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OCTUPOLE FRAGMENTATION AND THE STRUCTURE OF THE O(6)-LIKE Ba NUCLEI

N. V. ZAMFIR
Brookhaven National Laboratory, Upton, NY 11973, USA
Clark University, Worcester, MA 01610, USA

R. F. CASTEN
WNSL, Yale University, New Haven , CT 06520, USA

P. D. COTTLE
Florida State University., Tallahassee, FL 32306, USA

S. DEYLITZ, A. GOLLWITZER, G. GRAW, R. HERTENBERGER, B. VALNION
Sektion Physik der Universität München, D-85748 Garching, Germany

G. CATA-DANIL
Institute of Atomic Physics, Bucharest- Magurele, Romania

A. OROS
Institut für Kernphysik, Universität zu Köln, Germany

W. T. CHOU
National Tsing Hua University, Hsinchu, Taiwan, Republic of China

Abstract: The low energy octupole states in ^{134}Ba were examined using proton inelastic scattering. The data show that there is no significant octupole strength in addition to that corresponding to the lowest 3^- state. Consequently, the strong fragmentation of the low energy octupole state expected for a γ soft nucleus does not occur in ^{134}Ba. The apparent contradiction that the positive parity states in this nucleus present an O(6) type structure and the negative parity ones do not follow the selection rules of the E3 operator for the O(6) symmetry might be explained by noticing that the wave function of an O(6) nucleus has a significant overlap with the wave function of an U(5) - SU(3) transitional nucleus.

1. Introduction

Although the collective negative parity states in even-even nuclei are much less studied than the positive parity ones, there are some basic features related to them that are well understood phenomenologically and microscopically and which constitute important signatures of nuclear structure. The evolution from spherical nuclei to deformed is reflected also in the negative parity states: a single spherical octupole vibrational state evolves into four different states having $K^\pi = 0^-, 1^-, 2^-$ and 3^-, where K is the projection of the octupole phonon angular momentum on the symmetry axis of the nucleus. The E3 strength which is concentrated in the single 3^- state in a spherical nucleus is distributed among the four 3^- states in a deformed one.

A useful measure for the evolution and behavior of the octupole states is the fragmentation of the octupole strength [1]:

$$\Delta E_3 = \frac{\Sigma_i E_i B(E3; 0^+_{gs} \rightarrow 3^-_i)}{\Sigma_i B(E3; 0^+_{gs} \rightarrow 3^-_i)} - E(3^-_1) \qquad (1)$$

where E_i is the energy of the ith 3^- state.

Figure 1 presents the evolution of the experimental octupole fragmentation; the data are graphed against $R_{4/2} = E(4^+_1)/E(2^+_1)$ which serves as a convenient structural indicator for collective nuclei. For spherical nuclei ($R_{4/2}$ near 2.0), the fragmentation is small, while octupole fragmentation is large in nuclei with large permanent quadrupole deformation ($R_{4/2}$ near 3.33) where the octupole mode splits into the four components (K=0,1,2,and 3).

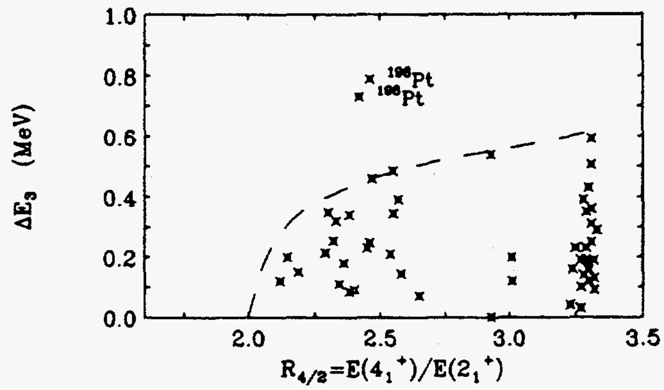

Figure 1: Values of ΔE_3 vs $R_{4/2} = E(4^+_1)/E(2^+_1)$ for all even-even nuclei with A>60

A striking result is that in $^{196,198}Pt$ ΔE_3 is larger than for any other nucleus by a significant amount, even though these nuclei do not possess a large quadrupole deformation. This anomalous behavior could be due to the γ- soft (O(6)) character of these Pt isotopes.

In order to see if the anomalously large fragmentation of the low energy octupole states is indeed a signature of this type of nuclei we use the interacting boson model (IBA) [2], which gives analytic results for limiting symmetries and can treat intermediate regions in terms of one or two parameter phase transitions. A version attempting to describe both the quadrupole and the octupole excitations was already proposed at an early stage in the development of the model by introducing an f boson of angular momentum and parity $L^\pi = 3^-$ in addition to the usual IBM s ($L^\pi = 0^+$) and d bosons ($L^\pi = 2^+$). Scholten, Iachello and Arima[3] succesfully explained in the framework of this model the octupole states in the transition from U(5) to SU(3). Using the same model Barfield et al[4] intrepreted the octupole vibrational states and their evolution in rare earth SU(3) nuclei. Engel[5] showed that in the O(6) limit the B(E3) strength to the ground state is spread out over two or more of the 3^- states.

DISCLAIMER

2. IBA calculation

Octupole states can be included in the IBA-1 by adding a single f boson with L=3 to the usual $s-d$ boson model space. The Hamiltonian for N_B bosons in an $(sd)^{N_B-x}f^x$ (x=0,1) system is given by [4]:

$$H = H_{sd} + H_f + V_{sdf} \tag{2}$$

Here the first term describes the even-even positive parity core structure upon which are built the negative parity excitations, incorporated in the last terms via an f boson. For the core Hamiltonian, H_{sd} has been adopted from the Extended Consistent Q-Formalism [6]:

$$H_{sd} = \epsilon_d n_d + a_1 L_d \cdot L_d - a_2 Q_d \cdot Q_d \tag{3}$$

where $n_d = d^\dagger \tilde{d}$ is the d boson number operator and

$$L_d = \sqrt{10}(d^\dagger \tilde{d})^{(1)} \tag{4}$$

$$Q_d = (s^\dagger \tilde{d} + d^\dagger s) + \chi_2 (d^\dagger \tilde{d})^{(2)} \tag{5}$$

The f-boson Hamiltonian is:

$$H_f = \epsilon_f n_f \tag{6}$$

where n_f, the number operator for f bosons, is 0 (for positive parity states) or 1 (for negative parity).

The interaction between the f boson and the $(N_B - 1)$ s, d boson system is considered in the multipole form [4]:

$$V_{sdf} = \quad A_1 L_d \cdot L_f + A_2 Q_d \cdot Q_f + A_3 : E_{df}^{+} E_{df} : \tag{7}$$

where:

$$L_f = 2\sqrt{7}(f^\dagger \tilde{f})^{(1)}, \tag{8}$$

$$Q_f = -2\sqrt{7}(f^\dagger \tilde{f})^{(2)} \tag{9}$$

$$: E_{df}^{+} E_{df} := 5 : (d^\dagger \tilde{f})^{(3)} \cdot (f^\dagger \tilde{d})^{(3)} : \tag{10}$$

The E3 transition rates are calculated with the operator [4]:

$$T(E3) = e_3 O^{(3)} \tag{11}$$

where e_3 is the boson octupole effective charge, and the octupole operator is

$$O^{(3)} = s^\dagger \tilde{f} + \chi_3 (d^\dagger \tilde{f})^{(3)} + h.c. \tag{12}$$

Although the calculated wavefunctions may be rather complex, it is possible to gain a simple qualitative understanding of the E3 strengths by an analysis of the selection rules for the octupole operator of eq. 12. Its matrix elements between the 3_i^- states and 0_1^+ state take the form [7]:

$$\begin{aligned}
< 3_i^- | O^{(3)} | 0_1^+ > &= < \alpha_i (sd)^{N_B-1} f | s^\dagger \tilde{f} + \chi_3 (d^\dagger \tilde{f})^{(3)} + h.c. | \alpha_0 (sd)^{N_B} > \\
&= < \alpha_i s^{N_B-n_i-1} d^{n_i} | k_1 s^\dagger + k_2 \chi_3 d^\dagger | \alpha_0 s^{N_B-n_0} d^{n_0} > \\
&= k_3 < \alpha_i s^{N_B-n_i} d^{n_i} | \alpha_0 s^{N_B-n_0} d^{n_0} > + \chi_3 k_4 < \alpha_i s^{N_B-n_i-1} d^{n_i+1} | \alpha_0 s^{N_B-n_0} d^{n_0} > \\
&= k_3 \delta_{n_0,n_i} \delta_{\alpha_0,\alpha_i} + \chi_3 k_4 \delta_{n_0,n_i+1} \delta_{\alpha_0,\alpha_i} \qquad (13)
\end{aligned}$$

where α_0 and α_i are additional quantum numbers and k_j are geometrical coefficients whose detailed values are not important in determining the basic selection rules. n_0 and n_i are numbers of d bosons in the ground state and in the 3_i^- states, respectively.

By definition (see eq. 1), contributions to the octupole fragmentation will be made only by those 3_i^- states having the same number of d bosons as the ground state ($n_i = n_0$), or one d boson less ($n_i = n_0 - 1$). That is, we have the $0_{gs}^+ \rightarrow 3_i^-$ selection rules: Δn_d=0 if χ_3=0 Δn_d=0 or -1 if $\chi_3 \neq 0$. Thus, the distribution of octupole strength depend on the d-boson structure of the 3^- levels and the ground state, which differ for different structure types. In the U(5) symmetry, $< n_d >$=0 and only one 3^- state, that with structure $f \otimes 0_{gs}^+$, satisfies the selection rule for χ_3=0. In any other case, O(6), SU(3) or intermediate, the d-boson structure of the ground state, and of any 3^- levels, is more complex. There will be several components in the ground state with different n_d values, and $< n_d >$ will be finite. Hence the fragmentation grows. In a U(5)$\rightarrow$ SU(3) transition it grows rapidly with boson number N_B. However, for $N_B \leq$10, the number of states satisfying the selction rules for the $O^{(3)}$ operator is much larger in O(6) than in the U(5) $\rightarrow$ SU(3) region. Consequently, the octupole fragmentation, ΔE_3, is structure and shape dependent and for $N_B \leq 10$, it is much larger in O(6)-type nuclei.

This result, which arises from very basic features of the O(6) limit, and which is observed in the O(6)-like Pt isotopes is therefore a potential signature of this symmetry. It is thus highly interesting to determine the octupole fragmentation in the A=130 region which has also been proposed[8] to have an O(6) symmetry.

3. ^{134}Ba

3.1. *Proton inelastic scattering*

The behavior of the low energy octupole state in ^{134}Ba was examined using proton inelastic scattering at 22 MeV at the Münich Tandem van de Graaff Accelerator Laboratory. The scattered protons were analyzed with the Q3D - magnetic spectrograph and detected with the high resolution focal plane detector. The target, isotopically pure prepared at the PARIS isotope separator by implantation in C foil of magnetically separated Ba ions, was 0.1 mg/cm^2. The data were taken in steps of 5 deg from 25 to 60 deg lab angles. The spectrograph setting covered a range of excitation energy in ^{134}Ba from 1.8 to 4.2 MeV. The 4-5 keV FWHM energy resolution allows the study of about 50 states up to 3.5 MeV excitation energy. In Table 1 we list the excitation

Table 1: Experimental results for ^{134}Ba obtained in proton inelastic scattering. Indicated are the excitation energies (uncertainties 2 keV), the maximum differential cross sections (uncertainties 10 %), and the corresponding scattering angle, θ_{lab}. The corresponding energies and their J^π values from Nuclear Data Sheets are also listed.

$E_{p,p'}$ (keV)	σ (μb/sr)	θ (deg.)	E_{NDS} (keV)	J^π ($\hbar$)	$E_{p,p'}$ (keV)	σ (μb/sr)	θ (deg.)	E_{NDS} (keV)	J^π ($\hbar$)
1970	404	40	1970	4^+	2792	16	45		
1985	222	50	1986	5^-	2811	100	40		
2089	49	55	2088	2^+	2819	120	50		
2120	50	30	2118	(4^+)	2834	93	25	2836	(8^+)
2167	120	40	2165	(4^+)	2924	35	50		
2213	59	40	2211	(6^+)	2930	25	35		
2254	2170	40	2255	3^-	2949	5	25		
2271	115	40	2271	7^-	3025	58	55	3027	1,2
2335	75	25	2335	$1,2^+$	3047	139	40		
2372	14	30	2371	2^+	3063	55	40	3061	1,2
2376	27	35	2377	(6)	3127	28	35		
2417	209	40			3149	23	50		
2461	17	40	2466		3159	202	40	3160	
2478	51	50	2479	4^+	3207	27	50		
2484	30	30			3240	93	40	3240	9^-
2501	20	45			3271	26	40	3272	
2532	18	50			3321	20	35		
2561	8	30			3334	21	55		
2568	14	30	2571	1	3369	184	40	3369	1,2
2626	32	35			3383	26	55		
2675	27	40			3404	48	55		
2692	17	50			3432	28	35		
2716	28	30			3528	52	45		
2740	18	40			3629	20	30		
2781	58	40	2780		3659	46	40		

energies of all states observed in this experiment. We also list the energies and the J^{π} values from Nuclear Data Sheets [9]. Indicated are also the observed differential cross sections at θ_{lab}=35 deg. Although the angular distributions in this experiment are not sensitive enough or the transitions are too weak to estabish the multipolarity of the transitions, a few states are candidates for octupole states.

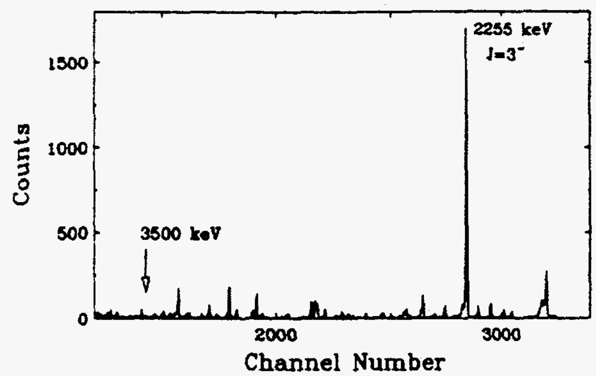

Figure 2: Proton spectrum for an excitation energy range of 1.8 to 4 MeV taken at 30 deg.

The proton spectrum in the energy range between 1.8 and 4 MeV, which is shown in Fig. 2, includes a strong peak corresponding to the lowest 3^- state at 2255 keV. No other peaks at higher excitation energy of comparable strength are observed. Regardless of which states might be 3^-, one conclusion emerges: there is no strong peak above the lowest 3^- state at 2255 keV. If we consider all the possible candidates for 3^- states, i.e. those states with a maximum in the angular distribution at 25-40 deg., this gives an upper limit to the octupole fragmentation which would be ΔE_3=0.31 MeV, a value in the range of other experimental U(5) $\rightarrow$ SU(3) transitional values.

We conclude that strong fragmentation of the low energy octupole state expected for a γ soft nucleus does not occur in ^{134}Ba.

3.2. IBA calculations for ^{134}Ba

In order to resolve the apparent contradiction that the positive parity states in this nucleus present an O(6)- type structure [8] and the negative parity ones do not follow the selection rules of the $O^{(3)}$ operator for the O(6) symmetry, we studied the wave functions corresponding to two sets of calculations which produce similar low-lying deexcitation schemes but which correspond to very different locations in the IBA symmetry triangle: pure O(6) and an U(5) $\rightarrow$ SU(3) fit. In figure 3 the low-lying positive parity excited states of ^{134}Ba are compared with these two sets of IBA calculations. For the O(6) symmetry limit the parameters (ϵ_d=0, a_1=0.012 MeV, a_2=0.1 MeV, $\chi_2 = 0$) are taken from Casten and von Brentano [8] and for the U(5) $\rightarrow$ SU(3) fit the parameters are ϵ_d = 0.6 MeV, a_1=0, a_2 =0.05 MeV, and χ_2=-0.17.

In Table 2 some relative experimental and theoretical B(E2) values, which could constitute sensitive signatures of structure, are compared. The last column gives the

Table 2: Relative B(E2) values in ^{134}Ba, from ref. 9, compared to the O(6) symmetry and U(5) → SU(3) calculation (see text for details). The last column shows the overlap of the wave functions in the two sets of calculations

I_i	I_f	^{134}Ba	O(6)	U(5)→SU(3)	$< O6 \mid U5 \rightarrow SU3 >$
2_γ	2_g	100.0	100.0	100.0	0.962
	0_g	0.6	0.0	0.2	
3_γ	2_γ	100.0	100.0	100.0	0.989
	4_g	52.8	40.0	38.9	
	2_g	0.6	0.0	0.3	
4_γ	2_γ	100.0	100.0	100.0	0.990
	3_γ	16.6	0.0	3.0	
	4_g	62.1	90.9	87.7	
	2_g	2.4	0.0	0.0	
0_2	2_γ	100.0	100.0	100.0	0.169
	2_g	3.8	0.0	26.8	

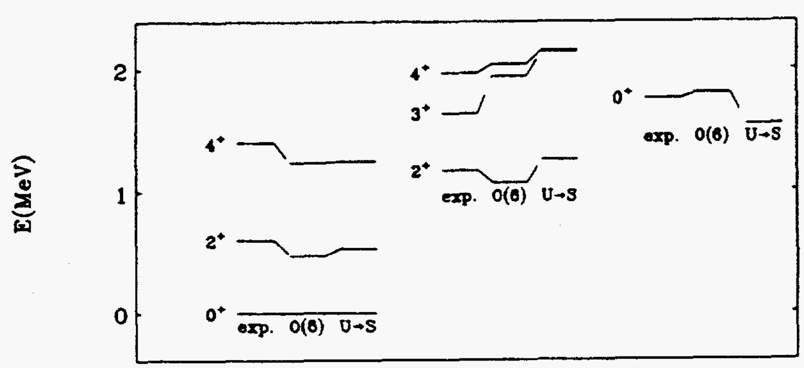

Figure 3: Experimental low-lying states in ^{134}Ba compared with two sets of IBA calculations: O(6) and U(5) → SU(3) (U → S) (see text for details).

overlap of the wave functions in the two calculations. For the quasi-γ band there is a large overlap of the U(5) $\rightarrow$ SU(3) wave functions with those corresponding to the O(6) symmetry. The overlaps for yrast states show that, except the ground state, they are also very similar (0.806, 0.926, and 0.963 for $0_1^+, 2_1^+$, and 4_1^+, respectively). The overlap for 3_1^- states in the two cases for the core, using the same parameters for V_{sdf} as those for Pt isotopes ($A_2 = -0.04 MeV, \chi_3 = 1.0$)[7] is 0.915.

We conclude that, despite their different characters, the two sets of the IBA calculations produce very similar results for the low-lying states. In contrast, the octupole fragmentation is quite different. In the U(5) $\rightarrow$ SU(3) case is $\Delta E_3 = 0.33$ MeV and in the O(6) limit it is 0.60 MeV (for $N_B = 5$), much larger than the upper limit of the experimental value for the region corresponding to ^{134}Ba ($R_{4/2} \sim 2.3$) .

4. Conclusion

The strong octupole fragmentation predicted for O(6) type of nuclei was not seen in ^{134}Ba. The apparent contradiction that in this nucleus the positive and the negative parity states follow different symmetries might be explained by noticing that the wave function of an O(6) nucleus has a significant overlap with the wave function of an U(5) - SU(3) transitional nucleus.

Similar studies of lighter Ba isotopes are being planned. These include (d,d') experiments, which should display angular distributions more characteristic for the transferred l-value.

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References

1. P.D. Cottle, M.A. Kennedy, and K.A. Stuckey, Phys. Rev. **C42** (1990) 2005
2. A. Arima and F. Iachello, Phys. Rev. Lett. **35** (1975) 1069
3. O. Scholten, F. Iachello, and A. Arima, Ann. Phys. (NY) **115** (1978) 325
4. A.F. Barfield, B.R. Barrett, J.L. Wood, and O. Scholten, Ann. Phys. (NY) **182** (1988) 344
5. J. Engel, Phys. Lett. B **171** (1986) 148
6. P.O. Lipas, P. Toivonen, and D.D. Warner, Phys. Lett. **155B** (1985) 295
7. N.V. Zamfir, P.D. Cottle, J.L. Johnson, and R.F. Casten, Phys. Rev. C48 (1993) 1745.
8. R.F. Casten and P. von Brentano, Phys. Lett. 152B (1985) 22.
9. Yu. V. Sergeenkov, Nuclear Data Sheets 71 (1994) 557