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MCNP6 Study of Fragmentation Products from ^{112}Sn+ ^{112}Sn and ^{124}Sn+ ^{124}Sn at 1 GeV/nucleon

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Production cross sections from ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at 1 GeV/nucleon, measured recently at GSI using the heavy-ion accelerator SIS18 and the Fragment Separator (FRS), have been analyzed with the latest Los Alamos Monte Carlo transport code MCNP6 using the LAQGSM03.03 event generator. MCNP6 reproduces reasonably well all the measured cross sections. Comparison of our MCNP6 results with the measured data and with calculations by a modification of the Los Alamos version of the Quark-Gluon String Model allowing for multifragmentation processes in the framework of the Statistical Multifragmentation Model (SMM) by Botvina and coauthors, as realized in the code LAQGSM03.S1, does not suggest unambiguously any evidence of a multifragmentation signature.

I. INTRODUCTION

MCNP6 [1] is used in various applications involving reactions induced by neutrons and other particles, but also heavy ion collisions at relativistic energies. The Los Alamos version of the Quark-Gluon String Model (LAQGSM) as realized in the code LAQGSM03.03 [2] is the main "working horse" (event generator) used by MCNP6 to describe relativistic heavy-ion interactions. It is critical that it describes such reactions as well as possible, therefore it is often validated and verified against available experimental data and calculations by other models (see, e.g., [3] and references therein). However, for relativistic heavy ion collisions, MCNP6 was compared mostly with different particle spectra measured from various reactions [3] and less against data on isotope production yields from such reactions. To fill this gap, here we test MCNP6 and the LAQGSM03.03 [2] and LAQGSM03.S1 [6] versions of LAQGSM against the recent GSI measurements of fragmentation products in the reactions ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at 1 GeV/A [4]. These new rich data are interesting to study the influence of the isotopic composition of the projectile on the kinematical properties of projectile residues and may help understand better the physics of nuclear fragmentation in such reactions.

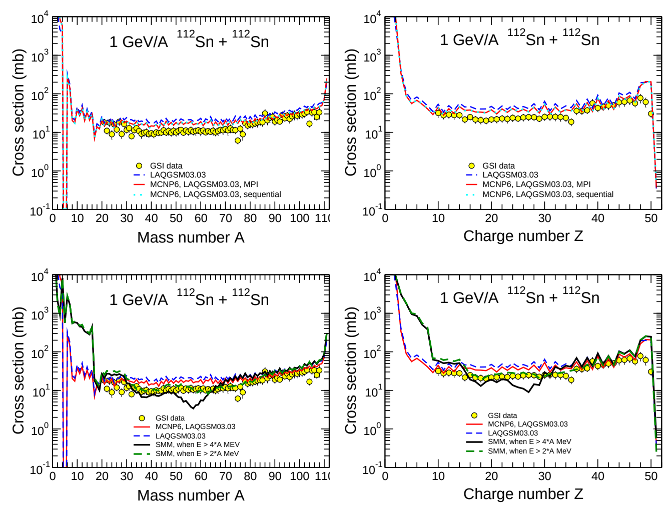

FIG. 1. Experimental [4] mass and charge distributions of products from 1 GeV/A ^{112}Sn + ^{112}Sn compared with results by LAQGSM03.03 used as a stand-alone code and with MCNP6 calculations in parallel (MPI) and sequential modes using the LAQGSM03.03 event generator (upper plots), as well as with results by the LAQGSM03.S1 version of LAQGSM taking into account multifragmentation processes with SMM [5] for nuclei with excitation energies $E > 2 \times A$ MeV (dashed green lines) and $E > 4 \times A$ MeV (black solid lines), lower plots.

II. RESULTS

As a step of MCNP6 Verification and Validation (V&V), we have calculated both ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn reactions using LAQGSM03.03 event gen-

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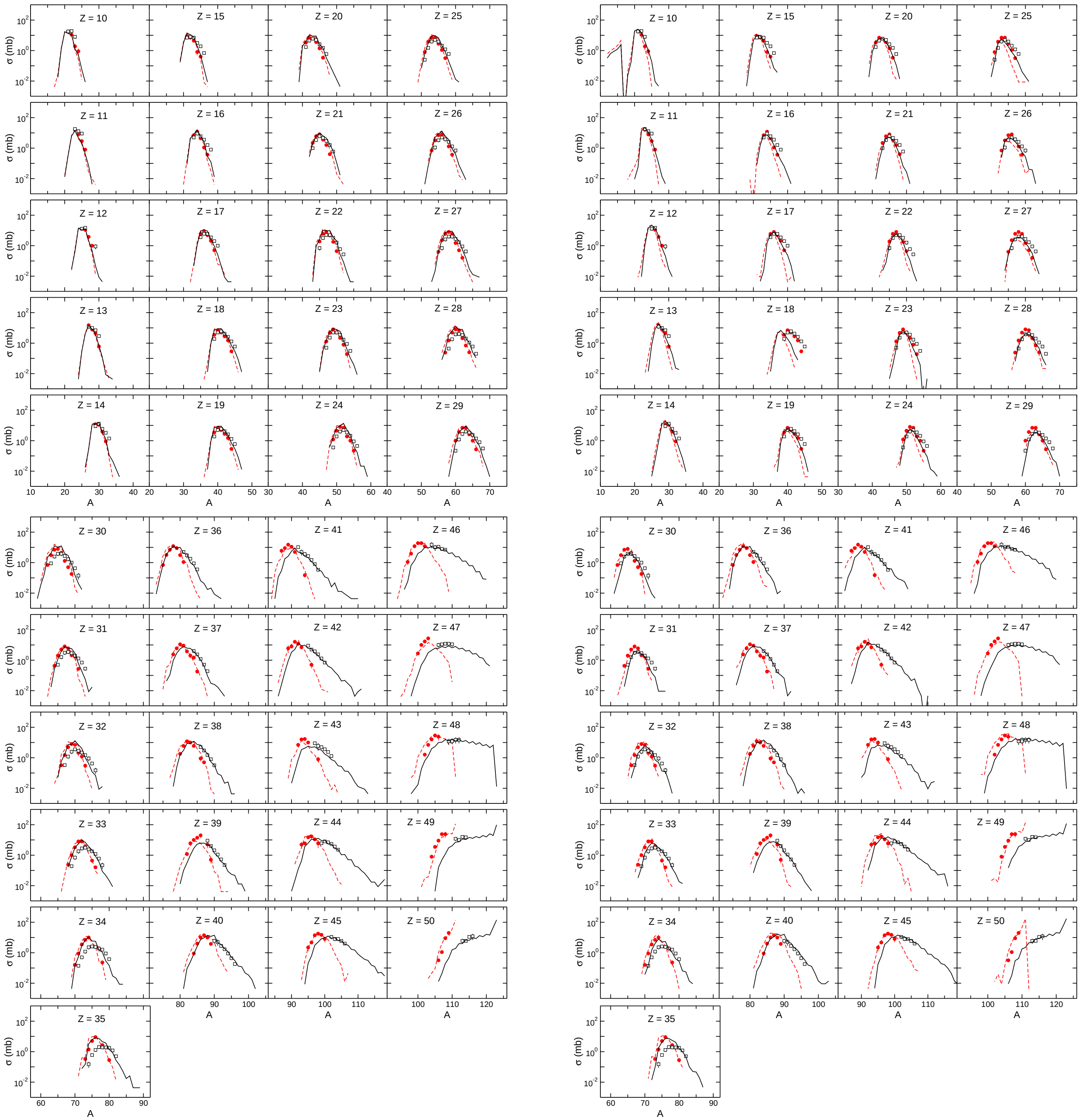

FIG. 2. Isotopic cross sections of all measured [4] fragments in reactions 1 GeV/A ^{112}Sn+^{112}Sn (red solid circles and lines) and ^{124}Sn+^{124}Sn (black squares and lines) compared with results by LAQGSM03.03 [2] (left panel) and by LAQGSM03.S1 [6], accounting for multifragmentation processes with SMM [5] for nuclei with excitation energies $E \geq 4 \times A$ MeV, (right panel).

erator running MCNP6 both in a sequential mode and in parallel, with MPI. We also have calculated both reactions with LAQGSM03.03 used as a stand alone code, outside MCNP6. As expected, all results obtained with MCNP6 ran with MPI coincide with the ones calculated in a sequential mode. Similarly, the all the results obtained with MCNP6 using LAQGSM03.03 are practically the same as the calculations done with LAQGSM03.03 used as a stand alone code, with only a tiny uniform difference in the absolute values of all cross sections, due to different values for the total reaction cross sections calculated by LAQGSM03.03 and used by MCNP6 for these reactions. Naturally, these facts do not guarantee that the LAQGSM03.03 implementation in MCNP6 and its run with MPI is absolutely free of any possible deficiencies; but at least we did not find any problems while calculating these reactions. Examples of some results from our study, for the ^{112}Sn+^{112}Sn reaction, are presented in the upper plots of Fig. 1.

Let us note that LAQGSM03.03 version of LAQGSM as implemented in MCNP6 does not account for multifragmentation of highly excited nuclei. It accounts for Fermi Break-up of light nuclei with $A < 13$ (see details in [2]), but this is not exactly what we usually understand by "multifragmentation" (see, e.g., [5] and references therein), and Fermi Break-up is used at present in LAQGSM only for light nuclei, with $A < 13$.

To understand better the mechanisms of nuclide production in these reactions, we calculated both reactions also with a version of LAQGSM, LAQGSM03.S1 [6], which accounts for multifragmentation processes using the Statistical Multifragmentation Model (SMM) by Botvina et al. [5]. Let us note that one of the most important details of SMM is the condition for the transaction between the multifragmentation and vaporization (or evaporation) modes of a reaction, which is determined by the temperature of the excited nucleus, or by its excitation energy, E. It is believed that such a transaction does occur at excitation energies E/A from ~ 2 to ~ 5 MeV/nucleon, depending on the concrete type of the reaction. We performed here calculations with LAQGSM03.S1 for two different transaction conditions, namely for values of E/A equal to 2 and 4 MeV/nucleon.

We found that, for these particular reactions, the results obtained with LAQGSM03.S1 are near to the values of the product cross section yields calculated with LAQGSM03.03 and with MCNP6 using LAQGSM03.03. Examples of mass and charge distributions of products from the ^{112}Sn+^{112}Sn reaction calculated with LAQGSM03.S1 are compared with similar results by LAQGSM03.03 and by MCNP6 using LAQGSM03.03 in the lower plots of Fig. 1.

A more detailed comparison of results by LAQGSM03.S1 and LAQGSM03.03 as implemented in MCNP6 is presented if Fig. 2, where the left panel shows isotopic cross sections of all measured products from both reactions compared with calculations by LAQGSM03.03, while the right panel, the same, but compared with results by LAQGSM03.S1. A careful, one by one, comparison of the plots from the left panel with the ones from the right panel does not suggest us an unambiguously evidence of a multifragmentation signature in these reactions. Note, that we came to a similar conclusion in Ref. [7] while analyzing other comparable heavy-ion reactions. Let us note that Mancusi et al. came recently to the same conclusion from a study of 1-GeV proton-nucleus reactions [8].

III. CONCLUSIONS

The recently measured at GSI ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn at 1 GeV/nucleon reactions have been analyzed with the Los Alamos transport code MCNP6 using the LAQGSM03.03 event generator. MCNP6 reproduces reasonably well all the measured cross sections. All the MCNP6 results obtained in a sequential run coincide with the ones obtained in parallel, with MPI. Comparison of our MCNP6 results with the measured data and with calculations by a modification of the Los Alamos version of the Quark-Gluon String Model allowing for multifragmentation processes in the framework of the Statistical Multifragmentation Model (SMM) by Botvina and coauthors, as realized in the code LAQGSM03.S1, does not suggest unambiguously any evidence of a multifragmentation signature in these reactions.

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