Low energy states in ^{180}Ta

T. Cousins, T. J. Kennett, and W. V. Prestwich
Department of Physics, McMaster University, Hamilton, Ontario
(Received 19 January 1981)

A study of both the ^{180}Ta$(n,\gamma)^{181}$Ta and ^{181}Ta$(\gamma,n)^{180}$Ta reaction reveals energy levels in ^{180}Ta at 38, 73, 109, 181, 231, 258, and 309 keV. The 73 keV level is shown to be the long-lived $J = 9$ state occurring in nature. Neutron separation energies of 7579 ± 2 keV and 6063.3 ± 0.5 keV have been determined for the ^{180}Ta-^{181}Ta and ^{181}Ta-^{182}Ta pairs, respectively. The Q value for thermal nuetron capture on ^{180}Ta was found to be 7652.3 ± 0.5 keV.

[NUCLEAR REACTIONS ^{180}Ta(n,γ), thermal, measured γ energies, ^{181}Ta(γ,n) ^{180}Ta, E_γ=7724, 7815 keV, measured neutron energies, deduces levels.]

I. INTRODUCTION

Very little information exists about the energy levels of the nucleus ^{180}Ta, which occurs in nature with an isotopic abundance[1] of 0.0123%. From the systematics of nuclidic masses[2] it is known that beta decay to both ^{180}Hf and ^{180}W is energetically possible. When ^{180}Ta is produced in a nuclear reaction it is found to exist in a configuration which decays with an 8.15-h half-life.[3] A lower limit of 10^{13} yr has been established for the naturally occurring configuration. The 8.15-h configuration was initially identified as an isomeric state with an energy of 212 ± 23 keV on the basis of photoneutron threshold experiments.[4]

A series of recent experiments, however, have indicated that the above interpretation is incorrect. First, Lanier *et al.*[5] reported a Q value of 7653 ± 4 keV for the ^{180}Ta$(n,\gamma)^{181}$Ta reaction. The target ^{180}Ta nuclei must, of course, be in the long-lived configuration in this reaction. Second, recent experiments[6] on the ^{181}Ta$(\gamma,n)^{180}$Ta reaction at this facility indicate that the neutron binding energy in ^{181}Ta is only 7580 ± 5 keV, considerably lower than the Q value observed for the neutron capture reaction. Finally, a mass-spectrometric value of 7693 ± 20 keV has been reported[7] for the mass difference between the long-lived ^{180}Ta configuration coupled to a free neutron and ^{181}Ta. From a consideration of the Q value for the beta decay of the short-lived state to ^{180}W, together with the ^{181}Ta-^{180}W mass difference, these authors have been able to explain the difference between the energetics of the complementary neutron capture and photoneutron reactions by identifying the short-lived configuration as the ground state of ^{180}Ta. This configuration is also identified as the final state of the photoneutron reaction while the long-lived level is the initial state in the neutron capture reaction. The difference between the neutron capture Q value and the neutron separation energy as observed in the photoneutron reaction is then the excitation energy of the long-lived state of ^{180}Ta and is given by 73 ± 6 keV. The long-lived state constitutes a naturally occurring isomer.

We report here on new neutron capture and photoneutron experiments which reduce the uncertainties in both the neutron capture Q value and the photoneutron threshold. In addition we report on several other excited states of ^{180}Ta populated in the photoneutron reaction.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. The ^{180}Ta$(n,\gamma)^{181}$Ta reaction

A 1 mg sample of tantalum oxide enriched to 4% in the ^{180}Ta isotope was enclosed in a graphite capsule and placed in the irradiation position of the McMaster reactor tangential facility. The neutron flux density at this position is approximately 2×10^{12} cm^{-2} s^{-1}. The gamma-ray spectrum was observed using a triple coincidence pair spectrometer which consists of an intrinsic germanium detector surrounded by a quadrisected annulus of sodium iodide. A more detailed description of the experimental arrangement is given elsewhere.[8] Data were collected for three weeks during which time the gain and zero intercept of the pulse processing system were stabilized on two reference peaks. The lower energy reference peak was produced by the 1.275 MeV gamma ray of ^{22}Na in triple coincidence with the time-correlated annihilation radiation arising from the associated positron decay. This radiation was introduced by placing a source of ^{22}Na on the face of the cryostat of the germanium detector. The higher energy reference peak was produced by the 4.945 MeV ground state transition

in the $^{12}C(n,\gamma)^{13}C$ reaction resulting from neutron capture in the graphite capsule. Upon completion of this experiment similar procedures were used to observe the spectra produced by a 30 mg sample of natural tantalum and by a 1 g sample of melamine ($C_6H_8N_{11}$).

The centroid and area of each peak in each of the three spectra were determined using digital filter techniques which have been described previously.[9] The results for the well-known transitions corresponding to the $^{14}N(n,\gamma)^{15}N$ reaction[10] were used to determine the relationship between centroid and energy and to calibrate the relative efficiency of the system. The spectrum of the enriched sample was compared with that of the natural tantalum in order to identify the transitions arising from ^{180}Ta. Transitions originating from capture in lead, iron, and nitrogen as well as the beta decay of ^{16}N were also observed in the spectrum of the enriched sample. The energies and relative intensities determined for transitions in the region from 6 to 7 MeV associated with tantalum are listed in Table I. The resolution obtained expressed as the full width at half maximum (FWHM) was 3.8 keV in the region of 7 MeV. The standard deviation in peak centroids contributes an uncertainty of approximately 0.2 keV to the transition energy. When combined with the uncertainty in calibration, we estimate that the standard deviation in the energy should be no greater than 0.5 keV. The error in relative intensity is based on the uncertainty in peak area. In this case the uncertainty in calibration makes a negligible contribution. Also shown in the table are the energies of those final states which have been independently observed in other reactions.[11] For completeness we have included the transitions corresponding to $^{181}Ta(n,\gamma)^{182}Ta$. The Q value obtained here is in excellent agreement with the value of 6062.9 ± 0.5 keV reported by Helmer and Greenwood.[12]

B. The $^{181}Ta(\gamma,n)^{180}Ta$ reaction

The experimental arrangement used for this study is shown in Fig. 1. Monochromatic gamma rays are generated from the capture of neutrons in a source suitably positioned in the reactor core. The gamma rays are extracted through a beam port and collimated to produce a beam of approximately 2 cm diameter with a photon flux of 10^5 s^{-1}. Photoneutrons which result from the interaction between photons in the beam and target nuclei are detected by means of a ^{3}He-filled gridded ionization chamber. A more detailed discussion of the experimental arrangement has been given by Barkman *et al.*[6] These authors also describe the first determination of the tantalum photoneutron threshold using 9-MeV gamma rays resulting from neutron capture in a nickel target.

The energy of a photoneutron group produced by a gamma ray of energy E_γ incident on a target of mass number A with neutron separation energy Sn is

$$E_n=(E_\gamma - S_n - E_x)\,\frac{A-1}{A}\ , \tag{1}$$

where E_x is the excitation energy of the product nucleus. By choosing incident gamma rays with energies close to the neutron separation energy, it is possible to take advantage of the greater efficiency and higher resolution of the ^{3}He detector for lower energy neutrons than were produced in the previous experiment.

For this experiment sources of aluminum and copper were chosen. These produce strong gamma rays with energies of 7724 and 7915 keV, respectively.[13] A target consisting of 4 cm square tantalum sheets stacked to a height of approximately 2.5 cm was placed in the photon beam. The detector wall was approximately 0.5 cm from the target and oriented with its axis perpendicular to the beam direction.

TABLE I. Energies and relative intensities of tantalum capture gamma rays.

Energy (keV) (standard deviation = 0.5 keV)	Relative intensity (10% uncertainty)	Isotope	Final state[a] energy (keV)	Final state spin and parity
5965.29	100	181	97.8	4^-
6062.90	60	181	0.	3^-
6097.58	86	180		
6112.25	38	180	1539.7	$\frac{21}{2}^+$
6180.67	54	180		
6420.00	33	180		
6935.26	36	180	716.59	$\frac{15}{2}^+$

[a] Final state properties taken from Ref. 11. Q values: $^{181}Ta(n,\gamma)^{182}Ta$, 6063.3 ± 0.5 keV; $^{180}Ta(n,\gamma)^{181}Ta$, 7652.3 ± 0.5 keV.

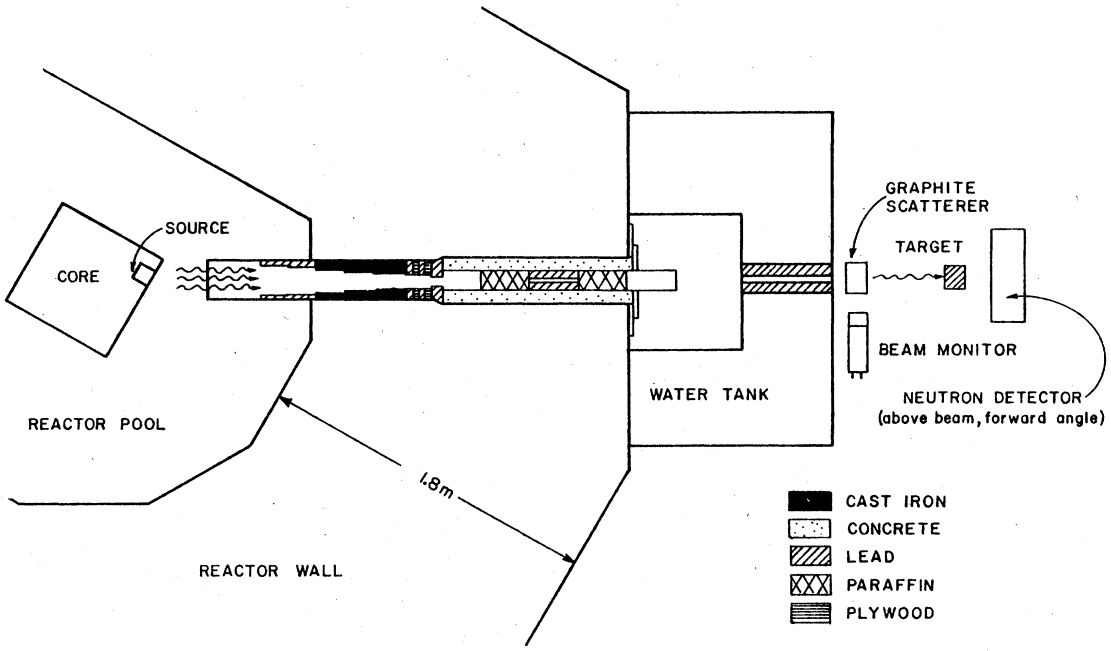

FIG. 1. The experimental arrangement used for the photoneutron study. Sources consisting of either Cu or Al are located in core. The ^{3}He neutron detector is oriented with the axis perpendicular to the beam and was located directly above the tantalum target in this experiment.

The photoneutron spectra resulting from exposure of the target to photons produced by neutron capture in copper or aluminum is shown in Fig. 2. The energy scale for each spectrum was determined by first using a precision pulser to establish the system zero, and then calculating the energy-pulse height relation from the position of the peak produced by thermal energy neutrons. The energy released in the $^3\mathrm{He}(n_{\mathrm{th}},p)^3\mathrm{H}$ reaction is 763.8 ± 0.1 keV.[14] The resolution for these spectra varied from 13 keV (FWHM) at the lowest energy to 20 keV (FWHM) for the highest energy groups. The energies of the photoneutron groups are then determined from the difference between the peak centroid of the particular group and the thermal peak. The relative intensities are determind from the peak areas corrected for the detector efficiency. The energies and relative intensities of the photoneutron groups observed in the two spectra are summarized in Table II. Also listed are the corresponding photoneutron Q values, given by

$$Q = E_\gamma - \frac{A}{A-1}\,E_n, \tag{2}$$

where E_γ is the incident photon energy, A is the target mass number, and E_n is the neutron kinetic energy. The uncertainty in the neutron energy is estimated to be 2 keV, while the relative intensities are uncertain by about 10%.

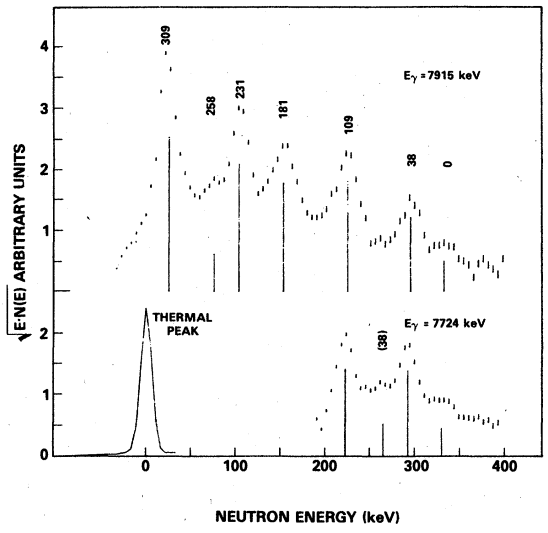

FIG. 2. The photoneutron spectra of tantalum following excitation by capture radiation from copper (top) and aluminum (bottom). The ordinate scale was chosen for clarity of presentation. The aluminum spectrum has been shifted by the energy difference between the Cu and Al radiation so that corresponding final states occur with the same abscissa. Also indicated is the equivalent line spectrum. The weak group indicated as (38) in the aluminum spectrum is believed to result from excitation by $E_\gamma = 7694$ keV.

TABLE II. Neutron groups and associated final states observed in the ^{181}Ta$(\gamma,n)^{180}$Ta reaction.

Neutron energy (keV)	Relative intensity (%)	Q value (keV)	Assigned final state (keV)
	Al E_γ=7724 keV		
145 ± 2	4.6	7578	0
107 ± 2	46	7616	38
37 ± 2	49	7687	109
	Al E_γ=7694		
80 ± 2	6.9	7614	38
	Cu E_γ=7915		
333 ± 2	0.95	7580	0
295 ± 2	6.2	7618	38
225 ± 2	15.3	7688	109
153 ± 2	16.3	7761	181
103 ± 2	24.5	7811	231
76 ± 2	2.1	7838	258
25 ± 2	34.6	7889	309

Average neutron binding energy 7579 ± 2 keV.

III. DISCUSSION

The identification of the $J^\pi = \frac{15}{2}^+$ level at 716.59 keV as the final state for the 6935.26 keV gamma ray in the ^{180}Ta$(n,\gamma)^{181}$Ta reaction is based upon the available mass data,[7] which requires a total energy release of 7693 ± 2 keV. The energy difference between the 6935.26 keV gamma ray and the 6112.25 keV gamma ray is in excellent agreement with the energy difference between the $J^\pi = \frac{15}{2}^+$ level and the $J^\pi = \frac{21}{2}^+$ level at 1539.7 keV. Both these levels have been identified in Coulomb excitation studies.[11] The intensity of the ^{181}Ta$(n,\gamma)^{182}$Ta ground state transition is given as[13] 0.43%, while the thermal cross section for this reaction is 21.0 b.[15] The partial cross section for this transition is thus 90 mb. From the relative intensity and isotopic abundance, the partial cross section for the ^{180}Ta$(n,\gamma)^{181}$Ta transition to the $J^\pi = \frac{15}{2}^+$ state is estimated to be 1.3 b. For a total cross section of 700 ± 200 b (Ref. 15) this would imply an absolute intensity of approximately 0.2%. The relative intensities of the five transitions observed for this reaction are comparable, indicating that they are most probably dipole transitions. If one assumes S-wave capture, the maximum angular momentum transfer in this reaction for these transitions would be $\frac{3}{2}$. This would imply that the target spin is 9 and that the capture state contains significant contributions from both $J = \frac{17}{2}$ and $\frac{19}{2}$ resonances in order to populate with comparable intensity both $J^\pi = \frac{15}{2}^+$ and $J^\pi = \frac{21}{2}^+$ final states. The only resonance reported is at 0.433 eV.[16] We calculate from the resonance parameters quoted that it would account for only some ten to fifteen percent of the thermal cross section.

It is most likely that the transitions observed are electric dipole since these are generally the strongest transitions. In this case the target state would be $J^\pi = 9^-$ and could result from the coupling of a $[514]\frac{9}{2}^-$ proton to a $[624]\frac{9}{2}^+$ neutron as has been previously suggested.[17] The $[514]\frac{9}{2}^-$ proton state has been identified as the first excited state at 6 keV in ^{181}Ta, while the $[624]\frac{9}{2}^+$ neutron state is the ground state of ^{181}W. It must be emphasized, however, that it is not possible to exclude the possibility that the observed transitions are magnetic dipole in character. It is difficult to see how a $J^\pi = 9^+$ state could be formed simply from the available low-lying single-particle states, however.

Decay of this state would have to take place by electron capture to the 641 keV state with $J^\pi = 6^+$ in ^{180}Hf, for which the Q value is 287 keV, or by negatron decay to the 688 keV, $J^\pi = 6^+$ state of ^{180}W with a Q value of 105 keV. The transitions would be third forbidden for which the value of logft is expected to be about 18.[18] The lower limit of 10^{13} yr indicates the value to be greater than 20. This higher value would be consistent with the fact that the decay corresponds to a transition from a state with $K = 9$ to one with $K = 0$.

The highest energy neutron group observed in both the photoneutron spectra, if identified as the ground state transition, leads to a neutron separation energy of 7579 keV. This result then places the 10^{13}-yr state at 73 ± 2 keV above the ground state. The energies of the final states populated by the lower energy neutron groups are then obtained from the Q values in Table II. The assignment is straightforward except for the case of the 80 keV group resulting from photoexcitation with the aluminum capture radiation. It is possible

that this group could have been excited by the much stronger 7724-keV ground state. This interpretation would require the existence of a level at 68 keV. The interpretation suggested in the Table II does not require the introduction of an additional excited state. Since the intensity of the 7694 keV transition is only five percent of the 7724-keV intensity, the neutron yield per incident photon would be approximately three times greater for the 80 keV group than for the corresponding 107 keV group if this interpretation is accepted.

The level structure revealed in this experiment is compared with the results of a previous study of the ^{181}Ta$(p,d)^{180}$Ta reaction[17] in Table III. The spin and parity of the states suggested by the previous work are also listed. Five of the states observed in this work correspond well with levels populated in the neutron pickup process. Two additional states at 231 and 258 keV are populated in the photoneutron reaction.

It is to be noted that the ground state is populated with much less probability than the 38 keV state in the photoneutron reaction. The intensity ratio is approximately 0.1 for $E_\gamma = 7724$ keV and 0.15 for $E_\gamma = 7915$ keV. This suggests that the character of these two states may be quite different. This is at variance with the identification of the 38 keV state as the first member of the rotational band built upon the $\{\frac{7}{2}^+[404]p, \frac{9}{2}^+[624]n\}$ configuration suggested in Ref. 17. For the $J^\pi = 1^+$ and 2^+ assignments, both states would have to be populated by p-wave emission following electric dipole excitation. It is difficult to understand why the ground state transition is so weak in this case, particularly when one considers the fact that the $l=1$ penetrability factor would favor the higher energy group.

Warde *et al.*[17] cite evidence that there are a pair of closely spaced levels at 173 keV, with spins and parities $J^\pi = 4^+$ and 8^+. In the photoneutron experiment the $J^\pi = 4^+$ member may be populated by p-wave emission. The $J^\pi = 8^+$ state is much less likely to be populated with comparable intensity, since this would require f-wave emission for which the penetrability is lower by approximately three orders of magnitude.

TABLE III. Comparison of final states observed in the ^{181}Ta$(\gamma,n)^{180}$Ta and ^{181}Ta$(p,d)^{180}$Ta reactions.

Level energy (keV) (γ,n)	Level energy (keV) (p,d)	J^π from Ref. 17
0	0	1^+
38(2)	41	2^+
73(2)[a]		9^-
109(2)	106	3^+
181(2)	173	$4^+, 8^+$
231(2)		
258(2)		
309(2)	302	5^+

[a]This level is inferred from the difference in (n,γ) and (γ,n) Q values and is not observed directly in the photoneutron reaction.

IV. CONCLUSIONS

The neutron separation energy for ^{181}Ta is 7579 ± 2 keV. The configuration with a half-life of greater than 10^{13} y is located 73 ± 2 keV above the 8-h ground state of ^{180}Ta and has $J=9$. There are at least seven excited states in this nucleus below an excitation energy of 310 keV. The photoneutron emission to the ground state appears to be inhibited relative to the first excited state. It is difficult to understand why this should be so if these two states are of similar character as has been previously proposed.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial assistance of the Natural Sciences and Engineering Research Council of Canada and the Province of Ontario. The authors wish to thank the staff of the McMaster Nuclear Reactor.

[1]F. A. White, T. L. Collins, and F. M. Rourke, Phys. Rev. 97, 1786 (1956).
[2]A. H. Wapstra and K. Bos., At. Data Nucl. Data Tables 20, 1 (1977).
[3]H. N. Brown, W. L. Bendel, F. J. Shore, and R. A. Becker, Phys. Rev. 84, 292 (1951).
[4]K. N. Geller, J. Halpern, and E. G. Muirhead, Phys. Rev. 118, 1302 (1960).
[5]R. G. Lanier, T. J. Larsen, D. H. White, and M. C. Gregory, Bull. Am. Phys. Soc. 17, 899 (1972).
[6]J. N. Barkman, J. E. McFee, T. J. Kennett, and W. V. Prestwich, Z. Phys. A 289, 325 (1979).
[7]K. S. Sharma, R. J. Ellis, V. P. Derenchuk, R. C. Barber, and H. E. Duckworth, Phys. Lett. 91B, 211 (1980).
[8]L. Nichol, A. Lopez, A. Robertson, W. V. Prestwich, and T. J. Kennett, Nucl. Instrum. Methods 81, 263 (1970).
[9]A. Robertson, W. V. Prestwich, and T. J. Kennett, Nucl. Instrum. Methods 100, 317 (1972).
[10]T. J. Kennett, M. A. Islam, and W. V. Prestwich, Can. J. Phys. 59, 93 (1981).
[11]*Table of Isotopes, 7th ed.*, edited by C. M. Lederer and

V. S. Shirley (Wiley, New York, 1978).
[12]R. G. Helmer, R. C. Greenwood, and C. W. Reich, Nucl. Phys. A168, 449 (1971).
[13]N. C. Rasmussen, Y. Hukai, T. Inouye, and V. J. Orphan, M.I.T. Report No. MITNE-85.
[14]R. G. Salgo, H. H. Staub, H. Winkler, and F. Zamboni, Nucl. Phys. 53, 457 (1964).
[15]Brookhaven National Laboratory Report No. BNL 325, 3rd ed., Vol. 1, 1973.
[16]J. E. Evans, E. G. Joki, and R. R. Smith, Phys. Rev. 97, 565 (1955).
[17]E. Warde, R. Seltz, G. Costa, D. Magnac, and C. Gerardin, J. Phys. (Paris) Lett. 40, L-1 (1979).
[18]M. A. Preston, *Physics of the Nucleus* (Addison-Wesley, Reading, Mass. 1962).