curve drops to half-value at about 3.7-mm absorber; this corresponds to a γ-ray of nearly 6-Mev energy. The quarter-value thickness is nearly 6.0 mm; this would indicate a γ-ray of energy slightly over 7 Mev. It is reasonable therefore[8] to assume that most of the γ-radiation lies in the vicinity of 6 Mev, while more energetic lines are also present but of somewhat weaker intensity. This interpretation is of course quite consistent with the nature of the neutron spectrum, which in turn shows the existence of anticipated levels in N^{15}.

[8] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 256 (1948).

ACKNOWLEDGMENTS

The writers wish to acknowledge the technical assistance of Mr. J. T. Peoples and the continued interest of Dr. W. F. G. Swann, Director of the Bartol Research Foundation.

* Note added in proof: L. Yaffe and W. H. Stevens, Phys. Rev. **79**, 893 (1950), have attempted to observe the reaction $C^{14}(n,)C^{15}$. The reaction was not observed, and it was concluded that the cross-section must be less than 1 microbarn.

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Radioactive Isotopes of Rubidium*

D. G. KARRAKER AND D. H. TEMPLETON
Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California
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Neutron deficient isotopes of rubidium have been prepared from bromine by bombardment with helium ions in the Berkeley 184-inch and 60-inch cyclotrons. The properties of these isotopes are as follows:

Isotope	Half-life	Type of radiation	Energy in Mev: Particles	Energy in Mev: Gamma-rays	Produced by
Rb^{84}	34 days	β^+, K, e^-	1.53(β^+) 0.37(e^-)	0.85	Br-α-n
Rb^{83}	107 days	K	—	—	Br-α-$2n$
Rb^{82}	6.3 hr.	β^+, K	0.670	1.2, 0.7	Br-α-n Br-α-$3n$
Rb^{81}	4.7 hr.	β^+, K	0.990	0.95	Br-α-$2n$ Br-α-$4n$

The mass numbers were determined with a mass spectrograph. Rb^{81} has been shown to decay to the 13-sec. krypton, thereby assigning it to Kr^{81}. Electrons from the conversion of a 190-kev gamma-ray caused by this krypton are observed with the Rb^{81} radiations.

I. INTRODUCTION

As part of a general program in this laboratory of investigation of the properties and mass assignments of radioactive isotopes, we have studied four neutron deficient isotopes of rubidium by mass-spectrographic and counting methods. The results of this work will be a basis for the assignment of some new strontium radioactivities now being studied, and perhaps ultimately of light yttrium and zirconium isotopes.

Barber[1] has assigned a 40-day positron-emitter to Rb^{84}; we have confirmed this assignment, but observe 34 days as the half-life. A 6.5-hour rubidium has been reported by Hancock and Butler.[2] Our mass-spectrographic results showing that there are actually two isotopes of about this half-life, at masses 81 and 82, have already been described.[3] However, subsequent experiments with a beta-spectrometer have yielded more accurate values for their properties than were reported there. A new 107-day activity assigned to Rb^{83} is also described in this paper.

II. CHEMICAL SEPARATIONS

Rubidium activities were produced by bombardment of bromine (as ammonium or cuprous bromide) with helium ions in the Berkeley 60-inch and 184-inch cyclotrons. Two principal procedures were used to separate the rubidium from the target material. In the case of ammonium bromide targets, 20 to 30 μg of inactive rubidium was added to the dissolved target material, the solution was evaporated to dryness and the ammonium bromide target material sublimed off by strong heating. The rubidium activities remained behind and were dissolved in a small volume of water. This solution was divided into two portions. The major portion was used without further purification for mass spectrographic determination of the mass numbers. The remainder was purified further by scavenging with precipitates of silver chloride, strontium carbonate, ferric

* This work was performed under the auspices of the AEC.
[1] W. C. Barber, Phys. Rev. **72**, 1156 (1947).
[2] J. O. Hancock and J. C. Butler, Phys. Rev. **57**, 1088 (1940).
[3] Reynolds, Karraker, and Templeton, Phys. Rev. **75**, 313 (1949).

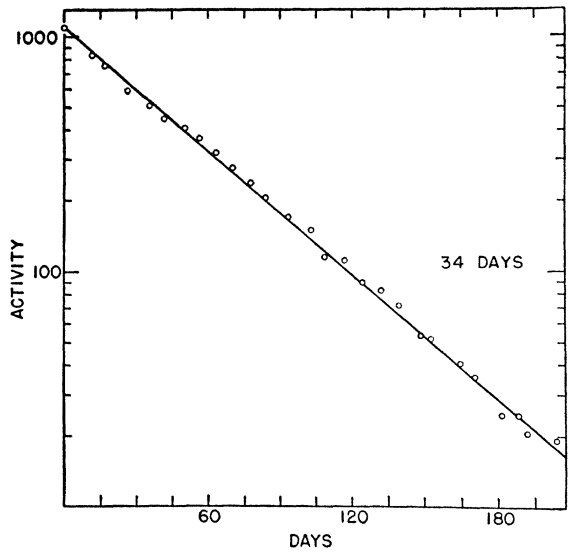

FIG. 1. Decay of 34-day Rb^{84}.

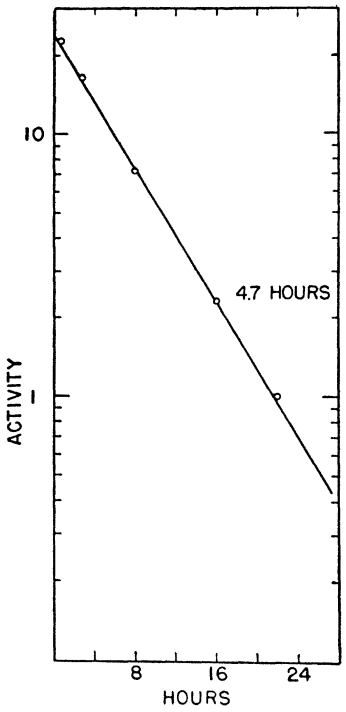

FIG. 2. Decay of Rb^{81}, measured by decay of the electron line of Kr^{81}.

hydroxide, and lead sulfide. This repurified portion was used for decay and absorption measurements.

Cuprous bromide targets were used for the production of rubidium activity for the beta-ray spectrometer measurements. In this case, the target was dissolved in hot aqua regia, and about 0.5 mg of inactive rubidium carrier was added. The copper was removed by precipitation as the sulfide, and the solution was scavenged with lanthanum hydroxide and strontium carbonate precipitates. The remaining solution was evaporated to dryness and heated strongly to sublime off ammonium salts, leaving solid rubidium chloride behind.

III. MASS SPECTROGRAPH TECHNIQUES

For use in the mass spectrograph, the solution of the active rubidium chloride, with a few micrograms of stable rubidium carrier, was evaporated on the tungsten filament of the ion source. The rubidium was ionized by heating the filament with an electric current. The Rb^+ ions, after acceleration by a voltage drop and resolution by a 60° magnetic field, were collected on an Eastman III-0 spectrographic plate, with the stable rubidium serving as a mass marker. The location of radioactivity on the plate was determined, before it was developed, by the photographic transfer technique. The exposures used for obtaining transfers ranged from a few hours to six weeks. In some cases a Geiger-Müller counter, provided with a slit, was used, but the slit did not shield the counter perfectly from adjacent mass numbers.

IV. RADIOACTIVITY MEASUREMENTS

Decay and absorption measurements were made with end-window Geiger-Müller counters filled with argon and alcohol, with a window thickness of ca 4 mg/cm² mica. Aluminum absorption measurements were made in the conventional manner. After an aluminum absorption measurement, sufficient beryllium to absorb all particles present was interposed between the sample and the counter. An aluminum absorption measurement of electromagnetic radiation was then made. Subtraction of the electromagnetic radiation from the total, after

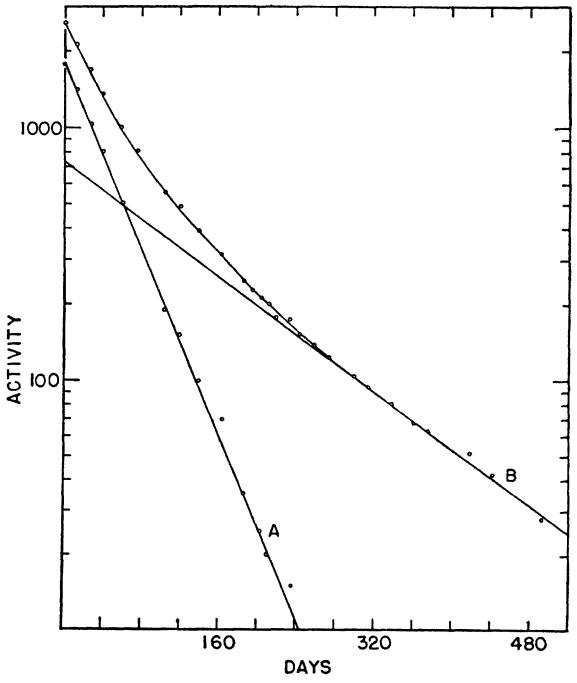

FIG. 3. Decay of long-lived rubidium activities; (A) 34-day Rb^{84}; (B) 107-day Rb^{83}.

correction for the effect of the beryllium, yielded the particle absorption curve.

Soft electromagnetic components of appropriate half-thickness in aluminum were interpreted as K x-rays. Their abundance was determined by subtraction of the harder components from the curve for aluminum absorption of electromagnetic radiation, with correction for the effect of the beryllium. Lead absorption measurements were taken at low geometry, using counters without the conventional lead shield. Lead absorbers were placed between two beryllium absorbers of sufficient thickness to absorb all secondary particles. Krypton K x-rays (about 13 kev) were assumed to count with 1.5 percent efficiency and gamma-rays over 0.5 Mev with an efficiency of 1.0 percent per Mev. Approximate branching fractions for the decay *via* positron emission and electron capture were estimated on the basis that K x-rays are emitted in only half of the electron capture events, because of the Auger effect.[4] It is assumed that all positrons in the proper angular interval are counted. Capture of electrons from shells other than K is neglected. The results will be in error if there are present highly converted low energy gamma-rays whose conversion electrons are too weak to have been observed. No correction has been made for backscattering from the sample.

For samples of low activity, rough measurements of the particle energies were made with a crude 180° magnetic spectrometer with about a 4-cm radius. Its use was necessary to determine the energy limit of the Rb^{84} positrons, and it also served to distinguish the sign of the particles in preliminary work.

The particles from Rb^{81} and Rb^{82}, which were prepared in high intensity, were observed with a beta-ray spectrometer of the 255° double-focusing type, similar to that invented by Svartholm and Siegbahn,[5] but with a 25-cm radius instead of the 12-cm radius of their first instrument. Samples were mounted on 1- to 4- mg/cm^2 mica backing with between 0.2 and 1.0 mg of material in the sample. The backscattering from these samples was quite marked at low energies, but was not serious in the region of interest (above 300 kev).

TABLE I. Isotope chart.[a]

Element	Mass Number 79	80	81	82	83	84	85
Sr						stable	70 min. I.T. / 65 days K
Rb			4.7 hr. β^+, K	6.3 hr. β^+, K	107 days K	34 days β^+, K	stable
Kr	34 hr. β^+, K	stable	13 sec. I.T.?	stable	113 min. I.T. / stable	stable	4 hr. β^- / 10 yr. β^-
Br	stable	4.4 hr. I.T. / 18 min. β^-, β^+	stable	34 hr. β^-	2.4 hr. β^-	30 min. β^-	3 min. β^-

[a] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).

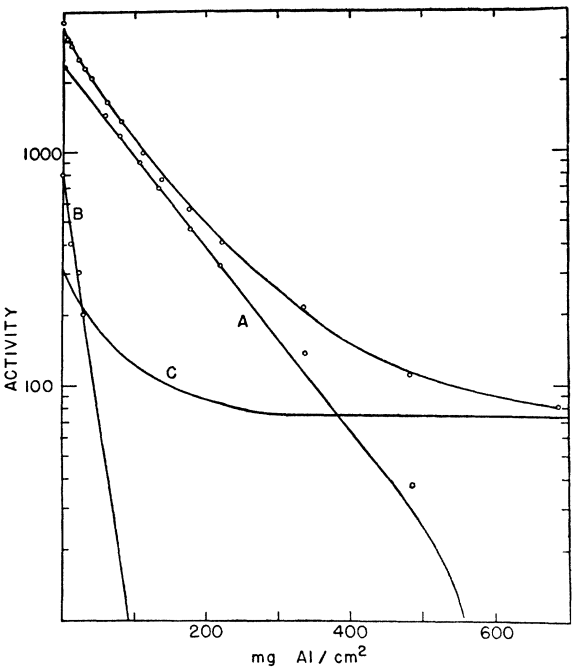

FIG. 4. Aluminum absorption of Rb^{84}; (A) 1.5-Mev positrons; (B) 0.37-Mev electrons; (C) K x-rays and gamma-rays.

V. MASS ASSIGNMENTS

In every bombardment of bromine with helium ions, which ranged in energy from 18 to 100 Mev, two main activities were observed in rubidium decay measurements, one of 5–6 hours half-life and one of the order of 1 to 3 months. Rubidium produced at bombardment energies of 40 to 100 Mev, when mass analyzed, gave photographic transfers at masses 81 and 82 in a few hours.[3] Direct measurement of the decay with the slit counter showed that both masses were of the order of six hours in half-life, with mass 82 being slightly longer lived than 81. Transfers exposed for several weeks showed radioactivity at masses 83 and 84 as well as at 81 and 82. Since masses 83 and 84 did not transfer in a few hours, they are known to be the long-lived activities.

Rubidium produced from bromine by 18-Mev helium ions gave radioactive transfers only at masses 82 and 84, showing that the major activities produced in these bombardments were the (α, n) products. Decay measurements on these activities showed the half-life of the short component (mass 82) to be 6.3 hours, corresponding to the 6.5-hr. activity previously identified by Hancock and Butler[2] (erroneously assigned to mass 84) and also showed a 34-day positron activity (Fig. 1) now assigned to mass 84, corresponding to the 40-day rubidium reported by Barber.[1]

[4] A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), p. 482.
[5] N. Svartholm and K. Siegbahn, Arkiv Mat., Astron. Fys. **33A**, 1 (1946).

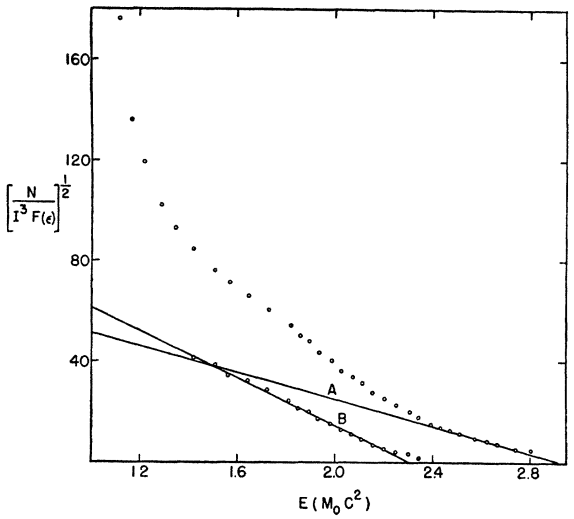

FIG. 5. Kurie plot of positrons of Rb^{81} and Rb^{82}; (A) $E_{max}=2.92$ m_0c^2 or 990 kev; (B) $E_{max}=2.30$ m_0c^2 or 670 kev.

Absorption and crude spectrometer measurements on the activities produced at low energy showed that Rb^{82} had virtually no conversion electrons compared to its positrons, whereas a strong conversion electron line had been observed from rubidium made at higher energy. Further work (described below) established that this line was due to a 13-sec. Kr^{81} daughter of Rb^{81}. Decay of this electron line, followed in the double-focusing spectrometer, gave a half-life of 4.7 hours for the half-life of Rb^{81} (Fig. 2). The half-life of Rb^{83} was determined by following the decay of a sample of rubidium activity produced by 60-Mev helium ion bombardment of bromine, very similar to the sample which gave a radioactive transfer at masses 83 and 84. Resolution of the decay curve showed a 107-day activity, assigned to mass 83, as well as the 34-day Rb^{84} (Fig. 3). The mass relations of these isotopes are shown in Table I. Radiation characteristics of each isotope will be discussed individually.

VI. RADIATION CHARACTERISTICS

34-day Rb^{84}

Measurements on the crude magnetic spectrometer have shown that Rb^{84} has positrons of 1.5-Mev energy limit, as determined by a Kurie plot of the spectrum. A broad electron distribution was also observed centered about 0.37 Mev. The width of the distribution showed that the electrons were complex. There may have been a small contribution from the 107-day Rb^{83}, although it was not observed to be present. Since Sr^{84} is found in nature, Rb^{84} is presumed to be unstable with respect to negative beta-decay, but we cannot say from these data whether any of the negative electrons observed are beta-particles. K x-rays have been identified by absorption in aluminum (Fig. 4), and a gamma-ray of 0.85 Mev (half-thickness, 8.5 g/cm² Pb) has been identified by absorption in lead. It is assumed that Rb^{83} did not affect the absorption measurements, since the decay curve indicated pure Rb^{84}. The ratio of positrons to K x-rays to gamma-rays, estimated from the absorption curve, was 0.15:1:*ca.* 0.6. From these data the mode of decay is estimated to be about 93 percent by K electron capture and seven percent by positron emission. Negative beta-decay would amount to about three percent if all the negative electrons observed were beta particles.

In a recent abstract Beckham and Pool[6] have listed properties of this isotope which are in reasonable agreement with those described above. They found the half-life to be 38 days, somewhat greater than our value. However, their bombardment of krypton with 10-Mev deuterons can be expected to produce Rb^{83} in smaller yield than Rb^{84}, but yet in amount large enough to influence the slope of the decay curve.

107-day Rb^{83}

The amounts of this activity available were so small that precise measurement of its radiations was not attempted. The ratio of particles to K x-rays to gamma-rays is very roughly 0.3:1:2. It is thus indicated that decay is to a large extent by electron capture. No positrons were detected, but the sensitivity for detection was poor.

Nothing can be said concerning the presence or absence of the 113-min. isomeric state[7] of Kr^{83} as a daughter of this activity; no experiments were at-

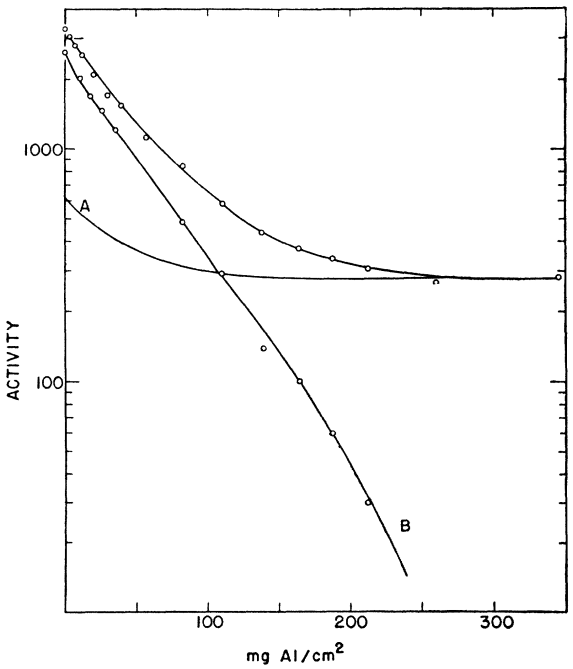

FIG. 6. Aluminum absorption of Rb^{82}; (A) K x-rays and gamma-rays; (B) 0.67-Mev positrons.

[6] W. C. Beckham and M. L. Pool, Phys. Rev. **80**, 125 (1950).
[7] G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).

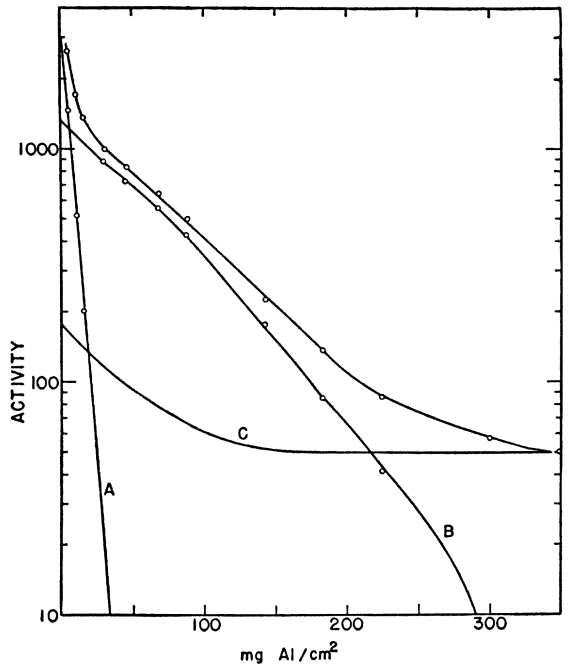

FIG. 7. Aluminum absorption of Rb^{81} and Kr^{81}; (A) 180-kev Kr^{81} electrons; (B) 0.99-Mev Rb^{81} positrons; (C) K x-rays and gamma-rays.

tempted to detect this krypton because of its soft radiations and the small amount of Rb^{83} which was available.

6.3-hr. Rb^{82}

The radiations of Rb^{82} are subject to some uncertainty since this isotope always was mixed with at least a small amount of the 4.7-hr. Rb^{81} when prepared for radiation measurements. The energy of the positrons is 670±50 kev, as determined by resolution of a Kurie plot of the mixed positrons of Rb^{82} and Rb^{81} (Fig. 5). Decay of the spectrum showed an enrichment of the longer-lived Rb^{82}.

Aluminum and lead absorption measurements were made on rubidium produced by 18-Mev helium ion bombardment of bromine, in which no transfer line for Rb^{81} was observed and which is supposed to be reasonably pure. Lead absorption shows two components, a strong gamma-ray of 1.2 Mev (12 g/cm² Pb half-thickness) and a gamma of about 0.7 Mev (5.5 g/cm² Pb) in lower intensity. A more detailed investigation of these gamma-rays and others which probably occur in this decay may aid in clarifying the energy levels of Kr^{82}, which are in some doubt even after considerable study[8] of the decay of Br^{82}. It seems likely that at least some of the rubidium gamma-rays are identical with some of the bromine gamma-rays.

On the basis of aluminum absorption measurements, (Fig. 6), the ratio of positrons to K x-rays to gamma-rays is 0.12:1:0.9, suggesting that this isotope decays about 94 percent by electron capture.

4.7-hr. Rb^{81}

The radiations of Rb^{81} are subject to the same uncertainties as those of Rb^{82} and are open to the further error of being confused with its 13-sec. Kr^{81} daughter. Measurement of the positron and electron energies, originally thought to be associated with Rb^{81}, in the double-focusing spectrometer gave 990±50 kev for the range of the positron (Fig. 5) and showed intense K and L conversion lines corresponding to a gamma-ray of 193±10 kev. The energy of this gamma-ray corresponds, within limits of error, to a gamma-ray of 187 kev found by Creutz, and co-workers[9] to be associated with a 13-sec. krypton activity produced by bombardment of bromine with protons of low energy. By flaming a strong sample of Rb^{81} to drive off the krypton, and observing of the growth of activity of the electron line in the crude spectrometer, Rb^{81} was shown to have a krypton daughter with a half-life of 10±6 sec.

In the same bombardments that Creutz and coworkers observed the 13-sec. Kr^{81}, they also observed a 55-sec. krypton isomeric transition with a strong conversion electron corresponding to a gamma of 127 kev. These activities were produced by bombarding bromine (masses 79 and 81) with protons of 5–6 Mev energy, and both isotopes are thought to be products of p, n reactions. Electrons from the 127-kev gamma were not observed by beta-ray spectrometer measurements of our rubidium activity. If the 55-sec. krypton does belong at mass 81, the amount formed by decay of Rb^{81} must be less than five percent as much as the 13-sec. activity.

Absorption data were taken on Rb^{81} samples prepared by bombardment of bromine with 100-Mev helium ions. A mass spectrographic transfer plate showed that the ratio of mass 81 to mass 82 was approximately 4. The data presented are corrected for the presence of the Rb^{82}.

Absorption in lead shows a gamma-ray of 0.95 Mev (9.5 g/cm² Pb half-thickness). Absorption in aluminum (Fig. 7) has given the positron to K x-ray to gamma-ratio as 0.1:1:0.6 after half of the x-rays observed were assumed to be due to the krypton daughter. It is estimated from this ratio that 87 percent of the decay is by electron capture. The number of conversion electrons from the 13-sec. krypton daughter is approximately three times the number of positrons of the rubidium parent.

We are indebted to F. L. Reynolds for assistance with the mass spectrograph and to G. D. O'Kelley for help with the beta-spectrometer. We are grateful to J. T. Vale and B. Rossi and the crews of the 184-inch and 60-inch cyclotrons for their cooperation which made these experiments possible.

[8] Siegbahn, Hedgran, and Deutsch, Phys. Rev. **76**, 1263 (1949); A. C. H. Mitchell, Rev. Mod. Phys. **22**, 36 (1950).

[9] Creutz, Delsasso, Sutton, White, and Barkas, Phys. Rev. **58**, 481 (1940).