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Short Note

Depopulation of the $J^{\pi} = 9^{-}$ isomer in ^{180}Ta to the $J^{\pi} = 1^{+}$ ground state by Coulomb excitation

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Abstract. In-beam Coulomb excitation of the exotic odd-odd nucleus ^{180}Ta has been studied by using a ^{136}Xe beam and a setup consisting of five EUROBALL CLUSTER detectors and the Darmstadt-Heidelberg Crystal Ball array. Spectroscopic information on the extremely rare ^{180}Ta is obtained from the comparison between an enriched ($3.6 \pm 0.3\%$ ^{180}Ta) and a natural tantalum target. Possible evidence for a depopulation from the long-lived high-spin $J^{\pi} = 9^{-}$ isomer to the short-lived $J^{\pi} = 1^{+}$ ground state is searched for by different methods. The decay of low-K bandheads, which are nanosecond isomers, towards the ground-state band can be demonstrated in delayed spectroscopy. A $\gamma\gamma$ coincidence analysis provides indications of $K = 5$ in-band transitions. Finally, when the Crystal Ball is used as an energy and γ multiplicity filter, signals of decay into the $K = 0$ band are observed.

PACS. 25.70.De Coulomb excitation – 27.70.+q $150 \leq A \leq 189$ – 23.90.+w Other topics in radioactive decay and in-beam spectrospcopy

1 Introduction

The odd-odd nucleus ^{180}Ta is unique in two ways. With a natural abundance of only 0.012% and tantalum being the rarest element, it is nature's rarest isotope. It is also the only naturally occurring isotope in an isomeric state ($J^{\pi} = 9^{-}$) with a lifetime longer than 10^{15} years while the ground state ($J^{\pi} = 1^{+}$) is short-lived. Recently, the spectroscopy of ^{180}Ta has attracted considerable interest for two reasons: Similar to the famous long-lived $J^{\pi} = 16^{+}$ isomer in ^{178}Hf [1–4], it provides a case where one can search for possible structure effects induced by a high-spin state of the target. Furthermore, information on excited states that are coupling the ground state (g.s.) to the isomer would be a crucial ingredient to resolve the long-standing puzzle of its nucleosynthesis [5,6]. Here, one is interested in possible modifications of the effective lifetime of the isomer by the hot photon bath accompanying heavy-element synthesis.

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Photoactivation [5,7,8] and Coulomb excitation [9–11] experiments have demonstrated a depopulation of the $J^{\pi} = 9^{-}$ isomer to the $J^{\pi} = 1^{+}$ g.s. via higher-lying intermediate states (IS) at energies $E_x \geq 1$ MeV. Because the g.s. β-decay with a half-life of 8.1 h can be measured offline, these studies reach a remarkable sensitivity. However, the information on the energy and excitation probability of the IS is obtained from (rather structureless) excitation functions and therefore the precision is limited. Gamma spectroscopy of ^{180}Ta with a variety of light-ion and light heavy-ion induced reactions [12–16], while providing a wealth of valuable data on the low-energy structure, has not been able to identify a single IS candidate with branchings populating both g.s. and isomer.

Here, we aim at a study of the linking between g.s. and isomer in ^{180}Ta by Coulomb excitation with heavy ions. This can be viewed as the reverse case to the "trapping" into a $J^{\pi} = 8^{-}$ isomer observed in the Coulomb excitation of ^{178}Hf [17,18]. While the analysis so far has not led to an unambiguous identification of IS, the present work demonstrates experimental evidence for a depopulation of

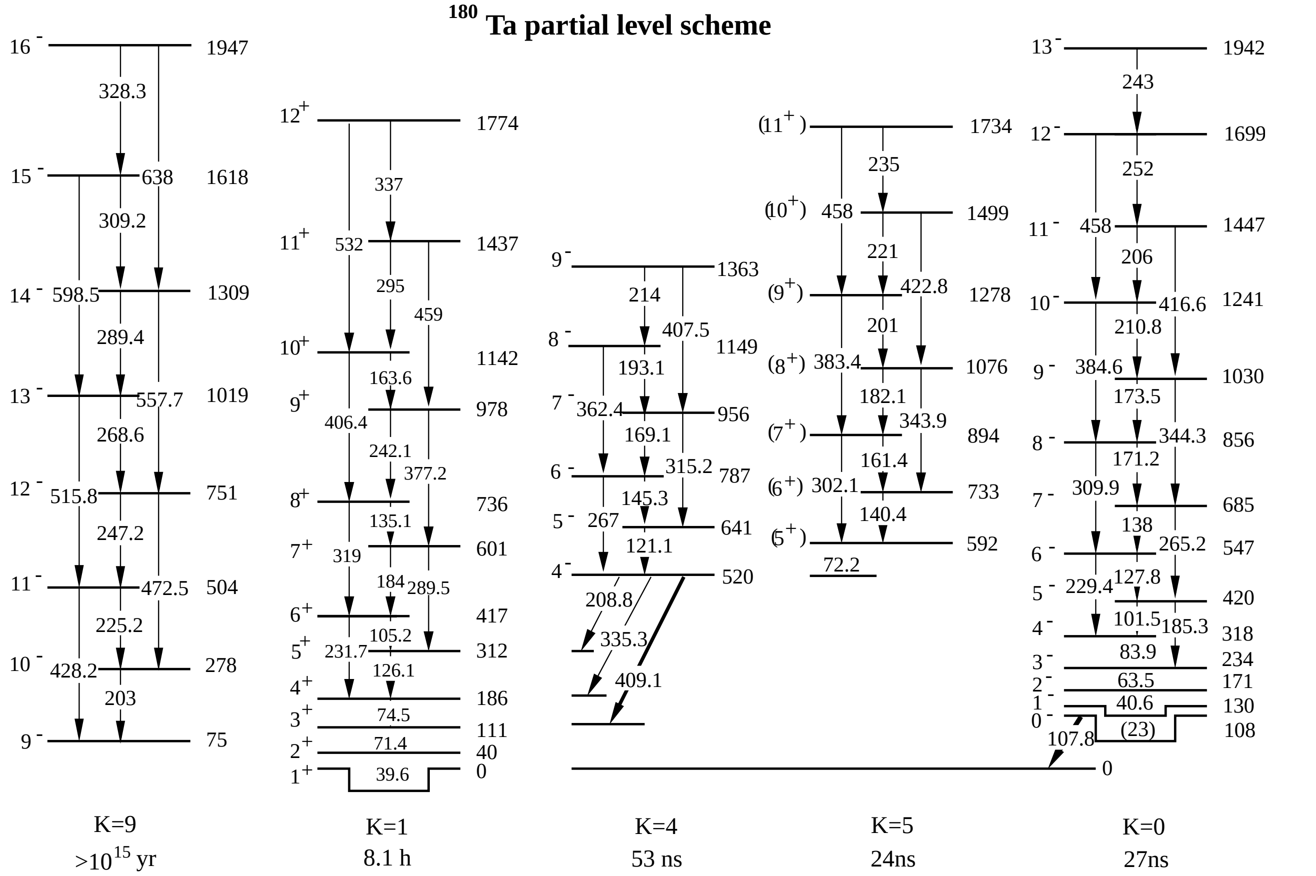

Fig. 1. Partial level scheme of ^{180}Ta based on the work of refs. [13,14]. For the new assignment of the $K = 5$ band see ref. [19].

the isomer to the g.s. in the Coulomb-excitation process. Figure 1 presents a partial level scheme of ^{180}Ta including the high-K band built on the isomer and a number of low-K bands whose band heads all decay to the g.s. band. Thus, any population of transitions coupling states between the latter bands provides a signature for the depopulation of the isomer. An experimental difficulty arises from the small natural abundance of ^{180}Ta which prevents the use of highly enriched targets. Thus, one has to rely on difference measurements between a moderatly ^{180}Ta enriched and a natural tantalum target. This technique has been used before in Coulomb excitation studies of ^{180}Ta, but concentrating on the high-K band built on the isomer [20].

2 Experimental technique

The experiment was performed at the UNILAC of the GSI with a 27 MHz pulsed beam of ^{136}Xe at an energy of 3.94 MeV/u. The target consisted of a Ta_2O_5 layer with a thickness of 800 μg/cm^2 on a carbon backing of 30 μg/cm^2. Two types of targets produced in an identical way [21] were used: one from material enriched to 5.6% ^{180}Ta and one from material with natural abundance. Unfortunately, during production some ^{180}Ta-enriched material was inadvertently mixed with that of the natural target. Thus, the analysis of the experiment showed 3.6% ^{180}Ta for the "enriched" and 0.6% ^{180}Ta for the "natural" target reducing the difference to a factor of about six.

The experimental setup consisted of 35 germanium crystals in form of 5 EUROBALL CLUSTER (EBC) detectors [22] in backward directions, centered on a ring at about 150° with respect to the beam, the Crystal Ball (CB) array of large-volume NaI detectors [23] covering 83% of the solid angle, and three trapezoidal PPAC counters [24] mounted in pyramid-like geometry around the target. The EBC detectors had a total photopeak efficiency of 2.2% at an energy of 1.33 MeV. For the CB the photopeak efficiency was 53%. The PPAC array covered a scattering angle region between 15° and 100°. These forward angles were chosen to emphasize single- or few-step excitations.

Data were stored if at least one PPAC and one EBC detector gave a signal. In the analysis shown here only events with the projectile scattered into an angular region 15°–35° were taken into account to allow for an unambiguous separation between projectile and ejectile and to guarantee a "safe" energy for Coulomb excitation so that other reaction channels can be excluded.

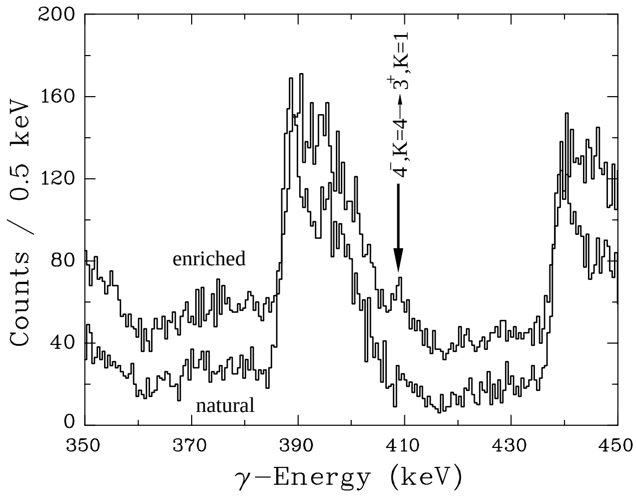

Fig. 2. Delayed-particle–γ-ray coincidence spectrum taken with the EBC detectors from a 100 ns wide time window after Coulomb excitation of a natural and an enriched (3.6% ^{180}Ta) tantalum target.

3 Results and discussion

In the following various approaches to identify in-band transitions of the low-K bands (see fig. 1) or transitions populating the $K = 1$ g.s. band in coincidence with Coulomb excitation are discussed. One obvious possibility is delayed spectroccopy because all relevant bandheads are nanosecond isomers (cf. fig. 1).

Figure 2 shows part of a spectrum obtained by a 100 ns wide time gate starting approximatly 10 ns after the prompt Ge signals of the cluster ring. One clearly observes a delayed transition at $E_\gamma = 409$ keV from the $K = 4$ bandhead to the 3^+ state of the $K = 1$ g.s. band in the measurement with the enriched target.

The two dominating bumps in the spectrum are Doppler-broadened transitions from the ^{181}Ta g.s. band. Because of the limited time resolution of the Ge detectors of about 15 ns, also prompt events (although suppressed) fall into the selected time gate. However, the assignment of the 409 keV transition is confirmed by its absence in the prompt spectrum. We note that indications for the population of the other low-K ns isomers shown in fig. 1 are also observed in the data.

Another possibility to identify ^{180}Ta g.s. population is given by $\gamma\gamma$ coincidences in the low-K bands observed with the EBC detectors. Figure 3 shows a projection of the prompt $\gamma\gamma$ matrix with a 3 keV wide gate on the $6^+ \to 5^+$ transition of the $K = 5$ band. The upper part depicts a comparison of the spectra obtained with the enriched and the natural target which exhibit no obvious candidate for another $K = 5$ in-band transition.

The lower part of fig. 3 shows the difference between both spectra. There, the channel contents of the natural target spectrum were multiplied by a factor of 1.3 to account for the different statistics. Indications of other transitions from higher-lying levels up to the 9^+ state in the

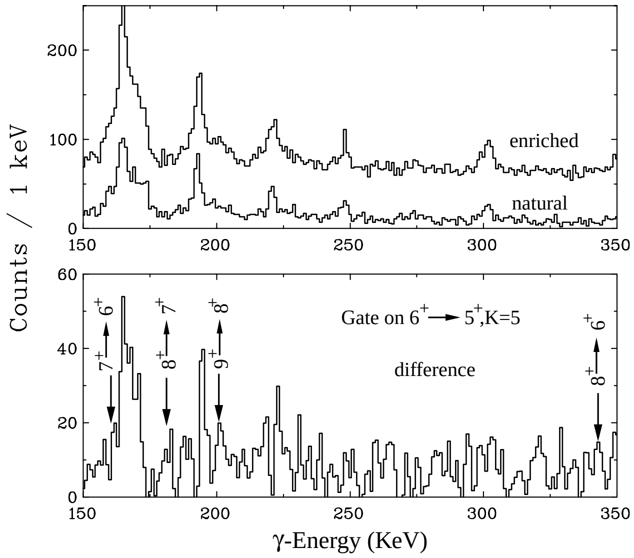

Fig. 3. Prompt particle-$\gamma\gamma$ coincidences summed over al EBC detectors with a gate on the $6^+ \to 5^+$ transition of the $K = 5$ band in ^{180}Ta.

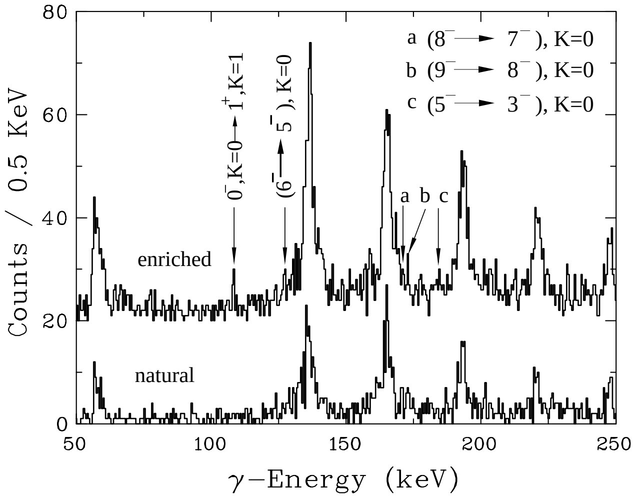

Fig. 4. Summed spectrum taken with the Ge cluster ring in coincidence with the CB, demanding six gamma-rays with a sum energy of 600–1200 keV in the latter.

$K = 5$ band are visible. However, the difference spectrum is complicated by considerable background, most likely originating from random coincidences with ^{181}Ta lines (caused by the low degree of ^{180}Ta enrichment). This, together with the fluctuations induced by the subtraction of two spectra with large background, prevents an unambiguous identification. The statistics is also too poor to test intensity relations between the transitions.

In the final example use is made of the CB as an energy and multiplicity filter. The activation work with electromagnetic probes suggests the lowest IS to be at excitation energies of about 1 MeV. The simplest mechanism would be a single-step excitation of the IS with a spin similar to that of the isomer and a subsequent decay cascade of about 4–8 γ rays to carry the large angular momentum change $\Delta J = 8$ between g.s. and isomer. We tried to identify possible decay cascades from the excitation regions ending in the low-K bands finally feeding the g.s. of ^{180}Ta. As an example, fig. 4 shows the case where a multiplicity of six and a total energy $E_\gamma \simeq 600$–1200 keV is required in the CB. Because of its high efficiency the CB turns out to be a powerful tool to clean up the spectra.

The comparison between the enriched and the natural target clearly shows a line at 108 keV in the spectrum enriched in ^{180}Ta. It corresponds to the transition between the $K = 0$ and $K = 1$ g.s. bandheads (see fig. 1). Besides, there are also some indications of lines which correspond to transitions within the $K = 0$ band. None of the above transitions appear for other multiplicity windows except $N_\gamma = 7$ (however, with lower statistics and for a slightly higher CB energy window). Generally, signals for different low-K bands can be observed for specific CB energy-multiplicity combinations.

4 Conclusions

In-beam Coulomb excitation of the exotic odd-odd nucleus ^{180}Ta was studied with a ^{136}Xe beam and a combined setup of 5 EBC cluster detectors and the CB. Because of the extremely low natural abundance, information on ^{180}Ta could only be obtained from the difference of measurements with a moderatly (3.6%) enriched and a natural tantalum target. The following evidence for a depopulation of the long-lived $J^\pi = 9^-$ isomer in ^{180}Ta to the short-lived $J^\pi = 1^+$ g.s. by Coulomb excitation has been obtained: i) In delayed spectroscopy one can observe the decay of bandheads of low-K configurations with lifetimes of a few tens of nanoseconds populating the g.s. band. These are not observed in the prompt spectra. ii) $\gamma\gamma$ coincidences indicate in-band transitions, *e.g.*, of the $K = 5$ band which in turn decays to the g.s. band. However, because of the large background from the ^{181}Ta transitions and the need of subtraction of spectra, evidence is considered tentative only. iii) The CB can be used as an effective energy and multiplicity filter. For the energy region, where the lowest IS are suggested by the activation experiments, and requesting a multiplicity of six to acquire the angular momentum change from isomer to g.s., population of the $K = 0$ band could be demonstrated.

The present work has shown that Coulomb excited states in ^{180}Ta can decay to the g.s. through different bands without a preference of particular K values. The data analysis is not completed yet. Future work will focus on the identification of the intermediate states. Here, the use of the CB as a multiplicity and energy filter should be particularly helpful to identify both the single- or few-step excitations of the IS as well as their decay cascades. Also, new theoretical concepts are required to understand the large cross-sections for the coupling of isomer and g.s. by electromagnetic probes. First attempts [25,26] seem to be able to account for IS at energies above $E_x \approx 1.2$-1.3 MeV, but IS at lower energies as observed in [5] are still not understood.

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