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Journal de Physique Lettres, 1979, 40 (1), pp.1-3. 10.1051/jphyslet:019790040010100 . jpa-00231555

**HAL Id: jpa-00231555**

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Submitted on 4 Feb 2008

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# LE JOURNAL DE PHYSIQUE-LETTRES

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Classification  
 Physics Abstracts  
 21.10H — 21.60

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

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(Reçu le 30 octobre 1978, accepté le 13 novembre 1978)

**Résumé.** — Des membres des bandes rotationnelles  $(1^+, 1)$  et  $(8^+, 8)$  ont été identifiés dans la région de faible excitation de  $^{180}\text{Ta}$  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  $^{180}\text{Ta}$ .

Until recently [1] only two levels have been observed in  $^{180}\text{Ta}$ , 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  $ft$  values for the decay of the latter level to the  $0^+$  and  $2^+$  first excited states of  $^{180}\text{W}$  and  $^{180}\text{Hf}$ , are consistent with allowed or possibly first forbidden transitions. Asaro *et al.* [7] suggested values of  $I^\pi$ ,  $K = 1^-, 0$  and  $I^\pi$ ,  $K = 8^+, 8$  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  $9/2^- [514 \uparrow]_p$  with  $9/2^+ [624 \uparrow]_n$  with antiparallel spins ( $\Sigma = 0$ ). The same experiment is consistent with  $(1^+, 1)$  explained as due to the coupling of  $7/2^+ [404 \downarrow]_p$  with the  $9/2^+ [624 \uparrow]_n$  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  $9/2^- [514 \uparrow]_p$  of the  $(9^-, 9)$  configuration in  $^{180}\text{Ta}$  appears in  $^{181}\text{Ta}$  at 6 keV above the  $7/2^+ [404 \downarrow]_p$  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  $7/2^+ [404 \downarrow]_p$  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  $^{166}\text{Ho}$  where the ground state is  $(0^-, 0)$  ( $\Sigma_p + \Sigma_n = \Sigma = 0$ ) 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  $\{ 7/2^+ [404 \downarrow]_p, 9/2^+ [624 \uparrow]_n \}$  has been observed in  $^{176}\text{Lu}$  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  $^{180}\text{Ta}$  and to try to explain some of the contradictions outlined above.

The  $^{180}\text{Ta}$  nucleus has been investigated by the  $^{181}\text{Ta}(p, d)^{180}\text{Ta}$  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.  $7/2^+ [404 \downarrow]_p$ . The lowest neutron state is  $9/2^+ [624 \uparrow]_n$ , ground state configuration of  $^{177}\text{Yb}$ ,  $^{179}\text{Hf}$  and  $^{181}\text{W}$ , all isotones of  $^{180}\text{Ta}$ . It is this configuration which produces the Gallagher-Moszkowski doublet with  $K_\pi^\pm = 1^+$  and

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$K_{\pi}^{\pm} = 8^{+}$ . Among other possible neutron states below 900 keV excitation the  $9/2^{+}$  [624 ↑] is the only one with even parity [12]. The expected transfers to the members of the two bands built with this neutron state are  $l = 4, j = 9/2$  ( $C_{ji}^{\sigma} = 0.126$ ) and  $l = 6, j = 13/2$  ( $C_{ji}^{\sigma} = 0.98$ ). We exclude the  $l = 6, j = 11/2$  transfer because the corresponding  $C_{ji}^{\sigma}$  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).

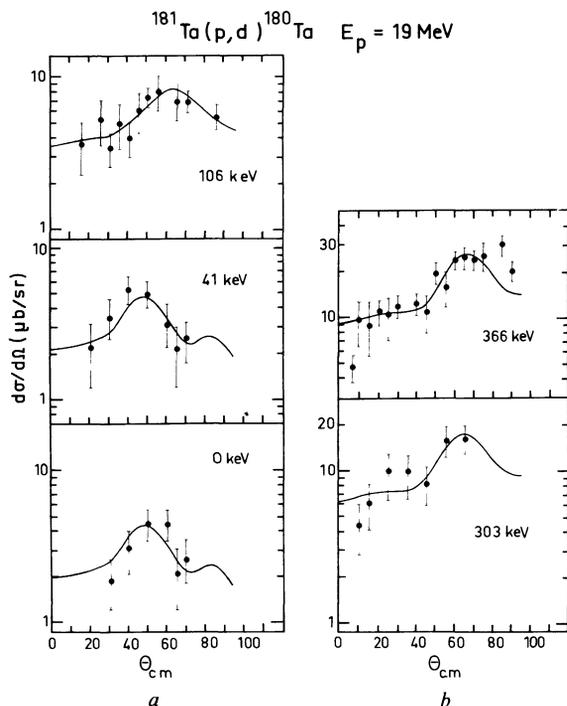


Fig. 1. — Angular distributions of states in  $^{180}\text{Ta}$  excited by the  $^{181}\text{Ta}(p, d)^{180}\text{Ta}$  reaction at  $E_p = 19$  MeV. Solid lines are theoretical calculations using Nilsson wave functions and DWBA : a) Members of the  $(1^{+}, 1)$  band ; b) Members of the  $(8^{+}, 8)$  band.

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  $\hbar^2/2J = 10.5$  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 good 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. — Experimental and theoretical cross-sections for members of the  $(1^{+}, 1)$  and  $(8^{+}, 8)$  bands in  $^{180}\text{Ta}$  excited in the  $^{180}\text{Ta}(p, d)^{181}\text{Ta}$  reaction.

$I^{\pi}, K$	Energy (keV)		Cross-section ( $\mu\text{b}/\text{sr}$ )			
	Exp.	Theory <sup>(b)</sup>	Experiment		Theory	
			$\sigma(45^{\circ})$	$\sigma(65^{\circ})$	$\sigma(45^{\circ})$	$\sigma(65^{\circ})$
$1^{+}, 1$	0	0	$4.5 \pm 1.0$ (c)	$2.1 \pm 0.9$	$2.50$ (c)	1.48
$2^{+}, 1$	41	42	$5.0 \pm 1.0$ (c)	$2.1 \pm 0.9$	$2.64$ (c)	1.57
$3^{+}, 1$	106	105	$6.3 \pm 1.7$	$7.0 \pm 2.0$	3.86	5.26
$4^{+}, 1$ (a)	173	189	$34.5 \pm 5.5$	$43.5 \pm 6.4$	5.93	10.68
$5^{+}, 1$	302	294	$8.2 \pm 2.2$	$16.0 \pm 3.0$	6.10	12.06
$8^{+}, 8$ (a)	173	177	$34.5 \pm 5.5$	$43.5 \pm 6.4$	10.07	9.87
$9^{+}, 8$	366	366	$11.0 \pm 4.0$	$24.5 \pm 5.0$	8.76	18.20

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

(b) Given by  $E(I^{\pi}, K) = E(K^{\pi}, K) + \hbar^2/2J [I(I+1) - K^2]$  with  $\hbar^2/2J = 10.5$  keV.

(c) Cross-section at  $\theta_{\text{lab}} = 50^{\circ}$ .

with calculations of Boisson *et al.* for this configuration [13].

There are many uncertainties in previous works on  $^{180}\text{Ta}$ . 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  $K \geq 8$ , 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  $\{7/2^+ [404 \downarrow]_p, 9/2^+ [624 \uparrow]_n\}$  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  $\{9/2^- [514 \uparrow]_p, 9/2^+ [624 \uparrow]_n\}$  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  $\{9/2^- [514 \uparrow]_p, 7/2^- [514 \downarrow]_n\}$  also unobservable in a pick-up from  $^{181}\text{Ta}$ . 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  $^{180}\text{Ta}$  only two assignments are possible, either  $(1^+, 1)$  from  $\{7/2^+ [404 \downarrow]_p, 9/2^+ [624 \uparrow]_n\}$  or  $(9^-, 9)$  from  $\{9/2^- [514 \uparrow]_p, 9/2^+ [624 \uparrow]_n\}$ . In any case the spin  $(8^+, 8)$  is excluded. The excitation of  $^{180}\text{Ta}$  via a proton transfer reaction, ( $^3\text{He}, d$ ) or  $(\alpha, t)$  would help to choose between  $1^+$  or  $9^-$ .

**Acknowledgments.** — We thank Dr. R. Piepenbring for his stimulating interest in this work and critical reading of the manuscript.

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