Giant Dipole Resonance in Highly Excited Thorium: Evidence for Strong Fission Hindrance

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(Received 31 July 1987)

The giant dipole resonance in ^{224}Th excited to 44, 64, and 82 MeV was observed following the fusion of ^{16}O+^{208}Pb. The total γ spectrum is analyzed in terms of prefission and postfission γ decay. The data can only be fitted by our requiring an enhancement of the giant-dipole-resonance γ rays from the prefission nuclei which is explained by a large fission hindrance in the early decay steps from the compound system. A measurement of the γ-fission angular correlation supports this conclusion and establishes a deformed shape of the compound nucleus.

PACS numbers: 24.30.Cz, 25.70.Gh, 27.90.+b

Recent experiments on neutron multiplicities in heavy-ion fusion reactions indicate a retardation of the fission process in the early decay steps of highly excited compound systems.[1] This observation has been explained in terms of the increased time required for the fissioning system to move over the barrier in the presence of nuclear friction. Such a retardation of the fission process must enhance the excited-state giant-dipole-resonance (GDR) γ rays which are emitted in the initial steps of compound-nucleus decay. We present here the observation of the excited-state GDR in the γ decay of thorium nuclei at initial excitation energies between 44 and 82 MeV. The total γ spectrum from the decay of such a fissile compound system is composed of prefission and postfission components. The fact that the GDR energies for the compound system and for the fission fragments are widely separated makes it possible to extract the relative prefission and postfission γ yields from the γ spectrum. The present experiment indicates the need for a large enhancement of the prefission γ yield over that calculated by the standard statistical model. This provides the first evidence from a γ-ray measurement for a strong fission hindrance in the early compound-nucleus decay steps.

Energy spectra of γ rays up to $\simeq 25$ MeV were measured in the reaction ^{16}O+^{208}Pb at 100-, 120-, and 140-MeV bombarding energies, producing Th nuclei at excitation energies of 44, 64, and 82 MeV, with average angular momenta of $25\hbar$, $37\hbar$, and $43\hbar$, respectively. In addition, γ-fission correlations were measured at 120 MeV. The anisotropy of γ rays with respect to the compound-nucleus spin axis as defined from the direction of the fission fragments is sensitive to the presence of the compound-nucleus GDR and yields information on the compound-nucleus deformation.[2]

A 3.5-mg/cm^2-thick lead target was bombarded with an ^{16}O beam from the Stony Brook Linac. A 25.4-cm×38.1-cm NaI(Tl) γ detector with a plastic anticoincidence shield was located 60 cm from the target. Discrimination of neutrons and pulse pileup was achieved by techniques described elsewhere.[3] For the coincidence measurements the target was 0.8 mg/cm^2 thick. The fission fragments were detected in four surface-barrier detectors located in the plane perpendicular to the beam, with 90° separation between adjacent detectors. The γ detector was collinear with one pair of fission detectors and perpendicular to the other, measuring the γ yields at 90° and 0°, respectively, with respect to the spin axis.

The measured γ spectra are shown in Fig. 1 for the three bombarding energies. The various curves in the figure represent standard parameter statistical-model calculations using an extended version of the code CASCADE[4] which includes the statistical decay of the fission fragments. Before discussing the results we briefly describe the necessary extension in the code for a consistent description of the prefission and postfission statistical decay. In the present procedure, the fission cross section for a given excitation energy (E) and angular momentum (J) of each decaying nucleus is used to create the population matrix in the E-J plane of the fission fragments (measured to be symmetric). The total excitation energy of the fragments is related to that of the compound system through the Q value and the total kinetic energy of the fragments. The total kinetic energy is assumed to have a Gaussian distribution around the mean value given by the Viola systematics[5] and a width extrapolated from measurements in heavy nuclei.[6] The total spin (J_T) of the fission fragments is obtained from that of the decaying nucleus (J) from the relation $J_T = \frac{2}{7}J + S(J)$, where $S(J) = 18.0 - 0.17J$ describes the deviation from a rigid rotation of two touching fragments.[7] The total excitation energy and spin are then divided equally between the fission fragments. At the end of the decay cascade of the compound nucleus, the population matrix of each fission fragment becomes the starting point for subsequent calculations of the statistical decay of the fragments.

The results of these calculations are compared to the γ spectra in Fig. 1. The solid, short-dashed, and long-dashed curves describe the total, prefission, and postfission yields, respectively, after folding with the response

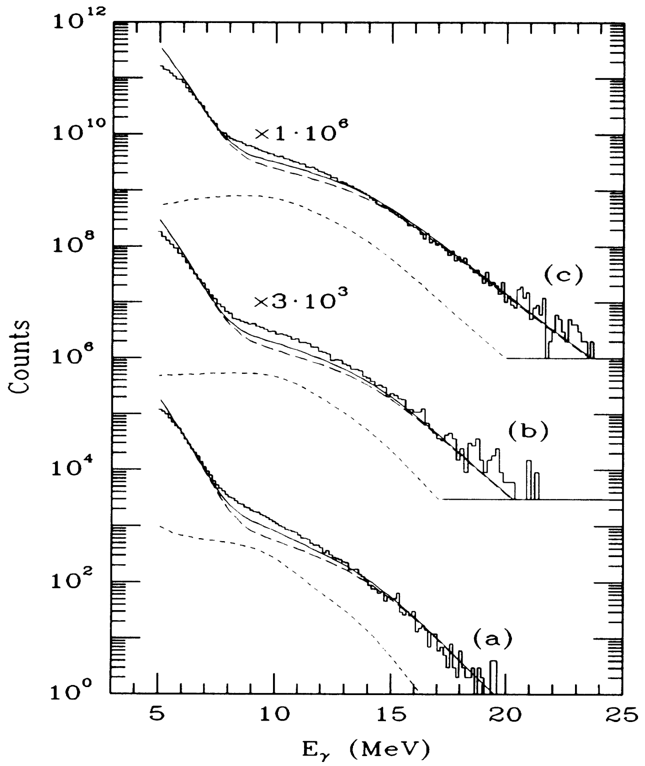

FIG. 1. Experimental γ spectra measured in the reaction $^{16}O+^{208}Pb$ at (a) 100, (b) 120, and (c) 140 MeV. Calculated prefission (short-dashed curves), postfission (long-dashed curves), and total (solid curves) γ spectra are obtained with the code CASCADE with use of GDR parameters listed in Table I and level-density parameters $A/8.8$ for the compound nucleus and $A/9.0$ for the fission fragments.

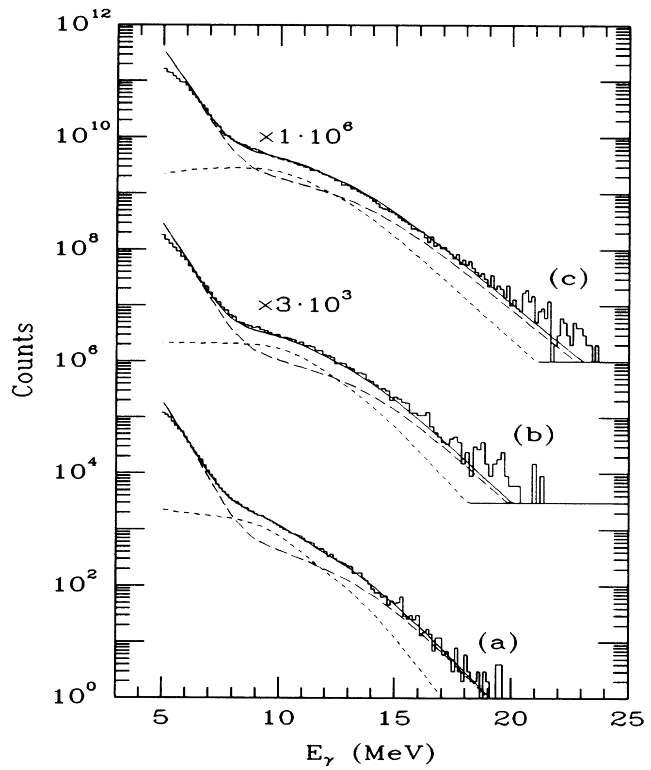

FIG. 2. Same as Fig. 1, but including fission hindrance factors described in the text and listed in Table I.

function of the γ detector. The GDR parameters of the fission fragments were chosen from the excited-state systematics in the mass region $A \simeq 112$,[3] and those of the compound nucleus were based on the ground-state values of natural thorium.[8] The fission barriers came from the prescription of Sierk[9] with a multiplicative constant of 0.8 required to reproduce the experimental fission and residue cross sections.[10] The ratio of the level-density parameter at the saddle point to that at the equilibrium deformation was $a_f/a_n = 1.0$. The calculated postfission γ yield reproduces the observed spectral shape below 7 MeV and above 13 MeV. This is expected since the compound system fissions before it reaches the yrast line and since the GDR energy of the fission fragments is higher than that of the compound system. However, most importantly, the measured spectra show a significant excess yield of γ rays in the energy region ($\simeq 11$ MeV) of the compound-nucleus GDR which is not obtained with standard statistical calculations.

In order to confirm the failure of standard statistical-model calculations, we examined carefully the influence of the various model parameters on the calculated cross sections. It is obvious that the data need either a drastic change in the predicted shape of the postfission spectrum, or a large enhancement of the prefission cross section. We have varied the level-density parameter from $A/7$ to $A/10$ and the GDR energies between 14.0 and 16.0 MeV, for the fission fragments. None of these variations can reproduce the cross section in the 11-MeV region. The proposition of deformed fission fragments also cannot explain the data. Conversely, a sum-rule strength of 300% to 400% for the compound-nucleus GDR yields very good fits to the data but is obviously unphysical.

If the GDR strength is limited to one sum rule (and this strength explained all previously studies cases[3,11]), a good fit requires a drastic reduction in the fission probability. However, this reduction can only be allowed in the early decay steps in order to maintain consistency with the experimental residue cross section. Accordingly, we propose fission hindrance factors $X(n)$ in the nth step of the decay chain. This means that the relative probability P_f of fission decay, for any value of (E,J) as calculated by standard statistical model in the nth step, is reduced to $P_f' = X(n)P_f$. The good fits obtained with this prescription are shown in Fig. 2 with the values of the hindrance factors listed in Table I. The error in $X(n)$ is 0.1 due to the search grid size. In order to satisfy the experimental residue cross section at each bombarding energy, the fission-barrier multiplicative con-

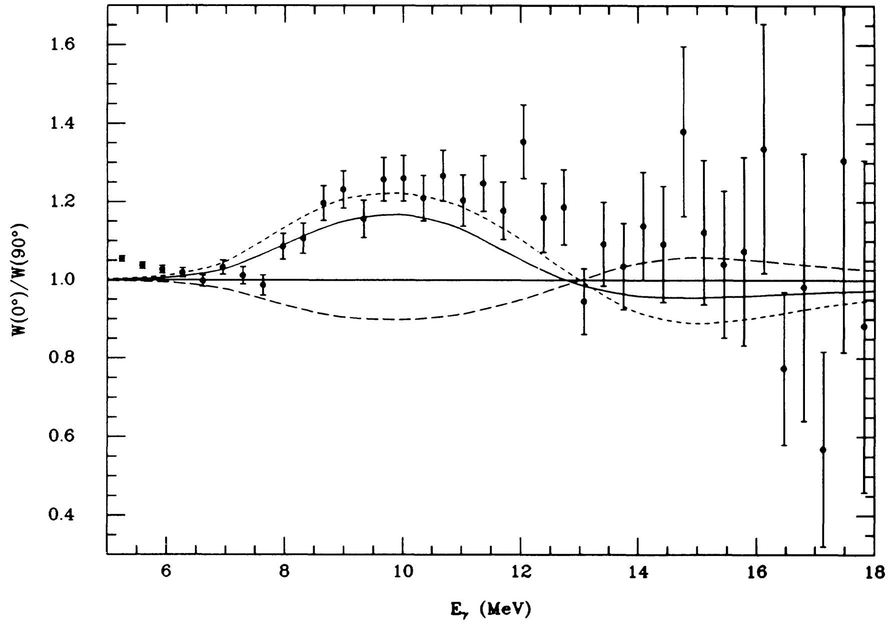

FIG. 3. Ratio of the experimental γ yields $W(0°)/W(90°)$with respect to the compound-nucleus spin in $^{16}O + ^{208}Pb$ at 120 MeV. The curves for prolate (solid), noncollective oblate (short dashed), and collective oblate (long dashed) deformations are calculated with use of GDR parameters obtained from fits to the γ energy spectrum including fission hindrance. For the prolate shape they are listed in Table I and for the oblate shapes they are $E_1 = 12.0$, $\Gamma_1 = 5.7$ MeV and $E_2 = 14.8$, $\Gamma_2 = 4.7$ MeV.

stant was reduced to $\simeq 0.6$ for all decay steps. This is equivalent to an increase in the ratio of the level-density parameters a_f/a_n from 1.0 to 1.1 as was done in the analysis of the neutron multiplicity experiments.[1] The application of the fission-barrier reduction only in the later steps changes the hindrance factors $X(n)$ by less than their errors.

Further confirmation for an excess prefission γ yield around 11 MeV comes from the measurement of the γ-fission correlation at 120-MeV bombarding energy. The experimental ratio of the γ yields $W(0°)/W(90°)$ with respect to the average spin is shown in Fig. 3. The very small anisotropy below 8 MeV is explained by an almost isotropic postfission yield which dominated the spectrum in this energy region. The anisotropy observed at higher γ energies can be obtained only by the assumption of (i) a strong enhancement of prefission γ rays over the statistical model and (ii) a deformed compound system. The possibility of deformed fission fragments giving rise to the measured anisotropy was ruled out by detailed calculations.

Because of the large fission γ-ray contribution it is clear that the extraction of the nuclear shape through GDR parameters of the compound system is not possible from the energy spectra alone. However, as mentioned above, the anisotropy data at 120 MeV unambiguously show a deformation. The curves in Fig. 3 were calculated with use of standard angular-correlation algebra in the high-spin limit[11] including averaging over the K distribution at the saddle point.[2] The data are in agreement with prolate (solid curve) or noncollective oblate (short-dashed curve) shapes and rules out a collective oblate (long-dashed curve) deformation. Since the ground state has a prolate shape ($\beta \sim 0.2$)[12] a large noncollective oblate deformation ($\beta \sim 0.24$) seems unlikely. The energy and width parameters of the compound-nucleus GDR extracted from the fits to the γ spectra, assuming a prolate shape (strength ratio $S_2/S_1 = 2.0$), are listed in Table I. The extracted deformations for 100, 120, and 140 MeV are $\beta = 0.37$, 0.30, and 0.29, respectively, with a large error $\Delta\beta = \pm 0.06$.

From the analysis of the present experimental data one concludes that fission is strongly hindered at high excitation energies and/or high angular momenta, in heavy nuclei. The first-chance fission probability is reduced to 10% to 20% of the statistical-model value and the hindrance effect persists even up to the third step at higher excitation energies. The systematics can be understood as an increase of the hindrance effect with temperature and/or angular momentum (Table I). The fission probability of the GDR based on the ground states of actinide nuclei, i.e., at zero temperature, agrees with the statistical model.[13] We note that a fission hindrance effect has been reported for the ground-state isoscalar giant quadrupole resonance,[13,14] although it is not clear how this observation relates to the present effect. The fission hindrance at high temperatures through the relative enhancement of the GDR of the compound system has

TABLE I. Fission hindrance factors $X(n)$, level-density parameters a $(=a_f=a_n)$, and GDR fit parameters for prolate $(S_2/S_1=2.0)$ compound nucleus in the reaction $^{16}O+^{208}Pb$. The last three columns contain the level-density and GDR parameters of the fission fragments. Energies and widths are in megaelectronvolts. Errors of $E_1\pm0.3$, $\Gamma_1\pm0.6$, $E_2\pm0.6$, $\Gamma_2\pm1.0$, $E_f\pm0.7$, $\Gamma_f\pm1.0$ were derived from inspection of the fits by the variation of one parameter at a time.

	Fission hindrance			Compound nucleus					Fragments		
E_{beam}	$X(1)$	$X(2)$	$X(3)$	a	E_1	Γ_1	E_2	Γ_2	a	E_f	Γ_f
100	0.2	0.6	1.0	$A/8.8$	10.3	4.0	14.0	5.4	$A/9.3$	14.8	8.5
120	0.1	0.3	0.7	$A/9.0$	11.2	4.2	14.2	5.8	$A/9.5$	14.8	8.5
140	0.1	0.3	0.6	$A/8.8$	11.0	5.0	14.0	6.5	$A/9.3$	15.1	9.3

the important advantage that is determines the time evolution of the fission process from the initial configuration to the saddle point. The diffusion model of the fission process relates the fission hindrance to the properties of the fission barrier and the nuclear friction coefficient β_1.[15] Based on calculations[16] in $A=226$, the present hindrance of first-chance fission is consistent with a value of $\beta_1=5\times10^{21}$ s^{-1}. The same value for β_1 had also been inferred from the observation[1] of excess prefission neutrons in the decay of ^{158}Er. The present work indicates that, contrary to recent model calculations,[9] highly fissile nuclei do survive long enough to establish a GDR vibration.

This work was supported in part by the National Science Foundation. One of us (R. B.) acknowledges the support of the Deutsche Forschungsgemeinschaft, Bonn, West Germany.

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