RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 34, NUMBER 6 DECEMBER 1986

Octupole deformation at high spin in the Ba-Sm region

Raymond K. Sheline and P. C. Sood*
Florida State University, Tallahassee, Florida 32306
(Received 11 September 1986)

Experimental evidence is presented for stable octupole deformation at high spin in ^{150}Sm and possibly other rare earth nuclei based on the evolution with increasing spin of the $K^{\pi}=0^{+}$ and 0^{-} bands into a single band. Comparisons and contrasts in the corresponding band evolutions are presented between the 88 and 90 isotones in the rare earths, and 88 and 90 protons (Ra and Th isotopes) in the actinides where stable octupole deformation is established.

Just beyond the double-closed shell in ^{208}Pb, the $g_{9/2}$ and $j_{15/2}$ neutron orbitals and the $f_{7/2}$ and $i_{13/2}$ proton orbitals lie energetically close together and close to the Fermi surface. Particle hole configurations with these orbitals, therefore, give rise to very low-lying $J^{\pi}=3^{-}$ two-quasiparticle states which form the basis for stable octupole deformation in the neutron-deficient actinides. In a similar way, the $f_{7/2}$ and $i_{13/2}$ neutron orbitals and the $d_{5/2}$ and $h_{11/2}$ proton orbitals just beyond the double-closed shell at ^{132}Sn are quite close together and near the Fermi surface. We therefore might expect the combinations of these orbitals to give rise to low-lying $J^{\pi}=3^{-}$ states, which could form the microscopic basis for stable octupole deformation in the Ba-Sm rare earth region.

The position of the appropriate orbitals suggests that this effect towards stable octupole deformation should be maximized in the neutron-deficient actinides in the vicinity of ^{224}Ra and ^{226}Th. This corresponds to the near-filling of the $f_{7/2}$ proton orbital and the filling of the $g_{9/2}$ neutron orbital—the ideal arrangement for producing the appropriate particle hole configurations. In a similar way, one might look for the filling or near filling of the $d_{5/2}$ proton orbital and the $f_{7/2}$ neutron orbital for the neutron-proton configuration most likely to lead to octupole deformation in the rare earths. Since the $d_{5/2}$ and $g_{7/2}$ proton orbitals are very nearly degenerate in energy, there is some ambiguity in the appropriate proton number which could correspond to anything from 56(Ba) to 64(Gd). If we assume the appropriate neutron number is 88 or 90, then the range of nuclei of interest is from ^{144}Ba and ^{146}Ba to ^{152}Gd and ^{154}Gd.

Thus, while the region of octupole deformation beyond ^{208}Pb is in the neutron deficient actinides, the region of possible octupole deformation in rare earths involves neutron excess species. This makes it more difficult to do experiments in the rare earth region because only decay scheme spectroscopy appears to be easily available—not nuclear reaction spectroscopy such as (HI, xn) as in the neutron deficient actinides.

In spite of these difficulties, Leander *et al.*[1] have shown the existence of a minimum in the 3^{-} energies in the $Z=56$ and $N=88$–90 region analogous to that observed in ^{224}Ra; Nazarewicz *et al.*[2] have calculated the potential energy functions in the rare earth region and shown the existence of octupole shape minima; and Leander *et al.*[3] have demonstrated the existence of a theoretical underbinding of nuclei in the ^{145}Ba region in the absence of octupole deformation similar to that observed near ^{222}Ra, and a gap at 88 neutrons and 56 protons for reflection asymmetric values of $\beta_3\cong 0.10$ using modified oscillator, folded Yukawa, and Woods-Saxon potentials. Indeed, the Woods-Saxon calculation of the single particle levels[3] for β_3 values $\cong 0.10$ shows almost as large a gap for $Z=62$ as for $Z=56$. This seems to mirror, to some extent, the fact that the $d_{5/2}$ orbital actually lies slightly higher in energy than the $g_{7/2}$ orbital.

Because the region around ^{144}Ba-^{146}Ba is so inaccessible experimentally, we have chosen to look at the ^{150}Sm-^{152}Sm region also, since it is more accessible. We also chose to look at the doubly-even nuclei because so much more experimental information is available for them.

In the nuclei around the neutron deficient radiums and thoriums, the odd-A nuclei have given more detailed spectroscopic information about stable octupole deformation.

Nonetheless, Nazarewicz *et al.*[4] have shown that octupole deformation is stabilized at high spin in a number of even-even Th nuclei. In order to see the effect of this stabilization on the rotational energies of the even parity and odd parity bands, they have introduced the function

$$\delta E(I)=E(I^{-})-\frac{[(I+1)E((I-1)^{+})+IE((I+1)^{+})]}{(2I+1)}\,, \tag{1}$$

which represents the displacement of the positive and negative parity bands. When $\delta E(I)=0$, the relative position of the positive and negative parity bands is such that the states of both parities comprise a single rotational band with an $I(I+1)$ energy dependence precisely as predicted in the strong coupling limit of stable octupole deformation. The innovation of Nazarewicz *et al.*[4] is that by plotting the displacement energy as a function of angular momentum, one can see whether or not the energy systematics is tending toward stable octupole deformation and at what spin. This approach has been used very recently by Schuler *et al.*[5] to study the evolution of octupole deformation as a function of spin in the doubly-even Th nuclei from ^{220}Th to ^{230}Th.

In this paper we apply the same rationale to the doubly-even rare earth nuclei in the vicinity where octupole deformation might be expected. Furthermore, we make the comparison between the Ra and Th isotopes with 88 and 90 protons, respectively, and the corresponding isotones of

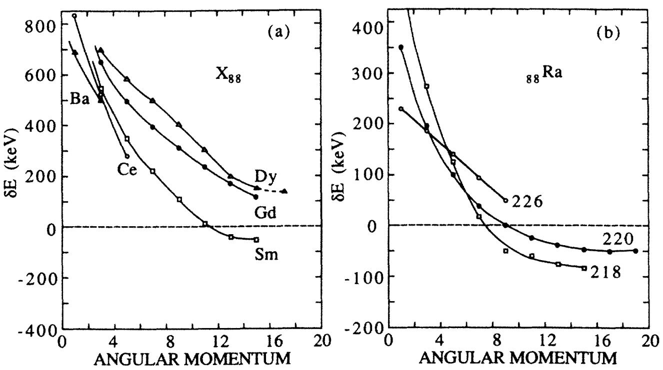

FIG. 1. A comparison of the displacement energies of the positive and negative energy bands (see text) for the isotones with 88 neutrons in the rare earth region of nuclei (a) with the displacement energy of the radium isotopes with 88 protons (b) as a function of angular momentum. The very limited low spin data for ^{148}Nd and for ^{222}Ra and ^{224}Ra are not included in (a) and (b), respectively, because they confuse the diagrams with greater complexity without contributing significantly to the systematics. The data are from Refs. 6, 7, 8, 9, and 10.

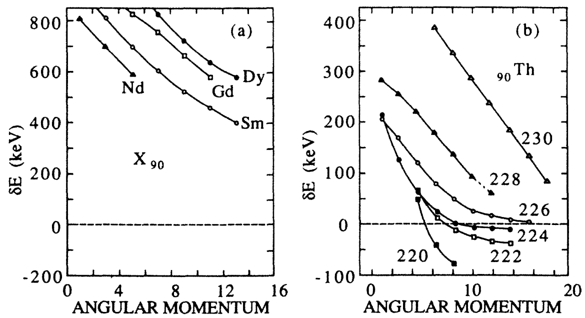

FIG. 2. A comparison of the displacement energy of the positive and negative parity bands (see text) for the isotones with (a) 90 neutrons and (b) 90 protons as a function of angular momentum. The data are from Refs. 5, 6, 11, 12, and 13.

the rare earth nuclei with 88 and 90 neutrons. These comparisons are shown in Figs. 1 and 2.

In Fig. 1 the displacement energies as a function of angular momentum of the isotones with 88 neutrons on the left are compared with the isotopes of Ra with 88 protons on the right. Very similar trends can be observed in both Figs. 1(a) and 1(b). However, whereas the displacement energy in the Ra isotopes is approaching the octupole deformation limit by spin $\cong 9$, it appears to be approaching this same limit in ^{150}Sm by spin $\cong 11$.

In Fig. 2 the displacement energies as a function of angular momentum of the isotones with 90 neutrons are compared with the isotopes of Th. Unfortunately, the systematics of the 90 neutron isotones is so incomplete that it is difficult to draw conclusions from the comparison. It does, however, seem probable that the 90 neutron isotones are much further from the octupole deformation limit than the Th isotopes [Fig. 2(b)] and the 88 neutron isotones [Fig. 1(a)]. This seems to imply that the 88 neutron configuration is better suited to achieve octupole deformation than the 90 neutron configuration, which has also been suggested theoretically.[3]

The fact that the evolution toward octupole deformation occurs at lower spin in the actinides than in the rare earths confirms the theoretical finding[2] that in their ground states the even-even actinides are closer to stable octupole deformation with appreciable barriers between their mirror octupole minima, while the minima in the rare earths are more shallow with smaller barriers. With higher rotational frequencies these mirror octupole potential minima and the corresponding barriers between them become more established. Clearly this should require higher rotational frequencies for the rare earths, whose ground state octupole minima are so much more shallow than for the actinides.

In spite of the strong suggestion of the energy systematics of Figs. 1 and 2 that the $K^\pi = 0^+$ and 0^- bands in the neutron excess rare earth region tend to and, in the case of ^{150}Sm, do merge into single bands characteristic of reflection asymmetric shape, a word of caution is in order. It is possible that a negative parity two-quasiparticle band crossing with the $K^\pi = 0^-$ band could cause an increase in the moment of inertia which might fortuitously cause an apparent merger of the $K^\pi = 0^+$ and 0^- bands. This appears very unlikely in the case of the Ra and Th isotopes of Figs. 1(b) and 2(b) since there are many examples with very similar displacement energy systematics. However, in the case of the rare earths, this possibility cannot be completely discounted since we have only one good example, ^{150}Sm, where the energies of the $K^\pi = 0^-$ and 0^+ bands are known for high enough angular momenta. In spite of the lack of experimental data, the great similarity in the displacement energy systematics between ^{150}Sm and the Ra and Th isotopes seems unlikely to arise from the fortuitous crossing of two-quasiparticle bands. It should also be mentioned that the observed crossings of two-quasiparticle positive parity bands with the $K^\pi = 0^+$ ground state band can cause an upbend in the displacement energies if one does not follow the ground state band (no longer yrast) to higher energies and spins.

The lack of experimental results in the rare earth region of interest should, however, stand as a challenge to experimentalists. In particular, it would be of great interest to identify the $K^\pi = 0^+$ and 0^- bands to high spins in ^{144}Ba, ^{146}Ba, ^{146}Ce, ^{148}Ce, ^{148}Nd, ^{150}Nd, ^{152}Sm, ^{152}Gd, ^{154}Gd, and ^{156}Dy. In addition, it would be of great value to complete the systematics for the Ra isotopes, particularly ^{222}Ra and ^{224}Ra.

Note added in proof. The feature of interlaced $K^\pi = 0^+$ and 0^- bands predicted for ^{144}Ba and ^{146}Ba in this paper has since been firmly established in the recent γ-γ coincidence studies of ^{252}Cf fission fragments by an Argonne group (W. R. Phillips, I. Ahmad, H. Emling, R. Holzmann, R. V. F. Janssen, T. L. Khoo, and M. W. Drigent, Argonne National Laboratory Report No. PHY-4891-HI-86, 1986). We are grateful to Dr. Irshad Ahmad for sending us a copy of the report.

Discussions with Georg Leander and Witek Nazarewicz during the preparation of this manuscript were very useful. This study was supported by the National Science Foundation with Florida State University under Contract No. PHY-8605032.

*Permanent address: Physics Department, Banaras Hindu University, Varanasi 221005, India.

[1]G. A. Leander, R. K. Sheline, P. Möller, P. Olanders, I. Ragnarsson, and A. J. Sierk, Nucl. Phys. **A388**, 452 (1982).

[2]W. Nazarewicz, P. Olanders, I. Ragnarsson, J. Dudek, G. A. Leander, P. Möller, and E. Ruchowska, Nucl. Phys. **A429**, 269 (1984).

[3]G. A. Leander, W. Nazarewicz, P. Olanders, I. Ragnarsson, and J. Dudek, Phys. Lett. **152B**, 284 (1985).

[4]W. Nazarewicz and P. Olanders, Nucl. Phys. **A441**, 420 (1985).

[5]P. Schuler, Ch. Lauterbach, Y. K. Agarwal, J. de Boer, K. P. Blume, P. A. Butler, K. Euler, Ch. Fleischmann, C. Günther, E. Hauber, H. J. Maier, M. Marten-Tölle, Ch. Schaundera, R. S. Simon, R. Tölle, and P. Zeyen, Phys. Lett. **174B**, 241 (1986).

[6]M. Sakai, Nucl. Data Tables **31**, 399 (1984).

[7]D. R. Zolnowski, M. B. Hughes, J. Hunt, and T. T. Sugihara, Phys. Rev. C **21**, 2556 (1980).

[8]J. F. Shriner, Jr., P. D. Cottle, J. F. Ennis, M. Gai, and D. A. Bromley, Phys. Rev. C **32**, 1885 (1985).

[9]R. Zimmerman, Ph.D. thesis, University of Munich, 1980 (unpublished).

[10]H. W. Cranmer-Gordon, P. D. Forsyth, D. V. Elenkov, D. Howe, J. F. Sharpey-Schafer, M. A. Riley, G. Sletten, J. Simpson, I. Ragnarsson, Z. Xing, and T. Bengtsson (unpublished).

[11]C. M. Baglin, Nucl. Data Sheets **30**, 1 (1980).

[12]R. L. West, E. G. Funk, and J. W. Mihelich, Phys. Rev. C **18**, 679 (1978).

[13]F. W. N. de Boer *et al.*, Nucl. Phys. **A290**, 173 (1977).