Evidence for Prolate Deformation in Highly Excited Neutron-Deficient Pb Isotopes

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We report the observation of the giant dipole resonance in Pb nuclei near $A \sim 200$ at excitation energies of 66, 88, and 103 MeV and with average angular momenta of $25\hbar$ to $44\hbar$. The fits to the dipole strength distribution require two components indicating a strongly deformed nuclear shape. Use of width parameters consistent with the ground-state systematics of heavy deformed nuclei gives $E_1 = 11.9$ MeV, $E_2 \cong 15.6$ MeV, and prolate deformation with $\beta \cong 0.3$. These results are compared with a prediction for superdeformed shapes in ^{196}Pb at $L = 30\hbar$.

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The observation of giant dipole vibrations of highly excited nuclei produced in fusion evaporation reactions has opened up the interesting possibility of our studying the shapes of hot rotating nuclei.[1,2] There are many theoretical calculations predicting the change of nuclear shape as a function of angular momentum and temperature. One of the most interesting predictions is that some nuclei attain a superdeformed prolate shape at angular momenta close to the fission limit.[3,4] The observation of such a superdeformed band has been recently reported in ^{152}Dy from the spectroscopy of discrete γ rays following fusion evaporation reactions.[5] These studies establish the properties of cold nuclei near the yrast line. The effect of increasing temperature is, in general, a washing out of the shell corrections which decreases any prolate deformation[6] and leads, at high temperature, to oblate shapes.[7] If the nuclei formed in a fusion evaporation reaction maintain their equilibrium shapes long enough to sustain a dipole vibration, then a measurement of the strength function of the giant dipole resonance (GDR) can determine the magnitude and sign of the deformation of the vibrating nucleus, even at high temperatures. We report here, from such a measurement, evidence for a large prolate deformation in Pb nuclei near $A = 200$ at excitation energies of $\sim$70–90 MeV. These nuclei should have nearly spherical ground states.

Detailed predictions for superdeformed shapes, with deformation parameter β close to 0.6, have been given[3] for the nuclei ^{152}Dy and ^{196}Pb. In ^{152}Dy, the superdeformed band becomes the yrast band at an angular momentum of $\sim 60\hbar$, whereas in ^{196}Pb this happens at $\sim 30\hbar$. Thus the deformed potential minimum is comparatively deeper in the second case and is predicted to persist up to a temperature $T \sim 1$ MeV. The heavy-mass region thus appears more suitable for observing the superdeformed nuclear shape through the measurement of GDR strength functions in fusion evaporation reactions. Accordingly, we give here experimental results on the measurement of high-energy γ spectra up to $E_\gamma \sim 25$ MeV in the heavy-ion fusion reactions $^{16}\mathrm{O} + {}^{\mathrm{nat}}\mathrm{W}$ at 100 and 140 MeV and $^{19}\mathrm{F} + {}^{181}\mathrm{Ta}$ at 105 and 126 MeV producing compound nuclei $^{198-202}$Pb at excitation energies from 66 to 102 MeV.

Self-supporting targets (~ 3 mg/cm^2) of W and Ta were bombarded with ^{16}O and ^{19}F beams from the Stony Brook linac. A 10-in.$\times$15-in. NaI detector with plastic anticoincidence shield, placed at 60 cm from the target was used for the detection of γ rays. Neutron suppression was achieved by time-of-flight measurements. Pulse pileup discrimination was obtained by routing the linear energy pulse into two charge-sensitive analog-to-digital converters gated over different time widths and determining the ratio of the respective integrated charges.[8] A γ-ray multiplicity filter consisting of ten 3-in.$\times$4-in. NaI crystals was used to select out fusion events by requiring at least a twofold coincidence for a good event.

The γ-ray spectra observed in the large NaI crystal at different bombarding energies are shown in Fig. 1. These spectra show the typical exponential decay at low γ energies and a broad bump above 8 MeV signifying the GDR decay between excited states. The data were fitted with statistical-model calculations using the code CASCADE[9] with an energy-independent level-density parameter $a = A/8$ MeV^{-1} at excitation energies > 20 MeV. The fission channel was included with use of a liquid-drop barrier adjusted (downward) to yield the measured fission cross sections.[10] The $E1$ strength function was taken as a one- or two-component GDR with the position(s), width(s), and strength distributions treated as free parameters. The calculated spectra were folded with the energy-dependent response function of the detector obtained from the EGS shower code, for a comparison with the data. To obtain the best fits the energies and widths were varied in steps of ≥ 0.1 MeV, the strength ratio S_2/S_1 in steps of 0.25 from 2.0 down to 0.5. The fit quality was judged by visual inspection. The calculations for the natural W target were done for $A = 184$ but at an excitation energy obtained from a weighted average of isotope Q values. The γ-ray contribution from the excited fission fragments was estimated from a separate CASCADE calculation for the (assumed symmetric) fission products with the relative normalization determined by the fission cross section. The average excitation energies were taken from the primary CAS-

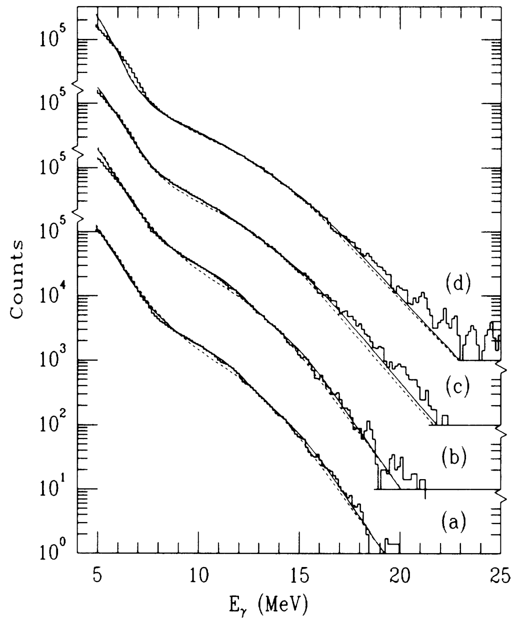

FIG. 1. Experimental γ spectra and fits from CASCADE calculations for (a) $^{16}O+{}^{nat}W$ at 100 MeV, (b) $^{19}F+{}^{181}Ta$ at 105 MeV, (c) $^{19}F+{}^{181}Ta$ at 126 MeV, and (d) $^{16}O+{}^{nat}W$ at 140 MeV. Solid and dashed curves are two-component and one-component fits, respectively.

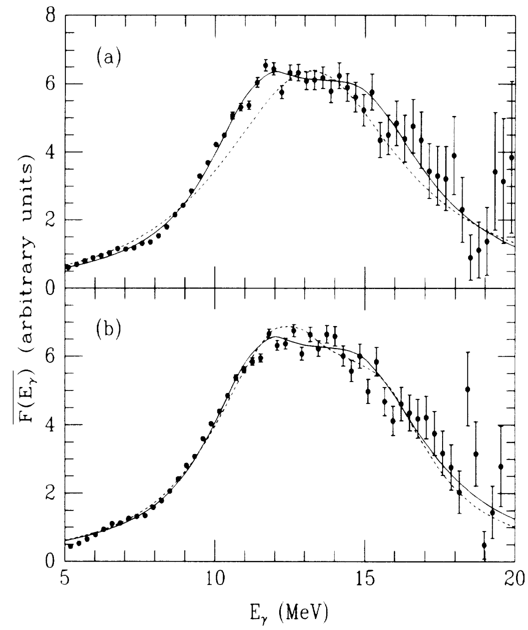

FIG. 2. Divided plots (see text) of the spectra measured in (a) $^{16}O+{}^{nat}W$ at 100 MeV and (b) $^{19}F+{}^{181}Ta$ at 105 MeV. The ordinate is proportional to the average GDR strength function $\overline{F(E_\gamma)}$. The various curves are explained in the text.

CADE results and Viola systematics.[11] The input GDR parameters, $E_{GD}=16$ MeV and $\Gamma_{GD}=8$ MeV, are close to experimental results[12] on $A=100$ nuclei.

Figures 1(a) and 1(b) show the best fits by the data at $E_x \sim 66$ MeV. The dashed curves show the fits obtained with a single component GDR of $E_{GD}=14$ MeV, consistent with the ground-state systematics of Pb isotopes, treating the width as free parameter. The poor fits could not be improved even by variation of the GDR energy. The degree of discrepancy is brought out more clearly in another representation of the spectra, shown in Figs. 2(a) and 2(b). These were generated by our dividing both the experimental and the fitted spectra by a calculated spectrum assuming a constant $E1$ strength function of an (arbitrary) strength of 0.2 W.u. and normalizing to the data at $E_\gamma \sim 7$ MeV. The fission γ-ray contribution ($<4\%$ above 8 MeV) was subtracted from the data. These "divided plots" show the need for a strength function with at least two components to fit the data. The solid curves are the best fits with two components having a strength ratio $S_2/S_1=2$ (prolate deformation). The fit values of the energies and widths of the two components are listed in Table I. The dashed curve in Fig. 2(a) shows the best, clearly inadequate, single-Lorentzian fit ($\Gamma_{GD}=7$ MeV). The dashed curve in Fig. 2(b) demonstrates the best fit obtained for $S_2/S_1=0.5$ (oblate deformation) with parameters listed in Table I. For the prolate fit the width obtained for the lower component is close to the ground-state GDR width (3.85 MeV) of ^{206}Pb and the ratio $\Gamma_2/\Gamma_1=1.4$ is typical of the ratios of the ground-state GDR widths of heavy deformed nuclei.[12] For the oblate fit the lower component width is 5

TABLE I. GDR fit parameters for $S_2/S_1=2.0$ corresponding to prolate deformation. In parentheses, fit values for $S_2/S_1=0.5$ corresponding to oblate deformation. Energies and widths in megaelectronvolts. Errors represent the parameter range which gave visually acceptable fits.

Reaction	E_{beam}	E_{ex}	E_1	Γ_1	E_2	Γ_2	β
$^{16}O+{}^{nat}W$	100	65.7	11.9 ± 0.1	3.8 ± 0.2	15.4 ± 0.2	5.3 ± 0.3	0.31 ± 0.02
$^{19}F+{}^{181}Ta$	105	68.5	11.9 ± 0.1	3.8 ± 0.2	15.4 ± 0.2	5.3 ± 0.3	0.31 ± 0.02
			(12.7)	(5.0)	(16.0)	(3.5)	(-0.26)
$^{19}F+{}^{181}Ta$	126	87.8	11.9 ± 0.2	5.8 ± 0.3	$15.8^{+0.5}_{-0.2}$	7.5 ± 0.5	$0.34^{+0.04}_{-0.02}$
$^{16}O+{}^{nat}W$	140	102.5	11.9 ± 0.2	5.8 ± 0.3	15.8 ± 0.3	8.5 ± 0.5	0.34 ± 0.03

[a]A single-component fit cannot be ruled out for this case.

MeV and the width ratio is $\Gamma_2/\Gamma_1 = 0.7$. Since this contradicts the ground-state systematics we conclude that the deformation is prolate. Assuming $\Gamma_2/\Gamma_1 \sim 1.4$ acceptable fits could be obtained only for $S_2/S_1 \gtrsim 1.75$, in agreement with the simple geometric model for dipole vibration in a prolate nucleus. The energies of the two components are related to the deformation parameter of a prolate spheroidal nucleus by the equation[13]

$$\beta = (4\pi/5)^{1/2}(E_2/E_1 - 1)/(E_2/2E_1 + 0.8665).$$

For oblate deformation the role of E_1 and E_2 is reversed. The β values so obtained are given in Table I.

The fit to the data at $E_x = 88$ MeV is shown in Fig. 1(c). Figure 3(a) shows the divided plot of the data generated after subtraction of the contribution from the fission fragments. The latter is shown by the dot-dashed curve after dividing by the same spectrum that divides the data. Again a single-component GDR ($E_{GD} = 14$ MeV, $\Gamma_{GD} = 8$ MeV) is not able to fit the data, as indicated by the dashed curves. The two-component fit obtained with $S_2/S_1 = 2$ is shown by the solid lines. The fit parameters are included in Table I. Figures 1(d) and 3(b) show the corresponding fits at $E_x = 102$ MeV with the dot-dashed curve showing the contribution from the fission fragments. Although a two-component GDR with parameters listed in Table I produces a better fit, one cannot rule out a fit with a single component ($E_{GD} = 13.8$ MeV, $\Gamma_{GD} = 9$ MeV).

The present observation of a large deformation of $\beta \sim 0.3$ for these neutron-deficient Pb isotopes invites some interesting and open speculations. The ground states of these isotopes are expected[14] to be nearly spherical with $\beta \sim 0.05$ and the low-lying intruder states have oblate deformation[15] with $\beta \sim -0.1$. The oblate-fit solution included in Table I of $\beta = -0.26$ would be difficult to explain on the basis of low-lying intruder states. Gallardo *et al.*[3] have predicted a superdeformed prolate shape with $\beta = 0.5$ for ^{196}Pb at temperature $T = 0$ and angular momentum $I = 30\hbar$. Their calculations also indicate that at $T = 0.8$ MeV the superdeformed minimum almost vanishes, with a decrease in deformation to $\beta = 0.35$. The shapes observed in our experiment are in overall agreement with these predictions although some detailed points are to be noted, as follows.

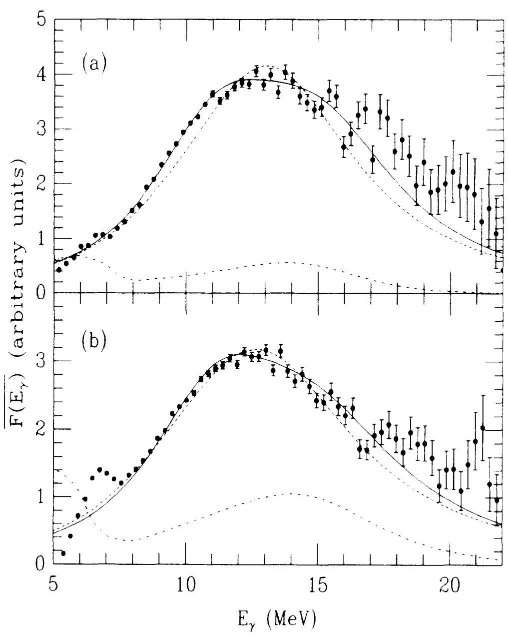

FIG. 3. Divided plots of the spectra measured in (a) ^{19}F + ^{181}Ta at 126 MeV and (b) ^{16}O + ^{nat}W at 140 MeV. The various curves are explained in the text.

The present work suggests the observed deformation effect to be a general feature for $A \sim 200$. This is because the reaction ^{16}O + ^{nat}W produced compound nuclei with $A = 198$ to 202 whereas in ^{19}F + ^{181}Ta the compound nucleus with $A = 200$. Also, the observed γ spectra were a sum from a number of decay steps, averaging again over different masses. This means that the factors producing the deformation do not depend critically on the neutral numbers although, in general, these shell effects are generated by the neutron orbitals.

The angular momenta populated in the compound nuclei have maximum values ranging from $38\hbar$ to $66\hbar$ at different bombarding energies. The code CASCADE assumes the same deformation for all L and all decay steps. If the onset of deformation occurs discontinuously at some value of L, the observed spectra could be the sum of a one-component and a two-component GDR strength function and this possibility cannot be ruled out by the data.

The observed average deformations are almost the same at $E_x \sim 66$ MeV and at $E_x \sim 88$ MeV. We note that both the average angular momentum and the temperature are higher in the second case. The temperatures of the nuclear states on which the giant dipole vibration is built were calculated from the relation $E^* = aT^2$, with $a = A/8$ MeV^{-1}. The energy E^* was obtained by our subtracting the average rotational energy and the GDR energy of ~ 14 MeV from the effective excitation energy calculated by averaging over the particle decay steps for which γ decay with $E_\gamma > 10$ MeV is significant. This gave $T = 1.1$, 1.3, and 1.5 MeV, respectively, for the three compound-nucleus excitation energies. Thus our results indicate that the deformation persists up to a temperature of at least 1.3 MeV, exceeding the value of 0.8 MeV above which the deformation minimum is predicted[3] to be washed out.

In summary, the present work indicates a prolate deformation in the spherical neutron-deficient lead isotopes of mass ~ 200 at high angular momenta and excitation energy up to ~ 90 MeV, corresponding to $T \sim 1.3$ MeV. This is the first observation of a nearly spherical nucleus changing into a deformed shape at high spin from a study of high-energy γ decay. This change is broadly consistent with the prediction of the onset of superdeformation for nuclei around this mass region at high spin, the equilibrium deformation being smaller than the $\beta \sim 0.6$ because of the finite temperature.

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