Conversion coefficients and band assignments in ^{180}Ta

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The conversion coefficients for several bandhead decays in ^{180}Ta have been measured using pulsed-beam techniques and the ^{176}Yb(^{7}Li,3n)^{180}Ta reaction. The spin and parity of the 520 keV intrinsic state is established as 4^+ and several earlier assignments are confirmed. Two-quasiparticle configurations for the 520 and 592 keV states are discussed and following reanalysis of the band properties, a consistent interpretation is reached. The 520 keV 4^+ state is associated with the favored coupling of the $\nu 1/2^-[521] \otimes \pi 9/2^-[514]$ configuration while the 592 keV (5^+) state is identified with the $\nu 1/2^-[510] \otimes \pi 9/2^-[514]$ configuration.

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The nucleus ^{180}Ta has been the subject of considerable recent interest, driven partly by its status as a rare isotope, the only one found naturally as an isomer, and considerations with respect to its formation and survival in nucleosynthesis which may be affected by its nuclear structure properties. While not easily accessible by conventional reactions because of its proximity to stability, we have recently reported a comprehensive level scheme [1] as has an NBI group [2]. These studies are largely in agreement but there remain a number of spectroscopic uncertainties and some points of disagreement. The present study focuses on conversion coefficient measurements aimed at resolving some of these problems.

Medium-spin states in ^{180}Ta were populated using the ^{176}Yb(^{7}Li,3n)^{180}Ta reaction at 28 MeV, under essentially the same conditions as the previous study in this laboratory in which comprehensive γ-γ-time coincidence studies (and several reactions) were used to establish an extensive level scheme for ^{180}Ta [1]. At this energy, which is below the nominal Coulomb barrier, the main population is of states in ^{179}Ta (4n channel), ^{180}Ta (3n channel), and ^{177}Lu ($\alpha 2n$ channel). The beam from the ANU 14UD Pelletron accelerator was pulsed, with approximately 1 ns pulses, separated by 963 ns, to allow separation of the otherwise complex spectra by selection of appropriate time periods.

Electron measurements were carried out using the superconducting solenoidal spectrometer described by Kibédi *et al.* [3]. In its lens mode of operation, electrons of a specific momentum range are transported to a cooled Si(Li) detector, and the magnetic field is ramped between upper and lower limits to maximize the efficiency for the energy range of interest, in this case to encompass electrons corresponding to conversion of several transitions in ^{180}Ta, from approximately 200 to 500 keV. While the spectrometer axis is at 90° to the beam axis, the electron orbits which are selected correspond to emission from angles near $\pm 70°$. Gamma rays were measured simultaneously in a Compton-suppressed Ge detector placed at about $-135°$ to the beam axis. All data including the time of electrons and γ rays with respect to the pulsed beam and a measure of the instantaneous magnetic field were recorded in event-by-event mode. The data were subsequently sorted to produce γ-time or electron-time matrices for analysis.

Two measurements were made, the first with a 2.2 mg/cm^2 target of ^{176}Yb (as in the previous study [1]), the second with a 0.9 mg/cm^2 target.

The initial focus of the measurements was the 409 keV decay from a 53 ns isomeric state, which we hoped to separate from possible short-lived and long-lived contaminants. The upper panels of Fig. 1 show electrons and γ rays observed in a region ± 8 ns around the beam pulse. The 458 keV γ ray is predominantly from the $M1$ transition depopulating the $5/2^+[402]$ intrinsic state in ^{177}Lu [4], which gives rise to a strong K-electron line at an energy which would translate (because of the difference in binding energy) to a transition in tantalum at 462 keV. This falls close to the L-conversion line of the 409 keV transition in ^{180}Ta. The ^{177}Lu line, however, also has a very long-lived component because of feeding from the 150 μs, $1/2^+[411]$ intrinsic state; hence the contaminant can be reduced, as will be demonstrated below. The prompt electron lines of relevance to ^{180}Ta are K lines of the 316 and 338 keV transitions whose γ rays are known to be uncontaminated from the earlier γ-γ experiments. Although relatively weak, they give rise to clear K-electron lines. The 338 keV transition is from the 514 keV state discussed in [1] while the 316 keV transition was placed in a nonyrast (1^-) band as shown on the right of Fig. 2 which reproduces a modified version of part III of the ^{180}Ta level scheme from [1], with changes in spin and parity assignments implied by the new results, and with some errors corrected.[1]

The lower two panels of Fig. 1 show the corresponding electron and γ-ray spectra obtained by gating in the 8–200 ns region and after subtraction of (time-normalized) spectra from later decays. These constraints and manipulations remove the contaminations mentioned above and optimize the intensity of the 409 keV transition from the decay of the 520 keV 53 ns intrinsic state, which is also fed by a 72.2 keV transition from a 24 ns isomer at 592 keV, as shown in Fig. 2. The K, L, and M lines for the 409 keV transition are identifiable. The 409 keV γ ray is clear and no other γ rays,

[1]Several typographical errors and incorrect level and transition energies pointed out by the compilers have been remedied.

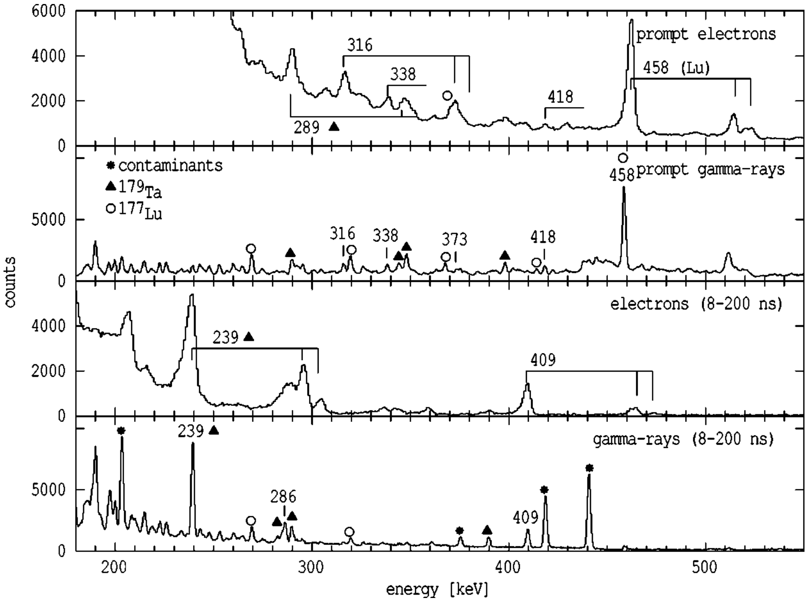

FIG. 1. Corresponding electron and γ-ray spectra in the time region around the beam pulse (upper two panels) and 8–200 ns after the beam pulse, with a longer time region subtracted. Note that the energy scale for the electron spectra has been adjusted so that lines which correspond to K conversion in tantalum appear at the corresponding γ-ray transition energy. The main K-, L-, and M-conversion lines are marked. The contaminant γ-ray lines marked are specific to this experimental arrangement and arise from neutron excitation of the material in the NaI(Tl) Compton suppression shield. They do not give rise to electron lines.

particularly transitions in other nuclear species, which could lead to contaminant electron lines, are observed. [The 419 keV and 441 keV γ rays are from inelastic neutron excitation of the NaI(Tl) suppression shield and do not produce electrons.] As a check on the purity of both K-electron and γ-ray lines from the 409 keV transition, the time spectra for each have been examined and reproduced using the lifetimes determined previously [1]. The results and fits (which use isomeric feeding of the same relative intensity for both electrons and γ rays) are shown in Fig. 3. These indicate that there is no significant contamination of either electron or γ-ray lines.

The other prominent transitions in the spectra have been identified as indicated in Fig. 1. These are largely from known lines in ^{179}Ta [5,6]. The 239 keV delayed line, in particular, is from the $5/2^+[402]\rightarrow 7/2^+[404]$ transition in ^{179}Ta which is known (from total conversion reported in [7]) to be mixed $M1/E2$, which is confirmed by the current measurements. For the ^{180}Ta lines, although partly contaminated, a limit is obtained for the conversion of the 286 keV dipole transition which depopulates the 7^- 44 ns isomer at 462 keV in ^{180}Ta (see Ref. [1]), which confirms the earlier $E1$ assignment. The measured conversion coefficients are listed in Table I. The 409 keV transition is unambiguously assigned

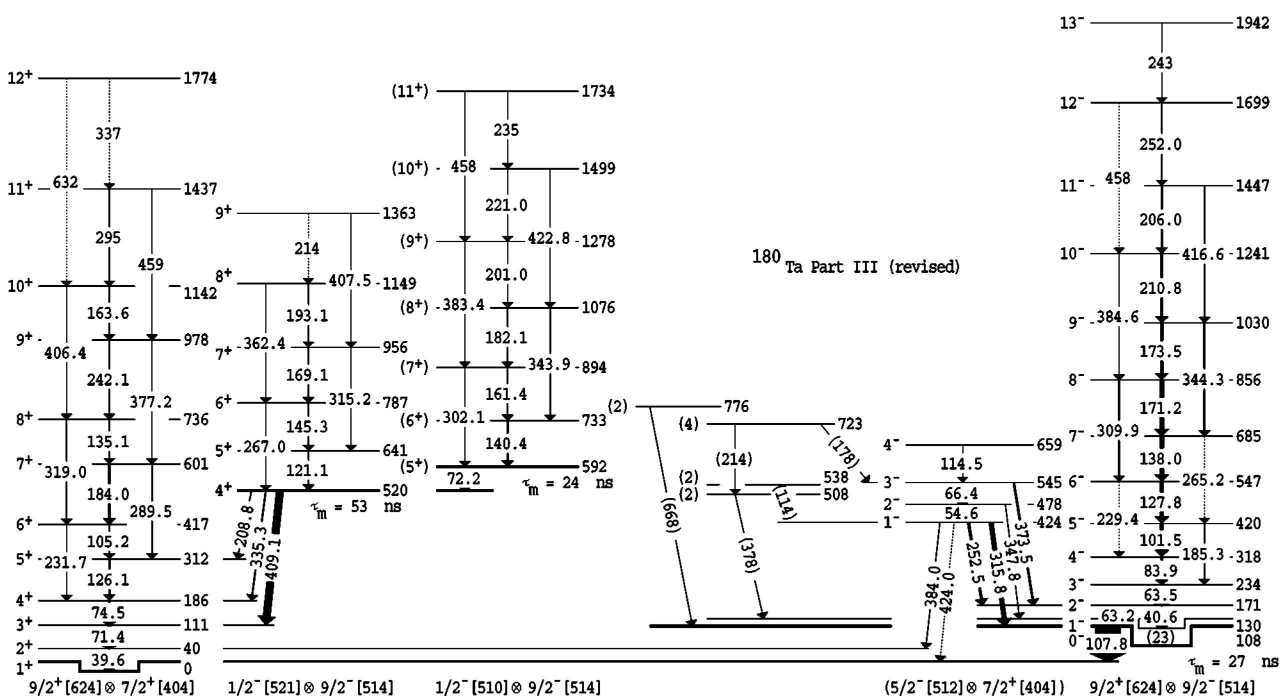

FIG. 2. Partial level scheme for ^{180}Ta showing selected bands with the new spin assignments, to be compared with Fig. 4 of [1]. (Note that some typographical errors have also been corrected.)

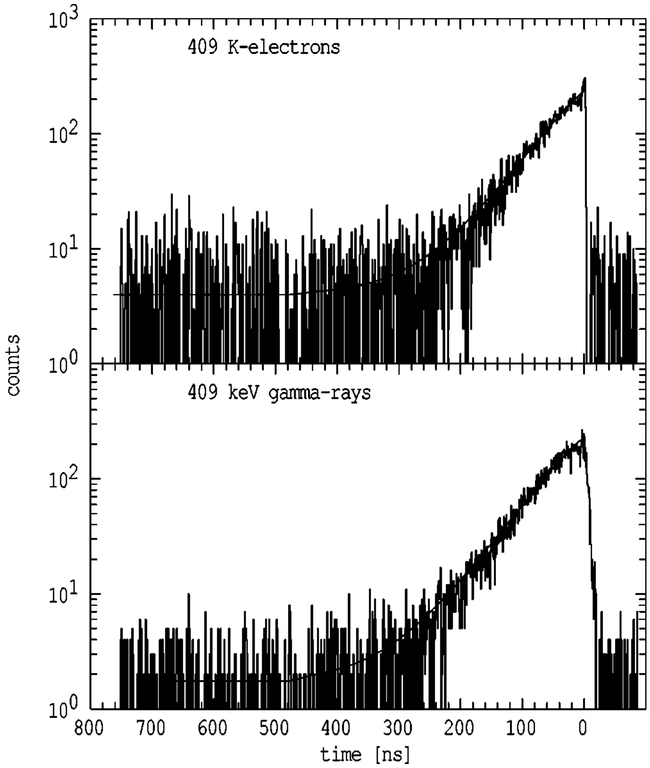

FIG. 3. Comparison of time spectra and fitted decay curves for the *K*-electron and γ-ray lines of the 409 keV transition.

as an $M1$, leading to a change from the spin and parity assignments and therefore configurations from the tentative ones discussed in Ref. [1].

We had previously assigned spin 4 to the 520 keV state on the basis of the measured angular distributions of the 409 keV transition and γ-ray branching of the 520 keV state. The suggested $M1$ or $M1/E2$ character of the 72.2 keV connecting transition constrained the 592 keV state to be of the same parity. Negative parity for both was tentatively favored because of the absence of an $E2$ transition to the 2^+ state of the 1^+ band which could occur in the case of a 4^+ assignment to the 520 keV state. Saitoh *et al.* [2] adopted a number of our assignments but preferred positive parity for the 520 keV state, largely on the basis of the properties of the excited

TABLE I. Measured conversion coefficients in ^{180}Ta compared with theoretical values.

E_γ	Shell	Experiment	Assignment	$E1$	$M1$	$E2$
286	K	$\leqslant(0.08)$	$E1$	0.0208	0.199	0.0638
316	K	0.23(3)	$M1$	0.016	0.152	0.0489
338	K	0.094(9)	$M1/E2$	0.0140	0.127	0.0411
409	K	0.082(7)	$M1$	0.0090	0.0767	0.0253
	L	$\leqslant 0.019(2)$		0.0014	0.012	0.007
	M	~ 0.004		0.00035	0.0026	0.0016
418	K	0.020(3)	$E2$	0.0086	0.0725	0.0240

rotational bands and the various configurations available. This argument will be readdressed below.

The conversion coefficient data now give an unambiguous $M1$ assignment for the 409 keV transition, leading to 4^+ for the 520 keV state and thus to a probable 5^+ assignment for the 592 keV state.

The multiquasiparticle calculations reported in Ref. [1] (see Table V of that paper) predict several pairs of states of positive parity in this energy region, specifically the $K = |\Omega_n \pm \Omega_p|$ partners from the $\nu 1/2^-[521\downarrow] \otimes \pi 9/2^-[514\uparrow]$ configuration, which would give 4^+ and 5^+ states at 496 and 655 keV, and similarly from the $\nu 1/2^-[510\uparrow] \otimes \pi 9/2^-[514\uparrow]$ configuration, which would give 4^+ and 5^+ states at 608 and 464 keV. The residual neutron-proton interaction favors parallel intrinsic spins and therefore the opposite couplings in the two cases. While the accuracy of the predictions for absolute energy of either pair could be uncertain by up to 100 keV, the ordering within each pair should be retained.

Analysis of the band properties leads to the conclusion that the favored state from each pair should be associated with the experimentally observed 4^+ and 5^+ states. The g_K values deduced from the measured in-band branching ratios obtained by both Refs. [1] and [2] are shown in Fig. 4. These have been extracted assuming $g_R = 0.26$ and $Q_0 = 6.79$ as previously [1]. While there is some systematic difference between the experimental results for the 4^+ band they are generally in agreement, at least within the uncertainties. The experimental results are compared with the theoretical values

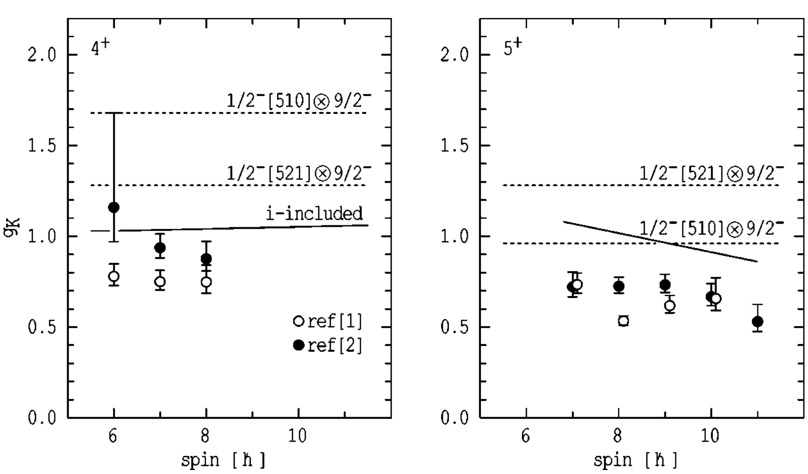

FIG. 4. Comparison of experimental g_K values from the γ-ray branching ratio data of [1] and [2] with various two-quasiparticle configurations discussed in the text.

shown by the dashed lines in the figure, given by the strong coupling equation

$$g_K = \frac{1}{K}(\Omega_n g_{\Omega_n} \pm \Omega_p g_{\Omega_p}),$$

with the sign depending on the coupling and taking $g_\Omega(9/2^-[514]) = +1.28$, $g_\Omega(1/2^-[521]) = +1.3$, and $g_\Omega(1/2^-[510]) = -1.9$. The latter two values are somewhat uncertain but the predictions are not very sensitive to them because of the small Ω projection.

As can be seen from the figure, the predicted g_K for the 4^+ state from the configuration containing the $1/2^-[510]$ neutron and the 5^+ state containing the $1/2^-[521]$ neutron (i.e., the energy-*unfavored* coupling in each case) are both much larger than experiment. The predicted g_K values for the remaining two (energy-*favored*) couplings are still significantly larger than experiment; however, a further correction is required since both associated rotational bands show significant alignment. When that is included, the predicted values are changed by a component approximately equal [8] to

$$-\frac{\Sigma(g_{\Omega_j} - g_R) i_j}{\sqrt{I^2 - K^2}},$$

where i_j is the alignment component from each orbital which sum to the total experimental alignment (Fig. 14 of Ref. [1]) at spin I. Since the $g_\Omega - g_R$ values for both $1/2^-[521]$ and $9/2^-[514]$ orbitals are nearly equal, the numerator reduces to $(g_K - g_R) \times i_{expt}$ for the 4^+ configuration, leading to a lowering of the effective g value as given by the solid line in the left panel of Fig. 4. This gives better agreement and supports the proposed configuration, which concurs with the configuration favored (if positive parity) in [2]. The situation for the 5^+ configuration is less clear because the $g_\Omega - g_R$ value for the $1/2^-[510]$ neutron is large and of opposite sign to that of the $9/2^-[514]$ proton; hence the magnitude and sign of the correction depend on how the alignment is apportioned between the two orbitals. If all of the alignment is attributed to the proton, a reduction comparable to that shown for the 4^+ state is obtained, resulting in agreement with experiment. The solid curve in Fig. 4, however, is the result assuming a constant alignment of $0.8\hbar$ for the neutron with the balance of the observed alignment attributed to the proton. This does not improve the agreement with experiment although the residual discrepancy is similar to that for the 4^+ state, an overestimate of approximately 0.1–0.2 in g_K.

The measured conversion coefficient for the 316 keV transition confirms $M1$ multipolarity and therefore negative parity for the 424 keV state. It also secures indirectly a 2^- assignment for the 478 keV state and 3^- for the 545 keV state. The lowest 1^- intrinsic state expected is that from the $(\Omega_n - \Omega_p)$ coupling of the $\nu 5/2^-[512\uparrow] \otimes \pi 7/2^+[404\downarrow]$ configuration which is predicted at 451 keV, close to the observed energy. The reliability of the energy prediction, in this case, can be gauged by the fact that its $(\Omega_n + \Omega_p)$ partner was predicted at 563 keV in good agreement with an observed 6^- state at 573 keV, as detailed in Ref. [1].

Reassignment of the 520 keV state above also opens the question of the whereabouts of the 4^- state from the $\nu 1/2^-[521\downarrow] \otimes \pi 7/2^+[404\downarrow]$ configuration with which it was originally associated. Its predicted energy was ~534 keV but there are several predicted states in this energy region and a number of unassigned states, including probable spin 4 states at 723 keV and 659 keV in Fig. 2.

Conversion coefficients have been measured for several transitions in ^{180}Ta, resulting in firm spin and parity assignments for several intrinsic states, especially the 4^+ and 5^+ states at 520 and 592 keV. A consistent interpretation of the band properties and proposed configurations has been reached, albeit with some residual discrepancies between predicted and measured g_K values.

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