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Possible Ground-State Octupole Deformation in ^{229}Pa

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Evidence is presented for the occurrence of a $\frac{5}{2}^{\pm}$ parity doublet as the ground state of ^{229}Pa, in agreement with a previous theoretical prediction. The doublet splitting energy is measured to be 0.22 ± 0.05 keV. The relation of this doublet to ground-state octupole deformation is discussed.

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Strong octupole correlation effects in nuclei heavier than Pb have been recognized for many years.[1,2] A manifestation of these effects is the occurrence of a low-lying $K^{\pi} = 0^-$ octupole band in many even-even nuclei[3] near mass 230. Although the correlation effects are strong, these nuclides are not deformed in an octupole sense. The existence of ground-state octupole deformation in these even-even deformed nuclides would be indicated by the presence of a 1^- level between the 0^+ and 2^+ members of the ground-state band. No such case is known. In odd-mass nuclides, the signature of octupole deformation is a parity doublet consisting of a pair of almost degenerate levels of the same spin and opposite parities and connected by a large $E3$ transition matrix element.

Recently, a treatment of cylindrically symmetric residual interaction modes, valid for all interaction strengths, has been applied[4] to a study of odd and even-even nuclides in the mass-230 region. These calculations predict octupole deformation in the ground state of ^{229}Pa, characterized by a $\frac{5}{2}^{\pm}$ parity doublet. In this work, we present experimental evidence for the existence of this predicted ground-state parity doublet.

Although both ^{231}Pa and ^{229}Pa have 91 protons, the low-energy level orderings are predicted[4] to be dramatically different. In ^{231}Pa, the ground state is known[3] to be the $I=\frac{3}{2}$ member of the $\frac{1}{2}^-[530]$ band; the $\frac{5}{2}^-[523]$ and $\frac{5}{2}^+[642]$ orbitals have been identified at 174 and 184 keV, respectively. A $\frac{5}{2}^\pm$ doublet is predicted to be the ground state of ^{229}Pa, with the $\frac{1}{2}^-[530]$ band predicted to be at ~50-keV excitation energy. The major single-particle components[4] of the positive- and negative-parity members of the doublet are the $\frac{5}{2}^+[642]$ and the $\frac{5}{2}^-[523]$ states, respectively. This shift of ~225 keV in the position of the $\frac{1}{2}^-[530]$ band relative to the $\frac{5}{2}^\pm$ doublet arises from octupole correlation effects.[4] Plausible changes in other deformation modes do not account for this shift.

To investigate the level structure of ^{229}Pa, we have carried out several different experiments utilizing high-resolution γ-ray spectroscopy, conversion-electron spectroscopy, and reaction spectroscopy. The reaction ^{231}Pa(p,t) was performed with a 16.5-MeV proton beam from the Argonne tandem Van de Graaff accelerator and the tritons were analyzed with an Enge split-pole magnetic spectrograph. Mass-separated sources of 1.4-d ^{229}Pa and 58-min ^{229}U were used in radioactive decay measurements.

(a) Evidence for the $\frac{5}{2}^+$ *ground state.*—The basis for our assignment of the ground-state spin and parity of ^{229}Pa as $\frac{5}{2}^+$ is the pattern of its electron-capture decay to known levels in ^{229}Th. Spin and magnetic-moment determinations[3] and ^{233}U α-decay measurements[5] established the ^{229}Th ground state as the $\frac{5}{2}^+[633]$ neutron orbital with its $\frac{7}{2}$ member at 42.4 keV. We have observed this 42.4-keV transition in both the γ-ray and the electron spectra of ^{229}Pa and derived its conversion coefficient, which is in agreement with the value obtained in the ^{233}U α-decay studies.[3,5] Our decay scheme for ^{229}Pa is shown in Fig. 1; spins and parities are taken from previous measurements. In the heavy-element region $\log ft$ values of <8 occur only for β transitions with $|\Delta K|$ and $|\Delta I|$ $=0$ or 1. Thus, the observed $\log ft$ values to the ground and 42.4-keV levels restrict the spin of the ground state of ^{229}Pa to $\frac{5}{2}$ and $\frac{7}{2}$. The fact that we see a β transition with $\log ft$ value of ~7 to the 29.2-keV state $(K,I^\pi=\frac{3}{2},\frac{5}{2}^+)$ rules out the $I=\frac{7}{2}$ assignment and establishes a spin of $\frac{5}{2}$ for the ^{229}Pa ground state. Reaction data[6] and calculations[4] indicate that the $\frac{5}{2}^+[633]$ state in ^{229}Th has very little octupole admixture. Since electron capture (EC)

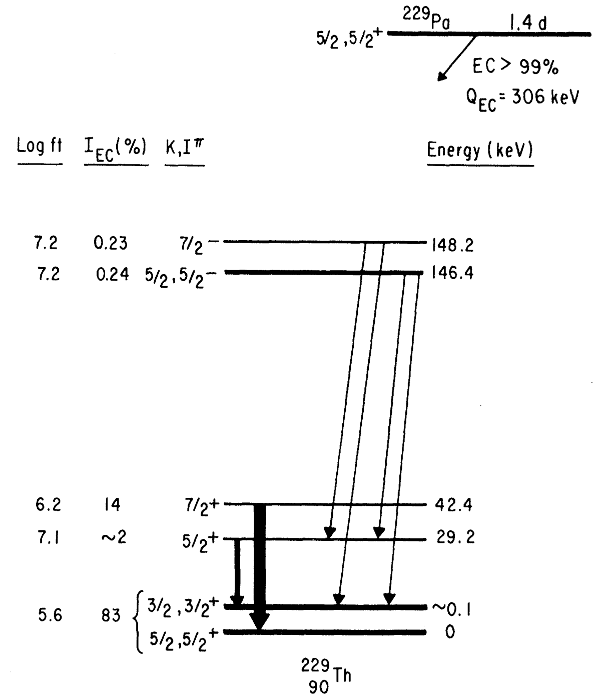

FIG. 1. Decay scheme of ^{229}Pa deduced from the present work. Spin and parity assignments in ^{229}Th were taken from Refs. 3 and 5.

involves one-body operators, the EC decay probability to this state will be sensitive to the single-particle component of the ^{229}Pa ground state and the octupole admixtures in the $\frac{5}{2}^\pm$ doublet will not substantially affect the $\log ft$ values. The single-particle components of the relevant states are the $\frac{5}{2}^+[642]$ and $\frac{5}{2}^-[523]$ orbitals. The $\log ft$ values between these two proton states and the $\frac{5}{2}^+[633]$ neutron state are quite different. For example, in ^{235}Pu EC decay,[3] the transition $\frac{5}{2}^+[633]\to\frac{5}{2}^+[642]$ has a $\log ft$ value of 5.4 and the transition $\frac{5}{2}^+[633]$ $\to\frac{5}{2}^-[523]$ has a value of 6.5. Our measured $\log ft$ value of 5.6 thus favors the $\frac{5}{2}^+$ assignment for the ^{229}Pa ground state. The $\log ft$ values for the 42.4- and 29.2-keV states (Fig. 1) clearly show that most of the 83% EC decay proceeds to the $\frac{5}{2}^+[633]$ state.

(b) Identification of the $\frac{1}{2}^-[530]$ *band.*—The $\frac{1}{2}^-[530]$ orbital is unambiguously identified in ^{229}Pa by our study of the reaction ^{231}Pa(p,t). It is well known[7] that the (p,t) reaction preferentially excites the state in the residual nucleus which has the same single-particle configuration as the target ground state. Thus the strongest peak in the ^{231}Pa(p,t) spectrum corresponds to the $\frac{3}{2}$ member of the $\frac{1}{2}^-[530]$ band. We have determined the excitation energy of this state to be 128 ± 15

keV. This large uncertainty comes from the uncertainty in the ground-state mass of ^{229}Pa. The $\frac{1}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ members of the $\frac{1}{2}^-$[530] band were also observed, at 140 ± 2, 217 ± 3, and 187 ± 3 keV, respectively. The errors do not include the uncertainty in the ground-state mass of ^{229}Pa. These spacings are very similar to those seen[3] for the $\frac{1}{2}^-$[530] rotational band in ^{231}Pa.

(c) Identification of the $\frac{5}{2}^-$ member of the ground-state doublet.—The $\frac{5}{2}^-$ member of the ground-state parity doublet in ^{229}Pa is identified by studying the γ and conversion-electron transitions in the ^{229}U EC decay. γ singles and $\gamma\gamma$ coincidence measurements were performed with Ge(Li) detectors and the electron spectrum was measured with a cooled Si(Li) spectrometer. γ transitions were assigned to the ^{229}U EC decay on the basis of half-life measurements, their presence in the spectrum of mass-separated samples, and their appearance in γ-ray spectra gated by Pa K x rays. Multiparameter $\gamma\gamma$ coincidences revealed which of the prominent γ rays were in coincidence with each other. This result also showed that all γ rays were in prompt ($2\tau = 20$ ns) coincidence with K x rays.

The strongest transition in the ^{229}U EC decay (see Fig. 2) is the 122.5-keV transition. In the electron spectrum its L and M conversion lines were observed which yield a predominantly (> 90%) $M1$ multipolarity for this transition. The large intensity (35% per EC decay) of this transition and the fact that no transition of comparable intensity is in coincidence with it suggest that the 122.5-keV transition originates from a 122.5-keV level and terminates at or near ground. In the reaction ^{231}Pa(p,t) the $\frac{3}{2}$ member of the $\frac{1}{2}^-$[530] band was identified at 128 ± 15 keV. This configuration is expected to receive significant EC population because the ^{229}U ground state is most likely[3] the $\frac{3}{2}^+$[631] orbital. For these reasons the 122.5-keV level observed in EC decay is assigned to the $\frac{3}{2}$ member of the $\frac{1}{2}^-$[530] band.

Since the ^{229}Pa ground state has been established as $\frac{5}{2}^+$, the $M1$ multipolarity of the 122.5-keV transition which originates from a $\frac{3}{2}^-$ state indicates a negative-parity state near ground with spin $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$. Spins $\frac{1}{2}$ and $\frac{3}{2}$ are ruled out because the transitions to higher members of this band would have been observed in the electron or γ-ray spectrum. Therefore, the most likely assignment for this state is $K, I^\pi = \frac{5}{2}, \frac{5}{2}^-$. The ($p,t$) reaction and γ-ray spectrum place an upper limit of 25 keV on the excitation energy of this state.

There are two ways to determine the splitting

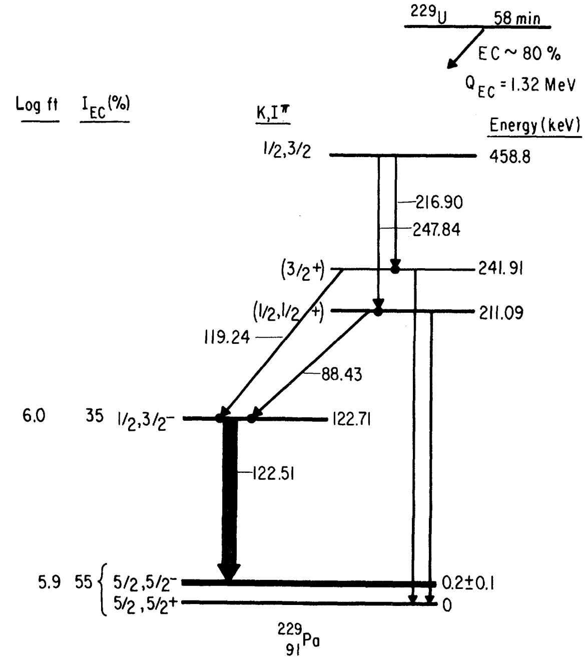

FIG. 2. A partial decay scheme of ^{229}U constructed from the results of this investigation. The uncertainties in γ-ray energies are 50 eV. Coincidences are shown by solid circles.

energy in the ground-state doublet. The first method uses the energy differences in closed cycles in the ^{229}Pa level scheme, and the other involves a direct measurement of the electron spectrum in delayed coincidence with Pa K x rays. The level scheme of ^{229}Pa, like those of other Pa nuclei, is extremely complex and despite many experiments we have only been able to construct a partial decay scheme for ^{229}U EC decay. However, our measurements established two closed cycles (Fig. 2) which give the $\frac{5}{2}^- - \frac{5}{2}^+$ energy difference. Detailed coincidence measurements establish levels at 211.09 and 241.91 keV and their decay pattern is shown in the figure. From the upper limits on the electron intensities and intensity balances in $\gamma\gamma$ coincidences we have established that the 88.43- and 119.24-keV transitions are $E1$. Hence the 211.09- and 241.91-keV levels have positive parity. Also, since $M1$ and $E2$ transitions in heavy elements are intrinsically faster than $E1$ and $M2$ transitions, respectively, the two levels should deexcite to the $\frac{5}{2}^+$ ground state. Thus the two closed cycles give the $\frac{5}{2}^- - \frac{5}{2}^+$ splitting energy as $211.09 - (122.51 + 88.43) = 0.15 \pm 0.10$ and $241.91 - (122.51 + 119.24) = 0.16 \pm 0.10$ keV, respectively.

A direct measurement of the $\frac{5}{2}^\pm$ doublet splitting

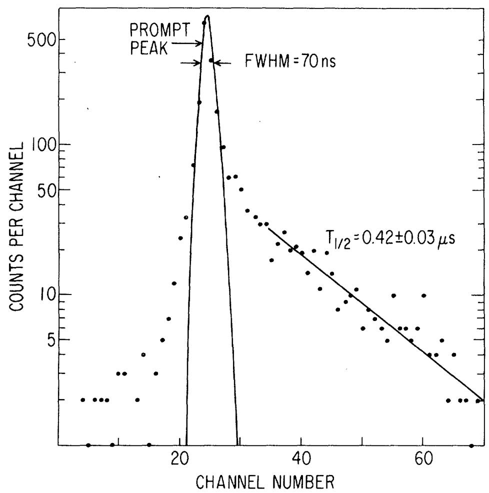

FIG. 3. A time spectrum for the decay of the $\frac{5}{2}^-$ member of the ground-state doublet in ^{229}Pa. The TAC was started by Pa $K\alpha$ pulses detected in a Ge detector and the stop pulses were ~80–400-eV electrons detected in a proportional counter. The prompt curve was obtained with a ^{99m}Tc source with the same electronic setup.

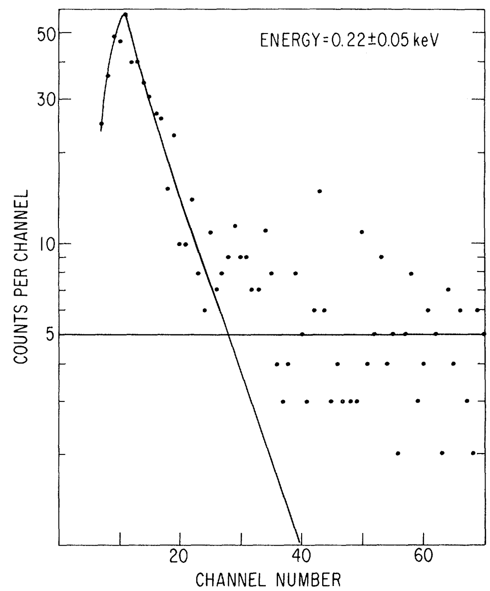

FIG. 4. The electron spectrum measured with a proportional counter in coincidence with Pa $K\alpha$ x rays and the delayed part of the TAC spectrum. The horizontal line represents the average background and the slope is drawn to guide the eye.

was made by performing a three-parameter coincidence experiment. A time-to-amplitude converter (TAC) was started by K x rays and γ rays in the decay of ^{229}U (the sample was not mass separated) and was stopped by pulses from a gas-flow internal-sample proportional counter. The time spectrum between the Pa K x rays and ~80- to ~400-eV electrons is shown in Fig. 3. The prompt peak is caused by coincidences between K x rays and Auger electrons in outer shells. Also shown in the figure is a prompt curve obtained under similar conditions with a ^{99m}Tc source. The least-squares fit to the data give a half-life of 0.42 ± 0.03 μs. The electron spectrum obtained in coincidence with Pa K x rays and the delayed part of the TAC is shown in Fig. 4. The spectrum was calibrated with a precision pulser and the 75-eV transition of ^{235m}U. The end points of the two electron spectra were used for their respective transition energies. This method for energy determination was used because of the difficulty in locating the centroids of the low-energy electron peaks. These data give a value of 0.22 ± 0.05 keV for the $\frac{5}{2}^{\pm}$ doublet splitting energy, in good agreement with the value deduced from closed cycles.

It is worth pointing out that the measured half-life is short for a 200-eV $E1$ transition. This might be an indication of parity mixing, because the mixing between the $\frac{5}{2}^+$ and $\frac{5}{2}^-$ states would allow a fast $M1$ component in this transition. We plan to investigate this mixing by studying the polarization of high-energy γ rays associated with decays to the doublet.

In conclusion, we have identified the predicted $\frac{5}{2}^{\pm}$ parity doublet as the ^{229}Pa ground state. This observation is consistent with the calculations of Chasman[4] and thereby provides evidence for possible ground-state octupole deformation in ^{229}Pa.

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