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REFLECTION ASYMMETRY IN ODD-A AND ODD-ODD ACTINIUM NUCLEI

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ABSTRACT

Theoretical calculations and measurements indicate that octupole correlations are at a maximum in the ground states of the odd-proton nuclei Ac and Pa. It has been expected that odd-odd nuclei should have even larger amount of octupole-octupole correlations. We have recently made measurements on the structure of ^{224}Ac. Although spin and parity assignments could not be made, two bands starting at 354.1 and 360.0 keV have properties characteristic of reflection asymmetric shape. These two bands have very similar rotational constants and also similar alpha decay rates, which suggest similarity between the wavefunctions of these bands. These signatures provide evidence for octupole correlations in these nuclides.

1. Introduction

In the last decade, there has been a large interest in the reflection asymmetric shape of nuclei. Theoretical calculations[1,2] showed that the presence of octupole-octupole correlations in nuclei can explain the discrepancies between the measured and calculated atomic masses of certain nuclei and provide a better understanding of the nuclear structure in the mass-225 region. In high-spin studies of even-even nuclei, a sequence of interleaved positive and negative parity levels were observed[3] in ^{222}Th, which is the signature of octupole deformation. In odd-mass nuclei ^{229}Pa and ^{227}Ac, parity doublets - a pair of almost degenerate states with the same spin but opposite parities - were identified[4,5] which provided evidence of reflection asymmetry. It was soon discovered that nuclei with octupole deformation display enhanced electric dipole transition rates[6,7] between the negative and positive parity members of the doublet. These two properties have been used to deduce octupole collectivity in many nuclei.

More recent studies show that the interleaved levels and enhanced E1 transition rates may or may not be associated with octupole deformation. For example, even octupole vibrational nuclei have large E1 transition rates. Although most octupole deformed nuclei show enhanced E1 rates, some nuclei with octupole deformation show very little enhancement. It appears that more meaningful quantities to characterize octupole deformation are α-decay transition probabilities, Coriolis matrix elements and M1 transition rates which probe the nuclear wavefunctions in a more direct way.

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Calculations and measurements show that the addition of an unpaired nucleon to an even-even core can enhance the octupole correlations and in favorable cases can make the nuclei octupole deformed. It has been expected that the addition of another unpaired nucleon would produce further enhancement in the octupole correlations. With the hope that odd-odd nuclei might show the maximum octupole deformation of any nucleus, we have undertaken the study of ^{224}Ac levels populated in the α-decay of ^{228}Pa. Although the available data do not establish the spins and parities of the ^{224}Ac levels, they do suggest larger octupole collectivity in ^{224}Ac than is present in odd-mass Ac nuclei[8].

2. Experimental Details

In this article, we discuss the structures of odd-proton nuclide Ac and Pa and the odd-odd nucleus ^{224}Ac. We present previously known data on ^{229}Pa, ^{223}Ac and ^{225}Ac and new information on the levels of ^{224}Ac. The level structure of ^{224}Ac was studied by measuring the alpha, gamma and electron spectra of ^{228}Pa. The ^{228}Pa activity was produced by the bombardment of Th foils with 45-MeV protons in the Indiana University Cyclotron. The Pa fraction was chemically isolated and thin sources for alpha spectroscopy were prepared. Because of the low α-decay branch (2.0%), the gamma and electron spectra were measured in coincidence with α-particles. The γ-ray spectra were measured with a 25% Ge detector, a 2-cm^{2}x1-cm LEPS detector and a Si(Li) spectrometer. For the detection of electrons, a Si PIN diode[9] was used. A triple $\alpha\gamma\gamma$ coincidence measurement was also performed in order to determine the relationships between high-energy γ rays and low-energy transitions.

3. Discussion

3.1. ^{229}Pa

The early theoretical calculations[1,2] predicted a $5/2^{\pm}$ parity doublet as the ground state of ^{229}Pa, with the energy difference between the two members of $\approx$1 keV. The ground state doublet in ^{229}Pa was soon observed[4] experimentally. In the experiment, the ^{231}Pa(p,t) reaction was used to locate the I=3/2 member of the $1/2^-$[530] band. However, only approximate energy of this level could be deduced because of the uncertainty in the ground state mass of ^{229}Pa. The data gave a value of $\approx$128 keV for the energy of the $3/2,1/2^-$[530] level with an uncertainty of 15 keV. Using this information, and ^{229}U electron capture decay data, the energy of the $3/2,1/2^-$[530] level was deduced to be 122.51(0.05) keV. A new measurement[10] of the ^{231}Pa(p,t) reaction determined the energy of the $3/2,1/2^-$ level as 19 keV with an uncertainty of 10 keV. The new experiment shows that the old (p,t) data is apparently in error. Using the new (p,t) data and reversing the order of transitions observed in the $\gamma\gamma$ coincidence data, a new level scheme (Fig. 1) has been proposed which is consistent with most of the data. This level scheme contains more transitions and levels than were presented in refs. 4 and 8. Coincidence relationships were observed only between intense transitions. The weaker transitions are placed in the level scheme on the basis of the match between the transition energy

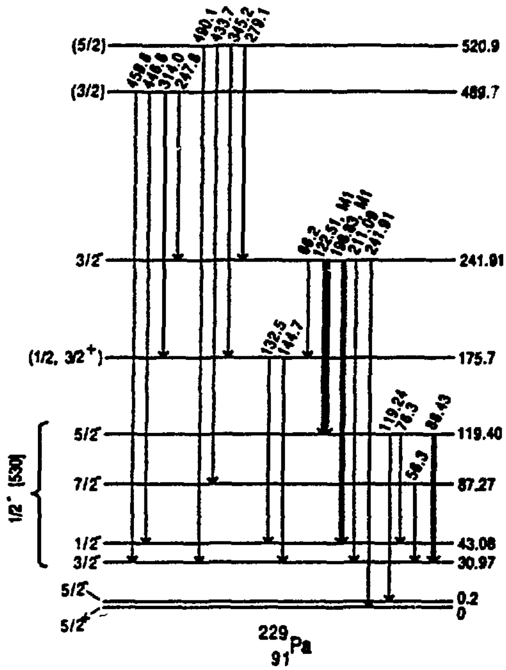

Fig. 1. ^{229}Pa level scheme proposed on the basis of the new (p,t) reaction data[10]. The level scheme contains more transitions and levels than those reported in refs. 4 and 8.

and the energy difference between the initial and final levels. However, new measurements are needed to identify the 31.0-keV transition which would then confirm the proposed level scheme.

3.2. ^{223}Ac and ^{225}Ac

The level scheme of ^{223}Ac was deduced from the α-decay studies of ^{227}Pa (38.3 min). The ground state of ^{227}Pa and ^{223}Ac are given a $5/2^+$ assignment by Ahmad et al[11] and an assignment of $5/2^-$ by Sheline et al[12]. The experimental data are not sufficient to allow a definite parity assignment. However, the spin assignment of 5/2 seems well established.

By far the most studied nucleus in the mass-224 region is ^{225}Ac. High-resolution magnetic spectrograph measurement[13] provides energies of the excited states in ^{225}Ac and αγ coincidence measurements[14] establish the spins and parities. Information on spins of ^{225}Ac levels was also obtained from the study of the β^- decay of ^{225}Ra whose ground state spin is known[15] to be 1/2. The γ-ray spectrum of a ^{225}Ra sample measured with a 15% Ge detector and a 0.9 g/cm^2 Cu absorber interposed between the source and the detector is displayed in Fig. 2. Only the 40.09-keV transition is visible. We have obtained upper limits on the 64.7-keV γ-ray and K-Xray intensities, from which lower limits on log ft values have been deduced.

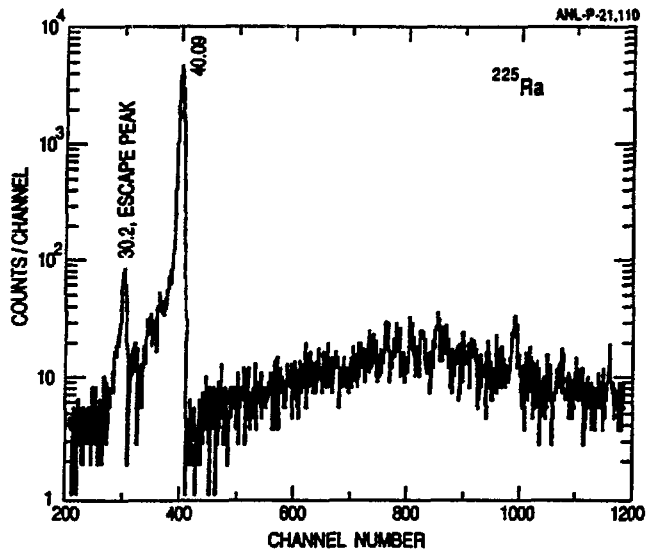

Fig. 2. γ-ray spectrum of a ^{225}Ra source measured with a 15% Ge detector and a 0.9 g/cm^2 Cu absorber. The energy scale is ~0.1 keV per channel.

In the recent study of ^{224}Ac levels described below, we have observed the conversion electron lines of the 115.6- and 120.8-keV transitions and also observed electron lines from previously unobserved transitions 90.9 (155.6 → 64.7) and 90.8 (120.8 → 30.0). An electron spectrum measured with a room temperature Si PIN diode and in coincidence with α_{156} group is shown in Fig. 3. The L line from the 90.8±0.5 keV (155.6 → 64.7) transition is present in the spectrum and has almost the same intensity as the 115.6 L line. The L line from the 90.2±0.5 (120.8 → 30.0) transition was observed in an electron spectrum gated by the α_{121} group. The multipolarity of both these transitions are deduced to be M1 and these are included in the new level scheme displayed in Fig. 4.

The available data on ^{225}Ac clearly establish a K,I=5/2,5/2 assignment for the 155.7-keV level in ^{225}Ac and the ^{229}Pa ground state. This can be seen from the level scheme where the log ft values, transition multipolarities and the α-decay hindrance factors provide the spin values shown there. Since the spin of the 40-keV level is deduced as 3/2, the 64.7-keV level is interpreted as the 5/2 member of the K=3/2 band and the 155.7-keV level is given the K,I=5/2,5/2 assignment. Positive parity assignments are favored for the 40.09, 64.7, and 155.7 keV levels because these K=3/2 (40.1) and K=5/2 (155.7) bands have larger Coriolis matrix element (0.9) than the value (0.6) between the ground and 120.8-keV bands. The K,I=5/2,5/2 assignment is in disagreement with the recent calculation of Ćwiok and Nazarewicz[16] which predicts the 3/2 member of the $1/2^-[530]$ band as the ^{229}Pa ground state.

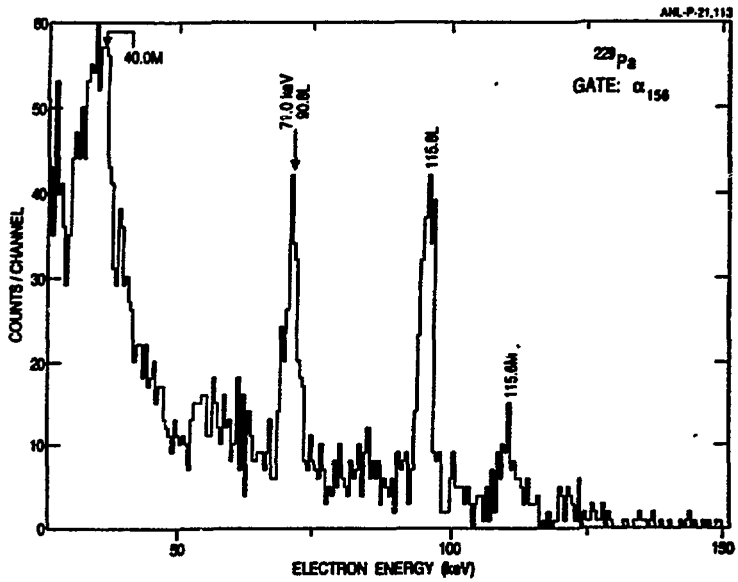

Fig. 3. Electron spectrum of a $^{229,228}Pa$ sample measured with a room temperature Si PIN diode and in coincidence with α_{156} group. Energy scale is 0.50 keV per channel.

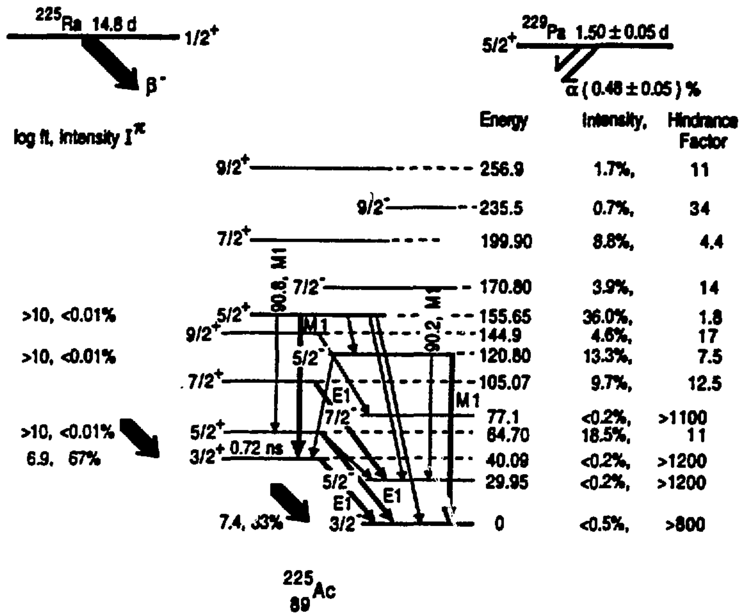

Fig. 4. Level scheme of ^{225}Ac deduced from the studies of α-decay of ^{229}Pa and β^--decay of ^{225}Ra.

3.3. ^{224}Ac

The level scheme of ^{224}Ac has been deduced from the study of the ^{228}Pa α-decay. The relative energies of levels in ^{224}Ac have been known for many years from the magnetic spectrograph measurement[17] of the ^{228}Pa alpha spectrum. However, in that work the α transition to the ^{224}Ac ground state was not observed. The level scheme of ^{224}Ac has also been studied by Sheline et al[18,19]. Most of the levels seen by these authors are observed in our investigation but we do not see any evidence for some levels reported by them. Figure 5a shows alpha spectrum gated by

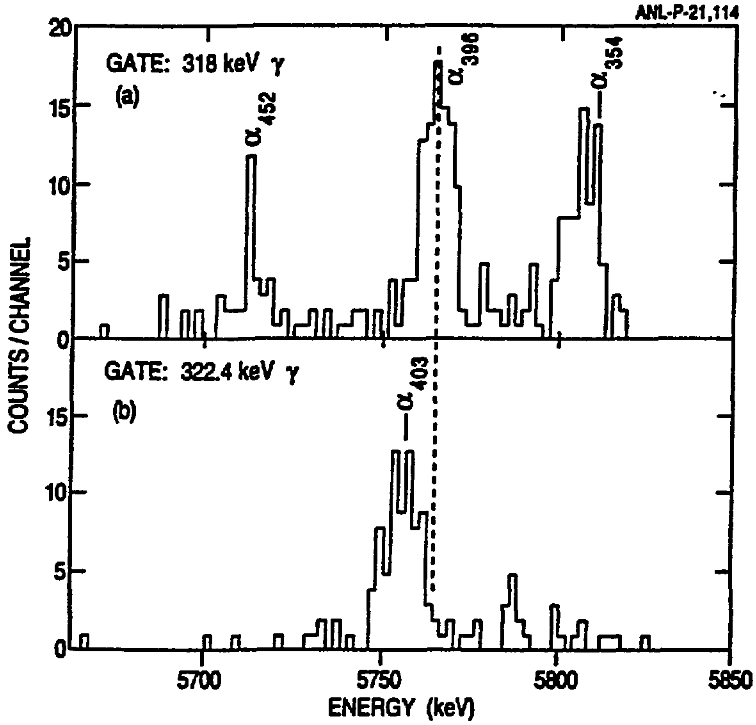

Fig. 5. ^{228}Pa α spectra gated (a) by the 318-keV photopeak and (b) by the 322-keV γ-ray. The α-particles were detected in a 25 mm^2 Si detector and the photons were detected in a 25% Ge detector.

the 318-keV photopeak and the spectrum gated by the 322-keV photopeak is shown in Fig. 5b. These data establish that there is a level at 395.7 keV which deexcites by a 317.5-keV γ-ray and another level at 402.7 keV which decays by a 322.4-keV γ-ray. However, the present experiment and that by Sheline et al[18,19] do not provide enough information for the assignment of spins and parities to the ^{224}Ac levels. Assuming 3^+ assignment[20] for the ^{228}Pa ground state, we have deduced the spins and parities of high-lying levels and these are shown in Fig. 6. Also shown in Fig. 6. Also shown in the level scheme are the α-decay hindrance factors. The hindrance factor is defined as the ratio of the experimental partial half-life to the theoretical value calculated with the spin-independent theory of Preston[21]. As can be seen, the hindrance factors to the 354.1- and 360.0-keV levels are almost identical. This

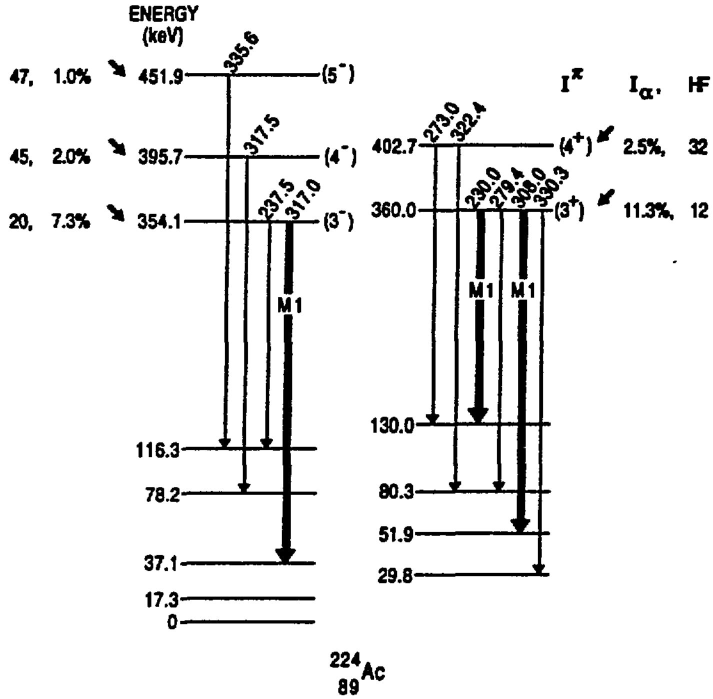

Fig. 6. A partial level scheme of ^{224}Ac deduced from the present work. Levels at 397.5 keV (4^-), 453.2 keV (5^-) and 406.0 keV (4^+) reported in ref. 19 were not observed in the present work.

shows that the wavefunctions of the two states are very similar. This is exactly what is expected for an octupole deformed nucleus, in which the positive and negative parity members of a parity doublet have a common origin. It should be pointed out the hindrance factors to the two members of a parity doublet are closest in ^{224}Ac, suggesting that this nucleus is the most octupole deformed nucleus in the mass-224 region.

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