

# The K-conversion Coefficient of the Retarded 482 keV Transition in $^{181}\text{Ta}$

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The K-conversion coefficient of the 482 keV transition in  $^{181}\text{Ta}$  has been measured by means of an electron-electron coincidence method. The result obtained is  $\alpha_K = 0.0240 \pm 0.0012$ . It is noticed that the M1 conversion process of the 482 keV transition is strongly affected by the penetration terms. The M1 conversion coefficient is about 10 times larger than the normal finite size corrected value.

The internal conversion penetration parameter  $\lambda$ , is found to be:  $\lambda = 175 \pm 8$  in accordance with what is expected on theoretical grounds.

## Introduction

It has been observed<sup>1</sup> that for certain strongly retarded magnetic dipole transitions large anomalies appear in the internal conversion process. The cause of these anomalies is the presence of the so-called “penetration matrix elements” in the internal conversion process. The penetration matrix element has only a small weight when compared to the normal gamma-ray matrix element. The small weighting, however, may be counterbalanced if the gamma-ray matrix element is considerably smaller than its dimensional value, i. e. if the electromagnetic transition is much retarded. A necessary requirement is of course, that the penetration matrix element for the same nuclear transition should be essentially unaffected and thus have its dimensional value. These requirements are fulfilled for the  $l$ -forbidden ( $\Delta l = 2$ ) M1 transitions between pure shell model states. In the deformed region  $l$  is no longer a good quantum and the  $l$ -selection rule is expected to break down. However, for strongly deformed nuclei the asymptotic quantum numbers introduced by Nilsson forbid M1 and also E2 single particle transitions between certain single particle configurations<sup>2</sup>. Moreover, collective M1 and E2 transitions between different rotational bands are, of course, forbidden in the lowest order.

In  $^{181}\text{Ta}$  there is a mixed M1-E2 transition from  $5/2+$  excited state at 482 keV to the  $7/2+$  ground state. In the Nilsson model the two states are classified as  $|I, K, \pi\rangle = |5/2, 5/2+\rangle \rightarrow |7/2, 7/2+\rangle$ , in other words as a transition between two different rotational bands. Both M1 and E2 transitions are

forbidden by the selection rules of the appropriate asymptotic quantum numbers.

The  $|5/2, 5/2+\rangle$  and the  $|7/2, 7/2+\rangle$  states originate from the shell model states at  $d_{5/2}$  and  $g_{7/2}$ , respectively. Consequently the 482 keV M1 (but not the E2) transition is expected to be forbidden also in the shell model picture. DeWaard<sup>3</sup> has measured the halflife for the 482 keV level. The result,  $1.06 \times 10^{-8}$  sec, together with the known<sup>4</sup> E2/M1 mixing ratio indicates that both the M1 and the E2 transitions are much slower than predicted by the Weisskopf formula. The retardation factors are  $R(\text{M1}) = 2.5 \times 10^6$  and  $R(\text{E2}) = 35$ .

Large anomalies are expected to show up in the M1 internal conversion process. Church and Weneser<sup>5</sup> have analysed the 482 keV transition. From published values for the conversion coefficient and angular correlations, they conclude that existing experimental data indicate that the penetration matrix element might in fact be important. The  $\lambda$ -value, defined as the ratio of the penetration matrix element to the gamma-ray matrix element, was found to be  $-7 \leq \lambda \leq -150$ . The uncertainties in the experimental values given for the conversion coefficient and for the E2/M1 mixing ratio do not allow for a more precise value for  $\lambda$ .

The penetration effects should also be seen in the electron-gamma angular correlations. Altogether four conversion electron directional correlations were measured<sup>6,7</sup> in  $^{181}\text{Ta}$ . However, only for one<sup>6</sup> of these the  $b_2$  (M1 + E2) sign reversal is of any significance, namely the crucial 482 K – (133 + 137)  $\gamma$  correlation, where large dynamic effects were found to be present.

An experimental study of the 482 keV transition in  $^{181}\text{Ta}$  especially aiming at a search for penetration effects in the internal conversion process is appar-

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ently of great interest. The present investigation has been undertaken mainly to determine precisely the K-conversion coefficients of the strongly retarded 482 keV transition in  $^{181}\text{Ta}$  applying the coincidence technique.

### 1. The Level Scheme of $^{181}\text{Ta}$

The strongly deformed  $^{181}\text{Ta}$  nucleus has been the subject of many investigations. A summary of the earlier level scheme studies was given by El-Nesr and Bashandy<sup>8</sup>. The presently accepted decay scheme of  $^{181}\text{Hf}$  is shown in Figure 1. All of the  $^{181}\text{Ta}$

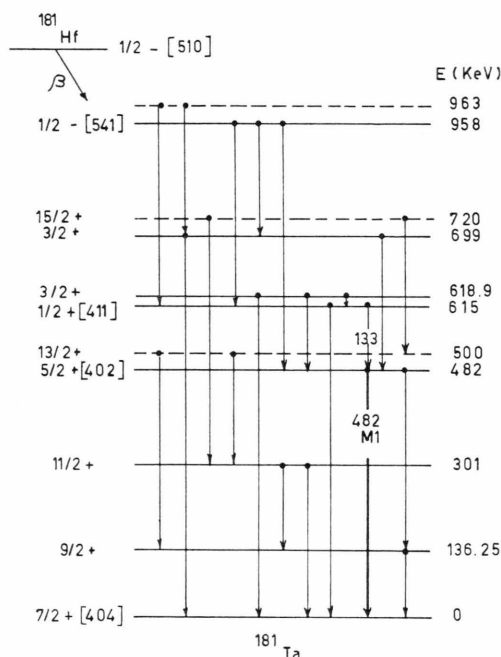


Fig. 1. Decay scheme of  $^{181}\text{Hf}$  as given in Reference 8.

excited states populated by the radioactive decay of  $^{181}\text{Hf}$  and of  $^{181}\text{W}$  are consistent with the predictions of the unified model of the nucleus.

The spin of the  $^{181}_{73}\text{Ta}$  ground state is measured<sup>2</sup> to be  $7/2$ . This is a very clearcut exception to the orderly filling of the levels, according to which the  $[404\ 7/2]$  orbital occurs as the ground state for  $Z=71$  (and is observed for  $^{175}_{71}\text{Lu}$  and  $^{177}_{71}\text{Lu}$ ) and the  $[402\ 5/2]$  or  $[514\ 9/2]$  orbital should provide the lowest configuration for  $Z=73$ . It appears that the near-lying orbital  $[514\ 9/2]$  is filled pairwise in going from Lu to Ta, and thus the orbital  $[404\ 7/2]$  occurs as a ground-state configuration a second time

in the Ta isotopes. The configuration  $[514\ 9/2]$  is not observed as a ground state in any stable nucleus. This irregularity in the filling of the single-particle states may possibly be a consequence of differences in the pairing energy for pairs of nucleons in the different orbitals. The rotational band built on the  $^{181}\text{Ta}$  ground state has levels at 136 keV ( $I=9/2$ ) and 301 keV ( $I=11/2$ ).

The configuration  $[402\ 5/2]$  which, as mentioned above, might have been expected as the  $^{181}\text{Ta}$  ground state in the absence of pairing effects, occurs at 482 keV as an excited configuration. The M1 transition from this level to the ground state is very strongly hindered ( $R=2.5 \times 10^6$ ) while the E2 decay is also hindered but much less ( $R=35$ ). These hindrances are in accord with the asymptotic selection rules. The magnetic moment of the 482 keV state has been measured<sup>2</sup> and is in accord with that calculated from the  $[402\ 5/2]$  orbital.

At 615 keV, the  $[411\ 1/2]$  configuration is found and the characteristic closely lying  $I=3/2^+$  rotational state associated with this configuration is at 618 keV. The 615 keV state decays by a hindered E2 transition to the 482 keV level ( $R=4 \times 10^2$ ) and an essentially unhindered M3 transition to the ground state ( $R=7$ ). These hindrances are in agreement with the asymptotic selection rules.

The  $^{181}\text{Hf}$  ground state should correspond to the  $[510\ 1/2]$  orbital just as the  $^{183}\text{W}$  ground state. The beta decay to  $^{181}\text{Ta}$  thus takes place almost entirely to the  $I=1/2^+$  and  $I=3/2^+$  members of the rotational band associated with the  $[411\ 1/2]$  configuration. The transition is thus classified as  $1u$  and has  $\log ft=7.1$ . An additional M2 gamma ray of 476 keV has been reported in the  $^{181}\text{Hf}$  decay and apparently represents a transition from a level at 958 keV. It is possible that this level corresponds to the orbital  $[541\ 1/2]$  which is really a member of the next shell ( $Z>82$ ), but which is brought into this region of excitation as a consequence of the nuclear deformation. If this is correct, additional information about this level would be very interesting. It should tend to increase the nuclear deformation considerably, and thus the moment of inertia associated with its rotational band should be especially great. Its decay to the lower lying  $[411\ 1/2]$  and  $[402\ 5/2]$  configurations should be appreciably retarded both as a consequence of the asymptotic selection rules and of the change in the equilibrium shape.

Interesting features of the level scheme, of particular interest in the present study, are (i) the highly-retarded multipole-mixed 482 keV transition, which exhibits strong penetration effects in its magnetic dipole internal conversion process, and (ii) experimental evidence of parity impurities in the 482 keV level of  $^{181}\text{Ta}$  found by observing circular polarization of the 482 keV  $\gamma$ -rays<sup>9,10</sup>. The degree of circular polarization of the parity mixed 482 keV  $\gamma$ -ray is given in Ref. (9) as:

$$P_\gamma = \left( \frac{-2}{1 + \delta^2} \right) \left( \frac{\langle E1 \rangle}{\langle M1 \rangle} \right) \quad (1)$$

where  $\langle E1 \rangle$  and  $\langle M1 \rangle$  are the electric and magnetic dipole matrix elements, respectively and  $\delta$  is the E2/M1 multipole mixing ratio. Considering equation (1), it is evident that a meaningful interpretation of  $\gamma$ -ray circular polarization data depends critically on an accurate knowledge of  $\delta$ . In the case of the 482 keV transition, the accurate determination of  $\delta$  is rather difficult. The unambiguous determination of  $\delta$  with L subshell conversion measurements is precluded by the presence of large penetration effects, while  $\gamma$ - $\gamma$  directional correlation measurements<sup>7</sup> are seriously complicated by extra-nuclear perturbations, arising from the large nuclear quadrupole moment and the long lifetime ( $\sim 11$  ns) of the 482 keV level. In addition, to eliminate the

interference between the 133  $\gamma$ -482  $\gamma$  and 137  $\gamma$ -482  $\gamma$  cascades in directional correlation experiments, it is necessary to use a detector that will resolve the 133 and the 137 keV  $\gamma$ -rays.

Based on the two recently reported values for the E2/M1 mixing ratio of the 482 keV transition, viz.  $\delta = 5.0 \pm 0.2$  (Ref. <sup>10</sup>) and  $\delta = 7.2 \pm 1.5$  (Ref. <sup>11</sup>), the uncertainty in the value of the circular polarization  $P_\gamma$  is of the order of 100% i.e.  $\Delta P_\gamma / |P_\gamma| \approx 1$ . Here  $P_\gamma$  is calculated from the average of the two central values of  $\delta$  given in Ref. <sup>10,11</sup>, and  $\Delta P_\gamma$  is computed with the extreme values. Similarly, the above uncertainty in  $\delta$  leads to an uncertainty of  $>40\%$  in the penetration parameter  $\lambda$  extracted from internal conversion data. Thus a careful measurement of  $\delta(482)$  appeared worthwhile.

## 2. Experimental Procedures

### 2.1 Source preparation

The  $^{181}\text{Hf}$  activity was produced by neutron irradiation of spectroscopically pure  $\text{HfO}_2$  enriched to 93.3% in  $^{180}\text{Hf}$ , at DIDO in Harwell over a period of three weeks in a neutron flux of  $10^{14}$  n/cm<sup>2</sup> sec. The active  $\text{HfO}_2$  was dissolved in nitric acid. A point source of 4 mm diameter was produced by evaporating the activity onto 0.7 mg/cm<sup>2</sup> aluminium foil. The evaporation temperature was kept sufficiently low to avoid simultaneous wolfram evaporation. The sources were estimated to have a thickness of less

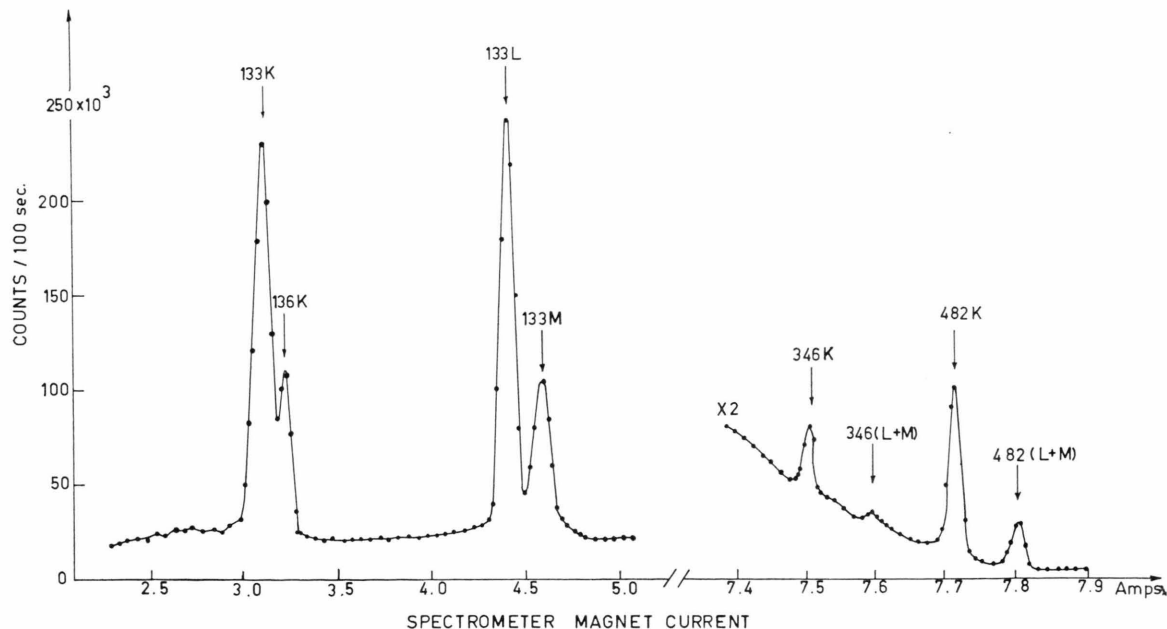


Fig. 2. Conversion electron spectrum of  $^{181}\text{Hf}$ .

than  $50 \mu\text{g}/\text{cm}^2$ . The only contamination is due to the  $^{175}\text{Hf}$  activity. Judging from our electron spectra this contamination was less than 1% and did not interfere with our  $^{181}\text{Hf}$  experiment.

## 2.2 Apparatus

In this investigation an electron-electron coincidence spectrometer described earlier<sup>12</sup> was employed. It consists of two long lens spectrometers for magnetic momentum selection. A plastic crystals coupled to RCA 6810 A photomultiplier tubes, through light guides, were used as electron detectors. The baffles of the spectrometers were adjusted to give a resolution of 3% at which the transmission is  $\sim 3\%$ . A fast-slow coincidence unit with an effective resolving time of  $2.5 \times 10^{-8}$  sec was used.

## 2.3 Measurements

In the electron-electron coincidence measurements\*, the magnetic spectrometers were set at a resolution of 3 per cent and were adjusted to focus the tops of the two conversion lines of interest and coincidences were recorded. A single conversion electron spectrum of  $^{181}\text{Hf}$  is shown in Fig. 2. It was proved from our earlier measurements<sup>8</sup> that the 133 keV gamma-ray is in coincidence with the 482 keV transition. In the experiment spectrometer I was adjusted to focus the K-conversion electrons of the 482 keV transition while spectrometer II was focused on the K-conversion electrons of the 133 keV transition. The number of coincidences,  $N_c$ , collected after subtraction of random coincidences and background is given by:

$$N_c = N_2 \delta_1 \mathcal{H}_1 f_1 \omega_1 \xi_1 \varepsilon_c \gamma \quad (2)$$

where  $N_2$  = The number of counts belonging to the conversion line accepted by spectrometer II,

$\mathcal{H}_1$  = conversion probability of transition 1,  
 $f_1$  = fraction of the conversion line focused in spectrometer I,

$\omega_1$  = transmission in spectrometer I,

$\xi_1$  = efficiency of the detector in spectrometer I,

$\varepsilon_c$  = efficiency of the coincidence circuit,

$\delta_1$  = fraction of transition 2 in coincidence with transition 1, and

$\gamma$  = coincidence correlation constant.

In our calculations  $\xi_1$  has been set equal to unity while the efficiency of the coincidence circuit  $\varepsilon_c$

was found to be 90 per cent and assumed to be constant during the experiment. The coincidence correlation constant  $\gamma$  was considered equal one since the aperture angle in each spectrometer is large. The transmission of the two spectrometers has been systematically investigated for different source diameters and baffle settings<sup>12</sup>.

From  $\mathcal{H}_K(482)$  thus determined, the K-conversion coefficient is obtained from the relation:

$$\alpha_K = \frac{\mathcal{H}_K}{1 - \mathcal{H}_K[1 + (L + M + N)/K]} \quad (3)$$

where the  $(L + M + N)/K$  ratio was taken from the measured electron spectrum.

## 3. Results and Discussion

The K-conversion probability of the 482 keV transition obtained from the coincidence experiments is,

$$\mathcal{H}_K(482) = 0.0252 \pm 0.0014.$$

To determine the conversion coefficient we have measured the  $K/(L + M + N)$  ratios. Our results are:

$$K/(L + M + N)_{482} = 3.9 \pm 0.3$$

and from equation (3) we get:

$$\alpha_K(482) = 0.0240 \pm 0.0012.$$

Our measured value of  $\alpha_K(482)$  is in good agreement with previous values reported<sup>7</sup>. A weighted average of five values is  $[\alpha_K(482)]_{av} = 0.0240 \pm 0.0007$ .

The dependence of the K-shell internal conversion coefficient on  $\lambda$  and  $\delta$  is given by:

$$\alpha_K(\lambda, \delta) = \frac{\beta(M1)(1 + B_1\lambda + B_2\lambda^2) + \delta^2\alpha(E2)}{1 + \delta^2} \quad (4)$$

where  $\beta(M1)$  and  $\alpha(E2)$  are the usual conversion coefficients given in Ref.<sup>13</sup>,  $B_1$  and  $B_2$  are penetration coefficients tabulated in Ref.<sup>14</sup> and  $\lambda$  is the penetration parameter in the approximation used in Ref.<sup>14</sup>. Using the value of the multipole mixing ratio  $\delta$  reported by Ref.<sup>7</sup> and our value for  $\alpha_K(482)$ , we find  $\lambda(482) = 175 \pm 8$  which is in good agreement with previous results<sup>6, 7</sup>.

A theoretical estimate of  $|\lambda|$  has been published<sup>5</sup>. For the 482 keV M1 transition in  $^{181}\text{Ta}$  the Nilsson model wave function give:

$$|\lambda|(\text{theor}) \approx 600.$$

Thus, it may be concluded that the 482 keV transition is strongly affected by nuclear structure depen-

\* The measurements were performed at the Institute of Physics, Uppsala, Sweden, during our staying.

dent penetration matrix elements, as suggested by the Nilsson theory. Moreover, the theory of the internal conversion process, including the dynamic effects, appears to be well understood and consistent. Penetration matrix elements may therefore, be used as independent and complimentary sources of information for the study of problems in nuclear structure.

As an example, transitions from excited nuclear levels take place through electromagnetic interaction determined by the angular momentum and parity selection rules. However, there is in principle also a small parity violating contribution originating from the weak interaction between the nucleons. On the basis of the current-current theory, proposed by Feynman and Gell-Mann, these contributions may be calculated<sup>6</sup>. For certain strongly retarded electromagnetic transitions these parity violating contributions are expected to appear. In the particular case of the 482 keV transition in <sup>181</sup>Ta, the current-current theory predicts an E1 + M1 interference effect, which should give rise to a circular polarization of the gamma radiation as shown by Equation (1). This effect has recently been experimentally<sup>9, 10</sup>

verified. The experiments give the sign and the absolute value for the ratio of the parity violating  $\langle E1 \rangle$  matrix element and the normal  $\langle M1 \rangle$  gamma ray matrix element. The weak interaction theories predict value for the  $\langle E1 \rangle$  matrix element. However, the  $\langle M1 \rangle$  gamma-ray matrix element cannot, in this case, be accurately calculated, since this strongly retarded transition depends in a critical fashion on the details of the nuclear wave functions. Therefore, one may replace the  $\langle M1 \rangle$  gamma-ray matrix element with the corresponding penetration matrix element, since the ratio of these two matrix elements i. e.  $\lambda$ , is known from experiments.

The penetration matrix element, which corresponds to an allowed transition, is far less sensitive to the details of the nuclear wave functions and may therefore be theoretically calculated with some confidence.

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