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*Short note*

# Experimental evidence on the ground-state energy of $^{229}$Pa

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**Abstract.** The E1 transition from the $3/2^-$ state to the ground state of $^{229}$Pa was identified in the (p,t$\gamma$) reaction. Its energy is found to be 11.6(3) keV. This leads to a value of $Q_{g.s.}$ = -4133(2) keV and to a mass defect of $^{229}$Pa of 29 894(3) keV. It is concluded that the ground-state configuration of $^{229}$Pa is 3/2[651].

**PACS.** 23.20.Lv Gamma transitions and level energies – 27.90.+b $220 \leq A$ – 21.10.Dr Binding energies and masses

## Introduction

In recent studies [1,2] of the $^{231}$Pa(p,t)$^{229}$Pa reaction the Q-value for the $3/2^-$ head of the $K^\pi = 1/2^-$ band was found to be −4145(1) keV. A ground-state Q-value of −4126(9) keV was evaluated from the Atomic Mass Tables [3] thus lying 19(9) keV below the $3/2^-$ level. A spin of $5/2^+$ was assigned to the ground state of $^{229}$Pa on the basis of the log$ft$ values for the electron-capture decay of $^{229}$Pa to the levels of $^{229}$Th with known $I^\pi$ and $K$ quantum numbers [4]. A level at 0.2 keV with spin $5/2^-$ was also suggested as the parity doublet for the $5/2^+$ ground state (manifestation of reflection asymmetry) based on the electron-capture decay of $^{229}$U to $^{229}$Pa and on the $^{231}$Pa(p,t)$^{229}$Pa reaction [4]. Our measurements [1,2] of the $^{231}$Pa(p,t)$^{229}$Pa reaction show that the last assignment is wrong. The angular distribution of tritons is consistent with the assignment of spin $5/2^-$ to a level 122.5 keV above the $3/2^-$ state. Nevertheless, using the (p,t) data of [1] and reversing the order of the transitions observed in the decay experiment [4], a new level scheme was proposed in which the parity doublet at the ground state was retained [5]. The energy of the $3/2^-$ state is 31.0 keV in this level scheme which does not contradict the value of 19(9) keV from [1,2]. Sheline [6] put forward an additional argument for the existence of a $5/2^\pm$ parity doublet in $^{229}$Pa based on the $\alpha$-decay hindrance factors from the $^{229}$Pa ground state to the $5/2^\pm$ parity doublet in $^{225}$Ac.

A decisive argument in this discussion would be the observation of the $3/2^- \rightarrow$ g.s. transition. Ahmad [5] also suggested the observation of the 31 keV transition as an important test of the suggested new level scheme. A transition with such a small energy can be observed only if it is of E1-multipolarity. Therefore its observation would support the assignment of spin $5/2^+$ to the ground state ($3/2^+$ is ruled out according to [4]).

## Experimental procedure and results

The $^{231}$Pa(p,t) reaction was used to populate the $3/2^-$ state. A radioactive $^{231}$Pa target of 105 $\mu$g/cm$^2$ was bombarded by 24 MeV protons from the Munich Tandem accelerator. More than 50% of the (p,t)-reaction cross section leads to this state directly or through the excitation of the rotational band built on it. Coincidences between $\gamma$-rays and tritons were used to select the (p,t$\gamma$) channel. A ø5cm×1cm planar Ge-detector with an energy resolution of 500 eV at energy 60 keV registered the $\gamma$-rays. Two telescopes each consisting of two PIN-diodes $2 \times 2$ cm$^2$ ($\Delta E$-detector) and a CsI(Tl) crystal of size $4 \times 2 \times 1$ cm$^3$ with photo-diodes on two sides of the crystal ($E$-detector) were used for particle identification. The information (pulse hights from the Ge, $\Delta E$, and E-detectors in the timing range of 100 ns) was stored event by event on magnetic tape. The counting rate of true events was limited by the counting rates from competing channels both in the particle and in the $\gamma$-detectors and by direct hits of protons of the Ge-detector. The $\gamma$-detector was placed at $\theta = 90°$, the maximum of the angular distribution for E1-radiation. To reduce the proton-to-triton counting-rate ratio the telescope was mounted at $\theta = 50°$ which corresponds to the second maximum in the triton angular-distribution. Under these conditions the counting-rate ratios for the tritons, the elastically scattered protons and the $\gamma$-rays from

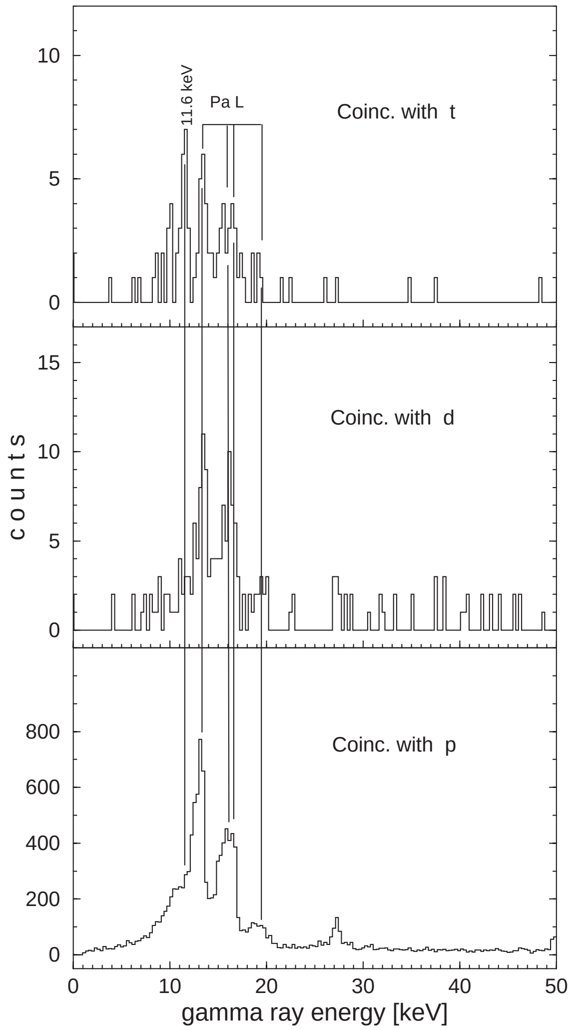


**Fig. 1.** Gamma-rays from the $^{231}$Pa(p,t$\gamma$) reaction in coincidence with protons, deuterons and tritons

the fission products and from the target radioactivity was about 1:2000:3000.

The results of the 20 hour exposure are shown in Fig. 1. Inelastic scattering of the protons, the (p,d) and (p,t) reactions lead to the excitation of different isotopes of Pa. Therefore Pa X-rays are produced and indeed observed in coincidence with protons, deuterons and tritons. The most intense are indicated by vertical lines. An additional line at 11.6(3) keV appears only, however, in coincidence with tritons. Its origin has to be nuclear excitation. Its multipolarity must be E1 or it could not be seen because of internal conversion ($k > 200$). The observed intensity ratio of the 11.6 keV and the 13.13+13.29 keV lines of 1.1(5) agrees with a value of 1.5 calculated assuming that the $K^{\pi} = 1/2^{-}$ band has no side feeding (the side feeding would decrease the ratio). The observed number of counts in the 11.6 keV line can be compared to the one calculated for the experimental conditions and under the same assumptions it is about 21:40.

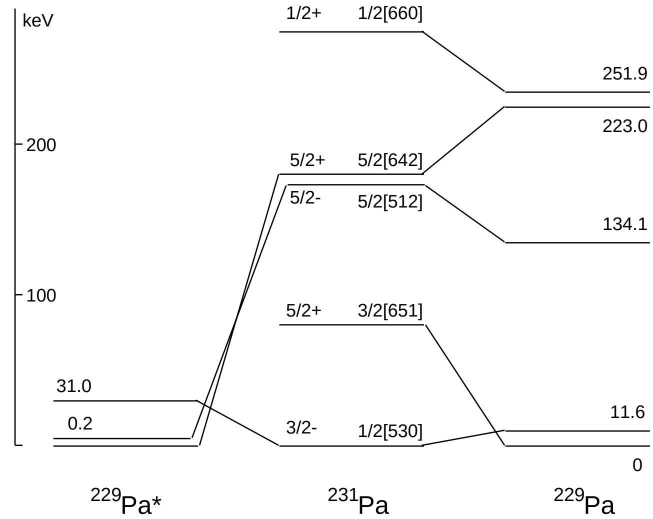


**Fig. 2.** Comparison of energies of some configurations in $^{229}$Pa and $^{231}$Pa, and in $^{229}$Pa$^{*}$ as suggested in [5]

The $3/2^{-} \rightarrow 5/2^{+}$ transition energy of 11.6 keV leads to a value of the (p,t)-reaction energy $Q_{\mathrm{g.s.}}$=-4133(2) keV and to the corrected mass defect of $^{229}$Pa 29 894(3) keV (the old value was 29 887(9) keV [3]).

The $^{229}$Pa and $^{231}$Pa nuclei show striking similarity of their 1/2[530] and 1/2[660] bands [2]. In a recent study of Coulomb excitation of $^{231}$Pa we have observed a strong population of the 3/2[651] band from the 1/2[530] band. There are indications of a similar population also in $^{229}$Pa [2]. The present result confirms such a population. Taking into account these facts and the results of calculations in the framework of the quasiparticle-plus-phonon model (to be published) the main configuration of the ground state with spin $5/2^{+}$ must be 3/2[651]. The previous assignment [4,5] was 5/2[642]. The $3/2^{-}$ level at 11.6 keV and the $1/2^{+}$ level at 251.9 keV (all energies are relative to the ground state, in [2] they are given relative to the $3/2^{-}$ state) have predominately the 1/2[530] and 1/2[660] configurations, respectively. The configuration 5/2[532] is suggested for the $(5/2^{-})$ level at 134.1 keV. Then the two positive-parity levels at 223.0 and 253.3 keV [2] have to belong to the 5/2[642] configuration. An assignment of spin $5/2^{+}$ is preferable for the 223.0 keV level (instead of $3/2^{+}$ in [2]).

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