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OCTUPOLE SHAPES IN HEAVY NUCLEI

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ABSTRACT

Theoretical calculations and measurements show the presence of strong octupole correlations in the ground states and low-lying states of odd-mass and odd-odd nuclei in the Ra-Pa region. Evidence for octupole correlations is provided by the observation of parity doublets and reductions in M1 matrix elements, decoupling parameters, and Coriolis matrix elements involving high-j states. Enhancement of E1 transition rates has also been observed for some of the octupole deformed nuclei. The most convincing argument for octupole deformation is provided by the similarities of the reduced alpha decay rates to the two members of parity doublets.

1. Introduction

Soon after the collective model [1,2] of the nucleus was established, low-lying K = 0 rotational bands with spin-parity sequence 1^-, 3^-, 5^- .... were identified [3,4] in even-even Ra and Th nuclei in high-resolution alpha spectroscopic measurements. Since the energies (~300 keV) of these bands were much lower than the energies of the two-quasi-particle states (~1.0 MeV), these bands were interpreted as octupole vibrations about a spheroidal equilibrium shape. Ever since the discovery of the octupole vibrations, suggestions have been made [5,6] concerning the possibility of permanent octupole deformation in nuclei.

The octupole vibration or octupole deformation in nuclei is produced by the long-range octupole-octupole interaction between nucleons. The octupole correlations depend on the matrix elements of Y_3^0 between single-particle states with $\Delta j = \Delta \ell = 3$ near the Fermi surface and the spacing between them. Calculations of shell model states show that for nuclei with Z~88, the Fermi surface lies between the $f_{7/2}$ and $i_{13/2}$ orbitals and for N~134 nuclei, the Fermi surface lies between the $g_{9/2}$ and $j_{15/2}$ states. Since nuclei with these nucleon numbers are deformed, the maximum octupole deformation will be spread over several nucleon numbers. Figure 1 shows the dependence of octupole collectivity on neutron number. The excitation energy of the $K,I^\pi = 0,1^-$ state is decreasing with the decrease in the neutron number and becomes the lowest at N=136, suggesting maximum octupole correlations in ^{226}Th. The hindrance factors for the alpha decays to Th nuclei are also shown in the figure and these correlate nicely with the octupole collectivity.

Calculations [7] show that the gain in the binding energy due to octupole deformation is much smaller (~1.0 MeV) than the gain in the binding energy (~10 MeV) when a spherical nucleus becomes quadrupole deformed. The amount of octupole correlations in nuclei can be estimated from the spacings of positive and negative parity levels. The shapes and the potential energy diagrams [8-10]

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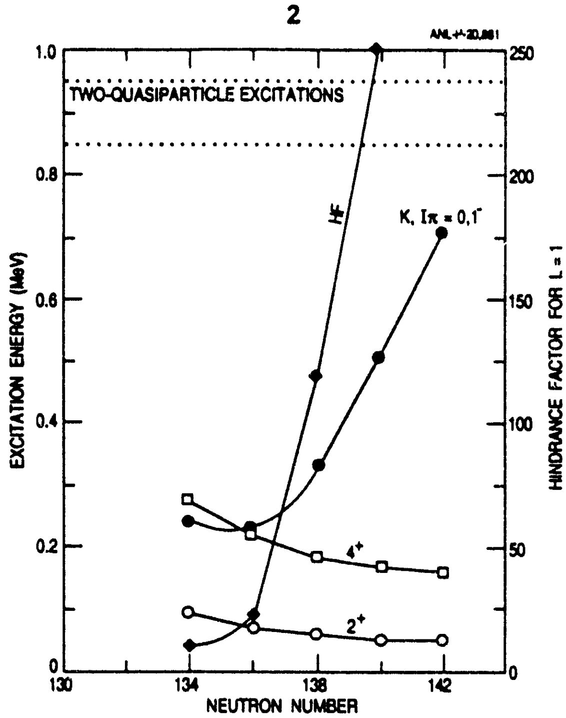

Fig. 1. Excitation energies of low-lying states in even-even Th isotopes. Also shown are α-decay hindrance factors to the K,I^{π} = 0,1⁻ states in Th.

associated with them are shown in Fig. 2. The situation in Fig. 2a, which applies to heavy actinides, occurs when the nucleus has a spheroidal equilibrium shape in the ground state and has a $K^{\pi} = 0^-$ vibrational band at ~1.0 MeV. The other limit (Fig. 2c) is achieved when the nucleus has β_3 deformation in its ground state and there is an infinite barrier between the reflection asymmetric

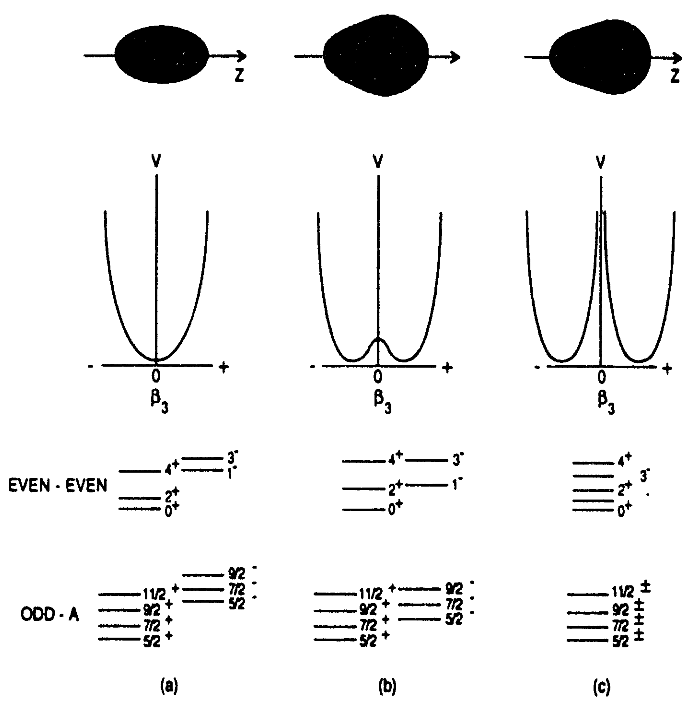

Fig. 2. Plots of potential energy against β_3 deformation and level spectra for three axially symmetric shapes. The left panel represents a rigid reflection symmetric spheroidal nucleus. The right panel shows a rigid pear-shaped nucleus, which is reflection asymmetric. The middle panel shows a soft pear-shaped nucleus with β_2 ~0.15 and β_3 ~0.09.

shape and its mirror image. Such a nucleus has permanent octupole deformation and is completely stable against a tunneling transition to its mirror image. The rotational levels of these nuclei are expected to be quite similar to those of well studied levels of asymmetric molecules. The third possible shape, displayed in Fig. 2b, is intermediate between these two limits, where a finite barrier exists between the reflection asymmetric shape and its mirror image and tunneling motion is possible between these two shapes. The rotational level sequences for these three shapes are included in Fig. 2.

Unlike quadrupole deformation, which can be deduced from measured quadrupole moments, octupole deformation is difficult to determine from direct measurements. In general, level sequences of rotational bands provide evidence for octupole deformation. The signature of octupole deformation in even-even nuclei is the presence of a rotational band of interleaved positive and negative parity levels. In odd-mass and odd-odd nuclei, the signature of octupole deformation is a parity doublet. A parity doublet is defined as a pair of states with the same spin, opposite parities, and a large B(E3) value between them. Experimentally, properties characteristic of large octupole-octupole correlations were discovered soon after their prediction in both odd-mass nuclei at low spins [11,12] and in even-even nuclei at high spins [13,14]. These include appropriate energy level sequences, enhanced E1 transition rates, and enhancement in alpha decay rates to opposite parity bands in the daughter nuclei. In the present article we will discuss experimental data which provide evidence for large octupole correlations in the ground and low-lying states of odd-mass and odd-odd nuclei in the Ra-Pa region.

2. Theoretical Development

The earliest calculations on the single particle states for actinide nuclei with octupole deformation were carried out by Chasman [15] and Leander and Sheline [16]. The presence of large octupole correlations was indicated by earlier calculations which provided a better explanation [17] of the excited 0^+ state in ^{234}U and improved [18] the agreement between measured and calculated atomic masses for nuclei in A~222 region. The calculation in ref. 15 used microscopic many-body approach where the Hamiltonian included quadrupole-quadrupole and octupole-octupole interaction. These calculations predicted parity doublets in several odd-proton and odd-neutron nuclei which have larger B(E3) values than the values encountered in the neighboring even-even nuclei. The single-particle spectra of odd-proton nuclei calculated in ref. 15 are displayed in Fig. 3.

The method of ref. 16 was a Nilsson-Strutinsky type calculation where the potential included β_3 deformation. It was found that the inclusion of $\beta_3 = 0.09$ in the potential reproduced most of the observed properties of octupole deformed nuclei. In this model all doublets should have the same β_3 deformation and the two members of the doublets should have equal matrix elements with appropriate signs. On the other hand, in the microscopic model different doublets can have different β_3 values, as shown in Fig. 3, and also there is no constraint on the matrix elements. Recently, shell correction type calculations with a Woods-Saxon average potential [19] have been carried out but these do not provide any better agreement with experimental data.

Some of the properties of the octupole deformed nuclei have also been explained by a multiphonon octupole model [20] which uses axially symmetric equilibrium shape.

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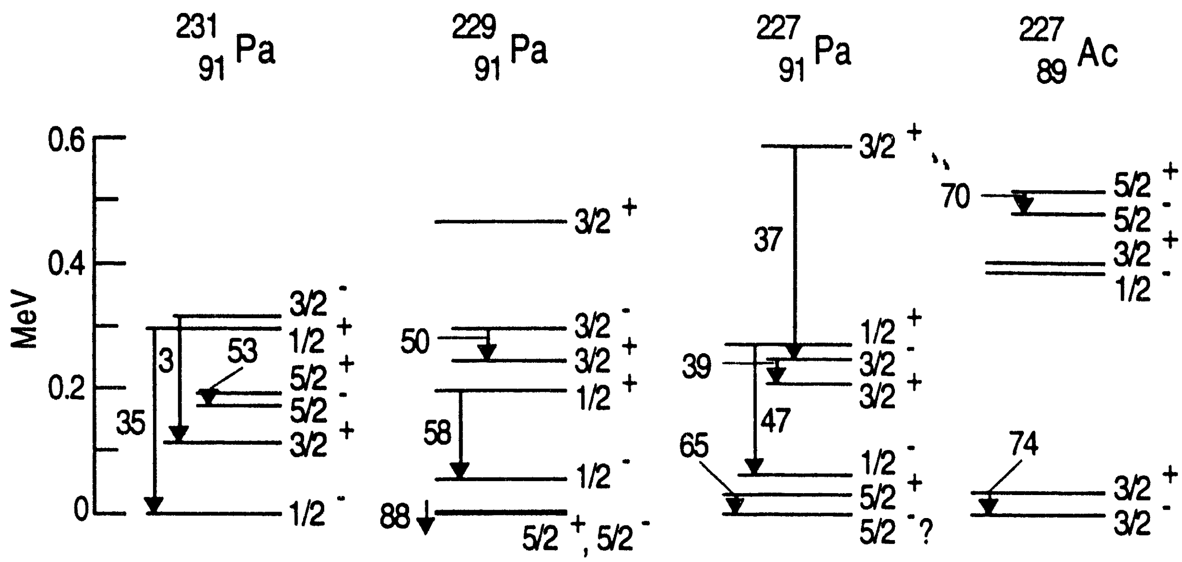

Fig. 3. Low-lying proton single-particle states calculated with a microscopic many-body approach [15]. States are denoted by K^π quantum numbers. The numbers beside the arrows represent intrinsic B(E3) values.

3. Experimental Evidence

As pointed out in the previous section, the signature of octupole deformation in even-even nuclei is the presence of the ground rotational band with level sequence 0^+, 1^-, 2^+, 3^-, ... No nucleus in the periodic table has been observed with this level sequence indicating that no even-even nucleus is octupole deformed in its ground state. However, the energy of the $K,I^\pi = 0,1^-$ state in some Ra and Th nuclei becomes very low (~0.25 MeV) suggesting large octupole-octupole correlations. Experimental data and calculations show that the octupole correlation may increase when an odd particle is added to these even-even nuclei or the even-even nucleus undergoes rotation. In the following sections we present experimental evidence for large octupole octupole correlations in odd-mass and odd-odd Ra, Ac and Pa nuclei. Additional details on octupole deformation can be found in ref. 21.

3.1. Energy Levels

In the fifties and sixties, large amount of information was gathered on energy levels of odd-mass Ra, Ac, Th and Pa nuclei but the observed levels could not be understood in terms of the Nilsson model of the axially symmetric nucleus which was extremely successful in explaining the structure of heavier actinide nuclei. Inclusion of octupole deformation in the potential changed the ordering of Nilsson single particle states and provided a natural explanation of the observed ground state spins [22]. The level structures of ^{223}Ra [23], ^{225}Ra [24-27], ^{223}Ac [28,29], ^{225}Ac [30,31], ^{227}Ac [12,32], ^{229}Pa [11,33] and ^{224}Ac [34,35] are found to be in better agreement with the results of calculations using octupole deformation in the potential than the results of a reflection symmetric model.

3.2. Decoupling parameter

The K = 1/2 bands arising from $i_{13/2}$ and $j_{15/2}$ orbitals have very large decoupling parameters, *a*. The 1/2 proton orbital in ^{227}Ac is expected to be predominantly $1/2^+$[660] configuration with a = ~6.0 and the $1/2^-$ neutron state in Ra isotopes are expected to have predominantly $1/2^-$[770] single-particle component with *a* = ~7.0. Experimental level energies give much smaller values of *a*. This can be understood in terms of the mixing of these states with opposite parity low-*j* states through the octupole term. As the data in table 1 show, the experimental values are in much better agreement with the calculations using a reflection asymmetric shape (with β_3 ~0.1) than the values calculated with a reflection symmetric model.

Table 1. Decoupling parameter

Nucleus	State	Decoupling parameter Experimental	Theory (β_3=0)	Theory (β_3=0.1)	Theory (Microscopic)
^{227}Ac	$1/2^-$	-2.01	-1.8	-3.0	-1.75
	$1/2^+$	+4.56	+5.9	+3.0	+4.95
^{225}Ra	$1/2^+$	+1.54	-0.68 (for $1/2^+$[631])	+2.5	---
			-4.5 (FOR $1/2^+$[640])		
		-2.59	-7.79 (FOR $1/2^-$[770])	-2.5	---
^{223}Ra	$1/2^+$	+1.35			
		-2.00			

3.3. Coriolis matrix element

It is well known that single-particle states arising from the proton $i_{13/2}$ shell state and the neutron $j_{15/2}$ shell state have large Coriolis matrix elements. The matrix elements between single-particle states have been calculated for axially symmetric actinide nuclei [36]. These matrix elements are reduced because of the pair occupation probabilities. The experimental energies of levels in bands in ^{245}Am [37,38] and ^{225}Ac, which originate from the $i_{13/2}$ shell orbit are displayed in Fig. 4. Favored alpha transition proceeds from the $7/2^+$[633] ground state of ^{249}Bk to the 327-keV level in ^{245}Am with a hindrance factor of 1.4. The mixing of the $7/2^+$[633] state with the I = 7/2 member of the $5/2^+$[642] band increases the alpha decay rate to the 19.2-keV level. Similarly, Coriolis mixing enhances the alpha decay rate to the I=5/2 member of the $3/2^+$[651] band. The spacing between the interacting levels in ^{245}Am is much larger (300 keV) than the spacing of 100 keV in ^{225}Ac. The fact that the relative alpha rates are larger in ^{245}Am than in ^{225}Ac and the lower band is more compressed in ^{245}Am than in ^{225}Ac clearly shows that the Coriolis matrix element is smaller in ^{225}Ac than in ^{245}Am. As shown in table 2, the deduced Coriolis matrix elements are in better agreement with the value calculated with a reflection asymmetric model with β_3 = 0.1 than the value obtained with β_3 = 0.

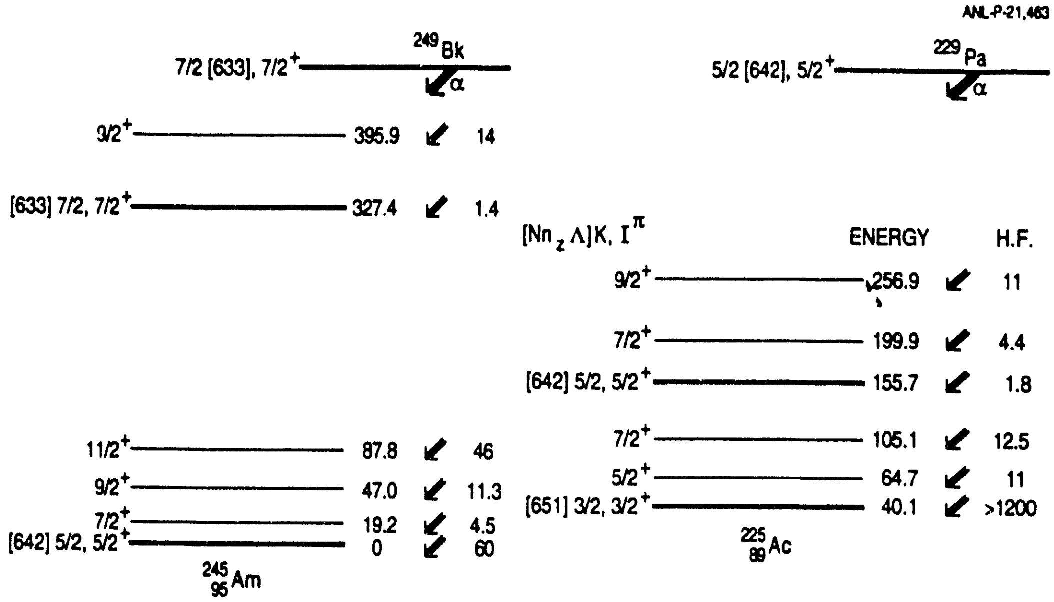

Fig. 4. Energy levels in ^{245}Am [37] and ^{225}Ac [31].

Table 2. Coriolis matrix elements

Nucleus	States	Matrix element		
		Exp.	Theo. with β_3 = 0	Theo. with β_3 = 0.1
^{225}Ac	$3/2^+,5/2^+$	0.9	~4.0	+0.6
	$3/2^-,5/2^-$	0.6	~1.0	-0.6

3.4. E1 transition rates

Soon after the observation of properties characteristic of octupole deformation in odd-mass nuclei, enhancement in E1 transition rates over the typical E1 rates in midactinide nuclei was discovered [39]. The B(E1) values in odd-mass Np and Am nuclei are between 10^{-4} to 10^{-7} Weisskopf units. In nuclei which display octupole deformation, the B(E1) values are 10^{-3} to 10^{-2} W.u.. Rates for E1 transitions in odd-mass Ra and heavier nuclei are displayed in Fig. 5. The nuclei which display characteristics of octupole deformation have, in general, higher B(E1) values. E1 transition rates are difficult to calculate and so far have not been calculated for odd-mass and odd-odd nuclei.

3.5. Alpha decay rates

Alpha decay rates provide one of the best means of deducing the relationship between the wavefunctions of the parent ground state and the levels populated in the daughter nucleus. The reduced α decay rate is fastest for the transition involving the same configuration in the parent and the daughter nucleus. Such transitions occur between the ground states of even-even nuclei and in odd-mass and odd-odd nuclei when the unpaired nucleon occupies the same orbital in the parent and the daughter. These transitions are called favored transitions and have hindrance factor (HF) close to unity. The hindrance factor is defined as the ratio of the experimental partial half-life to a level to the half-life calculated with the spin-independent theory of Preston [40].

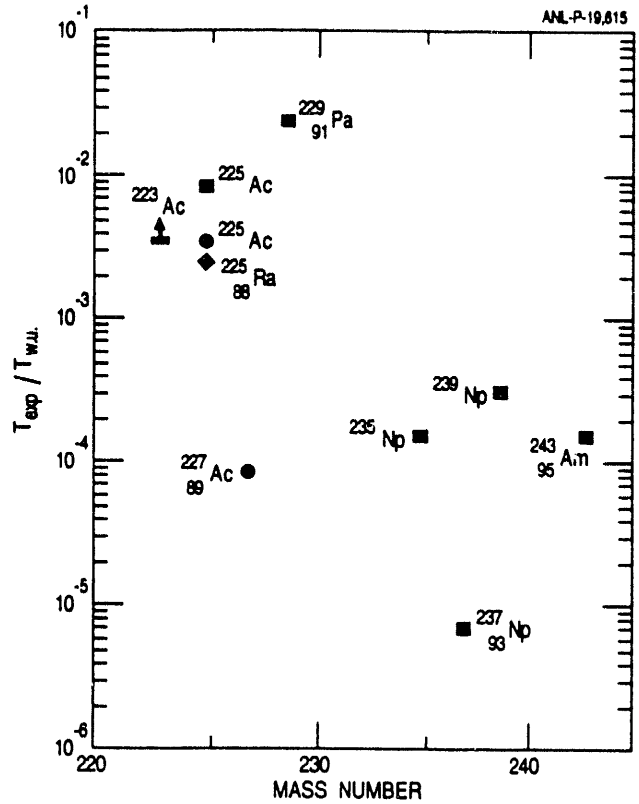

Fig. 5. Transition rates for K = 0 E1 gamma rays in actinide nuclei. T_{exp} denotes the experimental γ-ray transition probabilities and $T_{W.u.}$ refers to Weisskopf single-particle units.

In the octupole deformation limit, the two members of a parity doublet are different projections from the same intrinsic state of broken reflection symmetry. Hence the hindrance factors for alpha transitions to the two members of a parity doublet should be almost equal. Since the intensities of strong peaks can be more reliably measured, intensities of favored α transitions and α transitions to the opposite parity member of the doublet, given in table 3, can be used to assess octupole collectivity in a nucleus.

Table 3. Alpha decay hindrance factor

Parent nucleus	Parent state	State in daughter	Hindrance factor
^{227}Pa,	$5/2^+$	$5/2^+$	2.5
		$5/2^-$	7.0
^{229}Pa,	$5/2^+$	$5/2^+$	1.8
		$5/2^-$	7.5
^{227}Th	$1/2^+$	$1/2^+$	6.1
		$1/2^-$	15
^{228}Pa	(3^+)	(3^+)	12
		(3^-)	20

The hindrance factors to the opposite-parity members of the parity doublets relative to that of the favored decay in ^{223}Ac, ^{225}Ac and ^{224}Ac are 2.8, 4.2 and 2.0, respectively. From the hindrance factors to the rotational members of a band one can deduce the hindrance factors for $\ell = 0$ and $\ell = 1$ partial waves. Also, centrifugal barrier increases the hindrance factor. To obtain the α-decay matrix elements, the hindrance factors for $\ell = 1$ transitions should be reduced [41] by a factor P_ℓ/P_0 which is 0.77 in ^{225}Ac and neighboring nuclei. We find reduced hindrance factors for $\ell = 1$ partial waves for ^{223}Ac, ^{224}Ac and ^{225}Ac as 1.2, 2.2 and 1.0, respectively. These numbers are relative to the hindrance factors for $\ell = 0$ alpha transitions and clearly indicate that the alpha-decay matrix elements to the opposite parity members are almost equal to that of the favored transitions. This is exactly what is expected for an octupole deformed nucleus. In the absence of octupole deformation these numbers should be in the 10-100 range [38].

4. Conclusion

Although no direct evidence has been obtained for the existence of nuclei with permanent octupole deformation, matrix elements have been deduced from experimental data which clearly demonstrate large octupole correlations in the ground states of ^{223}Ac, ^{224}Ac ^{225}Ac and ^{229}Pa. Parity doublets with very small splitting energies have been observed in these nuclei. Very large B(E1) values have been measured between the members of the doublets in these nuclei which provide another evidence for the octupole deformation. Finally, Coriolis matrix elements and reduced alpha decay rates have been deduced which show that the wavefunctions of the two members of the parity doublet are almost identical. This is the strongest evidence for octupole deformation in these nuclei.

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