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Spin distribution of evaporation residue cross section within a stochastic approach*

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Abstract The Langevin equation including particle emission was used to reproduce the recently measured spin distribution of evaporation residue cross sections in the reaction ^{16}O+^{184}W at beam energies of 84, 92, 100, 108, 116 and 120 MeV. By comparing the theoretical calculations with the experimental data, the validity of the stochastic approach to dissipative fission is verified. Moreover, a pre-saddle nuclear viscosity coefficient of 5×10^{21} s^{-1} is extracted.

Key words spin distribution of evaporation residue cross section, pre-saddle viscosity coefficient, Langevin equation

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1 Introduction

In recent years the strength of nuclear viscosity in the fission process has been extracted[1—3] by systematically analyzing experimental data of light particle multiplicities[4, 5], evaporation residue cross sections[6] and giant dipole resonance (GDR) γ-ray[7, 8] emission for a lot of fissioning systems. It is well known that light particles stem from the pre-saddle and saddle-to-scission emission. Therefore it is difficult to determine the pre-saddle viscosity coefficient merely using particle multiplicities. At present information on the pre-saddle viscosity coefficient is mainly obtained by measuring the evaporation residue cross section[6]. Since in this context an accurate knowledge of the pre-saddle viscosity coefficient is also important for determining the viscosity strength outside the saddle, searching for new observables sensitive to the viscosity coefficient inside the fission barrier is necessary. Recently it was suggested that the spin distribution of the evaporation residue cross section, namely the angular momentum distribution leading to evaporation residues, is a sensitive probe of the pre-saddle viscosity coefficient[9]. Thus it is interesting to investigate this new probe by Langevin equations. Such investigation provides not only a stringent test for the validity of the widely adopted stochastic approach dealing with dissipative fission[1, 3, 10—12], which, to our best knowledge, has not been carried out so far, but also new knowledge about the viscosity coefficient. Usually in a statistical model analysis of the dissipation effects only a reduction of the asymptotic fission width relative to the conventional Bohr-Wheeler value is included[9], which is a very simple treatment of dissipative fission. Hence a full Langevin dynamical treatment of fission would certainly be preferable for studying evaporation residue spin distributions. It considers the time evolution of the fission decay width and contains a number of dynamical features in the decay of the hot compound nucleus, e.g. the angular momentum dependence of pre-saddle and saddle-to-scission time, etc. These advantages are not considered in a simple statistical model analysis. Therefore, it is highly expected that based on the Langevin model one can extract a more precise value of the viscosity coefficient inside the fission barrier.

2 Brief description of the theoretical model

In the present paper a combination of the dynamical Langevin equation and a statistical model (CDSM)[1] is utilized. The dynamical part of the CDSM model is described by the Langevin equation

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which is expressed by the free energy F. In the Fermi gas model F is related to the level density parameter $a(q)$ by

$$F(q,T)=V(q)-a(q)T^2\,, \tag{1}$$

where $V(q)$ is the fission potential and T is the nuclear temperature. It is worth pointing out that the level density parameter $a(q)$ is taken from the work of Ignatyuk et al.[13] which incorporates the nuclear shell structure effects at low excitation energies and approaches smoothly the liquid drop value at higher excitation energies.

The one-dimensional overdamped Langevin equation is given by

$$\frac{\mathrm{d}q}{\mathrm{d}t}=-\frac{1}{M\beta(q)}\frac{\partial F(q,T)_{\mathrm{T}}}{\partial q}+\sqrt{D(q)}\varGamma(t)\,, \tag{2}$$

where q is the dimensionless fission coordinate and is defined as half of the distance between the centers of mass of the future fission fragments divided by the radius of the compound nucleus. $\beta(q)$ is the viscosity coefficient. The fluctuation strength coefficient $D(q)$ can be expressed according to the fluctuation-dissipation theorem as

$$D(q)=\frac{T}{M\beta(q)}\,, \tag{3}$$

where M is the inertia parameter which drops out of the overdamped equation. $\varGamma(t)$ is a time-dependent stochastic variable with Gaussian distribution. Its average and correlation function are written as

$$\langle\varGamma(t)\rangle=0$$

$$\langle\varGamma(t)\varGamma(t')\rangle=2\delta(t-t')\,. \tag{4}$$

The potential energy $V(Z,A,L,q)$ is obtained from the finite-range liquid-drop model[14]

$$V(A,Z,L,q)=a_2\left[1-k\left(\frac{N-Z}{A}\right)^2\right]A^{2/3}[B_{\mathrm{s}}(q)-1]+ c_3\frac{Z^2}{A^{1/3}}[B_{\mathrm{c}}(q)-1]+c_{\mathrm{r}}L^2A^{-5/3}B_{\mathrm{r}}(q), \tag{5}$$

where $B_{\mathrm{s}}(q)$, $B_{\mathrm{c}}(q)$ and $B_{\mathrm{r}}(q)$ are the surface, Coulomb, and rotational energy terms, respectively, which depend on the deformation coordinate q. a_2, c_3, k, and c_{r} are parameters not related to q[1].

After the fission probability flow over the fission barrier attains its quasi-stationary value, the decay of the compound system is described by a statistical model which is called statistical part of the CDSM. In the CDSM model the light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure allowing for the discrete emission of light particles. The widths for light particles $(\mathrm{n},\mathrm{p},\alpha)$ and GDR γ decay are given by the parametrization of Blann[15] and Lynn[16], respectively.

3 Results

The spin distribution of evaporation residue cross sections only depends on the viscosity coefficient inside the barrier. Accordingly β is chosen here as 3, 5, 7, 10, and $20\times10^{21}\mathrm{s}^{-1}$ throughout the fission process. In addition, in order to accumulate sufficient statistics, 10^7 Langevin trajectories are simulated. In the calculations the loss of angular momentum is taken into account by assuming that a neutron carries away $1\hbar$, a proton $1\hbar$, an α-particle $2\hbar$, and a γ-quantum $1\hbar$.

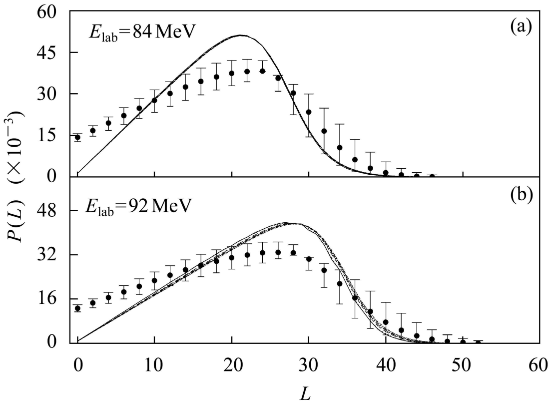

Fig. 1. Evaporation residue spin distributions for the reaction $^{16}\mathrm{O}+^{184}\mathrm{W}$, at 84 MeV (a) and 92 MeV (b) beam energy are compared with Langevin model calculations for β=0 (solid line, corresponding to standard statistical-model calculations), β=3 (dotted line), β=5 (dashed line), β=7 (dash dot line), β=10 (double dot dash line) and β=20 $\times10^{21}\mathrm{s}^{-1}$ (short dash dot line). Experimental data (solid points with error bars) are taken from Ref. [9].

Figure 1 shows the measured evaporation residue spin distributions $P(\ell)$ at lower beam energies E_{lab}= 84 and 92 MeV and theoretical calculations for several different viscosity coefficients β. One can see that at a beam energy of 84 MeV the data can be described without dissipation. In addition, using different β's has no significant effect on the calculations. We interpret this as follows. Although nuclear dissipation delays the fission process, providing more time for particle emission, at low beam energy and hence at low excitation energy particle evaporation time is rather long. Consequently pre-saddle particles are not influenced strongly by dissipation (see Fig. 2), where it can be clearly seen that at E_{lab}=84 MeV, N_{gs} changes little with increasing β. Generally speaking, another reason is that a low beam energy results in a smaller fusion angular momentum. At low angular momenta ℓ fission barriers are high. So fission cross sections make only a small fraction of fusion cross sections. Further reduction by introducing a dissipation hardly makes any noticeable change in the fission cross section and accordingly in the evaporation residue cross section. Since evaporation residues are a sum of evaporation residue spin distributions over all relevant ℓ values, the above analysis actually shows that at the energy of 84 MeV the effects of different dissipation strengths on the evaporation residue spin distribution are negligible. In other words, at small beam energy evaporation residue spin distributions are not sensitive to the dissipation strength. For $E_{\rm lab}$=94 MeV, using different β's in the analysis has still a marginal effect on the spin distribution. At larger beam energies (see Figs. 3 and 4), however, the spin distribution shows a characteristic change in shape. The nuclear dissipation shifts the spin distribution towards high ℓ values, the shift itself becoming larger with increasing viscosity coefficient.

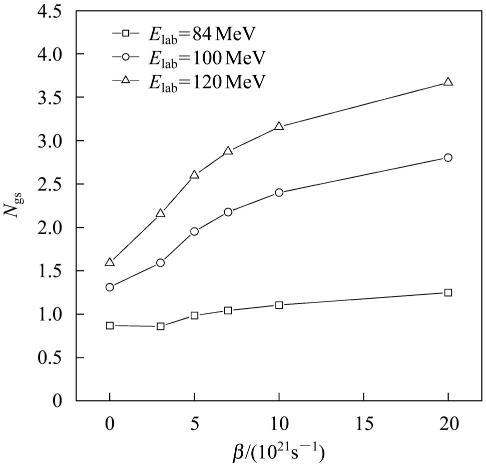

Fig. 2. Comparison of pre-saddle emitted neutrons ($N_{\rm gs}$) for the reaction $^{16}{\rm O}+^{184}{\rm W}\longrightarrow{}^{200}{\rm Pb}$ at three beam energies 84 MeV, 100 MeV and 116 MeV as a function of nuclear viscosity coefficient (β).

Figure 3 shows the theoretical and measured results at beam energies 100 and 108 MeV. It can be seen that the calculations with β=0 somewhat underestimate the experimental data. A careful comparison shows that both $\beta=3\times10^{21}{\rm s}^{-1}$ and $\beta=5\times10^{21}{\rm s}^{-1}$ reproduce the data equally good. A larger viscosity coefficient makes the fit less good. To better demonstrate the dissipation effects we also evaluate the spin distribution at larger beam energies (116 and 120 MeV). The comparison with experiment is shown in Fig. 4. It is evident that at 120 MeV beam energy the statistical-model calculation cannot describe the data at all at large ℓ values. The agreement between calculations and data is substantially improved if dissipation effects are included, indicating the crucial role of nuclear dissipation in understanding the data of the evaporation residue spin distribution. This also implies that dissipation effects become important at higher beam energies. It is due to the fact that the maximum angular momentum leading to fusion increases with increasing bombarding energy. At higher ℓ the fission barrier is significantly reduced. As a result the fission cross section becomes a substantial part of the fusion reaction cross section, i.e. the effect

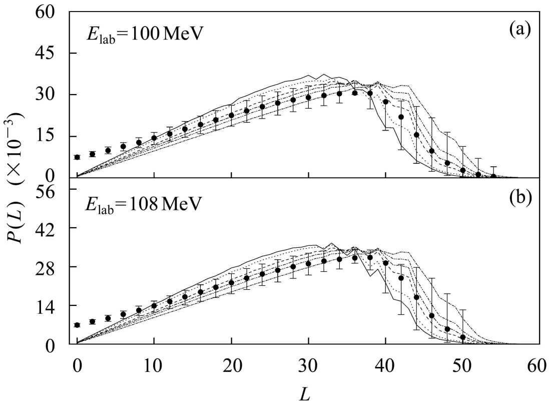

Fig. 3. Evaporation residue spin distributions for the reaction $^{16}{\rm O}+^{184}{\rm W}$, at 100 MeV (a) and 108 MeV (b) beam energy are compared with Langevin model calculations for β=0 (solid line, corresponding to standard statistical-model calculations), β=3 (dotted line), β=5 (dashed line), β=7 (dash dot line), β=10 (double dot dash line) and β=20 $\times10^{21}{\rm s}^{-1}$ (short dash dot line). Experimental data (solid points with error bars) are taken from Ref. [9].

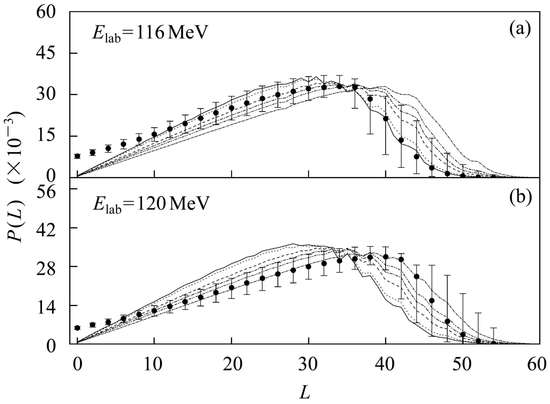

Fig. 4. Evaporation residue spin distributions for the reaction $^{16}{\rm O}+^{184}{\rm W}$, at 116 MeV (a) and 120 MeV (b) beam energy are compared with Langevin model calculations for β=0 (solid line, corresponding to standard statistical-model calculations), β=3 (dotted line), β=5 (dashed line), β=7 (dash dot line), β=10 (double dot dash line) and $\beta=20\times10^{21}{\rm s}^{-1}$ (short dash dot line). Experimental data (solid points with error bars) are taken from Ref. [9].

of slowing down of the fission process arising from dissipation is quite apparent. This means that fission cross sections (or equivalently evaporation residue cross sections) vary substantially with increasing viscosity coefficient. In addition to this, high excitation energy shortens the particle evaporation time, i.e. particle emission competes more effectively with fission, particularly at a larger dissipation strength. Fig. 2 illustrates that dissipation effects on the pre-saddle neutrons are enhanced with increasing beam energy. Pre-saddle particle emission carries away angular momentum and energy. This in turn increases the fission barrier and decreases the excitation energy. Both aspects favor the survival of evaporation residues. Thus a higher particle emission rate prior to the saddle point influences strongly the evaporation residue spin distribution, i.e. it increases the survival probability of evaporation residues at high spins. Furthermore, at larger ℓ the theoretical spin distribution using β=3×10^{21}s^{-1} is lower than the experimental data. However, a rather satisfactory agreement between theory and experiment is achieved for β=5×10^{21}s^{-1}. Therefore, combining the results shown in Figs. 1, 3, 4 we can safely conclude that β=5×10^{21}s^{-1} is needed to reproduce the overall trend of the evaporation residue spin distribution data at the six beam energies investigated. It should be mentioned that this extracted viscosity coefficient inside the barrier is not strong in comparison to the prediction of one-body dissipation. This conclusion is consistent with that obtained by Fröbrich[1] and also consistent with a recent estimation by Nadtochy et al.[17] arising from a detailed study of fission dynamics in fusion-fission reactions.

4 Summary

In summary, by performing a detailed comparison between Langevin calculations with the measured evaporation residue spin distribution of the ^{200}Pb system populated in the ^{16}O+^{184}W reaction, it is found that the stochastic approach to dissipative fission can describe this suggested new observable very well. Moreover, a pre-saddle viscosity coefficient of 5×10^{21}s^{-1} is extracted.

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