PHYSICAL REVIEW C VOLUME 54, NUMBER 4 OCTOBER 1996

Viscosity and fission time scale of ^{156}Dy

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(Received 6 May 1996)

In the fusion-fission reaction ^{40}Ar+^{116}Cd→^{156}Dy→fission, performed at beam energies E_b=216 MeV and 238 MeV, γ rays were measured in coincidence with fission fragments. The γ-ray spectra are interpreted using a modified version of the statistical-model code CASCADE. From a comparison of the experimental and calculated spectra it is deduced that the nuclear viscosity is in the range $0.01<\gamma<4$. The extracted fission time scale is of the order of 10^{-19} s. [S0556-2813(96)50310-9]

PACS number(s): 25.70.Jj, 21.65.+f, 24.30.Cz, 24.60.Dr

Two of the interesting open questions in nuclear physics are the viscosity of nuclei and the time scale of the fission process. In Ref. [1] it is claimed that nuclei with an excitation energy of a few hundred MeV are very viscous (dissipation coefficient $\gamma\approx10$). This large viscosity hampers the fission motion, and therefore the compound nucleus lives longer than estimated with statistical considerations in which neutron decay and fission are in competition. Furthermore, once the compound nucleus has decided to fission, particles and γ rays can be emitted during its descent from the saddle to the scission point. Therefore, the nuclear viscosity and the fission time scale are closely related, and can be determined from experimental observations of prefission particle yields [2] or from γ-ray spectra [1]. Hinde *et al.* deduced from neutron spectra and multiplicities fission time scales of the order of 10^{-20} s. A reanalysis of their data in terms of a dynamical model, however, yields fission time scales of the order of 10^{-19} s [3]. This time scale is also reported by Paul *et al.* [1].

In this Rapid Communication we report on the measurements of two γ-ray spectra obtained in coincidence with fission fragments for the compound nucleus ^{156}Dy* produced at excitation energies of 104 and 124 MeV and large angular momenta. From these spectra the nuclear viscosity and the fission time scale are extracted, using a modified version of the statistical model code CASCADE [4]. Our analysis results in considerably lower values for the nuclear viscosity than reported in Ref. [1].

The fusion-fission experiment ^{40}Ar+^{116}Cd→^{156}Dy* →fission was performed with the K=160 cyclotron at KVI. Two experiments were performed. In the first experiment performed at a beam energy E_b=216 MeV compound nuclei were formed at an excitation energy E^*=104 MeV and angular momenta in the range $0<J<92\hbar$. In the second experiment the beam energy was E_b=238 MeV, leading to compound nuclei with E^*=124 MeV and $0<J<105\hbar$. The angular momentum distribution was calculated with the program CASCADE using as input the fusion cross section determined from the systematics of Wilcke *et al.* [5]. In these reactions fission occurs only at angular momenta larger than $J_{crit}\approx70\hbar$. Since the γ rays were measured in coincidence with fission, a selectivity on the angular momenta of the compound nucleus above $70\hbar$ is obtained. Close to the target, eight small BaF_2 crystals were placed to provide a time reference. The γ rays were measured with a large-volume NaI detector surrounded by a plastic shield that was used in anticoincidence mode. The fission fragments were detected by two position-sensitive avalanche detectors, of which the wire signals give the position where the particle impinged, and the anode signals its energy loss in the gas and a time signal.

In the off-line analysis the fission fragments were distinguished from projectilelike fragments and targetlike fragments by setting two-dimensional gates in the ''energy loss'' versus ''time-of-flight'' spectra, and only the events satisfying the criteria for fission fragments were considered. Neu-

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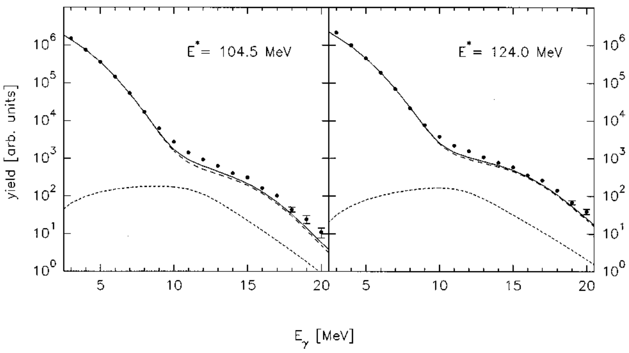

FIG. 1. The γ-ray spectrum (dots) measured at $E_b = 216$ MeV (left panel) and $E_b = 238$ MeV (right panel). The curves are the results of CASCADE calculations. The program was modified to calculate exclusively the prefission spectrum (dotted curve) and the postfission spectrum (dashed curve). The solid curve is the sum of the two.

trons and γ rays were discriminated by setting gates in the time-of-flight spectrum. Events for which two γ rays were detected within 400 ns were rejected and random coincidences were subtracted.

In Fig. 1 the obtained γ-ray spectra are presented along with results of model calculations. These model calculations were performed with the computer code CASCADE [4], which had to be modified in several aspects before meaningful calculations could be performed for these experiments. Because the γ rays associated with the channels leading to evaporation residues were not registered in the experiment, CASCADE was modified to calculate only the prefission component, ignoring the γ-ray emission from residual nuclei. This was achieved by an elaborate bookkeeping procedure for the contributions of all nuclear states to the final γ-ray spectrum [6]. For the level density we used $a=A/8$ MeV^{-1} and the parameters of the giant dipole resonance (GDR) for the compound nucleus were varied to fit the γ-ray spectra. The height of the fission barrier [7] had to be scaled with a factor $B_{\mathrm{scale}}=1.4$ in order to reproduce the fission cross section measured for various reactions in this mass region. For more details see Ref. [6].

In the standard program CASCADE the Bohr-Wheeler [8] description is used to calculate the fission cross section, but the conversion of this cross section to population cross sections of fission fragments and the consecutive decay of the fragments is not calculated. We have implemented this in the code starting from the compound nucleus formation cross section $\sigma_{\mathrm{CN}}(E^*,J)$. The program now provides matrices for the fission cross sections $\sigma_f(E^*,J)$ as a function of the mass and charge of the fissioning nucleus. These are subsequently used to calculate the population cross sections for the fission fragments. The calculations were performed assuming a symmetric mass distribution for the fission fragments with a width $\sigma\approx 12$ u [9]. The charge-to-mass ratio of the two fragments was taken to be equal. More elaborate schemes for the charge distribution, see, e.g., Ref. [10], lead to essentially the same result. The excitation energies of the fragments, E_1^* and E_2^*, were calculated from

$$E_{\mathrm{CN}}^* = E_1^* + E_2^* + \mathrm{TKE} - Q \tag{1}$$

and the assumption that the two fragments have equal temperature. Here, Q denotes the Q-value for fission, and TKE the total kinetic energy of the fragments. A Gaussian distribution for TKE was adopted. The mean value for TKE has been calculated from the Viola systematics [11]. The expression derived by Viola was modified in order to account for the dependence of the TKE on the mass split

$$\langle \mathrm{TKE} \rangle = 0.7750 \frac{Z_1 Z_2}{A_1^{1/3} + A_2^{1/3}} + 7.3 \ \mathrm{MeV}. \tag{2}$$

The width of TKE was deduced from published data [12]: $\sigma\approx 15$ MeV. The angular momentum distribution of the fragments was calculated with the statistical model of Moretto and Schmitt [13] following the description of Back *et al.* [14].

Using the mass, charge, excitation energy, and angular momentum of the fragments thus obtained, the contribution to the total γ-ray spectra from γ-ray decay of the fission fragments has been calculated with CASCADE. The γ-ray spectra from the fission fragments were calculated using the level-density parameter $a=A/8$ MeV^{-1} and GDR parameters inferred from existing systematics. This implies that it is assumed that 100% of the TRK sum-rule strength is exhausted, that the energy of the GDR resonance scales with mass, and that the nuclei are either spherical or deformed depending on their mass [6]. Furthermore, the moments of inertia, θ, of the fission fragments were determined from fits of the relation $(\hbar^2/2\theta)J(J+1)$ to the yrast states [6]. In Fig. 1 the results are shown. The theoretical spectrum is normalized to the data at 5 MeV. The slope of the spectrum is reproduced nicely, but for $E_\gamma > 9$ MeV the experimental yield exceeds the calculated strength. The agreement could not be improved by adjusting the GDR parameters, the level-density parameters, the parametrization of the excitation energy or the parametrization of the angular momentum of the fragments within reasonable limits.

Hence, it was concluded that the observed discrepancy was likely due to an inadequate description of the fission process. An underestimation of the γ-ray yield around 9 MeV can, for example, be explained by an underestimation of the prefission contribution to the γ-ray spectrum. Enhanced prefission γ-ray yield can in turn stem from hindrance of the fission process [1,2].

In order to investigate this effect, the fission width was modified in accordance with the results obtained by Grangé *et al.*, see Ref. [15] and references therein, in which the fission degree of freedom is treated as a random walk process and the fission flux across the saddle point is calculated from a Fokker-Planck equation. Their results can be approximated by the following equation:[1]

$$\Gamma_f(t) = \Gamma^{\mathrm{BW}}(\sqrt{1+\gamma^2} - \gamma)[1 - \exp(-2.3t/\tau)] \tag{3}$$

[1]Here, we follow Ref. [1]. Note, however, that our equation contains the required factor 2.3.

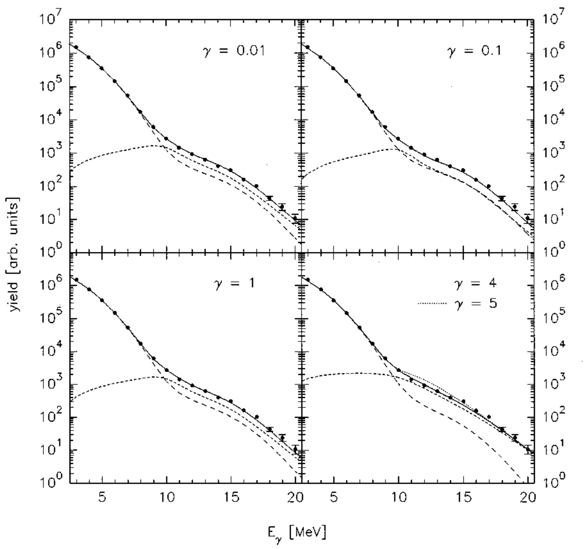

FIG. 2. Results of the fits of the GDR parameters at four different values of γ, for the experiment with E_b=216 MeV. The solid curve indicates the sum of the prefission spectrum (short-dashed curve) and the postfission spectrum (long-dashed curve). For comparison, a calculation with γ=5 is also shown (dotted curve).

with Γ^{BW} the Bohr-Wheeler fission width, γ the nuclear viscosity, t the time, and τ the time at which the flux across the barrier reaches 90% of the quasistationary value. We parametrized τ anew from the results of Grangé *et al.*

$$\tau(\beta,T)=(2\gamma)^{-1}\ln(10E_f/T)+0.0112\gamma A/T \quad [10^{-21}\ \mathrm{s}]. \tag{4}$$

Here, E_f is the height of the fission barrier, T is the temperature, and A is the mass number. τ has been calculated for every nuclear state in the cascade. Another expression for τ was obtained by Bhatt *et al.* [16], but the γ-ray spectra calculated with this expression are hardly different.

In the original version of CASCADE the probability for decay of a nucleus moving from the saddle point to the scission point is not calculated. To take this effect into account, the fission width has been treated analogously to the fission flux. The flux at time t at the saddle point is (almost) equal to the flux at the scission point at time $t+t_{ssc}$, with t_{ssc} the time required to propagate from the saddle point to the scission point [17]:

$$t_{ssc}=t^0_{ssc}(\sqrt{1+\gamma^2}+\gamma). \tag{5}$$

From the graphs presented by Grangé *et al.* [15], a value for t^0_{ssc} the saddle-to-scission time in nonviscous nuclei, can be inferred: $t^0_{ssc}=2.2\times10^{-21}$ s. Assuming the same time dependence for the fission width, one can approximate the latter as follows:

$$\begin{aligned}\Gamma_f(t)&=0, \quad t<t_{ssc}\\ &=\Gamma_f^{BW}(\sqrt{1+\gamma^2}-\gamma)\\ &\quad\times\{1-\exp[-2.3(t+\tau_d-t_{ssc})/\tau]\}, \quad t>t_{ssc}. \end{aligned}\tag{6}$$

The concept of time, which is unknown in the statistical code CASCADE, was implemented as follows. The lifetime τ_d of a nuclear state with excitation energy E^* and angular momentum J, which is used as a time step in the calculations, is given by

$$\tau_d=\frac{\hbar}{\Gamma_n(E^*,J)+\Gamma_p(E^*,J)+\Gamma_\alpha(E^*,J)+\Gamma_\gamma(E^*,J)+\Gamma_f(E^*,J,t)} \tag{7}$$

in which Γ_n etc. are the decay widths for all decay channels taken into account by CASCADE: i.e., neutron, proton, α particle, γ ray, and fission decay. The justification for the use of Γ_f in this equation is that the lifetime of a state is inversely proportional to the total width including Γ_f. The bookkeeping of these time increments is done in matrices $t(E^*,J)$ with the same dimensions as the matrices for the population cross sections, i.e., every nuclear state is characterized by the charge, mass, excitation energy, angular momentum, and the time at which the decay to it took place. Note that Eqs. (6) and (7) are coupled; therefore, they are solved iteratively. Including Γ_f in Eq. (7) will influence through the coupling to Eq. (6) the fission probability and thereby the GDR yield.

In the original CASCADE code no distinction is made between compound nuclear fission and quasifission. We implemented this distinction as follows. With the one-body dissi-

TABLE I. Results of the fission time scale for the different values for the viscosity.

E_b [MeV]	γ	B_{scale}	t_f[a] (10^{-20} s)
216	0.01	1.0	45±7
216	0.1	1.2	15±5
216	1	1.0	47±8
216	4	0.7	493±2
238	0.01	0.8	45±1
238	0.1	1.0	8±1
238	1	0.8	47±1
238	2	0.65	240±1

[a]The numbers used as error bars indicate the sensitivity to the threshold on the fission cross sections that is taken into account in the calculation. Here, it represents the difference in t_f for threshold of σ_f=0.5 mb compared to 0 threshold.

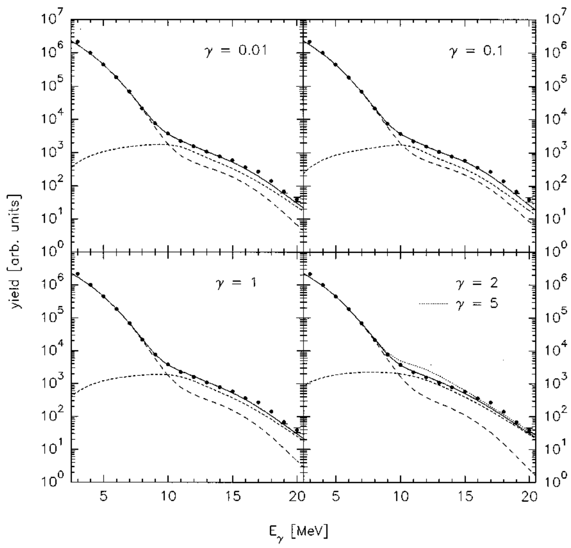

FIG. 3. The same as in Fig. 2, but now for the experiment with $E_b = 238$ MeV.

pation code HICOL [18], the angular momentum is calculated beyond which no equilibrated compound nucleus is formed. For the low- and high-beam-energy experiments, these values are, respectively, $87\hbar$ and $95\hbar$. For angular momenta larger than these critical values, the fission probability is set to zero when $t < t_{ssc}$ and to unity when $t > t_{ssc}$.

With this modified version of CASCADE, we performed fits to the data, with the aim to extract the GDR parameters for the compound nucleus and the value of the dissipation coefficient in Eq. (6). For the compound nucleus the level-density parameter $a = A/10$ MeV^{-1} was used. The scaling factors for the fission barrier, needed to reproduce the fission cross section, now depend on the value of the viscosity parameter γ and are given in Table I. For the fission fragments we used the previously mentioned parameters.

Results of calculations performed with different values of γ are shown in Figs. 2 and 3. The agreement between the calculations and the data is quite good. In these calculations the values for the GDR parameters of the compound nucleus are fitted to the data. The range of centroid energies in these fits is between 14.2 and 15.2 MeV, in fair agreement with the systematics value of 14.7 MeV. The widths varied in the range of $(3-5)\times 10^{-2}E^2$, where E is the resonance energy and sum rules were generally between 100 and 130%. The fits seem to indicate that a prolate deformation of the compound nucleus, with deformation $\beta \approx 0.5$, is favored. The results for the GDR parameters and deformations will be discussed in detail in a forthcoming paper [6]. It should be noted, however, that the dependence of these on the γ values is minimal.

The fission time scales t_f are calculated as an average of the times at which fission occurs weighted with the fission cross section (see Table I). They are dependent on the nuclear viscosity and vary within a few times 10^{-19} s. This is in agreement with the fission time scales obtained from the reanalysis [3] of the neutron measurements by Hinde *et al.* [2]. At the upper limits of γ, determined from fits to the γ-ray spectra, the time scales jump by about an order of magnitude again implying that a further increase in γ is not realistic.

The main point we want to emphasize in this paper are the values for the nuclear viscosity, and the way in which they were obtained. Different from earlier observations [1], the results presented in this paper show that no large value for the nuclear viscosity is needed to reproduce the data. The values $\gamma = 4$ and $\gamma = 2$ for the low- and high-beam-energy experiments are upper limits. Larger values for the nuclear viscosity lead to a profound overshooting of the data at $E_\gamma \approx 10$ MeV (see Figs. 2 and 3 for the $\gamma = 5$ calculation) resulting in sizeable deterioration of the χ^2. The scaling factors for the fission barrier, see Table I, also support the statement that $\gamma = 4$ and $\gamma = 2$ are upper limits since the scaling factor starts to deviate significantly from one at these values.

To understand more clearly the discrepancy with the results of Ref. [1] we also have compared our experimental data with calculations performed with the model described in Ref. [1]. It appears that these calculations reproduce reasonably the data for $\gamma > 10$ and $\gamma > 5$ for the low- and high-beam-energy experiments, respectively, but that the agreement worsens considerably when smaller values of γ are used. Therefore, the differences between our results and the ones presented in [1] (where the nuclei have mass $A > 200$) cannot be explained as a mass dependence of the nuclear viscosity, but should be ascribed to the differences between the two approaches.

An important difference between the two approaches is the way in which the time steps are calculated. We turned again to our own model to investigate this difference and removed as in Ref. [1] the fission width Γ_f from Eq. (7). The difference between the calculations thus obtained and the ones presented in Figs. 2 and 3 is considerable: only the calculations performed with $\gamma \approx 3$ are now able to reproduce the data [6]. This result still differs from the one obtained with the model described in Ref. [1], but the agreement is much better now since the smaller values for γ are ruled out. The remaining discrepancy probably can be ascribed to the different treatment of the saddle-to-scission process, the bookkeeping of time steps in matrices instead of using an average time as was done in [1], and the calculation of τ for every nuclear state instead of using an average value [1].

In conclusion, our analysis shows that fission hindrance is needed to explain γ-ray spectra obtained in coincidence with fission, but that in the analysis one has to take into account the fission width in the calculation of the time step if one wants to calculate the nuclear viscosity or the fission time scale. During the decay of the compound nucleus, a large number of states are populated in which the fission width is larger than the neutron decay width, and can, therefore, not be neglected. If the fission width is taken into account, the nuclear viscosities do not necessarily have to be large. With values in the range $0.01 < \gamma < 4$, the data can be described satisfactorily. The fission time scale depends on the value that is used for the nuclear viscosity. A typical value, however, can be said to be $t_f \approx 10^{-19}$ s.

This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek.

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