SURVIVAL PROBABILITY IN DEEXCITATION OF HEAVY NUCLEI*

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A method of calculating statistical decay of heavy compound systems characterized by strong competition between fission and evaporation processes is described. The method consistently accounts for shell effects in both evaporation and fission decay modes.

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1. Introduction

In this report we present a model describing deexcitation of heavy compound nuclei, in which statistical emission of light particles competes with the dominating fission decay mode. The aim of this work is to verify the method of calculating the survival probability. The essential question is whether the survival probability can be calculated in conventional way or new physical effects (*e.g.*, "collective factors", Kramers factor), used in some recently published studies indeed influence the deexcitation process. We have developed a method of calculating the survival probabilities, practically free of adjusted parameters, which consistently accounts for shell effects in both evaporation and fission decay modes. For comparisons with experimental data we selected the ^{16}O + ^{208}Pb system, for which not only the evaporation-residue $2n$, $3n$ and $4n$ cross sections [1], but also fusion cross

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sections [2] have been measured, and moreover — experimental values of the fission barriers in successive compound nuclei are known. Besides, the system is not too heavy and not too symmetric to show significant “dynamical hindrance” effects.

2. Fusion and evaporation cross sections

In the absence of the dynamical hindrance effects, the overcoming the barrier inevitably results in fusion and formation of the compound nucleus. Thus the evaporation residue cross section $\sigma_{\rm res}$ can be written as:

$$\sigma_{\rm res}(E) = \sigma_{\rm cn}(E) \cdot P_{\rm surv}(E)\,, \tag{1}$$

where $\sigma_{\rm cn}$ denotes the compound nucleus formation cross section at an incident energy E, and $P_{\rm surv}$ is the survival probability of the compound nucleus, associated with formation of a given final evaporation-residue nucleus. The fusion cross section $\sigma_{\rm cn}$, if not known from experiments, can be calculated as prescribed in Refs. [3, 4].

3. Survival probability

We propose a consistent and relatively simple scheme of calculating survival probabilities in terms of the Monte Carlo method. The survival probability is then given by the number of deexcitation cascades leading to a given final evaporation-residue nucleus in its ground state, $N_{\rm res}$, divided by the total number of generated deexcitation cascades $N_{\rm tot}$:

$$P_{\rm surv} = \frac{N_{\rm res}}{N_{\rm tot}}\,. \tag{2}$$

Successive stages of the deexcitation cascade are determined by branching ratios expressed by relative partial decay widths for all possible decay modes, $\Gamma_i/\Gamma_{\rm tot}$, where $i = n, p, d, t, \alpha,$ *etc.*, and $\Gamma_{\rm tot}$ is the sum of all particle decay widths Γ_i and the fission width $\Gamma_{\rm f}$. To calculate partial widths for emission of light particles we use the Weisskopf formula [5]:

$$\Gamma_i = \frac{(2\,s_i+1)\,m_i\,\sigma^i_{\rm inv}}{\pi^2\,\hbar^2} \int\limits_0^{E_i^{\rm max}} \varepsilon_i\,\frac{\rho_i\,(E_i^{\rm max}-\varepsilon_i)}{\rho\,(E^*)} d\varepsilon_i\,, \tag{3}$$

where m_i, s_i and ε_i are the mass, spin and kinetic energy of the emitted particle i, respectively, ρ_i is the level density of the daughter nucleus at the excitation energy $E_i^{\rm max} - \varepsilon_i$, and $\rho\,(E^*)$ is the level density of the parent nucleus at the excitation energy E^*. The maximum available excitation energy, $E_i^{\max} = E^* - B_i$ is determined by the energy threshold for emission of the particle i. (In case of neutron emission this amounts to the neutron binding energy B_n, but in case of emission of charged particles the threshold is increased by respective value of the Coulomb barrier.) The quantity $\sigma_{\rm inv}^i$ denotes the cross section for formation of the compound nucleus in the inverse process of absorption of the particle i. For the neutron emission channel $\sigma_{\rm inv}$ equals to the geometrical cross section πR^2, while for emission of charged particles it is reduced accordingly due to the Coulomb interaction.

The fission width is given by conventional formula based on the transition-state method (see *e.g.* Ref. [6]):

$$\Gamma_{\rm f} = \frac{1}{2\pi} \int\limits_0^{E^*-B_{\rm f}} \frac{\rho_{\rm saddle}\left(E^* - B_{\rm f} - K\right)}{\rho\left(E^*\right)} dK\,, \tag{4}$$

where $\rho_{\rm saddle}$ denotes the level density of the fissioning nucleus in the saddle configuration at a given excitation energy. The integration runs over the possible range of kinetic energies K of the fissioning system, corresponding to the range of excitation energies from 0 to the maximum value above the saddle point energy, $E^* - B_{\rm f}$, where $B_{\rm f}$ is the height of the fission barrier.

Expressions (3) and (4) can be integrated analytically using the Fermi-gas model formula for the level density:

$$\rho\left(E\right) \,\propto\, \exp\left(2\sqrt{aE}\right). \tag{5}$$

In final formulae obtained with this assumption, we accounted for the odd–even effects by subtracting from the excitation energy E corrections $E_{\rm pair}$ (parameterized as in Ref. [7]) and the rotation energy $E_{\rm rot}$, thus using the effective thermal excitation energy $U = E - E_{\rm pair} - E_{\rm rot}$. The level densities depend in a crucial way on shell effects. We use in our model the well tested expressions for the level density parameter a proposed by Reisdorf [7], combined with the Ignatyuk formula for shell effects [8]:

$$a = \bar{a}\left[1 + \frac{\delta_{\rm shell}}{U}\left(1 - e^{-U/E_{\rm d}}\right)\right]\,, \tag{6}$$

where $\delta_{\rm shell}$ is the shell correction energy in the ground state of a given nucleus (when calculating Γ_i) or at the saddle point (when calculating $\Gamma_{\rm f}$), and $E_{\rm d}$ is the damping energy constant [7]. The quantity $\bar{a}$ represents the smooth, shell independent level-density parameter accounting for the volume, surface and curvature dependence of the single-particle level density at the Fermi surface, derived by Reisdorf [7].

4. Results and discussion

In this report we present results obtained with our model tested on the data on the ^{16}O + ^{208}Pb reaction. As mentioned in the Introduction, this set of data and the existing complementary information are complete enough to unambiguously test the way of calculating the survival probability. The role of other possible effects such as the dynamical hindrance of fusion, uncertainties in determination of the fusion cross section, *etc.* are eliminated. The experimental data and calculated cross sections for $2n, 3n$ and $4n$ evaporation channels are shown in Fig. 1. Experimental values of fission barrier heights in consecutive compound nuclei (isotopes of Th) have been taken from Ref. [9]. Precise knowledge of the barriers (and thus the saddle-point energies) is of great importance because $\Gamma_{\rm i}/\Gamma_{\rm f}$ ratios are very sensitive to this quantity. Shell corrections at the saddle configuration, determining the level density parameter $a_{\rm f}$ [see Eq. (6)], were assumed to be completely damped [7, 10].

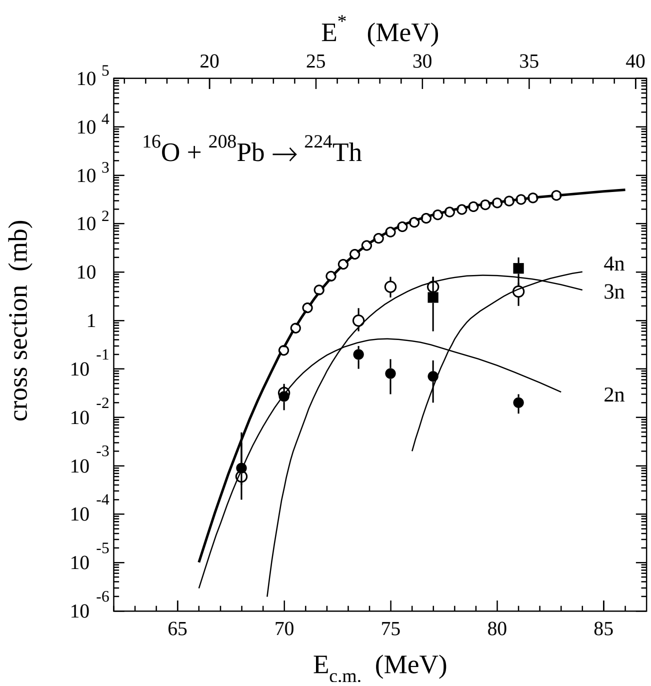

Fig. 1. Fusion cross sections for the ^{16}O+^{208}Pb reaction measured by Morton *et al.* [2] (small open circles), extrapolated with the "diffused barrier formula" [4] (solid line), and independently measured evaporation-residue cross sections [1] for $2n$ (solid circles), $3n$ (large open circles), and $4n$ (solid squares) channels — compared with predictions of the present model.

Results of our calculations agree very well with the measured cross sections. They show that any modifications which would influence the preexponential factor in $\Gamma_i/\Gamma_{\rm f}$ ratios, such as collective factors or the dissipative Kramers factor used *e.g.,* in Ref. [1], have no empirical justification.

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