Enhanced $E1$ Transition Rates and Octupole Deformation in ^{225}Ac

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The levels of ^{225}Ac are reliably assigned by detailed measurements of the radiations associated with the α decay of ^{229}Pa and the β decay of ^{225}Ra. Extremely large enhancements of $E1$ transition rates are found in ^{225}Ac. The adequacy of a single-particle description of strong octupole correlations is examined.

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In this work, we consider the structure of ^{225}Ac. Recent theoretical[1,2] and experimental[3,4] studies show that strong octupole correlation and/or octupole deformation effects play an important role in the description of the nuclides of this mass region. A signature of strong octupole correlation effects in a deformed nucleus is a pair of closely spaced rotational bands with members having the same spins and opposite parities. We denote such parity doublet bands as PD bands. Early studies of Aguer, Peghaire, and Liang[5] show two PD bands in ^{225}Ac: a ground-state $\frac{3}{2}^{\pm}$ PD band and a $\frac{5}{2}^{\pm}$ PD band starting at 121-keV excitation energy. However, the spin and parity assignments in this nuclide are considered tentative.[6] Therefore, we have carried out a series of measurements to establish these assignments. The measurements described below confirm the assignments made by Aguer, Peghaire, and Liang.[5]

A major reason for our study of ^{225}Ac is the observation[3] of a strong enhancement in the transition rate between the $\frac{5}{2}^{+}$ and $\frac{5}{2}^{-}$ members of the ground-state doublet in ^{229}Pa relative to the usual $E1$ rates between one-quasiparticle states. A detailed understanding of this enhancement is necessary in order to utilize the ground-state parity doublet in ^{229}Pa for the study of terms[7] in the nucleon-nucleon interaction that violate time-reversal invariance. Typically, $B(E1)$ values in the heavy elements range from 10^{-4} to 10^{-6} Weisskopf units (W.u.). If the transition in ^{229}Pa is $E1$ in nature, the value of $B(E1)$ is $\sim 10^{-2}$ W.u. Because the splitting between the two levels in the ground-state doublet of ^{229}Pa is only 220 eV, it is plausible that this enhanced transition rate is a direct manifestation of parity mixing in the laboratory system, i.e., the transition is $M1$ in nature. For low-energy transitions, $M1$ rates for protons are typically three orders of magnitude faster than $E1$ rates in heavy elements and parity-mixing matrix elements are expected to be on the order of electronvolts. In ^{225}Ac, the splittings in the $\frac{5}{2}^{\pm}$ PD band are roughly 30 keV. If parity mixing is the reason for enhanced transition rates in ^{229}Pa, we expect a reduction in the equivalent $B(E1)$ value of 10^4 in ^{225}Ac, as the mixing amplitude is inversely proportional to the energy splitting.

The level structure of ^{225}Ac was studied by measuring the radiations associated with the α-decay of 1.5-d ^{229}Pa and the β decay of 15-d ^{225}Ra. The new results that allow us to make more reliable spin and parity assignments are given below.

(1) We determined the multipolarity of the 115.6-keV transition in ^{225}Ac as $M1$. We obtained the K conversion coefficient (and hence the multipolarity) from the ratio of the K x-ray intensity to that of the γ ray measured from a γ-ray spectrum gated by the 40-keV photopeak.

(2) We obtained upper limits on the ft values of the β transitions to the 120.8- and 155.7-keV levels. We deduced these limits from the upper limit on the Ac K x-ray intensity in the ^{225}Ra γ-ray spectrum.

(3) The ^{225}Ra ground-state spin and parity have been established as $\frac{1}{2}^{+}$ rather than $\frac{3}{2}^{+}$ as assigned in earlier studies.[6] The evidence for a $\frac{1}{2}^{+}$ assignment comes from the measurement[8] of transition multipolarities in ^{225}Ra and from a direct measurement[9] of its ground-state spin as $\frac{1}{2}$.

(4) The ground-state spin and parity of ^{229}Pa has been established as $\frac{5}{2}^{+}$ in our earlier work.[3]

The ^{225}Ac level scheme is displayed in Fig. 1. Using the results discussed above and the fact that in heavy elements $\log ft$ values of < 8 occur only for transitions with $|\Delta K|$ and $|\Delta I| = 0$ or 1, we can deduce the spins and parities of ^{225}Ac levels. Since the ^{225}Ra ground state is $\frac{1}{2}$, the observed $\log ft$ values to the ground and the 40.1-keV levels restrict their spins to $\frac{1}{2}$ and $\frac{3}{2}$. Similarly, the $\log ft$ values of > 10 to the 120.8- and 155.7-keV levels fix their spins as $\frac{5}{2}$ or greater. These facts along with the $M1$ multipolarity of the 120.8- and 115.6-keV transitions unambigu-

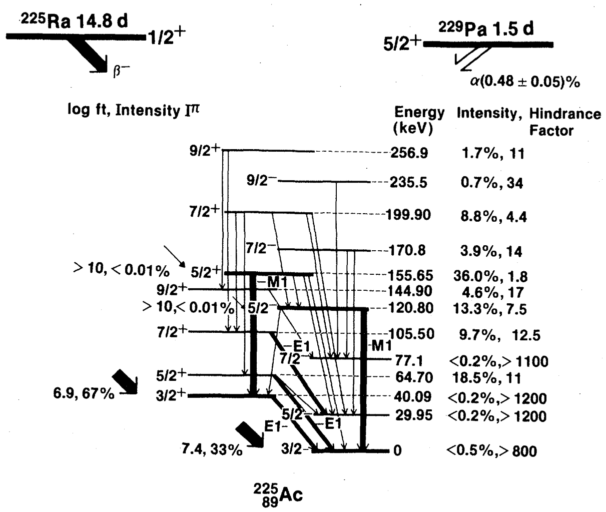

FIG. 1. Level scheme of ^{225}Ac. α intensities are taken from Ref. 5. Thick lines denote the bandheads.

ously establish the spin of the ground and the 40.1-keV states as $\frac{3}{2}$ and that of the 120.8- and 155.7-keV states as $\frac{5}{2}$. Since the 155.7-keV level is populated by the favored α transition (hindrance factor 1.8), it must have the same configuration as the ^{229}Pa ground state, namely $\frac{5}{2}^+$. Thus the spins and parities of the ground and the 40.1-, 120.8-, and 155.7-keV states are $\frac{3}{2}^-$, $\frac{3}{2}^+$, $\frac{5}{2}^-$, and $\frac{5}{2}^+$, respectively. Spins and parities of other levels in Fig. 1 are deduced from the α-decay pattern and γ-ray branching.

It is very unusual for a 34.8-keV $E1$ transition ($155.7 \rightarrow 120.8$) to compete with a 115.6-keV $M1$ transition. Using the experimental gamma-ray branching ratio of $I_{115.6}/I_{34.8} = 7.2$ and a theoretical $M1$ matrix element of 1.24 obtained from single-particle wave functions discussed below, we deduce an $E1$ transition rate. This rate of 9×10^{-3} W.u. is extremely fast and is quite similar to the $E1$ rate measured in ^{229}Pa. We have also deduced that the $B(E1)$ value between the $\frac{5}{2}^+$ and $\frac{3}{2}^-$ states of the $\frac{3}{2}^\pm$ PD band is 5×10^{-3} W.u. This transition rate was obtained from a measurement of the branching ratio of the 64.7-keV $E1$ and the 24.6-keV $M1$-$E2$ transitions originating at the $\frac{5}{2}^+$ level. This intensity ratio was determined from the γ-ray spectrum gated by the α_{65} peak and using the intensity of the 40.1-keV $E1$ transition for that of the 24.6-keV $M1$-$E2$ transition (see Fig. 1). The $M1$-$E2$ rate was calculated with an $M1$ matrix element of 0.61 and a quadrupole moment of 6.0 b, deduced[8] from measured lifetime in ^{225}Ra. The theoretical $M1$ rate should be quite reliable since these calculations

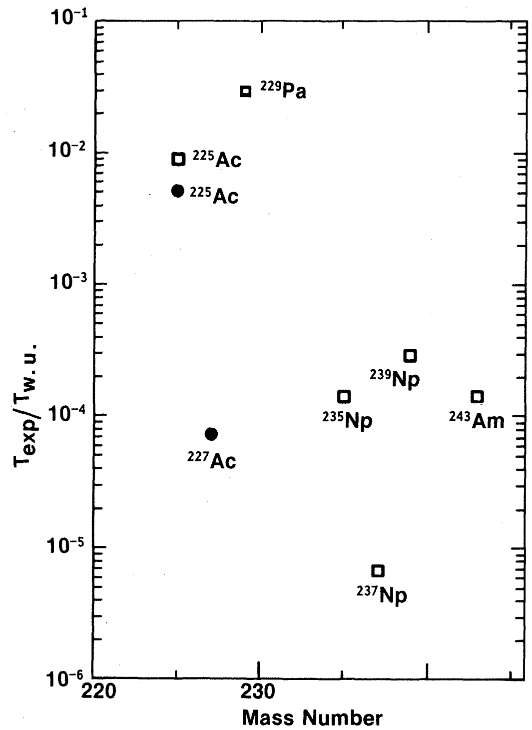

FIG. 2. $E1$ transition rates for $\Delta K = 0$ transitions in odd-mass heavy elements. Filled circles denote transitions in the $\frac{3}{2}^\pm$ bands and the open squares indicate transitions in the $\frac{5}{2}^\pm$ bands. Transition rates are given in Weisskopf units, where 1 W.u. $= 1.0\times10^{14}A^{2/3}E_\gamma^{\,3}$, with E_γ expressed in megaelectronvolts.

reproduce[4] the experimental g_K values in ^{227}Ac.

The above results make large-scale parity mixing in the laboratory system an unlikely cause of the $E1$ enhancement in ^{229}Pa. Rather, it seems that the $E1$ enhancements are associated with octupole deformation. The relation between octupole deformation and $E1$ enhancement is, however, far from simple. In ^{227}Ac, direct measurement of the isomer lifetime[6] gives a $B(E1)$ value of $\sim10^{-4}$ W.u. between the $\frac{3}{2}^+$ and $\frac{3}{2}^-$ ground-state doublet, which is two orders of magnitude slower than the values in ^{229}Pa and ^{225}Ac. In Fig. 2, we have plotted known $B(E1)$ values for $\Delta K = 0$ transitions in odd-mass heavy elements. Data for Np and Am nuclides have been taken from the analysis of Asaro *et al.*[10] We propose a qualitative explanation of the $E1$ transition rates based on our calculations using the many-body wave functions of Ref. 1. Our primary observation is that the $E1$ matrix elements between heavy-element valence orbitals are strongly correlated in sign with the $E3$ matrix elements between the same orbitals. This correlation is particularly strong for pairs of states connected by large $E3$ matrix elements, for both the proton and neutron valence orbitals. The effect of this correlation is to induce large $E1$ moments for both the neutron and proton contributions connecting states within a PD band, when octupole correlations are strong. The effect of neutron-proton terms in the two-body octupole-octupole interaction terms is to give a positive phase relation between proton and neutron $E1$ moments. We would get a $B(E1)$ value of ~1 W.u. for either the protons or neutrons considered separately. Because of the center-of-mass correction, however, we have

$$B(E1)\propto\left[\left\langle\Psi^+\left|\sum_{\text{protons},\,\alpha,\beta}\langle\alpha|rY_1^0|\beta\rangle a_\alpha^\dagger a_\beta-\frac{Z}{N}\sum_{\text{neutrons},\,\alpha,\beta}\langle\alpha|rY_1^0|\beta\rangle a_\alpha^\dagger a_\beta\right|\Psi^-\right\rangle\right]^2, \quad (1)$$

where Ψ^+ and Ψ^- are positive- and negative-parity many-body wave functions. This value of $B(E1)$ depends on a small difference between two large sums. We are not yet able to calculate this difference reliably. However, the large induced enhancements in both the proton and neutron sums that we do calculate make the large values and large fluctuations of $B(E1)$ a very plausible consequence of octupole correlations in this mass region.

In the study of Aguer, Peghaire, and Liang,[5] a large attenuation of Coriolis matrix elements was noted for both the positive- and negative-parity levels of the two PD bands. In fact, they suggested octupole effects as a possible explanation for this phenomenon. Their analysis of level energies, which included only $\frac{3}{2}$ and $\frac{5}{2}$ bands, gave $\langle\frac{5}{2}^+|j^+|\frac{3}{2}^+\rangle=0.85$ and $\langle\frac{5}{2}^-|j^+|\frac{3}{2}^-\rangle=0.56$. However, the agreement between calculated and measured level energies was poor. For this reason, we have performed mixing calculations which also include $\frac{1}{2}$ and $\frac{7}{2}$ bands, and get reasonable fits between the experimental and calculated energies for all observed levels. Our calculations also account for the experimentally observed alpha transition rates to the positive-parity members of the $\frac{3}{2}$ PD band. The best fit was obtained with $\langle\frac{5}{2}^+|j^+|\frac{3}{2}^+\rangle=0.90$ and $\langle\frac{5}{2}^-|j^+|\frac{3}{2}^-\rangle=0.60$ and a rotational constant of 7.0 keV. These data provide an interesting test of the strong-coupling limit of octupole deformation. The relevant predictions of this model[2] are that the Coriolis matrix elements between the positive-parity members of the two PD bands should be the same as the matrix elements between the negative-parity members of the two bands. Direct calculation[11] of the j^+ matrix element gives a value of 1.05 with a folded Yukawa potential. This is a dramatic decrease from the value of 6.6 that we calculate between the $\frac{5}{2}^+[642]$ and the $\frac{3}{2}^+[651]$ orbitals which would be the assignments for these levels in the absence of octupole deformation. The agreement between the experimental and theoretical values of the Coriolis matrix elements shows that the strong-coupling limit gives a reasonable description of the j^+ matrix elements. As the $M1$ matrix elements between the two PD bands are very closely related to the corresponding j^+ matrix elements, the deduced $B(E1)$ values discussed above, which depend on $E1/M1$ branching ratios, should be similarly reliable. The calculated $M1$ rates are an order of magnitude faster in the absence of octupole deformation. That would make the corresponding $B(E1)$ values an order of magnitude larger as well.

The splittings between opposite-parity members of the $\frac{3}{2}^\pm$ PD band are -40 keV and are -35 keV in the $\frac{5}{2}^\pm$ PD band. In the strong-coupling model,[2] these splittings are proportional to Δ, where Δ is the difference between the squares of the positive- and negative-parity amplitudes in the relevant intrinsic wave function. We have calculated $\Delta_{3/2}=-0.47$ and $\Delta_{5/2}=+0.13$. The calculated sign of the splitting in the $\frac{5}{2}$ PD band is wrong. Although the sign might be reversed by increasing the magnitude of ν_4, the relative magnitudes of the splittings in the two PD bands remain a problem.

A final point worth noting is the enhanced α-decay rate to the negative-parity members of the $\frac{5}{2}^\pm$ PD band. We have remeasured the α-decay branching, which reduces the quoted[6] α-decay hindrance factors by a factor of 2. The observed hindrance factor to the $\frac{5}{2}^-$ state is 7.5 which is even smaller than the values observed to the octupole bands in the neighboring even-even nuclei (11 for ^{224}Ra, 16 for ^{226}Th). This indicates the enhancement of octupole correlation effects in odd-mass nuclides suggested previously.[1] The unusually low hindrance factors show that alpha decay provides a good experimental signature of strong octupole correlations in odd-mass nuclides.

In conclusion, we have made the first experimental determination of fast $E1$ transition rates in the recently discovered[3,4] region of octupole deformation near mass 228. We have found large enhancements in $E1$ transition rates associated with the intraband transitions of the $\frac{3}{2}^{\pm}$ and $\frac{5}{2}^{\pm}$ PD bands of ^{225}Ac, and inferentially in the $\frac{5}{2}^{\pm}$ ground-state doublet of ^{229}Pa. On the other hand, measurements[6] show no such enhancement in the $E1$ transition rate between the members of the $\frac{3}{2}^{\pm}$ PD band of ^{227}Ac. These observations show that there is no simple relation between $E1$ transition rate and octupole deformation. We have pointed out a possible microscopic explanation for large variations in $B(E1)$ values. We find that the strong-coupling limit of octupole deformation provides a good general description of ^{225}Ac. However, it fails in describing the finer features such as the differences in j^+ matrix elements between positive- and negative-parity bands and the splittings of positive- and negative-parity levels within a PD band.

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