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The ground state spin of $^{180}$Ta is not $8^+$

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Résumé. — Des membres des bandes rotationnelles $(1^+, 1)$ et $(8^+, 8)$ ont été identifiés dans la région de faible excitation de $^{180}$Ta par une comparaison des sections efficaces de transfert (p, d) avec des calculs en DWBA, utilisant des fonctions d'onde de Nilsson.

Abstract. — Experimental (p, d) cross-sections are compared with calculations using Nilsson wave functions and the DWBA in order to locate the members of the low lying $(1^+, 1)$ and $(8^+, 8)$ rotational bands in $^{180}$Ta.

Until recently [1] only two levels have been observed in $^{180}$Ta, both isomers. The long-lived isomer, considered as the ground state, has $T_{1/2} > 10^{13}$ y [2], [3]. The other level with $T_{1/2} = 8.15$ h. has been previously located at 212 keV [4], [5] and recently at 32 keV [6]. The log $f$ values for the decay of the latter level to the 0$^+$ and 2$^+$ first excited states of $^{180}$W and $^{180}$Hf, are consistent with allowed or possibly first forbidden transitions. Asaro et al. [7] suggested values of $I^*$, \( K = 1^- \), 0 and $I^*$, \( K = 8^+ \), 8 or 9$^-$, 9 respectively for the short-lived (SLI) and long-lived (LLI) isomers.

Experimental observations by Gallagher et al. [8] on the SLI decay exclude the $(1^-)$, 0 assignment which arises from the coupling of 9/2$^-$ \([514]_p\) with 9/2$^+$ \([624]_n\) with antiparallel spins ($\Sigma = 0$). The same experiment is consistent with $(1^+, 1)$ explained as due to the coupling of 7/2$^+$ \([404]_p\) with the 9/2$^+$ \([624]_n\) with parallel intrinsic spins ($\Sigma = 1$). The two configurations mentioned above give rise also to states with $(9^-, 9) \Sigma = 1$ and $(8^+, 8) \Sigma = 0$. Both of these spins have been proposed for the LLI and the experimental study has not solved this ambiguity. The intrinsic proton state 9/2$^-$ \([514]_p\) of the $(9^-, 9)$ configuration in $^{180}$Ta appears in $^{181}$Ta at 6 keV above the 7/2$^+$ \([404]_p\) ground state which corresponds to the $(8^+, 8)$ configuration. Due to this very small energy difference the $(9^-, 9)$ as well as the $(8^+, 8)$ states could be the LLI. However in all other known odd-odd tantalum nuclei the ground state proton configuration is due to the coupling with parallel intrinsic spins of the 7/2$^+$ \([404]_p\) with a neutron state.

If one adopts $(1^+, 1)$ for the SLI, the identification of the $(8^+, 8)$ member of this configuration with a lower lying state would violate the Gallagher-Moszkowski empirical rule (G-M rule) [9]. This rule states that the member of the doublet corresponding to parallel intrinsic spins of the unpaired nucleons has the lowest excitation. As far as is known, such a violation has been observed once in $^{166}$Ho where the ground state is $(0^-, 0) \Sigma_p + \Sigma_n = 0$ but only 5 keV below the $(7^-, 7)$ member ($\Sigma = 1$). It must be pointed out that in this case the long-lived isomer ($T_{1/2} > 1.2 \times 10^3$ y) is not the ground state which has $T_{1/2} = 27$ h. [10].

The doublet $K^* = 1^+$ and $K^* = 8^+$ from the configuration \{ 7/2$^+$ \([404]_p\), 9/2$^+$ \([624]_n\) \} has been observed in $^{176}$Lu and the $(8^+, 8)$ member lies 206 keV above the $(1^+, 1)$ again in agreement with the G-M rule [1].

The aim of this letter is to propose, with the help of new experimental data, an alternative to the low lying level scheme of $^{180}$Ta and to try to explain some of the contradictions outlined above.

The $^{180}$Ta nucleus has been investigated by the $^{181}$Ta(p, d)$^{180}$Ta reaction at $E_p = 19$ MeV using a magnetic spectrograph. The experimental procedure is described elsewhere [1].

Assuming a direct transfer mechanism, the observed excited states in the low energy region result from the coupling of the transferred neutron with the unpaired proton of the target ground state e.g. 7/2$^+$ \([404]_p\). The lowest neutron state is 9/2$^+$ \([624]_n\), ground state configuration of $^{177}$Yb, $^{179}$Hf and $^{181}$W, all isotones of $^{180}$Ta. It is this configuration which produces the Gallagher-Moszkowski doublet with $K^* = 1^+$ and

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$K^*_2 = 8^+$. Among other possible neutron states below 900 keV excitation the $9/2^+ \left[ ^6_{24} T \right]$ is the only one with even parity [12]. The expected transfers to the members of the two bands built with this neutron state are $l = 4$, $j = 9/2 \left( C^0_{12} = 0.126 \right)$ and $l = 6$, $j = 13/2 \left( C^0_{11} = 0.98 \right)$. We exclude the $l = 6, j = 11/2$ transfer because the corresponding $C^0_{12}$ is negligible.

For the two first members of the $1^+$ band, the only allowed transfer is $l = 4$ with a relatively small intensity. The $8^+$ band, in contrast is excited by $l = 4$ and strongly so by $l = 6$. Referring to the energy of the observed lowest level, taken to zero, we see that the angular distributions of the levels at 0 and 41 keV are well fitted by a pure $l = 4$ transfer (Fig. 1a).

The two first levels are observed with a large experimental error, but the theoretical absolute cross-sections represent 60% of the observed cross-sections. In contrast the $(8^+, 8)$ absolute theoretical cross-section is more than two times too large to fit either of these levels. Furthermore the $(3^+, 1)$ member of the $1^+$ band is easily identified with the level at 106 keV by taking an inertia parameter $h^2/2 J = 10.5$ keV [1]. Both the angular distribution and absolute cross-sections are fitted (Table I; Fig. 1a).

In a previous paper [1], we have shown that the $(4^+, 1)$ member of this band is a part of the experimental multiplet at 173 keV including the $(8^+, 8)$ state. An additional proof of the location of this member of the G-M doublet is given by the state observed at 366 keV which is identified as the $(9^+, 8)$. Its angular distribution is $l = 6$ as expected (see Fig. 1b). This is the only $l = 6$ angular distribution in this energy region and a good agreement between theoretical and experimental cross-sections is found (Table I). This identification leads to the location of the $(8^+, 8)$ band head at 177 keV in good agreement with a previous identification based essentially on cross-section considerations [1].

The $(5^+, 1)$ state is expected at 294 keV, with an $l = 6$ angular distribution. Experimentally one observes a level at 303 keV showing an angular distribution dominated by $l = 6$ (see Fig. 1b). The major part of the measured cross-section comes from the $(5^+, 1)$ state.

Hence the members of the $(1^+, 1)$ band have been identified with a high degree of confidence up to $(5^+, 1)$. The $(8^+, 8)$ member of the G-M doublet is shown to be above the $(1^+, 1)$ level. In addition to arguments quoted in the introduction it has been shown that if the lowest level observed in our experiment was assigned $(8^+, 8)$ it would be impossible to explain the energy and transfer cross-sections of other low lying observed levels. Finally, the proposed level scheme leads to a G-M term of the $V_{np}$ residual interaction of $A = -104$ keV in very good agreement.

### Table I.

<table>
<thead>
<tr>
<th>$I^*$, $K$</th>
<th>Energy (keV)</th>
<th>Cross-section ($\mu b/sr$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp.</td>
<td>Theory (*)</td>
</tr>
<tr>
<td>$1^+$, 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$2^+$, 1</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>$3^+$, 1</td>
<td>106</td>
<td>105</td>
</tr>
<tr>
<td>$4^+$, 1 (°)</td>
<td>173</td>
<td>189</td>
</tr>
<tr>
<td>$5^+$, 1</td>
<td>302</td>
<td>294</td>
</tr>
<tr>
<td>$8^+$, 8 (°)</td>
<td>173</td>
<td>177</td>
</tr>
<tr>
<td>$9^+$, 8</td>
<td>366</td>
<td>366</td>
</tr>
</tbody>
</table>

(*) Unresolved in experiment (see Ref. [1]).

(*) Given by $E(I^*, K) = E(K^*, K) + h^2/2 \not\{n I + 1 - K^2\}$ with $h^2/2 \not= 10.5$ keV.

(*) Cross-section at $\theta_{lab} = 50°$. 

Fig. 1. — Angular distributions of states in $^{180}$Ta excited by the $^{181}$Ta(p, d)$^{180}$Ta reaction at $E_p = 19$ MeV. Solid lines are theoretical calculations using Nilsson wave functions and DWBA:

a) Members of the $(1^+, 1)$ band; b) Members of the $(8^+, 8)$ band.
with calculations of Boisson et al. for this configuration [13].

There are many uncertainties in previous works on $^{180}$Ta. It was first admitted that the SLI is located above the LLI. But from more recent data [14] and from neutron binding energy systematics [15] it cannot be excluded that the lower excited state is the SLI. The facts which appear to be well established are that the SLI is a $(1^+, 1)$ state and the LLI a state with $K > 8$, although experimental results on the decay of the long-lived isomer are scarce [2], [3]. From the present work it is established that the $(1^+, 1)$ state with configuration \{7/2$^+$ [404 \text{i}]_p, 9/2$^+$ [624 \text{j}]_n\} is excited at lower energy than the $(8^+, 8)$ which belongs to the same G-M doublet.

If the LLI is the $(8^+, 8)$ state then it must be an excited state at least at 180 keV.

The other state of high spin, the $(9^-, 9)$ of configuration \{9/2$^-$ [514 \text{j}]_p, 9/2$^+$ [624 \text{j}]_n\} which cannot be excited in this neutron transfer reaction, could be the long-lived isomer and be above or below the $(1^+, 1)$. Furthermore we cannot completely exclude another configuration for the $(1^+, 1)$ that is \{9/2$^-$ [514 \text{j}]_p, 7/2$^-$ [514 \text{j}]_n\} also unobservable in a pick-up from $^{181}$Ta. The $\beta^-$ and E.C. decay properties measured experimentally [8] are compatible with such a configuration but the corresponding $1^+$ state is expected above the $(1^+, 1)$ band head identified here.

From these results one concludes that if the long-lived isomer is the lower excited state and if the short-lived isomer is the $(1^+, 1)$ identified here, then the $(9^-, 9)$ state is the only reasonable candidate for the long-lived isomer. Finally, concerning the ground state spin of $^{180}$Ta only two assignments are possible, either $(1^+, 1)$ from \{7/2$^+$ [404 \text{i}]_p, 9/2$^+$ [624 \text{j}]_n\} or $(9^-, 9)$ from \{9/2$^-$ [514 \text{j}]_p, 9/2$^+$ [624 \text{j}]_n\}. In any case the spin $(8^+, 8)$ is excluded. The excitation of $^{180}$Ta via a proton transfer reaction, ($^3$He, d) or ($\alpha$, t) would help to choose between $1^+$ or $9^-$. 

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References