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Viscosity of Saddle-to-Scission Motion in Hot ^{240}Cf from Giant Dipole Resonance γ Yield

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The giant dipole resonance γ decay of ^{240}Cf excited to 67 and 93 MeV was measured from the fusion of ^{32}S + ^{208}Pb. The γ spectrum and γ-fission angular correlation are analyzed in terms of prefission and postfission γ-ray yields using a statistical model with nuclear viscosity in the fission process. The results show a strong increase in the prescission γ yield from 67 to 93 MeV. A saddle to scission time $\tau_{ssc} = 30 \times 10^{-21}$ s is extracted from this γ yield, equivalent to a normalized viscosity $\gamma \approx 5$ and full one-body dissipation.

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The dynamics of the fission process, in particular the effect of dissipation on the evolution of the nucleus from compound nucleus (CN) to the scission point, is a subject of current interest [1–3]. Dissipation governs the time taken by the nucleus to evolve to the scission point; thus it affects the multiplicity of giant dipole resonance (GDR) γ rays, neutrons, and charged particles which are emitted by the system on its way to fission. Prescission γ-ray and particle multiplicity measurements have, therefore, led to a reinvestigation of the viscous mass flow of the fission motion. These studies indicate that fission is hindered at higher excitation energies, i.e., higher temperature, as compared to standard statistical model predictions [4–6]. However, a consistent picture of the damping process is yet to emerge. A major question is whether one-body dissipation [7–9] (which is essentially temperature independent) or two-body viscosity [9–12] (which varies strongly with temperature) dominates the motion. The first GDR γ-ray studies that provided quantitative insight into these questions explored hot thorium compound systems. These results indicated a surprisingly large nuclear friction coefficient ($\gamma = 10 \pm 3$), with most of the GDR γ rays emitted before the system reached the saddle point configuration [13]. Statistical model calculations which include viscosity predict (see Fig. 1) that in heavier systems the emission of GDR γ rays during the descent from saddle to scission becomes increasingly dominant. This raises the prospect of using the GDR in californium to extract the time scale and thus the viscosity of the fission motion beyond the saddle point.

Use of the GDR γ decay to deduce the magnitude of nuclear dissipation has several important advantages. First, the high energy GDR γ rays are mainly emitted in the early decay steps of the CN, thus probing the high temperature dynamics of the system. Second, the prescission and postscission GDR γ-ray yields are readily separated since the GDR energy is proportional to $A^{-1/3}$ and independent of temperature (± 7%) [15]. In the case of the compound Cf system, the average GDR γ-ray energy is $\sim$ 12 MeV, whereas the mean energy of the fission fragment GDR strength is $\sim$ 16 MeV. Third, the GDR γ emission rate is one sum rule [16] (± 10%), making it a reliable nuclear clock independent of deformation. Finally, in deformed systems the GDR strength splits into components reflecting the nuclear dimensions along the principal axes. Therefore, the average shape of the γ emitting nucleus prior to fission can be deduced from the prescission γ-fission angular correlation [17].

The results presented here consist of high energy γ rays ($E_\gamma \leq 20$ MeV) measured in coincidence with fission fragments from the reaction $^{32}\mathrm{S} + {}^{208}\mathrm{Pb} \rightarrow {}^{240}\mathrm{Cf}$ at 200 and 230 MeV bombarding energy. The experiments were performed using a $\sim$ 3 particle nA pulsed ^{32}S beam from the Stony Brook LINAC incident on a self-supporting 675 μg/cm^2 ^{208}Pb target. The γ rays were detected with a 25.4×38.1 cm^2 cylindrical NaI crystal using a plastic anticoincidence shield for cosmic ray and energy leakage suppression, pulse shape analysis for pile-up rejection,

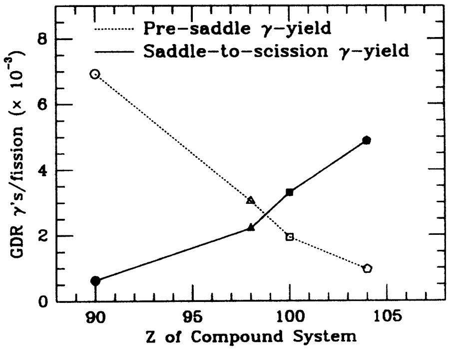

FIG. 1. Statistical model calculations of the total GDR γ-ray yield (E_γ=6–32 MeV) emitted from compound systems behind the fission barrier (presaddle) and during the saddle-to-scission motion. The calculations extrapolate from the 140 MeV $^{16}\mathrm{O} + {}^{208}\mathrm{Pb} \rightarrow {}^{224}\mathrm{Th}$ results of Ref. [13] (circles) using a nuclear friction coefficient γ=10. The additional calculations use the measured fission cross sections [14] for ^{16}O on ^{232}Th, ^{238}U, and ^{248}Cm forming compound systems ^{248}Cf (triangles), ^{254}Fm (squares), and ^{264}Rf (pentagons), all at an initial excitation energy of 84 MeV.

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and time-of-flight discrimination of neutrons [15]. The correlated fission fragment pairs were detected in kinematic coincidence with position sensitive parallel plate avalanche counters both parallel and perpendicular to the direction of γ rays [18]. This enabled a measurement of the total γ-ray yield as well as the γ-fission angular correlation.

The measured γ-ray spectra are compared with statistical model calculations using the code CASCADE modified to contain the effects of nuclear dissipation on the fission degree of freedom as well as the subsequent decay of the individual fission fragments [13]. The effect of nuclear dissipation on the motion from equilibrium deformation to the saddle point is included through modifications to the normal, nondissipative Bohr-Wheeler fission width, Γ_f^{BW}, according to

$$\Gamma_f(t) = \Gamma_f^{\mathrm{BW}}\{1 - \exp(-t/\tau_D)\}\frac{\hbar\omega_{gs}}{T}\left\{\sqrt{1+\gamma_i^2} - \gamma_i\right\}.$$

Thus the buildup of the fission motion in the potential minimum occurs with a time delay τ_D [19], and $\hbar\omega_{gs}/T\{\sqrt{1+\gamma_i^2} - \gamma_i\}$ results from Kramers' stationary solution [20] for the dissipative fission width. Here $\gamma_i = \beta/2\omega_{\mathrm{sp}}$ is the normalized linear friction coefficient for the interior, β is the reduced dissipation coefficient [21], and ω_{sp} is the characteristic frequency describing the potential energy surface at the saddle point. The value $\gamma_i = 1$ is the boundary between underdamped ($\gamma_i < 1$) and overdamped ($\gamma_i > 1$) motion. We assume $\hbar\omega_{gs}/T \approx 1$, which is reasonable for our calculations of high energy GDR γ rays since they are mainly emitted in the early CN decay steps. Additionally, the motion from saddle to scission is included by a time τ_{ssc} during which the system is allowed to further emit γ rays and particles. Since this analysis depends crucially on the ability of our statistical model code to reproduce the decay of the fission fragments, we have compared calculations [22] to recent high energy γ-ray measurements in the spontaneous fission of ^{252}Cf [23]. The results give confidence that the statistical code correctly calculates the deexcitation of the fission fragments.

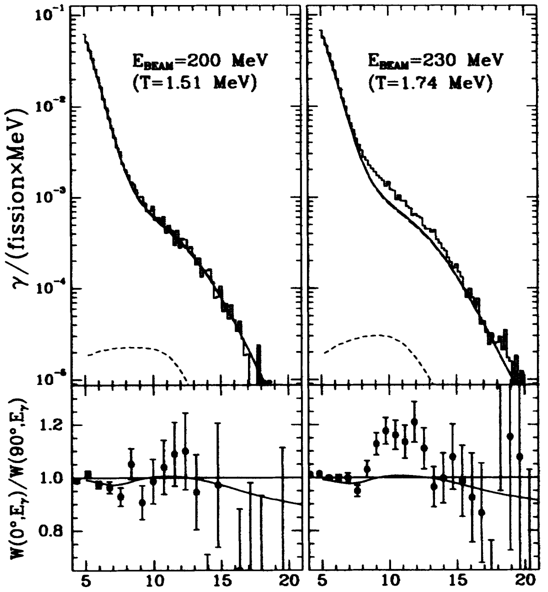

FIG. 2. Fits to the experimentally measured γ-ray energy spectra for 200, 230 MeV ^{32}S+^{208}Pb without the inclusion of nuclear viscosity. The short dashed line is the presaddle yield; the long dashed line is from the subsequent decay of the fragments; the solid line is a sum of these components; and the histogram is the experimental data. The fits are folded with the detector response and normalized to the data in the 5–7 MeV region. The lower two panels show the γ-fission correlation data (points with error bars) compared to the calculated correlation resulting from the respective fits to the γ energy spectra. The temperatures are calculated using $T = [(E^* - E_{\mathrm{rot}})/a]^{1/2}$ with $a = A/8.8$ and the rotational energy E_{rot} for the average angular momentum using the rigid sphere moment of inertia.

As a starting point in the analysis of the ^{240}Cf γ-ray data, a standard CASCADE calculation *without* dissipation was done for each bombarding energy. The CASCADE parameters are listed in Table I. Figure 2 shows the resulting predictions for the energy spectra and γ-fission angular correlations. One sees a dramatic increase

TABLE I. Summary of important statistical model parameters used in the calculations. The columns list the beam energy E_{lab} (MeV), compound nucleus (CN) excitation energy E^*_{CN} (MeV), total fusion cross section σ_{tot} (mb) [14], CN level density parameter a_n, average deformation β for the equilibrium configuration [24], and the corresponding energies and widths of the split GDR, E_1, Γ_1, E_2, Γ_2. The average CN GDR energy is taken to be 12.7 MeV, in agreement with the measured ground state GDR energy of ^{238}U [30]. The widths are calculated from the measured ground state widths of ^{238}U [30] using the results of Ref. [15]. Full Sierk fission barriers [31] are used and $a_f/a_n = 1$. Parameters for the subsequent decay of fission fragments are $a_{\mathrm{frag}} = A/9.0$, mean GDR energy $E_{\mathrm{frag}} = 79A^{-1/3}$ MeV, and $\Gamma_{\mathrm{frag}} = 9.3$ MeV [6,15].

E_{lab}	E^*_{CN}	σ_{tot}	a_n	β	E_1	Γ_1	E_2	Γ_2
200	67	400	$A/8.8$	−0.07	12.4	4.4	13.3	6.8
230	93	750	$A/8.8$	−0.14	12.2	5.9	13.7	8.3

in prescission γ yield when going from 200 MeV to 230 MeV bombarding energy. While the lower energy can be fit without inclusion of nuclear dissipation and shows no evidence of GDR γ rays from the compound system, the data at 230 MeV clearly indicate the presence of a strong prescission yield (E_γ = 9–14 MeV) in both the γ-ray energy spectrum and γ-fission angular correlation. Thus we concentrate on analyzing the 230 MeV data including the effects of nuclear dissipation. Because of the expected sensitivity to GDR γ rays from the saddle-to-scission decay, the saddle-to-scission time, $\tau_{\rm ssc}$, was left as a free parameter to fit the γ yield. The average excitation energy of the system during the saddle-to-scission decay was determined from $0.5(U_{\rm saddle} + U_{\rm scission})$ to be $\sim$ 100 MeV, and the nuclear friction coefficient *inside* the fission barrier was taken as either $\gamma_i = 10$ from the Th measurement [13] or $\gamma_i = 5$ for comparison. A collective prolate deformation of $\beta = 0.6$ was used for the splitting of the GDR for the saddle-to-scission γ rays. This deformation corresponds to the average RLDM saddle point shape [24] and is in close agreement with that used in the prior Th analysis [13]. The resulting saddle-to-scission GDR parameters are E_1 = 8.9 MeV, Γ_1 = 6.3 MeV, E_2 = 14.6 MeV, and Γ_2 = 8.7 MeV, where the widths are calculated in the same manner as for the equilibrium configuration (see Table I). The result of this procedure is shown in Fig. 3, where the fits show reduced χ^2 curves with a pronounced minimum at $\tau_{\rm ssc}$ = 26 (γ_i=10) and 30 (γ_i=5) $\times 10^{-21}$ s. As can be seen from the bottom panels of Fig. 3, these calculations approximate the magnitude of the measured γ–fission angular correlation, and even better agreement with the correlation is obtained by assuming the saddle-to-scission γ rays to come from a more compact shape with narrower widths for the GDR [25].

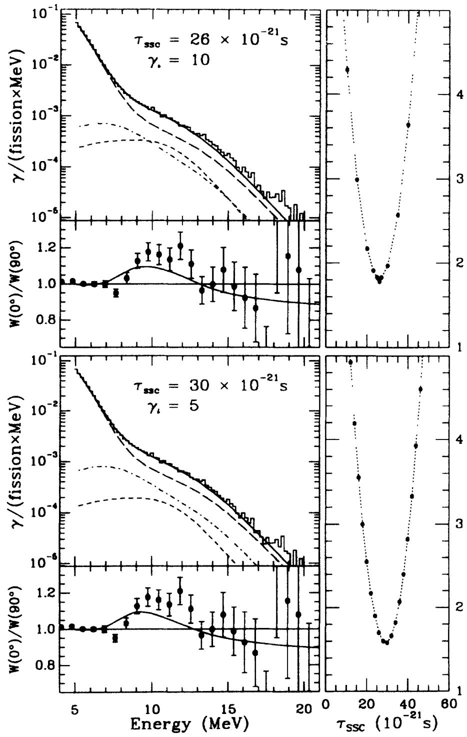

FIG. 3. Fits to the experimental γ-ray spectrum (histogram) from ^{240}Cf at bombarding energy 230 MeV ($T \approx 1.74$ MeV) and the corresponding χ^2 surfaces for the γ energy region 8–25 MeV using two values of the normalized nuclear friction coefficient inside the fission barrier. The contributions to the total γ-ray spectrum (solid) are from the three sources of presaddle (short dashed), saddle-to-scission (dot dashed), and fission fragment (long dashed) γ rays. The γ-fission angular correlation resulting from these fits (solid line) is shown below each γ-ray energy spectrum along with the measured data (points with error bars).

To relate this very long time scale to a viscosity we use the calculation of Hofmann and Nix [26], who found the saddle-to-scission time resulting from Kramers' stationary solution to the Fokker-Plank equation for the inverted oscillator to be $\tau_{\rm ssc} = \tau^0_{\rm ssc}(\sqrt{1+\gamma_0^2} + \gamma_0)$. Using $\tau^0_{\rm ssc} = 3 \times 10^{-21}$ s [27] and our result for $\tau_{\rm ssc} = 30 \times 10^{-21}$ s gives a value for the viscosity *outside* the barrier of γ_0 = 5. Thus we obtain a large viscosity corresponding to strongly overdamped fission mass motion from the saddle to the scission point, comparable to the viscosity inside the barrier. The sensitivity of the extracted time to the level density parameter values is given in Table II. The value $a = A/8.8$ is favored by experiment and theory [6,28].

Several theoretical estimates exist for the saddle-to-scission time scale in nuclei near Cf. Calculations of the saddle-to-scission time with the full effect of one-body surface-plus-window (wall-window) dissipation yields $\tau_{\rm ssc} \approx 35 \times 10^{-21}$ s [9,29], in agreement with our results. However, Nix and Sierk have described measured fission fragment mean total kinetic energies (TKE) as well as isoscalar giant quadrupole and octupole widths using a wall-window dissipation strength of k_s=0.27, resulting in a much shorter time $\tau_{\rm ssc} \approx 6 \times 10^{-21}$ s [29]. Calculations of the saddle-to-scission time for two-body viscosity which also describe the available fission fragment

TABLE II. Extracted saddle-to-scission times for the 230 MeV ^{32}S + ^{208}Pb reaction using different level density parameters. The columns list the level density parameter a_n, nuclear friction coefficient inside the barrier γ_i, extracted saddle-to-scission time $\tau_{\rm ssc}$ (10^{-21} s), and corresponding nuclear friction coefficient outside the barrier γ_0.

a_n	γ_i	$\tau_{\rm ssc}$	γ_0[a]
$A/8.0$	10	34	5.6
	5	36	6.0
$A/8.8$	10	26	4.3
	5	30	5.0
$A/10.0$	10	15	2.4
	5	12	1.9

[a] γ_0 calculated from $\tau_{\rm ssc} = \tau^0_{\rm ssc}(\sqrt{1+\gamma_0^2} + \gamma_0)$ [26].

TKE data result in very short times of $\tau_{\rm ssc} \approx 3.5 \times 10^{-21}$ s [9]. Both calculations assumed T=2 MeV. Very recent calculations of neutron multiplicities and fission fragment TKE's in hot ^{200}Pb favor one-body dissipation over two-body viscosity [1].

However, some discrepancies remain, and two-body viscosity should not be ruled out prematurely. The most direct way to differentiate between surface and bulk viscosity is by their energy dependence. In this connection we draw attention to the very rapid rise in the prescission GDR γ-ray yield from 200 to 230 MeV bombarding energy, over a range in excitation energy from 67 to 93 MeV. A comparable rapid rise in GDR yield is also evident in measurements of the Th system (see Fig. 5 of Ref. [18]) which we have recently confirmed. Although the effects of dissipation are necessary to fit our 230 MeV results, including dissipation in the calculation at 200 MeV overpredicts the measured γ yield. A similar effect in the same excitation energy region has been observed in the prescission time from the analysis of neutron emission [32], and more directly in the time scale of fission induced by peripheral collisions, where the entire energy region is simultaneously explored [33]. Our studies show that this rapid rise is not due to any formation effect, and thus should not impact on the extraction of $\tau_{\rm ssc}$ in the energy region of high γ multiplicity.

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