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Interpretation of the excitation and decay of ^{180}Ta^m through a $K^\pi=5^+$ band

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The production and survival of ^{180}Ta in stars presents a nuclear structure and astrophysics puzzle. From earlier work in the laboratory, photon scattering from the 9^-, 75 keV isomeric state has been shown to result in eventual de-excitation to the relatively short-lived 1^+ ground state, through intermediate states whose character is uncertain. It is suggested here that the lowest observed photon resonances match the energies of known states in the rotational band based on the recently assigned $K^\pi=5^+$ state at 592 keV, states which are accessible by $E1$ excitation from the 9^- isomer. Analysis of the previously observed resonance strengths and the known in-band properties implies γ-ray $E1$ transition probabilities which are stronger than expected given the nominal K forbiddenness. Predicted widths for "back"-decay to the 9^- isomer and its rotational band are calculated and shown to be significant. Their observation would have implications for the proposed associations and mixing effects above the yrast line.

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The uniqueness of ^{180}Ta^m, the only naturally occurring nuclear isomer (with an excitation energy of 75 keV and a long mean-life of $\tau_m > 1.2\times 10^{15}$ y), gives it a special place in nuclear-structure and nuclear-astrophysics investigations. Its stellar nucleosynthesis has been the subject of conjecture (see, for example, the summary by Schlegel *et al.* [1]) and there is the possibility that it could be destroyed in the very same stellar photon bath in which it may be synthesized. Early measurements of the ^{180}Ta^m (γ,γ') reaction, in fact, yielded large cross sections leading from the 9^- isomer to the ground state [2–5] implying excitations through an intermediate state (or states) and subsequent decay that would mitigate against its survival in stellar processes. The additional implication, that the inelastic excitation required K mixing to allow for the change of eight units in the quantum number K (the projection of the spin on the nuclear deformation axis) to pass from the $K^\pi=9^-$ isomer to the $K^\pi=1^+$ ground state, provided one of the imperatives for detailed studies of its nuclear structure. Since the nucleus ^{180}Ta is prolate deformed but axially symmetric, the angular-momentum projection, K, on the symmetry axis should be approximately conserved [6].

Recent work on the spectroscopy of ^{180}Ta [7–9] and more precise studies of photon excitation [10] have given information which may provide the ingredients for a more detailed understanding of the excitation and decay process. The general difficulty faced, is that while the spectroscopic studies are effective in identifying yrast states which are predominantly of high-K, the states involved in the (γ,γ') excitations which eventually lead to the $K^\pi=1^+$ ground state, are likely to be nonyrast and of relatively low-K.

With the benefit of recent reassignment of parities for some known nonyrast states [9] it is now possible to identify a path via a band of medium-K states accessible initially by $E1$ excitation from the 9^- isomer. The previously measured photon-scattering cross sections can then be analyzed to extract decay widths and the implied $E1$ strengths. Taken in combination with the known in-band decay properties of the proposed intermediate states, this analysis leads to the prediction of "back" decays whose intensities are significant and, in principle, measurable.

The lowest photon energy identified to date, which is able to deplete ^{180}Ta^m through the short-lived ($\tau_m=12$ h) ground state, has been measured to be 1010(10) keV [10], corresponding to an excitation energy in ^{180}Ta of 1085(10) keV. The same experimental study has observed subsequent resonances at photon energies of 1220(30) and 1430(30) keV [11], corresponding to excitation energies of $\sim$1295 and $\sim$1505 keV.

Since the most likely photon character is electric dipole ($E1$), the only isolated states which are expected to be strongly excited from the 9^- isomer would have spin and parity, I^π of 8^+, 9^+, and 10^+. Figure 1 shows the known positive-parity bands in ^{180}Ta incorporating the recent reassignments, based on conversion-electron measurements, for the $K^\pi=4^+$ and 5^+ bands [9]. Superimposed on this figure are the excitation energies [the group of asterisks labeled (A)] implied by the lowest three photon-scattering resonances observed by Belic *et al.* [10,11], assuming they are in order of increasing spin. These fall very close (within experimental uncertainties) to the energies of the 8^+, 9^+, and 10^+ members of the band based on the 592 keV, $K^\pi=5^+$ state. This, and the fact that the K value of the band is midway between those of the isomer and the ground state, is the basis of the associations proposed here. The properties of the lowest resonance are the most precisely determined to date [10], so we begin with its analysis.

Belic *et al.* [10] determine a resonance cross section of 0.057(4) eV.b for the 1010(10) keV photoexcitation, which we associate with the 1076 keV 8^+ state. (Details of the level scheme are shown in Fig. 2.) In the case of an isolated resonance, the Breit-Wigner form of the energy and angle-integrated cross section (s_E) for inelastic photon excitation from an initial state with angular momentum I_m to an inter-

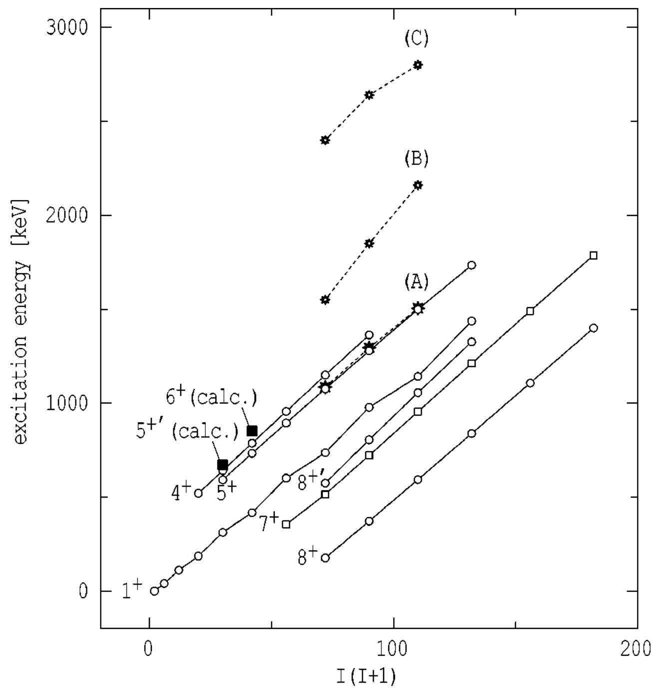

FIG. 1. Excitation energies of known positive-parity bands in ^{180}Ta. The asterisks indicate the excitation energies corresponding to known photon-scattering resonances [10,11] plotted assuming spins of 8, 9, and 10, in sequential groups labeled (A), (B), and (C), as discussed in the text. [Groups (B) and (C) are preliminary and have been communicated [11] as 1550, 1850, and 2160 keV, and 2400, 2640, and 2800 keV, with uncertain errors. The grouping is our construction.] The calculated energies of the second $K^{\pi}=5^{+}$ bandhead and the first $K^{\pi}=6^{+}$ bandhead [7] are also indicated.

mediate state I_a, involves the statistical factor $g=(2I_a+1)/(2I_m+1)$, the photon wavelength λ, and the decay widths [12,13], with

$$s_E=\int_{E_R}\sigma dE=\frac{\lambda^2}{4}g\frac{\Gamma_m\Gamma_0}{\Gamma}, \qquad (1)$$

where the total decay width of the intermediate state is Γ, the decay width for all paths that reach the 1^+ ground state is Γ_0, and Γ_m is the width for decay back to the initial (9^-) state.

It is evident that $\Gamma_0<\Gamma$, and thus the cross section of 0.057(4) eV.b measured by Belic *et al.* [10] for a transition energy of 1010(10) keV translates to a width $\Gamma_m>1.68\times10^{-5}$ eV. (Note that Belic *et al.* also quote a 20% systematic error which we ignore for this discussion.) Since we consider the proposition that the states being excited are members of a previously observed $K^{\pi}=5^{+}$ rotational band whose decay properties are known, or can be reliably estimated, Γ_0 (and its components) can be specified. Furthermore, in the absence of any other decay paths except for the in-band decays, then $\Gamma=\Gamma_0+\Gamma_m$ where Γ_m, the "back"-decay width, has to be consistent with the proposed excitation.

In these circumstances rearrangement of Eq. (1) gives

$$\Gamma_m=\frac{s_E}{(\lambda^2/4)g}\Bigg/\left[1-\frac{s_E}{(\lambda^2/4)g}\frac{1}{\Gamma_0}\right]. \qquad (2)$$

As will be shown below, the 1076 keV state has Γ_0, the sum of all in-band decays (γ-ray and internal conversion) equal to 3.85×10^{-5} eV, which from Eq. (2) gives $\Gamma_m(1076\ \text{keV})=2.98\times10^{-5}$ eV. Now, the decay width for an $E1$ transition of single-particle (Weisskopf) strength is given by

$$\Gamma_W(E1)=6.75\times10^{-2}A^{2/3}E_{\gamma}^{3}\quad[\text{eV}] \qquad (3)$$

for transition energy E_{γ} in MeV. This gives 2.15 eV for a 1 MeV single-particle transition. The decay width of 2.98×10^{-5} eV therefore corresponds to a transition strength of 1.39×10^{-5} single-particle units (W.u.), or equivalently, a hindrance $F_W=7\times10^4$. While this hindrance is substantial, it is less than would be expected given the K mismatch, at least superficially. Allowed $E1$ transitions between rotational bands have hindrances which may vary substantially because of structure effects (such as specific configuration changes) but normally they would fall in the range of 10^4 to 10^5. *Additional* hindrance is expected for transitions which are K forbidden [6,14]. In the present case, with a K change of four units, and a multipolarity of unity, the transition is threefold K forbidden, which would normally carry an additional hindrance of about 10^2 per degree of forbiddenness [14]. While there is considerable variation and uncertainty in such estimates, the present hindrance value (7×10^4) must be seen as marginal if it is to be understood in this context.

One effect which will modify hindrances is the specific K mixing associated with the configurations of the states involved. The 9^- configuration, for example, consists of the neutron (ν) and proton (π) Nilsson-model orbitals $\nu9/2^+[624]\otimes\pi9/2^-[514]$. The $\nu9/2^+[624]$ orbital is from an $i_{13/2}$ neutron, which will have significant K mixing due to Coriolis coupling. Estimates of this mixing using the particle-rotor model give amplitudes of about 0.30 for a $K=8$ admixture in the 9^- state, with slightly higher values in the higher-spin members of the same band. Similarly, the 5^+ band, with probable configuration $\nu1/2^-[510]\otimes\pi9/2^-[514]$, itself shows the effects of rotation alignment [7] which is a manifestation of Coriolis mixing, hence it must also contain significant K admixtures. The systematic effect of such mixtures on $E1$ rates for a given configuration change has been documented for specific cases (e.g., Ref. [15]).

We can also look to cases involving the same configuration change as occurs between the 5^+ band and the 9^- band as a further guide; the only comparable $E1$ transitions in the region are in ^{181}Hf, where a $9/2^+[624]$, 80 μs isomer decays to members of the $1/2^-[510]$ band [16]. Note that this involves the same level of K forbiddenness. In ^{181}Hf, the hindrance factors are in the range $F_W=10^{10}-10^{11}$, approximately the strengths that would be expected normally. While the different Fermi levels ($N=107$ for ^{180}Ta, and $N=109$ for ^{181}Hf) may have an effect, and the Coriolis K-mixing con-

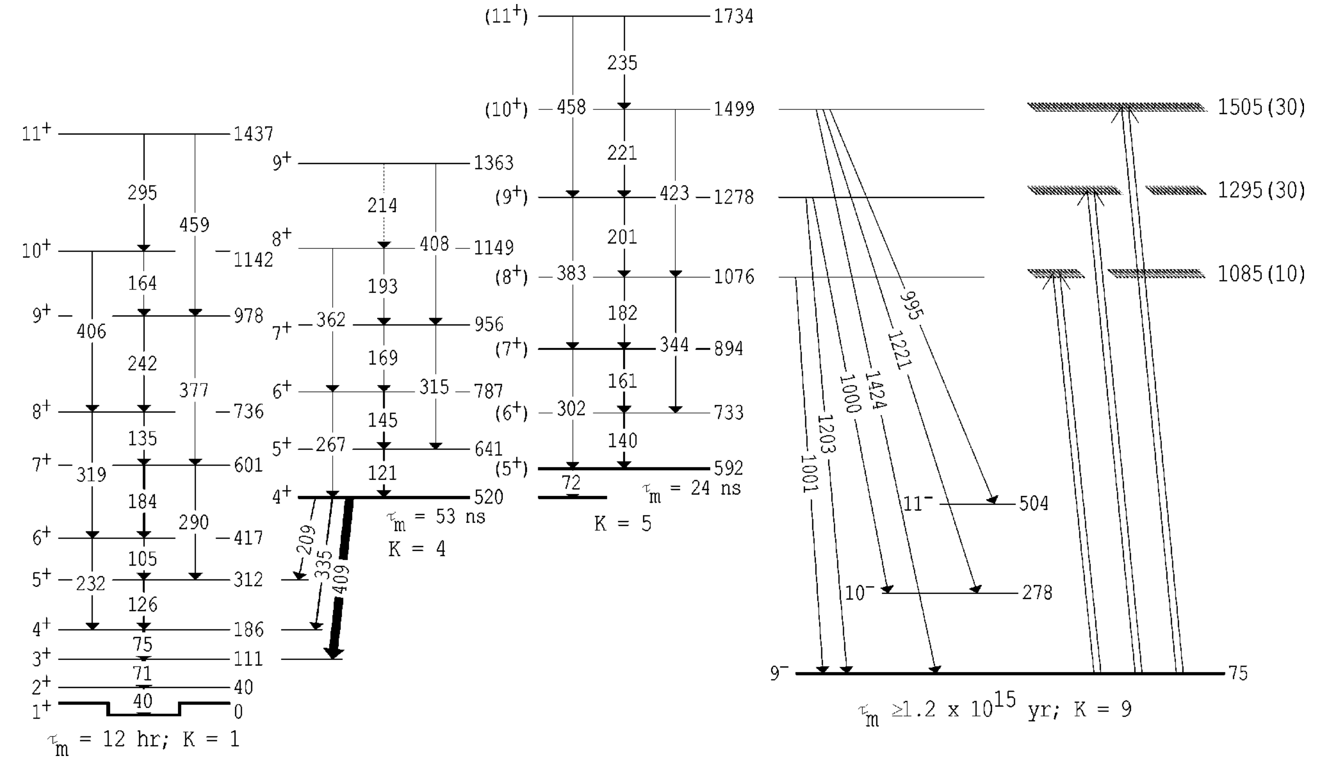

FIG. 2. Partial level scheme for ^{180}Ta, adapted from Ref. [9], with energies in keV. The low-energy photoactivation transitions [10,11] from the long-lived isomer are illustrated on the right-hand side. They correspond to photon resonance energies of 1010(10) keV, ~1220 keV, and ~1430 keV. The corresponding *excitation* energies are 75 keV higher. Also shown are the *predicted* $E1$ transitions decaying from the $K^\pi=5^+$ band back to the $K^\pi=9^-$ band.

ditions will not be precisely the same in both nuclei, the purported ^{180}Ta transitions are apparently orders of magnitude faster.

The major and perhaps most pertinent difference between these cases, however, is that the upper states in ^{180}Ta are very nonyrast, in contrast to the states in ^{181}Hf. Level-density effects (random mixing due to overlapping levels) may be the key feature, as these are already known to reduce hindrances for $E2$ transitions from states, depending on their position above the yrast line [17].

Independent of the explanation, to be consistent with the inferred $E1$ excitation strength, this treatment also implies a significant γ-ray branch from the 1076 keV 8^+ state back to the 9^- isomer. As is clear from Figs. 1 and 2, the next two resonances also match (within the uncertainties) the energies of $K^\pi=5^+$ band members. The situation is summarized in Table I (and schematically in Fig. 2) where the decay widths are listed for all states of the $K^\pi=5^+$ band which might be accessible by $E1$ excitation from the 9^-, 75 keV isomer.

The decay widths within the rotational band are estimated using a combination of the rotational-model formulas for a band with $K=5$, and the known in-band γ-ray branching ratios from which the other band properties associated with the intrinsic configuration (g_K-g_R values, mixing ratios, etc.) have previously been extracted [7,9]. A quadrupole moment of 6.79 e b, consistent with that measured [18] for the $K^\pi=9^-$ state, has been assumed. Also included are the total widths for each branch (column seven of the table) including conversion, estimated from calculated conversion coefficients [19] and where necessary the mixing ratios implied by the rotational-band analysis [7,9].

Note that neither the in-band γ-ray widths, nor the conversion-electron widths (the sum of which give Γ for each state) are dependent on any assumptions about the strengths of the $E1$ decay paths. The $E1$ width for the 1076 keV state is extracted from the photon-scattering cross-section data, as discussed above, and all other $E1$ widths in Table I have been estimated assuming the same hindrance of $F_W=7\times10^4$. As can be seen from the table, there are several $E1$ decay paths possible from each of the 9^+ and 10^+ members of the $K^\pi=5^+$ band, which would also result in significant γ-ray branches back to the 9^- band. These are illustrated schematically in Fig. 2.

Furthermore, the results of Table I can be used in Eqs. (1) and (2) to predict the cross sections which should be observed at resonance energies corresponding to the 9^+ and 10^+ states. Application of these formulas gives cross-section predictions of 0.073 eV.b and 0.089 eV.b at photon energies of 1203 keV and 1424 keV, respectively. Belic *et al.* [10] observe a clear second discontinuity at 1220(30) keV in their (γ,γ') data and subsequent analyses [11] for it and a third resonance at 1430(30) keV, give even larger cross sections (0.27 and 0.24 eV.b) than those predicted here. If the large cross sections are substantiated, then they are at the limit of what can be understood within the present scenario, i.e., by only lowering the hindrances for the $E1$ transitions (to, say, $F_W\leqslant10^4$) which is equivalent to increasing Γ_m. It may also be necessary to consider mechanisms for increasing Γ_0 (and

TABLE I. Partial γ-ray decay widths for the $K^{\pi}=5^{+}$ band at 592 keV in ^{180}Ta and predicted $E1$ branches to the $K^{\pi}=9^{-}$ band. Total widths including conversion are shown in the last column.

Initial state	I_i^{π}	I_f^{π}	$M\lambda$	E_{γ} (keV)	Γ_{γ} [a] (10^{-5} eV)	$(1+\alpha_T)\Gamma_{\gamma}$ (10^{-5} eV)
1499	10^{+}	8^{+}	$E2$	423	8.79	9.06
		9^{+}	$M1/E2$	221	4.73	6.88
		9^{-}	$E1$	*1424*	*8.7* [b]	*8.7*
		10^{-}	$E1$	*1221*	*5.5*	*5.5*
		11^{-}	$E1$	*995*	*3.0*	*3.0*
1278	9^{+}	7^{+}	$E2$	383	4.29	4.47
		8^{+}	$M1/E2$	201	2.74	4.34
		9^{-}	$E1$	*1203*	*5.2* [b]	*5.2*
		10^{-}	$E1$	*1000*	*3.0*	*3.0*
1076	8^{+}	6^{+}	$E2$	344	1.75	1.85
		7^{+}	$M1/E2$	182	1.15	2.00
		9^{-}	$E1$	*1001*	[*2.98*] [b]	[*2.99*] [b]

[a] Calculated with $K=5$ and $Q_0=6.79e$ b for the $\Delta I=2$ $E2$ transitions, combined with measured branching ratios to obtain the $\Delta I=1$ transitions; predicted $E1$ widths are in italics, assuming a strength of 1.4×10^{-5} W.u.

[b] This decay width back to the isomer corresponds to Γ_m in Eqs. (1) and (2). The value [*2.98*] is obtained from the cross section given by Belic *et al.* [10].

therefore Γ) implying decay routes to the 1^{+} ground state additional to the in-band rotational paths shown in Table I and Fig. 2. Such branches become more probable as the excitation energy increases.

As stated earlier, even with the $E1$ strengths restricted to that obtained for the first resonance, all predicted $E1$ γ-ray branches back to the 9^{-} band are significant. Out-of-band $E1$ transitions are not unusual, but their importance in the present context is that their observation could establish conclusively the relationship between the photon-scattering resonances and the states observed in high-resolution γ-ray spectroscopy. Their presence is both a stringent test of the internal consistency of the proposition, and a test of the transition strengths implied. Such branches were not assigned in the work to date [7–9] and while this might imply that the $E1$ strengths should be lower (which would then be in conflict with the cross sections), at this stage the nonobservation can be attributed to experimental limitations. The members of the $K^{\pi}=5^{+}$ band are well above the yrast line, and their very weak population in in-beam experiments makes very difficult the γ-γ gating on transitions feeding into each state. Such gating is necessary to identify properly the relatively high-energy $E1$ branches. Experiments planned with more efficient γ-ray detector arrays should reach the sensitivity required to test specifically the precise predictions made here, or at least to quantify the $E1$ strengths further. The match between the location of resonances in the photon-scattering experiments and the members of the known $K^{\pi}=5^{+}$ band is striking and we emphasize that, even if the $E1$ transitions turn out to be more hindered, they must occur at some level, which will result in resonance behavior. (Note also that very recent Coulomb excitation studies of ^{180}Ta [20] have suggested a deexcitation path through the $K^{\pi}=5^{+}$ bandhead, but without identification of the specific states excited.)

It should also be emphasized, as illustrated by Fig. 2, that while there are other positive-parity states known which decay to the ground state, and which are, in principle, accessible by $E1$ excitation, only the $K=5$ band seems to be populated in the photon scattering. This is consistent with the need to minimize the change in K. For example, the lowest-energy 8^{+} state that decays to the short-lived $K=1$ ground state is at 736 keV [7] equivalent to an isomer photoactivation energy of only 661 keV. From the total angular-momentum and parity values, which permit an $E1$ transition from ^{180}Ta^{m}, it might be expected that the stellar photon bath would destroy ^{180}Ta^{m} through this state. However, the $E1$ transition would be sevenfold K forbidden, and the transition hindrance factor would be expected to be much greater than that observed for transitions to the $K=5$ band. Thus, the ability of ^{180}Ta^{m} to survive in stars may be attributed, at least in part, to axially symmetric nuclear deformation and the consequent influence of the K quantum number.

Finally, still higher-energy resonances have recently been observed by Belic *et al.* [11] and these can be arranged in sets of three, indicated by the groups of asterisks labeled (B) and (C) in Fig. 1. The nonyrast experimental states in the higher-energy region are probably inaccessible to conventional spectroscopy, but it should be noted that the roughly monotonic energy spacing is consistent with band structure. Further, group (B) falls in the region expected for the band members of the second $K^{\pi}=5^{+}$ band or the first $K^{\pi}=6^{+}$ band (from the unfavored couplings of the $\nu1/2^{-}[521]\otimes\pi9/2^{-}[514]$ and $\nu3/2^{-}[512]\otimes\pi9/2^{-}[514]$ configurations) predicted by calculations [7] and indicated in Fig. 1.

In summary, the comparison of recent photon-scattering and γ-ray spectroscopy data enables discrete levels from a band with $K^{\pi}=5^{+}$ to be identified as intermediate states in an excitation/decay process. The lowest of these is at 1076 keV. If its identification with the 1085(10) keV resonance is correct, then a 1001 keV, $E1$ back-decay transition is predicted. Similar transitions are predicted from the 9^{+} and 10^{+} states of the same rotational band whose energies also match photon resonances, if the equivalent $E1$ hindrances are preserved. Observation of such transitions would serve both as confirmation of the proposed associations and as a quantitative test of the implied $E1$ strengths and K hindrances. Importantly, the $E1$ transitions implied by these analyses are significantly less hindered than expected given the K forbiddenness. The ability to match nonyrast rotational states identified in spectroscopy with individual photon-scattering resonances may provide a means of probing, quantitatively, K-mixing well above the yrast line.

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