Observation of Superdeformation in the Doubly Closed-Shell Nucleus ^{146}Gd

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Two-dimensional γ-ray energy correlations have been measured at high spins in ^{146}Gd with the anti-Compton spectrometer array OSIRIS. Pronounced ridges have been found consisting of stretched $E2$ transitions. The separation of the ridges gives a dynamical moment of inertia $2\theta^{(2)}_{\text{band}}=(150\pm6)\hbar^2/\text{MeV}$, suggesting a superdeformation with an axis ratio $c/a=1.7$ ($\beta_2\approx0.6$). The quadrupole moment of the superdeformed nucleus is $Q_0=11^{+14}_{-4}\ e\cdot\text{b}$.

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The investigation of prolate superdeformation at high spins has become an important field of nuclear structure studies in the last years.[1-3] In ^{152}Dy, a superdeformed band up to a spin of 60 with a moment of inertia of $83\hbar^2/\text{MeV}$ and an intrinsic quadrupole moment of 19 $e\cdot\text{b}$, corresponding to a deformation of $\beta_2\approx0.6$, was found.[1] In ^{132}Ce and $^{134-136}$Nd bands corresponding to a somewhat smaller deformation of $\beta_2\approx0.4$–0.5 were established.[2,3] Superdeformation with $\beta_2\approx0.6$ has been predicted in theoretical studies using the Strutinsky shell correction method.[4,5] The most favored particle numbers to find superdeformed nuclei of intermediate mass are suggested to be $Z=64$ and $N=86$.[5] These calculations[4,5] indicate that the Gd nuclei are suitable candidates to search for superdeformation. Several studies of ^{144}Gd have been carried out which, however, did not show evidence for the existence of superdeformed shapes.[6,7] We have investigated the nucleus ^{146}Gd because a strong collectivity above spin 42 was found in quasicontinuum studies by Stwertka *et al.*[8] Our experiments give clear evidence for the existence of superdeformation above a spin of ≈30. This is a remarkable result considering that ^{146}Gd is a doubly closed-shell nucleus of spherical shape at low excitation energies.[9,10] It should be stressed that ^{146}Gd is the only doubly closed-shell nucleus which can be studied to very high spins because (i) it can be produced with a large cross section in heavy-ion–induced compound nuclear reactions and (ii) the limiting angular momentum which a nucleus can accommodate is largest for $A\approx140$.[11]

In order to establish superdeformation in ^{146}Gd, we have studied the ridge-valley structure and Doppler-shift effects in γ-ray-energy correlation matrices $E(\gamma_1)$ vs $E(\gamma_2)$.[1] To produce ^{146}Gd, we bombarded ^{110}Pd with ^{40}Ar projectiles of 180 MeV. The pulsed beam was delivered by the VICKSI accelerator combination at the Hahn-Meitner-Institut, Berlin. The time between beam bursts was 96 ns. A maximum transferred angular momentum of $\approx63\hbar$ was estimated for this reaction with use of the Julian-Pace code.[12] The γ radiation was measured with the OSIRIS spectrometer[13] consisting of twelve Compton-suppressed Ge detectors. We have carried out two experiments. (i) To study fast high-energy transitions with optimum resolution we used two self-supporting Pd foils with a thickness of 0.45 mg/cm^2 each and a distance of ≈0.4 mm between them. The γ rays are emitted from the recoiling ^{146}Gd nuclei in flight so that they are fully Doppler shifted, and the γ-line shape is governed by Doppler broadening because of the solid angles of the Ge detectors and the energy and angle straggling. (ii) Information about lifetimes with use of the Doppler-shift-attenuation (DSA) method[14] was obtained from an experiment with a ^{110}Pd target of 2.1 mg/cm^2 backed by a layer of 60-mg/cm^2 ^{209}Bi. In these two experiments 2.5×10^8 and 2.0×10^8 twofold coincidences were measured, respectively. We recorded γ-ray energies and times with respect to the beam burst for twofold and higherfold events.

To study the ridge-valley structure in the two-dimensional energy-correlation spectrum, we produced a

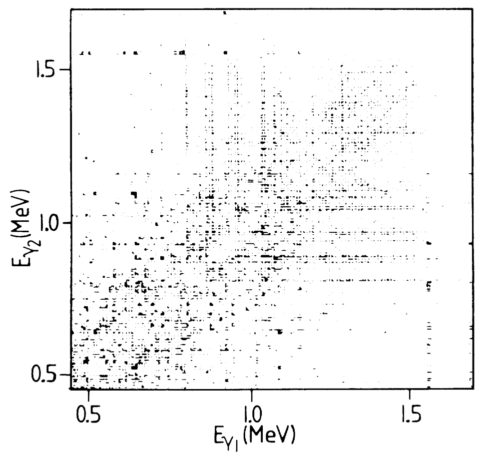

FIG. 1. Correlation spectrum of $E(\gamma_1)$ vs $E(\gamma_2)$ for ^{146}Gd as obtained in the thin-target experiment.

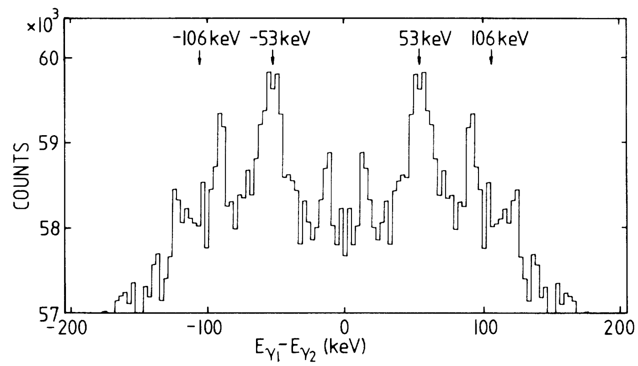

FIG. 2. Spectrum of $\Delta E = E(\gamma_1) - E(\gamma_2)$ obtained from the raw correlation matrix of ^{146}Gd in the thin-target experiment for an energy range of 1050 to 1425 keV. The peaks resulting from the ridges are marked by energies. The peaks at ± 92 keV result from coincidences between discrete lines of 1058.2 and 1150.5 keV. The peaks at ± 12 keV are due to the 1077–1088.4- and 1150.2–1162.5-keV coincidences of discrete lines.

matrix of γ-γ coincidences from the thin-target experiment. In the sorting of the list-mode data, the energies were corrected for Doppler shifts, and a prompt time window of 14 ns was used to reduce delayed background. In Fig. 1, part of the $E(\gamma_1)$ vs $E(\gamma_2)$ energy-correlation matrix for γ rays between about 0.5 and 1.7 MeV is shown. Uncorrelated events have been removed from the matrix by an iterative background-subtraction method.[15] The horizontal and vertical stripes in Fig. 1 are due to strong discrete γ transitions between low-spin states. Well-defined ridges parallel to the $E(\gamma_1) = E(\gamma_2)$ diagonal are observed for the energy range from about 0.8 to 1.5 MeV. The separation between the ridges remains constant over the full energy range. Such parallel ridges result from coincidences between consecutive transitions in rotational bands with a constant moment of inertia. To determine the separation and the width of the ridges, a spectrum has been produced by our cutting the energy-correlation matrix perpendicular to the diagonal $E(\gamma_1) = E(\gamma_2)$. The energy range of the cut was $1050 \leq [E(\gamma_1) + E(\gamma_2)]/2 \leq 1425$ keV. In Fig. 2 the spectrum of $\Delta E = E(\gamma_1) - E(\gamma_2)$ obtained from the raw correlation matrix is shown. No background correction has been applied to allow for a judgement of the statistical significance of the results. The ridges appear as peaks at energies of $\Delta E_{\text{ridge}} = \pm 5 \pm 2$ keV. The width of the ridge is 13.6 keV FWHM, which is about twice as large as the instrumental resolution of 7.1 keV FWHM. This observation suggests that the ridge consists of several bands with similar moments of inertia.[5] The dynamic moment of inertia of the rotational bands relates to the separation of the ridges as $2\theta^{(2)}_{\text{band}} = 8\hbar^2/\Delta E_{\text{ridge}}$. In this experiment a value of $2\theta^{(2)}_{\text{band}} = (150 \pm 6)\hbar^2/\text{MeV}$ was obtained. This moment of inertia is 1.34 times larger than that of a rigid spherical nucleus of mass number $A = 146$, if we assume a nuclear radius $R = 1.2A^{1/3}$ fm. The ratio of the moments of inertia of a rigid rotational-symmetric ellipsoid and a rigid sphere of same volume is given by $\theta/\theta_0 = [1 + (c/a)^2]/2(c/a)^{2/3}$, where c and a are the long and short half-axes, respectively. The experimental ratio $\theta/\theta_0 = 1.34$ corresponds to a very large axis ratio $c/a = 1.7$ ($\beta_2 \approx 0.6$).[16] This axis ratio can be considered as a lower limit, since the superdeformed nucleus may still not be a rigid rotor. In ^{152}Dy, for comparison, the quadrupole moment gives an axis ratio of $c/a = 1.9$, whereas the moment of inertia yields $c/a = 1.7$.[1] The observed energy range of the ridge structure corresponds to a spin range of ≈ 30 to 56 with the assumption that $E_\gamma = (\hbar^2/2\theta)(4I - 2)$.

In our experiments the final nuclei ^{145,146}Gd were produced with similar yields. In order to find out to which nucleus the superdeformed ridges belong, we analyzed the 10^7 threefold-coincidence events obtained in our study. We placed a two-dimensional gate of 22-keV width on the ridge in the energy-correlation matrix for energies from 1050 to 1510 keV and sorted a spectrum of $E(\gamma_3)$. Furthermore, background gates were set on either side of the ridge. The analysis of strong lines from ^{145,146}Gd in the $E(\gamma_3)$ spectrum gave, after background subtraction, -13 ± 75 counts for ^{145}Gd and 172 ± 90 counts for ^{146}Gd. This result favors an assignment of the superdeformed ridges to ^{146}Gd rather than ^{145}Gd. This assignment is supported by the fact that in the $4n$ channel (^{146}Gd) the nucleus is excited to considerably higher spins than in the $5n$ channel (^{145}Gd).

The experimental data of the thin-target measurement allowed us to determine the multipole order of the transitions forming the ridges utilizing angular correlation information. Two energy-correlation matrices have been produced, viz., a "forward-backward" (fb) matrix involving detectors with angles close to 34° and 146° and a

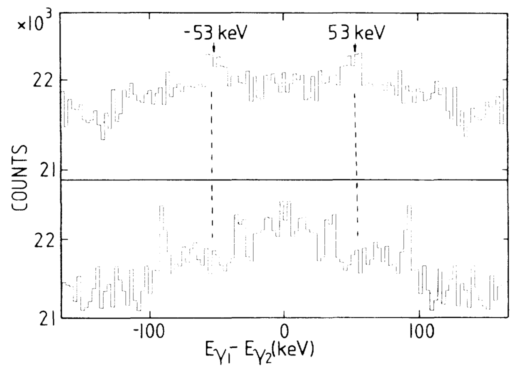

FIG. 3. Spectra of $\Delta E = E(\gamma_1) - E(\gamma_2)$ obtained from the raw correlation matrix of ^{146}Gd in the experiment with the backed target for an energy range of 1020 to 1390 keV. In the upper portion a full Doppler-shift correction has been applied, whereas in the lower portion no correction was made.

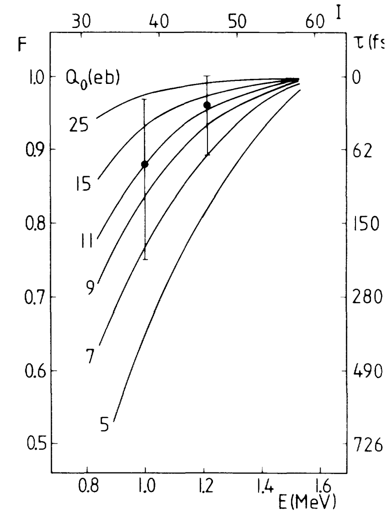

FIG. 4. Fraction F of the full Doppler shift as a function of transition energy. Average experimental values for two energy regions of 0.8–1.2 and 1.0–1.4 MeV are compared with calculations assuming different quadrupole moments for the superdeformed bands.

"perpendicular" (p) matrix with detectors at angles close to 90° with respect to the beam direction. The matrices were cut perpendicular to the diagonal $E(\gamma_1) = E(\gamma_2)$ for the energy range from 1050 to 1320 keV which does not contain strong discrete lines. In these cuts the intensities of the peaks corresponding to the ridges were determined. An intensity ratio $I_{\rm fb}/I_{\rm p} = 2.0 \pm 0.6$ has been obtained which has to be compared with theoretical predictions for our detector configuration.[17] For stretched quadrupole transitions, an intensity ratio of 1.6 is calculated, and for stretched dipole transitions, one of 0.7. Therefore, the transitions in the ridges are considered to have stretched quadrupole character.

The γ transitions in superdeformed bands are expected to be strongly enhanced $E2$ transitions. In ^{152}Dy a $B(E2)$ strength of 2660 W.u. (Weisskopf units) corresponding to lifetimes ≤ 30 fs for $I \gtrsim 30$ was found.[1] Lifetime information for superdeformed bands in ^{146}Gd was obtained from the experiment with the backed target. The ^{146}Gd nuclei recoiling with an initial velocity of $v_0 = 0.026c$ were slowed down and finally stopped in the target plus backing. Only γ rays from levels which have effective lifetimes shorter than 100 fs will be emitted from recoiling nuclei which fly with a velocity $v \geq 0.85 v_0$ showing essentially the full Doppler shift. "Slow" γ transitions ($\tau \gtrsim 2.5$ ps) will exhibit no Doppler shift. The γ transitions will only appear as sharp peaks in the summed spectra if the appropriate Doppler-shift correction is applied for each detector angle. Two energy-correlation matrices have been sorted by our making a full Doppler-shift correction and no correction, respectively. In Fig. 3, cuts of these matrices perpendicular to the diagonal $E(\gamma_1) = E(\gamma_2)$ for an energy range of 1020 to 1390 keV are shown. Only in the upper portion, corresponding to a full Doppler-shift correction, are the superdeformed ridges seen which vanish completely in the lower portion, in which no correction was applied. In the lower spectrum of Fig. 3, slow discrete γ transitions are visible. This result indicates that the superdeformed ridges consist of very fast γ transitions. A more detailed analysis of the lifetimes allows us to determine the quadrupole moment of the superdeformed bands. In the Doppler-shift–attenuation method, the decay time of the excited state is correlated to the fraction of the full Doppler shift $F = \bar{v}/v_0$ by which the energy of the γ line is shifted.[14] We determined F for two energy regions of 0.8 to 1.2 and 1.0 to 1.4 MeV. Several matrices with different fractions of the full Doppler-shift correction have been sorted. Subsequently we produced spectra of $\Delta E = E(\gamma_1) - E(\gamma_2)$ and determined the width of the ridges. The width is minimal in the spectra, which are summed over all detector angles, for which the accurate fraction F of the full Doppler shift is applied. The fractions F of the two energy regions are compared in Fig. 4 with F values calculated as $F = (\lambda_k / v_0 N_0) \int v(t) N_k(t)\, dt$. The velocity distribution of the recoiling nuclei $v(t)$ was obtained from a Monte Carlo calculation[18] including electronic and nuclear stopping. The decay rate $\lambda_k N_k(t)$ of the kth members of the superdeformed band was calculated under the assumption of a constant quadrupole moment and a complete feeding into the member of the superdeformed band with the highest spin.[1] From Fig. 4 it can be concluded that the quadrupole moment is $Q_0 = 11^{+4}_{-4}\ e \cdot {\rm b}$, which corresponds to about 1000 W.u. This result is in good agreement with a quadrupole moment of 13 $e \cdot$b of a uniformly charged ellipsoid with an axis ratio of $c/a = 1.7$ as calculated from $Q_0 = \frac{2}{5} Z R^2 [(c/a)^2 - 1]/(c/a)^{2/3}$.

In conclusion, pronounced ridges have been found in energy-correlation spectra for ^{146}Gd with a constant energy separation corresponding to a moment of inertia of $2\theta^{(2)}_{\mathrm{band}}=(150\pm6)\hbar^2/\mathrm{MeV}$. The ridges consist of fast stretched $E2$ transitions with lifetimes corresponding to a quadrupole moment of $Q_0=11^{+14}_{-4}\ e\cdot\mathrm{b}$. From the moment of inertia a prolate deformation with an axis ratio $c/a=1.7$ ($\beta_2\approx0.6$) has been deduced. These observations are associated with superdeformed structures in ^{146}Gd with features similar to those in ^{152}Dy.[1] Our results provide the first experimental evidence for superdeformation at high angular momenta for a nucleus which has a doubly closed shell and hence a spherical shape at low spins. The shell structure has to change drastically at high spins to overcome the stability against shape changes of a doubly closed-shell nucleus.

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