Oblate Deformed Shapes of Hot Rotating Nuclei Deduced from Giant-Dipole-Resonance Decay Studies

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The spectrum shape and the angular distribution of γ rays from highly excited and rotating ^{90}Zr and ^{92}Mo compound nuclei were measured and analyzed. The results are in good agreement with theory including both intrinsic-shape fluctuations and shape-orientation fluctuations about an equilibrium shape which changes from spherical to oblate deformed with increasing spin.

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Most of our understanding of the shapes of hot rotating nuclei comes from studies of the giant dipole resonance (GDR) built on excited states. At temperatures $T \sim 1$–2 MeV nuclei exhibit significant shape fluctuations,[1] which is inferred from the observed broadening of the γ-ray strength function deduced from the decay of excited nuclei[2-4] as compared to the width of the GDR in cold nuclei. Except for a few special cases involving strongly deformed nuclei and the persistence of ground-state-like deformation,[5] analyses of GDR γ-decay spectrum shapes from excited nuclei have not led to definitive determinations of the equilibrium shape. The components of a deformation-split GDR are generally not resolved, due in part to the thermal shape fluctuations, and this has made it difficult if not impossible in most cases to deduce the equilibrium shape.

However, the γ-ray angular distribution provides important independent information on the deformation of an excited, rotating nucleus.[6] For example, a spherical nucleus will, to a good approximation, have an isotropic γ-ray angular distribution even in the presence of shape fluctuations. When the equilibrium shape is deformed, the angular distribution at finite spin is anisotropic, with a magnitude which depends on the equilibrium deformation. Although angular distributions have been measured in recent experiments,[4,7-9] they have not been interpreted in an analysis which includes effects due to intrinsic-shape fluctuations and to shape-orientation fluctuations.

In this Letter we present accurate angular-distribution and spectrum-shape measurements for excited ^{90}Zr and ^{92}Mo nuclei in a temperature range $T \approx 1.6$–2.0 MeV and spin range $I \approx (0$–$45)\hbar$, where shell effects should be mostly dissolved away, and where the nuclear shape is expected to be approximately that of a rotating liquid drop. We find good agreement with the calculations of Alhassid and Bush,[10] in which nuclear shape-orientation fluctuations are included together with intrinsic-shape fluctuations about a deformed equilibrium shape. As a result we are able, for the first time, to extract with confidence the equilibrium deformation of a nucleus in the presence of large shape fluctuations. The results also demonstrate, for the first time, a spin-induced spherical-to-deformed shape change for a hot nucleus.

The compound-nuclear fusion reactions studied were $^{18}O + ^{72}Ge \rightarrow ^{90}Zr^*$ at $E_{proj} = 50$ and 74 MeV and $^{28}Si + ^{64}Ni \rightarrow ^{92}Mo^*$ at $E_{proj} = 137$ MeV. For these three reactions, the average spins and temperatures are $\bar{I} = 9\hbar$, $22\hbar$, and $33\hbar$, and $\bar{T} = 1.6$, 1.7, and 2.0 MeV.[11] Pulsed ^{18}O beams were obtained from the University of Washington FN tandem accelerator and ^{28}Si beams from the Lawrence Berkeley Laboratory 88-in. LBL cyclotron. Chemically pure, isotopically enriched targets of about 1 mg/cm^2 were used; the ^{72}Ge was backed by thick, water-cooled Pt while the ^{64}Ni was a self-supporting foil. We used a large-volume NaI detector, 25.4 cm × 38.1 cm at Seattle and 25.4 cm × 25.4 cm at LBL, with anticoincidence and lead shielding. The detectors were positioned at a distance of ≈ 1 m from the target to allow time-of-flight neutron discrimination. The detectors were calibrated before and during the experiments using $^{11}B(p,\gamma)$ ($E_\gamma = 22.6$ MeV), and radioactive sources. The detector and electronics gain was stabilized with a light-emitting diode pulser. The integrated beam charge served as normalization and a Ge(Li) monitor detector was used as a normalization check. Spectra were taken at five angles in the range $\theta_\gamma = 35°$–$145°$ and converted from the laboratory system to the compound-nuclear center-of-mass system. The measured detector response was folded into the statistical-model calculation for comparison with experiment.

In order to illustrate the deformations expected for these nuclei, we show in Fig. 1 the calculated[10] free energy F for the three measured cases as a function of the intrinsic quadrupole deformation coordinates β,γ. The probability of finding an excited, equilibrated nucleus in a particular configuration is given by $e^{-F/T}d\tau$, where the free energy F and the phase-space element $d\tau$ are determined in terms of the relevant degrees of freedom, which here are taken to be β, γ, and the Euler angles of

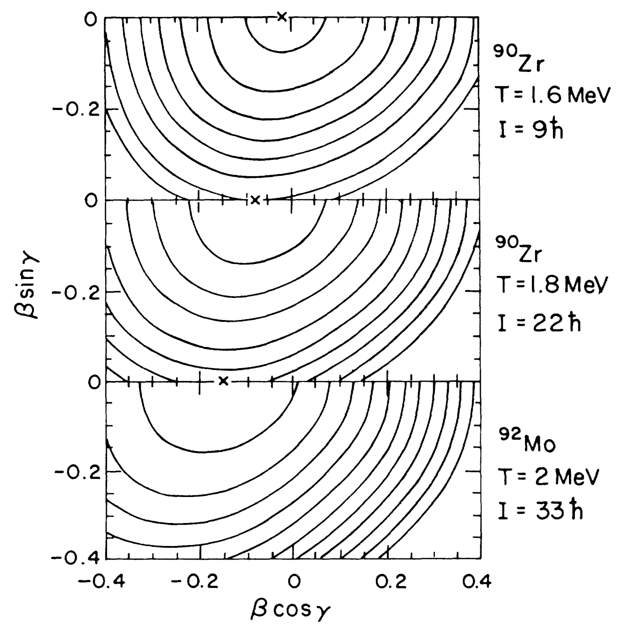

FIG. 1. Calculated potential-energy (free-energy) surfaces for the three cases of interest (Ref. 10). Contour lines are spaced every 1 MeV. Crosses indicate the locations of the minima, which lie along the oblate noncollective axis ($\gamma = -180°$). These surfaces demonstrate the expected nuclear shape change from spherical to oblate.

the nuclear shape orientation with respect to the spin axis. At these temperatures the shell corrections (included in F) are small, and F is predominantly given by the properties of a rotating liquid drop.[12] The calculated equilibrium shape is oblate noncollective ($\gamma_0 = -180°$) with equilibrium deformations $\beta_0 \approx 0.02$, 0.08, and 0.16 for $\bar{I} = 9\hbar$, $22\hbar$, and $33\hbar$, respectively.

The γ-emission cross section $\sigma_\gamma(E_\gamma)$ measured at $\theta_\gamma = 90°$ is shown in Fig. 2 (top row), together with fitted CASCADE (Ref. 13) statistical-model calculations. The photon absorption cross section $\sigma_{abs}(E_\gamma)$, which enters in the γ-decay width in the usual manner,[2] is described as the sum of two Lorentzians with six free parameters. Figure 2 (bottom row) shows the fitted $\sigma_{abs}(E_\gamma)$ along with points which represent our best estimate of the absorption cross section obtained from the measured $\sigma_\gamma(E_\gamma)$ by dividing out the statistical-model phase space (see Fig. 2 caption). The GDR properties determined by the fits are shown in Table I. The GDR sum-rule strengths and mean resonance energies are in agreement with ground-state systematics, while the widths are substantially broader than the ground-state GDR width[14] of 4–5 MeV. All spectra are best fitted with two Lorentzians. As has been commonly found in other GDR decay experiments with excited nuclei, the sense of the deformation (oblate versus prolate) is undetermined due to the large errors on S_2/S_1. The fitted energies suggest substantial deformations, $\beta \approx E_2/E_1 - 1 \approx 0.2$–0.3. We note here, and discuss below, the fact that these deformations are larger than the calculated equilibrium values of β_0 presented above. This is because thermal fluctuations, if they are sufficiently large as in the present cases, will obscure the equilibrium deformation and can give rise to an apparent two-Lorentzian splitting.[4]

The data points in Fig. 3 (top row) show again the absorption cross section $\sigma_{abs}(E_\gamma)$ determined from the spectrum fit, and the bottom row shows $a_2(E_\gamma)$, the measured angular distribution coefficient of $P_2(\cos\theta_\gamma)$. The a_1 coefficient was also determined, and found to be ap-

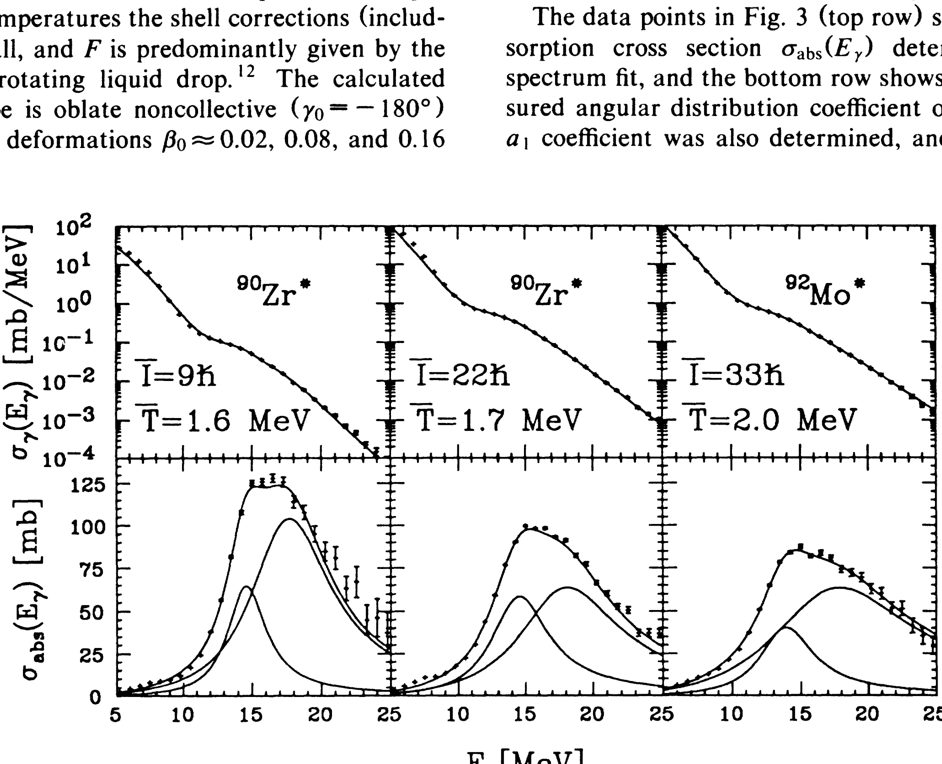

FIG. 2. Top row: measured and fitted γ-emission cross section $\sigma_\gamma(E_\gamma)$. Bottom row: solid curves, fitted absorption cross section $\sigma_{abs}(E_\gamma)$ corresponding to the parameters given in Table I; data points, measured $\sigma_\gamma(E_\gamma)$ divided by the calculated ratio $\sigma_\gamma(E_\gamma)/\sigma_{abs}(E_\gamma)$.

TABLE I. GDR parameters deduced from CASCADE fits to the spectrum shape. The error bars shown include estimated systematic errors as well as statistical errors. Energies and widths are in MeV, and strengths S_1+S_2 in units of the classical $E1$ sum rule.

	E_x	$\bar{E}$ [a]	E_2/E_1	S_2/S_1	S_2+S_1	Γ_1	Γ_2	FWHM [b]
$^{90}Zr^*$	54.4	16.97 ± 0.28	1.21 ± 0.06	3.32 ± 2.37	1.12 ± 0.15	3.42 ± 0.80	7.02 ± 1.25	8.22 ± 0.24
$^{90}Zr^*$	75.0	16.98 ± 0.34	1.25 ± 0.02	1.89 ± 1.03	1.04 ± 0.08	5.24 ± 0.88	9.07 ± 0.77	9.67 ± 0.39
$^{92}Mo^*$	93.5	17.13 ± 0.71	1.28 ± 0.14	4.23 ± 7.94	1.15 ± 0.17	4.78 ± 2.50	12.78 ± 2.37	12.08 ± 0.97

[a]Mean resonance energy $\bar{E}\equiv(E_1S_1+E_2S_2)/(S_1+S_2)$.

[b]Full width at half maximum.

proximately zero for $E_\gamma \gtrsim 11$ MeV, consistent with statistical decay. The nearly isotropic angular distribution at the lowest spin is consistent with an approximately spherical shape for the decaying nucleus. At the two higher spins, a_2 has a dispersionlike energy dependence characteristic of GDR γ decay from a deformed rotating nucleus, with a magnitude which increases with spin, indicating that the deformation of the excited nucleus also increases with spin.

A quantitative interpretation of the measured angular distributions and spectrum shapes requires comparison with a theory including shape fluctuations. The solid curves in Fig 3 show the spectrum shapes and angular-distribution coefficients calculated with the fluctuation theory of Ref. 10, in which the GDR vibration is averaged over the free-energy surfaces shown in Fig. 1, using the unitary metric $d\tau=\beta^4|\sin 3\gamma|d\beta d\gamma d\Omega$, where Ω represents the Euler angles. This theory has been shown previously to provide a good description of spectrum shapes observed in a variety of different reactions.[15] The calculated spectrum shapes also agree well in the present cases. Because of the phase-space weighting, the most probable deformation is considerably larger than β_0; for the three measured cases the values are 0.24, 0.31, and 0.46 for $9\hbar$, $22\hbar$, and $33\hbar$, respectively. Thus, the fluctuations dominate in the spectrum shape. Note that the apparent deformation inferred from the CASCADE two-Lorentzian fits to the spectrum shape, as discussed above, lies in between the most probable deformation and the equilibrium deformation, and hence does not appear to be a reliable indicator of either.

The calculated a_2 coefficient at each γ-ray energy is determined by the difference in GDR vibration strengths along and perpendicular to the spin axis, averaged over the free-energy surface. Here effects due to thermal fluctuations in the orientation of the deformed shape with respect to the spin axis are very important.[10] The calculated a_2 is expected to be valid above $E_\gamma=11$ MeV.[16] The agreement with the measured a_2 values is good in the important region $11\leq a_2\leq 20$ MeV, where the GDR strength is concentrated, and where the errors on the measured values are small. For the highest-spin case, there appears to be a disagreement for $E_\gamma>20$ MeV, on the high-energy tail of the GDR, which is not understood.

The angular anisotropy is very sensitive to the equilib-

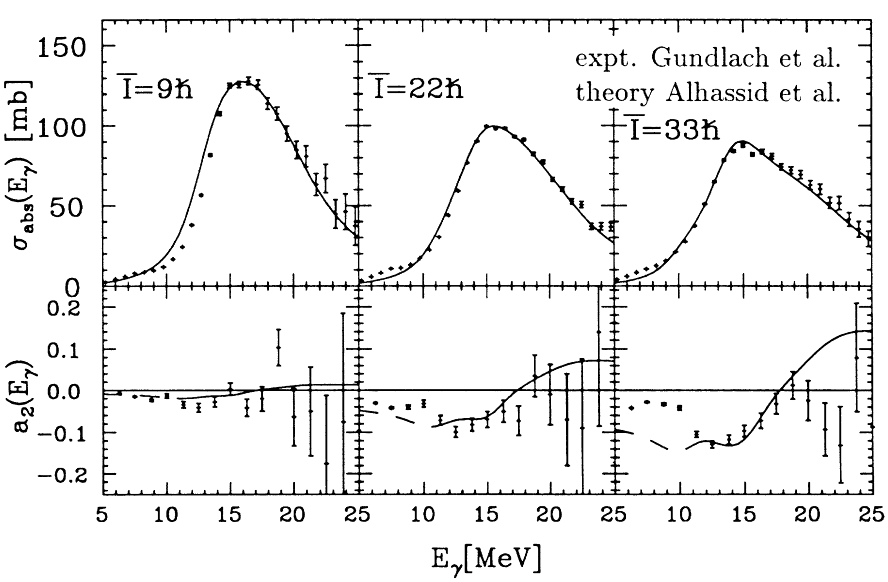

FIG. 3. Data points: top row, absorption cross section $\sigma_{abs}(E_\gamma)$ as in the bottom row of Fig. 2; bottom row, angular-distribution coefficient $a_2(E_\gamma)$. Curves: calculations of Ref. 10. The calculated $\sigma_{abs}(E_\gamma)$ have been scaled by factors of 1.17, 0.97, and 0.90 for the three cases, respectively, in order to match the experimental magnitudes.

rium deformation β_0; indeed, the increase of the anisotropy with spin is due primarily to an increasing β_0. As in the spectrum shape, the measured angular anisotropy is insensitive to the sense of the deformation—oblate versus prolate.[4] However, from the good agreement between measured and calculated a_2 coefficients as a function of spin, shown in Fig. 3, we conclude that the deformation β_0 is given correctly by theory (to within $\pm 25\%$ for the two higher spins) and that the nuclear shape is oblate. It should be noted that, since the calculations were done in the adiabatic limit (i.e., $\tau_{def} \gg \Delta\omega^{-1}$, where τ_{def} is the time interval over which appreciable changes in the deformation occur, and $\Delta\omega$ is the GDR frequency spread due to deformation fluctuations), the present results show no evidence for nonadiabatic effects (i.e., "motional narrowing").[17,18]

In conclusion, we have presented accurate measurements of the spectrum shape and angular distributions of GDR γ rays emitted from hot rotating nuclei. We have shown, by comparison with results of a theory[10] including intrinsic-shape fluctuations and shape-orientation fluctuations calculated using the $\beta^4|\sin 3\gamma| d\beta d\gamma d\Omega$ phase-space element, that both the spectrum shapes and the angular anisotropies are well understood. Thus we were able to deduce the equilibrium shape in the presence of large shape fluctuations, and to demonstrate a liquid-drop-like shape change from spherical to oblate deformed with increasing spin.

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[1]M. Gallardo, M. Diebel, T. Dossing, and R. A. Broglia, Nucl. Phys. **A443**, 415 (1985).

[2]K. A. Snover, Annu. Rev. Nucl. Part. Sci. **36**, 545 (1986).

[3]J. J. Gaardhoje, C. Ellegaard, B. Herskind, R. M. Diamond, M. A. Dekplanque, G. Dines, A. O. Macchiavelli, and F. S. Stephens, Phys. Rev. Lett. **56**, 1783 (1986).

[4]K. A. Snover, in *Proceedings of the First Topical Meeting on Giant Resonance Excitation in Heavy Ion Collisions, Legnaro, Italy, 1987* [Nucl. Phys. **A482**, 13c (1988)].

[5]C. A. Gossett, K. A. Snover, J. A. Behr, G. Feldman, and J. L. Osborne, Phys. Rev. Lett. **54**, 1486 (1985).

[6]K. Neergard, Phys. Lett. **110B**, 7 (1982).

[7]P. Thirolf, D. Habs, D. Schwalm, R. D. Fisher, and V. Metag, in *Proceedings of the First Topical Meeting on Giant Resonance Excitation in Heavy Ion Collisions* (Ref. 4) [Nucl. Phys. **A482**, 93c (1988)].

[8]A. M. Bruce, J. J. Gaardhoje, B. Herskind, R. Chapman, J. C. Lisle, F. Khazaie, J. N. Mo, and P. J. Twin, Phys. Lett. B **215**, 237 (1988).

[9]R. Butsch, M. Thoennessen, D. R. Chakrabarty, M. G. Herman, and P. Paul, Phys. Rev. C **41**, 1530 (1990), and references therein.

[10]Y. Alhassid and B. Bush, following Letter, Phys. Rev. Lett. **65**, 2527 (1990).

[11]Computed as the average spins and temperatures following high-energy γ-ray emission using the computer code CASCADE.

[12]S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) **82**, 557 (1974).

[13]F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977); (private communication).

[14]B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975); H. Beil, R. Bergere, P. Carlos, A. Lepretre, A. De Miniac, and A. Veyssiere, Nucl. Phys. **A227**, 427 (1974).

[15]Y. Alhassid, B. Bush, and S. Levit, Phys. Rev. Lett. **61**, 1926 (1988); Y. Alhassid and B. Bush, Nucl. Phys. **A509**, 461 (1990).

[16]At lower E_γ, where the spectrum rises rapidly, later nuclides in the decay chain dominate. Here the angular momentum, alignment, temperature, and deformation may be substantially less than in the first few decay steps. These effects have not been included in the a_2 calculation.

[17]Y. Alhassid and B. Bush, Phys. Rev. Lett. **63**, 2452 (1989).

[18]W. E. Ormand, P. F. Bortignon, R. A. Broglia, T. Dossing, and B. Lauritzen, Phys. Rev. Lett. **64**, 2254 (1990).