Rapid increase in prescission giant-dipole-resonance γ-ray emission with bombarding energy

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A rapid increase with energy has been observed in the emission of prescission giant dipole resonance (GDR) γ rays in excited Th and Cf nuclei formed in the ^{16}O+^{208}Pb and ^{32}S+^{nat}W,^{208}Pb reactions, which is not explained by the normal reaction dynamics near the barrier. This increase occurs over a narrow excitation energy range of E_{exc} = 40–60 MeV for the ^{16}O+^{208}Pb reaction and E_{exc} = 70–90 MeV for the ^{32}S-induced reactions. Below the transition energy the γ-ray spectra can be described by the standard statistical model, whereas inclusion of an increasingly strong nuclear dissipation is required to account for the data at higher excitation energies. For the ^{16}O+^{208}Pb reaction a fit to the GDR γ-ray spectra and evaporation residue cross sections is used to extract the temperature dependence of the linear dissipation parameter.

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I. INTRODUCTION

The issue of nuclear dissipation in the fission process has come to the fore again since many recent experiments now indicate large dissipation already at temperatures between 1 and 2 MeV. These experiments observe a large excess in prefission neutrons [1–3] or γ-ray multiplicities from the compound nucleus giant dipole resonance (GDR) [4–7], indicating that the fission process has slowed down. The evidence from charged particle emission is still controversial [8,9]. The GDR "clock" has additionally demonstrated that this slowing down affects the fission process inside the barrier as well as on the path from the barrier to the scission point [10]. The multiplicity data are analyzed in terms of the linear dissipation coefficient γ which can be compared to one-body or two-body dissipation processes. The experimentally deduced dissipation for the saddle-to-scission path is found to be equal to full one-body dissipation [10–12] while dissipation inside and at the barrier may even exceed it. These two mechanisms have a very different dependence on temperature; one-body dissipation is only weakly dependent on T, while two-body dissipation can vary strongly with increasing T. Thus the temperature dependence of the observed large dissipation is an important question for differentiating between the two processes.

Intuitively, one would expect that the substantial slowdown of the fission process observed at temperatures above 1 MeV cannot persist down to the barrier since this would affect all fission probabilities. Thoennessen and Bertsch [13] have demonstrated that the standard statistical model (without dissipation) agrees with experimental data at low energies but fails to describe the prescission particle yields for nuclei ranging from mass 160 to 260 above a universal energy threshold of $T > 0.26B_f(T)$. Here, T is the nuclear temperature and $B_f(T)$ is the temperature-dependent fission barrier. It has, however, recently been pointed out [14,15] that this observation reflects the sensitivity threshold for prescission neutron emission given the observed fission delay times of (20–40) $\times$ 10^{-21} s, rather than the onset of dissipation, and it should not be interpreted as such. In contrast, some experiments, including one where the fissioning system is populated in deep inelastic scattering [16], have already demonstrated that nuclear dissipation varies with excitation energy. The recent data using the GDR clock in ^{240}Cf through the reaction ^{32}S + ^{208}Pb appear to show a remarkably rapid increase of dissipation over a bombarding energy interval from only 200 to 230 MeV [10].

This has prompted us to review existing cases where fission hindrance was observed from GDR γ-ray multiplicities, for an explicit energy dependence of the linear friction coefficient. In one case, the reaction ^{16}O + ^{208}Pb $\rightarrow^{224}$Th, a complete data set of neutron multiplicities [17], γ-ray spectra, and, most importantly, the evaporation residue cross section [18] as a function of bombarding energy is avaliable. The latter is an especially sensitive check on the fission slowdown [19]. We report here, for this case, the energy (or temperature) dependence of the friction parameter γ directly from a fit to the data. We believe this is the first time that the functional dependence of nuclear friction on temperature has been explicitly obtained.

II. ANALYSIS

In the present work we have reanalyzed high-energy γ-ray spectra measured in coincidence with fission fragments in reactions of ^{16}O+^{208}Pb at E_{lab} = 100, 120, 140

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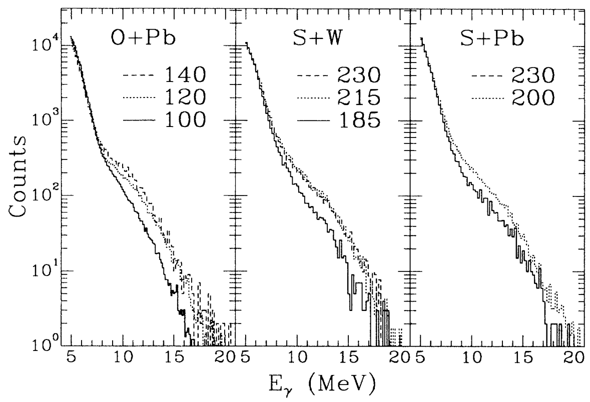

FIG. 1. Data shown are the result of measurements for the systems $^{16}O+^{208}Pb$, $^{32}S+^{nat}W$, and $^{32}S+^{208}Pb$ at the given bombarding energies. Data have been normalized at low energies to show the relative contribution of prescission GDR yield for different bombarding energies (given in the figure).

MeV [4–6], $^{32}S+^{nat}W$ at E_{lab} = 185, 215, 230 MeV [6], and $^{32}S+^{208}Pb$ at E_{lab} = 200, 230 MeV [10] with the purpose of exploring the effects of increasing temperature on the magnitude of nuclear dissipation. Figure 1 displays the experimental γ-ray energy spectra normalized in the low-energy region to illustrate the relative yields of the prescission GDR γ rays (E_γ = 7–15 MeV) for various bombarding energies. In all cases, the GDR strength in this region rises strongly with increasing bombarding energy, showing an increased ability for the prescission GDR γ-ray emission to compete with a hindered fission decay channel. It points to a dissipation in the fission process which is small at the low excitation energy and increases in strength at higher energies.

For further refinement, these experimental γ-ray spectra and corresponding γ-fission anisotropies are compared with two statistical model calculations in Fig. 2. The solid curves represent CASCADE (expanded to include the fission process [5]) statistical model calculations without dissipation in the fission decay (γ=0), and the dashed curves correspond to a constant dissipation

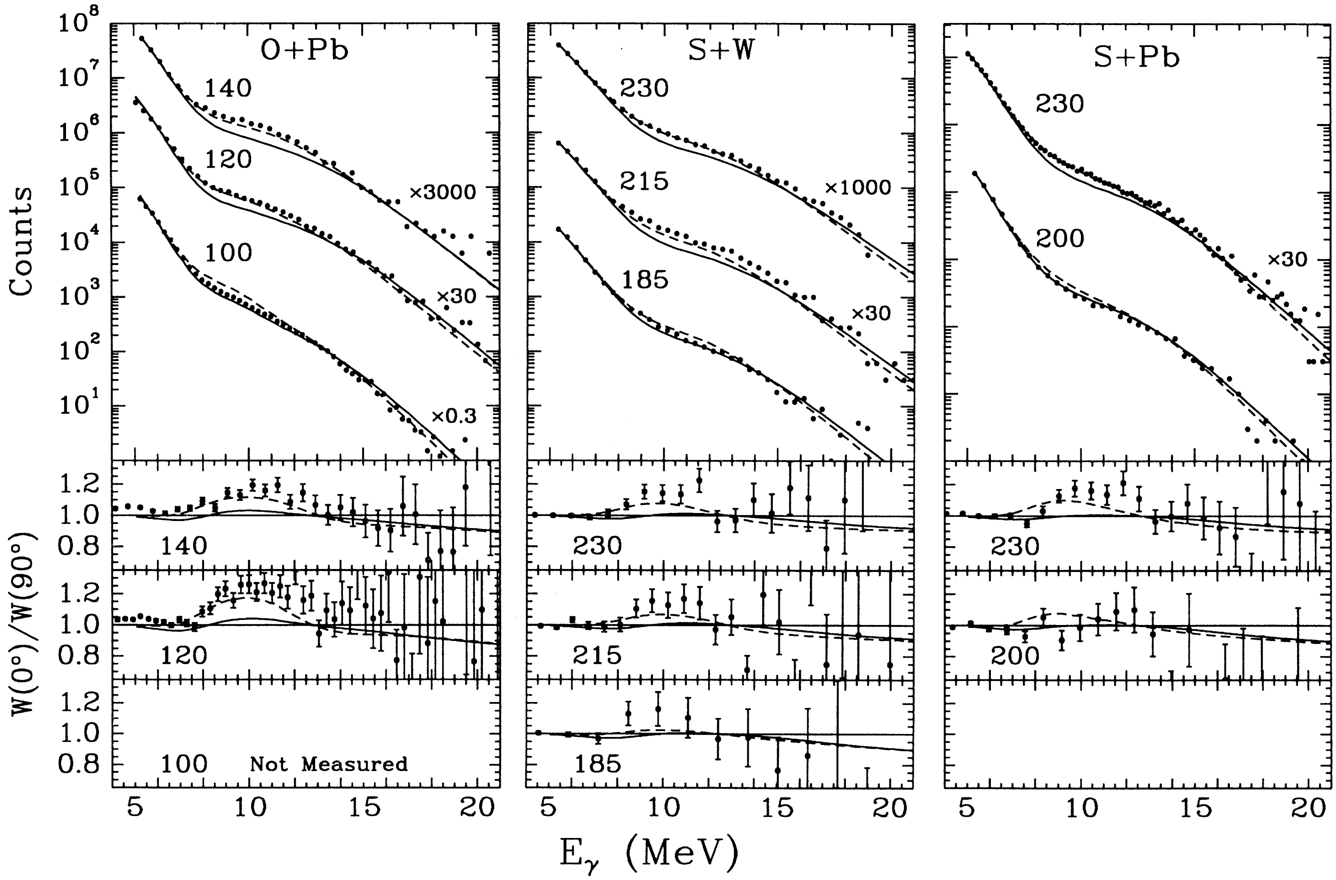

FIG. 2. Upper panels: experimental γ-ray spectra (solid points) are compared to statistical model calculations without the effects of dissipation (solid curves) and with constant dissipation γ = 5 (dashed curves) for the systems $^{16}O+^{208}Pb$, $^{32}S+^{nat}W$, and $^{32}S+^{208}Pb$. Lower panels: the corresponding γ-fission anisotropies. The curves are the theoretical anisotropies resulting from the statistical model fits to the energy spectra shown in the upper panels.

TABLE I. Some parameters relevant for the reactions studied and used in the calculations of Figs. 2, 3. The compound nucleus formation cross section σ_{CN} and the capture cross section σ_{cap}, which include complete fusion and quasifission reactions, were obtained from the extra push model using the parameters of Ref. [26].

Reaction	CN	E_{lab} (MeV)	E^* (MeV)	σ_{CN} (mb)	σ_{cap} (mb)	L_{cap} ($\hbar$)	$L_{B_f=0}$ ($\hbar$)
$^{16}O+^{208}Pb$	$^{224}Th_{134}$	100	46.5	630	670	38	76
		120	64.9	1035	1190	55	
		140	83.5	1250	1530	67	
$^{32}S+^{nat}W$	$^{\sim216}Th_{\sim126}$	185	76	290	580	62	71
		215	101	505	985	87	
		230	114	575	1110	95	
$^{32}S+^{208}Pb$	$^{240}Cf_{152}$	200	67	240	635	68	61
		230	93	445	1010	92	

value corresponding to full one-body dissipation (γ=5). Here, $\gamma = \beta/2\omega$ is the normalized linear friction coefficient which describes the magnitude of nuclear dissipation in terms of β, the reduced dissipation coefficient, and ω, the frequency describing the curvature of the potential energy surface at the saddle point. β is connected directly with macroscopic (dynamical) calculations of fission employing the Fokker-Planck equation [20–22]. For the CASCADE calculations of Fig. 2 the level density parameter at high excitation energies is taken as $a_n = A/8.8$ and the full Sierk fission barrier [23] is employed (i.e., k_f=1). The relevant reaction parameters are listed in Table I. The GDR γ strength is based on one classical dipole sum rule, in agreement with presently known experimental data [24]. The remaining input is the same as in prior work [4–6,10]. For comparison with the data the calculated spectra have been folded with the response function for the NaI(Tl) detector and were normalized to the experimental spectra over the E_γ = 5–7 MeV region. Gamma rays in this energy range are predominantly emitted by the fission fragments.

For each reaction the statistical model calculations without dissipation (solid lines) give a reasonable account of the experimental spectra at the lowest beam energies. However, an excess γ-ray yield is present in the energy region E_γ = 7–15 MeV at higher bombarding energy, and the calculations including constant dissipation (γ=5, full one-body dissipation) begin to describe these spectra. As demonstrated in earlier work [5,10], the excess γ-ray yield in the E_γ =7–15 MeV region stems from the compound nucleus and results from the slowing down of the fission process caused by nuclear dissipation.

The γ-ray anisotropies relative to the fission direction, shown in the lower panels of Fig. 2, also indicate an increased dissipation in the fission motion at the higher energies. The positive anisotropy in the region E_γ = 7–13 MeV is direct evidence for prescission emission since it arises from the spatial orientation of the nuclear symmetry axis of the fissioning compound system [25]. Conversely, the absence of this anisotropy for the E_{lab} = 200 MeV $^{32}S+^{208}Pb$ and a reduced anisotropy for the E_{lab} = 185 MeV $^{32}S+^{nat}W$ reactions is consistent with a reduced dissipation at low beam energy or indicates that a compound system has not been formed.

In order to quantify this enhancement of the prescission γ-ray yield, the excess γ-ray multiplicities in the energy region E_γ = 7–15 MeV were extracted by subtracting the nondissipative statistical model prediction (solid curves in Fig. 2) from the measured spectra. These excess multiplicities are shown as a function of excitation energy in Fig. 3. A sharp transition to increasing prescission γ-ray emission occurs at an excitation energy between E_{exc} = 40–60 MeV for the $^{16}O+^{208}Pb$ reaction and at a higher excitation energy of E_{exc} = 70–90 MeV for the ^{32}S-induced reactions. Calculations which include a constant dissipation strength for the saddle-to-scission motion only (dotted line), as well as for the motion both inside and outside the saddle point (dashed line), fail to describe the energy dependence of this excess yield.

A reason for the rapid increase of prescission γ rays could be a threshold effect in the formation of the com-

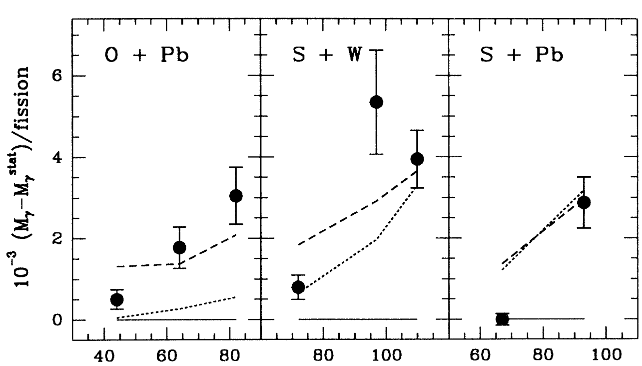

FIG. 3. The excess γ-ray multiplicity is shown (solid points) as a function of the excitation energy in the compound system. The dotted curves represent statistical model calculations including the effects of a saddle-to-scission time of $t_{ssc} = 30 \times 10^{-21}$ s (γ_o=5), whereas the dashed curves also include the effects of dissipation inside the saddle point (γ_i=5). Error bars reflect the contribution of three sources of uncertainty: pure statistical ($\sim$ 5%), calculational ($\sim$ 15%), and normalization ($\sim$ 80%).

pound system. Perhaps a larger percentage of complete fusion is occurring for the higher beam energies. As a check on this possibility, the partition of the cross section between complete fusion-fission and quasifission reactions was estimated from the extra push model with the parameters of Ref. [26]. As seen in Table I no dramatic change in the ratio between the two reaction types is expected in the excitation energy range studied. Quasifission is thus ruled out as a possible cause of the observed rapid increase. In any case, the effect of quasifission was taken into account in these calculations, as follows. For complete fusion-fission reactions, γ emission both prior to passage over the saddle point and during the saddle-to-scission motion is included in the calculation, whereas the quasifission component contains only the latter part. However, even assuming complete fusion-fission for all reactions does not noticeably change the calculated spectra at the higher beam energies where the excess yield of γ rays is visible. This is because the high partial waves, for which the fission barrier has vanished ($L > L_{B_f=0}$), will not lead to the formation of a compound system in either calculation. Thus it is unlikely that the observed rapid increase in prescission γ rays is associated with a sudden change in the reaction mechanism.

In a recent work, Thoennessen *et al.* [27] have suggested that an observed entrance channel effect may be caused by differences in the fusion time scale which affects the the γ-emission strength during the fusion process. The HICOL nuclear reaction code [28] which includes full one-body dissipation predicts that fusion time scales in the present reactions are essentially independent of beam energy. On this basis, an entrance channel effect is also unlikely to be responsible for the observed sudden increase in prescission γ emission.

A clearer picture of this effect emerges when other measurements are included to constrain the model calculations over the entire excitation energy region of interest. Presently this is only possible for the ^{16}O + ^{208}Pb reaction, where both the evaporation residue measurements of Brinkmann *et al.* [18] and the neutron multiplicity measurements of Rossner *et al.* [17] cover the energy region of interest, from E_{exc} = 30–87 MeV (E_{lab}= 80–140 MeV).

As a starting point, Fig. 4 shows the evaporation residue cross section (σ_{ER}), and the prescission (ν_{pre}) and postscission (ν_{post}) neutron multiplicity data compared to CASCADE calculations without dissipation. Three sets of calculations were performed, each with different values of the k_f multiplier to the Sierk [23] fission barrier. These calculations were based on experimental fusion cross sections at the different bombarding energies given by Refs. [29–31]. The l diffuseness of the spin distribution was taken from [19]. As already pointed out by Brinkmann *et al.* [18], the full Sierk fission barrier must be reduced by 10% ($k_f = 0.9$) to fit the residue yields at the lower bombarding energies (assuming $a_n = A/8.8$ and $a_f/a_n = 1$). This factor is in good agreement with the predicted effect of temperature on the fission barrier [32]. The barrier temperature dependence (for L=0) goes as [(1.0-0.115T^2 (MeV)], yielding values for k_f = 0.89–0.66 over the region of interest. Using this T dependence yields the correct

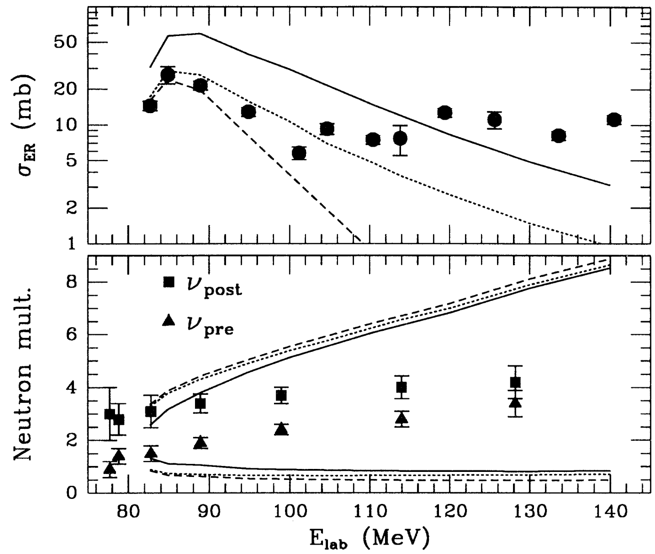

FIG. 4. CASCADE calculations of σ_{ER}, and $\nu_{pre,pos}$ for the reaction ^{16}O + $^{208}Pb \to {}^{224}Th$ without dissipation using different k_f multipliers to the Sierk fission barriers: k_f = 1.0 (solid lines), k_f = 0.9 (dotted lines), and $k_f = 1.0 - 0.115T^2$ (dashed lines). The experimental data are from Refs. [18,17].

σ_{ER} for E_{lab} < 94 MeV. We note that recent calculations by Fröbrich and Tillack indicate a much weaker temperature dependence [33]. However, as Fig. 4 illustrates, in order to describe the experimental σ_{ER} and $\nu_{pre,post}$ data at the higher energies some additional effect is clearly necessary in either case (k_f = const or reduced at higher energy).

Thus, as the next step we include dissipation in the calculations. Figure 5 shows the complete data set, σ_{ER}, $\nu_{pre,post}$, and the three known GDR γ-ray energy spectra, compared with two CASCADE calculations. The dashed line, reproduced from Fig. 4, corresponds to statistical model calculations without dissipation but including the reduced fission barriers for increasing bombarding energy. It fails in all cases for E_{lab} > 94 MeV. The solid lines include dissipation through the linear friction parameter γ which is varied as a function of bombarding energy to reproduce σ_{ER} for data below E_{lab} = 94 MeV and, independently, to describe the three measured γ-ray spectra for E_{lab} > 94 MeV. The extracted dissipation values γ_{fit} are shown in the bottom three panels. The same value of the linear dissipation coefficient γ_{fit} was used to describe the fission flux over the saddle point and the descent from saddle to scission. The sensitivity to the latter part for this reaction is rather insignificant as shown in Fig. 3. It is satisfying that this procedure results in a good description of both σ_{ER} and the GDR γ-ray data over the entire bombarding energy region even though σ_{ER} was not used to constrain γ_{fit} for E_{lab} > 94 MeV. However, this excitation energy dependence of the dissipation strength fails to reproduce the neutron multiplicity data (except maybe at the highest energy), although a clear improvement over the nondissipative statistical model estimate is evident.

The two lower right panels of Fig. 5 show the extracted dissipation values $\gamma_{\rm fit}$ versus $T_{\rm saddle}$ and $T^2_{\rm saddle}$ together with straight line fits to the last four data points where the deviation from $\gamma_{\rm fit} = 0.2$ begins (i.e., $E_{\rm lab} \geq 94.9$ MeV, $T_{\rm saddle} \geq 1.17$ MeV). The resulting fit values are

$$\gamma = 16.49 T_{\rm saddle} - 18.57,$$
$$\gamma = 5.71 T^2_{\rm saddle} - 6.91.$$

We cannot differentiate between a T or T^2 dependence. The saddle point temperature $T_{\rm saddle}$ is chosen because in the ^{16}O + ^{208}Pb reaction the dissipation affects the fission process mostly through the Kramers [20] factor which reduces the flow rate over the saddle [5]. $T_{\rm saddle}$ is defined by $E^*_{\rm saddle} = aT^2_{\rm saddle}$, with the level density parameter $a = A/8.8$ and the excitation energy at the saddle point $E^*_{\rm saddle} = E_{\rm lab} + Q_{\rm fus} - E_{\rm rot} - B_f$. The rotational energy $E_{\rm rot}$ and fission barrier B_f are taken at the average angular momentum of the compound nucleus.

As a final step in exploring an energy-dependent dissipation coefficient, further calculations were performed with two improvements: an excitation energy cut below which the nondissipative fission rate is restored and a fission barrier height which increases smoothly as the temperature of the compound nucleus decreases due to particle and γ emission. Taking the energy threshold as $E_{\rm exc} = 40$ MeV and employing the barrier temperature dependent factor of $(1.0\text{–}0.115T^2)$ yields results in full agreement with the above analysis (the two calculations agree to within 9% for $\sigma_{\rm ER}$, 1% for $\nu_{\rm pre,post}$, and 2% for the GDR γ-ray spectral multiplicities). This results from the fact that, as the excitation energy is lowered, the effect of vanishing dissipation on the fission process is compensated by the restoration of the fission barrier.

III. DISCUSSION

The main result of this analysis is that the hindrance of the fission process sets in over a surprisingly narrow region in bombarding energy. In the ^{16}O + ^{208}Pb reaction it is the Kramers [20] factor which plays the major role in

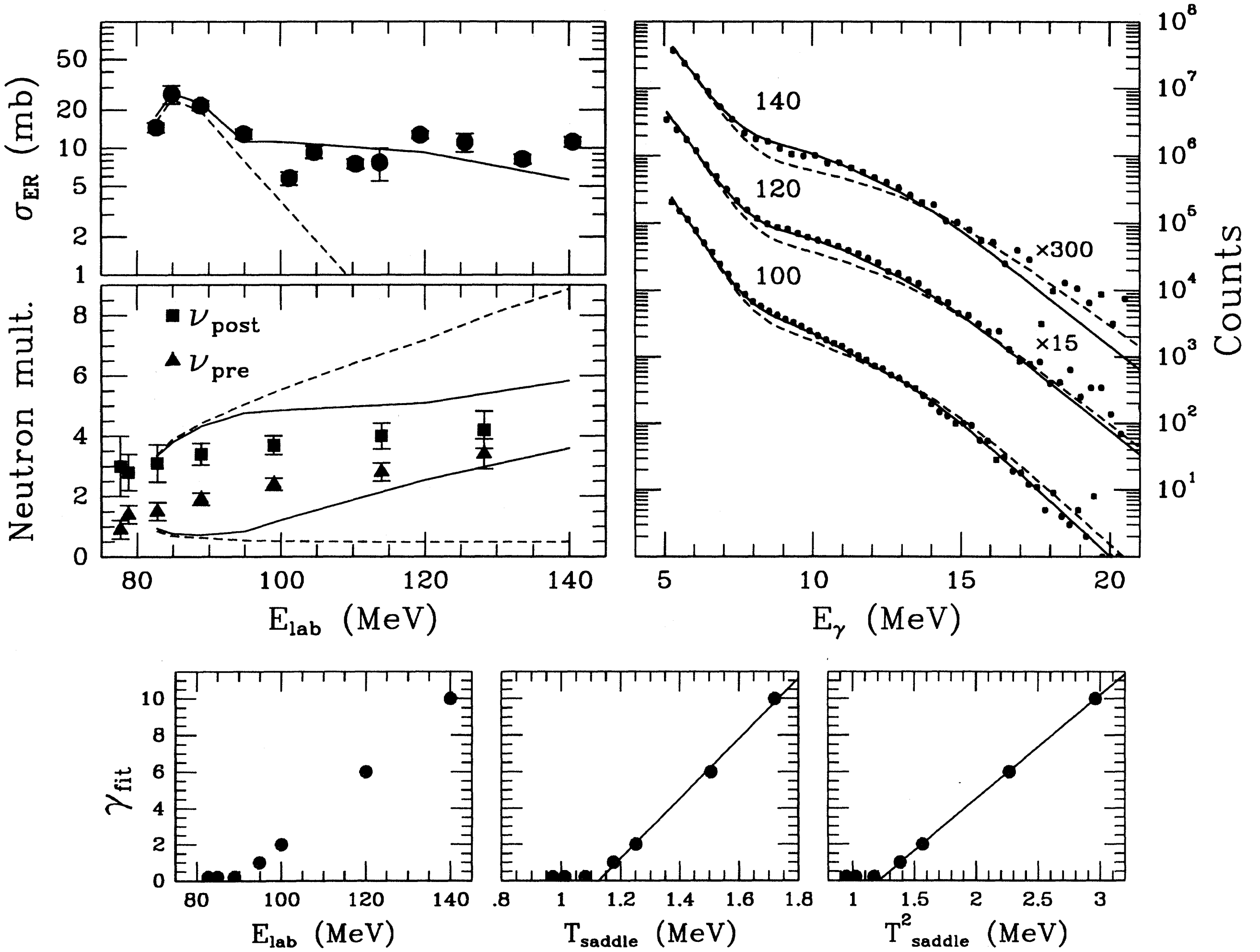

FIG. 5. Comparison of CASCADE calculations to known GDR γ-ray spectra, $\sigma_{\rm ER}$ values, and neutron multiplicities for the ^{16}O + ^{208}Pb reaction. Dashed lines are calculations without dissipation and solid lines are the result including the dissipation values $\gamma_{\rm fit}$, shown in the bottom three panels.

the hindrance through the dissipation coefficient γ. Thus our analysis implies it is this dissipation (at or inside the saddle point) which increases strongly with temperature. The Kramers factor, derived from random-walk fluctuations, is essentially a two-body viscosity arising from classical Brownian motion. An explanation of the apparent onset of this viscosity with temperature may lie in the fact that the nucleus is not a classical system. The effect of quantum Brownian motion on the fission process has been shown to deviate significantly from classical expectation below a critical temperature $T_{\rm cr}$ = 1–2 MeV [34]. At lower temperatures quantum fluctuations *enhance* the fission rate over the classical dissipative case. At higher temperatures the effects of quantum Brownian motion on the fission process agree with classical predictions. This is in full agreement with the analysis of this work; i.e., the magnitude of viscosity obtained with the classical Kramers factor must be reduced at lower temperatures in order to increase the fission rate to the observed level. A reduction in viscosity from γ=5 to γ=0.2 corresponds to a factor 8.3 increase in the fission rate. This is in good agreement with the magnitude of the predicted fission rate increase for the quantum case at T = 0.5 MeV [34]. Recent theoretical work employing a quantal transport equation by Hofmann *et al.* [35] also demonstrates this enhancement of the dissipative fission decay rate at low temperature. In this light, the observed rapid increase in prescission γ-ray emission is caused by an onset of two-body viscosity at the saddle point.

Several additional theoretical models for nuclear dissipation have been put forward. The one-body dissipation mechanism has been successful in describing a large variety of phenomena in fusion, fission, and quasifission reactions. It applies to systems with low shape symmetries and nucleon mean free paths comparable with the nuclear dimensions [36]. In particular, one-body dissipation reproduces the systematics of fission fragment kinetic energies very well, even at low excitation energies. This is not surprising for the lower symmetry of the fissioning system approaching the scission point. If the motion from saddle to scission is governed by one-body dissipation, this results in time scales of the order $t_{\rm ssc} = 30 \times 10^{-21}$ s [11] corresponding to a normalized dissipation constant of γ = 5 [37,38]. This is in agreement with experiment [10]. However, one-body dissipation has a negligible temperature dependence [39]. This can be seen from the following estimate for the reduced dissipation strength [40]:

$$\gamma^q_{\rm wall} = \frac{\beta_{\rm wall}}{2\omega} = \frac{\eta_{\rm wall}}{2\omega M_q}, \qquad (1)$$

where ω is the oscillator frequency of the inverted parabola describing the fission barrier. $\eta_{\rm wall}$, the damping coefficient for quadrupole deformations, is given on the basis of the wall formula [39] by

$$\eta_{\rm wall} = \frac{9(9\pi)^{1/3}\hbar A^{4/3}}{40}. \qquad (2)$$

$M_q = \frac{3}{10}M_0R_0^2$ is the mass parameter for incompressible irrotational flow, with $M_0 = nA$ the mass of the system and $R_0 = 1.2A^{1/3}$ fm its radius. This results in values $\gamma^q_{\rm wall}$ = 5.5, 5.6, and 5.4 for the O+Pb, S+W, and S+Pb reactions, respectively, again in agreement with expectation. Within this model $\eta_{\rm wall}$, and therefore $\gamma^q_{\rm wall}$, does not depend on temperature, and it cannot by itself account for the rapid onset of the fission dissipation strength observed in the present data.

However, it is well known that the full classical one-body dissipation limit is not reached at low excitation energies in near-spherical nuclei as evidenced by, e.g., the width of the isoscalar giant quadrupole resonance, which falls in the excitation energy region $E^* \approx 10$ MeV in heavy nuclei. Nix and Sierk [40] have shown that experimental GQR widths are grossly overpredicted by the wall formula for one-body dissipation for convex shapes. It was concluded that a reduction to 27% of its chaotic regime limit is required to reproduce these widths [41]. Such a reduction is still able to describe measured fission fragment mean total kinetic energy values if applied to the saddle-to-scission motion, but it results in a much shorter saddle-to-scission time $\tau_{\rm ssc} \approx 6 \times 10^{-21}$ s. For the shape symmetries expected in the GQR excitation energy region it may be unreasonable to expect that the conditions for the wall formula are fulfilled.

Additional evidence for negligible dissipation in the fission motion at low excitation energy is obtained from the analysis of fission probabilities in the energy range up to E^*=12 MeV in (^{3}He,df) and (^{3}He,tf) reactions on actinide nuclei [42]. These authors find that an enhancement of the fission width is necessary in order to reproduce the fission probability at E^* = 7–12 MeV. This enhancement is attributed to the breaking of shape symmetries at the second barrier thereby increasing the number of fission channels. Thus, a substantial (Kramers factor) reduction of the fission width is not compatible with these data, placing an upper limit of $\gamma \leq 1$ on the normalized dissipation strength in this excitation energy region. Similarly, Dagdeviren and Weidenmüller find $\gamma \leq 0.22$ for the ground state fission of uranium [43], and Schultheiss and Schultheiss find low dissipation favored in the spontaneous fission of ^{252}Cf [44].

An intriguing possibility is that the observed onset of dissipation is a manifestation of the transition from ordered to chaotic nucleon motion with excitation energy [36]. This transition may stem partly from the disappearance of shell-stabilized shape symmetries with excitation energy or the breaking of pair correlations. In this context, we note that the S+W,Pb reactions produce shell-stabilized initial compound systems with N = 126 and N = 152, respectively, while the O-induced reaction does not (N = 134). This may explain the difference in transition energy between the two reactions (see Fig. 3).

Alternatively, the sudden increase in γ-ray yield might be explained on the basis of linear response theory for which the onset of two-body dissipation is expected to occur at a temperature near 1 MeV. However, the dissipation described by this theory is too weak to account for the present observations and it rises too slowly with temperature [45]. Recent work [46,47] predicts a strong change near T = 1.5–2 MeV, with $\gamma \approx 0.7$ at T = 0.5 MeV and $\gamma \approx 4.7$ at T = 4 MeV by taking into account the effect of temperature on the collective modes which produces the dissipation. This approaches the observed dissipation strength at high temperature, but underestimates the observed rapid increase.

In addition to increased temperature at higher bombarding energies, the compound nuclei considered here are also formed with increasingly large angular momenta. Within the framework of linear response theory the magnitude of the axial component of nuclear dissipation has been shown to increase by a factor of 3–5 when the spin is raised from $J = 0$ to $100\hbar$ [45]. Although the magnitude of this effect is smaller than measured, it is in qualitative agreement.

The work of Bush *et al.* [48] predicts that at high excitation energies the dissipation coefficient γ varies as $1/T^2$. This represents a direct contrast with the T or T^2 dependence presently observed. However, the actual dissipation strength predicted by Bush *et al.* at our highest energy agrees with the observed value. They use two-body residual interactions in a basis of static Hartree-Fock solutions to describe fission as a diffusion in the nuclear shape degree of freedom. This approach finds that the diffusion coefficient D_β scales as T^3/A, and their calculations for ^{158}Er at $T = 2.0$ MeV and 2.5 MeV yields

$$D_\beta \approx 40T^3/A \quad (\mathrm{keV}/\hbar).$$

This can be translated into the linear friction coefficient γ $(= \beta/2\omega)$ via the Einstein relation $(\beta M_q = T/D_\beta)$ [49]. Inserting the inertial mass parameter M_q and taking $\hbar\omega = 0.9$ MeV yields $\gamma_{\mathrm{Bush}} \approx 1340/(A^{2/3}T^2)$. Thus, for ^{224}Th at $T = 1.8$ MeV (corresponding to the 140 MeV ^{16}O + ^{208}Pb reaction), $\gamma_{\mathrm{Bush}} \approx 11$ in reasonable agreement with the observed value $\gamma_{\mathrm{fit}} = 10$, perhaps predicting an even higher-temperature region where dissipation decreases.

Recently Fröbrich and co-workers have developed a combined dynamical statistical model (CDSM) in order to study the effects of dissipation on the fission process [50–53]. Their approach combines Langevin dynamical calculations in the early stage of fission with a statistical model decay for the later stages. CDSM calculations applied to the ^{16}O+^{208}Pb [19] reaction are able to describe the available data reasonably well using a *deformation*-dependent dissipation parameter, as opposed to a temperature-dependent dissipation resulting from the CASCADE calculations. [Their calculations underpredict the measured ν_{pre} multiplicities [Fig. 4(a) of [19]] in a similar manner to the CASCADE results of Fig. 5.] The dissipation was set low ($\gamma \approx 1$) for compact shapes at the equilibrium deformation and assumed to increase to $\gamma \approx 15$ as the system moves from the saddle to the scission point. This deformation-dependent dissipation was found to describe the systematics of prescission neutron multiplicities and fission probabilities for many systems [53]. The effect of a temperature-dependent dissipation was not explored. A dissipation which depends on deformation in the manner proposed by Fröbrich and co-workers tends to support one-body dissipation as the dominant mechanism, whereas two-body viscosity is suggested by a temperature-dependent dissipation.

A direct comparison of the calculated prescission GDR γ-ray multiplicity spectra for the reaction ^{16}O + ^{208}Pb at 100 and 140 MeV bombarding energy is shown in Fig. 6. The solid histograms show the theoretical spectra as calculated by CASCADE for the temperature-dependent dissipative fits of Fig. 5. The increase in prescission γ-ray emission from $E_{\mathrm{lab}} = 100$ to 140 MeV is clearly evident. The dashed histograms represent the CDSM results as calculated by Fröbrich and co-workers [see Fig. 10(a) of [19]]. The agreement between the calculations at both bombarding energies is remarkable, and it is clear the CDSM calculations reproduce the observed rapid rise of prescission γ rays. The fact that they predict moderately higher γ-ray multiplicities for $E_\gamma > 10$ MeV could be due to different choices for the GDR energy parameters and an emission rate corresponding to more than one classical sum rule.

One way to differentiate between temperature and shape effects on dissipation is to measure the shape of the compound system as a function of time. One-body dissipation is primarily effective for deformed shapes with low shape symmetries (e.g., during the saddle-to-scission motion). Two-body viscosity can additionally manifest itself during the higher symmetries of compact shapes (e.g., compound nuclear shapes). The γ-fission anisotropy in excited Cf indicates emission from a compact shape, possibly more compact than the rotating liquid drop model (RLDM) saddle point deformation [54]. It would be of interest to compare this result to the average shape of the GDR γ-ray emitter predicted by the CDSM calculations.

IV. CONCLUSIONS

A rapid increase of prescission GDR γ rays with bombarding energy is observed in fusion reactions forming Th and Cf compound nuclei. For both Th and Cf compound

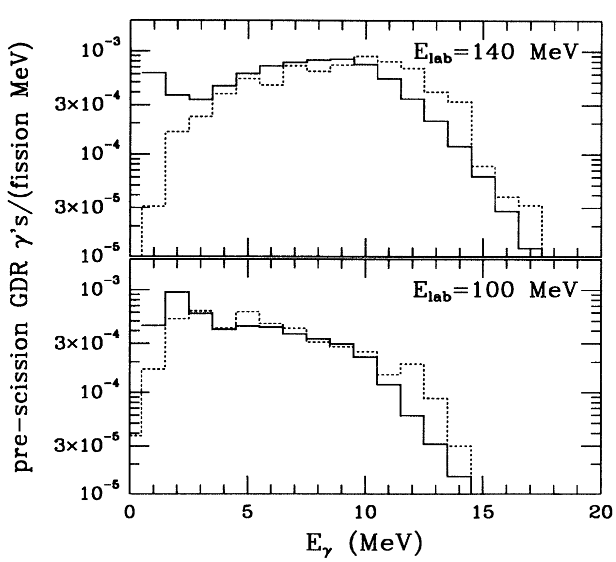

FIG. 6. Prescission GDR γ-ray multiplicity spectra for the reaction 100, 140 MeV ^{16}O + ^{208}Pb as given by the dissipative CASCADE calculations of this work (solid histograms) and the CDSM results of [19] (dotted histograms).

systems this increase occurs within a narrow 20 MeV excitation energy window. The rapid increase can be reproduced by employing a modified CASCADE statistical model and a temperature-dependent nuclear dissipation parameter γ. For the ^{16}O + ^{208}Pb reaction, where complementary evaporation residue data are now available, this dissipation is found to rise with temperature above a threshold $T_{\text{saddle}} \geq 1.17$ MeV and is well described by either a T or T^2 dependence. Thus, on the assumption that the approximations in the analysis with the modified statistical model are a reasonable simulation of the actual dynamical effects, one needs a temperature dependence of the viscosity coefficient. This result provides evidence for a significant two-body viscosity at or inside the saddle point.

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