Nuclear Shape at High Spin and Excitation Energy

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High-energy gamma rays from the deexcitation of giant dipole resonance modes have been measured for the decay of ^{108}Sn* and ^{166}Er*. The structure of the observed resonances can be correlated with the shapes of these nuclei at high excitation energy ($E^* \simeq 60$ MeV). For the deformed system ^{166}Er* a shape change with increasing temperature is suggested.

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The shapes of nuclei arise from basic correlations in nuclear matter. It is important to study these correlations and find the limits where they break down. This is possible to do by subjecting the nucleus to extreme conditions, such as high rotation and internal exciation energy, and studying the shapes which then result. Much work has been done in recent years both theoretically and experimentally to understand the shapes of "cold" nuclei. This work expands these studies to the mostly unexplored region of high nuclear temperature.

A recent development[1] in continuum spectroscopy has provided a new tool for studying high spin spin states in the unbound region where gamma-ray emission, although weak, can compete with particle evaporation. It relies on the observation of high-energy γ rays ($E_\gamma \geqslant 10$ MeV) emitted predominantly in the first stages of the decay of compound nuclei formed in heavy-ion–induced fusion reactions. These gamma rays have been associated with the deexcitation of giant dipole isovector resonance (GDR) modes. This has been substantiated[1,2] by comparing the measured cross section for gamma decay to the predictions of the classical dipole sum rule. The dependence of the GDR strength on excitation energy E^* has been studied,[3] and the GDR yield from the first step of the decay has been isolated.[4] The results are consistent with the statistical theory for nuclear decay and indicate that the observed GDR decay is from equilibrated systems.

In the present work we use this tool to study the shapes of nuclei in regions of excitation energy not otherwise accessible. At low excitation energy, for resonances built on the ground state, it is well known that the shape of the GDR reflects the shape of the nucleus.[5] The average resonance energy is related to the nuclear symmetry energy and in deformed nuclei the resonance is split into components corresponding to vibrations along the three principal nuclear axes. In rotating nuclei, because of the Coriolis force, the resonance is further divided into a total of five components. However, because of the small Coriolis splitting and the finite widths of these components, only two major peaks can be expected to be identified experimentally for axially symmetric nuclei. For prolate nuclei approximately $\frac{2}{3}$ of the total GDR strength is expected to be found in the peak of highest energy, while the situation is reversed for oblate nuclei.

This investigation focuses on the structure of the GDR up to excitation energies $E^* \simeq 60$ MeV and angular momenta $I\hbar \simeq 40\hbar$, and we find a significant difference in the shape and width of the GDR built on excited states between the (at $T = 0$ MeV) spherical nucleus ^{108}Sn and prolate deformed ^{166}Er. Furthermore we find evidence for a shape change of ^{166}Er* with increasing excitation energy. This work is the first which shows such an effect and which demonstrates that the study of giant resonances can yield detailed nuclear-structure information also at large nuclear temperature.

The compound nuclei ^{108}Sn* and ^{160}Er* were formed with the ^{92}Mo + ^{16}O, ^{96}Ru + ^{12}C, and ^{150}Nd + ^{16}O reactions with beams from the Niels Bohr Institute FN tandem accelerator and self-supporting metal targets 1–2 mg/cm^2 thick. High-energy gamma rays were measured in an array consisting of seven 12.7-cm by 15.2-cm NaI(Tl) detectors located at 40 cm from the target, at 90° and backward angles with respect to the beam direction. Absorbers of 6 mm Pb were placed in front of the detectors to reduce the count rate due to low-energy transitions. Only gamma rays with $E_\gamma \geqslant 5$ MeV were recorded in coincidence with a small-volume, fast CsF detector, located close to the target and subtending $\simeq 10\%$ of the total solid angle. This requirement favored the high-multiplicity events of interest since the background reactions (Coulomb excitation and transfer) have low gamma-ray multiplicity. The contribution from cosmic rays to the spectra was kept low by requiring a high data rate and by employing fast coincidence timing. This good timing also gave an excellent discrimination against slow and fast neutrons by time of flight. The absolute energy calibration of the detectors was determined by the $E_\gamma \simeq 17.3$-MeV rays from the 3-MeV $^{11}B(p,\gamma)$ reaction on a thick target. Gain stability of the detectors was established by monitoring the constancy of the energy spectrum corresponding to capture of slow neutrons in NaI as a function of time. Contamination from possible light impurities was also investigated and found to be completely negligible in the region of interest (10 MeV $\leq E_\gamma \leq$ 25 MeV).

Spectra from the decay of $^{108}Sn^*$ produced at $E^* \simeq 61$ MeV with a ^{16}O beam and at $E^* \simeq 51$ MeV with ^{16}O and ^{12}C beams are displayed in Fig. 1. The contribution from the GDR is clearly seen above $E_\gamma = 9$ MeV where the spectrum deviates from the exponentially decreasing shape characteristic of the low-E^* region of statistical transitions. Also shown in Fig. 1 are spectra calculated with a modified version of the statistical model code CASCADE[6] in which the energy dependence of the electric dipole matrix elements is given by a Lorentzian function. The calculations, which represent best fits to the data, have been obtained by varying the centroid E_G^c, width Γ_G^c, and strength S_G^c of the Lorentzian. The strength is given as the fraction of the classical $E1$ sum rule needed to reproduce the data. For all calculations mentioned in this article a level density parameter $a = 7.5$ was used. Because of the large statistical fluctuations at high E_γ, the experimental spectra cannot be unfolded. Furthermore, it is difficult to measure the detector response at these high transition energies. The procedure adopted has therefore been to fold the calculated spectra with a response function calculated with the EGS (electron-gamma-shower) computer program.[7] This code, which follows the propagation of gamma rays through matter, was tested for the actual detector geometry, by simulation of the gamma-ray distributions originating from the $^{11}B(p,\gamma)$ reaction (for $E_\gamma > 10$ MeV) and from known radioactive sources (including ^{66}Ga). The calculated spectra were found to reproduce well the measured spectra.

We find that the spectra in Fig. 1 are well described by statistical calculations using a single Lorentzian function with $E_G^c = 15.5$ MeV and $S_G^c = 65\% \times S(E1)_{class}$. Because of the lack of an accurate absolute gamma-ray normalization the total dipole sum-rule strength is poorly determined. However, the resonance parameters E_G^c and Γ_G^c are quite insensitive even to substantial variations of S_G^c. The estimated uncertainties are ± 0.5 MeV in E_G^c and ± 0.7 MeV in Γ_G^c. In the case of the 84-MeV ^{16}O reaction, an increase of Γ_G^c from 6.0 to 6.5 MeV produces a better fit. These widths are in excess of typical $T = 0$ MeV values ($\Gamma \simeq 4.5$ MeV) but the general structure of the resonance is consistent with an essentially spherical shape. Broadenings due to the coexistence of several shapes around the equilibrium shape and to the "wobbling" of the nucleus around the total angular momentum vector have been investigated by Døssing and Neergaard,[8] while the contributions from

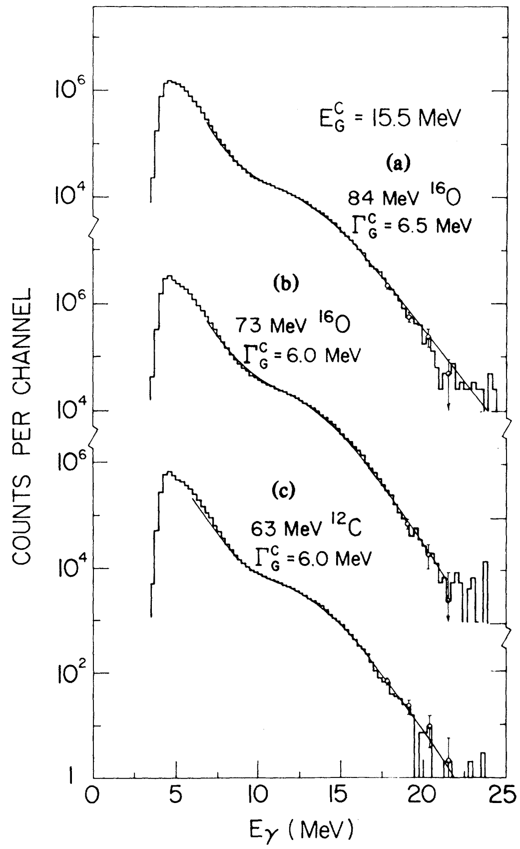

FIG. 1. Measured gamma-ray spectra from the decay of $^{108}Sn^*$. The abscissa respresents the energy registered in the detectors. The excitation energy is (at the middle of the target) in each case (a) $E^* = 61.2$ MeV, (b) $E^* = 51.8$ MeV, and (c) $E^* = 51.0$ MeV. The data have been fitted with statistical model calculations done with the code CASCADE and folded with a calculated detector response function. The GDR parameters used are indicated in the figure and are explained in the text.

Coriolis effects are discussed by Egido and Ring.[9] The authors of Ref. 8 find a 1–2-MeV increase in Γ_{GDR}, as compared to the ground state width, for the spin and temperature region discussed here. Although this predicted width increase can approximately account for the observations, an increase in the damping width of the vibration is also a possibility. Such an increase is also expected because of the decresasing level distance at higher temperature. Microscopic calculations of the damping width at high excitation energy have, however, just begun and no quantitative predictions are yet available.

In Fig. 2(a) we compare the measured γ-ray spectrum from the reaction $^{16}\mathrm{O} + {}^{150}\mathrm{Nd} \rightarrow {}^{166}\mathrm{Er}^*$ at 84 MeV to the spectrum of $^{108}\mathrm{Sn}^*$ at the same beam energy. While the excitation energy brought into these two systems is similar, the temperature associated with $^{166}\mathrm{Er}^*$ is lower because of the larger level density factor. The $^{166}\mathrm{Er}^*$ spectrum has also been fitted with a statistical model calculation. In this case a reduced resonance energy ($E_G^c = 14.9$ MeV) and a substantially larger width ($\Gamma_G^c = 9.5$ MeV) would be needed in order to describe the spectral shape. However, an accurate fit to the data is obtained only if two Lorentzian functions are used. In Fig. 2(a) we have fixed the width of the each Lorentzian to $\Gamma_G^c = 5.2$ MeV. The energies of the two components are $E_G^c(1) = 12.6$ MeV and $E_G^c(2) = 16.4$ MeV, and the relative strengths are 60% and 40%, respectively, indicating an essentially oblate shape for this nucleus at high E^*, although a weak ($< 5\%$) contamination from an isoscalar quadrupole mode at the lower energy cannot be excluded. The quality of these fits may be judged with more sensitivity in Fig. 2(b). Here we emphasize the GDR region in both experimental and calculated spectra by multiplying the spectra by the statistical level density factor $\exp(E_\gamma/T_G)$, taking into account the different average temperatures associated with the two systems. It is clearly seen that the shape of the GDR in $^{166}\mathrm{Er}^*$ reflects a composite structure. The energy splitting deduced by use of two GDR components of Lorentzian shape implies

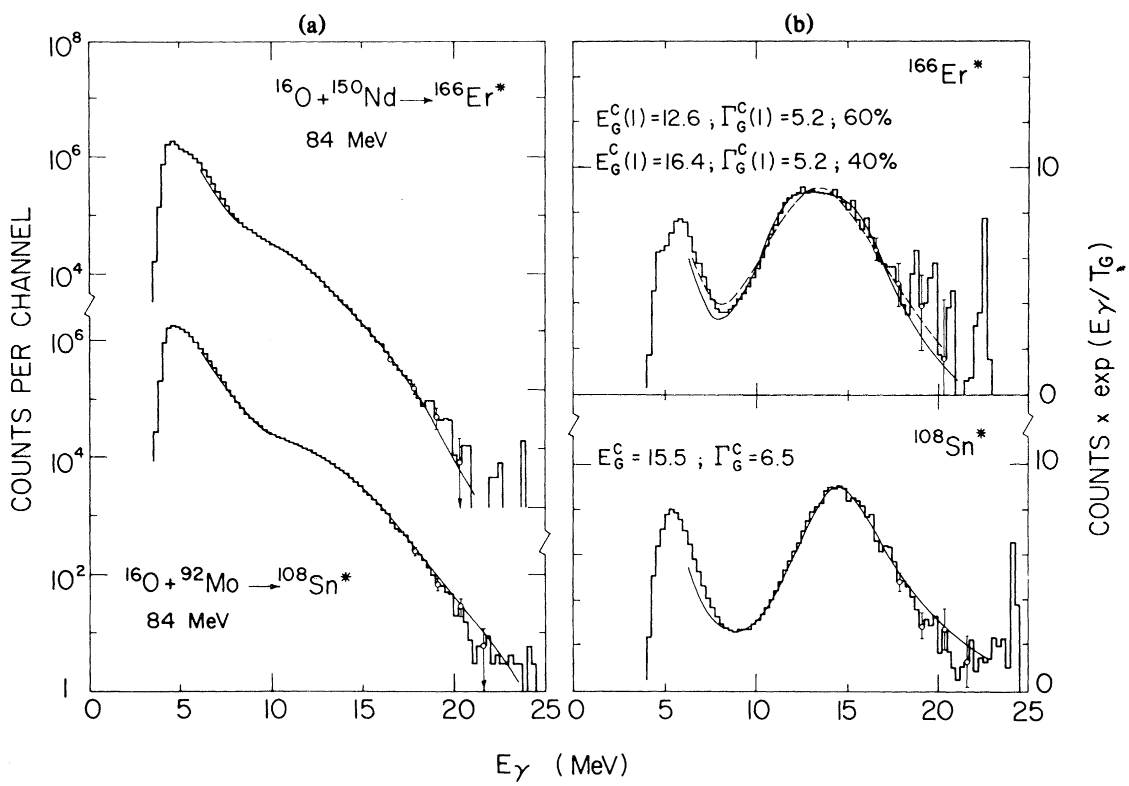

FIG. 2. (a) Measured gamma-ray spectra from the decay of $^{166}\mathrm{Er}^*$ (top) at $E^* = 61.5$ MeV and $^{108}\mathrm{Sn}^*$ (bottom) at $E^* = 61.2$ MeV, plotted as a function of the detected gamma-ray energy. The $^{166}\mathrm{Er}^*$ spectrum has been fitted with a statistical model calculation using an electric dipole strength function given by a double Lorentzian shape with the parameter values indicated in (b). (b) Same spectra multiplied by $\exp(E_\gamma/T_G)$, with $T_G(\mathrm{Sn}) = 1.6$ MeV and $T_G(\mathrm{Er}) = 1.4$ MeV, and normalized to approximately the same height at $E_\gamma = 14$–15 MeV. The ordinate is in arbitrary units. The quality of the fits and the different structures of the GDR's in the two systems is hereby emphasized.

a nuclear deformation $\delta = \Delta E_G^c / E_G^c \simeq 0.27 \pm 0.07$. Calculations[10] using the Strutinsky minimization procedure predict (for $T = 0$ MeV) prolate shapes for the $N = 98$ nuclei with $\delta = 0.25$ for angular momenta up to $70\hbar$. It is also stressed that the measured average resonance energies are consistent with the systematics for resonances built on the ground state, which indicates that the restoring force of the dipole vibration is not significantly affected by the increase in temperature.

In summary, these measurements for $^{108}Sn^*$ and $^{166}Er^*$ establish that the shape of the observed GDR's, which are built on highly excited states, can be used to determine the shape of the nucleus at high temperature, as is the case for resonances built on the ground state. It is found that while the data on $^{108}Sn^*$ are consistent with a mostly spherical shape up to $T \simeq 2$ MeV, a substantial deformation can be measured for the $^{166}Er^*$ system at $T \simeq 1.6$ MeV, a temperature at which approximately half the contribution of the shell structure to the free energy is expected to have vanished.[11] The deduced relative strengths of the $^{166}Er^*$ GDR components ($\simeq 60\%$ in the lower peak) indicate a predominantly oblate shape, which would imply a change of the shape of this nucleus with increasing I and/or E^*. These measurements therefore indicate that it will be possible to obtain detailed nuclear information by gamma spectroscopic methods, far from the yrast region. In particular, it should be possible to search for superdeformation in nuclei at high temperature and to study the disappearance of the nuclear shell structure as excitation energy increases.

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[1]J. O. Newton, B. Herskind, R. M. Diamond, E. L. Dines, J. E. Draper, K. H. Lindenberger, C. Schuck, S. Shih, and F. S. Stephens, Phys. Rev. Lett. **46**, 1383 (1981).

[2]A. M. Sandorfi, J. Barette, M. T. Collins, D. H. Hoffmann, A. J. Kreiner, D. Branford, S. G. Steadman, and J. Wiggins, Phys. Lett. **130B**, 19 (1983).

[3]J. E. Draper, J. O. Newton, L. G. Sobotka, K. H. Lindenberger, G. J. Wozniak, L. G. Moretto, F. S. Stephens, R. M. Diamond, and R. J. McDonald, Phys. Rev. Lett. **49**, 434 (1982).

[4]J. J. Garrdhøje, O. Andersen, R. M. Diamond, C. Ellegaard, L. Grodzins, B. Herskind, Z. Sujkowski, and P. M. Walker, Phys. Lett. **139B**, 273 (1984); J. J. Gaardhøje, in Proceedings of the XX International Winter Meeting on Nuclear Physics, Bormio, Italy, 1982 (unpublished), Vol. I, p. 107.

[5]E. G. Fuller and E. Hayward, Nucl. Phys. **30**, 613 (1962).

[6]P. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).

[7]R. L. Ford and W. R. Nelson, SLAC Report No. 210, 1978 (unpublished).

[8]T. Døssing and K. Neergaard, in Proceedings of the Fourth Nordic Meeting on Nuclear Physics, Fuglsø, Denmark, 1982 [Phys. Scr. **T5** (1983)].

[9]J. L. Egido and P. Ring, Phys. Rev. C **25**, 3239 (1982), and Nucl. Phys. **A388**, 19 (1982).

[10]G. Andersson, S. E. Larsson, G. Leander, P. Möller, S. G. Nilsson, I. Ragnarsson, S. Åberg, R. Bengtsson, I. Dudek, B. Nerlo-Pomorska, K. Pomorski, and Z. Szymanski, Nucl. Phys. **A268**, 205 (1976).

[11]A. Bohr and B. Mottelson, *Nuclear Structure II* (Benjamin, Reading, Mass., 1975), p. 610.