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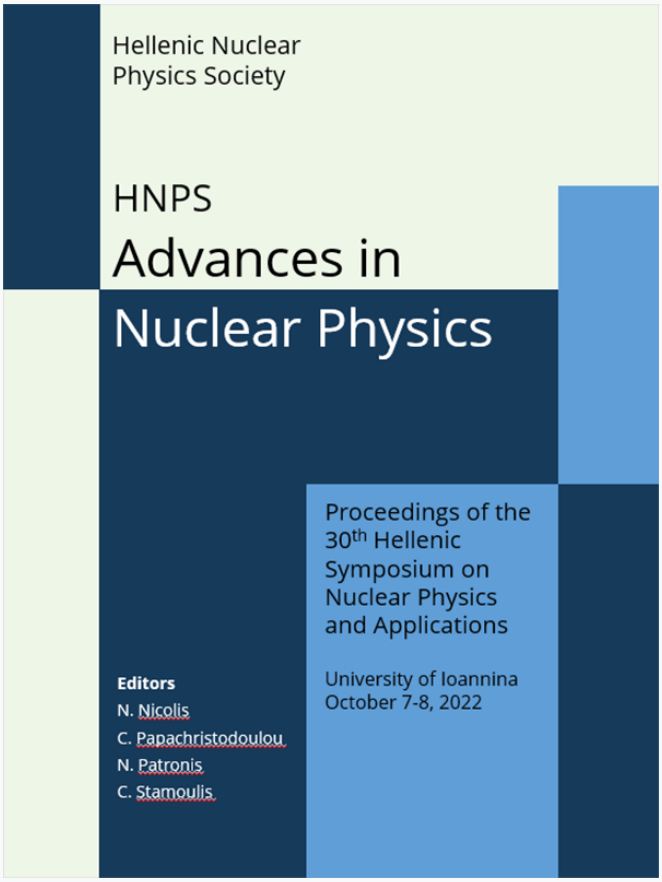

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Development of a simple algorithm for pre-fragment formation in proton-nucleus spallation reactions

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Abstract A Monte-Carlo algorithm is developed to calculate the energy, mass and charge distribution of the pre-fragments produced in proton induced spallation. The algorithm is based on Glauber's theory together with a reasonable assumption on the type of promptly emitted nucleons. For the evaporation stage, correlated values of pre-fragment mass, charge and excitation energy were fed into a properly modified version of the code MCEF (Monte-Carlo Evaporation-Fission). A good agreement is obtained with the experimental mass and charge distributions of residues observed in ^{56}Fe+p spallation reactions at 300, 500 and 750 MeV/A.

Keywords Spallation reactions, two-stage model, Monte-Carlo, isotope production

INTRODUCTION

A spallation reaction is essentially the disintegration of a target nucleus that takes place after its bombardment by a high-energy hadron. Serber's two-step hypothesis is widely accepted and offers a rather realistic view of the spallation mechanism [1].

In the first (fast) step of the reaction, the relativistic projectile initially collides with one of the target's nucleons. As it traverses the nuclear volume, it triggers a course of consecutive collisions between the target's nucleons. This process, referred to as the Intra-Nuclear Cascade (INC), may also involve the production of pions which interact with the target nucleons. Thus, the INC stage involves both elastic and inelastic collisions and causes some of the energetic nucleons/pions to escape the nucleus. There results a distribution of highly excited pre-fragments moving towards thermal equilibrium.

The second step involves the decay of the equilibrated pre-fragments considered as compound nuclei. The de-excitation occurs with the emission of nucleons, clusters of nucleons and gamma radiation. Fission may also occur. While the first step lasts approximately (10^{-19} - 10^{-21}) s, the second step is slow and may take roughly (10^{-16} - 10^{-20}) s.

In the present work, we develop a FORTRAN Monte-Carlo algorithm to predict the energy, mass and charge distribution of the pre-fragments in a proton-induced spallation reaction.

THEORETICAL BACKGROUND

For the INC stage, a major assumption is made; the pre-fragments excitation energy is determined exclusively by the number of primary collisions between the projectile proton and the target nucleons. This may be obtained from Glauber's multiple scattering theory [2, 3]. It has been shown [4] that the exact result is closely approximated by the formula:

$$\sigma_n = \frac{\sigma_R}{\langle n \rangle - 1}\left(1 - \frac{1}{\langle n \rangle}\right)^n , \quad (1)$$

where σ_R is the reaction cross section. Assuming an exponential distribution e^{-E/E_0} for the excitation

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energy deposited to the pre-fragment in one projectile collision, the excitation energy of the pre-fragments after n collisions is:

$$F_n(E) = \frac{1}{(n-1)!}\frac{E^{n-1}}{E_0^n}e^{-E/E_0}, \quad (2)$$

where E_0 is the mean energy deposited to the pre-fragments per primary interaction. Thus, the cross section per unit energy transferred to the excited system is given by [4]

$$\frac{d\sigma}{dE^*} = \sum_{n\geq 1}\sigma_n F_n(E^*)\,. \quad (3)$$

For the second step of the reaction, the statistical decay of the excited pre-fragments is calculated in the framework of the Weisskopf model, as coded in Ref. [5]. Competition between evaporation of neutrons, protons, alpha-particles and fission was considered. For n, p and α competition, the ratio of decay widths of k-particle relative to the j-particle is given by:

$$\frac{\Gamma_k}{\Gamma_j} = \left(\frac{\gamma_k}{\gamma_j}\right)\left(\frac{E_k^*}{E_j^*}\right)\left(\frac{a_j}{a_k}\right) exp\left\{2\left[(a_k E_k^*)^{1/2} - \left(a_j E_j^*\right)^{1/2}\right]\right\}, \quad (4)$$

where γ, E^*, a refer to the spin degeneracy, excitation energy and level density parameter. The fission with is calculated according to the Bohr and Wheeler expression.

MONTE-CARLO CALCULATIONS

For the INC stage, a FORTRAN based Monte Carlo algorithm was developed with the purpose to produce correlated values of (Z, A, E^*) of the excited pre-fragments. Using a random number, we determine the number n of collisions by sampling σ_n/σ_R according to Eq. (1). Sampling Eq. (2) gives the excitation energy of the pre-fragment for the given n. At this stage, we introduce an assumption that one nucleon escapes after each primary collision. Its type was chosen with a random number according to the N/A ratio of the pre-fragment.

For the evaporation stage, the JAVA based Monte-Carlo code MCEF [5] was used properly modified to read the correlated (Z, A, E^*) values produced by the INC Monte-Carlo and calculate the mass and atomic number of the residual nucleus. MCEF calculates the compound nucleus decay considering n, p, a emission and fission. Relative decay probabilities are calculated according to Eq. (4). The decay process continues until the excitation energy drops down to zero. Various event files were created for tests and comparisons with the experimental data.

RESULTS

Figure 1 shows calculated mass and charge distributions in ^{56}Fe+p spallation reactions at 300 MeV/A. The histograms show the primary distributions of excited pre-fragments. These distributions involve excited pre-fragments. When these events are fed into MCEF, the final distributions are produced. They are shown with solid curves. The plot demonstrates that because of evaporation the mass and charge distributions of the final reaction products extend to low A and Z values with an exponential dependence.

Figure 2 shows mass and charge distributions of residual nuclei formed in ^{56}Fe+p reactions at 300, 500 and 750 MeV/A, respectively. Experimental data (symbols) from Ref. [6] are compared with our Monte-Carlo calculations (solid curves). In these calculations, the model parameter E_0 was adjusted to 19, 24 and 30 MeV, respectively. They were found to vary linearly with the bombarding energy T according to $E_0(T) = 0.024 \cdot T - 11.71\ (MeV)$.

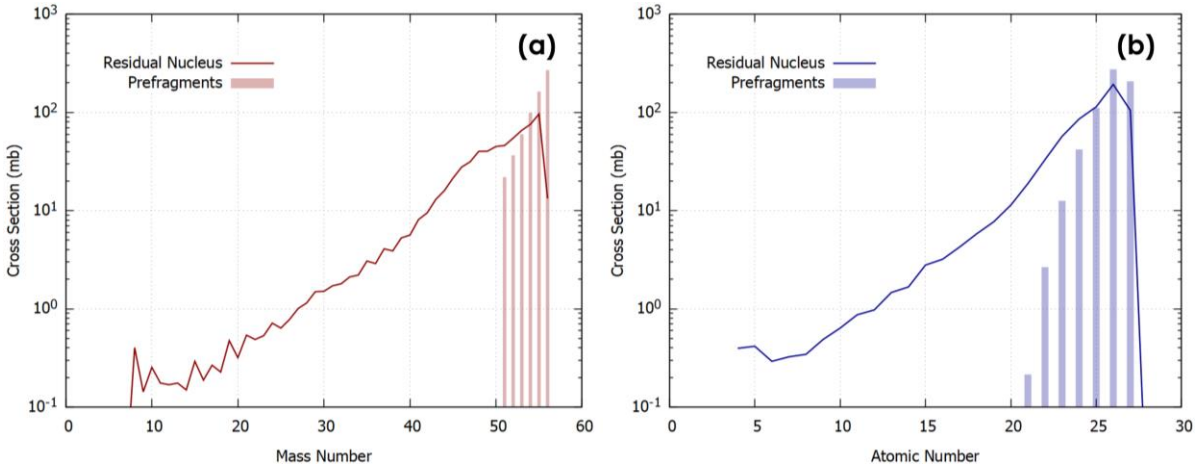

Figure 1. *Calculated mass and charge distributions in $^{56}Fe + p$ spallation reactions at 300 MeV/A. The primary distributions of excited pre-fragments (histograms) are compared with the final distributions after the de-excitation (solid curves).*

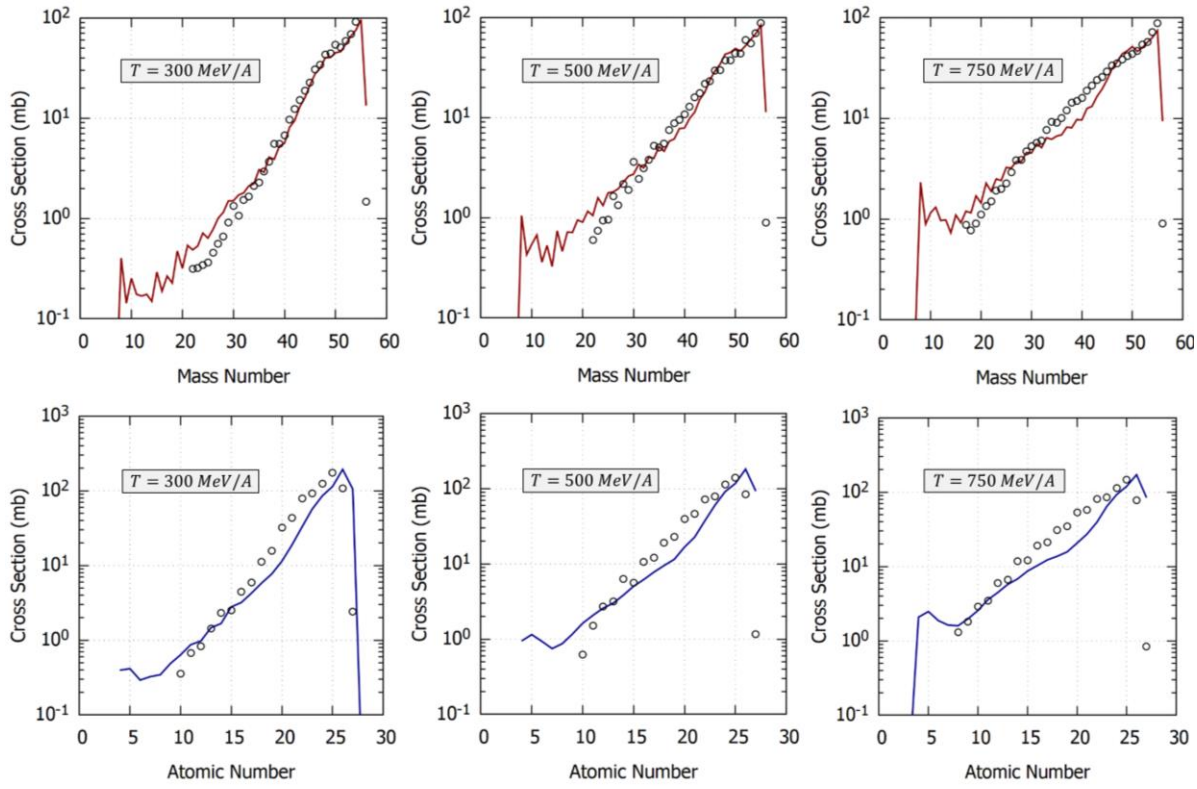

Figure 2. *Mass and charge distributions of residual nuclei formed in $^{56}Fe + p$ reactions at 300, 500 and 750 MeV/A, respectively. Experimental data (symbols) are compared with Monte-Carlo calculations shown with the solid curves.*

The agreement of the calculations with the experimental data is remarkably good, given the simplicity of the model and the fact that only one physical parameter (the mean energy E_0 transferred to the pre-fragments per collision) was used to generate the correlated (Z, A, E^*) values of pre-fragments. For a comparison, a Monte-Carlo calculation with an elaborate treatment of the INC and evaporation stage of the same systems has been reported in Ref. [7].

Improvements to the INC model involve the consideration of direct knock-out processes and using a more detailed evaporation calculation. These improvements, together with investigations of other reaction systems are in progress.

CONCLUSIONS

We have developed a simple Monte-Carlo algorithm for the pre-fragment characteristics (A, Z, E^*) in proton-induced spallation reactions. The algorithm is based on Glauber's multiple scattering theory and involves a single parameter: the average energy transferred to the pre-fragment per collision (E_0). The evaporation stage was treated with the Monte-Carlo code MCEF. Mass and charge distributions in $^{56}Fe + p$ spallation reactions at 300, 500 and 750MeV/A were calculated and found to be in good agreement with the experimental ones. The deduced values of E_0 were found to vary linearly with bombarding energy. Refinements of the model and studies of other reaction systems are in progress.

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