Beta-Ray Spectra of Arsenic, Rubidium, and Krypton*

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Cloud-chamber measurements are described in which the β-rays emitted by the radioactive nuclei As^{76} ($T=27$ hours), $Kr^{88,\geq 90}$ ($T=3$ hours), and the latter's decay product, $Rb^{88,\geq 90}$ ($T=18$ minutes), were investigated. The krypton and rubidium activities were separated from uranium fission products. The observed upper energy limit of the disintegration electrons from As^{76} is 2.71 Mev. The complexity of the spectrum is apparent from the observed momentum distribution. A Fermi plot yields an extrapolated end point of 2.78 Mev. A K-U plot analyzes into components with extrapolated end points of 0.97 Mev and 3.32 Mev. The decay of As^{76} was followed and found to have a half-life of 26.8 hours. The β-rays from the active rubidium have an observed upper energy limit at 5.1 Mev. Although a Fermi plot analyzes into two components with extrapolated end points at 2.5 Mev and 5.0 Mev, a K-U plot indicates a single group with extrapolated end point at 5.8 Mev. The possible instability of the rubidium decay product, a strontium isotope, is discussed. A measurement of the half-life of the rubidium activity yields $T=17.5$ minutes. The measurement and K-U analysis of the complex spectrum due to krypton and rubidium disintegrations yields an extrapolated upper energy limit of 2.5 Mev for the β-rays emitted by $Kr^{88,\geq 90}$. A plot of the Sargent points indicates that all of the β-transitions involved in the above measurements are of the "forbidden" type.

INTRODUCTION

THIS paper is a report on some cloud-chamber investigations of the disintegration electrons from As^{76} and certain rubidium and krypton activities separated from uranium fission products. Preliminary communications[1] of some of the results have already been published. The arsenic measurements were performed in collaboration with Dr. W. H. Barkas.

Although the beta-ray spectrum of As^{76} had been previously investigated,[2] because of the complexity of the spectrum and disagreement as to the relative populations of the two energy groups, it seemed worthwhile to repeat the measurement with a larger total number of tracks in the spectrum and higher resolution.

Arsenic ($Z=33$) has a single stable isotope with mass number 75. The radioactive isotope As^{76} can be produced by the following nuclear reactions: As(d, p), As(n, γ), Br(n, α), Ge(p, n), and Se(d, α). It has a half-life of about 27 hours with emission of negative electrons corresponding to the transition

$$As^{76}\rightarrow Se^{76}+\beta^{-}.$$

A relatively small number of positrons are also emitted[3] which arise from the transition

$$As^{76}\rightarrow Ge^{76}+\beta^{+}.$$

The isotopes of rubidium found in nature have the mass numbers 85 and 87. The latter is observed to be naturally β^{-}-active with a period of the order of 10^{10} years. On irradiating rubidium with slow neutrons two β^{-}-activities are observed[4] with half-lives of about 18 days and 18 minutes. These activities are attributed to the isotopes Rb^{86} and Rb^{88}, which would be expected to be formed by Rb(n, γ) reactions. However, from these observations it is impossible to assign the two activities to the specific isotopes. Recently[5] the 18-day Rb activity has been produced by a Sr(d, α) reaction, thus identifying this period with Rb^{86}, and, consequently, the 18-minute period with Rb^{88}.

An 18-minute rubidium activity was also identified among the fission products of uranium,[6] and later shown to be the decay product of an active krypton having a period of about 3 hours.[7]

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[1] G. L. Weil and W. H. Barkas, Phys. Rev. **56**, 485 (1939); G. L. Weil, Phys. Rev. **60**, 167A (1941).

[2] M. V. Brown and A. C. G. Mitchell, Phys. Rev. **50**, 593 (1936); Harteck, Knauer, and Shaeffer, Zeits. f. Physik **109**, 153 (1938).

[3] W. Schaeffer and P. Harteck, Zeits. f. Physik **113**, 287 (1939).

[4] A. H. Snell, Phys. Rev. **52**, 1007 (1937).

[5] Helmholz, Pecher, and Stout, Phys. Rev. **59**, 902 (1941).

[6] O. Hahn and F. Strassmann, Naturwiss. **27**, 529 (1939).

[7] Heyn, Aten, and Bakker, Nature **143**, 516 (1939); A. Langsdorf, Jr., Phys. Rev. **56**, 205 (1939); G. N. Glasoe and J. Steigman, Phys. Rev. **58**, 1 (1940).

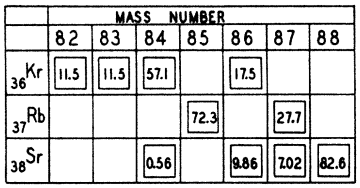

FIG. 1. The stable isotopes of Kr (mass numbers 78 and 80 omitted), Rb, and Sr, with percent abundance.

From the mass numbers of the stable nuclei in the neighborhood of rubidium (Fig. 1), it is clear, if one neglects the possibility of isomers, which will be done here and in following discussions, that the fission 18-minute activity cannot be due to Rb^{86}, since Kr^{86} is stable. Glasoe and Steigman[7] have shown that the decay product of this rubidium activity either is stable, or is unstable with a half-life less than five minutes or greater than a year. Furthermore, they separated a 14.5-minute rubidium activity from the uranium fission products which is assigned to Rb^{89} on the basis of its decaying into a known 55-day strontium.[8] Thus, the 18-minute activity must be attributed to $Rb^{88, \geq 90}$, and because of the similarity between it and the slow neutron induced activity, it has been tentatively assigned to Rb^{88}.

Krypton ($Z=36$) has the stable isotopes with mass numbers 78, 80, 82, 83, 84, and 86. The 175-minute krypton separated from uranium fission products cannot be produced by the usual nuclear reactions. It is genetically related to the 18-minute rubidium discussed above,

$$Kr^{88} \xrightarrow{175 \text{ min.}} Rb^{88} \xrightarrow{18 \text{ min.}} Sr^{88} \text{ (Stable)}$$

and accordingly must be given the same mass number as that tentatively assigned to its decay product, namely, Kr^{88}. Another interpretation is also possible, namely,

$$Kr^{\geq 90} \rightarrow Rb^{\geq 90} \rightarrow Sr^{\geq 90}.$$

In this case the Sr might very well be radioactive.

APPARATUS

Cloud Chamber

The cloud chamber used for the measurements was 6″ in diameter and $\frac{3}{4}$″ deep. The floor of the chamber consisted of a brass plate covered with black velvet and sealed by means of a rubber diaphragm. The expansion was produced mechanically through the action of a compressed spring and rotating cam. An intermediate expansion was used in order to clear the chamber more effectively before the main expansion. As source of vapor a 50-50 ethyl alcohol and water mixture was used. Before all runs the chamber was flushed and filled with hydrogen.

Magnetic Field

The chamber was situated in a magnetic field, produced by a pair of Helmholtz coils. The mean diameter of the coils was 16″, and the mean separation of the pair 8″. Each half of the Helmholtz pair was made up of four separate coils each wound with 500 turns of No. 10 B and S copper wire and connected in series. Spaces between the coils allowed for air cooling.

The uniformity of the magnetic field in the region of the cloud chamber was investigated with a flip coil (1 cm^2 effective area) and ballistic galvanometer. It was found that the field intensity perpendicular to the plane of the chamber was constant to within ± 2.5 percent over the sensitive volume of the chamber. By calibrating the flip coil and galvanometer in the known field of a standard solenoid, the constant of the Helmholtz coils was found to be 42.7 gauss per ampere. With a 240-volt d.c. supply, the maximum field obtainable was 1200 gauss. In order to avoid overheating of the coils, the field was applied two seconds before an expansion and removed immediately afterward. The field current was monitored during a run with an ammeter which was calibrated and checked from time to time with a standard resistance, Weston cell, and potentiometer. During a run the field was maintained constant to ± 1 percent.

Illumination

Illumination was provided by condenser discharges in air at low pressure. Two discharge tubes were used, each about 4″ long and made of 4-mm I.D. capillary Pyrex tubing with 60-mil tungsten seal-ins at each end. They were roughly evacuated and each connected across a bank of thirty condensers,[9] each of 1-μf capacity, con-

[8] L. A. DuBridge and J. Marshall, Phys. Rev. **57**, 348A (1939).

[9] The author is indebted to the Bell Telephone Laboratories, New York, New York, for the loan of these condensers.

nected in parallel. The condensers were charged to about 2500 volts, and the discharges through the capillary tubes were initiated by ionization produced by ignition coils. The capillary tubes had a useful life of about 3000 discharges, after which time their light producing efficiency became too low, due to discoloration and minute cracks on the inner wall, to enable photographing of beta-tracks. The light from these sources was collimated by means of slits and cylindrical lenses. The depth of the illuminated region of the cloud chamber was about $\frac{3}{8}''$.

Camera

Photographs were taken with a single camera mounted directly above the chamber with the lens axis perpendicular to the plane of the chamber. The camera was equipped with a Kern f : 1.8, 45-mm focal length lens, which was used at full aperture. The distortion of the lens was found to be negligible. 200 feet of 35-mm film in the camera could be moved one frame at a time by means of a ratchet and toothed wheel operated by a plunger and solenoid.

Timing

The various operations of a cycle were timed by means of switches operated by cams mounted on the same shaft as the cam controlling the expansion of the chamber. A complete cycle was performed in 15 seconds.

Source Holders

The glass top of the chamber had a 1″ hole near its periphery through which the arsenic and rubidium sources were introduced. The sources were held in a light wire frame attached to a brass plug which fitted in the hole. By using a rubber gasket seal the plug and source could be inserted and the cloud chamber operated within a few minutes afterward. Once inside the chamber the source could be rotated about an eccentric axis so that it was "seen" by the camera.

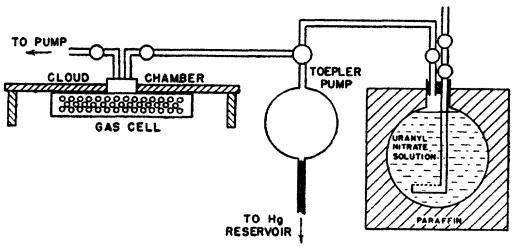

FIG. 2. Diagram illustrating method of extracting active Kr from irradiated uranyl nitrate solution, and of introducing it into gas cell.

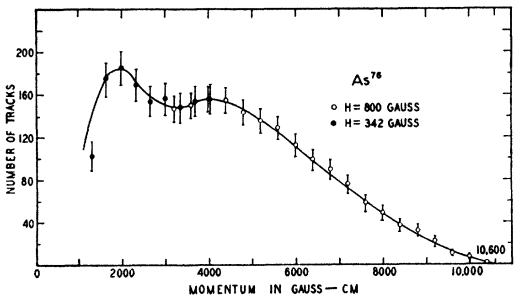

FIG. 3. The momentum distribution of the electrons from As^{76} ($T = 26.8$ hours). The complexity of the spectrum is indicated by the resolution of the two peaks. The length of a vertical line through a point is the uncertainty estimated by taking the square root of the number of observed tracks corresponding to the point.

For the measurements of the krypton disintegrations a thin-windowed gas cell was introduced inside the cloud chamber. This cell was a rectangular brass box $4'' \times 1'' \times \frac{5}{8}''$ with $\frac{1}{16}''$ walls. One of the faces, $4'' \times \frac{5}{8}''$, consisted of an aluminum foil (12.4 mg/cm^2) held between two $\frac{1}{32}''$ brass plates drilled out with $\frac{1}{8}''$ holes to form a grill. The hole area amounted to 62 percent of the total area of that face. The aluminum foil was sealed between the plates with a rubber gasket. The cell could be evacuated and filled with the active krypton by means of $\frac{1}{8}''$ copper tubing connecting to the interior of the cell and brought out through a hole in the glass top of the chamber. In order to reduce back-scattering of the β-particles, the inside walls of the cell were coated with a 2 mm thick layer of Aquadag. It was found that the presence of the cell in the cloud chamber produced no noticeable effect beyond two or three millimeters from the front face.

METHOD OF TRACK MEASUREMENT

For measuring the tracks the film was replaced in the camera and reprojected to full size on to a screen. The radii of curvature of the tracks were then compared with arcs of known radii drawn on white cardboard in steps of 0.5 cm from 2 to 26 cm. In the region of small curvatures the error in matching a track was of the order of 10 percent.

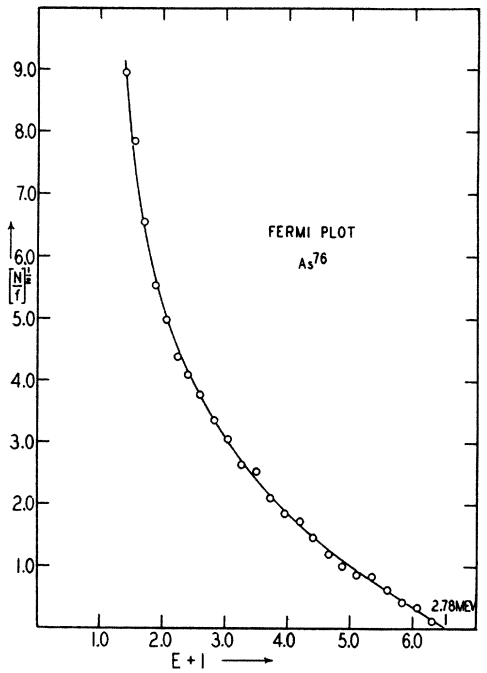

FIG. 4. Fermi plot of As^{76} data shown in Fig. 3. The total electron energy, $E+1$, is given in mc^2 units.

In the matter of selection of tracks the following rules and criteria were adhered to: (1) the track must originate at the source; (2) the track must not be visibly scattered within the first 10 cm of its length; (3) at least 10 cm of track length must be measurable; (4) the tangent to the track at its point of origin must lie within a certain fixed angle, that angle being determined by two lines drawn from the two edges of the source such that the distance along each line from the source to the periphery of the chamber was exactly 10 cm. The last two criteria made certain that the solid angle remained constant for particles in different momentum intervals.

The error introduced in the momentum by neglecting the vertical component was at the most 0.5 percent due to the small depth of the illuminated region and the minimum track length measured.

PREPARATION OF SOURCES

Arsenic

The preparation and separation[10] of the active isotope was as follows. The radioactive isotope As^{76} was produced by the As(n, γ) reaction using slow neutrons. The arsenic was irradiated in the form of a saturated aqueous solution of cacodylic acid. The solution was contained in a boron-free glass flask imbedded in a paraffin block. For the neutron irradiations three different types of sources were used; (1) about 750 millicuries (Rn+Be); (2) D−D source;[11] (3) Be(p, n) reaction in the cyclotron. After irradiation the active arsenic, present as ions in the solution, was precipitated as a sulphide by passing H_2S through the solution. Previously the solution had been slightly acidified and a few milligrams of $AsCl_3$ added as a carrier. The precipitate was then dried, pressed between two pieces of filter paper, and inserted in the source holder. The total surface density of a source averaged about 29 mg/cm².

Rubidium

The preparation of the rubidium sources was as follows. A saturated aqueous solution of uranyl nitrate was irradiated for several hours with neutrons, which had been slowed down in paraffin, from the cyclotron. After irradiation the solution was set aside for 3 hours to allow short period gaseous products to decay. After this period, air was bubbled through the solution and, together with the active krypton it had accumulated, collected by water displacement in a brass vessel. An aluminum foil, of surface density 3.5

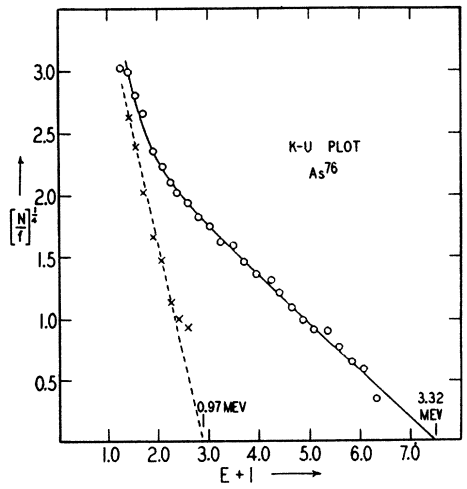

FIG. 5. K-U plot of As^{76} data shown in Fig. 3.

[10] L. Szilard and T. A. Chalmers, Nature **134**, 462 (1934).

[11] The author is indebted to Dr. W. H. Zinn for the use of his D–D neutron source.

mg/cm², was supported inside the vessel, insulated from it, and maintained at a negative potential of about 1200 volts with respect to the container. This foil collected the positively charged recoil rubidium ions produced in the gas by the krypton disintegrations. After collecting for 45 minutes the foil was removed and placed in the source holder.

Krypton

The active krypton was collected in the gas cell in the following manner. The boron-free glass flask containing the uranyl nitrate solution was sealed with a rubber stopper through which a tube led to a sintered glass disk at the bottom of the solution. Another tube through the stopper connected to the air space above the solution. Both these tubes were equipped with stopcocks. After evacuating the space above the liquid the solution was irradiated for several hours with neutrons from the cyclotron. After irradiation the short period gaseous products were allowed to decay for three hours. The flask was then connected to the gas cell through a Toepler pump, this system having previously been evacuated. The arrangement is shown in Fig. 2. After passing a few cubic centimeters of air through the solution, the air, together with the active krypton picked up, was pumped into the gas cell. This process was repeated twice. The pressure in the cell amounted to about 5 cm of Hg.

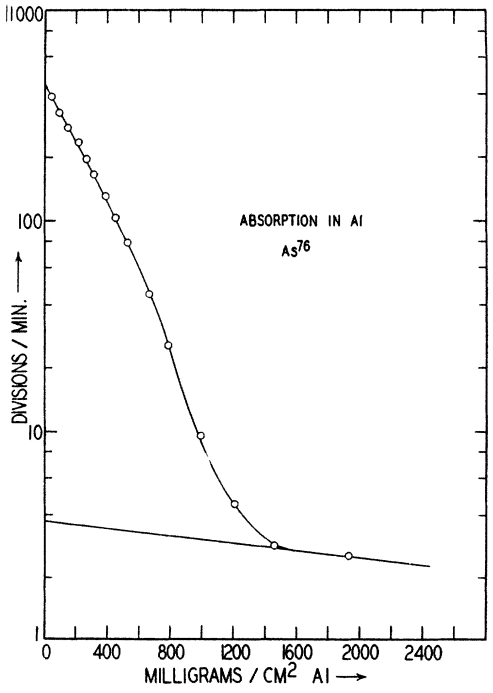

FIG. 6. Absorption in Al of β-rays from As^{76}. Measurements were made using a high pressure ionization chamber and string electrometer. The maximum range of 1.48 g/cm² corresponds, according to Feather's formula ($R=0.543\,E-0.160$), to an energy of 3.0 Mev.

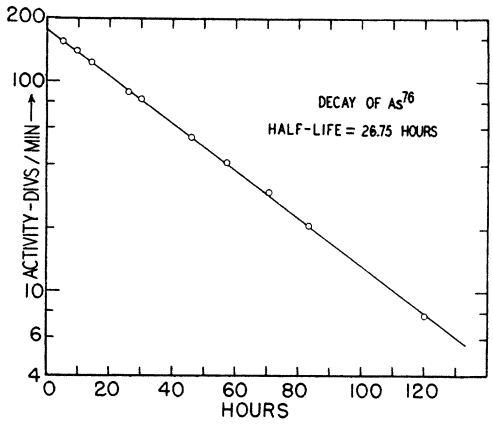

FIG. 7. The decay of As^{76}.

Since the half-life of the krypton is 3 hours, and that of the rubidium 18 minutes, the electrons observed in the cloud chamber resulted from the disintegrations of both types of nuclei. In order to be sure that the ratios of the two activities would be the same for different runs, the track photography was always started 10 minutes after the gas cell had been filled.

RESULTS

Arsenic

The observed momentum distribution of the disintegration electrons from As^{76} is shown in Fig. 3. Runs were taken at two magnetic field strengths of 342 and 800 gauss. The purpose of this procedure was to bring the low and the high momentum parts of the spectrum into the region of easily measured curvatures. The data obtained at the two field strengths overlapped sufficiently to allow correlation of the two sets of observations. The spectrum represents the results of the measurement of 2650 tracks plotted in intervals of 400 $H\rho$.

From Fig. 3 one obtains the upper limit of the β-rays from As^{76} at $H\rho=10{,}600\pm500$ gauss-cm, corresponding to an energy of 2.71 ± 0.14 Mev.

The complexity of the spectrum is readily seen from the presence of the two maxima at $H\rho = 2500$ and $H\rho = 4000$. The average energy of the electrons is found to be 0.94 Mev.

Fermi and K-U plots[12] of the data are shown in Figs. 4 and 5. The upper energy region of the observed spectrum can be fitted by a Fermi distribution, which, upon extrapolation, yields an end point of 2.78 Mev. The K-U plot can be analyzed into two components having extrapolated end points of 0.97 and 3.32 Mev. In agreement with other similar measurements a 20 percent difference is found between observed and K-U extrapolated end points. On the basis of the K-U analysis, the low energy component contains about 20 percent of the total number of tracks in the spectrum.

An absorption measurement in aluminum of the β-rays from As^{76} yielded a range of 1.48 g/cm^2, corresponding to an energy of 3.0 Mev as determined by Feather's range-energy formula.[13] Figure 6 shows the absorption curve obtained.

The decay of As^{76} was followed for over five half-lives (Fig. 7) and found to have a single period of $T = 26.75 \pm 0.15$ hours. By assuming the existence of the two groups suggested by the K-U analysis, the partial disintegration constants were computed. These values, taken with the K-U extrapolated energies and also with the latter reduced by 20 percent, are plotted on a Sargent[14] diagram (Fig. 8). Both transitions are of the "forbidden" type.

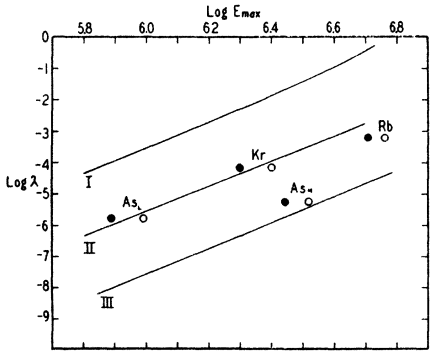

FIG. 8. Sargent diagram. The open circles represent points corresponding to K-U extrapolated energy limits, the filled circles to K-U end points decreased by 20 percent. As_H and As_L represent, respectively, the high and low energy groups of As^{76}.

[12] Kurie, Richardson, and Paxton, Phys. Rev. **48**, 167 (1935).

[13] N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938).

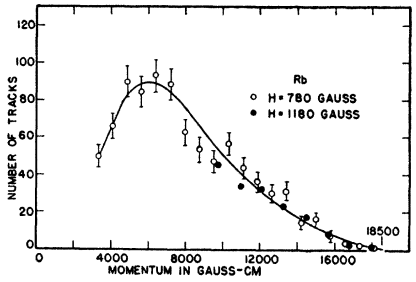

FIG. 9. Momentum distribution of β-rays from Rb ($T = 17.5$ minutes) separated from uranium fission products.

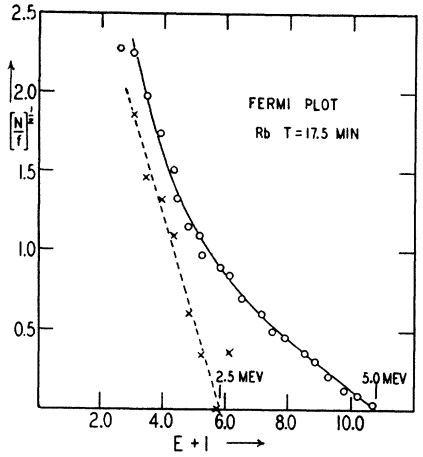

FIG. 10. Fermi plot of Rb data shown in Fig. 9.

Rubidium

The observed distribution in momentum of the β-particles from the 18-minute rubidium separated from uranium fission products is shown in Fig. 9. A total of 1360 tracks was measured at magnetic field strengths of 780 and 1180 gauss. The observed upper limit at $H\rho = 18{,}500 \pm 500$ gauss-cm corresponds to an energy of 5.06 ± 0.15 Mev. The mean energy of electrons is found to be 1.8 Mev.

A Fermi plot of the data is given in Fig. 10. It is possible to analyze the observed spectrum into two components having the shapes of Fermi "allowed" distributions. The extrapolated end points are 2.5 Mev and 5.0 Mev. A K-U plot of the data (Fig. 11) indicates a single distribution with extrapolated end point of 5.8 Mev.

[14] B. W. Sargent, Proc. Roy. Soc. **139**, 659 (1933).

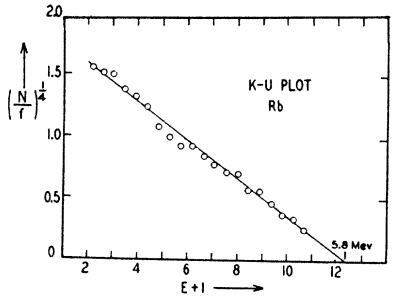

FIG. 11. K-U plot of Rb data shown in Fig. 9.

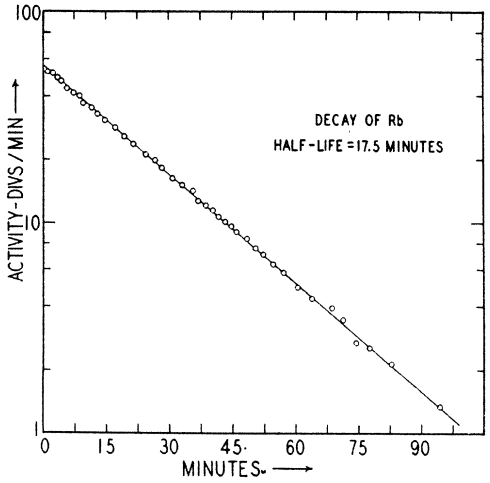

FIG. 12. Decay of Rb activity.

The decay of the rubidium activity was followed for over 5 half-lives (Fig. 12) and found to have a half-life $T=17.5\pm0.5$ minutes.

Krypton

As previously mentioned, the electrons observed from the gas cell are due to both krypton ($T=175$ minutes) and rubidium ($T=18$ minutes) disintegrations. Figure 13 gives the observed momentum distribution of the Kr+Rb β-particles, representing the measurement of 900 tracks at a magnetic field strength of 700 gauss. The end point at $H\rho=18{,}000$ agrees closely with that obtained for the rubidium disintegration electrons, indicating that the upper energy region of the composite spectrum is due to the rubidium disintegrations.

A K-U plot of the complex Kr+Rb spectrum (Fig. 14) can be analyzed into two components. The extrapolated end point of the high energy group occurs at 5.8 Mev, in agreement with that obtained for the 18-minute rubidium, while the low energy group, due to krypton, has an extrapolated end point of 2.5 Mev.

The Sargent points (Fig. 8) for the rubidium and krypton activities indicate that both transitions are "forbidden."

DISCUSSION OF RESULTS

Arsenic

The observed momentum distribution of the electrons from As^{76} is undoubtedly distorted slightly in the low energy region due to scattering in the source itself.[15] The result of this distortion will be to lower the ratio of the population of the high to that of the low energy group.

A comparison of the present results with those reported by other investigators is given in Table I. In all cases the measurements were made with a Wilson cloud chamber. It is seen that the agreement as to the observed upper energy limit is very good. Although in the other investigations the complexity of the spectrum was apparent only in the K-U analysis, in the present results the observed spectrum clearly indicates the presence of at least two groups. The results reported here also confirm the relative populations of the two energy groups as found by Harteck (*et al.*). The K-U extrapolated end point of the low energy group is found to be about 10 percent lower than that found by the other authors.

From the existence of the two energy groups of electrons emitted by As^{76} one would also expect the emission of a γ-radiation with an energy

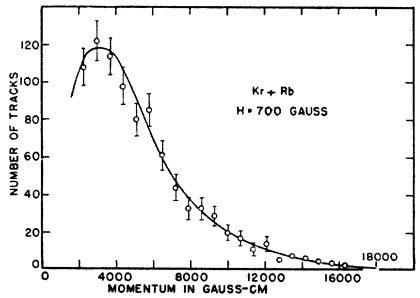

FIG. 13. Momentum distribution of β-rays from Kr ($T=175$ minutes) and Rb ($T=17.5$ minutes). Since the Kr, separated from uranium fission products, decays into the shorter-lived Rb, disintegration electrons from both isotopes are present in the observed spectrum.

[15] A. W. Tyler, Phys. Rev. **56**, 125 (1939); J. L. Lawson, Phys. Rev. **56**, 131 (1939).

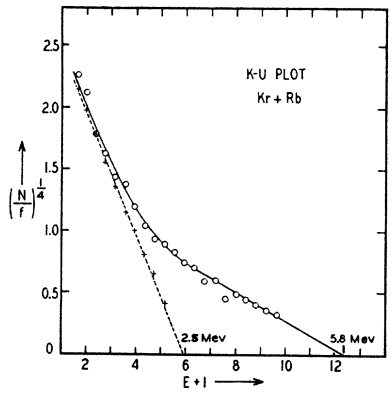

FIG. 14. K-U plot of (Kr+Rb) data shown in Fig. 13. The agreement of the extrapolated end point of the high energy group with that found for Rb alone (Fig. 11) identifies the low energy group as due to Kr disintegrations.

equal to the energy difference of the two end points. Harteck (*et al.*) observed 5 electron-positron pairs with an average energy of 2.16 Mev, which value is in substantial agreement with the difference of the K-U extrapolated upper limits. They also found two pairs with an average energy equal to 3.15 Mev, suggesting the existence of another low energy electron group. Measurements[16] of β and γ coincidences also suggest the presence of this third component in the As[76] β-spectrum. At present the available information is not of sufficient accuracy to allow more than speculation as to the energy level system of Se[76].

It should be mentioned that the upper limit of the low energy group of a complex spectrum, as determined by a K-U analysis, has rather large uncertainty limits. The K-U method of analysis is, to a large extent, arbitrary, and the only justification for its use is the fact that the present theory of β-decay is unable to give precise information as to the shape of β-spectra resulting from various types of "forbidden" transitions.

Rubidium

Because of the fact that a "thin" source was used for the measurement of the β-particles emitted by rubidium ($T=18$ min.), one would expect little distortion of the observed spectrum resulting from scattering within the source.

The analysis of the observed distribution into two components having the shapes of Fermi "allowed" distributions is doubtful because of the statistical errors of the observations. It is still quite possible that we have a single group with a K-U distribution. However, if one assumes the analysis to be correct, the two energy groups might either be due to transitions from rubidium to two strontium energy levels, or, on the other hand, to a rubidium disintegration followed by a very short-lived strontium disintegration. On the basis of the latter hypothesis, the 18-minute rubidium activity must be attributed to $Rb^{\geq 90}$. Furthermore, attributing the high energy component to the short-lived strontium, one would expect, for an "allowed" transition, a strontium activity with a half-life of the order of 2 sec.

Glasoe and Steigman measured the absorption of the β-particles in aluminum, and found a maximum range equivalent, by Feather's formula, to 4.6 Mev. This value is in reasonable agreement with the present observed upper limit of 5.1 Mev. From their absorption curve it appears that about 1 percent of the total ionization with no absorbing material is accounted for by γ-radiation. This would indicate that the rubidium spectrum is complex.

Krypton

It is of interest to note that in this measurement, where the existence of two energy groups of electrons, namely Kr and Rb disintegrations, is to be expected, the K-U plot does analyze into two components. This perhaps justifies to some extent the practice of interpreting K-U plots as indicating simple or complex spectra, particularly so, since in Fig. 10 there is not much indication of complexity.

Since the krypton isotope responsible for the

TABLE I. Comparison of As[76] results.

	No. of tracks measured	Observed upper energy limit (Mev)	Average energy (Mev)	K-U extrapolated end points (Mev)	Intensity ratio—high to low energy groups
Brown and Mitchell (reference 2)	150	2.81	0.62	3, 4, 1.09	0.8
Harteck (*et al.*) (reference 2)	1750	2.81	1.3	3, 2, 1.1	3.7
Sagane (*et al.*)[a]	1515			2.75, 1.31	4.9
Weil	2650	2.71	0.94	3.3, 0.97	3.5

[16] F. Norling, Zeits. f. Physik **111**, 158 (1938); Mitchell, Langer, and McDaniel, Phys. Rev. **57**, 1107 (1940).

[a] Sagane, Kojima, Miyamoto, and Ikawa, Proc. Phys. Math. Soc. Japan **21**, 660 (1939).

175-minute activity must have the same mass number as the rubidium nucleus with 18-minute half-life, we must assume the radioactive krypton isotope to be $Kr^{\geq 90}$ if the rubidium activity should be due to $Rb^{\geq 90}$.

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Ionization of Argon and Neon by Electron Impact

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The "ionization efficiency curve" for singly charged argon is found to have at least one inflection of the type first observed by E. O. Lawrence for mercury. The relative probabilities of forming singly and doubly charged argon and neon are tabulated. Careful examination of the initial portions of the "ionization efficiency curves" for singly charged neon and argon and doubly charged argon shows the "tails" to be largely characteristic of the ionization cross section and not purely caused by spread in electron energy as often has been assumed.

THE ionization efficiency curves of the rare gases, particularly argon, are very commonly used to calibrate electron acceleration voltage scales in mass spectroscopic studies. Despite this, the form of these curves has not been extensively studied. The most complete reports on the ionization of the rare gases by electron impact are in the important papers of P. T. Smith[1] and W. Bleakney.[2] The former studied the total ionization cross sections of helium, neon, and argon as a function of the impacting electron energy. Bleakney determined the relative probability of forming singly and multiply charged ions.

In the course of checking the behavior of our 180° mass spectrometer tube we have obtained considerable data on the ionization efficiency curves of argon II (A^+), argon III (A^{++}) and neon II (Ne^+), for electrons of less than 250-volt energy. Since our data, which we believe to be more reliable for reasons given below, differ in significant detail from the previous work, we are reporting them here.

The instrument used in this research will be described in detail elsewhere, hence only pertinent details are recorded. The 180° mass spectrometer tube (16-cm radius) with the wide slits in use has a resolving power of about 1 in 150. The tube and accessories are mounted in the cavity of a water cooled spherical solenoid. A magnetic field strength of ~1000 oersteds was used. The electrons were supplied by an oxide coated, platinum cathode. The electron accelerating voltage is controlled by a wire wound potentiometer and the apparent voltage measured with calibrated voltmeter which can be read with an accuracy of ±0.1 percent. The linear variation of the positive ion current with the pressure and the current in the electron beam showed that only primary processes were observed. The total electron emission ranged from 10 to 18μ amp. while the beam itself carried from 0.5 to 4μ amp.

In Fig. 1 we show the ionization efficiency curves of the ions A^+, A^{++}, Ne^+, and Ne^{++} for electrons of less than 225-electron volt energy. The broken lines show Bleakney's results. Al-

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[1] P. T. Smith, Phys. Rev. **36**, 1293 (1930).
[2] W. Bleakney, Phys. Rev. **36**, 1303 (1930).