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L TO K RATIOS IN THE ELECTRON CAPTURE  
DECAY OF  $W^{181}$  AND  $Ta^{179}$

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### ABSTRACT

The L to K ratios in the electron capture decay of the isotopes  $Ta^{179}$  and  $W^{181}$  have been redetermined. Thin (0.060 in.) NaI crystals with thin (0.002 in.) Be windows were used to detect the L and K x rays. The partial fluorescent yields of the L sub shells of Hf and Ta were also measured by determining the coincidence rates between the L and the K x rays emitted by the sources. It is necessary to know the fluorescent yields if the L to K ratios are to be determined from the measured intensities of the L and the K x rays. The L to K ratio of  $Ta^{179}$  was found to be  $0.63 \pm 0.06$ , which implies a total decay energy of approximately  $115 \pm 5$  kev for this isotope. This energy is consistent with the observation that no gamma rays accompany the decay of  $Ta^{179}$  since the first excited level of  $Hf^{179}$  has an energy (122 kev) exceeding the total decay energy of  $Ta^{179}$ . The L to K ratio of  $W^{181}$  was found to be  $0.23 \pm 0.05$  from which a decay energy of approximately 260 kev is computed. This result is in agreement with the fact that two weak gamma rays are emitted by the source, one at 137 kev and the other at 152 kev. These gamma rays correspond to excited levels in  $Ta^{181}$ . These gamma rays are in coincidence with the L x rays emitted by the source but not with the K x rays, which means that the total decay energy of  $W^{181}$  must exceed 166 kev. The L to K capture ratios reported here are not in good agreement with previously reported values.

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### INTRODUCTION

Whenever a nucleus is unstable against positron emission but does not have the decay energy necessary to create the positron, then it decays by capturing an orbital electron and emitting a neutrino. The most prominent electromagnetic radiations observed in an electron-capture decay are usually the characteristic x rays of the daughter nucleus. These may be either the K, L, or higher-shell x rays, depending upon which electron is captured in the decay. The relative number of vacancies created in the various atomic sub shells by the decay process depends on the nature of the  $\beta$  decay and on the total energy of the transition.

If the decay energy is very much larger than the electron binding energy in the various sub shells, then, for allowed and first-forbidden transitions, the ratios of K to L to M capture depend only on the electron densities in these shells at the nucleus. On the other hand, if the decay energy is comparable to the binding energy in the K shell, then the L to K capture ratio is a function of the decay energy, the dependence being such that the emission of high-energy neutrinos is favored.<sup>1</sup> Since no other way exists to determine the decay energy for electron capture processes, it is of some importance to measure as accurately as possible the L to K capture ratios.



It is difficult to determine the relative number of L and K vacancies from the relative intensities of the L and K x rays emitted by the source. In the case of K capture, most of the K x rays emitted also create an L-shell vacancy, and the L x rays emitted by the filling of these vacancies must somehow be distinguished from L x rays which follow L electron capture. In addition, every K or L vacancy created does not always result in the emission of the corresponding x ray. The energy of the transition can be dissipated by the emission of one of the outer electrons of the atom. (Electrons resulting from such processes are called Auger electrons.) For the isotopes studied here, this effect was not too important for K electrons since only about 7% of the K vacancies lead to the emission of an Auger electron. However, over 70% of the L vacancies decay by emitting electrons, and it is therefore very important to know the ratio of electrons to x rays emitted by L vacancies since only the x rays are counted. The usual way in which Auger transitions are taken into account is to define a quantity called the "fluorescent yield" which is the ratio of the number of x rays emitted to the number of vacancies created in a given shell. Part of the object of the present experiment is to measure the fluorescent yields of the various atomic shells which take part in the electron capture decay.

Two isotopes which decay by pure electron capture were studied,  $W^{181}$  and  $Ta^{179}$ . Both of these have long enough half-lives so that very detailed experiments can be performed. Previous work on  $W^{181}$  is somewhat contradictory. Bisi, Terrani, and Zappa<sup>2</sup> have measured the L to K ratio and find a number ( $C_L/C_K = 1.54 \pm 0.1$ ) which implies a decay energy of 92 kev. On the other hand, Cork, Nester, LeBlanc, and Brice<sup>3</sup> have observed internal conversion electrons emitted by a  $W^{181}$  source corresponding to energy levels in  $Ta^{181}$  at 137 and 152 kev. The observed intensity of these lines is about

0.2% of the total number of decays. Debrunner, Heer, Kündig, Rüetschi, and Lindquist<sup>4</sup> have also observed these gamma rays with a scintillation spectrometer. These workers have also shown that the gamma rays are in coincidence with L x rays emitted by the  $W^{181}$  source, indicating that the gamma rays are not due to impurities. If these gamma rays correspond to levels in  $Ta^{181}$  at 137 and 152 kev, then the decay energy must exceed 164 kev and the L to K ratio must be considerably smaller than the value reported in reference 2. The results reported in the present work confirm the existence of the high-energy gamma rays and the value obtained for the L to K capture ratio is consistent with the higher decay energy required by the existence of the gamma rays. The present work therefore resolves the contradictory situation with regard to  $W^{181}$ .

In the case of  $Ta^{179}$ , the decay is simpler since no gamma rays are emitted by the source. The measured L to K ratio is sufficiently large so that the decay energy computed from this result does not exceed the energy of the first known level in  $Hf^{179}$ . However, the L to K ratio reported here is not as large as the value ( $1.4 \pm 0.4$ ) given in reference 5.

## EXPERIMENTAL METHODS

Scintillation counters were used in all the measurements reported here. There are two important features which a scintillation crystal sensitive to low-energy x rays must possess. The first is that the light output per ion pair must be as large as possible so that pulses due to low-energy quanta can be distinguished from phototube noise. This requirement means that NaI(Tl) crystals must be used. The second requirement is that absorption of the low-energy quanta in the window of the crystal must be minimized. (CsI crystals, which are not hygroscopic, could be operated without any windows; however, their light output is not sufficiently large for the purposes of this experiment.)

The most successful crystals were made as follows: A large piece of sodium iodide was taken and thin ( $\approx 0.060$  in.) slices were cleaved from it using the usual techniques. A slice was then placed into a brass holder with a glass face on one side. Optical contact with the glass face was made with standard Dow Corning silicone grease. A 0.002-in.-thick beryllium window was then cemented to the top of the holder in such a way that the container was airtight. The glass face was attached to the photomultiplier with mineral oil when the crystal was used. It was found that it was not necessary to polish the faces of the crystal if it had good cleavage surfaces. In fact, better resolution was usually obtained with unpolished crystals. No levigated alumina was used as a light reflector since a layer of this material on the surface of the crystal would introduce a large, unknown absorption factor for the low-energy x rays. The pulse-height spectra obtained with the  $W^{181}$  and  $Ta^{179}$  sources are shown in Fig. 1. Three peaks are clearly visible in each spectrum, one at about 60 kev corresponding to the K x ray, one at about 30 kev corresponding to the escape peak of the high-energy x rays, and finally a peak at about 9 kev corresponding to the L x rays emitted by the source. The resolution obtained for the 59-kev  $Am^{241}$  gamma-ray peak with this system was 16%. The rather prominent escape peak is observed because the crystals were thin. Thin crystals give lower backgrounds and also give a slightly larger light output for the very low-energy x rays.

The preparation of the sources used for these experiments required considerable care. The  $W^{181}$  source was made by bombarding  $Ta^{181}$  with 7-Mev protons in the LRL Livermore 90-inch cyclotron. The target was made of four 0.00025-in. Ta foils. These foils were then dissolved and the  $W^{181}$  was chemically separated using carrier-free methods so that the number of heavy atoms in the source was reduced to a minimum. The tungsten was

prepared in a water solution as an ammonium salt. Some drops of this solution were then placed on a 0.001-in. Mylar backing and evaporated. Another 0.001-in. Mylar piece was then glued to the top of the source to make the seal. The  $\text{Ta}^{179}$  source was made by bombarding hafnium metal with 24-Mev deuterons at the 60-inch Crocker Laboratory cyclotron. The Ta was again separated chemically by carrier-free methods and the sources were prepared as described above. Since many short-lived activities due to Ta isotopes result from this bombardment, old ( $\approx 2$  years) sources were used for this work. (The half-life of  $\text{Ta}^{179}$  is about 660 days.).

Standard electronic equipment was used throughout the experiment. RCA 6810A photomultiplier tubes were employed and the tube base circuits were modified so that the resistances between the cathode, the focusing grid, and the first two dynodes could be varied to adjust the tubes for maximum resolution. For the coincidence measurements on the L and K x rays, circuits with a resolving time of about 1  $\mu\text{sec}$  were used.

## EXPERIMENTAL RESULTS

In order to interpret the results obtained in the measurements to be described, certain relations between the observed counting rates and the actual L and K vacancies created by electron capture must be derived. These relations involve the fluorescent yields of the L and K shells. The object of some of the experiments described in this paper is to make new measurements of the fluorescent yields of the L and K sub shells of these materials.

Let  $D$  be the number of disintegrations per second of the source,  $C_K$  the fraction of K-shell vacancies produced by the decay, and  $C_L$  the fraction of L-shell vacancies produced by the source, so that the L to K ratio is  $C_L/C_K$ . If  $\Omega_K$ ,  $E_K$ , and  $A_K$  are the geometrical factor, efficiency, and

transmission for the K x-ray counter and  $\Omega_L$ ,  $E_L$ , and  $A_L$  are similar quantities for the L x-ray counter, then the number of K counts per second is

$$N_K = \left(C_K D\right) \left(\Omega_K A_K E_K\right) \omega_K, \quad (1)$$

where  $\omega_K$  is the fluorescent yield of the K shell. The expression for the number of L x rays observed is complicated by the fact that the L x rays arise from two sources: x-ray emission after L capture which is proportional to  $(C_L D)$ , and L x-ray emission following K x-ray emission which is proportional to  $(C_K D)$ . The number of L counts observed is therefore:

$$N_L = \left(C_L D\right) \left(\Omega_L A_{LL} E_{LL}\right) \omega_{LL} + \left(C_K D\right) \left(\Omega_L A_{KL} E_{KL}\right) \omega_{KL} n_{KL}. \quad (2)$$

In this formula,  $A_{LL}$ ,  $E_{LL}$ , and  $\omega_{LL}$  are the transmission, efficiency, and fluorescent yields for L x rays following L capture, and  $A_{KL}$ ,  $E_{KL}$ , and  $\omega_{KL}$  are similar quantities for L x rays following the emission of K x rays. The reason for distinguishing between the two species of L x rays is that the L capture process creates vacancies mainly in the  $L_I$  ( $2s_{1/2}$ ) shell and hence leads to transitions into this level, whereas the K x-ray emission creates vacancies only in the  $L_{II}$  ( $1p_{1/2}$ ) and  $L_{III}$  ( $1p_{3/2}$ ) shells. Since the energies of the resulting transitions are slightly different (8 kev to 10 kev), the transmissions, efficiencies, and fluorescent yields will also differ. These differences must be taken into account if accurate results are desired. The quantity  $n_{KL}$  in Eq. (2) is equal to the number of L vacancies created per K vacancy. This quantity is defined in detail in the review paper by Robinson and Fink.<sup>6</sup> For the present computations, values given in that review article were used.

The L to K capture ratio,  $C_L/C_K$ , can now be expressed in terms of the quantities defined in Eqs. (1) and (2). If the ratio of the number of L counts to K counts ( $N_L/N_K$ ) is measured, then the L to K capture ratio is

given by

$$\frac{C_L}{C_K} = \left( \frac{N_L}{N_K} \right) \left( \frac{\Omega_K}{\Omega_L} \right) \left( \frac{A_K}{A_{LL}} \right) \left( \frac{E_K}{E_{LL}} \right) \left( \frac{\omega_K}{\omega_{LL}} \right) - n_{KL} \left( \frac{A_{KL}}{A_{LL}} \right) \left( \frac{E_{KL}}{E_{LL}} \right) \left( \frac{\omega_{KL}}{\omega_{LL}} \right). \quad (3)$$

In order to compute  $C_L/C_K$  from  $N_L/N_K$ , all the quantities in the parentheses on the right-hand side of the equation must be evaluated. Since the same counter is used to detect both the K and L x rays,  $\Omega_K = \Omega_L$  if the distance between the source and the counters is large enough so that edge effects can be neglected. For the beryllium window crystals used here, the ratios of the A's and the E's are quite close to unity. The most important correction which must be applied is the absorption in air of the L x rays which appears in  $(A_K/A_{LL})$  and this is only of the order of 5% for the geometries used in the experiment. However, the L-shell fluorescent yields are not well known and it is therefore necessary to perform another experiment to determine them.

The partial fluorescent yield,  $\omega_{KL}$ , can be obtained by measuring the coincidence rate between the L and the K x rays. This counting rate is given by

$$N_C = N_K' \left( a \omega_{KL} A_{KL} E_{KL} \Omega_L \right), \quad (4)$$

where  $N_K'$  is the observed K x-ray counting rate in the K x-ray counter and the expression in the parentheses is the probability that the L counter will detect an x ray. Solution of Eq. (4) for  $\omega_{KL}$  gives

$$\omega_{KL} = \left( \frac{N_C}{N_K'} \right) \frac{1}{a A_{KL} E_{KL} \Omega_L}. \quad (5)$$

The factor  $a$  must be included in Eq. (5) because the K x-ray counter cannot resolve the  $K_\alpha$  from the  $K_\beta$  x rays. The number  $a$  is therefore the fraction of the observed K x-ray counts due to  $K_\alpha$  x rays. To compute  $\omega_{KL}$ , the values of  $a$  given in reference 6 were used.

The arguments made in the last paragraph are true only if there is no angular correlation between the L and the K x rays emitted following K capture. The assumption of isotropy is implicit in Eq. (4). Several experiments were performed with both sources to measure the coincidence rate at 180° (back-to-back) and 90°. The coincidence rate in these two positions was found to be the same to within 5%. This result is not surprising since a great many atomic levels are involved in the transitions, and the counters are not able to resolve the individual K and L x-ray fine structure in the spectrum. Estimates of the expected distribution show that it should be nearly isotropic.

The decay of  $\text{Ta}^{179}$  proceeds directly to the ground state of  $\text{Hf}^{179}$ . No radiations other than the Hf K and L x rays were observed from this source. The transition is most probably an allowed transition since the ground state of  $\text{Hf}^{179}$  has the spin  $9/2^+$  and the ground state of  $\text{Ta}^{179}$  probably has a spin  $7/2^+$ . The decay energy can be computed from the L to K capture ratio using the formula given in reference 1. The decay energy obtained in this manner is consistent with the fact that the first excited level in  $\text{Hf}^{179}$  is at 122 kev, an energy exceeding the computed decay energy. The results are summarized in Table I.

In the case of  $\text{W}^{181}$ , the decay is more complex since it proceeds to the ground state about 99.7% of the time. In the remainder of the transitions, two energy levels in  $\text{Ta}^{181}$  at 137 kev and 152 kev are populated. A weak composite peak corresponding to these transitions is observed in the scintillation pulse-height spectrum. The 152-kev gamma ray is about twice as intense as the 137-kev line. Both gamma rays are in coincidence with the L x rays emitted by the source but are not in coincidence with the K x rays. The two gamma rays are also not in coincidence with each other. The decay scheme

for this isotope given in reference 4 is therefore confirmed and the intensities of the gamma-ray lines relative to the x rays quoted by these authors are found to be correct. The transition to the ground state of  $\text{Ta}^{181}$  is a first-forbidden transition since the spin of  $\text{Ta}^{181}$  is  $7/2^+$  and the probable spin of  $\text{W}^{181}$  is  $7/2^-$ . The decay to the 137-kev level also proceeds by a first-forbidden transition since the spin of the 137-kev level is  $9/2^+$ . The decay energy for this isotope as obtained from the L to K ratio is computed using the formula for allowed transitions. This procedure is justified by the fact that first-forbidden transition probabilities apparently do not contain any energy-dependent terms other than those introduced by phase space considerations.<sup>7</sup> It follows therefore that the energy dependence of the L to K capture ratio for these transitions also is due only to the phase space factor which means that the formula of reference 1 is applicable. The decay energy computed from the L to K ratio using this method is sufficiently large (260 kev) to explain the existence of the observed gamma rays. The electron wave functions used to compute the decay energies are tabulated in reference 8. The large errors quoted in the decay energy of  $\text{W}^{181}$  are characteristic of small ( $\approx 0.2$ ) values of  $C_L/C_K$ , since the decay energy in this region is a very sensitive function of  $C_L/C_K$ . It should also be pointed out that the decay energy of  $\text{W}^{181}$  is probably not quite as large as the value given in Table I, since K capture to the excited levels would then be possible. Since no K capture is observed (i.e., no K x rays are observed in coincidence with the gamma rays), the decay energy must be less than 210 kev, which is within the limits of error of the quoted energy. The above argument is true only if K capture to the excited levels is not forbidden for other reasons.

The circumstance that  $\text{W}^{181}$  can also decay to excited levels in  $\text{Ta}^{181}$  by pure L-shell capture makes it possible to measure the partial fluorescent



yield  $\omega_{LL}$  by a method similar to that used to determine  $\omega_{KL}$ . The coincidence rate between the gamma rays and the L x rays is given by

$$N_C = N_Y b \left( \omega_{LL} A_{LL} E_{LL} \Omega_L \right) . \quad (6)$$

This formula is identical in form to Eq. (4). The quantity  $b$  is the fraction of L capture to L+M+N capture and has the value 0.735 according to best estimates of electron densities given in reference 9.  $N_Y$  is the gamma-ray counting rate in the gamma counter. Since the transition to the 137-kev level is also a first-forbidden transition, the value of  $\omega_{LL}$  computed from Eq. (6) can be used in calculating  $C_L/C_K$  for the ground-state transition in Eq. (3).

It should also be pointed out that the method outlined for the measurements of  $\omega_{KL}$  and  $\omega_{LL}$  has the additional advantage that some of the efficiency and transmission factors in Eq. (3) are cancelled. It is therefore not necessary to compute them.

The experimental results are summarized in Table I. In order to show how the final values of  $C_L/C_K$  were obtained, all the important numbers appearing in Eqs. (3) and (5) are included. The measured ratios of  $N_L/N_K$  are shown in the first column. The next columns show the quantities  $n_{KL}$  and  $a$ . The measured fluorescent yields,  $\omega_{KL}$  and  $\omega_{LL}$  are shown in the next two columns. Finally, the values of  $C_L/C_K$  and the decay energies are listed in the last two columns. Since no measurement of the partial fluorescent yield,  $\omega_{LL}$ , could be made in the case of Ta<sup>179</sup>, it was assumed that the values of  $\omega_{LL}$  for the two isotopes studied are in the same ratio as the values of  $\omega_{KL}$ . This assumption is not unreasonable since both  $\omega_{LL}$  and  $\omega_{KL}$  probably have the same Z dependence.

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TABLE I. Summary of results.

Isotope	$\frac{N_L}{N_K}$	$n_{KL}$	$a$	$\omega_{KL}$	$\omega_{LL}$	$\frac{C_L}{C_K}$	Decay energy (kev)
Ta <sup>179</sup>	$0.375 \pm 0.005$	0.83	0.79	$0.24 \pm 0.01$	$0.27 \pm 0.02$	$0.63 \pm 0.06$	$115 \pm 5$
W <sup>181</sup>	$0.312 \pm 0.005$	0.83	0.79	$0.28 \pm 0.01$	$0.32 \pm 0.02$	$0.23 \pm 0.05$	$260 \pm 160$

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\* Work done under the auspices of the U. S. Atomic Energy Commission.

† On leave of absence from the Department of Physics, Massachusetts Institute of Technology, Cambridge, Mass.

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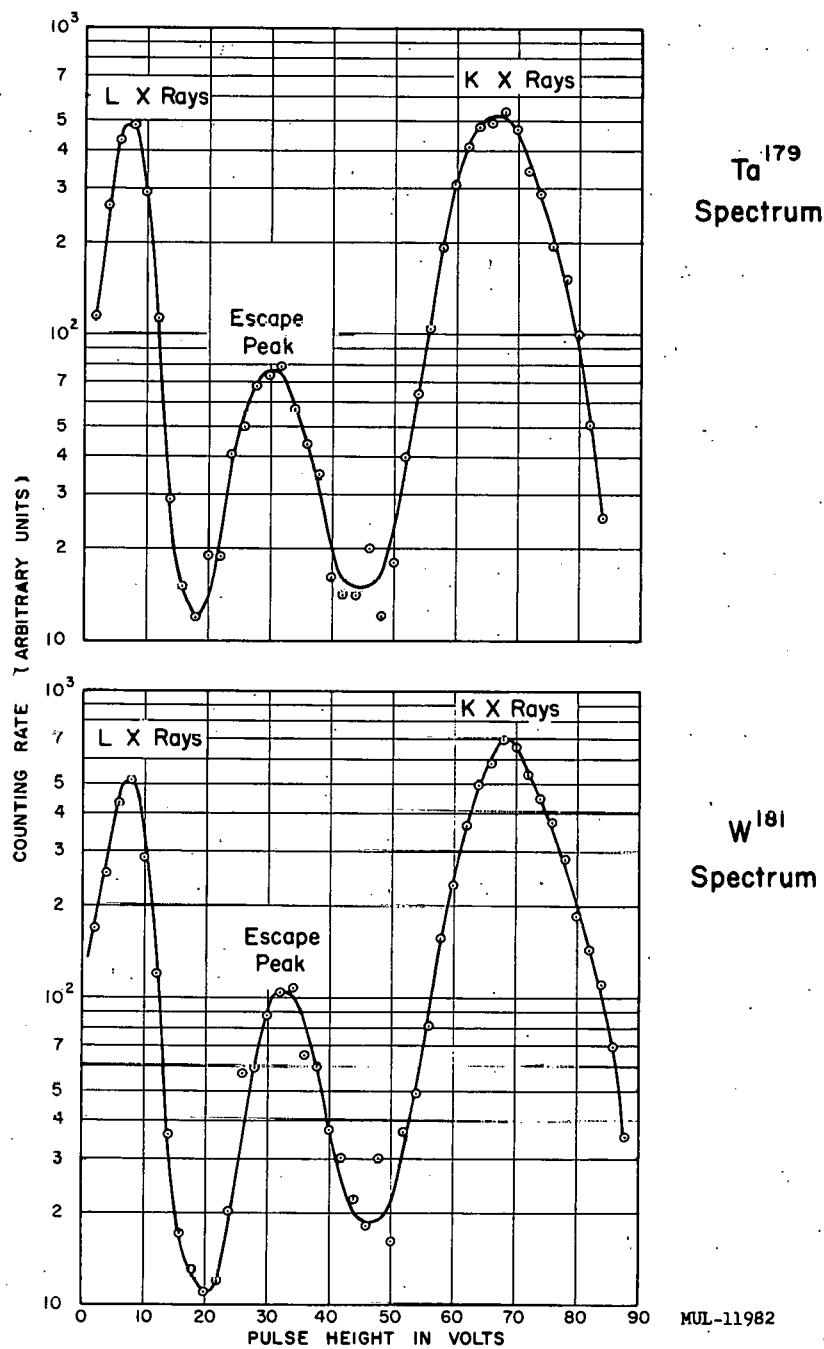


Fig. 1. Pulse-height spectra of  $Ta^{179}$  and  $W^{181}$  sources. Note that the K x-ray peak of the  $W^{181}$  spectrum is larger relative to the L x-ray peak than the K x-ray peak in the  $Ta^{179}$  spectrum. This difference is reflected in the values of  $N_L/N_K$  listed in Table I.

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