# Nuclear levels in the doubly odd $^{182}$Ta nucleus

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(Received 19 December 1978)

The low-energy part of the radiation emitted after thermal neutron capture in $^{181}$Ta has been investigated by different experimental techniques: Gamma-ray measurements were performed with a diffraction spectrometer. The conversion electron spectrum was recorded with a $\beta$ spectrograph and measurements of gamma-gamma coincidences were carried out. For ten rotational bands in $^{182}$Ta, which were already proposed in an earlier work, a large amount of new decay data has been obtained and for most of these bands higher rotational levels have been found. These ten bands have for their lowest level the following energies and $I^\pi K$ values: 0 keV $3^-3$, 16 keV $5^+5$, 114 keV $4^-4$, 150 keV $4^+4$, 173 keV $5^-5$, 250 keV $3^+3$, 270 keV $2^-2$, 402 keV $2^+2$, 547 keV $3^-3$, and 558 keV $1^-0$. New rotational bands with the following band head energies and structure have been established: 443.6 keV $\{5/2^+[402]_p, 3/2^-[512]_n\}_{K=1}$, 593.0 keV $\{7/2^+[404]_p, 9/2^+[624]_n\}_{K=1}$, and 647.6 keV $\{5/2^+[402]_p, 1/2^-[510]_n\}_{K=2}$. Tentative band heads have been proposed at 390, 740, and 749 keV with $I^\pi K$ values $6^+6$, $2^-2$, and $3^+3$. For the sake of completeness, previously found levels with $K$ values ranging from seven to ten are also discussed.

[NUCLEAR REACTIONS $^{181}$Ta$(n,\gamma)$, $E$=thermal; measured $E_\gamma$, $I_\gamma$, $I_{ce}$, $\gamma\gamma$ coincidences. $^{182}$Ta deduced levels $J$, $\pi$, $K$, $cc$, $\gamma$ multipolarities, $J$ of $^{181}$Ta neutron resonances. Natural targets.]

## I. INTRODUCTION

The odd-odd nucleus $^{182}$Ta has been investigated during the last twenty years by different experimental methods. The first studies, before 1960, using the $(\eta,\gamma)$ reaction (see, e.g., Ref. 1) were not able to provide any insight into the structure of this complex nucleus, due to the lack of resolving power of the instruments available at that time.

In 1961, the decay of $^{182}$Hf (Refs. 2–4) and $^{182}$Ta$^m$ (Refs. 5–8) was studied, but it was not until 1968 that Clark and Stabenau[9] clearly demonstrated the relationship between the 16 min isomeric state, the ground state, and a low-lying 0.3 s isomer, discovered by Campbell and Good.[10] This relationship had already been proposed from model considerations by Bizzarri *et al.*[6] Indications about the spin values of some low-lying excited levels were obtained from $(n,\gamma)$ experiments with resonant neutrons[11,12] and from measurements of the conversion spectrum following thermal neutron capture.[13–15] In 1971, Helmer, Greenwood, and Reich[16] published the results of a series of experiments on $^{182}$Ta: They studied the decay of $^{182}$Hf and $^{182}$Ta$^m$, together with the primary gamma radiation, resulting from the capture of thermal and 2 keV neutrons and the low-energy gamma radiation from thermal neutron capture. This investigation, combined with data from the $^{181}$Ta$(d,p)^{182}$Ta reaction,[17] yielded a level scheme containing 53 excited levels below 1 MeV. Of these levels, 37 were interpreted as members of 15 rotational bands, involving 9 two-particle configurations. Reich, Helmer, and Greenwood[18] also studied the influence of the Coriolis coupling on the four lowest negative parity bands, which came out to be quite decisive, especially for several transition probabilities.

Although the level scheme known so far gave a comprehensible picture in terms of a two-particle model, most of the spin values were confined between $I=2$ and $I=5$, thereby seriously truncating the rotational bands. On the other hand, a confident location of low-energy transitions was hindered by the limited energy resolution of Ge(Li) singles spectroscopy; also weaker transitions could not be detected. There also remained several intense transitions, which did not fit between the observed levels.

In an attempt to clarify these and other problems, a study of the low-energy transitions following thermal neutron capture in $^{181}$Ta was undertaken. The gamma radiation was observed by means of a bent-crystal diffraction spectrometer and in a $\gamma\gamma$-coincidence experiment. A new measurement of the conversion electrons was also carried out to gain more information about the multipolarities of the transitions. Parts of the results of these experiments were published previously.[19-21]

## II. EXPERIMENTAL METHODS AND RESULTS

### A. High-resolution gamma singles spectroscopy

The low-energy $\gamma$-ray spectrum was recorded with the bent-crystal diffraction (BCD) spectrometer of the Technical University, Munich, located at the DR-3 reactor of the AEK, Risø. This spectrometer has been described previously.[22] The target consisted of a foil of natural Ta (99.988% $^{181}$Ta and 0.012% $^{180}$Ta) with dimensions $2.5\times 0.5\times 0.0035$ cm$^3$. The foil was either clamped between Al U-shaped profiles or, in order to reduce the background at low energies, freely suspended.

In the runs with the clamped target, the resolution was

$$\Delta E(\mathrm{FWHM}) = 4.1\times 10^{-6} E^2/n \ , \qquad (1)$$

where FWHM stands for full width at half maximum, $n$ stands for the diffraction order, and $\Delta E$ and $E$ are given in keV. The freely suspended target yielded a somewhat larger linewidth. In the most favorable region, 200–400 keV, transitions with intensities down to about $4\times 10^{-4}$ photons per captured neutron could be observed.

The spectrum contains transitions in five different nuclei: $^{181}$Ta and $^{182}$Ta, formed by capture in $^{180}$Ta and $^{181}$Ta; $^{182}$W, the radioactive daughter of $^{182}$Ta; and, because of the high cross section for thermal neutron capture in $^{182}$Ta($\sigma$ = 8200 b, Ref. 23) and the long half-life of $T_{1/2}$ = 115 days, $^{183}$Ta and its daughter $^{183}$W. The origin of the different transitions was determined by comparing the time dependence of their intensities with the calculated $I(t)$ functions.

So, for instance, the intensity of a transition in $^{183}$Ta is given by

$$I(t) = \frac{nN\sigma_1\sigma_2\phi^2}{\sigma_2\phi + \lambda_2 - \sigma_1\phi}\left[\exp(-\sigma_1\phi t) - \exp(-\sigma_2\phi - \lambda_2)t\right], \qquad (2)$$

where $n$ stands for the number of photons per captured neutron, $N$ for the original number of $^{181}$Ta nuclei, $\sigma_1$ and $\sigma_2$ for the cross section for thermal neutron capture in $^{181}$Ta and $^{182}$Ta, $\phi$ for the thermal neutron flux, and $\lambda_2$ for the $^{182}$Ta to $^{182}$W $\beta$-decay constant. The neutron flux $\phi$ could be determined from the time dependence of the intensities of some strong, well-known transitions in $^{183}$Ta as $\phi = (3.9\pm 0.5)\times 10^{13}$ cm$^{-2}$ s$^{-1}$.

The spectrum was recorded from 47 keV in first order to 3500 keV in fifth order with the clamped target, and from 40 keV in first order to 700 keV in fifth order with the unclamped target. Three different runs were made with the clamped target to follow the intensity changes.

The nonlinearity of the spectrometer is corrected for by comparing spectrometer readings of intense lines in different diffraction orders, as described in Ref. 22. The energies were calibrated using the tungsten $K\alpha_1$ Roentgen ray as a standard.[24]

After correcting the intensities for gamma absorption in the source material, using the measured dimensions of the source and assuming that the target was completely parallel to the $\gamma$-ray direction, the values for low-energy transitions ($E < 270$ keV) turned out to be higher by a factor of up to 2 when compared with the results of Helmer *et al.*[16] Therefore, the parameters involved in the correction were least-squares fitted, so as to minimize the deviations in intensity for nine strong transitions ($E$ = 47.8, 114.4, 133.9, 156.1, 173.2, 190.3, 297.1, 360.5, and 408.6 keV). This procedure permitted a decrease in the chi-squared value from 20 to 6, while the values of the parameters remained compatible with the measured dimensions and the experimental possibilities for the angle between source and observed $\gamma$ rays. These parameter values were then used in the calculation of the intensity corrections for all transitions.

The final values for energy and intensity are calculated as the weighted means of the individual measurements. The number of these varies from 1 to 15, depending on energy and intensity of a transition. These measurements yielded about 600 transitions in $^{182}$Ta, given in Table I.

Because separate experiments for the determination of absolute intensities were not carried out, the intensities are given in relative units. The intensity for the 270.40 keV line was normalized to 100. From the total population of the ground state, this intensity can be estimated to be $I_\gamma \approx 15$ per 100 captured neutrons.

### B. Conversion electron measurement

The $\beta$ spectrograph[25] at the IRT-2000 reactor in Riga (USSR) was used for the measurement of

TABLE I. Data on low-energy $\gamma$-ray transitions. In columns 4 and 9 all assignments possible from an experimental point of view are given. Those in parentheses are more or less unlikely from model-dependent considerations. When more than one assignment is possible, the least probable ones (on both experimental and theoretical grounds) are also enclosed in parentheses.

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks |
|---|---|---|---|---|
| 987.48(18) | 3.1 | 27 | | |
| 984.64(22) | 6.5 | 37 | | |
| 959.02(18) | 3.9 | 26 | | |
| 909.15(16) | 1.9 | 36 | | |
| 905.94(26) | 3.2 | 33 | | |
| 894.75(13) | 3.0 | 49 | | |
| 887.75(28) | 1.7 | 31 | | |
| 885.75(25) | 3.1 | 27 | | |
| 875.25(16) | 3.8 | 15 | | |
| 871.28(8) | 4.9 | 12 | | |
| 837.52(22) | 1.1 | 42 | | |
| 833.8(4) | 1.0 | 39 | | |
| 818.12(8) | 2.0 | 27 | | |
| 804.26(18) | 2.9 | 50 | | |
| 796.96(12) | 2.4 | 18 | | a |
| 795.94(20) | 1.2 | 42 | | |
| 791.86(8) | 3.6 | 12 | | a |
| 790.10(9) | 1.6 | 17 | | |
| 773.45(11) | 1.4 | 22 | | |
| 764.46(12) | 1.5 | 33 | | |
| 760.13(9) | 2.5 | 19 | | |
| 759.85(7) | 2.9 | 16 | | |
| 744.94(9) | 2.1 | 22 | | |
| 739.37(5) | 1.9 | 28 | | |
| 732.41(15) | 0.87 | 33 | 749 – 16 | e |
| 728.94(8) | 5.7 | 48 | | |
| 727.92(9) | 1.6 | 19 | | |
| 726.06(5) | 3.1 | 12 | | a |
| 725.33(8) | 4.9 | 52 | | |
| 721.65(16) | 0.76 | 35 | | |
| 717.21(5) | 4.9 | 9 | | a |
| 709.03(8) | 2.0 | 14 | | |
| 708.10(22) | 0.79 | 52 | (724 – 16) | |
| 683.58(14) | 1.6 | 15 | 781 – 98 | |
| 675.65(6) | 1.4 | 11 | | |
| 668.39(9) | 1.1 | 23 | | a |
| 661.56(6) | 1.7 | 15 | | |
| 657.25(5) | 2.3 | 9 | | |
| 651.34(7) | 0.98 | 14 | 651 – 0<br>(749 – 98) | |
| 647.46(5) | 1.2 | 11 | 647 – 0 | |
| 645.89(5) | 1.2 | 12 | | |
| 642.58(6) | 0.90 | 19 | | |
| 633.59(11) | 0.57 | 22 | | |
| 632.03(5) | 1.3 | 22 | | |
| 629.64(4) | 2.1 | 7 | | |
| 627.25(6) | 0.75 | 20 | | |
| 617.52(14) | 0.34 | 49 | | |
| 613.23(14) | 0.52 | 33 | 776 – 163 | |
| 605.72(11) | 0.65 | 23 | | |
| 603.14(4) | 1.4 | 9 | 776 – 173 | |
| 602.10(11) | 0.98 | 37 | | |
| 600.94(6) | 1.2 | 30 | | |
| 597.72(24) | 0.59 | 35 | 835 – 237 | |
| 593.50(7) | 0.62 | 19 | | |
| 591.05(5) | 0.56 | 16 | | |
| 589.50(6) | 0.87 | 19 | | |
| 584.22(5) | 0.63 | 14 | | |
| 583.07(8) | 0.43 | 27 | | |
| 579.97(5) | 0.36 | 67 | | |
| 574.31(4) | 1.0 | 16 | | |
| 573.73(15) | 0.31 | 59 | (724 – 150) | |
| 567.71(5) | 0.81 | 12 | 805 – 237 | |
| 566.92(9) | 0.59 | 30 | 817 – 250 | |
| 563.54(19) | 0.51 | 34 | 579 – 16<br>(856 – 293)<br>(960 – 396) | e<br>e<br>e |
| 559.47(3) | 1.7 | 28 | | |
| 559.10(6) | 2.1 | 29 | | |
| 558.29(9) | 0.54 | 16 | 558 – 0 | |
| 553.71(8) | 0.67 | 17 | | |
| 552.65(3) | 1.6 | 22 | | |
| 552.28(6) | 1.1 | 38 | | |
| 550.25(16) | 0.52 | 27 | 648 – 98 | e |
| 549.51(4) | 0.78 | 12 | (940 – 390) | |
| 547.16(4) | 0.67 | 14 | 547 – 0 | |
| 541.01(6) | 0.49 | 19 | | |
| 538.85(9) | 0.52 | 38 | 776 – 237 | e |
| 536.80(4) | 1.1 | 19 | 651 – 114 | a |
| 535.26(7) | 2.9 | 44 | | |
| 530.633(26) | 1.4 | 7 | 628 – 98 | |
| 530.16(8) | 1.0 | 46 | | |
| 525.20(8) | 0.47 | 44 | | |
| 514.70(4) | 0.25 | 73 | | |
| 514.11(4) | 0.51 | 31 | 628 – 114 | |
| 513.91(5) | 0.99 | 59 | | |
| 513.11(4) | 1.6 | 40 | | |
| 512.43(4) | 2.0 | 47 | 781 – 269 | |
| 512.27(3) | 0.55 | 30 | | |
| 511.70(3) | 0.45 | 38 | | |
| 511.20(5) | 6.9 | 22 | | |
| 510.952(20) | 0.49 | 16 | | |
| 510.67(5) | 1.7 | 53 | | |
| 510.44(4) | 0.44 | 94 | | |
| 509.936(21) | 2.1 | 22 | 673 – 163 | |
| 509.31(5) | 0.65 | 75 | | |
| 508.92(4) | 2.3 | 38 | | |
| 508.65(5) | 0.43 | 66 | | |
| 508.02(3) | 0.20 | 59 | | |
| 507.74(5) | 2.5 | 73 | | |
| 506.04(4) | 1.2 | 27 | | a |
| 505.14(5) | 0.46 | 47 | | |

TABLE I. (*Continued*)

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks |
|---|---|---|---|---|
| 503.83(7) | 0.66 | 17 | | |
| 501.077(30) | 1.3 | 8 | 651 – 150 | |
| 499.31(4) | 1.3 | 12 | | |
| 499.05(4) | 1.7 | 19 | 749 – 250 | |
| 496.73(5) | 0.54 | 17 | | |
| 495.052(23) | 1.5 | 18 | | |
| 491.26(7) | 0.61 | 34 | 491 – 0 | e |
| 490.00(5) | 0.85 | 19 | | |
| 489.525(22) | 1.4 | 7 | (783 – 293) | e |
| 488.89(8) | 0.45 | 40 | 805 – 316 | e |
| 488.44(7) | 0.47 | 30 | 781 – 293 | |
| 483.67(9) | 0.58 | 15 | 776 – 293 | e |
| 482.17(7) | 0.83 | 51 | 720 – 237 | |
| 481.241(15) | 4.0 | 14 | | |
| 480.022(15) | 2.1 | 14 | 480 – 0 | |
| | | | (749 – 269) | |
| 478.694(19) | 1.5 | 13 | 749 – 270 | |
| 477.383(24) | 1.4 | 13 | | |
| 476.07(4) | 0.95 | 24 | | |
| 474.60(6) | 0.90 | 46 | | |
| 473.796(16) | 2.0 | 8 | 572 – 98 | |
| 471.33(8) | 0.45 | 31 | | |
| 468.29(6) | 0.47 | 19 | | |
| 466.722(20) | 1.3 | 10 | | |
| 465.11(9) | 0.48 | 51 | 781 – 316 | |
| 464.56(5) | 0.63 | 11 | 702 – 237 | |
| 463.08(3) | 0.61 | 14 | | |
| 461.29(5) | 0.41 | 27 | | |
| 456.57(3) | 0.54 | 14 | 817 – 361 | e |
| 453.74(6) | 0.40 | 16 | 724 – 270 | e |
| 449.137(22) | 0.82 | 9 | 720 – 270 | |
| 448.34(4) | 0.44 | 22 | | |
| 447.03(5) | 0.65 | 46 | | |
| 446.76(8) | 0.35 | 42 | | |
| 443.95(6) | 0.50 | 58 | | |
| 443.591(13) | 1.8 | 6 | 444 – 0 | |
| 440.75(17) | 0.20 | 49 | | |
| 437.37(4) | 0.29 | 28 | | |
| 434.55(4) | 0.31 | 18 | | |
| 432.81(6) | 0.27 | 31 | 547 – 114 | |
| | | | (835 – 403) | e |
| 432.327(28) | 0.53 | 15 | | |
| 431.68(5) | 0.35 | 26 | 702 – 270 | e |
| 431.18(7) | 0.30 | 41 | | |
| 428.29(4) | 0.38 | 20 | | |
| 425.34(13) | 0.21 | 41 | | |
| 423.66(3) | 0.78 | 14 | | |
| 423.290(23) | 0.72 | 13 | | |
| 422.76(7) | 0.45 | 18 | 660 – 237 | e |
| 420.410(14) | 1.3 | 6 | | |
| 416.95(6) | 0.49 | 15 | 781 – 364 | |
| 416.36(5) | 0.26 | 25 | 579 – 163 | |
| 415.755(26) | 0.60 | 19 | | |
| 414.446(30) | 0.58 | 18 | | |
| 412.14(4) | 0.26 | 22 | | |
| 408.67(4) | 0.35 | 14 | (572 – 163) | |
| | | | 805 – 396 | |
| 406.885(12) | 1.4 | 11 | | |
| 406.211(10) | 1.9 | 7 | | |
| 405.747(18) | 0.69 | 13 | | |
| 403.870(28) | 0.54 | 16 | | |
| 402.619(7) | 47 | 6 | 403 – 0 | |
| 402.42(3) | 1.2 | 54 | | |
| 402.12(3) | 0.55 | 30 | | |
| 401.58(4) | 1.0 | 21 | | |
| 401.221(10) | 1.7 | 6 | 651 – 250 | |
| 399.638(17) | 0.66 | 11 | | |
| 398.85(4) | 1.1 | 50 | | |
| 397.909(25) | 0.36 | 55 | | a |
| 397.21(5) | 0.48 | 55 | | |
| 396.952(9) | 2.4 | 6 | 547 – 150 | |
| 396.031(12) | 0.67 | 9 | | |
| 395.013(26) | 0.29 | 23 | 411 – 16 | |
| 394.01(3) | 1.1 | 58 | | |
| 392.13(4) | 0.47 | 47 | | |
| 391.83(6) | 0.45 | 26 | 835 – 444 | e |
| 391.140(16) | 0.65 | 8 | 628 – 237 | |
| 390.40(3) | 0.26 | 24 | 488 – 98 | |
| 389.87(4) | 0.51 | 25 | | |
| 389.528(20) | 0.34 | 14 | | |
| 386.27(4) | 0.64 | 12 | 776 – 390 | |
| | | | 783 – 396 | |
| 383.61(4) | 0.16 | 76 | | |
| 383.245(16) | 0.68 | 14 | | a |
| 382.186(10) | 2.5 | 5 | 480 – 98 | |
| 381.81(5) | 0.29 | 41 | | |
| 381.49(3) | 0.47 | 12 | | |
| 380.919(26) | 0.27 | 27 | | |
| 377.248(7) | 4.6 | 5 | 648 – 270 | |
| 375.72(6) | 0.34 | 33 | | |
| 373.880(7) | 1.9 | 6 | 390 – 16 | |
| | | | 547 – 173 | e |
| 370.42(4) | 0.25 | 18 | | a |
| 368.984(21) | 0.22 | 17 | | |
| 367.551(17) | 0.53 | 22 | | |
| 367.36(3) | 0.34 | 26 | | |
| 365.73(5) | 0.21 | 18 | 480 – 114 | c |
| 362.915(21) | 0.53 | 9 | | |
| 361.786(23) | 0.48 | 10 | | |
| 360.991(26) | 0.76 | 51 | | |
| 360.531(8) | 6.9 | 6 | 361 – 0 | |
| 359.001(16) | 0.42 | 11 | 720 – 361 | |
| 358.40(6) | 0.19 | 60 | 651 – 293 | e |
| | | | 940 – 581 | |
| 357.742(20) | 0.21 | 68 | | |
| 357.45(4) | 0.48 | 48 | | |
| 355.477(14) | 0.40 | 10 | 506 – 150 | |
| 352.059(9) | 0.72 | 9 | | |
| 349.937(7) | 1.3 | 6 | | |
| 348.086(7) | 0.95 | 7 | 364 – 16 | |
| 346.762(28) | 0.72 | 62 | | |
| 346.465(7) | 3.7 | 7 | 749 – 403 | |

TABLE I. (*Continued*)

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i-E_f$ (keV) | Remarks |
|---|---|---|---|---|
| 345.277(9) | 0.52 | 12 | | |
| 343.912(18) | 0.23 | 19 | 581 − 237 | |
| | | | (835 − 491) | e |
| 343.233(17) | 0.24 | 24 | | |
| 342.544(23) | 0.21 | 24 | 506 − 163 | |
| 337.291(20) | 0.32 | 22 | | |
| 336.953(25) | 0.30 | 34 | 817 − 480 | |
| 333.52(3) | 0.33 | 29 | | |
| 333.28(4) | 0.37 | 20 | | |
| 332.298(27) | 0.23 | 24 | 506 − 173 | e |
| 330.23(3) | 0.23 | 37 | | |
| 326.26(3) | 0.26 | 35 | | |
| 326.019(19) | 0.43 | 11 | | |
| 325.041(14) | 0.41 | 10 | 805 − 480 | |
| 323.906(23) | 0.26 | 20 | | |
| 322.546(6) | 1.5 | 6 | 593 − 270 | |
| 321.355(11) | 0.43 | 10 | 724 − 403 | |
| 319.78(4) | 0.19 | 42 | | |
| 319.18(3) | 0.19 | 31 | | |
| 318.381(23) | 0.28 | 15 | 335 − 16 | |
| 317.624(28) | 0.55 | 43 | | |
| 317.406(23) | 0.37 | 12 | | |
| 317.18(4) | 0.17 | 48 | | |
| 316.465(9) | 0.82 | 19 | | a |
| 316.156(11) | 0.68 | 13 | | a |
| 315.003(11) | 0.46 | 11 | 488 − 173 | |
| 310.534(27) | 0.20 | 17 | | |
| 308.85(6) | 0.22 | 35 | 856 − 547 | |
| 308.683(22) | 0.23 | 33 | 673 − 364 | |
| 308.413(7) | 0.91 | 7 | | |
| 306.755(27) | 0.24 | 16 | 480 − 173 | |
| 305.52(3) | 0.15 | 33 | 749 − 444 | |
| 300.649(16) | 0.26 | 14 | 961 − 660 | |
| 299.33(4) | 0.19 | 45 | 660 − 361 | |
| | | | (702 − 403) | |
| 298.501(13) | 0.42 | 10 | 396 − 98 | |
| 297.123(5) | 24 | 6 | 547 − 250 | |
| 296.537(8) | 0.78 | 18 | 740 − 444 | |
| 295.659(29) | 0.61 | 52 | | |
| 293.62(4) | 0.19 | 26 | | |
| 292.520(27) | 0.21 | 32 | | |
| 291.900(24) | 0.43 | 40 | | |
| 290.363(6) | 0.84 | 8 | 856 − 566 | |
| 289.64(4) | 0.23 | 43 | | |
| 289.152(7) | 0.63 | 8 | | |
| 287.758(8) | 0.48 | 15 | | a |
| 287.135(6) | 0.89 | 11 | 648 − 361 | |
| 286.861(6) | 0.85 | 10 | 651 − 364 | |
| 286.442(5) | 0.77 | 12 | | a |
| 285.17(3) | 0.22 | 40 | | |
| 284.584(17) | 0.88 | 49 | | |
| 284.252(22) | 0.77 | 45 | | |
| 284.117(5) | 1.00 | 7 | | |
| 283.430(18) | 0.78 | 53 | | |
| 282.026(12) | 0.31 | 12 | 396 − 114 | |
| 281.72(3) | 0.22 | 35 | | |
| 280.850(27) | 0.25 | 57 | | |
| 280.441(9) | 0.29 | 12 | | |
| 280.196(16) | 0.35 | 23 | | |
| 279.777(10) | 0.34 | 14 | 940 − 660 | |
| 278.705(22) | 0.26 | 22 | 572 − 293 | |
| 278.244(7) | 0.37 | 10 | | |
| 277.743(19) | 0.24 | 26 | | |
| 277.640(26) | 0.25 | 26 | | |
| 276.853(18) | 0.25 | 45 | | |
| 276.713(5) | 0.96 | 8 | 547 − 270 | e |
| 276.514(9) | 0.41 | 18 | | |
| 276.037(12) | 0.24 | 18 | | |
| 275.444(13) | 1.3 | 36 | | |
| 274.855(4) | 1.3 | 7 | | |
| 270.406(4) | 100 | 6 | 270 − 0 | |
| 269.734(18) | 0.27 | 31 | | |
| 269.646(17) | 0.74 | 54 | 835 − 566 | e |
| 268.712(7) | 0.45 | 9 | | |
| 268.19(5) | 0.20 | 69 | 506 − 237 | e |
| 267.908(5) | 0.82 | 7 | 628 − 361 | |
| 263.91(3) | 0.14 | 39 | | |
| 262.666(16) | 0.20 | 20 | 361 − 98 | |
| 262.328(8) | 0.20 | 38 | | |
| 262.11(6) | 0.21 | 47 | | |
| 261.93(4) | 0.11 | 52 | | |
| 261.175(28) | 0.15 | 33 | 411 − 150 | |
| 260.085(4) | 1.5 | 6 | 740 − 480 | e |
| 259.196(4) | 1.2 | 7 | | |
| 258.818(12) | 0.32 | 13 | | |
| 258.551(11) | 0.32 | 13 | 961 − 702 | |
| 257.817(10) | 0.47 | 29 | | |
| 257.639(6) | 0.54 | 10 | 749 − 491 | ae |
| 257.141(19) | 0.35 | 23 | | |
| 255.607(8) | 0.33 | 13 | 506 − 250 | |
| 252.769(5) | 1.2 | 7 | 269 − 16 | |
| 251.990(20) | 0.30 | 45 | | |
| 251.772(6) | 0.50 | 9 | | |
| 251.322(7) | 0.42 | 9 | 817 − 566 | |
| 250.972(6) | 0.54 | 8 | 488 − 237 | |
| 249.955(7) | 0.29 | 13 | 250 − 0 | e |
| 248.953(16) | 0.20 | 26 | | |
| 248.701(11) | 0.20 | 17 | 740 − 491 | |
| 248.268(21) | 0.17 | 23 | 411 − 163 | |
| 247.683(19) | 0.67 | 47 | | |
| 246.204(5) | 1.2 | 10 | 361 − 114 | |
| 244.808(4) | 1.5 | 6 | 579 − 335 | |
| | | | 647 − 403 | |
| 242.745(8) | 0.43 | 9 | 480 − 237 | |
| 242.186(7) | 0.37 | 11 | | |
| 240.631(12) | 0.36 | 22 | | |
| 239.513(13) | 0.25 | 17 | 720 − 480 | |
| 237.761(5) | 0.57 | 9 | | |
| 237.287(4) | 1.1 | 7 | 237 − 0 | |
| 236.561(4) | 0.79 | 7 | 506 − 269 | |
| 234.276(9) | 0.33 | 14 | 781 − 547 | |
| 233.714(4) | 2.8 | 6 | | |

TABLE I. (*Continued*)

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks |
|---|---|---|---|---|
| 233.603(21) | 0.30 | 52 | | |
| 233.447(16) | 0.33 | 29 | | |
| 233.24(9) | 0.70 | 33 | 396 – 163 | |
| 232.079(9) | 0.27 | 16 | 628 – 396 | |
| 231.473(5) | 0.72 | 8 | | |
| 230.440(11) | 0.23 | 18 | | b |
| 228.713(4) | 1.3 | 7 | | |
| 228.117(6) | 0.28 | 13 | 720 – 491 | |
| 227.112(12) | 0.23 | 21 | 390 – 163 | |
| 226.001(18) | 0.18 | 22 | | |
| 223.761(7) | 0.71 | 10 | | |
| 222.541(7) | 0.31 | 13 | 666 – 444 | |
| 220.227(17) | 0.17 | 31 | | |
| 220.16(4) | 0.28 | 47 | 940 – 720 | e |
| 218.550(14) | 0.29 | 15 | 316 – 98 | |
| 218.235(23) | 0.26 | 47 | | |
| 216.822(14) | 0.20 | 22 | 783 – 566 | |
| 215.04(4) | 0.25 | 51 | | |
| 214.207(3) | 2.3 | 6 | 364 – 150 | |
| 212.124(7) | 0.28 | 19 | | |
| 210.544(3) | 3.3 | 6 | 702 – 491 | |
| 209.633(4) | 0.70 | 3 | 480 – 270 | |
| 205.662(19) | 0.28 | 44 | | |
| 204.986(10) | 0.43 | 16 | | b |
| 204.039(4) | 1.00 | 7 | 648 – 444 | |
| 203.53(3) | 0.25 | 43 | | |
| 202.950(12) | 0.26 | 31 | | |
| 197.604(6) | 0.43 | 13 | | |
| 196.24(4) | 0.17 | 81 | 856 – 660 | |
| 196.056(15) | 0.23 | 22 | | |
| 195.329(5) | 0.64 | 9 | 488 – 293 | |
| 195.111(3) | 2.8 | 6 | 293 – 98 | |
| 193.222(5) | 0.53 | 10 | | |
| 193.087(8) | 0.33 | 15 | | |
| 190.338(3) | 7.9 | 7 | 593 – 403 | |
| 189.909(7) | 0.27 | 19 | 856 – 666 | |
| 189.076(6) | 0.33 | 17 | | |
| 188.662(22) | 0.30 | 34 | 817 – 628 | e |
| 185.917(7) | 0.36 | 24 | | |
| 185.822(18) | 0.19 | 36 | | |
| 185.591(4) | 0.60 | 13 | | a |
| 184.902(6) | 0.39 | 18 | | |
| 184.859(14) | 0.35 | 26 | 581 – 396 | |
| 184.809(26) | 0.40 | 45 | 673 – 488 | e |
| 184.560(6) | 0.44 | 15 | | |
| 183.628(6) | 0.56 | 29 | | |
| 182.750(3) | 1.9 | 7 | 547 – 364 | |
| 181.620(14) | 0.39 | 39 | | |
| 180.970(12) | 0.38 | 47 | | |
| 180.903(4) | 0.76 | 9 | | |
| 180.271(6) | 0.66 | 26 | | |
| 178.969(5) | 0.46 | 13 | | b |
| 178.621(3) | 3.4 | 7 | 293 – 114 | |
| 177.329(3) | 1.3 | 8 | | |
| 176.1569(30) | 6.6 | 12 | | a |
| 175.991(16) | 0.35 | 29 | | |
| 174.722(6) | 0.35 | 16 | 666 – 491 | |
| 174.453(8) | 0.32 | 20 | 740 – 566 | |
| 174.268(5) | 0.42 | 14 | | |
| 173.292(8) | 1.9 | 29 | | |
| 173.2035(29) | 58 | 7 | 444 – 270 | |
| 172.563(9) | 0.41 | 19 | 270 – 98 | |
| 172.456(5) | 0.48 | 15 | 720 – 547 | |
| 171.868(5) | 0.50 | 20 | 488 – 316<br>647 – 476 | |
| 171.5794(28) | 2.0 | 7 | 335 – 163<br>(660 – 488) | e |
| 171.500(27) | 0.22 | 84 | | |
| 168.462(10) | 0.25 | 26 | 660 – 491 | e |
| 168.132(5) | 0.78 | 9 | 579 – 411 | |
| 167.718(11) | 0.42 | 53 | | |
| 167.4124(29) | 1.2 | 8 | 673 – 506 | |
| 166.686(4) | 0.52 | 12 | | |
| 166.544(11) | 0.19 | 33 | | |
| 165.809(5) | 0.42 | 15 | 817 – 651 | |
| 165.0606(29) | 0.84 | 15 | | a |
| 164.744(16) | 0.29 | 41 | | |
| 163.637(10) | 0.54 | 44 | 480 – 316 | |
| 161.267(9) | 0.50 | 33 | 720 – 558 | |
| 159.639(17) | 0.48 | 32 | | |
| 159.469(10) | 0.49 | 24 | | |
| 159.279(3) | 0.80 | 13 | | |
| 159.047(3) | 2.3 | 9 | 396 – 237 | |
| 158.930(7) | 0.38 | 20 | | |
| 156.233(4) | 1.8 | 8 | 648 – 491 | |
| 156.0892(28) | 10 | 8 | 270 – 114 | |
| 155.650(7) | 0.33 | 21 | 558 – 403 | e |
| 154.0846(30) | 4.4 | 9 | 856 – 702 | |
| 153.736(7) | 0.47 | 15 | | |
| 152.341(4) | 0.65 | 12 | 724 – 572 | b |
| 151.927(3) | 0.67 | 11 | | |
| 150.142(4) | 0.59 | 14 | 150 – 0 | |
| 149.345(7) | 0.50 | 18 | 593 – 444 | |
| 149.237(11) | 0.44 | 34 | | |
| 148.901(7) | 0.48 | 24 | | |
| 148.391(4) | 0.77 | 10 | 628 – 480 | |
| 146.7731(25) | 8.0 | 9 | 163 – 16 | |
| 144.731(15) | 0.35 | 46 | | |
| 144.464(5) | 0.42 | 19 | 547 – 403 | e |
| 143.684(4) | 0.87 | 12 | 702 – 558 | |
| 143.511(6) | 0.55 | 19 | 961 – 817 | |
| 143.1767(30) | 10 | 22 | 316 – 173 | d |
| 142.270(20) | 1.6 | 30 | 411 – 269 | c |
| 141.2454(30) | 3.3 | 14 | 506 – 364 | |
| 139.662(3) | 1.1 | 10 | 583 – 444 | |
| 139.4546(27) | 5.3 | 10 | 237 – 98 | |
| 138.692(7) | 0.33 | 23 | | |
| 138.603(18) | 0.59 | 46 | | |
| 137.492(5) | 0.50 | 17 | | |
| 137.271(4) | 0.84 | 11 | | |
| 136.256(8) | 0.37 | 21 | 702 – 566 | e |
| 133.8770(26) | 46 | 10 | 150 – 16 | |

TABLE I. (*Continued*)

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks |
|---|---|---|---|---|
| 133.739(13) | 1.1 | 30 | | |
| 132.692(4) | 1.2 | 16 | | |
| 132.550(3) | 1.1 | 11 | | |
| 132.231(10) | 0.34 | 27 | 403 – 270 | |
| 131.157(11) | 0.33 | 31 | | |
| 131.050(4) | 0.66 | 18 | | |
| 130.910(6) | 0.45 | 20 | 491 – 361 | |
| 130.509(7) | 0.31 | 31 | | |
| 130.182(3) | 1.5 | 10 | 781 – 651 | |
| 129.298(3) | 0.95 | 11 | | |
| 128.934(11) | 0.56 | 62 | | |
| 127.166(4) | 0.49 | 20 | | |
| 125.1259(28) | 2.2 | 9 | 960 – 835 | |
| 125.024(3) | 1.1 | 12 | | |
| 124.283(6) | 0.45 | 26 | | |
| 123.608(4) | 0.63 | 16 | | |
| 122.9727(25) | 2.9 | 11 | 237 – 114 | |
| 122.6753(28) | 3.9 | 11 | 783 – 660 | |
| 122.6117(30) | 1.4 | 11 | 940 – 817 | |
| 121.5341(30) | 1.2 | 11 | 781 – 660 | |
| 119.6996(30) | 1.6 | 12 | 293 – 173 | |
| 119.516(4) | 1.5 | 13 | 480 – 361 | |
| 118.8960(25) | 7.6 | 9 | 269 – 150 | |
| 117.674(7) | 0.59 | 27 | | |
| 117.164(8) | 0.45 | 33 | | |
| 117.0039(30) | 1.7 | 10 | | |
| 115.096(5) | 0.92 | 21 | | |
| 114.6788(24) | 7.4 | 10 | 558 – 444 | |
| 114.3763(28) | 6.8 | 11 | 364 – 250 | |
| 114.3151(25) | 23 | 14 | 114 – 0 | |
| 112.249(12) | 1.3 | 44 | | |
| 109.773(9) | 0.93 | 60 | | |
| 108.163(5) | 1.4 | 18 | | |
| 107.865(4) | 5.0 | 10 | 666 – 558 | |
| 106.006(11) | 0.64 | 23 | 269 – 163 | |
| 105.957(10) | 1.5 | 42 | | |
| 105.867(9) | 1.7 | 37 | | |
| 105.792(3) | 1.7 | 11 | | |
| 104.576(6) | 1.2 | 43 | | |
| 104.476(5) | 0.81 | 20 | 961 – 856 | |
| 104.1152(29) | 2.8 | 24 | 651 – 547 | |
| 104.063(6) | 0.65 | 31 | | |
| 103.533(3) | 1.7 | 12 | | |
| 101.442(7) | 0.62 | 41 | 749 – 648 | |
| 100.553(3) | 2.3 | 18 | 648 – 547 | |
| 99.8304(22) | 12 | 12 | 250 – 150 | |
| 99.477(6) | 0.72 | 31 | | |
| 98.555(17) | 0.59 | 55 | | |
| 97.8318(19) | 12 | 14 | 98 – 0 | |
| 97.601(6) | 0.68 | 32 | | |
| 97.466(4) | 2.5 | 13 | 817 – 720 | |
| 96.588(6) | 1.1 | 18 | | |
| 96.077(6) | 0.79 | 32 | 572 – 476 | |
| 95.155(3) | 3.1 | 11 | 835 – 740 | |
| 94.1677(25) | 5.9 | 19 | 660 – 566 | |
| 92.480(3) | 2.5 | 13 | 740 – 648 | |
| 91.543(5) | 1.2 | 26 | | |
| 90.120(6) | 2.0 | 76 | 361 – 270<br>(566 – 476) | |
| 89.116(6) | 0.67 | 41 | | |
| 87.849(7) | 0.60 | 46 | | |
| 86.527(8) | 1.9 | 44 | | |
| 85.600(8) | 2.5 | 46 | | |
| 85.285(18) | 2.0 | 35 | | |
| 83.370(6) | 2.3 | 39 | | |
| 82.880(9) | 1.1 | 42 | 666 – 583 | |
| 82.665(6) | 4.5 | 32 | | |
| 82.000(6) | 0.82 | 46 | | |
| 81.951(5) | 0.94 | 34 | 648 – 566 | e |
| 79.299(8) | 1.3 | 37 | | |
| 78.027(8) | 1.5 | 38 | | |
| 76.557(10) | 1.1 | 47 | 724 – 647 | |
| 75.507(5) | 3.6 | 35 | | |
| 75.414(5) | 3.0 | 25 | 173 – 98 | |
| 74.300(6) | 2.4 | 52 | | |
| 74.2664(26) | 5.5 | 23 | 566 – 491 | |
| 73.576(7) | 2.8 | 36 | | |
| 73.499(8) | 2.2 | 44 | 856 – 783 | e |
| 73.335(5) | 5.5 | 22 | | |
| 73.244(7) | 2.3 | 38 | | |
| 72.929(6) | 2.1 | 31 | 476 – 403 | |
| 72.866(9) | 1.7 | 50 | | |
| 72.551(7) | 3.0 | 53 | | |
| 71.900(5) | 2.3 | 26 | 720 – 648 | |
| 69.482(6) | 1.8 | 37 | | |
| 67.409(4) | 2.3 | 30 | | |
| 67.245(3) | 1.8 | 24 | | |
| 66.473(4) | 1.1 | 37 | | |
| 66.424(5) | 1.1 | 39 | | |
| 66.394(4) | 1.3 | 34 | | |
| 66.357(4) | 2.2 | 22 | | |
| 65.667(4) | 4.2 | 22 | | |
| 65.623(4) | 4.0 | 23 | | |
| 65.573(4) | 3.0 | 19 | 335 – 269 | |
| 65.540(4) | 1.6 | 29 | | |
| 64.278(5) | 0.96 | 46 | | |
| 64.0051(28) | 1.4 | 18 | | |
| 59.692(4) | 1.6 | 32 | 720 – 660 | |
| 59.280(3) | 5.8 | 20 | | |
| 59.255(3) | 2.9 | 29 | | |
| 58.9277(19) | 1.9 | 18 | 173 – 114 | |
| 58.885(4) | 1.1 | 49 | | |
| 58.371(5) | 1.5 | 56 | | |
| 58.117(4) | 2.0 | 40 | | |
| 57.124(4) | 1.7 | 49 | | |
| 57.102(4) | 1.6 | 50 | | |
| 56.7165(30) | 3.7 | 30 | | |
| 56.677(3) | 2.7 | 38 | | |
| 55.756(4) | 3.1 | 40 | | |
| 54.4710(24) | 2.0 | 27 | 647 – 593 | |
| 54.383(5) | 0.64 | 42 | | |
| 54.080(4) | 1.3 | 27 | | |

TABLE I. (*Continued*)

| $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks | $E(\sigma_E)$ (keV) | $I$ (relative units) | $\sigma_I/I$ (%) | Possible assignments $E_i - E_f$ (keV) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 53.949(4) | 1.7 | 53 | | | 47.726(4) | 0.70 | 42 | | |
| 53.1409(26) | 2.0 | 19 | | | 46.4961(27) | 4.6 | 39 | | |
| 52.812(4) | 0.68 | 39 | | | 45.677(5) | 0.56 | 49 | | |
| 49.2098(23) | 1.0 | 31 | | | 44.6249(22) | 1.9 | 20 | | |
| 47.8096(17) | 5.0 | 26 | 491 − 444 | | | | | | |

[a] Possibly belonging to $^{183}$Ta.
[b] Possibly belonging to $^{181}$Ta (see Ref. 26).
[c] This transition in $^{182}$Ta could not be resolved from a nearby $^{183}$W line (Ref. 27). Only a time-dependent shift in energy and intensity was observed, consistent with the proposed doublet. The presence of a doublet is further supported by the comparison of the observed intensity with the intensity of the $^{183}$W line in Ref. 27.
[d] A transition at this energy is observed in the decay of $^{182}$Hf$^{m}$ (Ref. 31) as well as in that of $^{183}$Hf (Ref. 28). So, this entry probably represents a doublet. Therefore, this assignment is given, although the transition energy only fits between the indicated levels within four times the standard deviation.
[e] This transition energy fits only between these levels within three times the standard deviation.

the $^{181}$Ta$(n, e)^{182}$Ta spectrum in the energy region 30–400 keV. The experimental equipment was modernized in comparison with that described in Ref. 25; namely, the tangential reactor channel was lengthened behind the reactor core through the biological shield in the opposite direction of the spectrograph. The construction of the channel allows manipulation of the target when the reactor has its nominal power.

The targets were prepared by covering thin Al foils of about 1 $\mu$m thickness with metallic Ta, using electron gun equipment. The thicknesses of the Ta layers ranged from 0.1 to 1 mg/cm$^2$ and their dimensions were $2\times 4$ cm$^2$. The targets of natural Ta were irradiated inside the tangential channel with a neutron flux of $3\times 10^{12}$ cm$^{-2}$s$^{-1}$. The resolution for the $K$ line of the 173.2 keV transition ($E_e = 105.8$ keV) was 0.12%.

Besides the lines assigned to $^{182}$Ta, only the $K$ and $L$ lines of the 143.17 keV doublet formed by the transitions in $^{182}$Ta and $^{183}$Ta were observed.

The conversion lines corresponding to the 97.83, 99.83, 114.67, 133.87, 139.45, 146.77, 173.20, 270.40, 346.46, 360.53, and 402.61 keV $\gamma$ transitions in $^{182}$Ta and the $KLL$ Auger lines of $^{182}$Ta were used for the energy calibration. The intensity normalization to $I_\gamma$ (270.40 keV) = 100 was performed using the $K$ and $L$ lines of the 173.2 keV transition, considering this transition as a pure $M1$.

The results of these measurements are listed in Table II. The relative errors of the conversion coefficients range from 10 to 70%, depending on the electron line intensity and the number of observations. The theoretical values $\alpha_{\text{theor}}$ were deduced from the tables of Hager and Seltzer.[29] In all cases where other conversion electron lines can contribute to an observed peak (see "Remarks" in Table II), the experimental values for the total internal conversion coefficients should be considered as an upper limit. When one checks the location of the transitions from Table II with a proposed multipolarity, one realizes that only one of them (the 177.3 keV transition) has not been assigned in the level scheme.

### C. Gamma-gamma coincidence measurements

Coincidences between the prompt $\gamma$ rays, resulting from slow neutron capture, were recorded with the two-dimensional coincidence apparatus[30] installed at the FRJ-2 (DIDO) research reactor of the KFA Jülich. The natural Ta target was exposed to a Bi-filtered slow neutron flux of $4\times 10^7$ cm$^{-2}$s$^{-1}$ between the two Ge(Li) detectors (6 cm$^3$ planar and 38 cm$^3$ true coaxial) positioned at an angle of 150°. The coincidence events ($4k\times 4k$) were stored on magnetic tape event by event, the recorded $\gamma$-ray energies ranging from 20 keV up to 5 MeV. Two separate runs were performed. In one run of short duration, to exclude even small electronic drifts, special attention was paid to energy resolution, while in the other run the statistical precision prevailed.

After a data reduction and correction for random coincidences carried out on the IBM/370-165 computer of the KFA, the information became available for the first measurement as a full printout

TABLE II. Data on $(n,e)$ measurements.

| $E_\gamma$ (keV) | $I_\gamma$ (relative units) | Shell | $E_e(\sigma_{E_e})$ (keV) | $I_e$ (relative units) | $\alpha_{expt}$ | Total conversion coefficient $\sigma_\alpha$ (%) | Theoretical values (Ref. 29) $\alpha$ (*E*1) | $\alpha$ (*E*2) | $\alpha$ (*M*1) | Multipolarity | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 47.81 | 5.0 | $L_1$ | 36.17(7) | 150 | 29[a] | 35 | 0.182 | 0.464 | 4.58 | *M*1 | |
| | | $L_2$ | 36.68(7) | 15 | 2.9 | 70 | 0.0966 | 34.6 | 0.435 | | |
| | | *M* | 45.11(5) | 45 | 8.8 | 30 | 0.0913 | 18.3 | 1.14 | | |
| 53.14 | 2.0 | $(L_1)$ | 41.51(7) | 15 | 7.5 | 70 | 0.143 | 0.340 | 3.36 | | |
| 54.47 | 2.0 | $(L_1)$ | 42.82(7) | 15 | 7.5 | 70 | 0.135 | 0.320 | 3.13 | | |
| 73.24 | 2.3 } | $(L_1)$ | 61.67(5) | 5.0 | 0.9 | 70 | 0.0678 | 0.179 | 1.32 | | |
| 73.33 | 5.5 } | | | | | | | | | | |
| 73.50 | 2.2 } | | | | | | | | | | |
| 73.58 | 2.8 } | | | | | | | | | | |
| 74.27 | 5.5 | $(L_1)$ | 62.572(30) | 7.0 | 1.3 | 35 | 0.0655 | 0.174 | 1.26 | 74.3(*M*1) | |
| 74.30 | 2.4 | | | | | | | | | | |
| 92.48 | 2.5 | $L_1$ | 80.79(7) | 1.7 | 0.7 | 70 | 0.0386 | 0.113 | 0.668 | *M*1 | |
| 94.17 | 5.9 | $L_1$ | 82.440(30) | 5.0 | 0.8 | 35 | 0.0369 | 0.109 | 0.634 | *M*1 | |
| | | *M* | 91.622(30) | 4.5 | 0.7 | 35 | 0.0139 | 0.709 | 0.159 | | $+K159.0+K159.2$ |
| 95.15 | 3.1 | $L_1$ | 83.43(7) | 1.5 | 0.5 | 70 | 0.0360 | 0.107 | 0.615 | *M*1 | |
| 97.83 | 12 | *K* | 30.41(5) | 48 | 4.0 | 20 | 0.321 | 0.970 | 3.98 | *M*1 | |
| | | $L_1$ | 86.151(20) | 9.5 | 0.8 | 20 | 0.0337 | 0.101 | 0.567 | | |
| | | $(L_2)$ | 86.623(30) | 3.2 | 0.27 | 70 | 0.0102 | 1.18 | 0.0527 | | $+K154.0$ |
| | | *M* | 95.07(5) | 2.3 | 0.19 | 70 | 0.0125 | 0.593 | 0.142 | | |
| | | *N* | 97.06(7) | 2.2 | 0.18 | 50 | 0.0031 | 0.15 | 0.036 | | $+M99.8$ |
| 99.83 | 12 | *K* | 32.42(5) | 45 | 3.8 | 15 | 0.305 | 0.935 | 3.75 | *M*1 | |
| | | $L_1$ | 88.138(20) | 9.5 | 0.8 | 15 | 0.0321 | 0.0972 | 0.535 | | |
| | | $(L_2)$ | 88.680(30) | 3.1 | 0.26 | 70 | 0.0096 | 1.08 | 0.0497 | | $+L_1100.5+K156.0$ |
| | | *M* | 97.06(7) | 2.2 | 0.18 | 50 | 0.0118 | 0.540 | 0.134 | | $+N97.8$ |
| | | *N* | 100.04(20) | 1.4 | 0.12 | 50 | 0.0030 | 0.14 | 0.034 | | |
| 100.55 | 2.3 | $L_1$ | 88.680(30) | 3.1 | 1.3 | 70 | 0.0315 | 0.0958 | 0.524 | | $+L_299.8+K156.0$ |
| 104.11 | 2.8 | $L_1$ | 92.39(5) | 1.5 | 0.5 | 70 | 0.0290 | 0.0891 | 0.474 | *M*1 | |
| 107.86 | 5.0 | *K* | 40.50(7) | 15 | 3.0 | 70 | 0.250 | 0.804 | 3.00 | *M*1 | |
| | | $L_1$ | 96.07(7) | 1.4 | 0.28 | 70 | 0.0266 | 0.0827 | 0.428 | | |
| 114.31 | 23 } | *K* | 46.910(30) | 75 | 3.3 | 20 | 0.215 | 0.710 | 2.54 | 114.3(*M*1) | |
| 114.38 | 6.8 } | $L_1$ | 102.639(30) | 9.0 | 0.4 | 25 | 0.0231 | 0.0730 | 0.362 | | |
| | | $L_2$ | 102.85(7) | 3.0 | 0.13 | 50 | 0.0062 | 0.580 | 0.0335 | | $+L_1114.6$ |
| | | $L_3$ | | | | | 0.0068 | 0.503 | 0.0040 | | |
| | | *M* | 111.63(4) | 3.5 | 0.15 | 50 | 0.0082 | 0.289 | 0.908 | | |
| | | *N* | 113.51(20) | 2.6 | 0.11 | 50 | 0.0020 | 0.072 | 0.023 | | $+L_1125.0+L_1125.1$ $+K180.9$ |
| 114.68 | 7.4 | *K* | 47.264(30) | 20 | 2.7 | 15 | 0.213 | 0.705 | 2.51 | *M*1 | |
| | | $L_1$ | 102.85(7) | 3.0 | 0.4 | 50 | 0.0229 | 0.0725 | 0.359 | | $+L_2114.31+L_2114.37$ |

TABLE II. (*Continued*)

| $E_\gamma$ (keV) | $I_\gamma$ (relative units) | Shell | $E_e(\sigma_{E_e})$ (keV) | $I_e$ (relative units) | $\alpha_{expt}$ | Total conversion coefficient $\sigma_\alpha$ (%) | Theoretical values (Ref. 29) $\alpha$ (E1) | $\alpha$ (E2) | $\alpha$ (M1) | Multipolarity | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 118.90 | 7.6 | $K$ | 51.491(30) | 30 | 4.0 | 30 | 0.194 | 0.650 | 2.27 | $M1$ | |
| | | $L_1$ | 107.199(30) | 3.5 | 0.5 | 50 | 0.0210 | 0.0669 | 0.324 | | |
| 119.51 | 1.5 } | $K$ | 52.23(7) | 5.0 | 3.1 | 70 | 0.190 | 0.640 | 2.23 | | |
| 119.70 | 1.6 } | $L_1$ | 107.75(7) | 2.0 | 1.3 | 50 | 0.0206 | 0.0659 | 0.317 | 119.7($M1$) | |
| 122.61 | 1.4 } | $K$ | 55.28(5) | 30 | 7.7 | 30 | 0.178 | 0.604 | 2.08 | 122.7($M1$) | $+KLM$ |
| 122.67 | 3.9 } | ($L_1$) | 111.21(7) | 1.5 | 0.4 | 50 | 0.0194 | 0.0623 | 0.296 | $M1$ | $+L_1122.9+K178.6$ |
| 122.97 | 2.9 | $K$ | 55.59(5) | 5 | 1.7 | 70 | 0.177 | 0.601 | 2.06 | $M1, E2$ | $+KLM$ |
| | | $L_1$ | 111.21(7) | 1.5 | 0.5 | 50 | 0.0193 | 0.0620 | 0.294 | | $+L_1122.61+L_1122.67$ $+K178.6$ |
| 125.02 | 1.1 } | $K$ | 57.72(5) | 10 | 4.5 | 30 | 0.170 | 0.576 | 1.96 | | |
| 125.13 | 2.2 } | $L_1$ | 113.51(20) | 2.6 | 1.2 | 50 | 0.0185 | 0.0596 | 0.280 | 125.1($M1$) | $+N114.31+N114.37$ $+K180.9$ |
| 132.55 | 1.1 } | ($K$) | 65.06(7) | 1.5 | 1.3 | 70 | 0.146 | 0.500 | 1.67 | | |
| 132.69 | 1.2 } | | | | | | | | | | |
| 133.88 | 46 } | $K$ | 66.480(20) | 77 | 1.7 | 15 | 0.142 | 0.489 | 1.62 | $M1$ | |
| | | $L_1$ | 122.173(30) | 10 | 0.22 | 15 | 0.0156 | 0.0509 | 0.231 | | |
| | | $L_2$ | 122.872(30) | 2.4 | 0.05 | 20 | 0.0038 | 0.282 | 0.0212 | | $+K190.3$ |
| | | $M$ | 131.00(4) | 3.3 | 0.07 | 20 | 0.0053 | 0.141 | 0.0577 | | $+L_1142.2$ |
| | | $N$ | 133.29(30) | 1.1 | 0.024 | 50 | 0.0013 | 0.035 | 0.014 | | $+L_3143.1$ |
| 139.45 | 5.3 | $K$ | 72.026(20) | 7.5 | 1.4 | 30 | 0.128 | 0.442 | 1.44 | $M1$ | |
| | | $L_1$ | 127.73(4) | 3.4 | 0.64 | 20 | 0.0141 | 0.0462 | 0.205 | | $+K195.1$ |
| 141.24 | 3.3 | $K$ | 73.81(5) | 4.5 | 1.4 | 30 | 0.123 | 0.428 | 1.39 | $M1$ | |
| | | ($L_1$) | 129.37(5) | 1.1 | 0.33 | 50 | 0.0137 | 0.0449 | 0.198 | | $+K197.6$ |
| 142.27 | 1.6 | $K$ | 74.769(30) | 3.0 | 1.9 | 70 | 0.121 | 0.420 | 1.36 | ($M1$) | |
| | | $L_1$ | 131.00(4) | 3.3 | 2.1 | 35 | 0.0135 | 0.0441 | 0.194 | | $+M133.8$ |
| 143.1 | 10 | $K$ | 75.690(30) | 3.0 | 0.30 [b] | 70 | 0.119 | 0.414 | 1.34 | $M1, E2$ | $^{182}Ta + ^{183}Ta$ |
| | | $L_2$ | 131.97(10) | 1.1 | 0.11 [b] | 50 | 0.0031 | 0.209 | 0.0174 | | |
| | | $L_3$ | 133.29(30) | 1.1 | | 50 | 0.0032 | 0.167 | 0.0020 | | $+N133.8$ |
| 146.77 | 8.0 | $K$ | 79.330(20) | 8.5 | 1.1 | 30 | 0.112 | 0.388 | 1.24 | $M1$ | |
| | | $L_1$ | 135.15(4) | 3.2 | 0.40 | 20 | 0.0124 | 0.0409 | 0.178 | | |
| 154.08 | 4.4 | $K$ | 86.623(30) | 3.2 | 0.7 | 70 | 0.0990 | 0.342 | 1.08 | ($M1$) | $+L_297.8$ |
| | | ($L_1$) | 142.23(7) | 1.0 | 0.23 | 50 | 0.0110 | 0.0364 | 0.155 | | |
| 156.0 | 10 | $K$ | 88.680(30) | 3.1 | 0.31 | 70 | 0.0958 | 0.331 | 1.04 | ($E2$) | $+L_299.8+L_1100.5$ |
| | | $L_2$ | 144.82(7) | 3.0 | 0.30 | 20 | 0.0023 | 0.142 | 0.0135 | | |
| | | $L_3$ | 146.03(5) | 2.0 | 0.20 | 20 | 0.0024 | 0.109 | 0.0016 | | |
| | | ($M$) | 153.54(20) | 1.0 | 0.10 | 50 | 0.0035 | 0.0712 | 0.0372 | | |
| 159.0 | 2.3 } | $K$ | 91.622(30) | 4.5 | 2.0 | 30 | 0.0914 | 0.314 | 0.993 | 159.0 $M1$ | $+M94.1$ |
| 159.2 | 0.80 } | | | | | | | | | | |

TABLE II. (*Continued*)

| $E_\gamma$ (keV) | $I_\gamma$ (relative units) | Shell | $E_e(\sigma_{E_e})$ (keV) | $I_e$ (relative units) | $\alpha_{expt}$ | Total conversion coefficient $\sigma_\alpha$ (%) | Theoretical values (Ref. 29) $\alpha$ (*E*1) | $\alpha$ (*E*2) | $\alpha$ (*M*1) | Multipolarity | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 173.20 | 58 | *K* | 105.770(30) | 50 | 0.86 | 10 | 0.0735 | 0.250 | 0.783 | *M*1 | |
| | | $L_1$ | 161.47(4) | 8.0 | 0.14 | 20 | 0.0083 | 0.0273 | 0.111 | | |
| | | $(L_2)$ | 161.87(10) | 1.0 | 0.017 | 50 | 0.0017 | 0.0893 | 0.0100 | | |
| | | *M* | 170.52(5) | 3.6 | 0.062 | 20 | 0.0027 | 0.0452 | 0.0277 | | |
| | | (*N*) | 172.00(30) | 0.9 | 0.016 | 50 | 0.0007 | 0.011 | 0.0069 | | |
| 177.3 | 1.3 | *K* | 109.87(7) | 1.3 | 1.0 | 50 | 0.0692 | 0.235 | 0.733 | *M*1 | |
| 178.62 | 3.4 | *K* | 111.21(7) | 1.5 | 0.44 | 50 | 0.0679 | 0.230 | 0.718 | | $+L_1122.61 + L_1122.67$ $+ L_1122.9$ |
| 180.27 | 0.66 | | | | | | | | | | |
| 180.90 | 0.76 | (*K*) | 113.51(20) | 2.6 | 3.4 | 50 | 0.0650 | 0.223 | 0.693 | | $+N114.31 + N114.37$ $+ L_1125.0 + L_1125.1$ |
| 180.97 | 0.38 | | | | | | | | | | |
| 181.62 | 0.39 | | | | | | | | | | |
| 182.75 | 1.9 | (*K*) | 116.11(20) | 1.3 | 0.68 | 50 | 0.0640 | 0.217 | 0.673 | | |
| 190.3 | 7.9 | *K* | 122.872(30) | 2.4 | 0.30 | 20 | 0.0576 | 0.194 | 0.601 | *E*2, *M*1 | $+L_2133.8$ |
| | | $L_2$ | 178.70(20) | 1.4 | 0.18 | 50 | 0.0012 | 0.0589 | 0.0076 | | |
| | | $L_3$ | 179.96(20) | 0.9 | 0.11 | 50 | 0.0013 | 0.0420 | 0.0009 | | |
| 193.0 | 0.33 | (*K*) | 125.45(20) | 1.2 | 2.3 | 50 | 0.0556 | 0.186 | 0.576 | | |
| 193.22 | 0.53 | | | | | | | | | | |
| 195.11 | 2.8 | *K* | 127.73(4) | 3.4 | 1.2 | 20 | 0.0541 | 0.181 | 0.561 | | $+L_1139.4$ |
| | | $L_1$ | 183.52(20) | 0.9 | 0.32 | 50 | 0.0062 | 0.0203 | 0.0797 | | $+K250.9$ |
| 197.60 | 0.43 | (*K*) | 129.37(5) | 1.1 | 2.6 | 50 | 0.0524 | 0.175 | 0.542 | | $+L_1141.2$ |
| 204.0 | 1.00 | *K* | 136.44(10) | 3.2 | 3.2 | 40 | 0.0483 | 0.160 | 0.496 | | |
| 210.54 | 3.3 | *K* | 143.02(7) | 2.0 | 0.60 | 20 | 0.0466 | 0.147 | 0.454 | *M*1 | |
| 214.2 | 2.3 | *K* | 146.59(5) | 1.0 | 0.43 | 50 | 0.0427 | 0.140 | 0.433 | *M*1 | |
| 250.97 | 0.54 | | | | | | | | | | |
| 251.32 | 0.42 | (*K*) | 183.52(20) | 0.9 | 1.7 | 50 | 0.0287 | 0.0910 | 0.280 | | $+L_1195.1$ |
| 251.77 | 0.50 | | | | | | | | | | |
| 252.7 | 1.2 | (*K*) | 185.22(20) | 0.9 | 0.75 | 50 | 0.0282 | 0.0873 | 0.275 | | |
| 270.4 | 100 | *K* | 203.16(10) | 8.0 | 0.080 | 10 | 0.0238 | 0.0744 | 0.229 | *E*2, *M*1 | |
| | | $L_{1,2}$ | 259.39(10) | 1.9 | 0.019 | 20 | 0.0033 | 0.0218 | 0.0353 | | |
| | | $L_3$ | 260.75(20) | 1.0 | 0.010 | 20 | 0.0004 | 0.0080 | 0.0003 | | |
| | | *M* | 268.00(20) | 0.8 | 0.008 | 50 | 0.0008 | 0.0072 | 0.0080 | | |
| 297.12 | 24 | *K* | 229.62(15) | 0.6 | 0.025 | 50 | 0.0190 | 0.0577 | 0.177 | *E*1 | |
| 346.46 | 3.7 | *K* | 279.33(15) | 0.8 | 0.22 | 50 | 0.0132 | 0.0385 | 0.117 | *M*1 | |
| 360.53 | 6.9 | *K* | 293.14(15) | 0.5 | 0.073 | 50 | 0.0120 | 0.0348 | 0.105 | *M*1, *E*2 | |
| 373.88 | 1.9 | *K* | 306.67(30) | 0.10 | 0.053 | 50 | 0.0110 | 0.0317 | 0.0957 | *M*1, *E*2 | |
| 377.2 | 4.6 | *K* | 310.19(20) | 0.20 | 0.043 | 50 | 0.0108 | 0.0310 | 0.0935 | *M*1, *E*2 | |

TABLE II. (*Continued*)

| $E_\gamma$ (keV) | $I_\gamma$ (relative units) | Shell | $E_e(\sigma_{E_e})$ (keV) | $I_e$ (relative units) | $\alpha_{expt}$ | Total conversion coefficient $\sigma_\alpha$ (%) | Theoretical values (Ref. 29) $\alpha$ (E1) | $\alpha$ (E2) | $\alpha$ (M1) | Multipolarity | Remarks |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 382.1 | 2.5 | K | 314.75(30) | 0.20 | 0.080 | 50 | 0.0105 | 0.0300 | 0.0903 | M1 | |
| 402.6 | 47 | K | 335.33(15) | 0.40 | 0.0085 | 50 | 0.0093 | 0.0263 | 0.0788 | E1 | |
| | | L | 392.0(5) | 0.10 | 0.0021 | 50 | 0.0014 | 0.0072 | 0.0120 | | |
| 405.7 | 0.69 } | | | | | | | | | | |
| 406.21 | 1.9 } | K | 338.91(20) | 0.15 | 0.08 | 50 | 0.0091 | 0.0257 | 0.0770 | | |
| 406.88 | 1.4 } | | | | | | | | | | |

[a] The experimental values should be considered as upper limits in all cases where unresolved peaks in the electron spectrum are present.
[b] A lower limit for the $\alpha_{expt}$ values is given for the lines K143, $L_2$143 because the component of the 143 keV doublet belonging to $^{183}$Ta has E1 multipolarity (Ref. 28).

of the two-dimensional matrix, and for the second measurement as a series of coincidence spectra with windows set on about 60 strong lines between 40 and 900 keV, and besides the lines to correct for background. The calibration of the spectra was performed by identification of the most prominent peaks with the corresponding lines in the BCD spectra.

A summary of the coincidence data is given in Table III, where for each gate the coincident transitions are listed, divided into groups of strong, medium, and weak coincidences.

## III. DISCUSSION

### A. Some general considerations

From previous work[9,16] the energies and the decay are well known for several band heads, strongly excited in the $(n,\gamma)$ reaction: 0, 16, 114, 150, 250, 270, and 402 keV. Our data allow us to establish the depopulation of previously known band heads at 173, 547, and 558 keV, as well as to propose additional bands starting at 444, 593, and 648 keV. New rotational levels are proposed for most previously known bands. From several high-$K$ bands, extensively discussed by Ward *et al.*,[31] we find in our data only the decay lines of the band head at 776 keV. Several tentatively assigned levels are proposed. The level scheme constructed in our work is shown in Figs. 1–3. The construction of the scheme is based mainly on the energy, multipolarity, and coincidence data obtained in our work (Tables I, II, and III), on the data of Helmer *et al.*[16] and those of Wasson *et al.*,[11] and on rotational model predictions and population considerations. The most complete information concerning the assignment of transitions is contained in Table I. In this table, all transitions fitting between two levels within three times the combined standard deviation are mentioned as such if their assignment is compatible with an $E1$, $M1$, or $E2$ character, in view of the proposed spin values and parities. In the detailed level schemes (Figs. 1–3), on the other hand, only the more reliably assigned transitions are included. Here, only transitions fitting within two times the combined standard deviation are presented, while for transitions with multiple assignments, only the most reasonable location is shown, wherever it was possible. Also, a few transitions with an intensity much higher than acceptable, or which are highly forbidden, were disregarded. This way of presenting the level scheme was chosen in order not to overcomplicate the figures, to emphasize the main aspects of the different decays, and, at the same time, to include as much information as possible in the paper.

TABLE III. Observed $\gamma\gamma$ coincidences. The coincidences are divided into groups for which strong, medium, or weak evidence is present. Coincidences marked with underlined numbers are in agreement with the proposed level scheme. Typical errors are 1 keV.

| Gate energy (keV) | Coincident transitions (energy in keV) Strong | Medium | Weak |
|---|---|---|---|
| 47.8 | 172,271 | | |
| 90.1 | | 271 | |
| 94.2 | 172,271 | 122,402,477,511 | |
| 97.8 | 139 | 298,381,511,5966[a] | 159,194 |
| 99.9 | 134,298 | 91,104,113,511,1120 | |
| 104.1 | 298 | 133 | |
| 107.9 | 172,271 | 133,154 | |
| 114.4 | 155,172,271 | 103,108,122,133,141, 194,233,246,259,511 | 286 |
| 118.9 | 133 | 142,154,169,236,271, 362,511 | 194 |
| 122.7 | 173,271 | 97,113,139,159 | 204,298,477 |
| 125.1 | 403 | | |
| 133.9 | 103,296 | 117,142,154,167,182, 214,397,511 | 870 |
| 139.5 | | 101,159 | |
| 141.2 | 133 | 102,116,166,214 | 146 |
| 146.7 | | 169,261 | 196 |
| 154.1 | 172,271 | 107,114,133,210,5206[a] | 143,154 |
| 156.1 | 114,171 | 189,211,402 | 154,228,376,511 |
| 168.1 | 142 | 134,214 | |
| 173.2 | 114,155,271 | 89,98,108,121,210, 228,361,406,422,511 | 139,282,351,477 |
| 178.6 | 113 | | |
| 182.7 | | 103 | 114,132,214 |
| 190.3 | 402 | 97,106,155,270,511 | 474 |
| 195.1 | | 101,114,172,271 | 195,399 |
| 210.5 | 154,171,271 | | |
| 214.2 | 133 | | |
| 222.1 | 230 | 103,171,229,271 | |
| 233.7 | 298 | 511 | |
| 237.3 | | 132,173,270,509 | 117 |
| 244.8 | 402 | | |
| 259 | 147 | | |
| 270.4 | 108,114,122,153,173, 210,377,511 | 48,84,94,229,259, 276,323,351,479 | 195,406,422 |
| 274.7 | | 114,172,271 | |
| 287 | | 113,133,270,360 | |
| 297.1 | 102,133 | 234,511 | |
| 346.5 | 402 | 119,285 | |
| 377.2 | 271 | | |
| 402.6 | 190,347 | 98,106,118,124,156, 245,511 | 137,165 |
| 480.8 | 271 | | |

[a] Primary transition; see Table III in Ref. 16.

A general survey of the level scheme (without transitions) is given in Fig. 4, featuring the rotational band structures and their configurations in terms of Nilsson orbitals. Data on the Nilsson levels observed in the neighboring odd-*A* nuclei are given in Table IV. They were taken mainly from the review paper of Bunker and Reich.[32]

Precise level energies are listed in Table V. This table also compares the spin and parity assignments with the results from the average resonance neutron capture of Helmer *et al.*[16] When our analysis was almost finished, new results on $^{182}$Ta were published by Stelts and Browne.[43] Their analysis relies upon neutron capture in individual resonances.

In general, our level scheme strongly supports

TABLE IV. Nilsson levels (Ref. 32) in odd-$A$ nuclei with $Z=73$ and $N=109$ (energies in keV).

| Nucleus | $\frac{1}{2}^+$[411] | $\frac{7}{2}^+$[404] | $\frac{9}{2}^-$[514] | $\frac{5}{2}^+$[402] | $\frac{1}{2}^-$[541] | Additional reference |
|---|---|---|---|---|---|---|
| | Orbitals at $Z=73$ | | | | | |
| $^{177}$Ta | | 0 | 73.6 | 70.5 | 216.6 | |
| $^{179}$Ta | 520.4 | 0 | 30.7 | 238.7 | 750.3 | |
| $^{181}$Ta | 615.0 | 0 | 6.3 | 482.0 | | |
| $^{183}$Ta | | 0 | 73.1 | 459.1 | | |
| | Orbitals at $N=109$ | | | | | |
| | $\frac{9}{2}^+$[624] | $\frac{1}{2}^-$[510] | $\frac{3}{2}^-$[512] | $\frac{11}{2}^+$[615] | $\frac{7}{2}^-$[503] | |
| $^{181}$Hf | | 0 | 255 | | 670 | |
| $^{183}$W | 622.9 | 0 | 208.8 | 309.5 | 453.1 | |
| $^{185}$Os | 402.6 | 0 | 127.8 | 275.7 | 102.3 | 33 |

the data from the average neutron capture.[16] The situation is such that the new levels proposed in this study are mostly consistent with the average neutron capture data, in the sense that the missing high-energy transitions to these new levels were either too weak or too close to stronger observed transitions. Examples are the new levels at 364.4, 647.4, and 724.0 keV. In some cases the presence of the other close-lying level was even presumed as e.g. at 269.0 and 647.7 keV.

Some spin and parity assignments differ from those proposed by Helmer *et al.*[16] Before stressing differences, we should have in mind that the average neutron capture experiment only distinguishes four groups of final states, according to the relative values of the reduced intensity of the involved high-energy transitions: 100% to $3^-$ and $4^-$ states, 50% to $2^-$ and $5^-$ states, 10% to $3^+$ and $4^+$ states, and finally 5% to $2^+$ and $5^+$ states. Therefore, the different spin assignments for the levels at 817.0 and 835.3 keV are *not* in disagreement with the average neutron capture data, as they stay within the same $3^-$, $4^-$ group. In this respect, our spin assignments for the levels at 659.9 and 856.1 keV do differ from those of Helmer *et al.*[16]

We have very good agreement with Stelts and Browne[43] for all the levels they observed up to 856.1 keV. Their data confirm our $4^-$ assignment at 856.1 keV, but we disagree on the spin for the 702.0 keV level.

A real disagreement resides in some states that are observed in the resonance capture studies, but not confirmed in our study, as, e.g., at 331.3 keV (by Helmer *et al.*[16]) and at 90.2, 245.8, and 458.2 keV (by Stelts and Browne[43]). Both the sensitivity of a bent-crystal spectrometer and the nonselective feeding of levels in the low-energy part of the level scheme make it very unlikely to miss a level below 500 keV with spin between 2 and 5.

Additional information about resonance spins can be derived from our data, when combined with the results of Wasson *et al.*[11] (see Sec. III G and Table VI).

### B. Negative parity states involving the $\frac{7}{2}^+$[404] proton orbital

The decay of these states is shown in Fig. 1.

#### 1. *The ground-state rotational band*

The ground state and the levels at 97.8 and 237.3 keV forming the ground-state rotational band in the work of Helmer *et al.*[16] were also found in this experiment, with the same deexciting transitions. In the calculations of Reich *et al.*[18] the spin 6 member of this band was predicted at about 397 keV.

Energy combinations involving the levels at 97.8, 114.3, and 237.3 keV established the possibility of a new level at 396.3 keV. The existence of this level was supported by the observation of a coincidence between transitions at 159 and 139 keV (see Table III). The conversion coefficient of the 159.0 keV transition shows this transition to have $M1$ multipolarity, (see Table II) so the level at 396.3 keV should have negative parity and $4 \leq I \leq 6$. As this level was not observed in the 2 keV neutron capture,[16] its spin value must be $I < 2$ or $I > 5$. This leads to the identification of this level with the spin 6 member of the ground-state rotational band.

In earlier reports[20] we proposed an energy 561.11 keV for the level $I^{\pi}K = 7^-3$. A better energy fit is obtained for a level at 581.20 keV. This energy is also in better agreement with our Coriolis-mixing calculations.[34]

TABLE V. Level energies and proposed quantum numbers. The assignments are compared with previous results.

| This work | | | Helmer *et al.*[a] | | Stelts and Browne[b] | |
|---|---|---|---|---|---|---|
| $E_x$ (keV) | $\sigma_E$ (eV) | $I^\pi K$ | $E_x$ (keV) | $I^\pi K$ | $E_x$ (keV) | $I^\pi$ |
| 0.0 | | $3^-3$ | 0.0 | $3^-3$ | 0.0 | $3,4^-$ |
| 16.2648 | 2.8 | $5^+5$ | 16.5 | $5^+5$ | 16.9 | $5^+$ |
| U[c] | | | U | | (90.2) | $3,4,\underline{5}^+$ |
| 97.8319 | 1.3 | $4^-3$ | 97.80 | $4^-3$ | 98.2 | $3,4^-$ |
| 114.3156 | 1.3 | $4^-4$ | 114.33 | $4^-4$ | 114.6 | $3,4^-$ |
| 150.1432 | 2.5 | $4^+4$ | 150.4 | $4^+4$ | 149.9 | |
| 163.037 | 3 | $6^+5$ | 163.3 | $6^+5$ | | |
| 173.2429 | 1.8 | $5^-5$ | 173.4 | $5^-5$ | 173.0 | $5^-$ |
| 237.2881 | 1.6 | $5^-3$ | 237.27 | $5^-3$ | 237.3 | $5^-$ |
| U | | | U | | 245.8 | |
| 249.9755 | 2.6 | $3^+3$ | 250.2 | $3^+3$ | 251.5 | $3,4^+$ |
| 269.0381 | 2.8 | $5^+4$ | d | | d | |
| 270.4043 | 1.7 | $2^-2$ | 270.41 | $2^-2$ | 270.1 | $\underline{2},3,4^-$ |
| 292.9403 | 1.8 | $5^-4$ | 292.97 | $5^-4$ | 292.5 | $5^-$ |
| 316.397 | 5 | $6^-5$ | 317[e] | $6^-5$ | | |
| U | | | 331.3 | $5^+4$ | U | |
| 334.614 | 3 | $7^+5$ | 334.8 | $7^+5$ | | |
| 360.5186 | 2.3 | $3^-2$ | 360.53 | $3^-2$ | 359.6 | $3,4^-$ |
| 364.3502 | 2.6 | $4^+3$ | U | | 365.5 | $3,4^+$ |
| 390.145 | 6 | $6^+6$ | | | | |
| 396.3363 | 2.7 | $6^-3$ | 397.3 | $6^+6$[f] | | |
| 402.6190 | 2.5 | $2^+2$ | 402.65 | $2^+2$ | U | |
| 411.293 | 5 | $6^+4$ | | | | |
| U | | | (423.5) | $2,5^+$ | U | |
| 443.6083 | 2.1 | $1^-1$ | | | | |
| U | | | U | | 458.2 | |
| 475.554 | 4 | $3^+2$ | 474.4 | $3^+2$ | U | |
| 480.0338 | 2.3 | $4^-2$ | 479.8 | $4^-2$ | 477.4 | $3,4^-$ |
| 488.265 | 3 | $6^-4$ | 488[e] | $6^-4$ | | |
| 491.4203 | 2.2 | $2^-1$ | 491.8 | $2,5^-$ | 491.0 | $2^-$ |
| 505.596 | 3 | $5^+3$ | 505.4 | $5^+3$ | 505.4 | $5^+$ |
| 519.596 | 15 | $10^-10$[g] | 519.7 | $10^-10$ | | |
| 547.0987 | 2.5 | $3^-3$ | 547.1 | $3^-3$ | 547.0 | $3,4^-$ |
| 558.2850 | 2.6 | $1^-0$ | 559[e] | $1^-0$ | | |
| 565.6877 | 2.6 | $3^-1$ | 565.7 | $3,4^-$ | 566.5 | $3,4^-$ |
| 571.633 | 4 | $4^+2$ | 571.5 | $4^+2$ | 571.8 | |
| 579.423 | 4 | $7^+4$ | | | | |
| 581.198 | 9 | $7^-3$ | | | | |
| 583.270 | 3 | $0^-0$ | 584[e] | $0^-0$ | | |
| U | | | 586.6 | $2,5^+$ | U | |
| 592.9548 | 2.8 | $1^+1$ | | | | |
| 628.425 | 3 | $5^-2$ | 628.4 | $5^-2$ | 627.8 | $5^-$ |
| 647.4255 | 2.9 | $2^+1$ | U | | U | |
| 647.6527 | 2.4 | $2^-2$ | d | | U | |
| 651.2111 | 2.7 | $4^-3$ | 650 | $4^-3$ | 650.5 | $3,4^-$ |
| 652.40 | 100 | $9^-9$[g] | | | | |
| 659.8565 | 2.7 | $4^-1$ | 659.6 | $2^-2$[f] | 659.2 | $2,3,4^-$ |
| U | | | U | | 662.8 | |
| 666.148 | 3 | $2^-0$ | 666.0 | $2^-0$ | 667.9 | $2^-$ |
| 673.009 | 4 | $6^+3$ | | | | |
| 701.9668 | 2.8 | $3^-0$ | 702.0 | $3^-0$ | 701.1 | $5^-$[f] |
| 719.5510 | 2.8 | $3^-2$ | 719.6 | $3^-2$ | 719.6 | $3,4^-$ |
| 723.975 | 4 | $3^+1$ | U | | U | |
| 740.135 | 3 | $2^-2$ | 740.3 | $2^-1$ | 740.9 | $2,3,4^-$ |
| 749.081 | 5 | $3^+3$ | U | | U | |
| 776.389 | 23 | $7^-7$ | 777[e] | $7^-7$ | | |
| 781.391 | 3 | $5^-3$ | 782.0 | $5^-3$ | 781.9 | $5^-$ |

TABLE V. (*Continued*)

| This work | | | Helmer *et al.*[a] | | Stelts and Browne[b] | |
|---|---|---|---|---|---|---|
| $E_x$ (keV) | $\sigma_E$ (eV) | $I^\pi K$ | $E_x$ (keV) | $I^\pi K$ | $E_x$ (keV) | $I^\pi$ |
| 782.532 | 4 | $5^-1$ | U | | U | |
| U | | | U | | 791.0 | |
| 805.075 | 12 | $6^-2$ | | | | |
| 817.018 | 3 | $4^-2$ | 817.0 | $3^-1$ [f] | 816.7 | $3,4^-$ |
| U | | | U | | 830.5 | |
| 835.290 | 4 | $3^-2$ | 835.4 | $4^-2$ [f] | 835.9 | $3,4^-$ |
| U | | | 843.3 | $(3,4)^-$ | 842.0 | $3,4,5^-$ |
| 856.052 | 3 | $4^-0$ | 856.0 | $2,5^-$ [f] | 856.1 | $3,4^-$ |
| 939.630[h] | 4 | $5^-2$ | 939.9 | $2,5^-$ | 939.5 | $5^-$ |
| 960.416 | 5 | $4^-2$ | 960.9 | $3,4^-$ | 960.0 | $3,4^-$ |
| 960.527 | 4 | $5^-0$ | U | | U | |
| 1116.00 | 100 | $7^-7$ [g] | | | | |
| 1336.80 | 100 | $8^-7$ [g] | | | | |

[a] See Ref. 16.
[b] See Ref. 43. The most probable $I^\pi$ is underlined.
[c] A U designates an unobserved level. This remark is only made for levels with proposed spin values between 2 and 5. All levels observed below 856 keV in one of the three experiments are reported.
[d] The presence of a doublet is presumed here.
[e] This assignment relies upon $(d,p)$ data from Bollinger *et al.*, published later in Ref. 35.
[f] The spin and parity assignments are different from those proposed in this study.
[g] The high-spin levels were not observed in this experiment; the values are those from Ward *et al.*, Ref. 31.
[h] Beyond 856 keV we only report the levels observed in this study, together with the corresponding values from Refs. 16 and 43.

### 2. The $K^\pi = 4^-$ band at 114.3 keV

Besides the levels at 114.3 and 292.9 keV, already present in Helmer's[16] work, a level found at 488.3 keV was interpreted as the spin 6 member of this band. Such a level is also observed in $(d,p)$ work.[35] According to Reich *et al.*[18] it should be found somewhere between 490 and 500 keV. It was also deduced from the study of the $^{182}Hf^m$ decay by Ward *et al.*[31] In the latter work the transition at 195 keV had to be placed between the 488 and 293 keV levels where Helmer *et al.*[16] assigned it to the 292.9 → 97.8 keV transition. In fact, high resolution data show that there are two transitions, one at 195.111 ± 0.003 keV, fitting between the 292.9 and 97.8 keV levels, and another at 195.329 ± 0.006 keV, which can be placed between the levels at 488.3 and 292.9 keV (see Table I).

### 3. The $K^\pi = 5^-$ band at 173.2 keV

One of the problems remaining in the work of Helmer *et al.*[16] was the deexcitation of the 173.4 keV level. Indeed, the strong transition at this energy has $M1$ multipolarity[14] and therefore can not explain this decay, as the ground state has $3^-$ for spin and parity. Our conversion measurement in Table II confirms this multipolarity. Energy combinations yielded a level at 173.240 ± 0.003 keV, decaying to the 97.8 and 114.3 keV levels. A ground-state transition could easily be hidden by the strong 173.204 ± 0.003 keV transition, regarding the limited resolution of only 50 eV FWHM at this energy. In the study of the $I^\pi = 8^-$ isomeric state in $^{182}Hf$ by Ward *et al.*[31] the decay of the 173 keV level was observed without interference from

TABLE VI. Proposed resonance spins for $^{182}Ta$.

| $E_{res}$ (eV) | Wasson *et al.* (Ref. 11) | This work |
|---|---|---|
| 4.3 | 4 | 4 |
| 10.3 | 3 | 3 |
| 13.9 | 4 | 4 |
| 20.3 | | |
| 22.7 | | 3,4 [a] |
| 23.9 | 3 | 4,3 [a] |
| 30.0 | | 3 |
| 35.1 | 3,4 [a] | 3,4 [a] |
| 35.9 | 4,3 [a] | 4,3 [a] |
| 39.1 | | 4 |
| 49.1 | | |

[a] In this doublet, which was not resolved in the measurement of Wasson *et al.* (Ref. 11), the two resonances have different spin values.

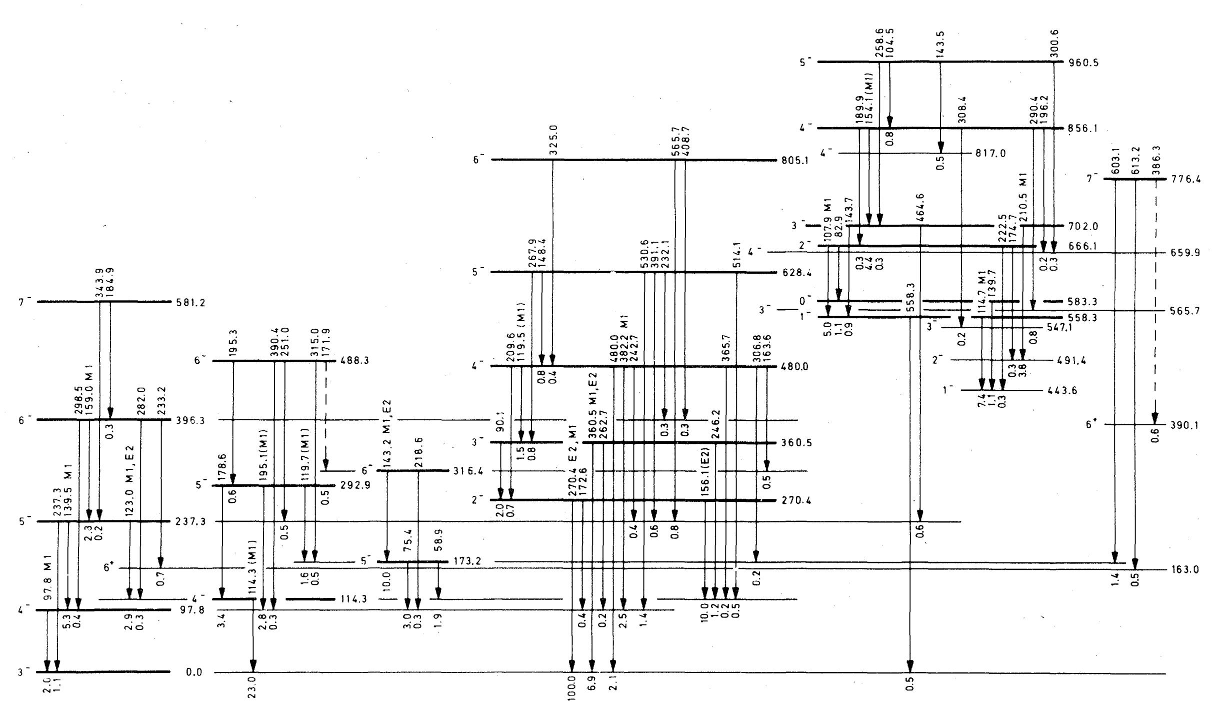


FIG. 1. Decay of the negative parity states with the proton in the $\frac{7}{2}^+$[404] state. In order not to overcomplicate the level schemes, all levels are drawn as solid lines and no energy or spin and parity values are put within brackets in Figs. 1–3. These visual indications of the degree of confidence can be found in Fig. 4. Transitions, drawn as dashed arrows, indicate that the transition is located in two different positions. The figure only gives gamma intensities in relative units, normalized to 100 for the 270.4 keV transition to the ground state.

the strong 173.2 keV transition. There a ground-state transition is present, together with the transitions to the 97.8 and 114.3 keV levels.

The level at 316.4 keV was already seen in the $(d,p)$ experiment[17] and interpreted by Helmer *et al.*[16] as the $I=6$ member of this $K=5$ band. The 143.2 keV transition to the level at 173.2 keV occurs also in the $^{182}Hf^m$ decay.[31] The $E2$ or $M1$ multipolarity of this transition (Table II) and the fact that the level was not observed in the 2 keV neutron capture[16] make an $I^\pi = 6^-$ assignment most likely.

The transition $6^- \rightarrow 5^-$ in this band cannot be used for a precise energy determination of the $6^-$ level, because of the presence of an intense close-lying $^{183}Ta$ transition: The difference between the measured energy 143.18 keV and the level energy difference, which is defined by the transition 488.26 → 316.39 keV, is about 30 eV. From the intensity variation during the experiment, one concludes that the part of the 143.18 keV transition belonging to $^{182}Ta$ is about $\frac{1}{3}$.

#### 4. *The $K^\pi = 2^-$ band at 270.4 keV*

The spin 5 member of this well established and obviously rather pure rotational band is depopulated by six transitions first observed in our gamma spectrum. The spin 6 member[18] was expected at 806.8 keV. Tentative levels can be proposed at 804.41 and 805.07 keV. The latter energy is preferred, having better energy combinations and a better agreement with Coriolis-mixing calculations.[18, 34, 36] The multipolarities of the 270.40, 360.53, 382.19, 156.09, and 119.52 keV transitions from Table II agree well with their location in the scheme.

#### 5. *The $K^\pi = 0^-$ band at 558.3 keV*

In the work of Helmer *et al.*[16] the two states at 666 and 702 keV were identified with levels seen in the $(d,p)$ reaction[17] at nearly the same energies. They were thought to form, together with the $(d,p)$ levels at 558 and 583 keV, the four lowest members of a $K=0$ band. The presence of rather intense transitions between these levels and their decay, which goes preferentially to the levels of the $K=1$ band at 443 keV, supports this assumption. For the same reason, the levels at 856.1 and 960.5 keV are considered to be the next two members of this band. Two of the intraband transitions, with energies 107.9 and 210.5 keV, were found to have $M1$ multipolarity (see Table II). The even spin members and the odd ones fit the rotational energy sequence rather well, yielding parameter values $A = 13.9$ keV and $B = -12$ eV for the even spin levels and $A = 14.4$ keV and $B = -0.1$ for the odd spin states.

The presumed spin values for the levels at 856.1 and 960.5 keV are in disagreement with those which Helmer *et al.* deduced from their 2 keV neutron capture experiment.[16] For the 960.5 keV level, the proposed doublet with a $4^-$ level at 960.4 keV (see Sec. III F) accounts for the observed intensity in the work of Helmer *et al.*, but in the case of the 856.1 keV level, an intensity lower than normally expected for a transition to an $I^\pi = 4^-$ level has to be accepted in the 2 keV capture. The 3, $4^-$ assignment by Stelts and Browne[43] supports our value.

The total intensity of the intraband $\Delta I = 1$ transitions of 24.99 keV ($0^- \rightarrow 1^-$) and 35.82 keV ($3^- \rightarrow 2^-$) can be estimated from the intensity balance to be about 10 relative units. Their energies are beyond our gamma-measurement limits, and the intensities of their $M$ lines (about 3 units) are beyond the sensitivity limit of the $(n, e)$ measurement.

### 6. The $I^\pi = 7^-$ level at 776.4 keV

This level was first observed in the $(d, p)$ reaction,[17] and its position was also deduced from the $\gamma$ spectrum following the decay of the $I^\pi = 8^-$ isomeric state in $^{182}$Hf by Ward *et al.*[31] The two transitions deexciting this level are present also in the diffraction spectrum with almost the same intensity ratio. They were found to form an energy combination with the levels at 173.2 and 163.0 keV, thus confirming the existence of a level at 776.4 keV. An additional transition deexciting to the tentative $I^\pi K = 6^+ 6$ level is also present in the spectrum.

## C. Other negative parity states

A detailed level scheme for these states can be found in Fig. 2.

### 1. The $K^\pi = 3^-$ band at 547.1 keV

The presence of an intense 297.12 keV $E1$ transition (see Table II) from this band head, for which a configuration $\{\frac{5}{2}^+[402]_p, \frac{1}{2}^-[510]_n\}$ is proposed, to the $3^+3$ state at 250.0 keV with configuration $\{\frac{9}{2}^-[514]_p, \frac{3}{2}^-[512]_n\}$ might be explained qualitatively

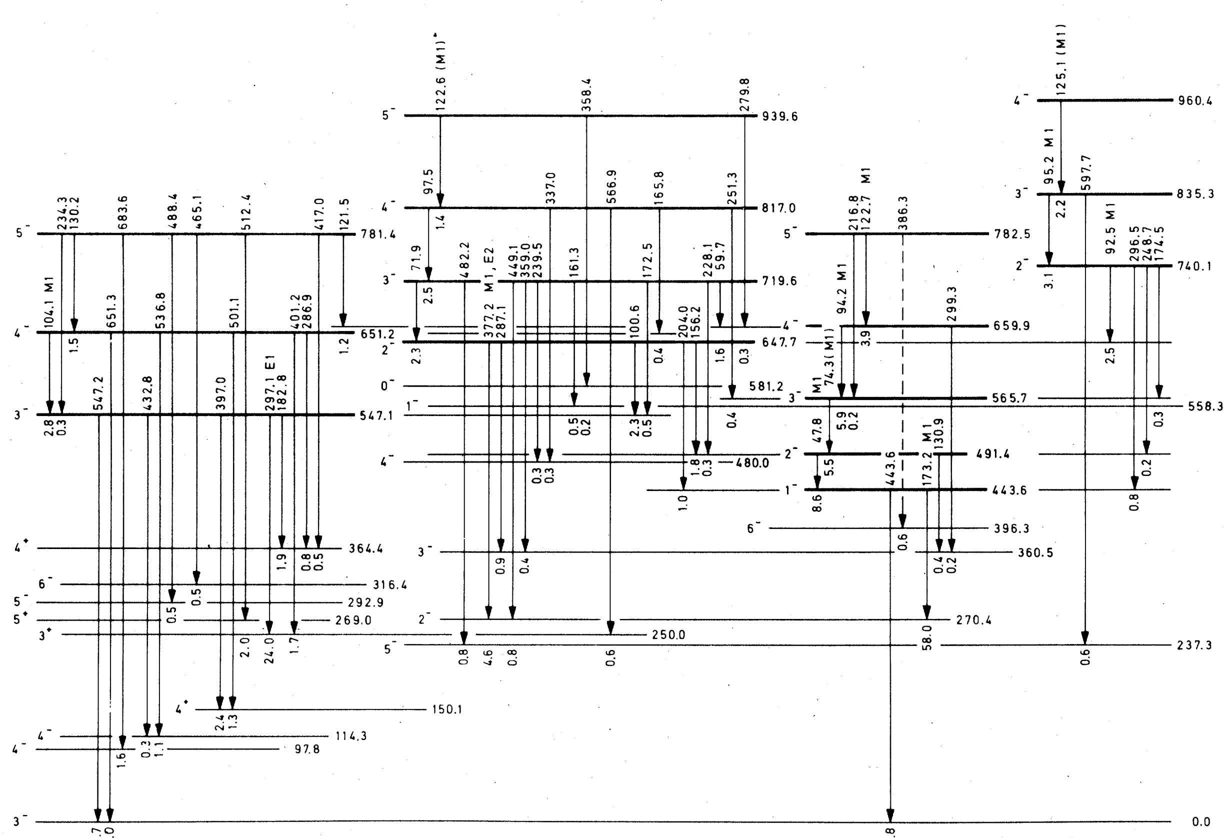


FIG. 2. Decay of the other negative parity states (see also, caption of Fig. 1).

by admixtures of the configurations $\{\frac{9}{2}^-[514]_p, \frac{3}{2}^+[651]_n\}$ to the $3^-$ state and/or $\{\frac{7}{2}^-[523]_p, \frac{1}{2}^-[510]_n\}$ to the $3^+$ state. These configurations are expected to occur at higher energies.

The admixtures would be caused by the residual proton-neutron interaction. When a central force is considered, the spin-exchange term yields, in general, the dominant contribution to the matrix element,[37] but only connects states with the same total intrinsic spins $\Sigma_p + \Sigma_n$. Now in both cases, the total asymptotic spin is different for the two states. However, for the actual deformation the spin in the $\frac{3}{2}^+[651]$ neutron orbital is almost unpolarized, i.e., the components with spin up and spin down in the wave function are almost equal, whereas for all other orbitals involved, the asymptotic spin value is a good approximation. Therefore, the matrix element connecting the configurations $\{\frac{5}{2}^+[402]_p, \frac{1}{2}^-[510]_n\}$ and $\{\frac{9}{2}^-[514]_p, \frac{3}{2}^+[651]_n\}$ could be much larger than that between the configurations $\{\frac{9}{2}^-[514]_p, \frac{3}{2}^-[512]_n\}$ and $\{\frac{7}{2}^-[523]_p, \frac{1}{2}^-[510]_n\}$. Although the excitation energy for the $\frac{3}{2}^+[651]$ neutron state is expected to be much higher than that for the $\frac{7}{2}^-[523]$ proton state, the influence of both admixtures could be comparable. The concurrent $M1$ transitions could also be strongly hindered. Therefore, lifetime measurements would be very useful for a better explanation of the structure of this 547.1 keV level.

The 651.21 keV $4^-$ state has transitions to the same group of levels as the 547.10 keV $3^-$ level. The 104.11 keV transition is in coincidence with the 297.12 keV transition and is found to have $M1$ multipolarity (see Table II). Its energy gives a reasonable value for the inertial parameter $A = 13.01$ keV. The 2 keV (Ref. 16) and resonance neutron capture data[11] support the existence of a doublet with levels at 647.65 and 651.21 keV (see also Sec. III C 2).

The $5^-3$ level is placed at 781.39 keV because it gives good energy combinations with transitions of the expected intensity and $A = 13.02$ keV for the inertial parameter. The high-energy gamma data[16] and our analysis of the $1^-$ band (see Sec. III C 3) indicate the presence of a doublet here also.

### 2. The $K^\pi = 2^-$ band at 647.7 keV

Helmer *et al.*[16] have already proposed the possibility of a doublet of levels at about 650 keV. Our gamma data give a good energy combination at 647.65 keV including the 377.25 keV $M1$, $E2$ transition (see Table II) to the 270.40 keV $2^-$ level. The transitions 100.55 and 204.04 keV cannot have $E1$ multipolarity, (see Table II) which also favors negative parity. The doublet in the 2 keV neutron spectrum does not allow for a spin 1, and the total $(n_{2\,\mathrm{keV}}, \gamma)$ intensity, as well as the rotational structure, strongly indicate spin 2.

The $3^-$, $4^-$, and $5^-$ rotational levels are found to be at 719.55, 817.02, and 939.63 keV. They are all formed by good energy combinations, have the expected depopulation intensity, and agree well with the levels seen in 2 keV neutron capture[16] and resonance capture gamma spectra.[11] The normalized $(n_{2\,\mathrm{keV}}, \gamma)$ intensity for the 817.02 keV $4^-$ level clearly has a lower value than expected. The same is true for several other states at these higher energies. The rotational parameters calculated from the $2^-$, $3^-$, $4^-$, and $5^-$ level energies are $A = 11.8$ keV and $B = 0.01$ keV.

The most probable structure for the 647.7 keV band is $\{\frac{5}{2}^+[402]_p, \frac{1}{2}^-[510]_n\}$, which has been assigned by Helmer *et al.*[16] to their tentative 659 keV band. Such structure is expected close to the 547.10 keV band with the same configuration, and these two bands are connected by a rather intense transition at 100.6 keV and several weaker ones. The Gallagher-Moszkowski rule[38] is also satisfied.

### 3. The $K^\pi = 1^-$ band at 443.6 keV

The strong transition at 173.2 keV, being clearly in coincidence with the 270.4 keV transition (see Table III) must feed the level at the latter energy because of its intensity. The $M1$ multipolarity of the 173.2 keV transition (see Table II) allows the deduced level at 443.6 keV to have $I = 1, 2$, or 3 with negative parity. A level with $I^\pi = 2^-$ or $3^-$ at this energy should have been observed by Helmer *et al.*[16] in their 2 keV neutron capture experiment, so $I^\pi = 1^-$ is the most plausible value.

The presence of the very strong transition to the $K^\pi = 2^-$ band leads to an interpretation of this level as a band head. The lowest configurations providing a $K = 1$ band are expected to be the $\{\frac{5}{2}^+[402]_p, \frac{3}{2}^-[512]_n\}$, $\{\frac{9}{2}^-[514]_p, \frac{11}{2}^+[615]_n\}$, and $\{\frac{1}{2}^+[411]_p, \frac{1}{2}^-[510]_n\}$ ones. Only in the first one, the $K = 1$ band would have the lowest energy, according to the Gallagher-Moszkowski coupling rule.[38] The $\{\frac{9}{2}^-[514]_p, \frac{11}{2}^+[615]_n\}$ is the configuration of the well known $K = 10$ isomeric state at 519 keV, so the $K = 1$ band of this configuration should occur at a higher energy. The main argument, however, in the assignment of a configuration to this $K = 1$ state is the presence of the 173.2 keV transition to the $\{\frac{7}{2}^+[404]_p, \frac{3}{2}^-[512]_n\}$ $K = 2$ state, which can only be explained by assuming a $\{\frac{5}{2}^+[402]_p, \frac{3}{2}^-[512]_n\}$ configuration for the level at 443.6 keV. Indeed, for the other two configurations, this transition would be overlap forbidden and could only proceed through admixed components.

The levels at 491.4, 565.7, and 659.9 keV were already observed by Helmer *et al.*[16] Negative parity can be assigned to these three levels, because $M1$ multipolarity is obtained for all transitions between them and for the 47.81 keV transition to the level at 443.6 keV (see Table II). The first of these levels was classified as an $I^{\pi}=2^-$ or $5^-$, according to its feeding after 2 keV neutron capture.[16] The value $5^-$ can be excluded since in the experiment by Wasson *et al.*[11] the level is fed from an $I=3$ resonance. The level at 659.9 keV was assigned a spin 2 or 5 by Helmer *et al.*,[16] but our proposed value of 4 is not strongly excluded.

The following expression can be used[39] for a $K=1$ band:

$$E_I = E_0 + AI(I+1) + D(-1)^{I+1} I(I+1) \; . \qquad (3)$$

The parameters $A = 12.1$ keV and $D = 87$ eV can be calculated from the $1^-$, $2^-$, and $3^-$ level energy values. The value $E_4 - E_3 = 94.21$ keV, obtained from these parameters, agrees well with the experimental energy difference $\Delta E = 94.17$ keV. Furthermore, we calculate $E_5 - E_4 = 125.56$ keV, where a transition energy of 125.13 keV is observed. However, the transition at 122.68 keV, possibly with $M_1$ multipolarity (see Table II), giving a doublet of two $5^-$ levels at 781.39 keV ($5^-3$) and 782.53 keV ($5^-1$), with a mean value of 781.96 keV, yields a better agreement with the mean level energy 781.91 ± 0.20 keV, deduced from the 2 keV neutron capture spectrum.[16]

### D. States of positive parity

The states described in this section are presented with their decay in Fig. 3.

#### 1. The $K^{\pi}=5^+$ band at 16.3 keV

This band is well known from the decay of the 16 min isomeric state in $^{182}$Ta.[5, 16, 31] The precise energy of this band head and the ones at 150.1 and 250.0 keV can be determined by considering levels decaying to both negative and positive parity (as, e.g., the level at 547.1 keV). The 171.6 keV transition can also be placed between the levels at 659.9 and 488.3 keV. This latter location can only involve a small fraction of the intensity, as the branching ratio between the 171.6 and 318.4 keV transitions is almost the same as in the work of Helmer *et al.*[16] and Ward *et al.*,[31] where the 171.6 keV transition is a single line.

#### 2. The $K^{\pi}=4^+$ band at 150.1 keV

For the $I=5$ member of this band Helmer *et al.*[16] proposed the level at 331.3 keV. This energy yields for the $A$ parameter in the rotational formula the value $A = 18.1$ keV, which is very large as compared to the values found in other bands (e.g., $A = 12.2$ keV in the $K^{\pi}=5^+$ band of the same configuration). Besides, only two transitions depopulating such a level can be found, with a total intensity (calculated from the gamma intensities, using theoretical conversion coefficients of Hager and Seltzer[29]) of only three relative units, which is quite unsatisfactory from statistical population considerations.[40]

From the results of our experiments, the existence of a level at 269.0 keV was deduced which has the same parity as the level at 150.1 keV.

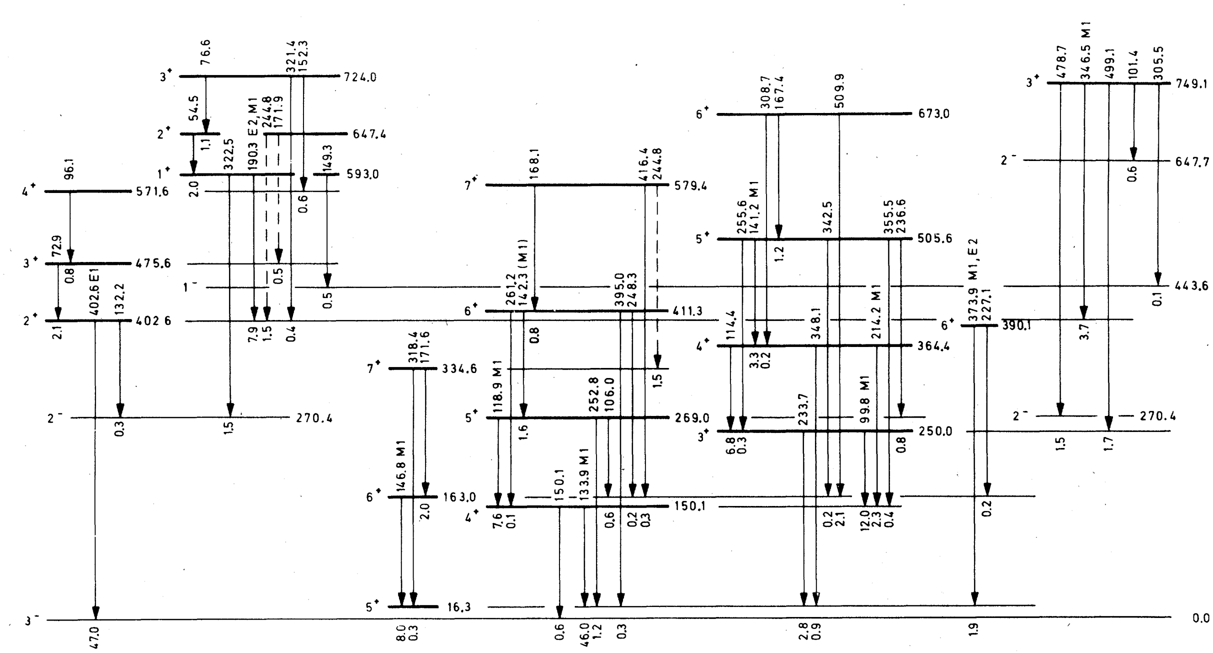


FIG. 3. Decay of the positive parity states (see also, caption of Fig. 1).

The most probable values for the spin, as inferred from the $M1$ multipolarity from Table II of the 118.9 keV transition involved, are $I=4$, 5, and 6. An interpretation of this level as the $I=5$ member of the $K=4$ band yields, for the $A$ parameter, a much more reasonable value of $A=11.9$ keV. The total intensity of the depopulating transitions in our version is calculated to be 46 relative units, which agrees with population considerations.

Additional levels were found at 411.3 and 579.4 keV. Mainly because of their position, these levels are assumed to be the $I=6$ and $I=7$ members of the band. The 142.27 keV transition, possibly $M1$ in Table II, indicates an even parity for the 411.3 keV level. This transition forms a doublet with a close-lying $^{183}W$ transition, whose contribution we evaluate to be about 10% of the intensity.

Coriolis-mixing calculations[34, 36] also strongly support the new version of the $K^\pi=4^+$ band energy sequence. However, we have not cleared the structure of the 331 keV level, if the corresponding transition in the 2 keV neutron capture gamma spectrum is not the result of an intensity fluctuation in the high energy spectrum.

### 3. The $K^\pi=3^+$ band at 250.0 keV

The levels at 250.0 and 505.6 keV can be identified with those observed by Helmer *et al.*[16] at $250.2\pm0.4$ and $505.4\pm0.2$ keV. At 364.4 keV a new level was found which was interpreted as the missing $I=4$ level in the scheme of Helmer *et al.*[16] The transition to this level was probably hidden by the much stronger transition to the $3^-$ level at 360.5 keV. The large error (1.0 keV) on the energy of the level at 361.8 keV in Table I of Wasson *et al.*[11] also might be an indication of the existence of a doublet at this energy. A level found at 673.01 keV is supposed to be the $I=6$ member of this band. All transitions from this band, except those deexciting the band head, have been located first in this study, and the 99.83, 141.25, and 214.21 keV transitions are found to have proper multipolarities. The $(n,e)$ lines of the rather strong 114.38 keV gamma line could not be observed because of the presence of another intense transition with an energy value 61 eV lower (see Table II).

### 4. The tentative band head $I^\pi K=6^+6$ at 390.1 keV

Helmer *et al.*[16] have assigned this band head to a level at $397.3\pm0.8$ keV, which they observed only after thermal neutron capture. The calculated doublet splitting with the $3^+3$ band head at 250.0 keV is 114 keV,[41] while population considerations require a total intensity of the order of three relative units for the decay of the $6^+6$ level. The moderately intense 373.88 keV $M1$, $E2$ transition gives a level at 390.1 keV, which agrees approximately with the calculated doublet splitting. Together with a weaker line to the 163.04 keV $6^+$ level, this transition also satisfies the population considerations. Besides, a weak line from the 776.4 keV $7^-$ level leads to the proposed 390.1 keV state, which, however, should be considered as tentative, because two weak transitions are involved and because it is not observed in reaction experiments. There could even be an alternative candidate for this $6^+6$ level at 423.13 keV, which would also decay to the 16.3 and 163.0 keV levels.

### 5. The $K^\pi=2^+$ band at 402.6 keV

The existence of a level at 402.6 keV with Nilsson configuration $\{\frac{7}{2}^+[402]_p,\ \frac{11}{2}^+[615]_n\}$, being depopulated by an intense $E1$ transition (see Table II) is confirmed. This band head is also connected with weaker lines to the $2^-2$ level at 270.40 keV and to some higher-lying negative parity levels: the $3^-3$ at 547.10 keV, $1^-0$ at 558.28 keV, and $3^-0$ at 701.98 keV.

Less reliable information can be derived about the rotational levels. The version of the $3^+2$ level at 474.2 keV proposed at the Munich conference[20] was later removed because of the relocation of the 71.90 keV transition into another place in the scheme. Assuming that the 2 keV neutron data[16] give the position of this level within the errors of the measurement, several transitions can be placed between the $3^+$ and $2^+$ levels. The version shown in Fig. 3 was chosen mainly because it gives some energy combinations with the 592.95 keV $1^+$ band. The same accounts for the $4^+$ level.

### 6. The $K^\pi=1^+$ band at 593.0 keV

It is seen from Table IV that the neutron orbit $\frac{9}{2}^+[624]$ should occur at energies of about 600 keV. Ward *et al.*[31] assigned the configuration $\{\frac{9}{2}^-[514]_p,\ \frac{9}{2}^+[624]_n\}$ to their 652.6 keV level. We found a level at 592.95 keV and assigned it as the band head for the configuration $\{\frac{7}{2}^+[404]_p,\ \frac{9}{2}^+[624]_n\}$. The strong 190.34 keV transition with $E2$, $M1$ multipolarity (see Table II) is in coincidence with the 402.62 keV transition, and weaker transitions to the levels at 443.61 and 270.40 keV were also found.

Two rotational levels are proposed, only in a tentative way, by taking into account energy combinations of rather weak gamma lines to the $2^+$ band (Fig. 3).

## E. The bands with high $K$ values

The band head $I^\pi K=10^-10\ \{\frac{9}{2}^-[514]_p,\ \frac{11}{2}^+[615]_n\}$ with a lifetime of 16 min has been studied in sev-

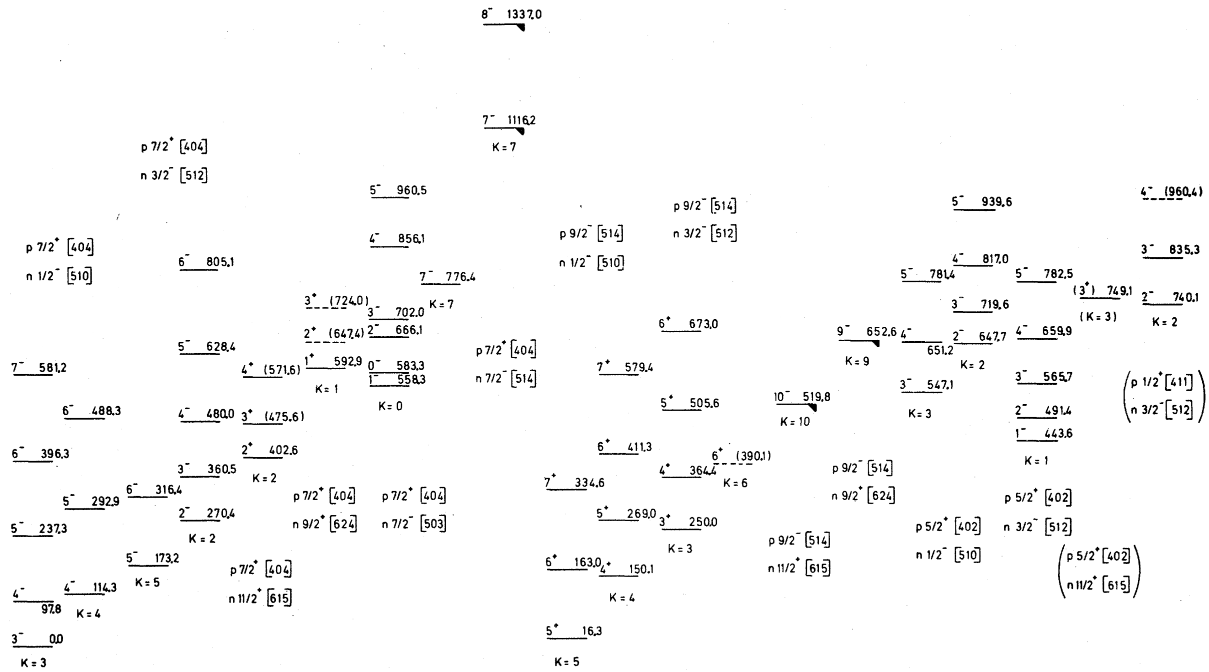


FIG. 4. Complete level scheme of $^{182}$Ta, showing the different configurations. States not observed in the experiments described in this paper are marked with ——◥ .

eral works.[5-8, 16, 31] Ward *et al.*[31] also observed transitions from levels at 652.6, 776.6, 1116.2, and 1337.0 keV in the decay of the $8^-8$ isomeric state in $^{182}$Hf. We include them all in our level scheme (Fig. 4) for the sake of completeness. Only the deexcitation of the 776.36 keV level is observed in our gamma spectrum (see Sec. III B 6).

### F. Tentatively assigned levels at higher energies

The levels and doublets observed in the 2 keV neutron capture spectrum[16] up to 720 keV, except for the 331 keV ($2^+$, $5^+$) level and two questionable ones, are discussed together with their structure and decay modes in Secs. III B–III E. We have tried to find in a somewhat higher energy region the odd-parity rotational bands with $K < 5$ from the configurations $\{\frac{9}{2}^-[514]_p,\ \frac{9}{2}^+[624]_n\}$ (having its $9^-$ state at 652.6; see Ref. 31) and $\{\frac{9}{2}^-[514]_p,\ \frac{11}{2}^+[615]_n\}$ (with the $10^-$ state at 519.7 keV), and from several structures containing the proton orbital $\frac{1}{2}^+[411]$.

In Fig. 2 we give a group of levels at 740.13, 835.29, and 960.41 keV. The strong decay of the 740.13 keV level to the $2^-2$ level at 647.65 keV, and the presence of strong rotational transitions from the two others, favors the assignment of the first level as a band head. The spin sequence 2, 3, 4 agrees with the data of Helmer *et al.*,[16] while the 835.3 → 740.1 keV transition and probably the 960.4 → 835.3 keV transition have $M1$ multipolarity (in Table II). An assignment $K = 2$ yields the values $A = 15.87$ keV (from $E_3 - E_2$) and $A = 15.64$ keV (from $E_4 - E_3$) for the rotational parameter. As we have only three moderately strong depopulating transitions, the energy combinations do not provide a high confidence and other decay modes for these 2 keV neutron capture levels cannot be excluded. From energy considerations mainly, we propose the structure $\{\frac{1}{2}^+[411]_p,\ \frac{3}{2}^-[512]_n\}$ for this tentative band.

The $M1$ transition at 346.46 keV is observed in coincidence with the 402.62 keV transition depopulating the $2^+2$ level; a coincidence between the 346.46 and 190.34 keV lines is not detected (see Table III). As a coincidence between the transitions at 478.69 and 270.40 keV is also observed, one can conclude that a positive parity level must be present at 749.09 keV, from which weaker transitions to the levels 443.61 keV ($1^-1$), 583.27 keV ($1^-0$), and 647.65 keV ($2^-2$) can also be found (see Fig. 3). As the spin value is unknown, the assignment of a configuration can only be speculative. The most probable configuration seems to be $\{\frac{5}{2}^+[402]_p,\ \frac{11}{2}^+[615]_n\}$, leading to $I^\pi K = 3^+3$.

### G. Spins of $^{181}$Ta neutron resonances

Our data on the levels with spins and parity $2^-$ and $5^-$, between them the 491.43 keV $2^-$, 666.15 keV $2^-$, 781.39 keV $5^-$, and 782.54 keV $5^-$ states, may contribute to the understanding of the resonance neutron capture $\gamma$-ray experiment of Wasson *et al.*[11] We find new spins $I=3$ for the 30.0 eV and $I=4$ for the 39.1 eV resonances, and stronger arguments for other resonance spins (see Table VI). In this respect, the results on resonance spins obtained by Riehs *et al.*[42] are unreliable, as their work is based on the assumption that the strong 173.2 keV transition depopulates a $5^-$ level, which from our data obviously is not the case.

### H. Final remarks

In comparison with previous studies on $^{182}$Ta (see Table V), the most complete being the work of Helmer *et al.*,[16] more precise data with great sensitivity are presented here on the gamma singles spectrum, with several previously unresolved multiplets (e.g., the strong triplet at 114 keV). More complete multipolarity data are deduced from the $(n,e)$ spectrum, and new $\gamma\gamma$-coincidence data are obtained. This experimental information has allowed us to obtain more reliable level energies, to propose several new rotational bands, to give more confidence to previously known levels and bands, and to extend known bands to higher rotational states.

For all levels up to an energy of 800 keV, previously observed in the work of Helmer *et al.*,[16] the decay was established and an interpretation could be given, except for the 331.3 keV level and the two tentative levels at 423.5 and 586.6 keV. The level at 397.3 keV, observed by Helmer *et al.*[16] and interpreted by them as the $I^\pi K=6^+6$ band head, could also have negative parity, as was suggested by Bollinger *et al.*,[35] and in this case it would be the $I^\pi K=6^-3$ level of the ground-state band.

At excitation energies above 800 keV, however, the decay modes were not found for all previously observed levels, not even for the ones with odd parity. The main reasons are: (1) larger errors for the higher gamma energies involved and a lack of good multipolarity data at these energies, and (2) the increasing level density and the occurrence of new types of structure.

As a rule, we have searched for two-quasiparticle bands, but have not taken into account possible four-quasiparticle and vibrational states, which from the general systematics for odd-mass nuclei can occur at 1 MeV and even lower.

## IV. CONCLUSIONS

Our considerations on the $^{182}$Ta level scheme are in agreement with a rotational model in its simplest form. We assigned the observed $^{182}$Ta levels to eight odd-parity and five even-parity rotational bands, involving the proton orbitals $\frac{7}{2}^+[404]$, $\frac{9}{2}^-[514]$, and $\frac{5}{2}^+[402]$ and the neutron orbitals $\frac{1}{2}^-[510]$, $\frac{3}{2}^-[512]$, $\frac{7}{2}^-[503]$, $\frac{11}{2}^+[615]$, and $\frac{9}{2}^+[624]$. Taking into account, also, three tentatively assigned rotational bands, these data provide a good framework for further theoretical analysis involving Coriolis mixing.

When our data are considered together with the data on bands with high $K$ values,[31] six doublets formed by states with angular momentum projection $K=\Omega_p+\Omega_n$ and $K=|\Omega_p-\Omega_n|$ in the same configuration are found, which agree with the Gallagher-Moszkowski rule.[38] The splittings between the experimental band head energies vary from 97 to 218 keV. The doublet splitting must have a rather high value (about 400 keV) in the case of the configuration $\{\frac{5}{2}^+[402]_p, \frac{3}{2}^-[512]_n\}$ if this structure is assigned, as in our discussion, to the 443.6 keV level, because the 2 keV neutron $(n,\gamma)$ spectrum[16] gives no possibility for the $4^-$ band head below 800 keV. On the other hand, the Gallagher-Moszkowski rule would be violated if the structure $\{\frac{9}{2}^-[514]_p, \frac{11}{2}^+[615]_n\}$ were mainly assigned to this 443.6 keV $1^-$ band.

The vibrational states in odd-$A$ nuclei about $A=180$ are expected at rather high energies (of the order of 1 MeV). No decay pattern, characteristic for vibrational states, was found for any of the proposed levels. The lowest energy for possible vibrational levels in $^{182}$Ta should be 800 keV, since an acceptable decay is found for practically all lower-lying odd-parity levels with $I=2$ to 5.

We assigned the proton state $\frac{1}{2}^+[411]$, observed at 615.0 keV in $^{181}$Ta,[32] to a tentative band at 740 keV in $^{182}$Ta. Three more bands involving this proton state and the neutron states $\frac{1}{2}^-[510]$ and $\frac{3}{2}^-[512]$ are expected at energies of about 800–1000 keV. We hope that our data will be useful in finding the decay for these and other levels, when their positions are obtained from reactions such as $^{183}$W$(d,{}^3$He$)^{182}$Ta.

## ACKNOWLEDGMENTS

The first four authors would like to express their gratitude to Professor O. Schult for his invitation to use the Risø diffraction spectrometer and for his continuous interest in the progress of the study. They also wish to acknowledge the kind hospitality of the Danish AEK extended to them during their stay in Risø. Many thanks are due to R. Greenwood and R. Piepenbring for helpful discussions. A part of this work was carried out in the framework of the Association KU Leuven-S.C.K. with financial support of the Belgian IIKW.

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