The Disintegration of Scandium[46], Gold[198], and Tungsten[185, 187] *

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A survey of the nature and energies of the radiations of some radioactive isotopes of Sc, Au, and W has been made with a small 180° spectrometer of fair resolution. Samples were produced by neutron and deuteron activation.

The 85-day isotope of Sc is found to decay by the emission of two groups of beta-rays of maximum energies 0.36 and 1.49 Mev. The low energy group constitutes 98 percent of the total number of electrons. The residual Ti^{46} nucleus returns to the ground state by the cascade emission of two gamma-rays with energies 0.89 and 1.12 Mev. The gamma-rays are converted with K conversion coefficients of 0.0008 and 0.0004, respectively.

The decay scheme of Au^{198} is found to be simple. The emission of a beta-ray of a single group, $E_{max}=0.97$ Mev, leads to an excited state of Hg^{198} which returns to the ground state by the emission of a 0.408-Mev gamma-ray. The gamma-ray is converted with $\alpha_k=0.25$.

The radiations of 24-hour W^{187} are complex. Two groups of beta-rays are present which have end points at 0.63 and 1.33 Mev. Five gamma-rays are noted with energies of 0.14, 0.21, 0.48, 0.62, and 0.69 Mev. The decay of the 77-day isotope, W^{185}, seems simple. A single beta-ray is found with an end point at 0.43 Mev.

I. INTRODUCTION

THE energies of the radiations of Sc^{46}, Au^{198}, W^{185}, and W^{187} have been reported by various workers with considerable variance in the results, not only in the energy values of the beta- and gamma-rays, but also in the number and nature of the components. This is particularly true of the early investigations carried out by absorption methods and with weak sources. More recent work tends towards consistency and, since the inception of this investigation, several workers have reported on some of the above-mentioned isotopes with results which are, in the main, in agreement with those of this paper.

The present work is concerned with a careful study of these disintegrations by means of a 180° spectrometer having a radius of 7.5 cm, used in a somewhat unconventional manner. The vacuum chamber is placed in the magnetic field so as to bring the outer electron paths into the fringing field. In this way the defocusing inherent in this type of instrument is reduced. The proper position of the chamber is determined experimentally by measuring known conversion lines and photoelectron lines for various settings of the chamber. An optimum half-width of 1.2 percent is found for conversion lines and 3.5 percent for photoelectron lines. In this way results have been obtained with fair resolution without sacrifice of transmission.

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Both neutron and deuteron induced activities were used in the study. Strong neutron activated samples were obtained from the Oak Ridge pile; others were prepared by deuteron bombardment with the Indiana University cyclotron. In all cases careful attention was given to source preparation. Sources were chemically purified and were made as thin as was compatible with reasonable counting rates.

II. SCANDIUM[46]

Sc^{46} can be produced either by an $n-\gamma$ or $d-p$ reaction on the single stable isotope Sc^{45}. Initial studies by Walke[1] and his co-workers showed that the decay went by beta- and gamma-ray emission to Ti^{46}, with possibly some decay to Ca^{46} by K-capture. The gamma-ray was reported as 1.25 Mev while the beta-rays were interpreted as being complex with two groups having energies of 0.26 and 1.5 Mev. Meitner[2] was unable to find the 1.5-Mev group and attributed Walke's result to scattering. More recently, Miller and Deutsch[3] have used spectrometer methods to obtain more accurate values of the energies. The results of their investigation indicate that the decay of Sc^{46} goes by the emission of beta-rays of a single group of maximum energy of 0.36 Mev to Ti^{46}, which then returns to the ground state by the

[1] Walke, Williams, and Evans, Proc. Roy. Soc. **A171**, 360 (1939).
[2] L. Meitner, Arkiv f. Mat. Astr. och Fys. **A32**, No. 6.
[3] A. E. Miller and M. Deutsch, Phys. Rev. **72**, 527(A) (1947).

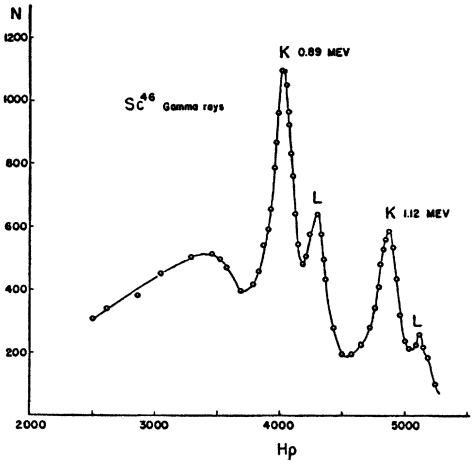

FIG. 1. Compton- and photoelectrons ejected from a 30-mg/cm² Pb radiator by the gamma-rays of Sc^{46}. The ordinate N is the number of counts per minute. The values of the energy are for the gamma-ray, not the photoelectron line.

cascade emission of two gamma-rays of energies 1.12 and 0.90 Mev. These results are substantiated by Feister and Curtiss[4] and Mandeville and Scherb.[5] No evidence for K-capture was found by Deutsch.

The preliminary work of this investigation was done with deuteron activated Sc_2O_3. Chemical separation from the rare earths and other impurities generally associated with scandium was performed. Since the samples were weak in activity, sources were necessarily thick and the

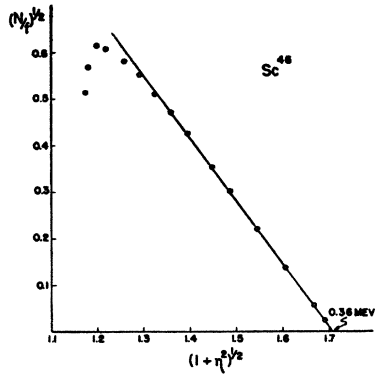

FIG. 2. Fermi plot of the low energy beta-ray group of Sc^{46}. The high energy component is too weak to be shown on this scale.

[4] I. Feister and L. F. Curtiss, J. Research Nat. Bur. Stand. **38**, 411 (1947).

[5] C. E. Mandeville and M. Scherb, Phys. Rev. **73**, 141 (1948).

data as previously reported[6] is undecisive. These experiments indicate that there are two groups of beta-rays of maximum energies of 0.36 Mev and 1.49 Mev, as well as two gamma-rays having energies of 0.89 and 1.12 Mev. Coincidence studies carried out by Jurney and Ramsey in this laboratory show that each beta-ray of the 0.36-Mev group is followed by the cascade emission of the two gamma-rays. No beta-gamma coincidences could be found to substantiate the existence of the 1.49-Mev beta-ray group. However, the high energy component appears to be very low in intensity and negative coincidence results are not surprising.

Since the 1.49-Mev beta-ray group was not found by others,[2–5] the validity of the above determinations was subject to question. The presence of impurities, scattering inherent in the instrument, secondary electrons from the thick source, and low energy photoelectrons produced in the lead shielding at the detector might be supposed to account for the effect. To check this a series of careful determinations were made with high specific activity neutron induced Sc^{46} from Oak Ridge. Following the procedure outlined by Noyes and Bray,[7] chemical purification of the samples was undertaken with special attention given to the removal of such elements as calcium, iron, yttrium, and other associated rare earths. Gamma-ray determinations were made by measuring the photoelectrons ejected from a lead radiator, 30 mg/cm² in thickness placed over a Sc_2O_3 sample. Figure 1 shows the photoelectron spectrum. The photoelectrons corresponding to the two gamma-rays are clearly resolved into their K and L components and rise well above the accompanying Compton electrons, in accordance with good source geometry. The spectrometer was adjusted for low resolution to insure high counting rates so that the lines have the rather large half-width of 5 percent. The K and L photoelectron lines correspond to gamma-ray energies of 0.89 ± 0.005 and 1.12 ± 0.005 Mev.

For beta-ray measurements, care was taken to keep the sources thin. A very pure solution of

[6] C. Peacock and R. G. Wilkinson, Phys. Rev. **72**, 251 (1947).

[7] A. Noyes and W. Bray, *Qualitative Analysis for the Rare Elements* (The Macmillan Company, New York, 1927), p. 210.

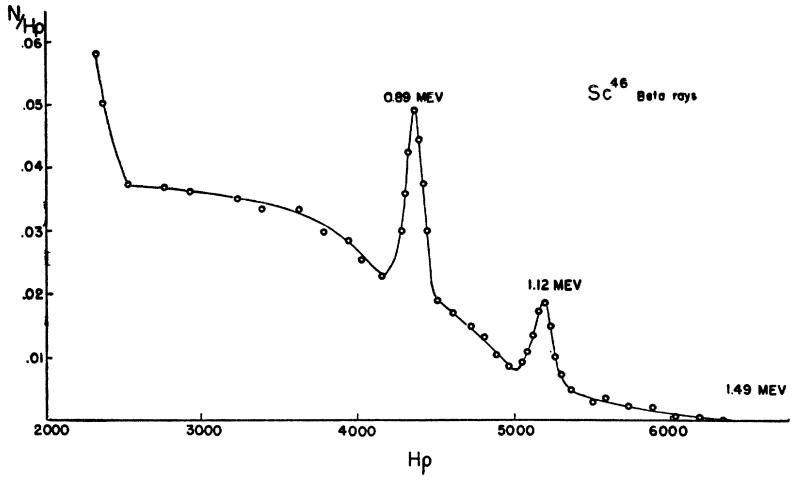

FIG. 3. High energy group of the beta-ray spectrum of Sc^{46} plotted on an extended scale. The conversion lines have a half-width of about three percent. The energies given are those of the gamma-rays.

$ScCl_3$ was evaporated on a backing of Zapon film 0.04 mg/cm² thick. Source thicknesses ranged from 0.25 to 1.0 mg/cm² with an area of about 20×3 mm². As in earlier runs, the beta-ray spectrum consists of two components with end points at 0.36±0.005 and 1.49±0.01 Mev with the high energy group comprising about 2 percent of the total number of electrons, both groups decaying with the characteristic 85-day half-life. The Fermi plot of the 0.36-Mev group, shown in Fig. 2, is a straight line down to energy values corresponding to window cut-off. Since the high energy group is much the weaker, it appears as a barely discernible tail to the low energy group when the latter is plotted on an ordinary scale. A much expanded plot of this tail obtained by using a stronger source is given in Fig. 3. Two lines are superimposed on the beta-ray spectrum and have energies corresponding to the gamma-rays. Because of the narrowness of the lines, they must be ascribed to conversion of the gamma-rays and not to secondaries ejected from the source material or backing.

Auxiliary experiments were performed to make certain that the high energy tail was not due to secondary electrons. These electrons cannot be attributed to source thickness or scattering defects in the instrument. If the effect were to be due to secondaries associated with the gamma-rays owing to source thickness, one would expect to register no electrons with energies greater than the gamma-ray energies. However, electrons above this energy are present. While it is true that some of the electrons were found to be secondaries when thick sources were used, the tail persisted for sources as thin as 0.25 mg/cm² on negligible backing. It is unlikely that scattering defects of the instrument are responsible for the tail since other spectra of comparable end points show no such effect; e.g., that of W^{185}, which has an end point at 0.43 Mev. There remains the possibility of electrons being produced in the lead between the source and detector by the gamma-rays which might appear in the counter region. The effect of this might be to record low energy electrons at much higher H values. To check this, copper absorbers of various thicknesses were placed over the counter window to shield out such radiation. With enough copper over the window to cut out 1.1-Mev electrons, the maximum energy to be expected, there was evidence of electrons above this energy entering

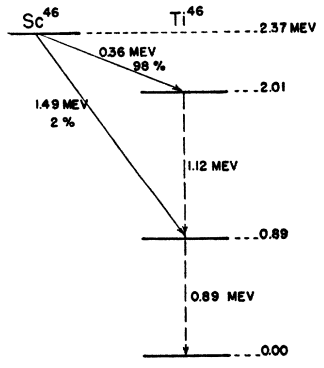

FIG. 4. Disintegration scheme of Sc^{46}.

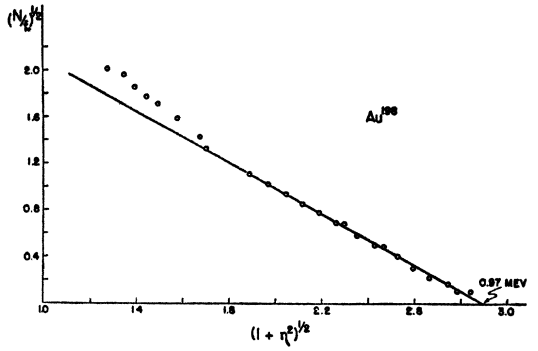

FIG. 5. Fermi plot of the beta-ray spectrum of Au^{198}. Deviation from the straight line begins at about 0.4 Mev.

the counter. It is concluded, therefore, that the 1.49-Mev group is real.

The results of these experiments and the coincidence experiments of Jurney and Ramsey lead conclusively to the disintegration scheme given in Fig. 4. About 98 percent of the disintegrations go by the emission of a beta-ray in the 0.36-Mev group to the 2.01-Mev level of Ti^{46}, which returns to the ground state by the cascade emission of the two gamma-rays. In the remaining 2 percent of the cases beta-emission leaves the Ti^{46} in the 0.89-Mev excited level, which returns to stability by gamma-emission. The measured relative intensities of the gamma-rays are consistent with this picture. Estimates based on Gray's[8] empirical curve show that the gamma-rays have about the same intensity, the 0.89-Mev radiation being slightly more abundant. This is merely an indication of consistency, however, since the magnitude of the error involved does not make the difference significant. If the above scheme is assumed, the K-conversion coefficients of the gamma-rays can be computed from the data. These are found to be 0.0008 and 0.0004, respectively, for the 0.89- and the 1.12-Mev gamma-rays. Some idea of the spin change involved can be obtained by comparing these results with the theoretical values of $\alpha_k{}^l$ predicted by the Morrison-Dancoff formula. Best agreement between experimental and theoretical values is obtained for $l=4$, i.e., if the radiation is assumed to be electric multipole; or $l=3$ if the radiation is magnetic octapole. The low energy beta-ray group has a ft value of 2×10^6 and is therefore first forbidden. On the other hand, the high energy group must be at least second forbidden since it has an ft value of 6.8×10^9. Since Ti^{46} is an even-even nucleus, it may be supposed to have zero spin; hence the spin of the Sc^{46} nucleus may have a large spin value.

III. GOLD[198]

Since the beginning of this study several papers have appeared concerning Au^{198}. The results of various recent investigations still seem to be somewhat at variance. Levy and Greuling[9] find conversion lines corresponding to three gamma-rays of energies 0.157, 0.208, and 0.408 Mev. From the non-linear Fermi plot which they obtain, they infer that the beta-ray spectrum has two components of energies 0.605 and 0.97 Mev. Their conclusions are supported by the coincidence studies of Mandeville[10] and Clark,[11] in which substantial gamma-gamma as well as beta-gamma coincidences are observed. On the other hand, Siegbahn[12] finds only one converted gamma-

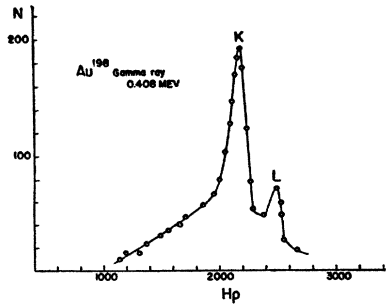

FIG. 6. Photoelectrons ejected from a 30-mg/cm² Pb radiator by the gamma-ray of Au^{198}.

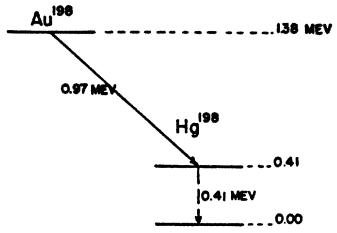

FIG. 7. Disintegration scheme of Au^{198}.

[8] L. H. Gray, Proc. Camb. Phil. Soc. **27**, 103 (1931).

[9] P. Levy and E. Greuling, Phys. Rev. **73**, 83 (1948).

[10] C. E. Mandeville and M. V. Scherb, Phys. Rev. **73**, 634 (1948).

[11] A. Clark, Phys. Rev. **61**, 242 (1942).

[12] K. Siegbahn, Proc. Roy. Soc. **189**, 527 (1947).

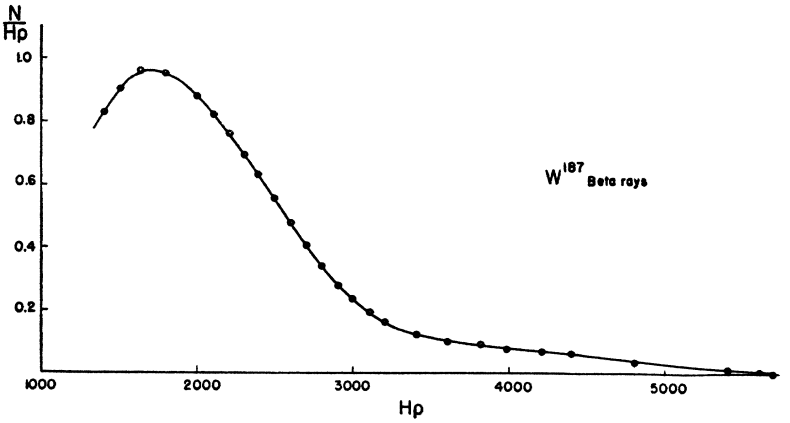

FIG. 8. Beta-ray spectrum of W^{187} showing the presence of two groups.

ray at 0.403 Mev and a single beta-ray group of maximum energy 0.92 Mev. His results are in agreement with the coincidence studies of Norling[13] and Jurney[14] who reported beta-gamma coincidences but found no appreciable gamma-gamma coincidences. Moreover, Cork[15] reports the presence of only one conversion line at 0.4 Mev.

Our results were obtained by studying Au^{198} prepared by deuteron activation. The material was chemically purified with special attention given to the separation from mercury. After adding mercury carrier, the gold was finally extracted from mercury with ethyl acetate. Sources were prepared by electro-plating the gold from a HCl solution on graphite strips approximately 28 mg/cm² thick. Sources ranging down to 5 mg/cm² in thickness were used. The use of the low Z material compensated for the relatively heavy backing and the scattering was thus minimized. The Fermi plot of the beta-rays is shown in Fig. 5. The K and L conversion lines associated with a single gamma-ray were observed. These are omitted from the plot. Deviation from the straight line does not occur down to about 0.4 Mev. Presumably, thinner sources would cause the deviation to occur at even lower energies, owing to less degradation of electron energies in the source. We conclude from our data that there is a single group of beta-rays with an end point at 0.97 ± 0.01 Mev. The photoelectron spectrum, obtained by using a 30-mg/cm² lead radiator, is shown in Fig. 6. Only one gamma-ray could be found in the region investigated, i.e., down to the counter window cut-off at 0.07 Mev. Measurements of the energy of the gamma-ray from the photoelectron lines and from the conversion line agree well and yield the value of 0.408 ± 0.002 Mev.

Initial surveys were made with unseparated samples to check the nature of possible contaminants. Two conversion lines in the region of 0.15 Mev were observed which decayed with a 24-hour half-life. These were attributed to Hg^{197} since the activity followed the chemistry of mercury. Accurate determinations could not be made of the gamma-ray energies, but they are estimated to be 0.17 and 0.23 Mev after adding the K binding energy of Hg.

These results are in excellent agreement with Siegbahn's[12] and suggest the decay scheme shown in Fig. 7. On the basis of this scheme, the K conversion coefficient of the gamma-ray is found to be 0.025. Our data suggests that the previously reported gamma-rays at 0.16 and 0.21 Mev[9] and the associated gamma-gamma coincidences might be due to mercury contamination. Consistent with this possibility is the fact that our Fermi plot rises above the straight line at a somewhat lower energy, although our sources were much thicker.

IV. TUNGSTEN[187, 185]

The radiations of tungsten have been reinvestigated[16] using metallic tungsten activated

[13] F. Norling, Arkiv f. Mat. Astr. och Fys. **A27**, No. 27 (1941).
[14] E. Jurney and M. R. Keck, Bull. Am. Phys. Soc. **22**, No. 6, 6 (1947).
[15] J. M. Cork, Phys. Rev. **72**, 581 (1947).
[16] W. M. Schwarz and M. L. Pool, Phys. Rev. **71**, 122 (1947).

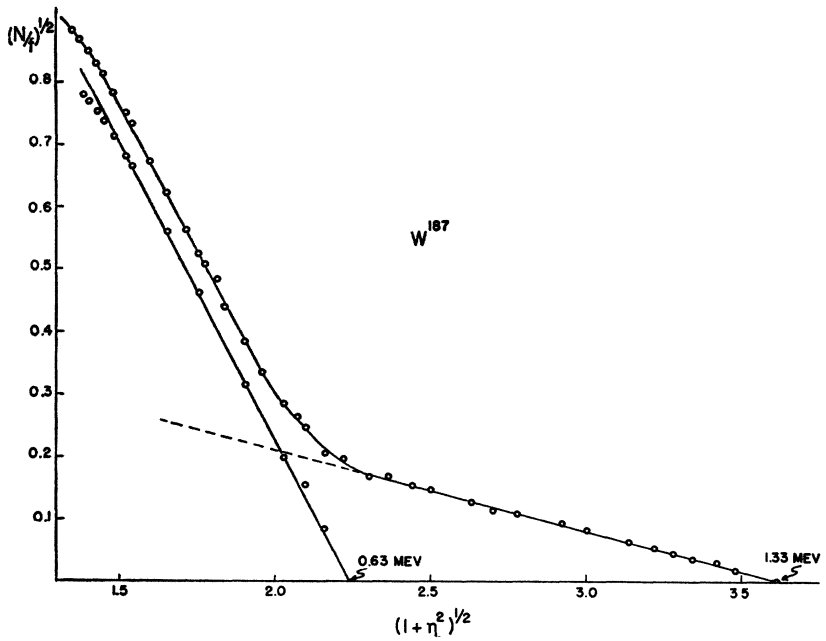

FIG. 9. Fermi plot of the beta-ray spectrum of W^{187} showing the analysis into two groups.

by intense cyclotron probe bombardments. As in previous cases care was taken to purify the samples. Since the tungsten was silver-soldered to the copper probe, it was necessary to extract Ag, Cd, Cu, and Zn, as well as Re and Ta which might result from the bombardment of the tungsten itself. This was accomplished by a standard sulfide precipitation, and finally, repeated precipitation of tungsten from an acid solution. All purified samples showed the characteristic 24-hour half-life with no indication of impurity. Bombardments were not strong enough to produce the 77-day W^{185}. Beta-ray sources of pure WO_3 varied from 7 to 2 mg/cm² in thickness. In order to check the results and to study the 77-day activity, neutron activated samples were obtained from Oak Ridge. The results of both samples are essentially the same, although neutron activated sources were of higher specific activity and allowed the use of beta-ray sources less than one mg/cm² in thickness backed by Zapon films 0.08 mg/cm² thick.

The beta-ray spectrum shown in Fig. 8 is obviously complex. All parts of the spectrum

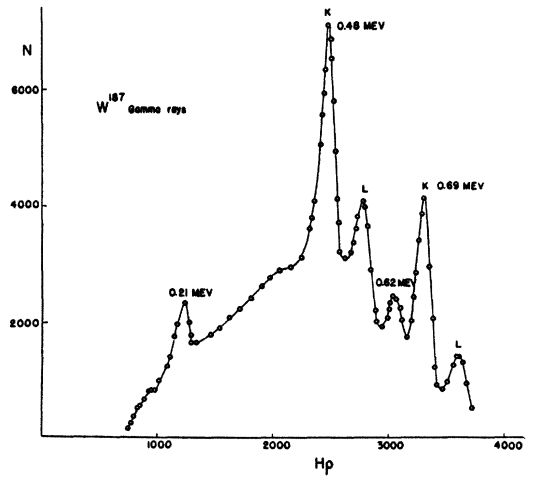

FIG. 10. Compton- and photoelectrons ejected from a 30-mg/cm² Pb radiator by the gamma-rays of W^{187}. The energy values are for the gamma-rays, not the photoelectron lines.

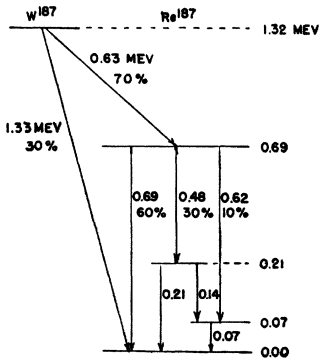

FIG. 11. A possible disintegration scheme of W^{187}. The 0.14- and 0.07-Mev gamma-rays are those reported by Valley.

decayed with the proper half-life. Figure 9 shows a Fermi analysis of the spectrum into two groups with end points at 0.63±0.01 and 1.33±0.01 Mev. The low energy group constitutes 70 percent of the total beta-rays; hence the inner end point is quite well determined. The outer end point is in fair agreement with absorption measurements of Fajans[17] and Clark.[11] The photoelectron spectrum resulting from the gamma-rays (Fig. 10) is also complex, with four gamma-rays definitely present at 0.21, 0.48, 0.62, and 0.69 Mev. In addition, there is evidence of a gamma-ray at 0.14 Mev as reported by Valley.[18] Counter window cut-off made it impossible to observe the two which he has reported at 0.1 and 0.086 Mev. No lines were found in any of the samples which did not decay with the 24-hour half-life. The predominant photoelectron lines are well resolved into their respective K and L components except for the one corresponding to the gamma-ray at 0.62 Mev. In this case the L line is masked by the K line of the 0.69-Mev gamma-ray. These results differ somewhat from those of Schwarz.[16] Apparently the gamma-rays which he reported at 0.57 and 0.79 Mev are to be ascribed to L photoelectron lines since they are displaced from the 0.48- and 0.69-Mev lines by the binding energy of uranium which he used as a radiator. Other lines are probably due to contamination or poor statistics resulting from weak sources and high backgrounds.

Coincidence studies carried out by Jurney in this laboratory show that there are substantial beta-gamma coincidences in W^{187}. However, in spite of the complex gamma-ray spectrum, the gamma-gamma coincidence rate is quite low, though not zero. It must be concluded that the main components are not in cascade. The disintegration scheme is therefore complex and cannot be directly inferred from the data. The scheme shown in Fig. 11 is a tentative one, but it is probably the one most consistent with our data and the coincidence studies. The estimated relative intensities of the stronger lines, as well as Valley's results, support this picture.

[17] K. Fajans and W. H. Sullivan, Phys. Rev. **58**, 276 (1940).
[18] G. E. Valley, Phys. Rev. **59**, 686 (1941).

TABLE I.

	Beta-ray energy Mev	Gamma-ray energy Mev	K conversion coefficient
Sc^{46}	0.36±0.005 (98%) 1.49±0.01 (2%)	0.89 ±0.005 1.12 ±0.005	0.0008 0.0004
Au^{198}	0.97±0.01	0.408±0.002	0.0250
W^{187}	0.63±0.01 (70%) 1.33±0.01 (30%)	~0.14 0.21 ±0.005 0.48 ±0.005 0.62 ±0.005 0.69 ±0.005	— — — —
W^{185}	0.43±0.003	—	—

The mode of disintegration of W^{185} is found to be simple. A simple beta-ray spectrum is obtained, with an end point at 0.43 Mev. No gamma-rays are found.

V. SUMMARY

A summary of the energy values reported in this paper is given in Table I. The limits of error indicate the extent of consistency of successive measurements and do not take account of possible systematic errors. In most cases, however, the results are thought to be valid to one percent.

VI. ACKNOWLEDGMENTS

We wish to thank Dr. Milo B. Sampson for his generous aid in this work. We are indebted to him for many cyclotron bombardments and for the preparation of the tungsten probes. We wish also to acknowledge the assistance of Mr. John Ricketts in connection with the chemistry. The frequent reference to the coincidence work of Mr. Edward T. Jurney is the result of many helpful conferences. His results will appear in a forthcoming paper.