Strong and Weak Coupling to the Octupole-Deformed Mode in $^{227}_{89}$Ac

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Hybrid values of the intrinsic gyromagnetic ratio and the absolute values of the decoupling parameters have been found for two sets of approximately degenerate opposite-parity bands with $K=\frac{3}{2}^{\pm}$ and $K=\frac{1}{2}^{\pm}$ in ^{227}Ac, as would be expected for intrinsic parity mixing in the single-particle states due to octupole deformation. These properties are able to test quantitatively the change in the Nilsson wave functions resulting from octupole deformation.

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In the Ra and Th nuclei with ≈136 neutrons, the $g_{9/2}$ and $j_{15/2}$ neutron levels and the $f_{7/2}$ and $i_{13/2}$ proton levels are energetically very close together. This gives rise to low-energy $J^{\pi}=3^-$ two-quasiparticle configurations which collectively could form the microscopic basis for a stable octupole deformation.[1] However, the success of the calculations of Neergård and Vogel[2] who have described the octupole states of even quadrupole-deformed nuclei in terms of $K=0^-$, 1^-, 2^-, and 3^- octupole *vibrational* bands has buttressed the general consensus that even nuclei do not develop stable octupole deformations in their ground states. In contrast, a few recent calculations[3-5] of potential energy surfaces suggest the existence of a limited region of *stable octupole deformation* for even nuclei around ^{224}Ra. The calculations give a barrier between the mirror octupole minima >1 MeV. Since the $K=0^-$ band heads lie in the vicinity of 200–300 keV, the amplitudes of the wave functions of the ground states and $J^{\pi}=1^-$ states at $\epsilon_3=0$ will be quite small.

Experimental evidence against a vibrational interpretation in this limited region comes from the fact that both decay-scheme studies[6] and Coulomb excitation of ^{226}Ra[7] failed to observe the 0^+ states from the two-phonon octupole vibration expected at approximately twice the one-phonon octupole vibrational energies. Furthermore, the additional stability of the permanent octupole deformation in the region around ^{222}Ra dramatically improves the agreement between calculated and experimental masses.[3,5] Recently, evidence for the sequence $4^+, 5^-, 6^+, 7^-, 8^+, 9^-$, etc. has been found in the even nuclei ^{218}Ra[8] and ^{222}Th.[9] This is the spin sequence expected for stable octupole deformation in deformed even nuclei. Very recently, the 1^- and 3^- states have been found[10] in ^{218}Ra with the sequence $0^+, 2^+, 1^-, 4^+, 3^-$. Finally, Ahmad *et al.*[11] have observed a $\frac{5}{2}^+$-$\frac{5}{2}^-$ ground-state parity doublet 0.22 keV apart in ^{229}Pa, as predicted by Chasman.[12] In an odd-A quadrupole-deformed nucleus one signature of octupole deformation is a rotational band with the sequence $K^{\pm}, (K+1)^{\pm}, (K+2)^{\pm}, \ldots$ for $K\neq\frac{1}{2}$. The near degeneracy of $\frac{5}{2}^{\pm}$ states at the ground state in ^{229}Pa suggests a common origin in a single Nilsson orbital strongly coupled to octupole deformation.

^{227}Ac has the same number of neutrons as ^{229}Pa, but two fewer protons, and is also a candidate for octupole deformation.[4,5] The spectroscopy of this nucleus is most conveniently studied following the α decay of ^{231}Pa and the β^- decay of ^{227}Ra. The earlier work on ^{227}Ac is summarized in the nuclear data compilation of Maples[13] with recent work by Teoh *et al.*[14] and Aničin *et al.*[15] Three rotational bands had been assigned[13-15]: a $\frac{3}{2}^-$ ground-state band, a $\frac{3}{2}^+$ band at 27.38 keV, and a $\frac{1}{2}^-$ band with a large decoupling parameter leading to a $\frac{3}{2}^-$ band head at 329.99 keV. These three bands were given Nilsson assignments of $\frac{3}{2}^-[532\downarrow]$, $\frac{3}{2}^+[651\uparrow]$, and $\frac{1}{2}^-[530\uparrow]$, respectively, and are shown in the level scheme of Fig. 1.

In the present paper an additional $K=\frac{1}{2}^+$ band has been assigned with a $\frac{5}{2}^+$ bandhead beginning at 425.6 keV. A brief summary of these assignments follows. The level at 425.6 keV decays to the $\frac{5}{2}^+$ state at 46.38 keV with a strong $M1+E2$ transition, implying $\frac{3}{2}^+$, $\frac{5}{2}^+$, or $\frac{7}{2}^+$ assignment. However, the decay to the $\frac{7}{2}^-$ at 74.11 keV excludes the $\frac{3}{2}^+$ assignment, and the logft of 7.5 from the recently determined[16] $\frac{3}{2}^+$ ground state

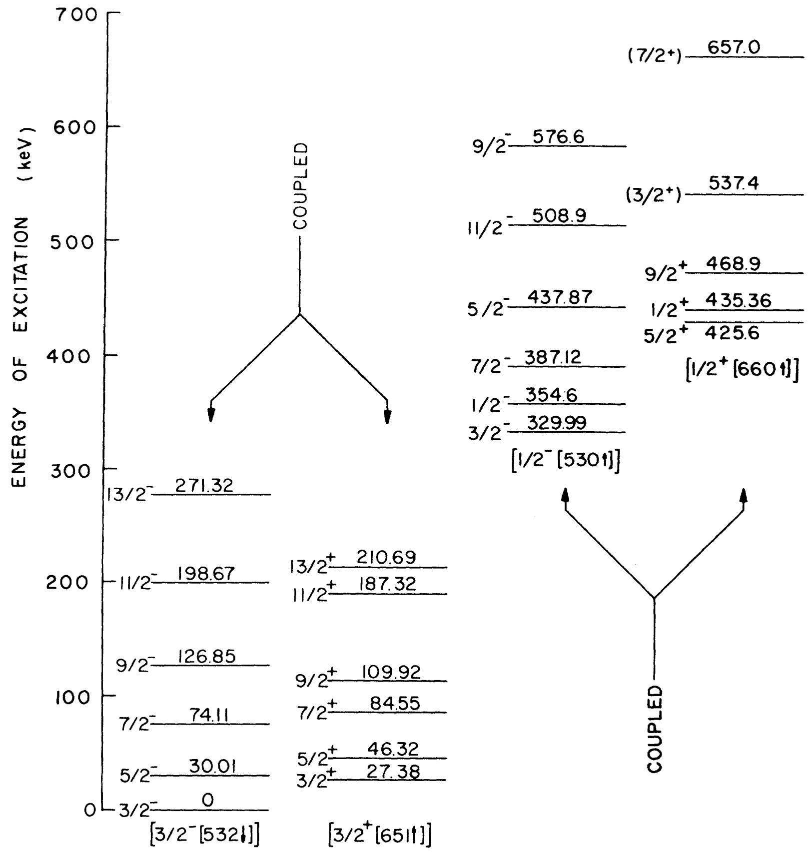

FIG. 1. Partial level diagram for ^{227}Ac. Energies and gamma ratios are those of Ref. 15 except the 657.0-keV level which is from Ref. 16. The two sets of coupled bands have hybrid properties of several Nilsson configurations. Hence the Nilsson configurations are written in brackets.

of ^{227}Ra excludes the $\frac{7}{2}^+$ assignment. Thus the $\frac{5}{2}^+$ assignment is firmly established. A 435.36-keV level decays with 100% $M1$ radiation to the $\frac{3}{2}^+$ bandhead at 27.38 keV, implying a $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$ assignment. The level also decays to the $\frac{3}{2}^-$ ground state but fails to decay to any of the $\frac{5}{2}^-$ or $\frac{7}{2}^-$ states, suggesting the $\frac{1}{2}^+$ assignment. The level at 468.9 keV decays to the $\frac{5}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$, and $\frac{13}{2}^+$ members of the $\frac{3}{2}^+$ band beginning at 27.38 keV, strongly suggesting a $\frac{9}{2}^+$ assignment. A level at 537.4 keV previously assigned as $\frac{3}{2}^+$ by Aničin *et al.*[15] decays to the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ members of the $\frac{3}{2}^+$ band at 27.38 keV and possibly to the $\frac{1}{2}^+$ state at 435.36 keV, suggesting a $\frac{3}{2}^+$ assignment. Finally, a state at 657 keV decays by four transitions to the $\frac{5}{2}^+$ (46.32 keV), $\frac{7}{2}^-$ (74.11 keV), $\frac{7}{2}^+$ (84.55 keV), and $\frac{9}{2}^+$ (109.92 keV) states, tentatively suggesting a $\frac{7}{2}^+$ assignment. These states and assignments are all shown in Fig. 1.

If we assume a $K=\frac{1}{2}^+$ band with a large positive decoupling factor, the $\frac{5}{2}^+$, $\frac{9}{2}^+$, and $\frac{3}{2}^+$ rotational band members may be used to fix the inverse moment of inertia ($\hbar^2/2\mathscr{I}$) and the decoupling parameter (a) as 6.287 keV and 4.556, respectively. The calculated energies of the $\frac{1}{2}^+$ and $\frac{7}{2}^+$ states are 432.6 and 670.1 keV, in good agreement for a transitional nucleus with the observed energies of 435.36 and 657 keV, respectively. The Nilsson diagram for protons suggests that the $\frac{1}{2}^+$[660↑] band with a large positive decoupling parameter should lie in this region. This is in fact the first observation of the $\frac{1}{2}^+$[660↑] band in the actinides. However, as in the case of the other three bands in Fig. 1, although there are large components of these Nilsson configurations, they are shown in brackets because a complete description requires a more complex coupled designation (see below).

Qualitatively, the nearly degenerate $\frac{3}{2}^-$ and $\frac{3}{2}^+$ bands (27.38 keV apart) and $\frac{1}{2}^-$ and $\frac{1}{2}^+$ bands (95.61 keV apart) seem to be approaching one of the criteria of strong single-particle coupling to an octupole-deformed core—degenerate bands of opposite parity. It is especially important therefore to determine if there are features of the spectroscopy which can more quantitatively test whether the parity-doubled bands arise from a single parity-mixed Nilsson orbital in an effectively octupole-deformed potential or from two different Nilsson orbitals with different intrinsic properties.

One possibility is to test the magnetic properties of the lowest two bands with $K^\pi = \frac{3}{2}^-$ and $\frac{3}{2}^+$. The two available Nilsson orbitals with good parity, $\frac{3}{2}^-[532\downarrow]$ and $\frac{3}{2}^+[651\uparrow]$, are spin flipped and would have quite different intrinsic magnetic moments, whereas octupole deformation would leave just one mixed orbital near the Fermi level with a hybrid magnetic moment. The test uses the experimental branching ratios[16] for each pair of $E2$ and $M1+E2$ intraband transitions depopulating a level to calculate $(g_K - g_R)^2$, where g_K and g_R are the intrinsic and rotational gyromagnetic factors, respectively. The magnetic dipole moment of the ^{227}Ac ground state has been measured[17] as $+1.1 \pm 0.1$ nm and is directly related to $g_K - g_R$. Using a value of Q_0 of 7.795 ± 0.800 b and the average of the experimental values of Q_0 for ^{226}Ra and ^{228}Th of 7.18 and 8.41 b, respectively, one obtains g_K values of 0.93, 0.91, 0.88, and 0.93 for the $\frac{7}{2}^-$, $\frac{9}{2}^-$, $\frac{11}{2}^-$, and $\frac{13}{2}^-$ states. This gives a weighted average of g_K of 0.92 ± 0.06 where the error is the weighted error in the four determinations. The corresponding value for g_R is 0.45 ± 0.05. The branching ratios also allow the determination of $(g_K - g_R)^2$ for the $\frac{3}{2}^+$ band. With the value of $g_R = 0.45$ and the reasonable assumption that it should be the same in the $K = \frac{3}{2}^\pm$ bands, the g_K values obtained from the branching ratios from the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states are 0.90 and 1.04, respectively, with a weighted average of 0.96 ± 0.10.

Theoretical values for g_K are calculated with and without octupole deformation by use of the equation

$$g_K = K^{-1}[g_s^{\text{eff}}\langle s_3\rangle + g_l\langle l_3\rangle],$$

a value g_s^{eff} of 3.91 (attenuation factor 0.7), and the wave functions of the folded Yukawa model at the equilibrium deformation.[5] Results of these calculations are shown in Table I. It is a matter of extreme interest that the experimental values of g_K for both the $\frac{3}{2}^-$ and $\frac{3}{2}^+$ bands are the same as the strong-coupling adiabatic octupole limit (0.891) within experimental error and deviate considerably from the values for the Nilsson orbitals without octupole deformation. In the case of strong single-particle coupling to an octupole-deformed core where both positive- and negative-parity states belong to a single band, a single value of g_K is expected.

TABLE I. Theoretical and experimental values for the intrinsic gyromagnetic ratios (g_K) and the decoupling parameters times the band parities ($a\pi$) for ^{227}Ac.

	No octupole	Adiabatic octupole	Experiment
g_K			
$K=\frac{3}{2}^-$	0.500	0.891	0.92 ± 0.06
$K=\frac{3}{2}^+$	1.500		0.96 ± 0.10
$a\pi$			
$K=\frac{1}{2}^-$	1.769	3.127	2.012
$K=\frac{1}{2}^+$	5.924		4.556

A second signature of octupole deformation, then, is that g_K and g_R should be the same in both positive- and negative-parity $K \neq \frac{1}{2}$ bands, while μ should be the same for each parity doublet. Measuring these magnetic properties is an important challenge particularly for the $\frac{5}{2}^\pm$ doublet of ^{229}Pa and the $\frac{3}{2}^+$ (27.38-keV) 41-ns state of ^{227}Ac where we calculate a μ of 1.14 ± 0.09 nm.

Another intrinsic matrix element and a third signature of octupole deformation are tested by comparing the experimental decoupling parameters for $\frac{1}{2}^-$ and $\frac{1}{2}^+$ rotational bands in ^{227}Ac. In the case of strong coupling to octupole deformation, $K = \frac{1}{2}^\pm$ bands are expected to have the *same absolute value for the decoupling parameter (a), but with opposite sign.* Actually, the fundamental intrinsic matrix element is that of j_+ between P and R conjugate states. Thus it is the decoupling parameter times the parity ($a\pi$) which should be the same for both parities in strong coupling to octupole deformation.

These matrix elements calculated with and without octupole deformation, with the folded-Yukawa-model wave functions, are presented in Table I. The $\frac{1}{2}^+[660\uparrow]$ and $\frac{1}{2}^-[530\uparrow]$ bands differ completely from each other in value although they do have the same sign. The $K = \frac{1}{2}$ octupole-deformed orbital near the Fermi level has an intermediate value. (Actually, the positive-parity admixture in this case consists mainly of components other than $\frac{1}{2}^+[660\uparrow]$). In the case of the $\frac{1}{2}^-[530\uparrow]$ band, experimental decoupling parameters are known for ^{231}Pa and ^{237}Np. These are close to the theoretical value in Table I, even slightly smaller in absolute value.

With use of the energies of $\frac{3}{2}^-$, $\frac{7}{2}^-$, and $\frac{5}{2}^-$ states of the $\frac{1}{2}^-[530\uparrow]$ band, values of 7.163 keV and -2.012 are obtained for $\hbar^2/2\mathscr{I}$ and a, respectively. The corresponding values for the $\frac{1}{2}^+[660\uparrow]$ band were 6.287 keV and +4.556, respectively. The experimental $a\pi$ values are given in Table I. It is clear that the experimental values of $a\pi$ of both bands are moving *toward* the intermediate value of 3.127 (Table I).

Thus the properties of both sets of negative- and positive-parity bands, shown in Table I, are intermediate between those of the pure Nilsson configurations of the main components of which the coupled bands are composed. This hybridization of the bands has gone approximately to completion in the case of the $K=\frac{3}{2}^{\pm}$ bands but less far in the case of the $K=\frac{1}{2}^{\pm}$ bands. This is mirrored in the closer approach to degeneracy of the $K=\frac{3}{2}^{\pm}$ bands (27.38 keV) than in $K=\frac{1}{2}^{+}$ bands (95.61 keV). One may take as a criterion for octupole "deformation" that the odd-A parity doublet manifests the properties of a single parity-mixed Nilsson orbital in an adiabatically octupole-deformed mean field (strong coupling), as opposed to two distinct single-particle orbitals in a reflection-symmetric field which are only partly mixed by the collective octupole mode in the core (weak or intermediate coupling). The coexistence of strong- and weak-coupled states in the same nucleus can be accounted for by using either limit as a basis representation, as is well known for quadrupole deformation. Thus, e.g., even with a somewhat different model, the $B(E3)$ and other predictions of Chasman[12] appear to be correct.

In summary, the situation is characteristic of a core with "soft" octupole deformation. Some single-particle states like the Nilsson orbitals $\frac{1}{2}^-[530\uparrow]$ and $\frac{1}{2}^+[660\uparrow]$ appear to be only weakly coupled to the octupole mode. However, a fully developed strong-coupled scheme of single-particle motion in an adiabatically octupole deformed core field occurs for $K=\frac{3}{2}$ in ^{227}Ac and probably for the $K=\frac{5}{2}$ case in ^{229}Pa found by Ahmad *et al.*[11]

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