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MCNP6 Simulation of Reactions of Interest to FRIB, Medical, and Space Applications

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The latest, production, version of the Los Alamos Monte Carlo N-Particle transport code MCNP6 has been used to simulate a variety of particle-nucleus and nucleus-nucleus reactions of academic and applied interest to the Facility for Rare Isotope Beams (FRIB), medical isotope production, space-radiation shielding, cosmic-ray propagation, and accelerator applications, including several reactions induced by radioactive isotopes, analyzing production of both stable and radioactive residual nuclei. Here, we discuss examples of validation and verification of MCNP6 compared to recent neutron spectra measured at the Heavy Ion Medical Accelerator in Chiba, Japan; to spectra of light fragments from several reactions measured recently at GANIL, France; INFN Laboratori Nazionali del Sud, Catania, Italy; COSY of the Jülich Research Center, Germany; and to cross sections of products from several reactions measured lately at GSI, Darmstadt, Germany; ITEP, Moscow, Russia; and, at LANSCE, LANL, Los Alamos, USA. As a rule, MCNP6 provides quite good predictions for most of the reactions we analyzed so far, allowing us to conclude that it can be used as a reliable and useful simulation tool for FRIB, medical, and space applications involving stable and radioactive isotopes.

KEYWORDS: MCNP6, cascade-exciton model (CEM), Los Alamos version of the quark-gluon string model (LAQGSM), FRIB, medical isotope production, space-radiation applications

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 Monte Carlo transport code representing a merger of MCNP5 and MCNPX. 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 [3]; 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 matter. Such a V&V work has been performed recently for many various reactions and results were documented in several publications (see, e.g., [4, 5] and references therein).

A direct “trigger” for the current V&V work presented here was a recent Report on Benchmarking Heavy Ion Transport Codes FLUKA, HETC-HEDS, MARS15, MCNPX, and PHITS [6], where not so good results by an old version MCNPX using an old version of LAQGSM were shown and even worse results by a version of MARS15 using a version of LAQGSM were published: We need to

check how the production version of MCNP6 describes such reactions.

2. Results

We have tested with the production version of MCNP6 [2] almost all neutron spectra measured at the Heavy Ion Medical Accelerator in the Chiba (HIMAC) facility of the National Institute of Radiological Science (NIRS) [7, 8]. Most of our results on this work have been published in [5]. Fig. 1 presents only two examples of n spectra, from 400 MeV/A $^{14}\text{N} + ^{12}\text{C}$ and ^{64}Cu . Similar results were obtained (see [5]) with the production version of MCNP6 for other measurements published in [7, 8].

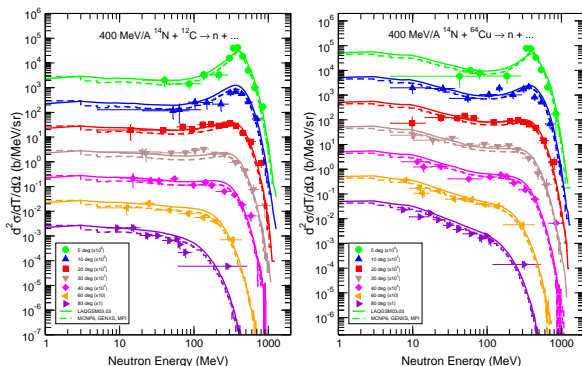


Fig. 1. Experimental [7,8] neutron spectra from 400 MeV/A $^{14}\text{N} + ^{12}\text{C}$ and ^{64}Cu , compared with calculations by the production version of MCNP6 [2] and by its LAQGSM event generator used as a stand alone code [3], as indicated.

Our current good results obtained with the production version of MCNP6 for the measurements published in [7, 8] make questionable to us the quite poor results by a version of LAQGSM used in a version of MCNPX and even worse results published in Ref. [6] by MARS15 using a version of LAQGSM. We can assume that either some errors were present in the input files used in the calculations performed in Ref. [6], or a questionable version of LAQGSM was used in calculation of the results published in Ref. [6].

Fig. 2 shows another example of reactions of interest to FRIB, namely fragmentation of ^{64}Ni at 140 MeV/nucleon on ^9Be target-nuclei measured at MSU for RIA [9] compared with results by LAQGSM03.03 as implemented in MCNP6 [1, 2]. Many more examples of such reactions, proper references, and discussions can be found in Ref. [10]. A comparison of our results for such reactions with calculations by several other models can be found in Ref. [4]. We can see that MCNP6 using LAQGSM03.03 describes these reactions very well.

Ref. [11] presents examples of several reactions of interest to FRIB, induced by radioactive isotopes, measured at GSI and calculated by LAQGSM03.03 as implemented in MCNP6 [1, 2]. Those reactions were also describes well enough by LAQGSM03.03.

Let us note that a recent V&V of the production version of MCNP6 [2] published in Ref. [12] proved that MCNP6 describes well also spectra of light fragments from several reactions measured recently at GANIL [13]; INFN, Catania [14]; and COSY, Jülich [15].

We have analyzed with MCNP6 or/and with its event generators practically all cross sections of products from spallation, fission, and fragmentation reactions induced by protons and nuclei measured lately at GSI, Darmstadt, Germany; ITEP, Moscow, Russia; and, at LANSCE, LANL, Los Alamos, USA. Examples of our results on these studies and further references can be found in [3–5, 10, 12, 16, 17]. Fig. 3 shows only one example on ^{225}Ac and other medical isotopes produc-

tion measured and studied recently at LANL [16] using MCNP6. Calculations with different event-generators of MCNP6 agree well with measured data, encouraging in light of MCNP6's ability to accurately predict yields of ^{225}Ac for medical radiotherapy (see details in [16]).

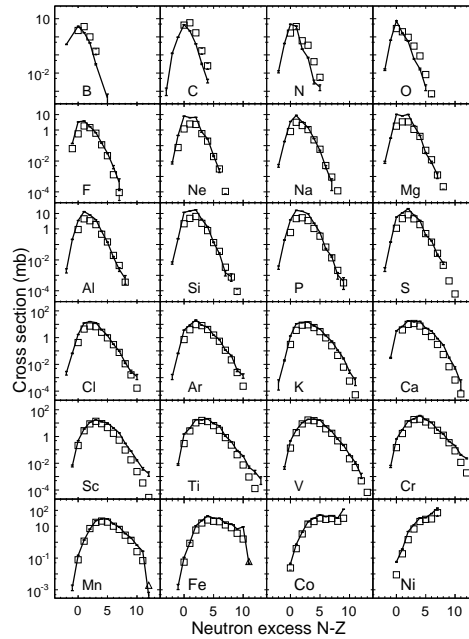


Fig. 2. Measured cross sections for ^{64}Ni fragmentation on ^9Be at 140 MeV/nucleon [9] compared with results by a version of LAQGSM03.03 as implemented in the production version of MCNP6 [2].

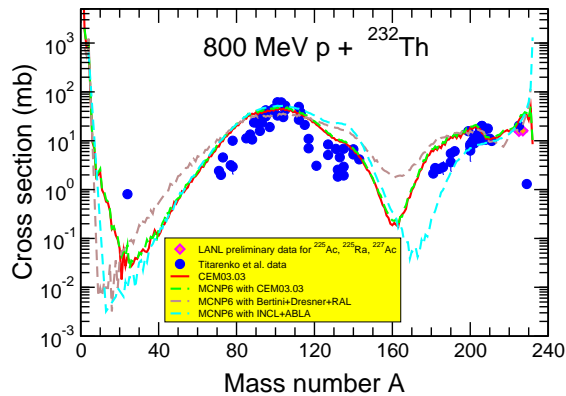


Fig. 3. Comparison of the mass distributions of products from 800 MeV $p + ^{232}\text{Th}$ calculated with MCNP6 using several of its event-generators (see details in [16]) with the cumulative cross sections measured at ITEP by Titarenko *et al.* [17] and with the recent LANL data [16].

We have tested lately MCNP6 on a number of reactions of interest to space-radiation shielding and cosmic-ray propagation. One example of results from our study is presented in Fig. 4, where we compare the MCNP6 results with the experimental yields of products from interactions π^+ with Fe at the highest energy measured so far for this reaction [18], of 120 GeV/c.

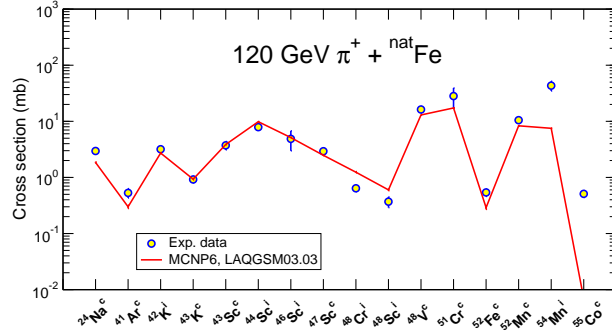


Fig. 4. Detailed comparison between all cross sections measured in Ref. [18] from interaction of 120 GeV/c π^+ with Fe and those calculated by MCNP6, as indicated.

3. Conclusions

Our study shows that the production version of MCNP6 provides quite good predictions for most of the reactions we analyzed so far, allowing us to conclude that it can be used as a reliable and useful simulation tool for FRIB, medical, and space applications involving stable and radioactive isotopes.

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