Rigid reflection-asymmetric rotor description of the nucleus ^{227}Ac

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A model based on a static quadrupole and octupole deformation of the intrinsic nuclear shape gives an accurate description of the low-energy level spectrum and wave functions in ^{227}Ac. Major discrepancies between strong-coupling theory and experiment are removed by taking into account the nonadiabaticity of the nucleonic motion.

The nature of a quantum spectrum is often characterized by the symmetries or asymmetries of the mathematical models which reproduce it. In nuclear physics, it is a long-standing question whether certain nuclei can be characterized by an "intrinsic shape" which violates the reflection symmetry as well as the rotational symmetry of the laboratory frame. According to mean field theory, the nuclei in the $A=220$—230 mass region have equilibrium shapes with both octupole and quadrupole deformation, but the energy gain relative to a reflection symmetric shape with quadrupole deformation only is rather small.[1-3] The orbits of the nucleonic motion, manifested by the spectroscopy of odd-mass nuclei, are characteristic of the reflection asymmetric equilibrium shape in some states but are more consistent with the quadrupole-deformed reflection-symmetric shape in other states. This has been interpreted as evidence that state-dependent dynamical octupole shape fluctuations, rather than a single octupole deformed equilibrium shape, are needed to characterize the spectra of nuclei like ^{227}Ac. Spectroscopic models with a microscopic basis large enough to embody such dynamical octupole correlations have been based on reflection symmetric intrinsic shapes.[4-6]

A quite different interpretation is that nonadiabaticity of the nucleonic motion in some states may decouple those orbits from the reflection asymmetry.[7] Such "parity decoupling" from the octupole deformation is analogous to the familiar rotational or Coriolis decoupling from quadrupole deformation. Both types of nonadiabatic couplings will be seen to arise in the same way within the rigidly deformed reflection-asymmetric rotor plus quasiparticle model. This paper presents a first realistic calculation, where this model is applied to the well-studied nucleus ^{227}Ac. The spectroscopy of ^{227}Ac has recently been extended by a study of the (α,t) and (^{3}He,d) reactions[8] in addition to the previous decay work.[9-11] Similar calculations for the other odd-mass nuclei in the $A=220$—230 region are in progress and are giving results of equal quality.

The Hamiltonian of the model,

$$\hat{H}=\frac{\hbar^2}{2\mathscr{I}}(\hat{R}_1^{\,2}+\hat{R}_2^{\,2})+\tfrac{1}{2}E_{0^-}(1-\hat{P})+\hat{H}_{\text{s.p.}}+\hat{H}_{\text{pair}}\ ,$$

is diagonalized in a strong-coupled basis symmetrized to good parity and angular momentum[12]

$$\Psi^{\nu}_{IM\Omega p}=\frac{1}{2N}(1+\hat{\mathscr{R}}_1)D^{I}_{M\Omega}(1+p\hat{P}\hat{\pi})\Phi_a\tilde{\chi}^{\,\nu}_{\Omega}\ .$$

These odd-A strong-coupled basis states form parity doublets with parity $p=\pm1$. The first part of the Hamiltonian is the core rotational energy which splits apart core states with different angular momenta: $R=0,1,2,\ldots$. As usual in the particle-rotor model,[12] the core angular momentum can be written as the difference between the total and single-particle angular momenta, $\hat{\mathbf{R}}=\hat{\mathbf{I}}-\hat{\mathbf{j}}$. The moment of inertia parameter, $\hbar^2/2\mathscr{I}$, is set equal to 8 keV for ^{227}Ac, slightly smaller than $E(2^+)/6$ in the two doubly even neighbors. The second part of the Hamiltonian splits apart the two sets of core states with opposite parity: $R^P=0^+,2^+,4^+,\ldots$ and $1^-,3^-,5^-,\ldots$, respectively. The core parity splitting parameter E_{0^-} for ^{227}Ac is chosen so as to put the 1^- level at 290 keV, the average of the values observed in the two doubly even neighbors. The core parity can be written as the product of the total and single-particle parities, $\hat{P}=p\hat{\pi}$. The diagonal matrix elements of $-\frac{1}{2}E_{0^-}p\hat{\pi}$ are analogous to rotational decoupling factors and give rise to an energy splitting of the odd-A parity doublets, while the off-diagonal matrix elements of this term give rise to the nonadiabatic parity decoupling discussed above. The single-particle term $\hat{H}_{\text{s.p.}}$ contains the deformed Woods-Saxon potential of Ref. 3. The deformation parameters ($\beta_2=0.168$, $\beta_3=0.1$, $\beta_4=0.094$, $\beta_5=0.01$, $\beta_6=0.0052$) lie in between the Strutinsky equilibrium deformations of the two doubly even neighbors, except for β_3, which is somewhat larger here so as to better describe the spectrum of ^{227}Ac. In the basis functions, χ^{ν}_{Ω} are the Woods-Saxon single-particle orbits, and Φ_a represents the deformed core with the same orientation in space as the single-particle potential. The last term of the Hamiltonian, $\hat{H}_{\text{pair}}$, represents the influence of the pair field and is dealt with by a transformation to BCS quasiparticle states, $\tilde{\chi}^{\,\nu}_{\Omega}$. The Fermi level for $Z=89$ is placed on the forty-fifth strong-coupled orbit, and the BCS gap parameter is set to 0.6 MeV, somewhat lower

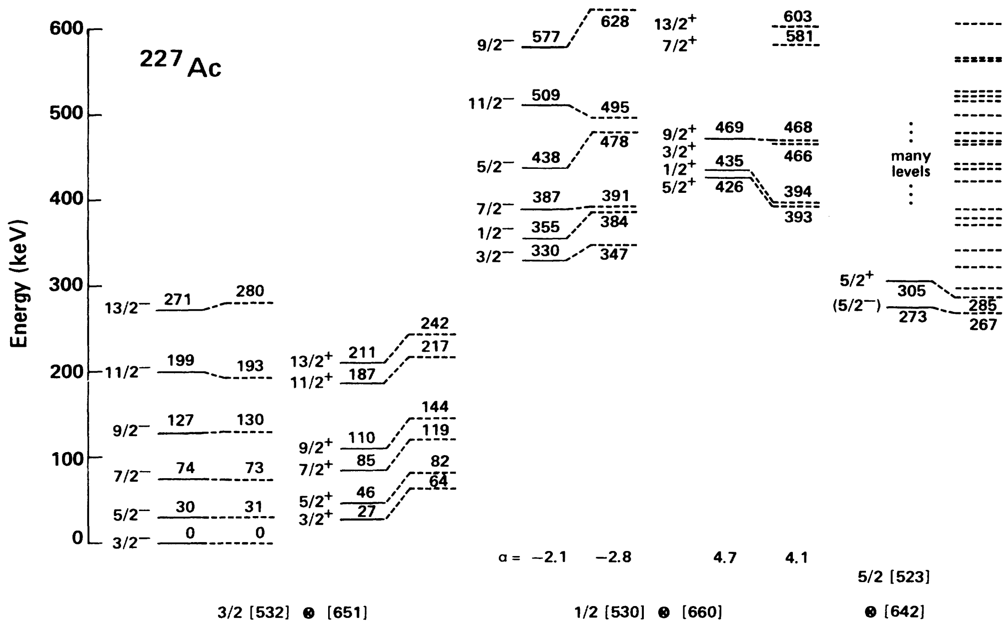

FIG. 1. Energy levels of ^{227}Ac from experiment (solid lines) and the rigid reflection-asymmetric rotor calculation (dashed lines).

than the odd-even mass difference.

The experimental spectrum of ^{227}Ac exhibits some states which appear to derive from a reflection asymmetric intrinsic shape and others which do not.[13] The $\frac{3}{2}^-$ ground state and first excited $\frac{3}{2}^+$ state manifest the parity doubling that is characteristic of reflection asymmetry. The common origin of the two states in a single reflection-asymmetric Nilsson orbital is established by the magnetic moments, which are equal to each other and to the calculated value. The Nilsson orbitals $\frac{3}{2}[532]$ and $\frac{3}{2}[651]$, which would be the reflection symmetric candidates, have spin down and up, respectively, and would give rise to widely different magnetic moments. No other known features of the spectrum of ^{227}Ac fit fully into the adiabatic reflection asymmetric picture of parity doubling, however. The level spacings are quite different in the rotational bands built on the $\frac{3}{2}^-$ and $\frac{3}{2}^+$ levels, respectively, with a strong signature splitting in the $\frac{3}{2}^+$ but not the $\frac{3}{2}^-$ band (Fig. 1). The particle transfer cross sections[8] to these bands strongly favor the $\frac{13}{2}^+$ level (Fig. 2). This is most compatible with a reflection symmetric $\frac{3}{2}[651]$ Nilsson assignment, because the reflection asymmetric Nilsson orbital is strongly mixed so that all spectroscopic factors should be small.[8,14] The two $K=\frac{1}{2}$ bands do have decoupling factors of opposite sign, as predicted for a parity doublet, but the absolute values of the decoupling factors are far from equal and approach the values expected for the two reflection symmetric Nilsson orbitals $\frac{1}{2}[530]$ and $\frac{1}{2}[660]$ (Ref. 13).

The results of the present rigid reflection-asymmetric rotor plus quasiparticle calculation are shown in Figs. 1 and 2, along with the experimental data. It is clear that this reflection-asymmetric model, which includes nonadi-

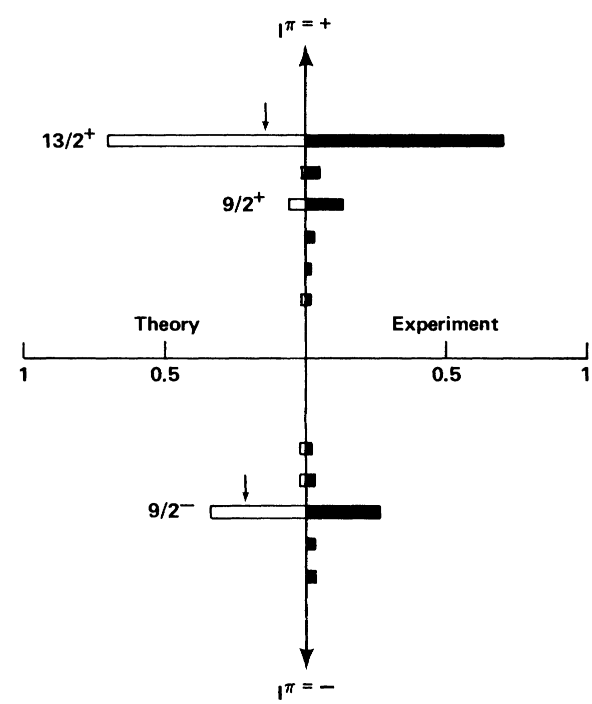

FIG. 2. Rotational signature of the parity-doubled ground-state band in ^{227}Ac. The structure factor $(\Sigma_{\nu\Omega} u^{\nu}_{\Omega} a^{\nu}_{\Omega} c^{\nu}_{j l \Omega})^2$ in the particle transfer cross sections is plotted above the abscissa for the positive-parity band members and below it for the negative-parity band members. The solid bars are experimental values (Ref. 8), and the unfilled bars are from the rigid reflection-asymmetric rotor calculation. The arrows indicate what the two largest structure factors would be in the limit of strong coupling.

abatic couplings, reproduces all the features of the spectrum that are described above. There is no need to introduce any state dependence of the octupole deformation.

Some further comments should be made on Figs. 1 and 2. For the $K=\frac{1}{2}$ bands the rotational decoupling factors a that can be extracted from the three lowest observed levels are given in Fig. 1. A deficiency of the calculation is that although the absolute values of the decoupling factors do split apart, they do not split apart as far as in experiment. This is not, however, a general failing of the model. For example, in the $K=\frac{1}{2}$ ground-state parity doublet bands of ^{225}Ra, the absolute values of the decoupling factors split apart equally far in theory and experiment. The energy splitting of the parity-doublet band heads is calculated with the right sign for all three cases in Fig. 1. Regarding the tentative $\frac{5}{2}^{\pm}$ doublet, it may be remarked that the opposite sign would be obtained in strong-coupling theory. The normalization of the experimental transfer cross sections in Fig. 2 has been chosen to make the $\frac{13}{2}^{+}$ structure factor equal to the calculated value of 0.7. With the normalization of Ref. 8, it would exceed the theoretical maximum of 1. The strong coupling prediction, indicated by arrows in Fig. 2, has the structure factor for $\frac{13}{2}^{+}$ smaller than for $\frac{9}{2}^{-}$.

In summary, the low-energy structure observables of ^{227}Ac are well accounted for with a static octupole deformation. There are features of the parity-doublet bands which are not characteristic of adiabatic nucleonic motion in a reflection-asymmetric potential, such as the parity-dependent magnitude of the signature splitting for $K=\frac{3}{2}$, the parity-dependent magnitude of the decoupling factors for $K=\frac{1}{2}$, and the large particle-transfer cross section to the $I^{\pi}=\frac{13}{2}^{+}$ member of the ground band. These features have been shown to derive from the energy splitting between the parities in the core ground band and the resulting nonadiabatic terms in the core-particle Hamiltonian. Thus, the odd nucleon as a probe of core structure provides no further evidence for state-dependent fluctuations of the intrinsic shape at low energy.

This result for "soft" octupole deformation agrees with what is known about "soft" quadrupole deformation. Transitional odd-mass nuclei which are not expected to have a well-defined shape can be beautifully described at low energy by the rigid triaxial rotor model.[15] There is usually little room for improvement from the introduction of shape dynamical[16] or boson model[17] cores; and in the fine detail of the electric quadrupole matrix elements, the rigid triaxial rotor often proves to be superior.[18] The magnitude of the effective triaxial quadrupole deformation is usually somewhat larger than the equilibrium deformation calculated by mean field theory, just as the β_3 deformation is found to be somewhat larger than the calculated equilibrium value in the present study of ^{227}Ac.

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