Structure and decay of a four-quasiparticle 15^- isomer in ^{180}Ta

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A four quasiparticle high-K isomer with a meanlife of 45(2) μs has been identified at 1451 keV in ^{180}Ta, populated in the ^{176}Yb(^{11}B,$\alpha 3n$)^{180}Ta reaction. The isomer decays into a rotational band which is associated with the two-quasiparticle 9^- isomer at 75.3 keV. Analysis of the branching ratios within that band and the magnetic moment for the 9^- isomer, supports the configuration assignment to the 9^- isomer. The K hindrance for the $E2$ decay of the 15^- isomer to the 9^- band is substantially lower than that for an apparently similar 15^- isomer in ^{178}Ta, a difference which can be attributed partly to a change from the $\pi 9/2^-[514]\nu^3 9/2^+[624]7/2^-[514]5/2^-[512]$ configuration in ^{178}Ta to the $\pi^3 9/2^-[514]7/2^+[404]5/2^+[402]\nu 9/2^+[624]$ configuration in ^{180}Ta. The reduced hindrance factors for $E2$ decays from related four-quasiparticle isomers in the isotopes ^{176,178,180}Ta match the hindrances of the corresponding $E2$ decays from component 6^+ core states in the hafnium isotopes, ^{174,176,178}Hf .

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I. INTRODUCTION

Interest has focused recently on the production of the isotope ^{180}Ta in stellar processes (e.g., [1–4]) and therefore on its structure. ^{180}Ta is one of the least abundant stable isotopes and the only one which occurs naturally in an isomeric state. Its 1^- ground state has a shorter half-life (8.1 h) than the $K^\pi = 9^-$ isomeric state at 75.3 keV which lives for more than 1.2×10^{15} y. The uncertainty of its production in nature, its possible candidature as the basis for an x-ray laser and evidence that excitation by bremsstrahlung can occur from the 9^- isomer to higher (but unidentified) states which also have substantial decay widths to the ground state [5,6], leading to propositions of as yet unexplained K mixing [7,8] between states at intermediate energies, underlines the need for firm spectroscopic data. Only fragmentary information is available [9], mainly from particle transfer studies, inelastic photon scattering and β decay. Information from γ-ray spectroscopy is very limited because the extremely low natural abundance of ^{180}Ta disqualified it from detailed study through Coulomb excitation, at least until recently [10], and its proximity to stability makes it difficult to reach easily with heavy ion, xn reactions with stable beams, which favour production of neutron-deficient isotopes.

As part of systematic spectroscopic studies of a range of tantalum isotopes (^{179}Ta being the heaviest accessible by reactions that involve only neutron evaporation with at least medium spin inputs) significant production of ^{180}Ta was achieved through the ^{176}Yb(^{11}B,$\alpha 3n$)^{180}Ta reaction in a bombardment whose main reaction channel proceeds via evaporation of four neutrons to ^{183}Re. The purpose of the present communication is to report on the identification and properties of a long-lived isomer whose decay reveals part of the ^{180}Ta level scheme.

II. EXPERIMENTAL CONDITIONS

Enriched targets of metallic ^{176}Yb of thickness 4.6 mg/cm^2 were bombarded with pulsed ^{11}B beams from the ANU 14UD accelerator at a range of energies, the optimum for four-neutron evaporation being approximately 55 MeV. Gamma-gamma-time measurements were carried out using the six Compton suppressed detectors which make up the CAESAR array, together with two LEPS detectors. For these experiments the beams were adjusted to give $\sim$1 ns wide pulses separated by 1.7 μs. All correlated γ-γ-time events within $\pm$856 ns were recorded and analyzed with different time-difference conditions.

A. Isomer decay and partial level scheme

1. Out-of-beam coincidences

The lowest panel of Fig. 1 shows γ rays in prompt coincidence with a 431.7 keV transition, with the additional constraint that all γ rays occurred between beam pulses, thus selecting only transitions that are initially fed by an isomer. The 431.7 keV transition was subsequently assigned as the main branch directly from a high-spin isomer, as confirmed by gates on transitions assigned as band members, examples of which are shown in the figure. The isomer also decays via a weaker 142.4 keV branch. (Because of the time conditions, high sensitivity was obtained even though population of the isomer is only $\sim$ 12% of the ^{180}Ta yield, which itself is only $\sim$ 7% relative to the ^{182,183}Re products.)

2. Lifetime

To establish the lifetime of the isomer, which was found to be long compared to the conditions used in the γ-γ-time measurements, γ-time measurements using chopped beams with time width/separations ranging from 0.1 μs/1.7 μs to 1 ms/17 ms were explored. The times of all γ rays were measured in a resettable ADC clock which could be interrogated whenever a γ ray was detected, avoiding effects which normally limit such measurements when time-to-amplitude converters are employed. A representative time spectrum com-

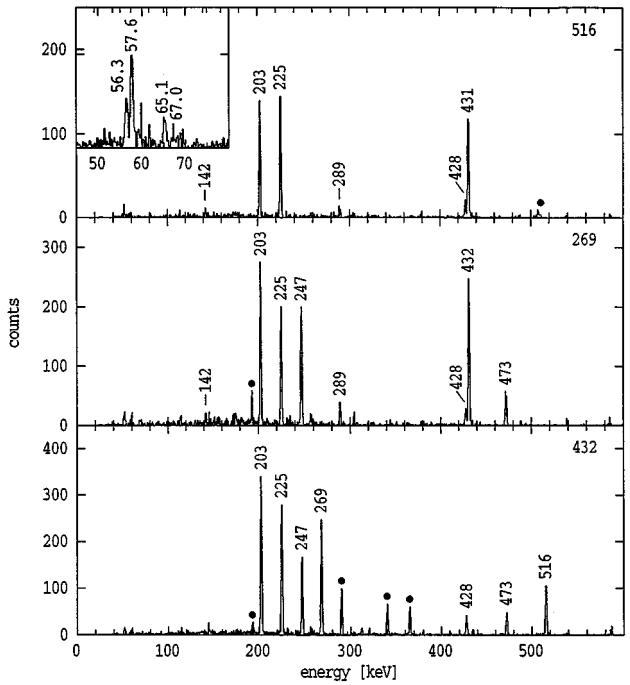

FIG. 1. Gamma-ray coincidence spectra gated on the 516, 269, and 432 keV transitions, in the out-of-beam region. (The filled circles indicate known contaminants.) Note that the relative γ-γ-time condition here is ± 10 ns, which reduces the efficiency at low energies. The inset shows the x-ray region as observed in the LEPS detector, combining the same γ-ray gates.

bining (background-subtracted) gates on individual γ rays, recorded with conditions of 22 μs/428 μs beam width/separation, and with a fast veto applied to remove most of the in-beam region, are shown in Fig. 2. The main component is attributed to a 45(2) μs meanlife.

3. Assignment to ^{180}Ta

Assignment to ^{180}Ta was made after considering a range of information; prompt coincidences between the main transitions and characteristic tantalum x rays as shown in Fig. 1;

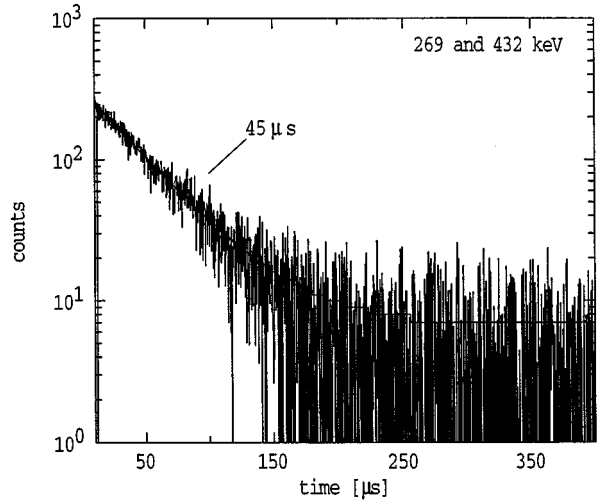

FIG. 2. Time spectrum gated on transitions in the isomeric path.

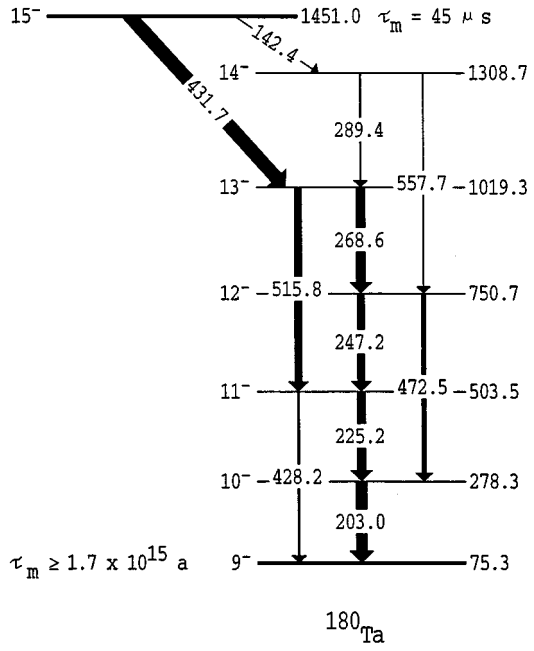

FIG. 3. Partial level scheme for ^{180}Ta.

the absolute and relative yields in both ^{7}Li induced reactions on ^{176}Yb and excitation functions leading by neutron evaporation to the tantalum isotopes and similar studies with ^{11}B beams leading to a range of rhenium isotopes of known mass number; elimination of other possible candidates, principally ^{179}Ta, through knowledge of its scheme which is under independent study [11].

4. Partial level scheme and spins

The proposed decay path of the isomer in ^{180}Ta is shown in Fig. 3. The main rotational sequence of states is defined clearly through the observation of cascade and crossover transitions and the appropriate γ-γ coincidence relationships. The band populated is assumed to be based on the 9^- isomer at 75.3 keV, consistent with the intensity observed (this band should be yrast) and with previous information from particle transfer studies [12] which gave an (imprecise) energy separation of 203 keV between candidate 10^- and 9^- states, to be compared with the precise 203.0 keV transition observed here.

From the delayed intensity balances, the 142.4 keV transition which feeds the suggested 14^- member of the 9^- band has a total conversion coefficient of $\alpha_T = 1.8(3)$, consistent only with $M1$ multipolarity, and suggesting $J^\pi = 15^-$ for the 1451 keV state. The main branch from the isomer is then by a 431.7 keV $E2$ transition to the 13^- state. This interpretation gives an internally consistent result for both the spin and decay branches of the isomer and the identification of the 9^- band itself.

III. INTERPRETATION

A low-lying, long-lived four-quasiparticle 15^- isomer with a similar decay pattern is known [13] in ^{178}Ta although it has a very long meanlife of 84(3) ms [11,13]. While a similar state might be expected in ^{180}Ta, the detailed proper-

TABLE I. Branching ratios and $(g_K-g_R)/Q_0$ values for the 9^- band in ^{180}Ta.

J^π	$E_\gamma(\Delta I=1)$ (keV)	$E_\gamma(\Delta I=2)$ (keV)	λ[a]	$\lvert(g_K-g_R)/Q_0\rvert$	$\lvert g_K\text{-}g_R\rvert$[b]
14^-	289.4	557.7	0.71(16)	0.062(7)	0.431(50)
13^-	268.6	515.8	0.79(6)	0.0479(19)	0.335(13)
12^-	247.2	472.5	0.52(5)	0.0464(26)	0.325(18)
11^-	225.2	428.2	0.24(4)	0.0463(41)	0.324(29)

[a]Branching ratios $\lambda=I_\gamma(I\rightarrow I-2)/I_\gamma(I\rightarrow I-1)$.
[b]Taking Q_0 = 7.0(1).

ties differ, as will be made clear below in discussing the configurations.

A. Configuration of the $J^\pi = 9^-$ band

The 9^- intrinsic state has previously been attributed [14] to the configuration $\pi 9/2^-[514]$ $\nu 9/2^+[624]$, a proposition which can be tested further by examining the rotational band structure identified here. The γ-ray branching ratios λ from each state can be used to deduce the $(g_K\text{-}g_R)/Q_0$ values as given in Table I, from the formulas for strongly coupled rotational bands, proceeding through a calculation of the cascade mixing ratios:

$$\frac{1}{\delta^2}=\frac{1}{\lambda}\left[\frac{E_\gamma(I\rightarrow I-2)}{E_\gamma(I\rightarrow I-1)}\right]^5\frac{\langle IK20|I-2K\rangle^2}{\langle IK20|I-1K\rangle^2}-1, \tag{1}$$

$$\frac{g_K-g_R}{Q_0}=\frac{1}{\delta}\frac{0.933E_\gamma(I\rightarrow I-1)}{\sqrt{I^2-1}}, \tag{2}$$

where E_γ is in units of MeV and Q_0 is in units of eb.

As can be seen from the table, consistent independent values are obtained for each member of the band. Values of g_K can be extracted and compared with the value calculated using the Nilsson model and the additivity relation $Kg_K=\Sigma g_{\Omega_i}\Omega_i$, if the quadrupole moment Q_0 and the rotational g factor, g_R, can be estimated.

The value calculated from the Nilsson model is $g_K(9^-)$ = 0.53, which agrees with the values obtained experimentally for $(g_K\text{-}g_R)/Q_0$ if $Q_0\sim 7.0$ and $g_R\sim 0.30$, as can be deduced from the last column of Table I. The quadrupole moment of ^{180}Ta has not been measured but the moment is known precisely for a number of bands in ^{181}Ta and for the 2^+ state in ^{178}Hf as compiled in [15], all of which suggest Q_0 $=7.0(1)$ eb. Assumption of the same value in ^{180}Ta gives, from the present measurements (Table I), a mean value of $(g_K\text{-}g_R)$ = 0.331(10).

Since the magnetic moment of the 9^- isomer has been measured independently (as 4.77(5) μ_N [14] corresponding to a gyromagnetic ratio of 0.530(6)), it can be used in the formula

$$g=g_R+(g_K-g_R)\frac{K^2}{I(I+1)} \tag{3}$$

to extract a value of g_R = 0.23(1). This rather low value compared to an expected value of about $0.7Z/A=0.28$ depends, of course, on the assumption that the quadrupole moment in ^{180}Ta is the same as it is in the neighbors. If that is substantiated, and if other bands in ^{180}Ta yield the same value, the low magnitude of g_R will need explanation.

Since the rotational band spacing is also indicative of the presence in the configuration of particles which experience Coriolis mixing, it is useful to examine the band in terms of the rotational alignment. As shown in Fig. 4, the alignment in the 9^- band in ^{178}Ta is consistent with the presence of the $9/2^+[624]$ neutron, judging by the comparison with the alignment in the $9/2^+[624]$ band in the isotone ^{179}W [16]. (For clarity only the $\alpha=+1/2$ signature is shown for the odd cases.) The alignment in ^{180}Ta is significantly lower, but that is again consistent with the expectation of lower Coriolis mixing and therefore lower alignment as the neutron Fermi level reaches the upper part of the $i_{13/2}$ neutron shell, as exemplified by the low alignment observed [17] for the $9/2^+[624]$ band in the isotone, ^{181}W.

B. Decay strengths and configuration of the 15^- isomer

Unfortunately, the relatively long lifetime obtained for the new isomer makes it difficult to identify directly, rotational band states based on it and therefore probe its configuration, however, its decay properties also give an indication of its configuration, as shown below. While the states in ^{178}Ta and ^{180}Ta have clear similarities, the strength of the 431.7 keV $E2$ transition connecting the 15^- isomer and the 9^- band is considerably larger than the analogous 227 keV transition in ^{178}Ta, which has a *partial* γ-ray lifetime T^γ of 101(4) ms [13,11].

For a transition of multipole order λ, the reduced K-hindrance factor per degree of K forbiddenness, f_ν, where $\nu=\Delta K-\lambda$, is defined as

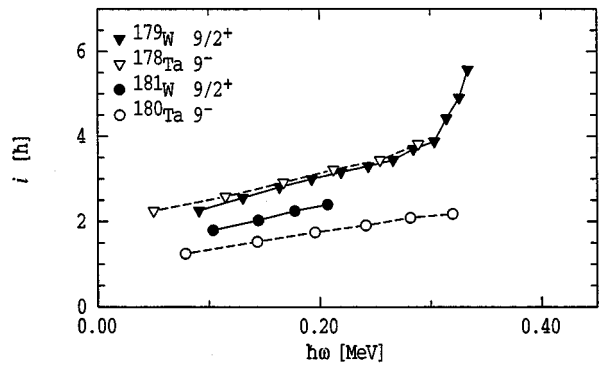

FIG. 4. Alignment curves for the 9^- bands in ^{178}Ta and ^{180}Ta compared to the $9/2^+[624]$ bands in the isotones ^{179}W and ^{181}W.

$$f_\nu = \left(\frac{T^\gamma}{T^W} \right)^{1/\nu} = (f)^{1/\nu}, \quad (4)$$

where T^W is the Weisskopf single-particle estimate and f is the corresponding hindrance factor. For the present interband transition, ν=4. The lifetime in ^{178}Ta corresponds to an $E2$ hindrance, $f = 4.4\times10^6$, and therefore a reduced hindrance of $f_\nu = 46$.

While the shorter lifetime in ^{180}Ta arises partly because the $E2$ transition is higher in energy and partly because the difference in excitation energies enables a transition to the 14^- band member, a decay path which is not possible in ^{178}Ta, it is significantly shorter than expected. The partial γ-ray lifetime for the 432 keV transition in ^{180}Ta is 60(5) μs, which corresponds to $f=6.7\times10^4$ and $f_\nu = 16$, a much lower hindrance than in ^{178}Ta.

K mixing might lower the hindrances but such mixing should be less in ^{180}Ta, as evidenced by the lower alignments and therefore lower Coriolis mixing as pointed out above. The difference is attributed instead to a specific change in configuration. Multiquasiparticle calculations similar to those reported recently [18] predict two possible 15^- states in ^{178}Ta, one from the $\pi 9/2^-[514]$ $\nu^3 9/2^+[624]7/2^-[514]5/2^-[512]$ configuration (which we abbreviate to $\pi\nu^3$), the other from the $\pi^3 9/2^-[514]$ $7/2^+[404]5/2^+[402]$ $\nu 9/2^+[624]$ configuration (or $\pi^3\nu$). These will be considered below as a 9^-, $\pi\nu$ configuration coupled to 6^+ states in the even-even hafnium core.

Although the former of the 15^- configurations is initially calculated to be somewhat lower, both are predicted to be close in energy after residual interactions are included, and thus an ambiguity arises as to which corresponds to the experimental state. In either case, some mixing would be expected. In ^{178}Ta, recent measurements of the properties of a rotational band based on the 15^- isomer give g_K-g_R values which suggest the $\pi\nu^3$ configuration is dominant but possibly with some admixture [11]. The $\pi^3\nu$ state is calculated to be lower in ^{180}Ta mainly because of the change in single quasiparticle energies. The essential difference between the competing configurations is whether the $[6^+]$ core is from a ν^2 or a π^2 configuration, coupled to the same $\pi\nu[9^-]$ component. The corresponding 6^+ core states in the hafnium nuclei are well recognized as cases where mixing occurs between the alternative configurations, and importantly, mixing which varies with neutron number.

One result of that is a difference in $E2$ decay strengths to the $K=0$ ground state band in the even-even cores. In ^{176}Hf where the 6^+ isomer (9.5 μs) is believed to be 61% π^2, 39% ν^2 (e.g., [19]) the $E2$ decay [19] has $f_\nu = 42$, while in ^{178}Hf where the configuration is nearly pure π^2 [20] the isomer is relatively short-lived (78 ns) [21] and the equivalent $E2$ decay has $f_\nu = 16$. The parallel between ^{176,178}Hf and ^{178,180}Ta can be extended to ^{174}Hf and ^{176}Ta. In the lighter nucleus, ^{176}Ta, the $\pi\nu$ component couples to 8^- rather than 9^- because of the shift in the neutron Fermi level towards the $7/2^+[633]$ orbital, leading to a 14^- isomer at about 1373 keV [22] with a $\pi^3\nu$ configuration and an $E2$ decay with $f_\nu\sim15$. This can be compared with the $E2$ decay for the 6^+ isomer in ^{174}Hf (92% π^2 [20]) which has $f_\nu\sim17$ in line with the proposed analogy.

The difference in hindrances therefore support a probably dominant $\pi^3\nu$ configuration, for the new 15^- isomer in ^{180}Ta, matching the 6^+, π^2 configuration in the ^{178}Hf core. An open question relates to the explanation of the quantitative relationship between the configuration admixtures and the hindrance factors. In this context the new results for ^{180}Ta serve also to underline the relatively high hindrance of the decay of the 15^- isomer in ^{178}Ta, a property which can also be correlated with its relatively low energy compared to the yrast line [23].

Calculations of the spectrum of intrinsic and collective states in ^{180}Ta, constrained in part by the new results presented here, will be required to evaluate propositions about the behavior of low- and high-K states at medium excitation energies.

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