ELECTROMAGNETIC COUPLING BETWEEN THE ISOMERIC STATE AND THE GROUND STATE IN ^{180}Ta *

Petr Alexa

Institute of Chemical Technology
Technická 5, 166 28 Prague 6, Czech Republic

Ivana Hřivnáčová

Institute of Nuclear Physics
250 68 Řež near Prague, Czech Republic

and Jan Kvasil

Charles University
V Holešovičkách 2, 180 00 Prague 8, Czech Republic

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We review proposed production mechanisms of ^{180}Ta during the nucleosynthesis process. In this nucleus, an electromagnetic coupling between the ground state and the 9^- isomeric state may strongly affect the produced abundances. Possible theoretical electromagnetic paths between the ground state and the isomeric state are discussed in the framework of the two-quasiparticle-plus-phonon model and the standard axially-symmetric rotor model including Coriolis mixing.

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1. Introduction

^{180}Ta is the heaviest among the only nine odd-odd nuclei present in nature (^{2}H, ^{6}Li, ^{10}B, ^{14}N, ^{40}K, ^{50}V, ^{138}La, ^{176}Lu and ^{180}Ta). Five of the odd-odd nuclei are stable (^{2}H, ^{6}Li, ^{10}B, ^{14}N, ^{50}V), three unstable, but long-lived (^{40}K, ^{138}La, ^{176}Lu) with half-lives $10^9 \div 10^{11}$ y.

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^{180}Ta does not occur naturally in its 1^+ ground state, since it decays to ^{180}Hf and ^{180}W (half-life 8.15 h). It is the only nucleus present in nature in an isomeric state (9^-) at an energy of 75.3 keV. For its half-life an experimental lower limit of 1.2×10^{15} y was obtained [1]. Gamma transitions from the isomer to the ground-state band are hindered by their high multipolarity. One can estimate the theoretical half-life for gamma transitions to be 10^{27} y [2]. $^{180\mathrm{m}}$Ta has a very small abundance. Only 0.012% of natural Ta consists of $^{180\mathrm{m}}$Ta, the rest is ^{181}Ta. The short-lived ground state was identified in 1930's, the isomer remained undiscovered until 1954 [3], while its spin and placement were uncertain until about 1979 [4].

2. Origin of $^{180\mathrm{m}}$Ta

It is of astrophysical interest to reproduce the solar abundance of $^{180\mathrm{m}}$Ta (3 units relative to 10^{12} units for Si, which is far smaller than the solar abundances of the neighboring nuclei — see Fig. 2 in [5]). It is clear from Fig. 2 in [5] that $^{180\mathrm{m}}$Ta is bypassed by the main s-process since ^{180}Hf is stable. $^{180\mathrm{m}}$Ta production in the r-process and the p-process is shielded by stable ^{180}Hf and ^{180}W, respectively. This implies that the explanation of the $^{180\mathrm{m}}$Ta abundance presents a fine test for nucleo-synthesis models.

Sometimes one reads that the production mechanisms of $^{180\mathrm{m}}$Ta are unknown and its abundance remains unexplained. This is not exactly true. $^{180\mathrm{m}}$Ta can be produced in the following processes [6] (updated, see also Fig. 1):

1. main s-process: in the s-process via ^{179}Hf(n,γ), 8^- isomer in ^{180}Hf at 1.142 MeV with 0.31% branching to $^{180\mathrm{m}}$Ta [7], about 5% of the observed $^{180\mathrm{m}}$Ta can be accounted for;

2. side s-process: in the s-process via ^{179}Hf* decaying to ^{179}Ta, ^{179}Ta(n,γ), 15–80% of $^{180\mathrm{m}}$Ta can be produced depending on the unmeasured branching ratio of the capture state in ^{180}Ta at 6.645 MeV to the isomer and to the ground state, on the effective electron density at the s-process site and on the s-process temperature (an effective s-process temperature assumed in the interval $(2.9 \div 3.3) \times 10^8$ K [6], experimental limits from branching of the mediating level in ^{176}Lu are $(2.4 \div 4.4) \times 10^8$ K [8]; stellar models predict sizeable $^{180\mathrm{m}}$Ta production during helium burning in the second neutron burst (duration 3 y): 75% of $^{180\mathrm{m}}$Ta for $T \approx 3.2 \times 10^8$ K [6]);

3. r-process: the r-process leading to ^{180}Lu decaying to the 8^- isomer in ^{180}Hf yields only a small amount of $^{180\mathrm{m}}$Ta since the experimental branching to the 8^- isomer in ^{180}Hf is compatible with zero;

4. for other proposed mechanisms, namely ν-process ^{181}Ta(ν, n) and Γ-process ^{181}Ta(γ, n), no reasonable estimates exist.

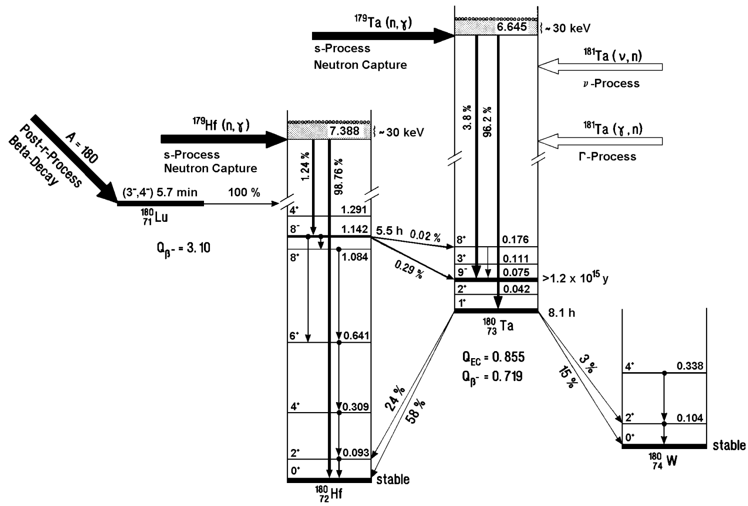

Fig. 1. Possible production processes of $^{180\mathrm{m}}$Ta (energies are given in MeV) [6] (updated).

In the s-process site thermal photons may excite higher-lying levels which then decay back either to the ground state or to the isomer. This photon coupling between the isomer and the ground state via intermediate levels below ≈ 1.5 MeV (which can be reached at typical s-process temperatures) [6] could substantially reduce the predicted s-process abundance of $^{180\mathrm{m}}$Ta. If it were possible for $^{180\mathrm{m}}$Ta and ^{180}Ta to come into thermal equilibrium the effective half-life of $^{180\mathrm{m}}$Ta at the s-process site would be much shorter than its laboratory value (in fact comparable with the half-life of ^{180}Ta, increasing up to ≈ 30 hr under stellar conditions due to the low probability for electron capture, since the number of bound atomic electrons is substantially reduced). Because of its importance concerning the s-process explanation of the $^{180\mathrm{m}}$Ta origin efforts are underway to find such a low lying mediating level. This search has been performed both experimentally and theoretically.

3. Experimental search for a mediating level in ^{180}Ta

Here we present a short list of two experimental approaches:

1. photoexcitation, $^{180\mathrm{m}}$Ta(γ, γ'):

   (a) Norman *et al.* (1983) [9] used intense ^{60}Co and ^{137}Cs sources and a natural Ta target (negative result);

(b) Yoshihara *et al.* (1986) [10] used a ^{60}Co source and an enriched (0.26%) Ta target (negative result);

(c) Collins *et al.* (1990) [11] used the bremsstrahlung facility at DALINAC and a natural Ta target: Mediating levels at 2.8 and 3.6 MeV were identified. These lie too high to be populated in the stellar photon bath at typical *s*-process temperatures.

(d) Kneissl *et al.* (1997,1998) [12] used the Stuttgart DYNAMITRON facility with both enriched (5.6%) and natural Ta targets. Ground-state decays as a sign of mediating level were observed down to $E_\gamma = 1.7$ MeV and 1.05 MeV [13] for natural and enriched targets, respectively. Only preliminary results are published, data analysis is in progress.

2. Coulomb excitation of $^{180\mathrm{m}}$Ta (activation experiments):

(a) Schlegel *et al.* (1994) [14] used ^{32}S and ^{36}S beams bombarding a thick natural Ta target: Results are consistent with a mediating level lying between 0.1 and 1 MeV. Nevertheless, the analysis of the experimental data is dependent on uncertain transfer cross-sections because the effect of ^{181}Ta(^{32}S,^{33}S) and ^{181}Ta(^{36}S,^{37}S) must be subtracted.

(b) Loewe *et al.* (1997,1998) [5] used ^{36}S and ^{64}Ni beams bombarding enriched Ta targets: A mediating level was found at ≈ 1.3 MeV.

4. Theoretical search for a mediating level in ^{180}Ta

4.1. Model description

For a theoretical description of ^{180}Ta the standard axially symmetric rotor model including Coriolis mixing is used [15]. The intrinsic degrees of freedom are described in the framework of the two-quasiparticle-plus-phonon model (TQPM) [16]. The model Hamiltonian is given by a deformed axially symmetric average field (Nilsson potential with parameters from [17]), monopole pairing interaction (proton and neutron gaps from [17]) and a long-range residual multipole-multipole interaction:

$$\hat{H}_{\mathrm{mm}} = -\frac{1}{2} \sum_{\lambda=2,3;\mu} \kappa_0^{(\lambda\mu)} \hat{Q}_{\lambda\mu} \hat{Q}_{\lambda-\mu} \ . \tag{1}$$

The strength constants, $\kappa_0^{(\lambda\mu)}$, are fitted to experimental energies of the $\lambda\mu$–vibrational states of the even-even core or from systematics.

The model Hamiltonian is treated in the BCS approximation. One-phonon even-even core excitations are obtained using the standard RPA [17]. All terms of the two quasiparticle interaction in the model Hamiltonian corresponding to the neutron-proton multipole-multipole interaction are replaced by a diagonal Gaussian force with central, spin-spin, Majorana and Majorana spin-spin components with parameters from [18].

The intrinsic model wave-functions are composed of one-neutron-quasiparticle plus one-proton-quasiparticle and one-neutron-quasiparticle plus one-proton-quasiparticle plus phonon components:

$$| \psi_K\rangle = \left\{ \sum_{np} C_{npK}\alpha_n^\dagger \alpha_p^\dagger + \sum_{npg} D_{npgK}\alpha_n^\dagger\alpha_p^\dagger Q_g^\dagger \right\} |\rangle, \qquad (2)$$

where the parameters C_{npK} and D_{npgK} are determined using the variational principle.

In the model, vibrational admixtures in neutron-proton wave functions can be calculated. This provides information about a possibility of Coulomb excitation of the corresponding state. Taking into account the Coriolis mixing enables us to predict possible K-allowed transitions between the ground state and the isomer.

An influence of vibrational admixtures on electromagnetic transitions can be demonstrated by the following example: In ^{181}W $B(\mathrm{E3})_{\mathrm{exp}} = (7.5 \pm 2.0)$ W.u. for a gamma transition from $5/2^-(K = 5/2[512])$ to $11/2^+(K = 9/2[624])$ has been measured [19]. If only a single-quasiparticle transition were assumed, the $B(\mathrm{E3})_{\mathrm{exp}}$-value would require an unphysical neutron effective charge $|e_{n,\mathrm{eff}}(\mathrm{E3})| = (10 \pm 2)e$. On the other hand, in the quasiparticle-plus-phonon model for ^{181}W the intrinsic wave functions of the states involved possess large $Q_{3\pm2}$-octupole-phonon vibrational admixtures: $|5/2[512]\rangle \approx 0.89|5/2[512]\rangle + 0.30|9/2[624] \otimes Q_{3-2}\rangle$ and $|9/2[624]\rangle \approx 0.94|9/2[624]\rangle + 0.17|5/2[512] \otimes Q_{32}\rangle$. Now the $B(\mathrm{E3})_{\mathrm{exp}}$-value can be reproduced with $|e_{n,\mathrm{eff}}(\mathrm{E3})| = (0.3 \pm 0.1)e$ not far from the value of $|e_{n,\mathrm{eff}}(\mathrm{E3})| = (0.05 \pm 0.03)e$ reproducing the vibrational transition with $B(\mathrm{E3}, 0^+ \to 3^-) = (27 \pm 5)$ W.u. [20] in even-even ^{178}Hf. It should be noted that octupole vibrational admixtures dominate in the intrinsic wave functions especially at the end ($A \sim 185$, Q_{32} admixtures) and at the beginning ($A \sim 155$, Q_{30} admixtures) of the quadrupole deformation region as it has been shown in [21]. This corresponds to the well-known fact that octupole correlations are important at the beginning and at the end of the deformation region.

For the calculation of electromagnetic transitions (and branching ratios of the ^{180}Ta levels to the ground state and the isomer), $e_{p,\mathrm{eff}}(\mathrm{E1}) = 0.6e$ and $e_{n,\mathrm{eff}}(\mathrm{E1}) = -0.4e$, $e_{p,\mathrm{eff}}(\mathrm{E2}) = e$ and $e_{n,\mathrm{eff}}(\mathrm{E2}) = 0.2e$, $e_{p,\mathrm{eff}}(\mathrm{E3}) = e$ and $e_{n,\mathrm{eff}}(\mathrm{E3}) = -0.2e$, $g_{s,\mathrm{red}} = 0.7$ and $g_{\mathrm{R}} = 0.3$ were used. Theoretical energies were replaced by known experimental energies and internal conversion was taken into account.

4.2. Results for ^{180}*Ta*

The main results can be summarized as follows:

1. In the intrinsic structure of the 9^- isomer band, octupole phonon admixtures play a dominant role: $|9^-\rangle \approx 0.87|\pi 9/2[514] \otimes \nu 9/2[624]\rangle - 0.45|\pi 5/2[402] \otimes \nu 9/2[624] \otimes Q_{32}\rangle - 0.12|\pi 9/2[514] \otimes \nu 5/2[512] \otimes Q_{32}\rangle$. As a consequence, B(E3) transition probabilities to rotational states based on the bandheads $|7^+(\pi 5/2[402] \otimes \nu 9/2[624])\rangle$ (at 361 keV – observed experimentally) and $|7^+(\pi 9/2[514] \otimes \nu 5/2[512])\rangle$ (at 550 keV – not observed experimentally) are large ($0.1 \div 10$ W.u.). Unfortunately, all these states decay back to the 9^- isomer (computed branchings to the 1^+ ground state are negligible).

2. There are no mediating levels at low energies (below 600 keV). This is demonstrated in Fig. 2 where theoretical energies *vs.* intrinsic spin projection K and parity are plotted.

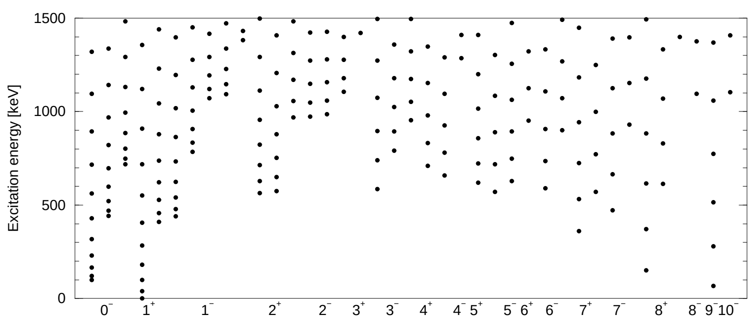

Fig. 2. Theoretical energies *vs.* intrinsic spin projection K and parity for ^{180}Ta.

3. Branching ratios from the model states below 1.2 MeV, which can be reached by a direct M1, E1, E2 or E3 excitation of the 9^- isomer, to the 1^+ ground state are all negligible. The previously proposed [22] K-allowed transition between the isomer and the ground state via a hypothetical intermediate level 6^+ at 940 keV with a dominant component $|6^+(\pi 9/2[514] \otimes \nu 3/2[512]\rangle$ has a negligible branching to the ground state.

5. Conclusions

We reviewed the proposed production mechanisms of $^{180\mathrm{m}}$Ta during the nucleo-synthesis process and discussed a possible effect of the electromagnetic coupling between the ground state and the isomer via mediating levels. Recent experiments [5,12] have found mediating levels below 1.5 MeV which make $^{180\mathrm{m}}$Ta survival uncertain in the s-process site. The results indicate mediating levels at ≈ 1.2 MeV. It is important to determine the cross section σ of the ^{180}Ta ground state production via these mediating levels, since from σ an effective half-life of $^{180\mathrm{m}}$Ta at the s-process site can be computed.

In our theoretical calculations using the TQPM and the standard axially-symmetric rotor model including Coriolis mixing no mediating level has been found. Nevertheless there is still room for improvement: First, in the present model-space only two-quasiparticle intrinsic states with possible two-quasiparticle-plus-phonon admixtures were taken into account. In the 1.2 MeV region, states with a dominant two-quasiparticle-plus-phonon component (vibrational states) occur and their mediating role should be examined. Second, for the model analysis of the branching ratios of the ^{180}Ta levels to the ground state and the isomer, new experimental data from the ^{176}Yb(^{11}B,α3n)^{180}Ta and ^{176}Yb(^{7}Li,3n)^{180}Ta reactions [23] might be used.

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