Fragment mass distributions for heavy nuclei fission induced by intermediate energy probes

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Abstract. Recent experiments have shown that the multimode approach for describing the fission process leads to some compatibility with the observed results. A systematic analysis of the parameters obtained by fitting the fission-fragment mass distribution to the spontaneous and low-energy data has shown that the values for those parameters present a smooth dependence upon the nuclear mass number. In the present work it is shown that the same parameter-values obtained for low-energy fission can be used to describe intermediate-energy fission results of fragment-mass distributions if one takes into account the appropriate distribution of the fissioning system. To calculate the fission-fragment mass distributions, Monte Carlo simulations are used. This simulation considers a two-step reaction mechanism, namely, an intranuclear cascade providing the compound nucleus followed by a mechanism of competition between particle evaporation and fission. The fission-fragment masses are obtained according to the multimode approach following the Statistical Scission Model. Simulations for fission induced by 660 MeV protons on $^{241}$Am and $^{237}$Np, and for fission of $^{238}$U induced by photons from Bremsstrahlung with end-point energy of 50 MeV have been performed, and the results have been compared with recent experimental data.

There is a growing interest on the fission process and on its products due to its importance in applications such as nuclear reactors and nuclear medicine. The possibility of transmutation of nuclear waste [1, 2] from traditional reactor in the so-called brewing reactor, for instance, has attracted the attention of researchers willing to solve the long-standing problem of storage of radioactive material produced in nuclear reactors. The mass distributions of fission fragments are fundamental informations to the development of such a brewing reactor as well as to understand material damage induced by radiation from nuclear fuel.

Fission fragments mass distributions can also give many informations about the fission mechanism, allowing the study of the dynamical process leading to nuclear fission [3, 4]. The different processes by which fission takes place can result in different masses of the fragments produced. Theoretically, the fission process has been successfully described by the Statistical Scission Model (SSM)[5, 6, 7], which takes into account the collective effects of...
nuclear deformation during fission through a liquid-drop model, and includes single-particle effects through microscopic shell-model corrections. The microscopic corrections create valleys in the space of elongation and mass number, each valley corresponding to one different fission mode [7]. The fission cross section results from the incoherent sum of the contributions of each channel, \( \sigma_i(A) \), which are usually written in the form

\[
\sigma_i(A) = \frac{K_i}{\sqrt{2\pi\Gamma_i}} \exp\left(\frac{-\left(A - A_i^\prime\right)^2}{2\Gamma_i^2}\right)
\]  

where \( K_i \) is the intensity of the \( i \)th channel, the parameter \( A_i \) is the position of the most probable mass for the fission fragments, and \( \Gamma_i \) is the width of the mass distribution according to SSM.

This method has been used for describing spontaneous fission [8], low-energy induced fission [9, 10], fission induced by thermal-neutrons [11, 12] and 12 MeV protons [13], and even for fission induced by intermediate energy probes such as 190 MeV protons [14], neutrons at energies up to 200 MeV [15], and also by heavy-ions [16]. More recently, it has been applied for describing \(^{238}\text{U}\) fission induced by photons from Bremsstrahlung [17] with end-point energies of 50 MeV and 3500 MeV, and fission induced by 660 MeV protons on \(^{241}\text{Am}\) and \(^{237}\text{Np}\) [18]. The results obtained have shown that for most of the actinide nuclei three modes are needed for explaining the existing experimental data, namely, the symmetric (Superlong, SL) mode, and two asymmetric modes, the Standard I (S1) and the Standard II (S2). In equation 1, the index \( i = S, 1, 2 \) corresponds to the modes SL, S1 and S2, respectively.

A systematic study of the values obtained for the parameters in equation 1 by fitting to experimental data for spontaneous or low energy fission of several nuclei was performed by Böckstiegel et al. [10], showing that those parameters can be described by smooth functions of the fissioning nucleus mass number. From that study it was extracted approximate values for the relevant parameters in the multimode approach which are used in this work.

Whereas for spontaneous or low-energy fission the parameter \( A_S \) in equation 1 may be correctly substituted by \( A_n/2 \), with \( A_n \) being the mass number of the target-nucleus, for fission induced by intermediate energy probes this substitution cannot be done, and \( A_S \) is then a free parameter in the fitting procedure, which is associated to the mass number of the fissioning nucleus, \( A_f \). This mass number, however, depends on the probe used, its incident energy and the properties of the target nucleus. Moreover, it is rather a mass distribution, not a fixed value. Therefore, at intermediate incident energies, the fragment mass distributions are folded into the fissioning-system mass distributions.

It is possible to unfold the contributions due to fission modes and to fissioning-nuclei distribution in the fragment-mass distribution by using Monte Carlo methods and obtain values for the multimode parameters corresponding to each fission mode by taking into account the \( A_f \)-distributions. CRISP is a Monte Carlo code for simulating nuclear reactions [19] that uses a two-step process. First, an intranuclear cascade is simulated following a time-ordered sequence of collisions in a many-body system [20, 21], and when the intranuclear cascade is finished the evaporation of nucleons and alpha-particles starts in competition with fission [22]. It was shown that CRISP code can give good results for total photonuclear absorption cross sections from approximately 50 MeV, where the quasi-deuteron absorption mechanism is dominant, up to 3.5 GeV, where the so-called photon-hadronization mechanism is dominant, leading to a shadowing effect in the cross section [23]. One important feature in the simulation of the intranuclear cascade is the Pauli blocking mechanism, which avoids violation of the Pauli principle. In CRISP a strict verification of this principle is performed at each step of the cascade, resulting in a more realistic simulation of the process.

In the present analysis we concentrate on results obtained with 660 MeV protons on \(^{241}\text{Am}\) and \(^{237}\text{Np}\) target nuclei, and on Bremsstrahlung with end-point energy of 50 MeV on \(^{238}\text{U}\). The number of intranuclear cascade events was \( N_c = 3000 \), and the number of evaporation/fission
simulations for each residual nucleus was $N_{ef} = 2500$, so that the total number of simulated processes was $N_t = 7.5 \times 10^6$ events. For Bremsstrahlung photons on $^{238}$U the energy was sorted according to a distribution $B(\omega) = C/\omega$ ($C$ is a normalization constant). Although all nuclei studied show high fissility values, not all simulated events end at the fission process, and some of them generate spallation products. Whenever the fission channel is chosen, the mass numbers of the heavy fragments produced, $A^H$, are sorted according to the probability distribution described by equation 1. The light fragments are obtained according to $A^L = A_f - A^H$.

Using the CRISP code it is possible to separate the effects of the fission-channel width and those of the mass-distribution of the fissioning nucleus because the fission process is considered for each individual fissioning nucleus. Notice that in the equation 1 the symmetric fragment mass, $A_S$, is no more a free parameter, but it is completely determined by simulations with the CRISP code till the fission point.

One good question we can pose now is whether it is possible to reproduce experimental data for intermediate energy induced fission with the same values obtained at low energies. To verify this hypothesis we fixed the values for the parameters in expression 1 according to the systematics at low energy [10].

**Figure 1.** Fragment-mass distribution for fission induced by 660 MeV protons on $^{241}$Am (a) and $^{237}$Np (b) targets using values from the systematic study of Ref. [10] for the parameters corresponding to the three fission modes considered in this work (full line). Best fit found in [18] are represented by the dashed line and open symbols are the experimental data [18].

**Figure 2.** Fragment-mass distribution for fission on $^{238}$U induced by bremsstrahlung of 50 MeV end-point energy using values from the systematics studied in Ref. [10] for the parameters corresponding to the three fission modes considered in this work as simulated with CRISP (full line). The dashed line represents the best fit of the formula 1 as done by Demekhina et al. [17], open circles are their experimental results. The dotted line represents the results obtained with CRISP when the mass dependence of the channel intensities are taken into account.
The simulated results for fission induced by 660 MeV protons are shown in Figure 1, and they are compared with the experimental results and the fitted curve from Karapetyan et al. [18]. It is possible to observe that the overall shape of the simulated results is different from that of the fitted curve, but it shows a somewhat better agreement with the experimental data for both nuclei. Same reasoning applies to the results obtained from the simulations for 235U (see Figure 2, full line).

Another consideration can be done. The parameters in equation 1 are highly dependent on the mass number, as shown by the systematic analysis performed by Böckstiegel et al. [10]. In fact, the calculations can be significantly improved by including the mass-dependence of the relative intensities of the fission modes. The new results are shown in Figure 2 (dotted line), and it is possible to notice that the fission-fragment mass distributions are very sensitive to the variations in the relative intensities. The new results show now a better agreement with the experimental data with respect to the calculations with constant $K_i$-values.

In the present work a Monte Carlo calculation method (the CRISP code) has been used for simulating the fission process in reactions of 660 MeV protons on $^{241}$Am and $^{237}$Np, and for Bremsstrahlung with end-point energy of 50 MeV on $^{238}$U. The fission-fragment masses have been calculated according to the multimode approach based on the Statistical Scission Model, and for all cases studied the same set of parameter-values has been used, fixed by an analysis of the systematics observed for spontaneous and low-energy fission for a variety of nuclei. The results obtained with CRISP are compatible with the experimental data for all cases studied here. It is important to notice that the relative probabilities for symmetric and asymmetric fission are strongly dependent on mass number of the fissioning system, as the systematics for low-energy fission clearly has shown [10].

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