Structure and decay of a four-quasiparticle 15− isomer in 180Ta

G. D. Dracoulis, F. G. Kondev, A. P. Byrne, T. Kibédi, S. Bayer, and P. M. Davidson
Department of Nuclear Physics, RSPhysSE, Australian National University, Canberra ACT, 0200, Australia

P. M. Walker, C. Purry, and C. J. Pearson
Department of Physics, University of Surrey, Guildford, Surrey, GU2 5XH, England
(Received 12 October 1995)

A four quasiparticle high-K isomer with a meanlife of 45(2) μs has been identified at 1451 keV in 180Ta, populated in the 176Yb(11B,α3n)180Ta 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 176Ta, a difference which can be attributed partly to a change from the π9/2 [514]p9/2+ [624]3/2 − [514]5/2− [512] configuration in 178Ta to the π9/2− [514]7/2− [404]5/2− [402]9/2+ [624] configuration in 180Ta. The reduced hindrance factors for E2 decays from related four-quasiparticle isomers in the isotopes 176,178,180Ta match the hindrances of the corresponding E2 decays from component 6+ core states in the hafnium isotopes, 174,176,178Hf.

PACS number(s): 21.10.Tg, 21.10.Ky, 23.20.Lv, 27.70.+q

I. INTRODUCTION

Interest has focused recently on the production of the isotope 180Ta in stellar processes (e.g., [1–4]) and therefore on its structure. 180Ta 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 = 9− isomeric state at 75.3 keV which lives for more than 1.2 × 1015 y. The uncertainty of its production in nature, its proximity to stability makes it difficult to reach easily 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 180Ta 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 (176Ta being the heaviest accessible by reactions that involve only neutron evaporation with at least medium spin inputs) significant production of 180Ta was achieved through the 176Yb(11B,α3n)180Ta reaction in a bombardment whose main reaction channel proceeds via evaporation of four neutrons to 183Re. 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 180Ta level scheme.

II. EXPERIMENTAL CONDITIONS

Enriched targets of metallic 176Yb of thickness 4.6 mg/cm² were bombarded with pulsed 11B 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 ~1 ns wide pulses separated by 1.7 μs. All correlated γ-γ-time events within ± 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 ~ 12% of the 180Ta yield, which itself is only ~ 7% relative to the 182,183Re 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-
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; 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-
ties differ, as will be made clear below in discussing the configurations.

**A. Configuration of the \( J^\pi = 9^- \)**

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 \( \gamma \)-ray branching ratios \( \lambda \) from each state can be used to deduce the \((g_K-g_R)/Q_0\) values as given in Table I, from the formulas for strongly coupled rotational bands, proceeding through a calculation of the cascade mixing ratios:

\[
\frac{1}{\sigma^2} = \frac{1}{\lambda} \left[ \frac{E_\gamma(I\rightarrow I-1)}{E_\gamma(I\rightarrow I-2)} \right]^5 \left( \frac{IK20[I-2K]}{IK20[I-1K]} \right)^2 - 1,
\]

\[
\frac{g_K-g_R}{Q_0} = \frac{1}{\delta} \frac{0.933E_\gamma(I\rightarrow I-1)}{\sqrt{T-1}},
\]

where \( E_\gamma \) 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 \( K g_K = \Sigma g_\Omega \Omega_i \), 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 \((g_K-g_R)/Q_0\) if \( Q_0 \approx 7.0 \) and \( g_R \approx 0.30 \), 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 \((g_K-g_R) = 0.331(10)\).

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

\[
g = g_R + \frac{K^2}{I(I+1)}
\]

to extract a value of \( g_R = 0.23(1) \). This rather low value compared to an expected value of about 0.72\( A = 0.28 \) depends, of course, on the assumption that the quadrupole mo-

\[
\begin{array}{cccccc}
J^\pi & E_\gamma(\Delta I=1) & E_\gamma(\Delta I=2) & \lambda & \frac{(g_K-g_R)}{Q_0} & g_K-g_R \\
\hline
14^- & 289.4 & 557.7 & 0.71(16) & 0.062(7) & 0.431(50) \\
13^- & 268.6 & 515.8 & 0.79(6) & 0.0479(19) & 0.335(13) \\
12^- & 247.2 & 472.5 & 0.52(5) & 0.0464(26) & 0.325(18) \\
11^- & 225.2 & 428.2 & 0.24(4) & 0.0463(41) & 0.324(29) \\
\end{array}
\]

\( ^b \)Branching ratios \( \lambda = I(\Delta I=1)/I(\Delta I=2) \).

\( ^b \)Taking \( Q_0 = 7.0(1) \).

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

---

 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.
where $T^W$ is the Weisskopf single-particle estimate and $f$ is the corresponding hindrance factor. For the present interband transition, $\nu=4$. The lifetime in $^{178}$Ta corresponds to an $E2$ hindrance, $f = 4.4 \times 10^{6}$, 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 $\gamma$-ray lifetime for the 432 keV transition in $^{180}$Ta is 60(5) $\mu$s, which corresponds to $f=6.7 \times 10^4$ 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 of $^{180}$Ta to 1512 Ta. Calculations similar to those reported recently [18] predict two possible $15^-$ states in $^{178}$Ta, one from the $\pi 9/2^- [514] \\nu 9/2^+ [624] [7/2^- [514] 5/2^- [512]$ configuration (which we abbreviate to $\pi \nu \lambda$), the other from the $\pi 9/2^- [514] 7/2^- [404] 2^+ [402] \nu 9/2^+ [624]$ configuration (or $\pi \nu \lambda$). 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 $g_K^2 g_R$ values which suggest the $\pi \nu \lambda$ configuration is dominant but possibly with some admixture [11]. The $\pi \nu \lambda$ 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 $\nu^2$ or a $\pi^2$ configuration, coupled to the same $\nu [9^-]$ 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 $\mu$s) is believed to be 61% $\pi^2$, 39% $\nu^2$ (e.g., [19]) the $E2$ decay [19] has $f_\nu = 42$, while in $^{178}$Hf where the configuration is nearly pure $\pi^2$ [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 $\pi^2 \nu$ configuration and an $E2$ decay with $f_\nu \sim 15$. This can be compared with the $E2$ decay for the $6^+$ isomer in $^{174}$Hf (92% $\pi^2$ [20]) which has $f_\nu \sim 17$ in line with the proposed analogy.

The difference in hindrances therefore support a probably dominant $\pi^2 \nu$ configuration, for the new $15^-$ isomer in $^{180}$Ta, matching the $6^+$, $\pi^2$ configuration in the $^{176}$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.

**ACKNOWLEDGMENTS**

We are grateful to Dr. M. Dasgupta and Dr. S. Mullins who participated in some of the measurements.