that it describes well proton-induced fission cross sections in our CEM2k and LAQGSM codes, we chose not to use the experimental fission cross sections directly as they are published in the literature. For intermediate- and high-energy reactions, where our codes are intended to be used, the experimental data on proton-induced fission cross sections are sparse and not as precise as for low-energy reactions measured for reactor applications. As one can see from Fig. 1, fission cross sections measured at such energies in different experiments differ so significantly from each other that it is difficult to use such data in development and validation of models and codes, without a special analysis of all details of every measurement. Fortunately, this has been done by Prokofiev [25] so we use his results. Prokofiev spent many years compiling proton-induced measured fission cross sections and on analyzing the details of each experiment. He developed systematics for proton-induced fission cross sections for all preactinide and actinide nuclei for which he was able to find enough data [25, 26]. At our energies, we consider Prokofiev's systematics as the most reliable "experimental" fission cross sections and prefer to use them to develop and test our codes instead of using experimental values published in original publications by different authors.

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. (2)) for preactinides, and parameter $C(Z)$ in Eq. (3) for actinides. The sensitivity of results to these parameters is much higher than to fission barriers used in calculation or other parameters of the model.

In Ref. [17] we chose to adjust only these two parameters in our merged CEM2k+GEM2 and LAQGSM+GEM2 codes. We did not change the form of systematics (2) and (3) derived by Atchison. We only introduced additional coefficients both to a_f and $C(Z)$, replacing $a_f \to C_a \times a_f$ in Eq. (2) and $C(Z_i) \to C_c \times C(Z_i)$ in Eq. (3) and fitted C_a and C_c separately for the CEM2k+GEM2 and LAQGSM+GEM2 codes for all nuclei and incident proton energies
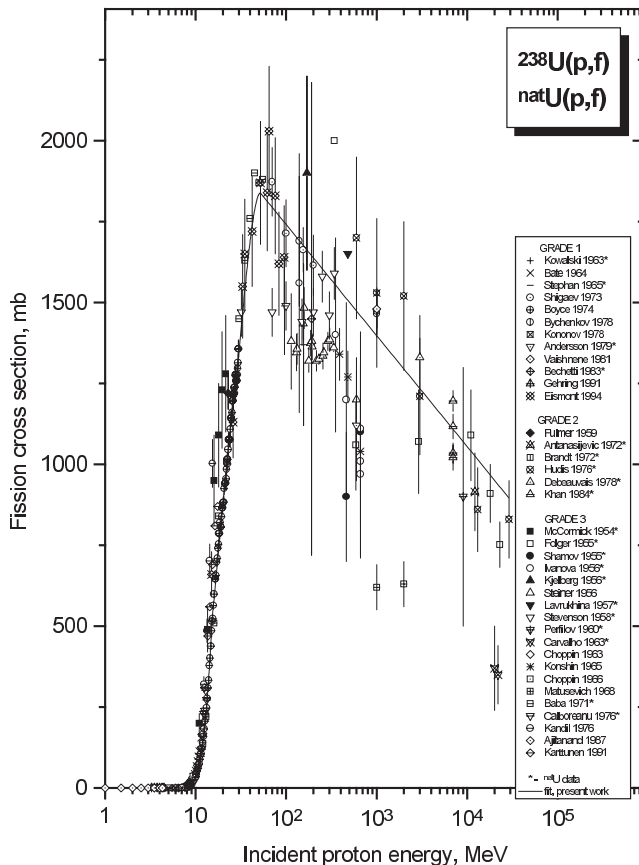
Figure 1: Experimental proton-induced fission cross sections of ^{238}U and ^{nat}U nuclei compiled by Prokofiev (symbols) compared with results of his systematics [25] for these cross sections (line). We thank Dr. Prokofiev for sending us this figure.

where Prokofiev's systematics apply. The other parameters in GEM2 were unchanged. For preactinides, we fit only C_a; these values are close to one and change smoothly with the proton energy and the charge or mass number of the target. This gives us confidence in our procedure, and allows us to interpolate or extrapolate the values of C_a for nearby nuclei and incident proton energies not covered by Prokofiev's systematics. For actinides, we fit both C_a and C_c. The values of C_a we found 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 and A of the target, again allowing us to interpolate and extrapolate them for nuclei and energies outside Prokofiev's systematics.

By fitting each of Prokofiev's systematics and employing interpolation routines, we found the results shown in Figs. 2 and 3 for CEM2k+GEM2 [17] and very similar results for LAQGSM+GEM2.

To see how this approach works for reactions induced by other projectiles, in Ref. [17] we tested our codes on several reactions induced by neutrons, pions, and photons, without any more changes or fitting. We found that our codes describe them from quite well to very well (see [17]), although experimental data on pion-induced fission cross sections are not so rich and precise, and it is difficult to draw unambiguous conclusions from a comparison to such data.

This fitting of C_a and C_c in GEM2 was done in 2003 [17]. In developing the 03.01 versions of CEM and LAQGSM in the period 2003–2005, we modified the INC and preequilibrium stages of our codes based on a careful comparison to types of data sensitive these portions of the reactions. These changes lead to changes of the distributions of Z, A, and E* at the beginning

of the equilibrium decay phase, and thus mandated a refitting of the C_a and C_c parameters. This process took place in late 2004 though early 2005. Unfortunately, the new parameters were not checked as carefully at that time as the earlier set had been. An error was committed during the refitting of C_a in CEM03.01 for ^{181}Ta.
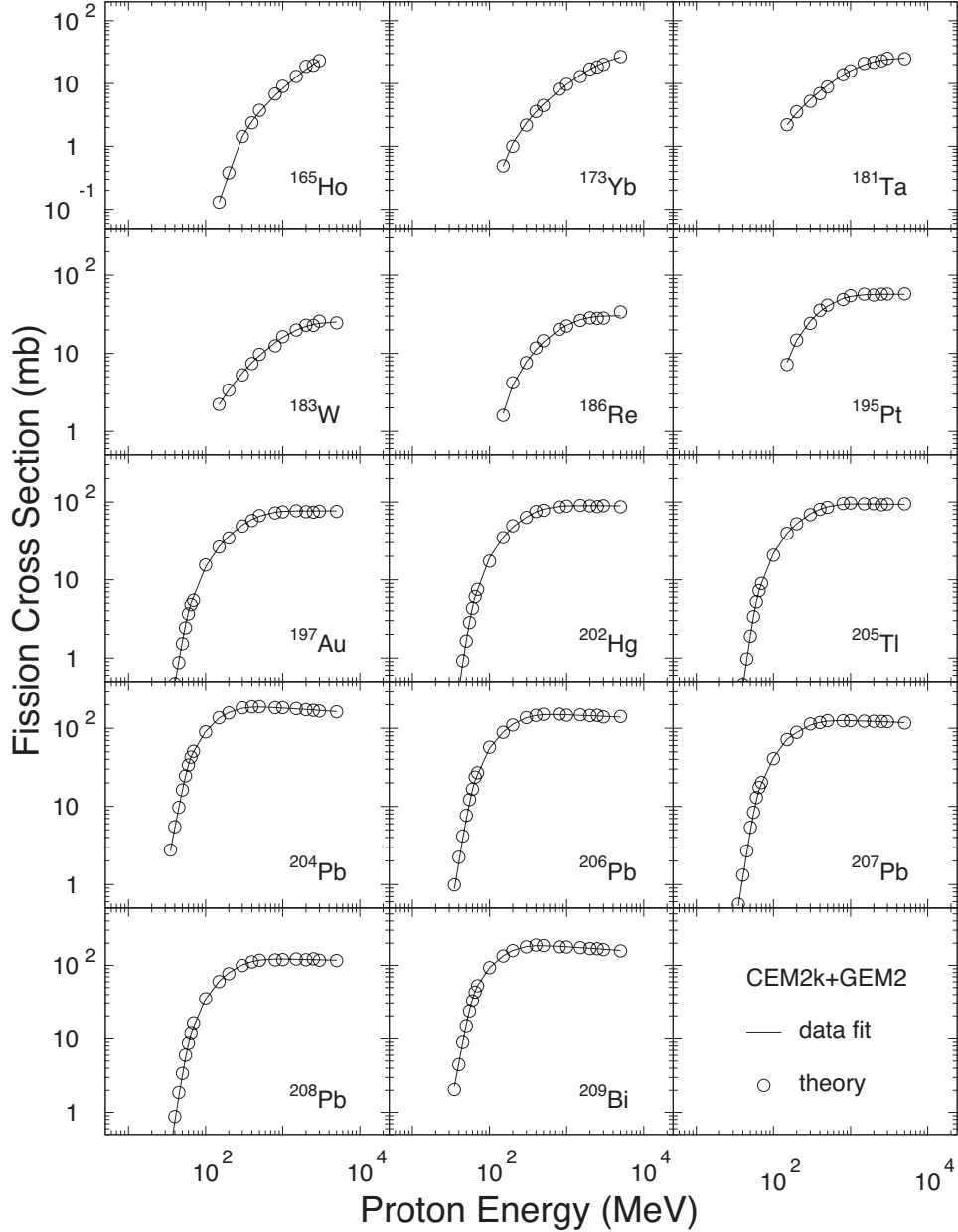

Figure 2: Comparison of Prokofiev's [25, 26] systematics of experimental (p,f) cross sections of ^{165}Ho, ^{173}Yb, ^{181}Ta, ^{183}W, ^{186}Re, ^{195}Pt, ^{197}Au, ^{202}Hg, ^{205}Tl, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, and ^{209}Bi nuclei (lines) with our CEM2k+GEM2 calculations (circles) from Ref. [17].
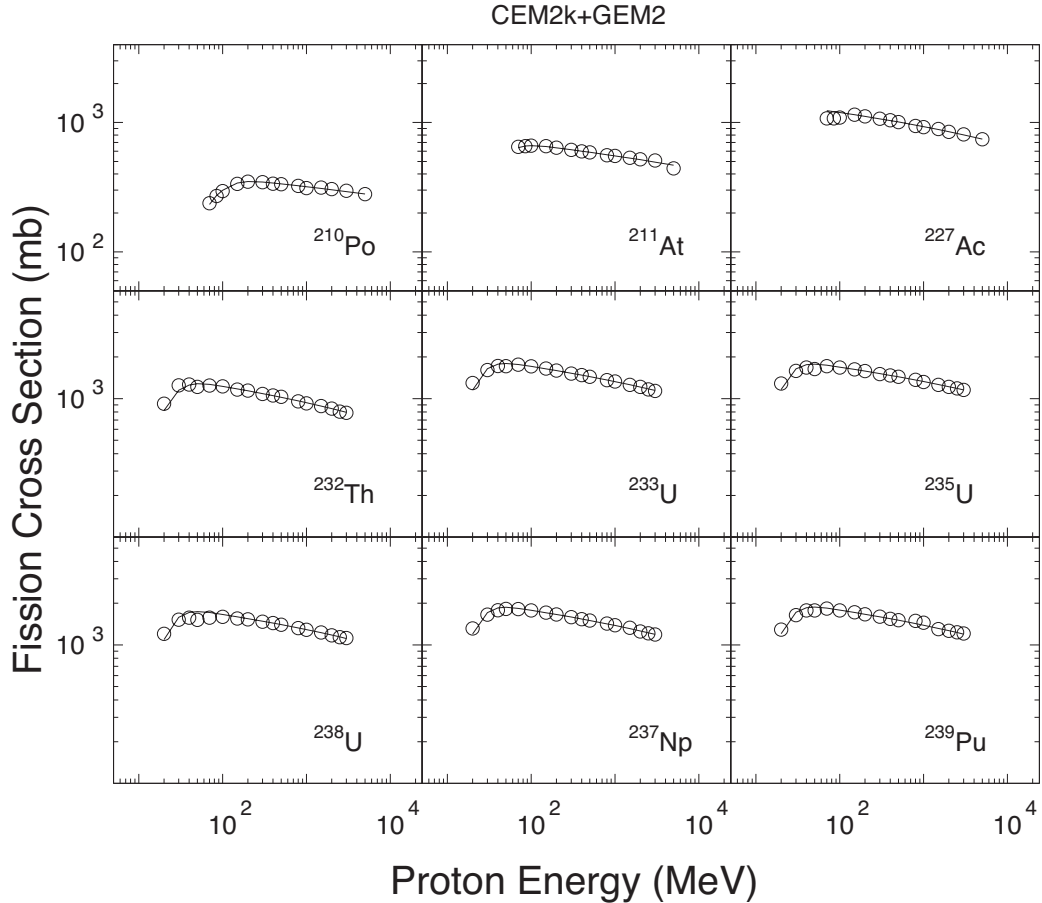
Figure 3: Comparison of Prokofiev's [25] systematics of experimental (p,f) cross sections of ^{232}Th, ^{233}U, ^{235}U ^{238}U, ^{237}Np, and ^{239}Np nuclei and of predicted [26] (p,f) cross sections for ^{210}Po, ^{211}At, and ^{227}Ac targets (lines) with our CEM2k+GEM2 calculations (circles) from Ref. [17].

This error was not detected until we undertook various V&V efforts by comparing MCNP6 calculated results to recent experimental measurements.

3. Results

Before presenting our current results, let us mention that the easiest way to calculate fission cross sections with MCNP6 (and many other characteristics of products) from a thin target is to use the special **GENXS** option of MCNP6. It was developed by one of us especially for MCNP6 and is described in detail in Ref. [28]. We use the GENXS option to calculate all the MCNP6 fission cross sections presented in this work. All the MCNP6 calculations are performed with MPI using 4 nodes (64 processors) at the Turing machine at LANL. We checked on several reactions studied here and confirmed that our MCNP6 results obtained while running the code in parallel (MPI) are practically the same as results from sequential running of MCNP6 on a single processor.

The initial MCNP6 results obtained with the CEM03.03 event generator for the proton-induced fission cross section of ^{181}Ta, shown here in Fig. 4, were shocking; we see that at proton energies above ~ 300 MeV, the fission cross section calculated by MCNP6 was almost one order of magnitude below the experimental values as predicted by the Prokofiev systematics.

This contradicts the results shown above in Fig. 2 and our expectation. We quickly verified that these MCNP6 results for this reaction, are duplicated by use of a stand-alone version of CEM03.03, demonstrating that unlike some previous discrepancies, this was not a problem of the incorporation of CEM03.03 in MCNP6, but was a serious problem of the CEM03.03 event generator itself.
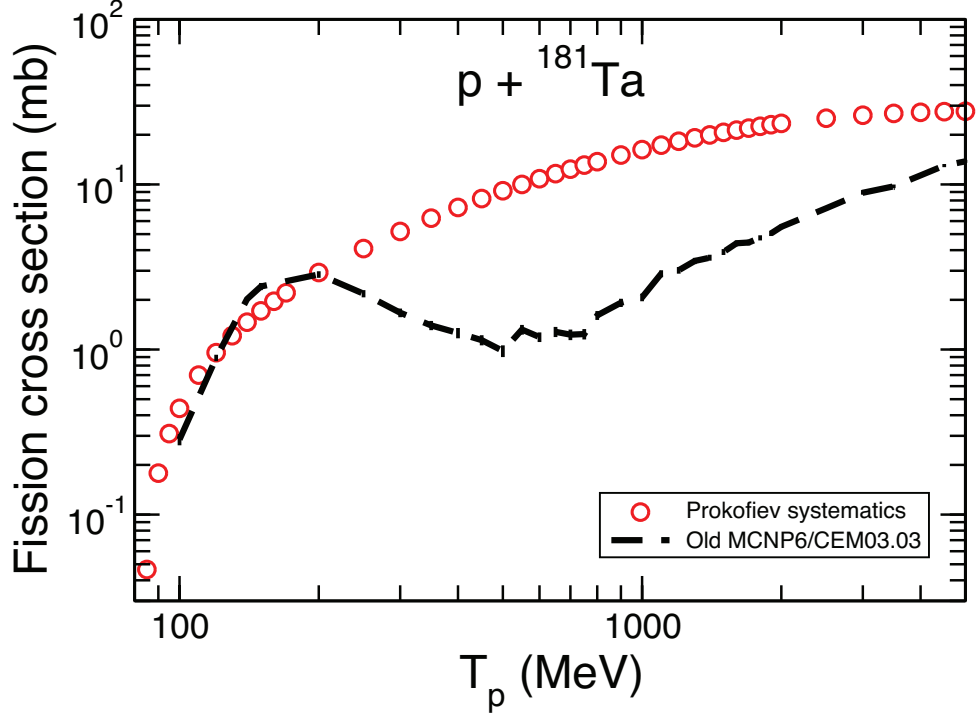

Figure 4: Comparison of Prokofiev systematics [25] of experimental (p,f) cross sections of ^{181}Ta nuclei (red circles) with our old MCNP6 calculations (black dashed lines) using the CEM03.03 event generator before we found and fixed the error (see text for details). CEM03.03 used as a stand alone code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

Unfortunately, all the calculations involving ^{181}Ta and a small number of nearby target nuclei performed from the middle of 2005 until recently (2011) with all the CEM03.xx modifications, used as either as stand-alone codes, or in MCNPX, MARS15, and the initial ("Beta 1") version of MCNP6 were affected by that error.

To fix this problem, we have refitted the values of C_a in GEM2 for ^{181}Ta. Our new CEM03.03 results for ^{181}Ta are shown in Fig. 5 with a green line together with the Prokofiev systematics [25] (open circles) as well as with the experimental data [33]-[43]. We have replaced in MCNP6 the initial defective CEM03.03 module with the corrected version with the correct values of C_a in GEM2. Results from the updated MCNP6 are also shown in Fig. 5 by a red dashed line.

The results of the modified CEM03.03 used as a stand alone code agree very well with the Prokofiev systematics and with available experimental data [33]–[43] and almost coincide with calculations by the updated here MCNP6.

Having discovered this 2005 error and knowing how it affects the CEM results, we can understand why in the recent works by Titarenko et al. [44, 45] it was found that CEM03.02 (which has practically the same physics as the version CEM03.03 used here) provided such a
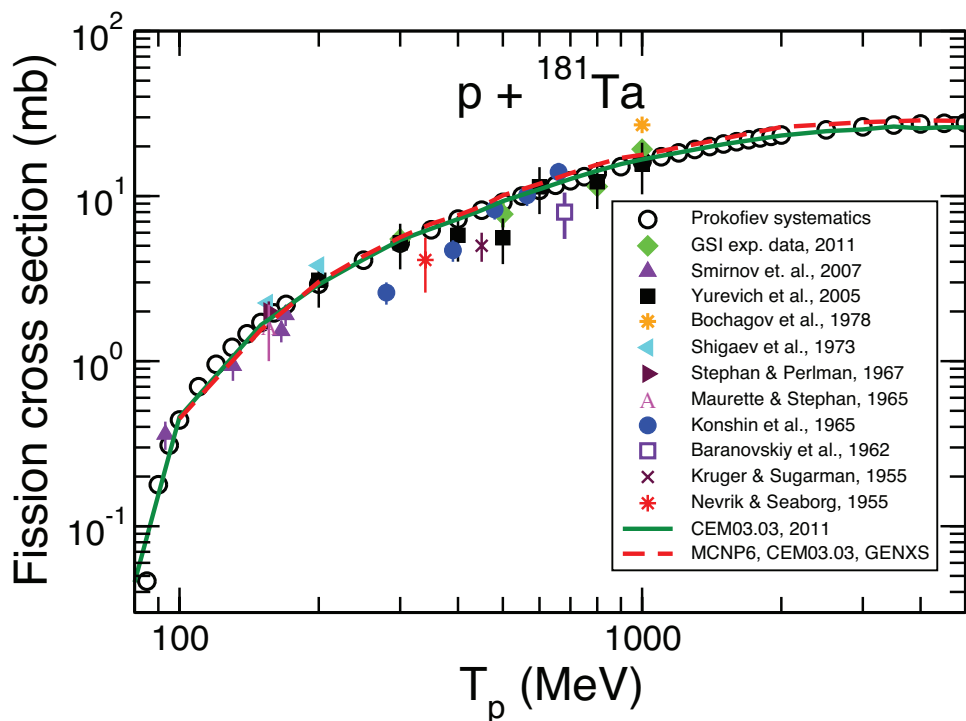
Figure 5: Prokofiev systematics [25] (open circles) and experimental proton-induced fission cross section of ^{181}Ta [33]–[43] (symbols) compared with corrected CEM03.03 results and with calculations by the updated MCNP6 using the CEM03.03 event generator (red dashed line), as indicated.

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.

We have collaborated with the ITEP Group of Prof. Titarenko for more than a decade and have analyzed with different versions of the CEM and LAQGSM codes practically all 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 [45] and, especially, Fig. 9 in Ref. [46]). However, this was only "usually," because in the case of ^{181}Ta, this factor $< F >$ between the measured products and results by CEM03.02 presented in Tab. 4 of Ref. [44] 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 at proton energies above 250 MeV, are significantly higher than two, and CEM03.02 does not provide for these cases the best agreement with the data in comparison with the other models tested in Ref. [44], an unexpected and not understood result when this paper was published. Similar, from Fig. 14 of Ref. [45], 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 is due to the 2005 error in the values of C_a in the GEM2 portion of CEM; as we see from Fig. 4, all nuclides arising from fission reactions will suffer from an under-prediction of the same order as the fission cross section.

As an indication of the improvement made, we show in Fig. 6 the excitation function ^{181}Ta(p,x)^{54}Mn calculated with the corrected CEM03.03 compared with the old results from CEM03.02 published in Refs. [44, 45] and with the experimental data from Tab. 3 of Ref. [44]. The corrected CEM03.03 provides a much better agreement with the measured data than the old version. Even now, the agreement is far from ideal; there is room for further improvement of these event generators, were resources available to develop a better evaporation/fission model for our CEM and LAQGSM models with more physics and less systematics than is employed in GEM2 [15]. We understand these limitations of GEM2 and have published this observation many years ago [47].
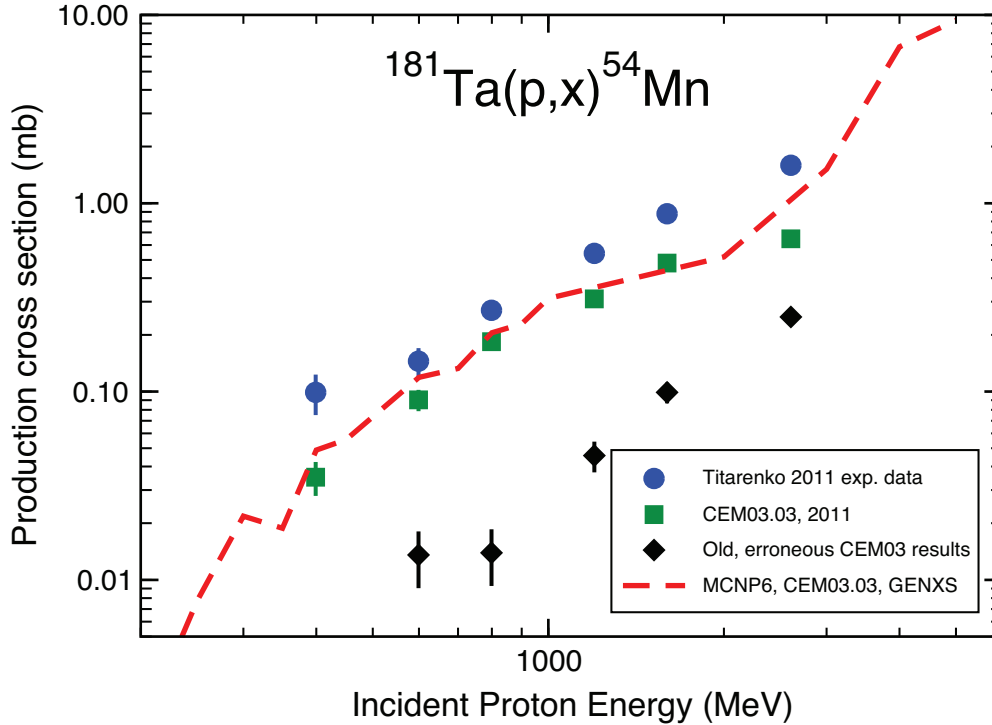

Figure 6: Experimental excitation function for the production of ^{54}Mn from p+^{181}Ta [44] (filled blue circles) compared with our present CEM03.03 results with refitted C_a for ^{181}Ta (filled green squares) and with calculations by the updated MCNP6 using the corrected CEM03.03 event generator (red dashed line), as well as with the incorrect CEM03.02 results (filled black diamonds) as published in Refs. [44, 45], as indicated.

After fixing C_a for ^{181}Ta in the GEM2 portion of CEM03.03, we checked how the current versions of CEM and LAQGSM describe fission cross sections for all other proton-induced reactions covered by the Prokofiev systematics [25, 26] and how MCNP6 using these event generators calculates such cross sections. Fig. 7 shows an example of such results, only for

^{165}Ho and ^{173}Yb target nuclei calculated with CEM03.03. We see that CEM03.03 used as a stand alone code describe these fission cross sections very well, in a perfect agreement with the predictions by the Prokofiev systematics [25]. The corresponding results obtained with MCNP6 using CEM03.03 practically coincide with the calculations by CEM03.03 used as a stand alone code, just as expected. Results for proton-induced fission cross sections on other target nuclei covered by the Prokofiev systematics [25, 26] calculated by CEM03.03 used as a stand alone code and by MCNP6 with the CEM03.03 event generator also agree very well with the Prokofiev systematics and practically coincide with our 2003 results shown in Figs. 2 and 3.

After we tested the updated MCNP6 with the refitted CEM03.03 event generator and also the stand-alone CEM03.03 on all proton-induced fission cross sections covered by the Prokofiev systematics, to see how this approach works for reactions induced by other projectiles, we tested our codes on several reactions induced by neutrons, photons, and pions, without any more changes or fitting. Figs. 8 to 10 show several examples of such results. We see that both codes describe them from quite well to very well, although experimental data on pion-induced fission cross sections are not so rich and precise, and it is difficult to draw conclusions from a comparison to this data. Let us note here that the difference in the absolute values of the pion-induced fission cross sections calculated with MCNP6 and CEM03.03 used as a stand alone code seen in Fig. 10 is related to the different normalization of the total reaction cross sections by the two codes: CEM03.03 calculates the total pion-induced reaction cross section itself, using the Monte Carlo method (see [30] for details), while MCNP6 uses a systematics by Barashenkov and Polanski [69] to normalize such cross sections.

We recommend using the CEM03.03 event generator in MCNP6 to describe nucleon-, pion-, and photon-induced reactions at energies below several GeV. At higher energies and for projectiles not covered by CEM03.03, the MCNP6 users must use LAQGSM03.03 as a proper event generator. LAQGSM03.03 used as a stand-alone code describes well all the fission cross sections tested above with CEM03.03: C_a and C_c parameters in the GEM2 portion of LAQGSM03.03 were fitted so that the fission cross sections calculated with LAQGSM practically coincide with the ones calculated by CEM, as shown in Figs. 2 and 3. Therefore, we do not present here figures similar to Figs. 2 and 3 with results by LAQGSM (such figures are presented, e.g., in Ref. [17]). However, we have tested here how MCNP6 using LAQGSM03.03 calculates fission cross sections for various reactions, to make sure that it does not have its own problems and that LAQGSM was implemented correctly in MCNP6.

As we mentioned previously, the easiest way to calculate fission cross sections with MCNP6 (and other characteristics of products) from a thin target is to use the special **GENXS** option [28] of MCNP6. This is true for all event generators incorporated in MCNP6, including LAQGSM03.03. We have tested previously MCNP6 using LAQGSM03.03 on many nuclear reactions on thin and thick targets of heavy nuclei and on several reactions induced by heavy ions that could fission (see Refs. [3, 5]), and found that MCNP6 describe correctly the yield of fission fragments and spectra of secondary particles from such reactions. This proves that LAQGSM03.03 was implemented correctly in MCNP6 and that it transports without problems through the matter of the target both particles and fragments produced in nuclear reactions. However, unfortunately, we have discovered that the fission cross sections printed in the output files of MCNP6 while using the GENXS option with LAQGSM are not correct; we present several examples of such erroneous results in Fig. 11, shown with in the plots with magenta crosses. Unfortunately, such erroneous fission cross sections were presented also in the Tem-
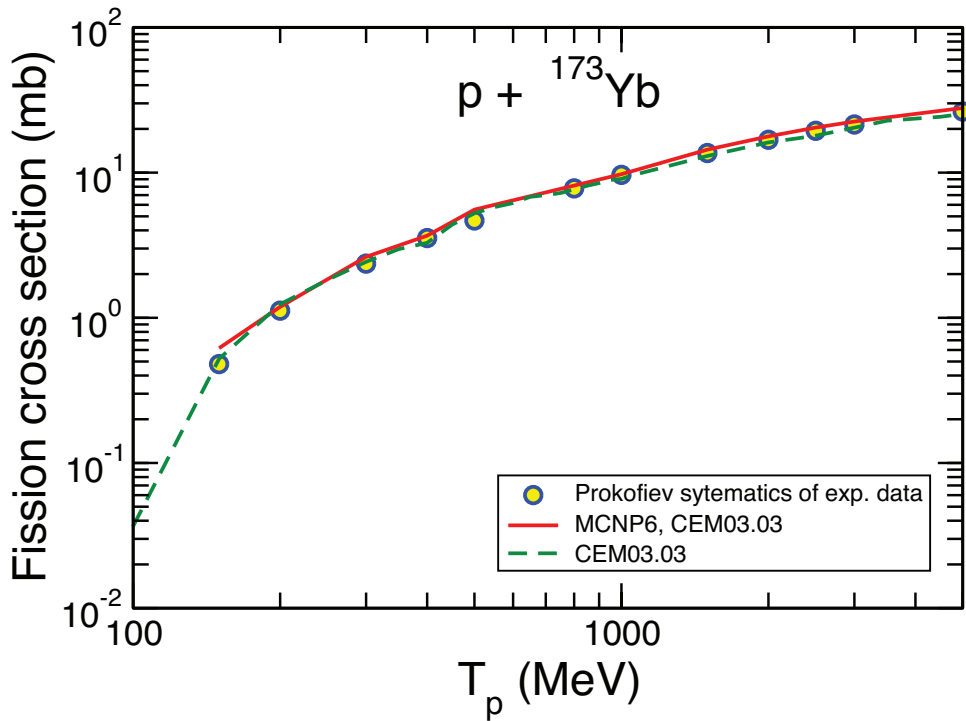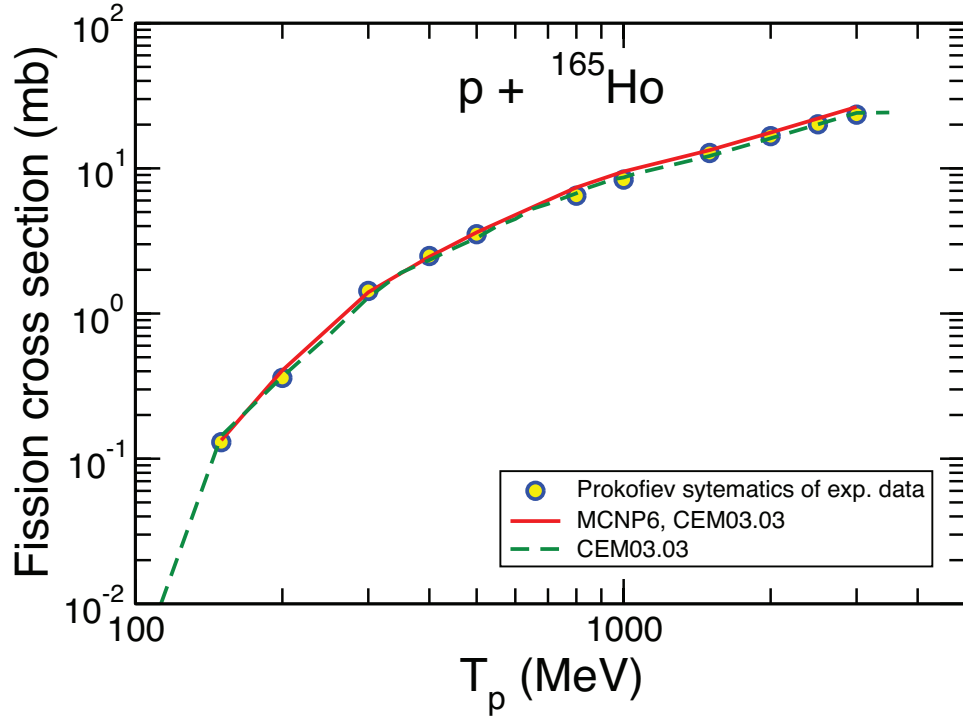
Figure 7: Prokofiev systematics [25] (open circles) for proton-induced fission cross sections of ^{165}Ho and ^{173}Yb compared with our present results by MCNP6 using the CEM03.03 event generator (red lines) and with calculations by CEM03.03 used as a stand alone code (green dashed lines), as indicated.
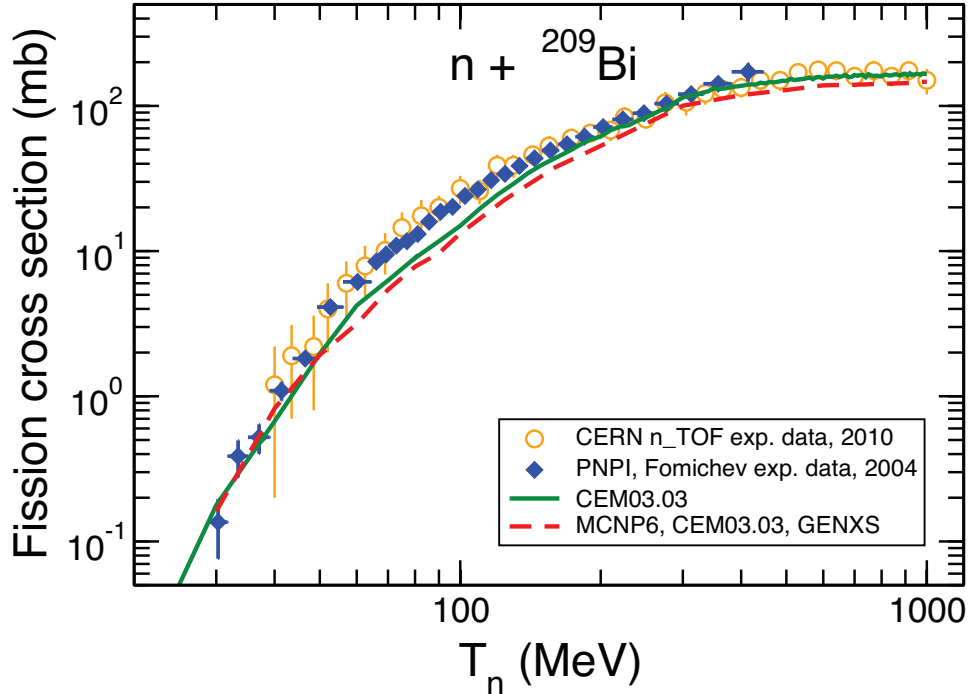
Figure 8: Experimental neutron-induced fission cross section of ^{209}Bi [48, 49] (symbols) compared with our present results by MCNP6 using the CEM03.03 event generator (red dashed line) and with calculations by CEM03.03 used as a stand alone code (green line), as indicated.

plates with MCNP6 output files calculated with the GENXS option using LAQGSM03.03 [5] (though the fission fragment yields and secondary particle spectra were correct): We performed those calculations with the Beta 1 version of MCNP6 [1] and simply did not check the values of fission cross sections in the MCNP6 output files.

The point is that LAQGSM03.03 as implemented in MCNP6 calculates correctly fission reactions and MCNP6 provides correct results for fission-fragment yields and for particle spectra in its output file. However, an unobserved error in counting the number of fissioning nuclei in the GENXS portion of MCNP6 when using the LAQGSM03.03 event generator was present in the initial, Beta 1, version of MCNP6 [1]. We have found and fixed that error. The current, Beta 2, version of MCNP6 [70] is free of that old error and provides in its output files correct values of fission cross sections, as can be seen from the results shown with red dashed lines in Fig. 11. Similar results were obtained for other reactions calculated with MCNP6 using LAQGSM03.03.

4. Conclusion

MCNP6, the latest and most advanced LANL Monte-Carlo transport code represents a recent merger of MCNP5 and MCNPX and has been Validated and Verified (V&V) against intermediate- and high-energy fission-cross-section experimental data. An error in the calculation of fission cross sections of ^{181}Ta and other nearby target nuclei by the CEM03.03 event generator of 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
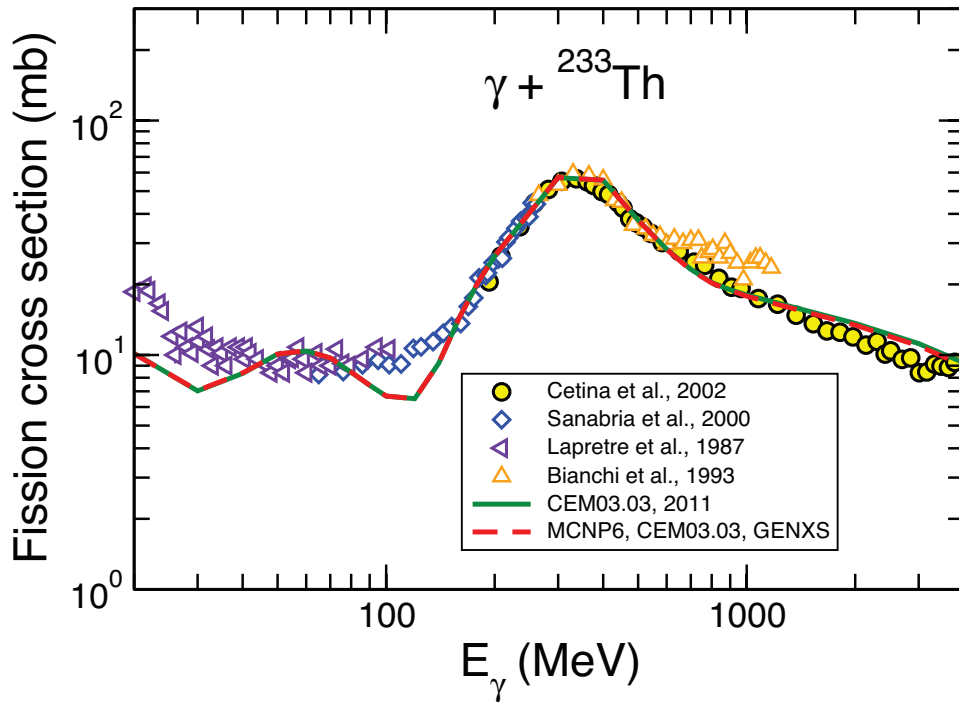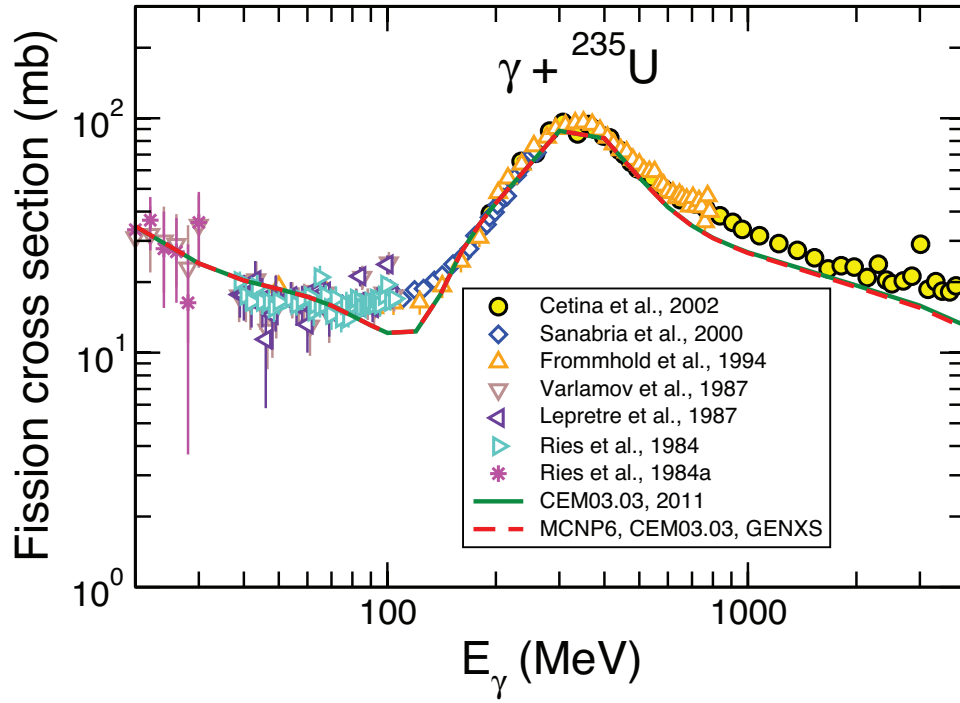
Figure 9: Experimental photonuclear fission cross sections of ^{235}U and ^{233}Th [50]–[57] (symbols) compared with present results by MCNP6 using the CEM03.03 event generator (red dashed lines) and with calculations by CEM03.03 used as a stand alone code (green lines), as indicated.

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Figure 10: Experimental π^--induced fission cross section of ^{209}Bi [58, 59] (symbols) compared with our present results by MCNP6 using the CEM03.03 event generator (red dashed line) and with calculations by CEM03.03 used as a stand alone code (green line), as indicated.
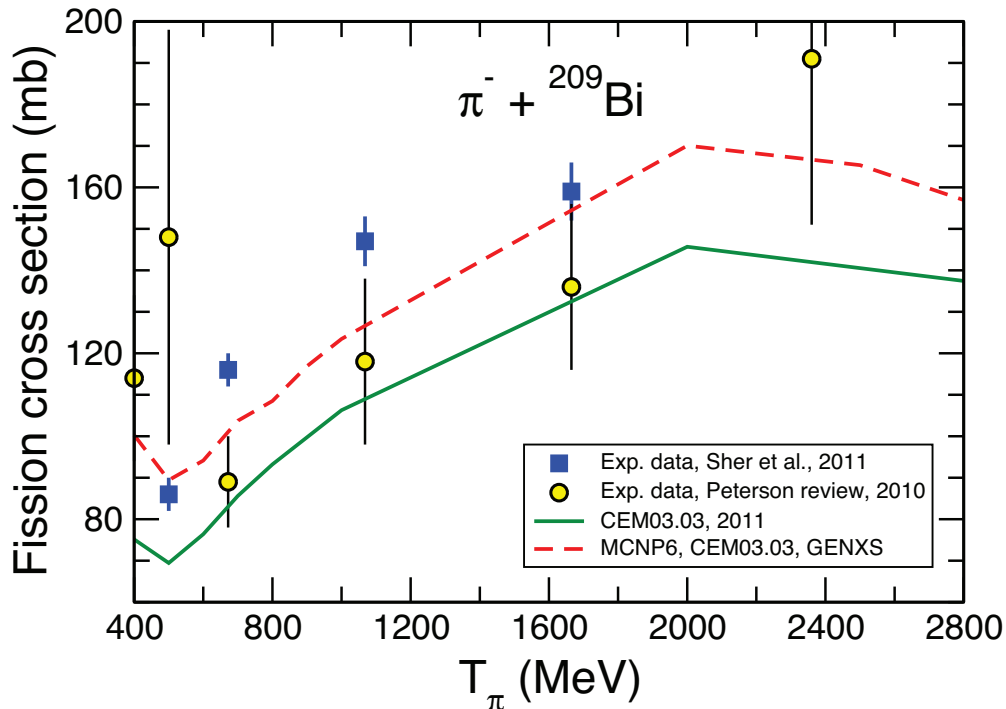
during our current V&V work. After fixing both these problems, we checked and found that MCNP6 using CEM03.03 and LAQGSM03.03 event generators calculates fission cross sections in a good agreement with available experimental data for reactions induced by nucleons, pions, and photons on both subactinide and actinide nuclei (from ^{165}Ho to ^{239}Pu) at incident energies from several tens of MeV to about 1 TeV.

Acknowledgments

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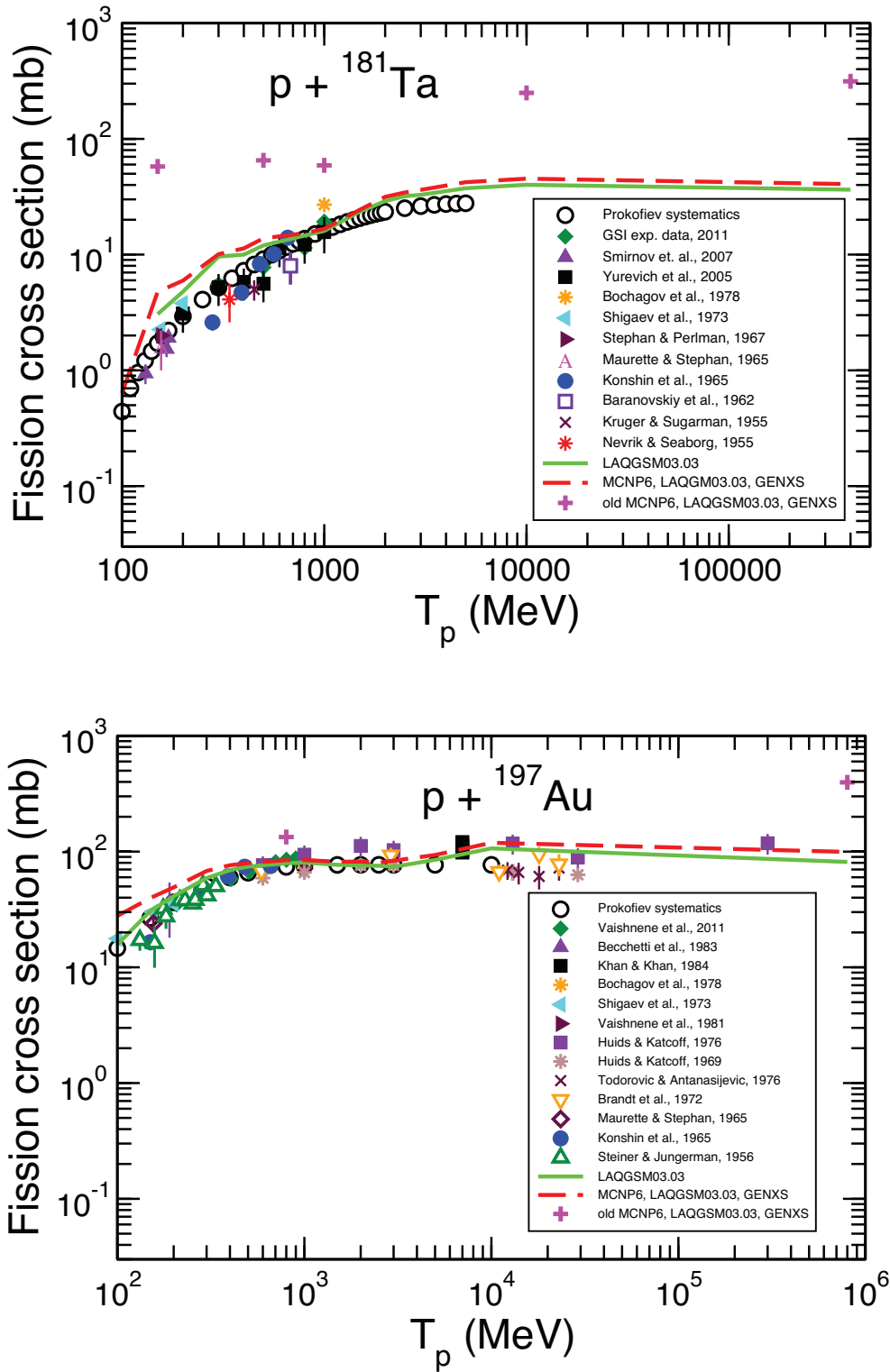
Figure 11: Prokofiev systematics [25] (open circles) and experimental proton-induced fission cross section of ^{197}Au and ^{181}Ta [33]–[43] and [60]–[68] (symbols) compared with our present results by the updated MCNP6 using the LAQGSM03.03 event generator with the GENXS option [28] (red dashed lines) and with calculations by LAQGSM03.03 used as a stand alone code (green lines), as indicated. For comparison, wrong initial results by an older version of MCNP6 (called "Beta 1"), before the "bug" in the calculation of the fission cross section with the GENXS option while using LAQGSM03.03 was fixed are shown as well with several magenta crosses.

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