Mediating states in $^{180}$Ta

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Possible theoretical electromagnetic paths between the ground state and the isomeric state at 75.3 keV in $^{180}$Ta are discussed in the framework of the two-quasiparticle-plus-phonon model and the standard axially-symmetric rotor model including Coriolis mixing. Experimental transition rates from the isomeric state to the ground state via observed mediating states are compared to the theoretical ones.

I. INTRODUCTION

$^{180}$Ta is the only nucleus present in nature in an isomeric state ($9^-$) at an energy of 75.3 keV. Its solar abundance is very small (2.48, normalized to $10^{12}$ for Si), thus presenting a challenge for different nucleosynthesis models (see [1] for a detailed discussion of proposed production scenarios).

In the s-process site thermal photons may excite higher-lying states in $^{180}$Ta which then decay back either to the $1^+$ ground state or to the $9^-$ isomer. To find these mediating states (MS) Belic et al. [2,3] used the Stuttgart Dynamitron facility with both enriched (5.6%) and natural Ta targets. Irradiations were performed for bremsstrahlung endpoint energies $E_0 = 0.8 - 3.1$ MeV. Depopulation of the isomer was observed down to $E_0 \approx 1.01$ MeV. This means that the lowest MS may have an excitation energy $E_{MS} = 1.085$ MeV (above the ground state). The experimental total integrated depopulation cross section $I_D$ then turns out to be $(5.7 \pm 1.2)$ eV fm$^2$. Higher lying mediating states (below 2 MeV) were found at $E_{MS} = 1.30$ MeV ($I_D = 27$ eV fm$^2$), 1.51 MeV ($I_D = 24$ eV fm$^2$), 1.63 MeV ($I_D = 70$ eV fm$^2$), and 1.93 MeV ($I_D = 111$ eV fm$^2$). The structure, spin and parity of the MS remain unknown, calculations in the framework of the two-quasiparticle-plus-phonon model (TQPM) [4] failed to reproduce their energies as well as $I_D$’s (MS found for $E_{MS} > 2.4$ MeV).

II. MODEL DESCRIPTION

For a theoretical description of $^{180}$Ta we use the standard axially symmetric rotor model including Coriolis mixing [5]. The intrinsic degrees of freedom are described in the framework of the TQPM [6]. The model Hamiltonian is given by a deformed axially symmetric average field (Nilsson potential with parameters from [7]), monopole pairing interaction (proton and neutron gaps from [7]) and a long-range residual multipole-multipole interaction:

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

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

The model Hamiltonian is treated in the BCS approximation. One-phonon even-even core excitations are obtained using the standard RPA [7]. 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 [8].

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:

$$
| \psi_K \rangle = \left\{ \sum_{np} C_{npK} \alpha_n^\dagger \alpha_p^\dagger \left\{ \sum_{npq} D_{npqK} \alpha_n^\dagger \alpha_p^\dagger Q_g^\dagger \right\} \right\} | \rangle,
$$

where the parameters $C_{npK}$ and $D_{npqK}$ are determined using the variational principle.
III. RESULTS AND CONCLUSIONS

In the model, vibrational admixtures in neutron-proton wave functions can be calculated. Taking into account the Coriolis mixing (without any attenuation) enables us to predict possible transitions between the ground state and the isomer. Recently, we improved our calculations [9]. The model space comprises now 260 lowest intrinsic two-quasiparticle states with one-phonon components and corresponding rotational bands. For the calculation of electromagnetic transitions (and branching ratios of the $^{180}$Ta levels to the ground state and the isomer), $\epsilon_{p,\text{eff}}(E1) = 1.2e$ and $\epsilon_{n,\text{eff}}(E1) = 0.8e$, $\epsilon_{p,\text{eff}}(E2) = e$ and $\epsilon_{n,\text{eff}}(E2) = 0.2e$, $\epsilon_{p,\text{eff}}(E3) = e$ and $\epsilon_{n,\text{eff}}(E3) = 0.2e$, $g_{s,\text{red}} = 0.7$ and $g_R = 0.26$ were used. Theoretical energies were replaced by known experimental energies [10,11,12] and internal conversion was taken into account.

The main results can be summarized as follows:

1. There are no MS at low energies (below 600 keV). This is demonstrated in Fig. 1 where theoretical energies vs. intrinsic spin projection $K$ and parity are plotted.

2. The total experimental transition rate $W_{\text{tot}}$ for the process ‘isomer $\rightarrow$ MS $\rightarrow$ ground state’ can be calculated from

$$W_{\text{tot}} = \frac{I_D}{\hbar} \cdot \left( \frac{E_{\text{MS}} - 75.3 \text{ keV}}{\pi \hbar c} \right)^2$$

and compared with the theoretical transition rate

$$W = \frac{8\pi}{\hbar} \sum_{Xl} \frac{l + 1}{l[(2l + 1)!]^2} \cdot \left( \frac{E_{\text{MS}} - 75.3 \text{ keV}}{\hbar c} \right)^{2l+1} \cdot B_{\text{eff}}(Xl) ,$$

where we sum over the relevant multipolarities E1, E2, and M1. $B_{\text{eff}}(Xl)$ is the effective reduced transition probability for the process ‘isomer $\rightarrow$ MS $\rightarrow$ ground state’. In Fig. 2 the summed $W_{\text{tot}}$ and $W$ are compared. The main trend is reproduced but we still fail to account for 1 or 2 orders of magnitude.
FIG. 2. Summed experimental transition rates $\sum W_{tot}$ (solid line) in comparison with the results of the TQPM+PRM calculations (dashed line).

In our theoretical calculations using the TQPM and the standard axially-symmetric rotor model including Coriolis mixing low-lying mediating states were found for the first time. The lowest mediating state lies at 670 keV, but the transition rate from the isomer to the ground state is very small (see Fig. 2). A larger increase of the transition rate was found in the region around 1.2 MeV near the lowest experimentally observed mediating state.

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