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Octupole deformation in odd-odd nuclei

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Comparison of the experimental and theoretical ground-state spins of odd-odd nuclei in the region $220 \leq A \leq 228$ generally shows agreement with a folded Yukawa octupole deformed model with $\epsilon_3 = 0.08$ and some lack of agreement with the same model with $\epsilon_3 = 0$. Thus, in spite of limited spectroscopic information, the ground-state spins suggest the existence of octupole deformation in odd-odd nuclei in the region $220 \leq A \leq 228$.

The detailed experimental spectra of both even-even and odd-A nuclei strongly suggest the existence of octupole deformation in nuclei with $219 \leq A \leq 229$.[1-3] However, the lack of reasonably complete spectroscopic data for any odd-odd nucleus in this region has made it difficult to look for evidence for octupole deformation in odd-odd nuclei.

Recently, the ground-state spins of a number of odd-odd Fr nuclei have been experimentally determined[4] using optical pumping combined with magnetic state selection of thermal atomic beams. When these spins are combined with a few tentative spins and parities of odd-odd nuclei from nuclear systematics[5-7] a total of nine spins in the $220 \leq A \leq 228$ region are known which can be compared with the quadrupole-octupole model.[2]

The level structure for the parity mixed proton and neutron orbitals resulting from the quadrupole-octupole model[2] is shown in Fig. 1. The calculation assumes an axially symmetric but reflection asymmetric shape and a folded Yukawa potential with octupole deformation $\epsilon_3 = 0.08$. The parity mixed orbitals are plotted against quadrupole deformation and are labeled by Ω and, in parentheses, with a set of matrix elements: $\langle \hat{s}_z \rangle$, $\langle \hat{\pi} \rangle$, and, if $\Omega = \frac{1}{2}$, $\langle \pi \text{ conj} | -j_+ | R \text{ conj} \rangle$. Circled numbers indicate the appropriate number of protons and neutrons.

If the experimental spins are consistent with the folded Yukawa model with $\epsilon_3 = 0.08$, but in general not consistent with the same model with quadrupole deformation only,[2] evidence for octupole deformation in odd-odd nuclei will have been deduced.

Table I compares the experimental and theoretical spins of all nine odd-odd nuclei in the region $220 \leq A \leq 228$, which can be tested. Reasonable candidates for the theoretical spins are determined both with the folded Yukawa model[2] with $\epsilon_3 = 0.08$, column 4, and with the same model with $\epsilon_3 = 0$,[2] column 6. Spins are calculated in the

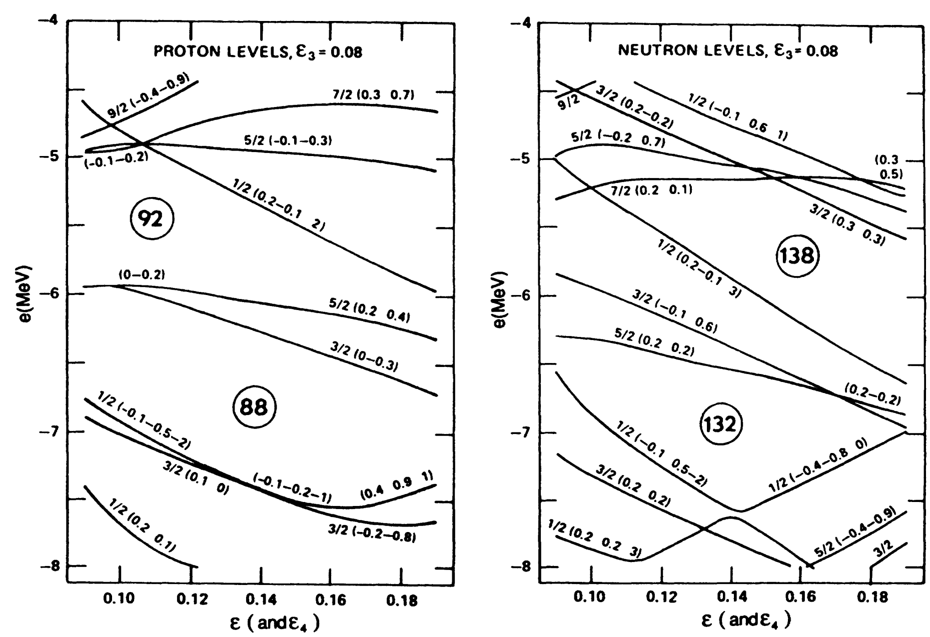

FIG. 1. The parity-mixed proton and neutron orbitals (Ref. 2) are plotted to the left and to the right, respectively, as a function of quadrupole deformation for constant octupole deformation $\epsilon_3 = 0.08$. For calculational assumptions and orbital labeling, see the text.

TABLE I. Experimental and theoretical ground-state spins of odd-odd nuclei in the region $220 \leq A \leq 228$. The theoretical proton and neutron orbitals in columns 2 and 3, respectively, are the parity mixed folded Yukawa octupole-deformed orbitals shown in Fig. 1, which are combined to produce the theoretical ground-state spins and parities in column 4. The theoretical J^π of column 6 results from combining the folded Yukawa orbitals (not shown) which are quadrupole deformed only. Both theoretical predictions of J^π (columns 4 and 6) can be compared with the experimental J^π in column 5.

Odd-odd nucleus	Theoretical (octupole deformed) Proton orbital	Neutron orbital	Combined orbital spin and parity	Expt. J^π	Theoretical J^π quadrupole deformed only	ϵ used
$^{220}_{87}Fr_{133}$	$\frac{3}{2}$ (0.1;0)	$\frac{5}{2}$ (0.2;0.2) or $\frac{1}{2}$ (−0.1;0.5;−2)	$4^\pm$ or $1^\pm$	1^+	$2^+(2^-)$ $1^-(1^+)$	∼0.09
$^{222}_{87}Fr_{135}$	$\frac{1}{2}$ (−0.1;−0.5;−2)	$\frac{3}{2}$ (−0.1;0.6)	2^-	2	$2^-(2^+)$	0.12
$^{224}_{87}Fr_{137}$	$\frac{3}{2}$ (−0.2;−0.8)	$\frac{1}{2}$ (0.2;−0.1;3)	1^-	$1^{(-)}$	$2^+(2^-)$	0.14
$^{224}_{89}Ac_{135}$	$\frac{3}{2}$ (0;−0.3)	$\frac{3}{2}$ (−0.1;0.6)	0^- or 3^-	0^-	$2^+(2^-)$	0.14
$^{226}_{87}Fr_{139}$	$\frac{3}{2}$ (−0.2;−0.8)	$\frac{3}{2}$ (0.3;0.3)	$K=0^-$, $J=1$	1^{a}	2^+ $K=0^-$, $J=1$	0.15
$^{226}_{89}Ac_{137}$	$\frac{3}{2}$ (0;−0.3)	$\frac{1}{2}$ (0.2;−0.1;3)	$1^\pm$	(1^-)	2^-	0.16
$^{228}_{87}Fr_{141}$	$\frac{3}{2}$ (−0.2;−0.8)	$\frac{7}{2}$ (0.2;0.1)	2^-(several other possibilities)	2^-	$3^-(1^+)$	0.15
$^{228}_{89}Ac_{139}$	$\frac{3}{2}$ (0;−0.3)	$\frac{3}{2}$ (0.3;0.3)	3^- or 0^-	$3^{(+)}$	3^+, 2^-	0.17
$^{228}_{91}Pa_{137}$	$\frac{5}{2}$ (0.2;0.4)	$\frac{1}{2}$ (0.2;−0.1;3)	3^+	(3^+)	3^+	0.18

[a]The negative quadrupole observed (Ref. 4) implies that the ground state spin is not the K value for the band (see text).

usual way for deformed nuclei with the triplet state of the Gallagher-Moszkowski doublets assumed low in energy for the combination of all reasonable proton and neutron orbitals near the Fermi surface. The octupole deformed model gives agreement in all nine cases with the possible exception of the ground-state spin of ^{228}Ac. In this case the tentative positive parity in experiment does not agree with the negative parity of the octupole deformed model. However, the folded Yukawa model without octupole deformation agrees in only five of the nine cases, and four of those five cases are the highest and lowest mass numbers (220, 222, and 228), that is the transition regions, where octupole deformation is less important. In order to test the odd-odd spins with another model without octupole deformation we also used the standard (modified) Nilsson model.[8] Results were fairly similar to the folded Yukawa model with $\epsilon_3=0$ except that the theoretical spins only agreed in 3 of the 9 cases.

It is necessary to note that the energy levels obtained in the octupole deformed model[2] for proton number 87 (Fr) are quite complex (Fig. 1). Over much of the applicable region of deformation the parity-mixed $\frac{3}{2}$ and $\frac{1}{2}$ levels are almost degenerate. They also change character with ϵ deformation. This explains why in Table I the $\frac{3}{2}$ (0.1;0), $\frac{1}{2}$ (−0.1;−0.5;−2), and $\frac{3}{2}^-$(−0.2;−0.8) orbitals have been used in the interpretation. In this regard it should be noted that the experimentally observed sequence of spins[4] for the odd-A Fr isotopes almost parallel the changing assignment for the proton orbital of the odd-odd nuclei with mass number odd $A+1$. The experimental spins for the ground state of ^{221}Fr, ^{223}Fr, ^{225}Fr, and ^{227}Fr are $\frac{5}{2}$ $(K=\frac{1}{2})$, $\frac{3}{2}$, $\frac{3}{2}$, $\frac{1}{2}$, respectively.

It should also be noted that the 137th parity mixed neutron orbital in Fig. 1 has a very small negative value of $\langle\hat{\pi}\rangle$ while the odd-A nuclei with 137 neutrons are experimentally known to have a $\frac{1}{2}^+$ ground state in ^{225}Ra and ^{227}Th. Ragnarsson[9] has shown that this orbital changes character at $\epsilon_3=0.09$ with the parity changing from negative to positive. In consequence, we have treated all 137 neutron species as having positive parity in octupole deformed systems.

Finally, it should be noted that ^{226}Fr provides a special test of the model. The optical pumping experiments[4] which determined the ground-state spin as 1 also determined the quadrupole moment as negative. This is very unusual and implies that the spin sequence in the ground-state band is anomalous. Specifically, spin 1 is not the lowest spin in the band. Such a circumstance can arise when the Newby splitting[10] of the odd spins in a $K=0$ band places them below the even spins resulting in a ground-state spin of 1. An example of this anomaly has been observed in ^{242}Am with a spin of 1^- ground state and a tentative $K=0^-$ state at 44 keV. Thus, the predicted $K=0^-$ band head in ^{226}Fr is consistent with a 1^- ground state with negative quadrupole moment. We must, of course, await more complete spectroscopic information to verify this prediction.

In summary, the ground state spins and the negative quadrupole moment of ^{226}Fr can uniquely be explained in the odd-odd nuclei in the region $220 \leq A \leq 228$ in terms of octupole deformation.

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