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ANALYSIS OF PRE-SCISSION NEUTRON MULTIPLICITIES IN TERMS OF THE STATISTICAL MODEL WITH KRAMERS DISSIPATIVE FISSION*

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Pre-scission neutron multiplicities in fusion-fission reactions, reported by Hinde *et al.*, have been analyzed in terms of the statistical model assuming a possible hindrance of the compound-nucleus fission width by the Kramers factor which depends on nuclear dissipation. Contrary to earlier results reported by Hofman, Back and Paul on an analysis of the GDR γ-decay, the nuclear dissipation deduced in the present analysis does not show a clear dependence on the temperature of the compound nucleus. On average, the deduced values of the nuclear dissipation are consistent with the one-body dissipation estimate.

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1. Introduction

The concept of nuclear dissipation was introduced into nuclear physics in 1940 by Kramers [1], and then revived in the early 70s in order to interpret deep-inelastic reactions in nucleus-nucleus collisions [2,3]. Empirical information on the magnitude of nuclear dissipation can be obtained

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on two ways: either from experiments on *non-fusion reactions* (strongly damped collisions, fast fission reactions) analyzed with *deterministic* trajectory calculations [4,5], or from so-called "delayed" fission characterized by an enhanced pre-scission emission of light particles and γ-rays which can be analyzed in terms of the statistical decay of the compound nucleus assuming the Kramers concept of *dissipative fission*. By using data on the pre-scission emission of γ-rays from the decay of giant dipole resonance, Hofman, Back and Paul [6] suggested a distinct dependence of the deduced dissipation constant on nuclear temperature, a feature that is inconsistent with the concept of one-body dissipation. In order to verify the results of Ref. [6], we have analyzed a rich set of pre-scission neutron multiplicities of Hinde *et al.* [7] and Rossner *et al.* [8]. Our results do not agree with conclusions of Ref. [6].

2. Calculations of the pre-scission neutron multiplicities

Experimentally measured pre-scission neutron multiplicities show significant deviations from predictions of the standard Bohr–Wheeler theory of compound-nucleus fission (see Ref. [9] and references therein). These deviations can be explained in terms of the Kramers diffusion theory, in which the diffusion process of the fission degree of freedom over the fission barrier is expressed in terms of the Fokker–Planck equation. The viscous diffusion process results in a fission width Γ^{K} that is reduced relative to the nonviscous Bohr-Wheeler width Γ^{BW} (calculated with the transition-state method):

$$\Gamma^{\mathrm{K}} = \Gamma^{\mathrm{BW}} \left(\sqrt{1+\gamma^2} - \gamma \right) , \tag{1}$$

where γ is the dimensionless dissipation coefficient.

In our approach we follow the Grangé–Weidenmüller method of estimating the time needed for the system to build up the quasistationary probability flow over the fission barrier (*i.e.* to reach the Kramers width Γ^{K}). We calculate the fission width as a function of time,

$$\Gamma_f(t) = \Gamma^{\mathrm{K}}[1 - \exp(-t/\tau_0)] \tag{2}$$

with the time constant τ_0 which can be related to the transient time τ between initiation of the diffusion process and the attainment of quasistationarity. For the case of an overdamped motion ($\gamma > 1$) Grangé *et al.* [10] estimated the time τ needed for the system to reach 90% of the asymptotic value Γ^{K}:

$$\tau = \frac{\gamma}{\omega} \ln(10 E_{\mathrm{B}}/T) , \tag{3}$$

where ω is the oscillator frequency in the potential well of the fissioning nucleus (typically, $\omega \approx 10^{21}$ s^{-1}), and E_{B} is the height of the fission barrier.

The result (3) inserted into Eq. (2) determines the time constant τ_0 in $\Gamma_f(t)$:

$$\tau_0 = \tau / \ln 10 = 0.43\tau. \tag{4}$$

We have included the friction-dependent fission width $\Gamma_f(t)$ into our Monte Carlo code that calculates event-by-event a sequence in time of the statistical decay of the composite system until fission is drawn. For a fixed value of γ and a given value of angular momentum one can calculate the average number of neutrons, $\nu_{\mathrm{presaddle}}$, evaporated before the instant of time when fission is decided and the system starts its no-return path from saddle to scission.

In a separate procedure we calculated with the program DYNSEQ [11] the average number of neutrons emitted during the final stage of the fission process, $\nu_{\mathrm{saddle-to-scission}}$. Since fission is decided beyond the saddle point, the fission channel is then excluded from the competition ($\Gamma_f = 0$). Light-particle emission is continued, starting with the value of the excitation energy that the system possessed at the saddle point. The process of generating the excitation energy during the descent from saddle to scission is calculated with the code HICOL [12] and coupled with the evaporation cascade calculation. Thus the actual excitation energy during the post-saddle cascade is continuously adjusted during the descent.

The sum of both components, $\nu_{\mathrm{presaddle}}+\nu_{\mathrm{saddle-to-scission}}$, can be related to experimentally measured values of the pre-scission neutron multiplicity, $\nu_{\mathrm{pre}}^{\mathrm{exp}}$. However, for quantitative comparisons the calculated multiplicities have to be averaged over the angular momentum. For the $\nu_{\mathrm{presaddle}}$ component, the averaging has been done up to an angular momentum ℓ_{lim} which limits a given fusion-fission reaction, $\ell_{\mathrm{lim}} = \min(\ell_{\mathrm{fu}}, \ell_{\mathrm{B_f=0}})$, where ℓ_{fu} is the limiting angular momentum for fusion (in the HICOL calculation), and $\ell_{\mathrm{B_f=0}}$ is the angular momentum for which the fission barrier (calculated according to Sierk [13]) vanishes.

Thus, for the pre-saddle component, the neutron multiplicity averaged over the angular momentum is:

$$\nu_{\mathrm{presaddle}} = \frac{\sum_{\ell=0}^{\ell_{\mathrm{lim}}}(2\ell+1)\nu(\ell)N_f(\ell)}{\sum_{\ell=0}^{\ell_{\mathrm{lim}}}(2\ell+1)N_f(\ell)}\,, \tag{5}$$

where $N_f(\ell)$ is a normalized number of Monte Carlo cascades which end in fission, and $\nu(\ell)$ is the corresponding pre-saddle neutron multiplicity for a given value of ℓ.

For the sake of simplicity, for the major part of the analyzed reactions, the saddle-to-scission component was not averaged, but calculated for the mean value of the angular momentum, $<\ell>=\frac{2}{3}\ell_{\mathrm{lim}}$. It has been checked in additional exact calculations carried out for selected reactions that this simplification does not significantly deteriorate accuracy of the calculations.

Figure 1 shows an example (for the ^{16}O + ^{238}U reaction) that illustrates how the value of the dissipation constant γ has been determined for each reaction. First, the neutron multiplicity originating from both, pre-saddle and saddle-to-scission stages (averaged over the angular momentum) was calculated as a function of the dissipation constant γ. It is seen from Fig. 1 that the saddle-to-scission component is significant and cannot be neglected in the calculations. The point where the calculated $\nu_{\rm presaddle}+\nu_{\rm saddle-to-scission}$ multiplicity equals to an experimental value $\nu_{\rm pre}$(exp) determines a value of the dissipation coefficient γ. (The two horizontal lines in Fig. 1 show the range of uncertainty in the determination of the $\nu_{\rm pre}$(exp) value. Thus, the crossing of the calculated $\nu_{\rm presaddle}+\nu_{\rm saddle-to-scission}$ dependence on γ with these two lines gives a measure of the uncertainty of the deduced value of γ.)

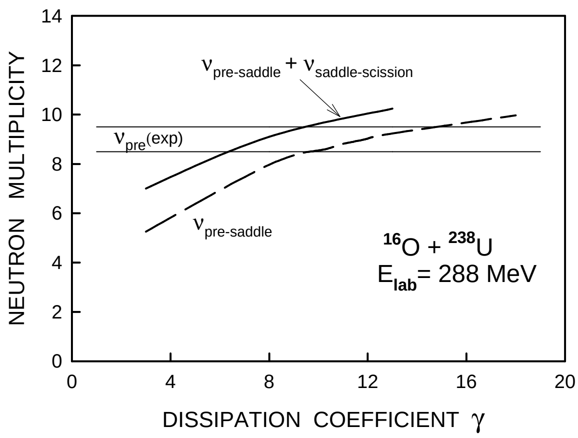

Fig. 1. Pre-scission neutron multiplicity in the ^{16}O + ^{238}U reaction at 288 MeV calculated as a function of the dissipation coefficient γ. Crossing of this dependence with a measured value $\nu_{\rm pre}$(exp) determines an experimental value of γ.

We performed our calculations for the whole set of pre-scission neutron multiplicities measured by Hinde *et al.* [7]. In Fig. 2 the results are plotted as a function of the temperature of the compound nucleus. The deduced values of γ are quite dispersed and do not show a clear trend in the temperature dependence. Thus, this result is inconsistent with the conclusions of Hofman, Back and Paul [6] who found in the analysis of the giant dipole resonance data a clear effect of the increase of γ with temperature. As it is seen from the error bars in Fig. 2, the measured pre-scission neutron multiplicities can give only an approximate information on the magnitude of the dissipation coefficient. However, on average, the deduced values of γ remain in agreement with the strength of one-body dissipation which is equivalent to γ in a range from 4 to 5.

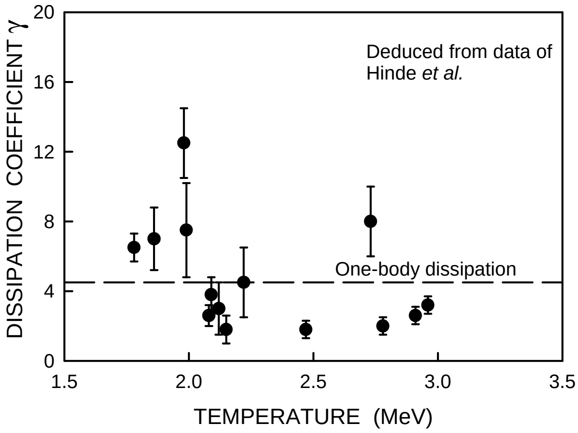

Fig. 2. Compilation of values of the dissipation coefficient γ deduced from pre-scission neutron multiplicities measured for different reactions by Hinde *et al.* [7]. The deduced values of γ are plotted as a function of the temperature of the compound nucleus.

We would also like to comment on the results of our earlier analysis of neutron multiplicity data in *fast fission* reactions [4]. Very large values of the dissipation coefficient ($\gamma = 10$–50) had been obtained in that analysis which definitely disagree with results of the present analysis of the *fusion-fission* data. We interpret this discrepancy as a result of "contamination" (due to fluctuations) of fast fission processes by a small component of fusion-fission reactions which, on grounds of the deterministic model calculations [4], were assumed to be totally absent. A contamination of fast fission reactions with fusion-fission processes (characterized by much higher pre-scission neutron multiplicity $\nu_{\rm pre}$) may lead to a considerable overestimation of the deduced value of the dissipation constant γ, especially due to the nonlinear relation between γ and $\nu_{\rm pre}$ which dramatically amplifies the effect of overestimation of $\nu_{\rm pre}$.

The inconsistency of the results of the present work with those of Refs. [6] and [4] demonstrates that determination of the nuclear dissipation is evidently very model-dependent and moreover — very sensitive to experimental uncertainties and precission of measurements. A more reliable and firm determination of the nature and magnitude of this very important quantity characterizing essential properties of nuclear matter will require new precise experiments and also well tested theoretical models for their interpretation.

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