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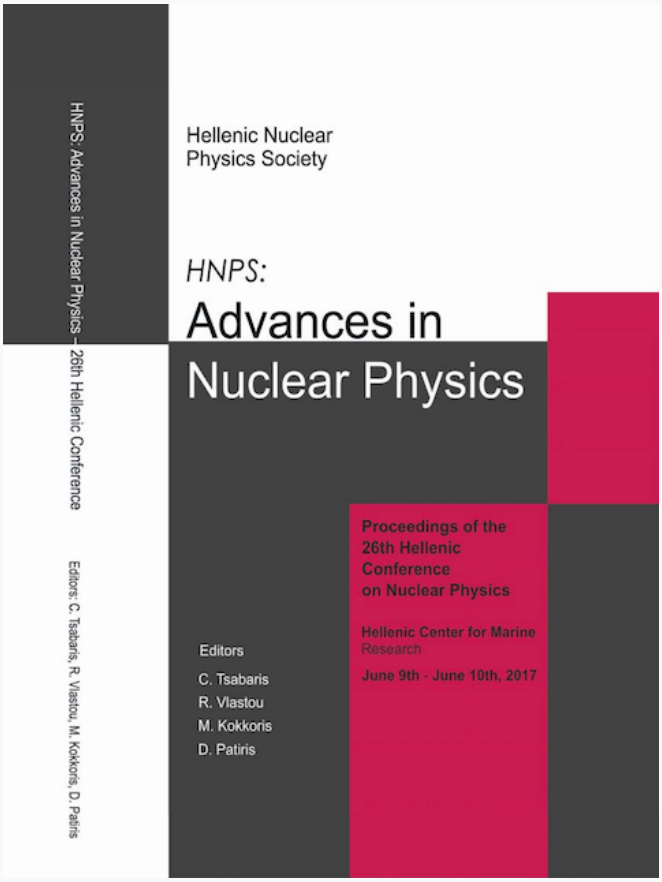

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Spallation Reactions of 0.1 – 1.0 GeV Protons on ^{208}Pb

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Abstract A number of projects of current interest such as transmutation of nuclear waste, neutron sources, radiation damage in space etc. require a detailed modeling of spallation reactions induced by high-energy protons. For a phenomenological description of spallation reactions, we couple the results of the intranuclear cascade model ISABEL with evaporation calculations performed with the statistical model codes SMM and MECO incorporating symmetric fission. Preliminary results of 200, 500 and 1000MeV protons on ^{208}Pb targets are compared with experimental data. Extension of our calculations to describe the reaction mechanism is discussed.

Keywords Nuclear reactions, Spallation, Intranuclear cascade model, Statistical model, Fission

INTRODUCTION

The study of nucleon-induced spallation reactions is a topic of extensive experimental and theoretical studies due to their importance in basic and applied Nuclear Science. Spallation reactions have numerous applications in accelerator-driven systems (ADS), transmutation of nuclear waste, spallation neutron sources and the production of rare isotopes. Astrophysics and space research also benefits from this research due to implications in interaction of cosmic rays with interstellar bodies and radiation damage of electronic devices in space. Last but not least, this type of reactions provides a framework for testing high-energy nuclear reaction models in the bombarding energy range above 150-200 MeV [1].

A proton-induced spallation reaction (SR) proceeds in two stages. In the first stage, the incident particle interacts with the nucleons of the target in a sequence of collisions. As a result, we have the formation of an intranuclear cascade (INC) of high-energy (greater than 20 MeV) protons, neutrons and pions within the nucleus. This is a fast process lasting approximately 10^{-22}s. During the intranuclear cascade, some of these energetic hadrons escape from the target. Others deposit their kinetic energy in the nucleus leaving it in an excited state. In the second stage, the produced excited nuclear species deexcite. Sequential evaporation is assumed to be the dominant process with a typical time scale of 10^{-8}s – 10^{-6}s. Emission of nucleons, protons, alpha-particles and gamma-rays is dominant. Emission of heavier nucleon clusters in their ground or excited states is also possible. If the target is heavy enough, high-energy fission may compete with sequential evaporation. The deexcitation

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products of target-like and/or fission fragments may be radioactive. In the case of thick target experiments, the secondary high-energy particles produced in the INC phase move roughly in the same direction as the incident proton and induce secondary spallation reactions. In such a case, a hadronic cascade is observed as a result of an accumulation of all reactions initiated by the primary and secondary particles. In many applications it is desirable to have a reliable model description of the number of neutrons emitted in a spallation reaction, as well as associated observables like fission cross sections, mass and isotopic distributions of the reaction products.

In the present work we are concerned with the description of thin target experiments. Our objective is to describe proton-induced spallation reactions on ^{208}Pb at 200, 500 and 1000 MeV. We choose a phenomenological approach in which we couple the results of an INC code with an evaporation code extended to describe high-energy symmetric fission. The employed nuclear reaction codes are briefly discussed in Section II. In Section III, results of preliminary calculations are compared with experimental data consisting of fission cross sections, neutron multiplicities, mass and isotopic distributions of evaporation residues and fission fragments. The results of two evaporation codes coupled to the same INC code input are compared in Section IV. A summary of our results is given in Section V.

DESCRIPTION OF THE NUCLEAR REACTION CODES

For the description of the INC phase, we use the code ISABELE [2,3]. It is a well tested Monte-Carlo code with a long history of improvements. The target nucleus is simulated by a continuous medium bounded by a diffuse surface. Collisions between the incident nucleon and the nucleons of the target occur with a criterion based on the mean free path. Between successive collisions, linear trajectories are assumed. Free nucleon-nucleon cross sections are used. The code allows for elastic and inelastic N-N collisions. Furthermore, it takes full account of Pauli blocking i.e. interactions resulting in nucleon falling below the Fermi sea are forbidden. From a typical run we obtain the mass number (A), atomic number (Z) and excitation energy (E*) of the various nuclear species produced in the INC phase. The deexcitation stage is described with the codes SMM and MECO.

The SMM code [4,5,6] combines a description of sequential compound nucleus decay with a multifragmentation model. Equilibrium compound nucleus decay dominates at excitation energies $E^*<2$-3 MeV/A. At higher energies, the importance of these processes diminishes and multifragment decay takes over. The fission decay channel is taken into account empirically, by producing fission fragment mass distributions with parameters adjusted to fit experimental data [6]. At $E^*>4$ MeV/A, multifragmentation is expected to dominate. Thus, all possible decay processes occuring in the wide excitation energy range realized in a spallation reaction should be adequately taken into account.

The code MECO [7] is a multisequential binary decay code. It describes the equilibrium decay of excited nuclei as a sequence of binary division processes involving the emission of light particles, gamma rays and nucleon clusters in their ground, excited bound and unbound states. Emission of nucleons and progressively heavier clusters leading to symmetric mass divisions are calculated in a generalized Weisskopf evaporation formalism. The computational method is Monte-Carlo, thus allowing the simulation of experimental conditions. Also, it may accommodate any number of user-defined channels. MECO provides a complete description of compound nucleus decay of medium to low mass (A<100) systems and excitation energies E*<2-3 MeV/A.

In order to calculate the decay of heavy compound nuclei with MECO, we introduce a fission decay mode. At each decay step, we calculate the fission probability, as the ratio of the fission decay width over the sum of decay widths of all possible decay modes. We calculate the fission decay width according to the transition stage theory [8]. As a first approximation, we assume symmetric mass divisions. The employed fission barrier heights correspond to a liquid drop model calculation including the finite range of nuclear forces [9]. It is well known that the standard theory of fission, just described underestimates the pre-fission neutron multiplicities. For this reason, we introduce a fission delay to account for the slowing effects of nuclear dissipation [10]. Our Bohr-Wheeler decay width was multiplied by the Kramer's reduction factor. The reduction parameter gamma was set equal to 5, a value suggested from fission studies of heavy-ion induced reactions [10].

Fission fragment masses are selected from a Gaussian distribution with an excitation energy dependent width, parametrized from experimental data [11]. Each fragment is assumed to have the same N/Z ratio as the parent nucleus. From the conservation of energy and linear momentum we obtain the kinetic energies of the two fragments. The excitation energy of the parent nucleus is divided among the two fragments in proportion to each fragment's mass, i.e. assuming equal temperatures. Then, we follow the particle decay of each fragment.

COMPARISONS WITH EXPERIMENTAL DATA

Figure 1 shows the mass distributions of evaporation residues and fission fragments in 500MeV p + ^{208}Pb spallation reactions. Experimental data (symbols) [12, 13] are compared with calculations performed with the code ISABEL followed by SMM (open histogram) and MECO (solid line).

The ISABEL-SMM calculation describes well the plateau of the mass distribution of evaporation residues. However, it underpredicts the low-mass region of the distribution. The same calculation predicts two nearby broad mass peaks for the mass distribution of fission fragments, implying an excess of asymmetric fission. This is in contrast of the experimental data, which show a broad mass peak, centered at approximately A=97.

The ISABEL-MECO calculation, predicts a plateau for the evaporation residue mass distribution in agreement with the shape but a greater magnitude than the experimental data. It also underpredicts the low-mass region. For the mass distribution of the fission fragments, this calculation predicts a broad distribution with a centroid that agrees with experiment. This was expected, since the code takes only symmetric fission into account. However, the width of the experimental mass distribution is underestimated. Since the width of the mass distribution in MECO was calculated in accordance with systematics, this underprediction means that we need to consider the asymmetric mode of fission as well.

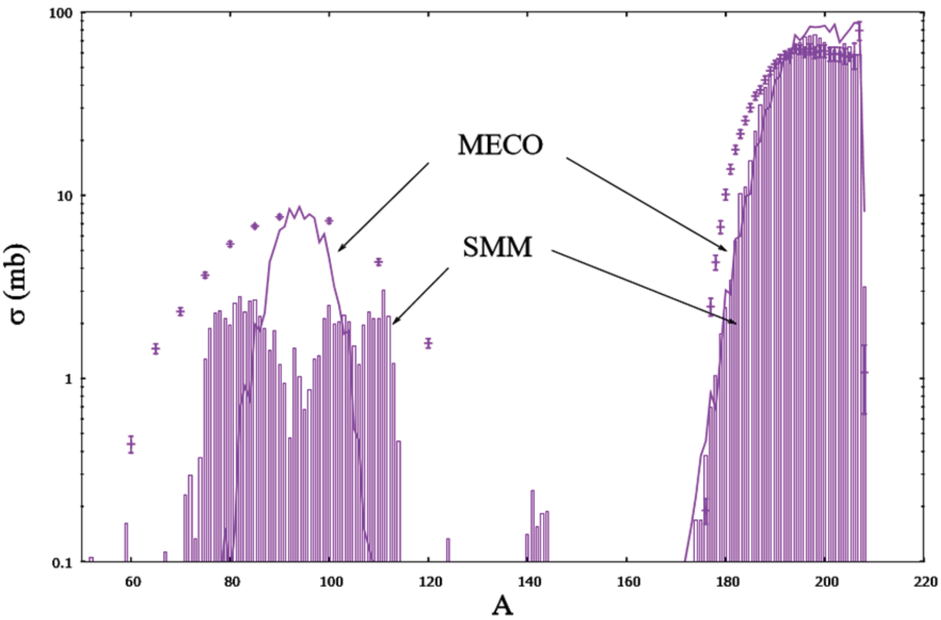

Fig. 1. Mass distributions of evaporation residues and fission fragments in spallation reactions of 500MeV p + ^{208}Pb . Experimental data (symbols) are compared with calculations performed with the code ISABEL followed by SMM (open histogram) and MECO (solid line).

Comparing SMM with MECO, we realize a rough agreement between the two codes in the description of the evaporation residue mass distribution. However, the two codes disagree with each other and both fail to describe fully the fission fragment mass distribution. The SMM code needs a symmetric fission component and MECO needs an asymmetric one. Charge distributions of evaporation residues and fission fragments calculated with the two codes were found consistent.

In Figure 2 we show the mass distributions of evaporation residues and fission fragments in 1000MeV p + ^{208}Pb spallation reactions. The experimental data [14] are shown with symbols and compared with calculations performed with ISABEL-SMM (open histogram) and ISABEL-MECO (solid line).

The ISABEL-SMM calculation predicts well the plateau of the evaporation residue mass distribution but underestimates the low-mass region. The fission fragment mass distribution is again predicted to have two peaks. However, its width is very broad and tends to approach the data. At this bombarding energy, we have a yield in the region between A=120 and A=150, filling the gap between the evaporation residue and the fission fragment mass distributions.

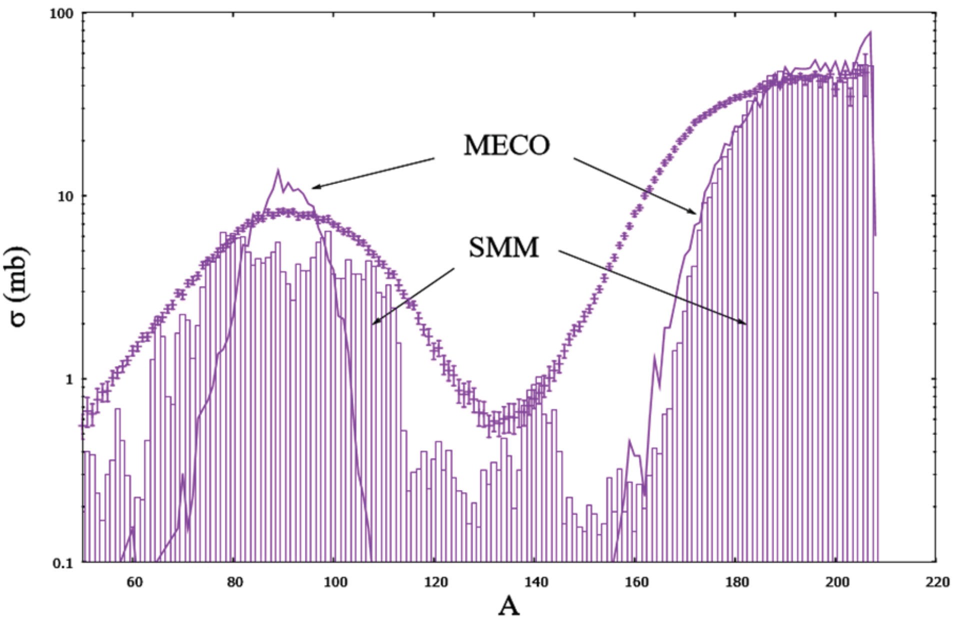

Fig. 2 Mass distributions of evaporation residues and fission fragments in spallation reactions of 1000MeV p + ^{208}Pb. Experimental data (symbols) are compared with calculations performed with the code ISABEL followed by SMM (open histogram) and MECO (solid line).

Comparing SMM with MECO at 1000MeV, we realize again a similarity in the description of the evaporation residue mass distribution. The two codes differ in the description of the fission fragment mass distribution, in a complementary way, as pointed out at 500MeV. A new feature of the SMM code at this energy is the appearance of masses in the A=120-150 range. Some analysis is needed in order to trace the origin of these events. Charge distributions of evaporation residues and fission fragments calculated with the two codes were found consistent.

In Fig. 3, we show isotopic yields of various elements produced by p + ^{208}Pb at 500MeV. The symbols on the panels show the cross sections as a function of the mass number for elements with (Z=82)Pb, (Z=81)Th, (Z=80)Hg and (Z=79)Au. The ISABEL-SMM calculation is shown with the open histogram. For Z=82 and Z=80, it describes well the majority of cross sections. However, it overestimates the experimental cross sections most neutron-deficient isotopes for Z=81 and Z=82. For Z=80 we have a good agreement with the data. However, for Z=79 the calculation starts underestimating the cross sections of all isotopes. The ISABEL-MECO shown by the solid curve provides a better description of the isotopic yields for Z=80-82. For Z=79, the calculation underestimates the data at the same level as the SMM calculation.

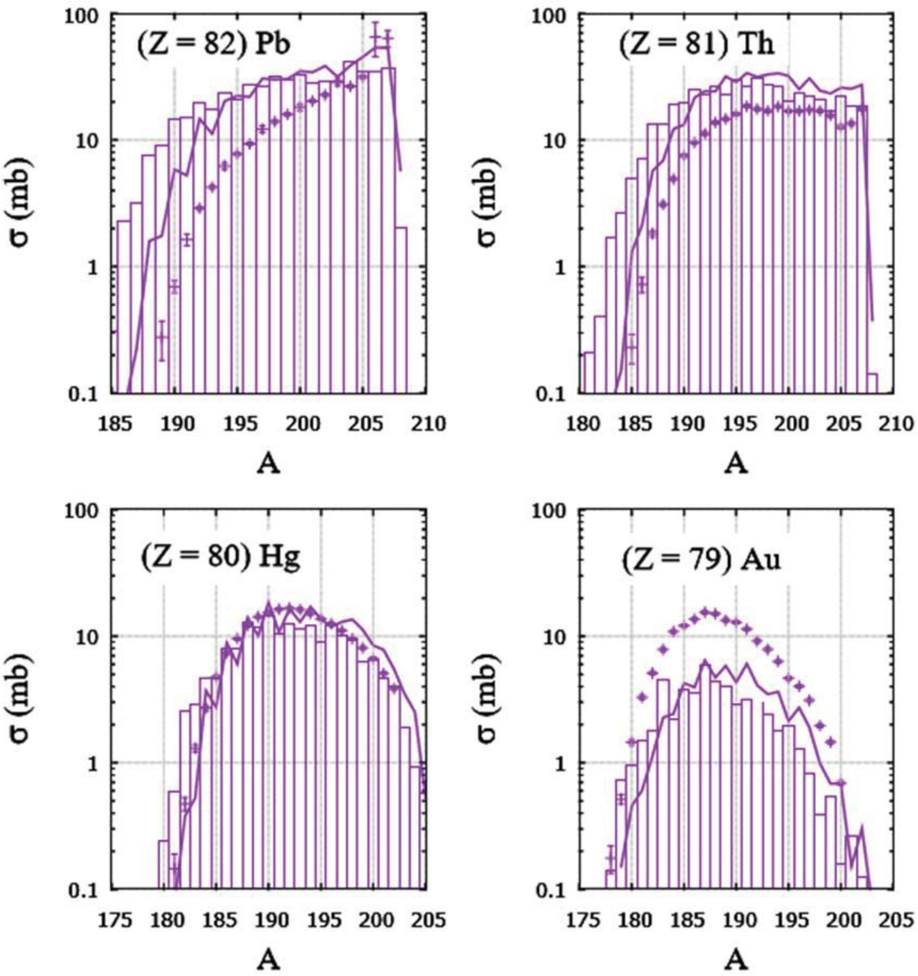

Fig. 3 Isotopic distributions in spallation reactions of 500MeV p + ^{208}Pb, for the indicated values of Z. Experimental data (symbols) are compared with calculations performed with the code ISABEL followed by SMM (open histogram) and MECO (solid line).

SUMMARY AND CONCLUSIONS

In the present work, we combined the intranuclear cascade code ISABEL with the code SMM as well as the sequential binary decay code MECO in an effort to study spallation reactions induced by high-energy protons. Preliminary calculations of p + ^{208}Pb at bombarding energies 500 and 1000MeV were compared with experimental mass and isotopic distributions. For the evaporation residue mass, charge and isotopic distributions our calculations with MECO are consistent with the predictions of the SMM code. They describe the heavy but underestimate the low-mass region of the evaporation residue mass distribution. Both codes require improvements for a successful description of the experimental fission fragment mass distributions. From the point of view of the MECO code, the fission decay mode is expected to improve with an appropriate treatment of asymmetric and symmetric fission. Work in this direction is in progress.

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