Collective Dipole Motion in Highly Excited ^{272}Hs ($Z = 108$) Nuclei

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The heavy nucleus $^{272}_{108}$Hs ($Z = 108$) and its evaporation daughters were produced using the reaction ^{232}Th(^{40}Ar, γxn) with beam energies 10.5 and 15.0 MeV/A. The giant dipole resonance γ radiation from the hot composite system prior to fission has been isolated using a differential method. The prefission component shows a strong dipole angular distribution relative to the spin direction.

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Studies of the γ radiation from the giant dipole resonance (GDR) built on excited states in atomic nuclei offer insight into nuclear behavior under extreme conditions with respect to temperature, angular momentum, and nucleon number [1]. Such investigations have shown that the main properties of the GDR are unaffected by temperature T, that collective motion persists up to excitation energies $E^* \sim 300$ MeV (in $A \sim 110$ nuclei), and that the decay in this energy range can be well described as statistical. Above this E^* a saturation of the GDR strength sets in [1]. Recent research has shown that fission is a far slower process than predicted by the standard statistical model [2,3]. Thus, in heavy nuclei ($A \sim 200-250$) the prefission GDR γ-ray emission competes with the fission process.

A main problem in the analysis of measured GDR γ-ray spectra from fissile systems is that the photons from the decay of the GDR can be emitted both from the hot compound nucleus before fission and from the excited fragments after fission [2,3]. Since the resonance energy scales as $E_{\mathrm{GDR}} \simeq 79A^{-1/3}$ MeV, the corresponding GDR frequencies will be located 3–4 MeV apart. This is insufficient to separate the two contributions experimentally, since typical GDR widths in hot nuclei are of the order of 6–10 MeV. It is nevertheless possible to analyze the entire γ-ray spectrum with the aid of statistical model calculations incorporating the decay of both the primary system and the fragments [2].

In this Letter, an alternative approach has been used: The energy differential method [4] has been employed to study the earliest decay steps of the heavy system, using the GDR radiation as a probe for the collectivity and stability of the excited ^{272}Hs ($Z = 108$) nucleus and its evaporation daughters at $T \approx 2.5-3$ MeV. The idea is illustrated in Fig. 1 in a schematic fashion. Compound nuclei of ^{272}Hs ($Z = 108$) are produced at two different initial excitation energies E_1 and E_2. A difference spectrum is created from the total γ spectra measured in coincidence with fission at the two beam energies. Fission is assumed to be important only after cooling of the intermediate system to some lower excitation energy E_f. If $E_1 > E_2 > E_f$, the contributions from the γ decay of the fragments are common to both decay chains (scenario 1), and the difference spectrum will contain only the prefission γ rays emitted between E_1 and E_2. If fission competes with γ emission at the lower or both initial excitation energies ($E_1 > E_f > E_2$ or $E_f >$

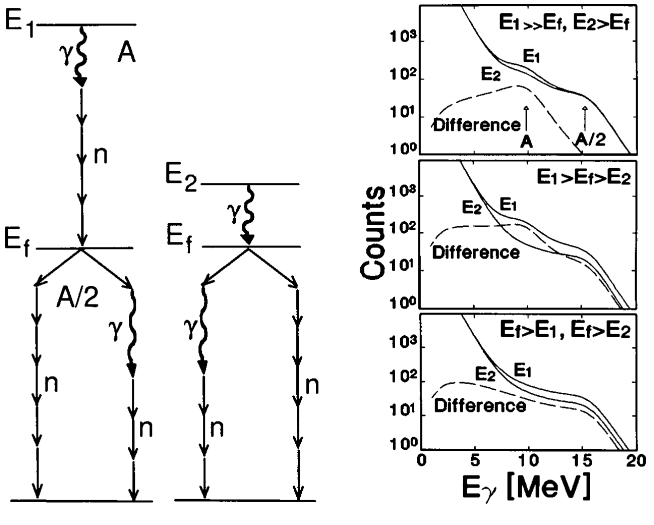

FIG. 1. Left: schematic illustration of the differential method (GDR structures are exaggerated for clarity). Right: the three different scenarios for the difference γ-ray yield as described in the text.

$E_1 > E_2$), the postfission contributions will not cancel in the difference spectrum (scenarios 2 and 3).

The hot ${}^{272}_{108}$Hs ($Z = 108$) nuclei were produced using ^{40}Ar beams at energies 10.5 and 15.0 MeV/A from the SARA Cyclotron at the ISN in Grenoble, impinging on self-supporting ^{232}Th targets ($\sim$1 mg/cm^2 thick). In an earlier test experiment, we also studied this reaction at beam energies of 6.8 and 10.5 MeV/A [5,6]. The experimental arrangement for measuring high-energy γ rays ($E_\gamma \sim 5-30$ MeV) consisted of the eight large BaF$_2$ detectors of the HECTOR Collaboration, placed in a plane perpendicular to the beam axis, 35 cm from the target. Four large area position sensitive parallel plate avalanche counters were used for detecting the fission fragments. An array of seven small BaF$_2$ crystals, located close to the target and registering low-energy γ rays, served as a trigger for time-of-flight measurements.

By gating on pairs of mass-symmetric fragments, complete fusion or quasifission events [7] were selected. Symmetric fission was found to dominate completely in the chosen geometry. This agrees with reaction systematics [7,8], which shows the fraction of mass-equilibrated fission to increase with beam energy. The coincident γ spectra for the two beam energies, bremsstrahlung subtracted and normalized to the same number of singles symmetric fission events, are displayed in Fig. 2.

Maximum angular momenta l_{CN} and l_{QF} associated with complete fusion and quasifission have been estimated as described in [8]. For the 15.0 MeV/A reaction, E^* is about 371 MeV, $l_{\mathrm{CN}} \approx 122\hbar$, and $l_{\mathrm{QF}} \approx 217\hbar$, while for the 10.5 MeV/A reaction, $E^* \approx 218$ MeV, $l_{\mathrm{CN}} \approx 95\hbar$, and $l_{\mathrm{QF}} \approx 172\hbar$. For the 6.8 MeV/$A$ reaction, $E^* \approx 92$ MeV, $l_{\mathrm{CN}} \approx 49\hbar$, and $l_{\mathrm{QF}} \approx 105\hbar$. In the case of complete fusion, a fully thermalized compound nucleus is formed. Quasifission creates a mononucleus usually assumed to be equilibrated in all degrees of freedom except shape. Hence, it will have approximately the same temperature as the compound nucleus at the same deformation [2]. Even in the case of nonequilibration of shape, the much shorter time needed for energy equilibration should imply the presence of the GDR mode.

Pileup between high-energy γ rays and postfission neutrons was found to be significant in the particular geometry of this experiment. Because of focusing of neutrons in the direction of the fast moving fragments, neutron pileup is important for spectra measured parallel to the fission axis (90° to the spin direction) [6,9]. The γ-ray spectra can be accurately corrected using the experimental neutron energy spectra measured at different angles combined with an iterative unfolding algorithm [6,10]. The rapidly converging unfolding routine was satisfactorily checked against an efficient hardware pileup rejection in a subsequent experiment [6].

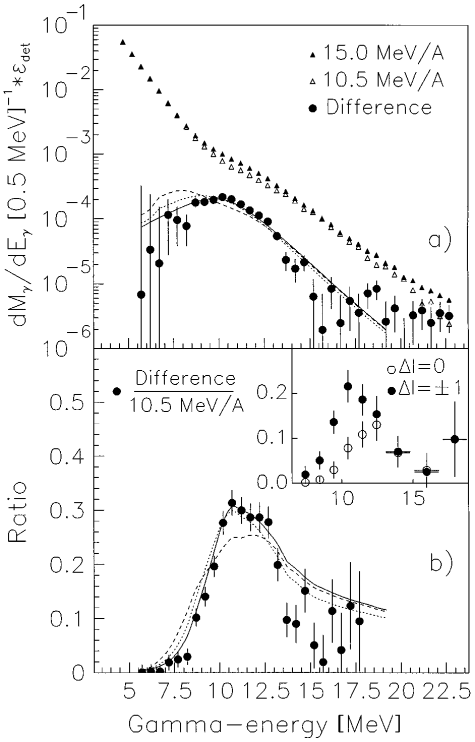

FIG. 2. (a) Total measured γ spectra in coincidence with symmetric fission for the 15.0 and 10.5 MeV/A reactions (filled and open triangles, respectively), and their difference spectrum (filled circles). The curves depict theoretical GDR energy distributions for various deformations (see text). (b) Difference spectrum (filled circles) and theoretical estimates (curves), all divided by the 10.5 MeV/A spectrum. Inset: Difference spectrum decomposed into $\Delta I = 0$ (open circles) and $\Delta I = \pm 1$ (filled circles) components based on angular distribution results (see Fig. 3).

The difference between the two total γ spectra in coincidence with fission, displayed in Fig. 2(a), shows a well-defined component in the range of the GDR energy predicted for the composite system [$E_{\mathrm{GDR}}(A = 272) \approx 12.2$ MeV]. The data are compared with approximations to the expected GDR distributions for an oblate nucleus with deformation $\beta = 0.19$ (solid curve), and prolate nuclei with $\beta = 0.19$ and 0.38 (short-dashed and long-dashed curves). The calculations were made using double Lorentzians of widths $\Gamma_i = 5.5(E_i/12.2)^{1.6}$ MeV ($i = 1, 2$ for the two axes), multiplied by $\exp(-E_\gamma/T)$ with $T = 2.2$ MeV. The GDR component energies were $E_1 = 11.5$ MeV, $E_2 = 13.6$ MeV (oblate, $\beta = 0.19$), $E_1 = 10.9$ MeV, $E_2 = 12.8$ MeV (prolate, $\beta = 0.19$), and $E_1 = 9.8$ MeV, $E_2 = 13.4$ MeV (prolate, $\beta = 0.38$). The relative yield of prefission γ rays, calculated as the ratio of the difference spectrum and the 10.5 MeV/A total spectrum, is shown in Fig. 2(b). The curves depict the respective calculations treated in a similar manner.

The observed energy distribution agrees with expectations for the GDR in $A \approx 270$ nuclei, based on extrapolated ground state values. Strongly deformed $A \approx 135$ fragments ($\beta \approx 0.4$) might produce a low-energy component at $E_\gamma \approx 12$ MeV, but the fact that no corresponding high-energy component around $E_\gamma \approx 17$ MeV is seen excludes this interpretation. The only way to obtain such an excess concentrated around $E_\gamma \approx 12$ MeV is through GDR γ-ray emission from the heavy system.

The γ-ray-fission angular distribution for the difference data, measured relative to the total angular momentum vector (assumed perpendicular to the fission axis), is shown in Fig. 3 (see caption for details). The unfolding procedure produces only minor changes in the distribution, supporting our interpretation of the difference as due to γ-ray emission from the conglomerate system, for which pileup effects should be negligible.

The anisotropy of the difference spectrum shows a crossing point at $E_\gamma \approx 12$ MeV, as expected for the heavy nucleus. The ratio $W(0°)/W(90°)$ indicates a collectively rotating prolate or a noncollectively rotating oblate system. In Fig. 3(b), the data are compared with calculations based on simple two-component Lorentzians, assuming an oblate nucleus with $\beta = 0.19$ (solid curve), and prolate nuclei with $\beta = 0.19$ and 0.38 (short-dashed and long-dashed curves) and widths as in Fig. 2. Because of the rapid rotation of the system, orientation fluctuations have been neglected, in accordance with the results of [11,12]. Estimates taking the K distribution into account, using the formalism of [13], confirm the validity of this approximation, even when excluding the highest partial waves ($I \geq 150\hbar$), allowing for an I-dependent lifetime as suggested in [14].

Based on the measured angular distribution, the experimental strength function has been decomposed into $\Delta I = 0$ and $\Delta I = \pm 1$ vibrational components, using the technique of [11]. The results (see inset of Fig. 2) are consistent with a mixture of shapes with a substantial oblate contribution.

In order to reproduce both the anisotropy and the difference energy spectrum simultaneously, a very heavy nucleus ($A \approx 270$) with a rather compact shape ($\beta \approx 0.20$) and narrow Lorentzian components ($\Gamma \leq 5.5$ MeV) is required. The large prolate deformations expected for a fissile system account approximately for the angular distribution, but are not consistent with the observed spectrum shape.

At the temperatures involved here, the distinction between the early decay steps of the compound nucleus and the mononucleus may no longer be very sharp. The large two-body dissipation predicted at high T and A [15] may allow the system to spend a relatively long time at small deformations.

In the absence of shape equilibration, thermal shape fluctuations are expected to be reduced. This is consistent with the small widths extracted for vibrational components. In lighter nuclei, the GDR widths have been found to saturate around $\Gamma \approx 10-13$ MeV $\approx (2-2.5)\Gamma_{T=0}$ for $E^*/A \geq 1$ MeV [1], corresponding to a width of $\Gamma \approx 8-10$ MeV in this system. If this interpretation is correct, it would be the first time a decrease in GDR width due to reduced shape fluctuations is observed in a hot nucleus.

At $E_\gamma > 15$ MeV, where GDR γ rays from the fragments are expected, the difference spectrum shows no significant intensity. This suggests that the onset of fission occurs after the nucleus has cooled down below the E^* of the reaction of lower energy ($E_f < E_2$).

The strengths of prefission and postfission contributions enable us to set limits on the lifetime of the fused system. In Fig. 4 the average emission time τ_n for neutrons, the

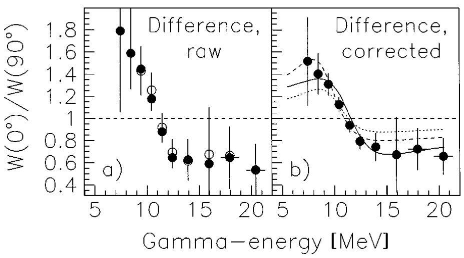

FIG. 3. Difference angular distributions $W(0°)/W(90°)$, measured relative to the spin axis (assumed orthogonal to fission axis). (a) Angular distributions measured before and after correction for neutron pileup, depicted by open and filled circles, respectively. (b) Distribution after correction for the differences in $l_{\max}$ of the two reactions, as described in [11]. The nonoverlapping fraction R of the 15.0 MeV/A cross section has been estimated to 0.37. The solid and dashed curves are theoretical calculations (see text).

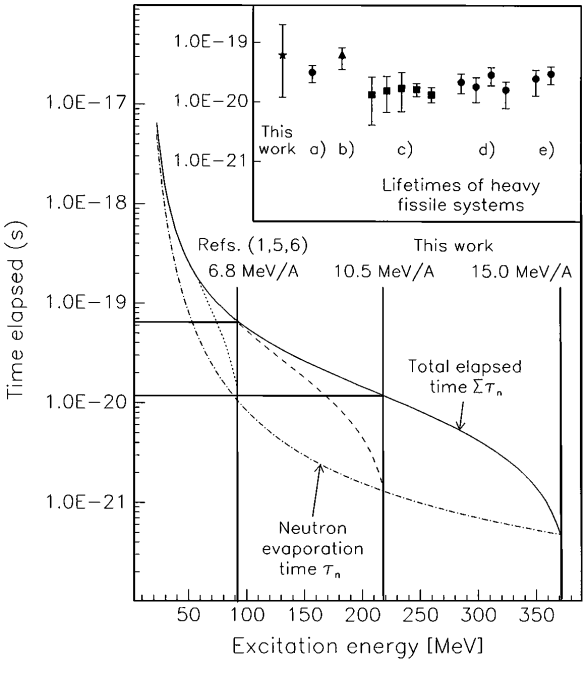

FIG. 4. Individual neutron decay times (dash-dotted curve) and total elapsed time as a function of E^* during decay for the reactions at 15.0 (solid), 10.5 (dashed), and 6.8 MeV/A (dotted curve). A constant neutron binding energy $B_n = 5.5$ MeV has been assumed. Inset: Lifetimes deduced for the reactions ^{40}Ar + ^{232}Th, this work, (a) ^{28}Si + ^{232}Th [15], (b) ^{32}S + ^{208}Pb [16], (c) ^{238}U + ^{27}Al, ^{32}S, ^{35}Cl, ^{40,48}Ca [8], (d) ^{64}Ni + ^{175}Lu, ^{197}Au, ^{208}Pb, ^{238}U, and (e) ^{40}Ar + ^{208}Pb, ^{238}U [17].

dominant decay mode for the heated nucleus, is plotted as a function of E^*, using a level density parameter $a = A/8$ (results obtained with $a = A/12$ are given in parentheses in the following). Also shown is the total elapsed time since the start of the cascade, given as $\sum_i \tau_n^i$ (with τ_n^i being the lifetime for the ith evaporation step), which is a good approximation to the actual lifetime of the heavy system.

The duration of the fission process must at least be equal to the time needed to decay from $E^* = 371$ to 218 MeV, $\sim 1.2 \times 10^{-20}$ s (5×10^{-21} s), since no fragment decay is observed in the difference spectrum. An approximate average lifetime and an upper limit can be obtained from the fact that the high-energy parts of the total γ spectra from the 10.5 and 6.8 MeV/A reactions are well fitted by fission fragment CASCADE calculations, using fixed E^* values of 80 and 60 MeV, respectively [1,5,6]. Similar results can be obtained with the more realistic assumption of fission occurring over a broad excitation region, governed by a fission width. The values $E^*_{ff} = 80$ and 60 MeV have been found to be roughly equivalent to the mean elapsed times 6×10^{-20} s (2×10^{-20} s) and 2×10^{-19} s (7×10^{-20} s) before fission. These estimates are comparable to lifetime data for various heavy systems with contributions from both fusion-fission and quasifission [8,15,16,17] (inset of Fig. 4). More accurate determination of the time scales of the two processes requires a full statistical analysis [18].

The intensity ratio of the difference spectrum relative to the 10.5 MeV/A total spectrum is about (25–30)% in the GDR region (see Fig. 2). In comparison, a simple statistical model estimate, obtained by summing the γ-ray emission probabilities $P(E_\gamma) \propto T^{-2} \exp[(B_n - E_\gamma)/T]$ over all evaporation steps of the cascades of Fig. 4, gives a difference yield of (50–60)% or more. Since the difference mainly originates from the first part of the cascade, with much shorter time scales than the later steps (see Fig. 4), this number is not very sensitive to the fission time within the limits deduced here. This is the first observation of high-T quenching of the GDR strength in this mass region.

In summary, for the first time the GDR radiation from a hot rotating nucleus with $A \sim 270$ has been isolated. The difference spectrum agrees well with the energy distribution expected for the prefission component. A γ-ray-fission angular distribution consistent with a compact shape and small thermal fluctuations has been measured. The observed energy spectrum combined with the angular distribution demonstrate unambiguously that the collective dipole vibration exists in the highly excited heavy nucleus.

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