Radioactive Kr Isotopes

L. L. WOODWARD,* D. A. MCCOWN,** AND M. L. POOL
The Ohio State University, Columbus, Ohio
(Received June 21, 1948)

A radioactive isotope of 1.1-hour half-life has been produced in krypton by alpha-particle bombardment of Se^{74}, enriched electromagnetically from 0.9 percent to 14.1 percent. Assignment of the isotope is made to Kr^{77}. Aluminum absorption measurements indicate a positron end point of 1.7 Mev. In addition to annihilation radiation, gamma-rays and K-capture have been observed. The ratio of K-capture to positron emission from the $Se^{74}(\alpha, n)$ reaction is computed as 2.6. The krypton 1.42-day isotope has been produced by an (α, n) reaction on electromagnetically enriched Se^{76}. The isotope is located as Kr^{79} and its half-life confirmed. A positron end point of 1.0 Mev is determined by aluminum absorption measurements. In addition to annihilation radiation, gamma-rays and K-capture have been observed. The ratio of K-capture to positron emission from the $Se^{76}(\alpha, n)$ reaction is computed to be 50. The cross-section ratio for formation of Kr^{77} compared to Kr^{79} by alpha-particle bombardment of selenium is computed as 1.4. The 4.6-hour Kr^{85} isotope has been produced by a $Se(\alpha, n)$ reaction.

I. INTRODUCTION

CYCLOTRON bombardments have been made with alpha-particles on electromagnetically enriched selenium.† Table I shows the percentages of stable selenium isotopes present in the two samples used. For comparison purposes, abundances of selenium isotopes of natural concentration are included in the table. Bombardments were also made with Hilger selenium.

As a result of these bombardments, a previously unreported radioactive krypton isotope has been found. The location and characteristic radiations of this isotope will be presented in this paper. The location and characteristic radiations of the Kr^{79} isotope, and production of the Kr^{85} isotope by alpha-particle bombardment of selenium will also be reported.

II. THE 1.1-HOUR Kr^{77} ISOTOPE

Samples of enriched Se^{74} and Se^{76} were prepared for simultaneous alpha-particle bombardment by pressing equal amounts by weight of the finely ground metallic selenium into the bottom of aluminum target holders under approximately 5000 pounds pressure. The two targets were then bombarded simultaneously in the cyclotron by means of a rotating probe.

In order to obtain separately the decay characteristics of positively and negatively charged particle activity, the samples were placed in a reversible electromagnetic field. A counter tube was located in such a position as to intercept β^-- or β^+-radiation, as desired.

Figure 1 shows a comparison between the decay of β^-- and β^+-activity in the two enriched selenium samples after simultaneous alpha-particle bombardment. β^--activity of similar characteristics and a β^+-activity of 1.4-day half-life were observed in both samples. In addition, as shown in the figure, a strong β^+-activity of 1.1-hour half-life was observed in the enriched Se^{74} sample but not in the enriched Se^{76} sample. This indicated that the 1.1-hour activity was formed by alpha-particle bombardment from the stable Se^{74} isotope. The activity was not observed in the Se^{76} sample because there was only 0.5 percent of stable Se^{74} in the Se^{76} sample.

TABLE I. Percentages of abundance of stable selenium isotopes in natural selenium and in the electromagnetically enriched selenium samples.

Se isotope	Percentages of abundance: Enriched Se^{74} sample	Enriched Se^{76} sample	Natural Se
74	14.1±1.0	0.5±0.2	0.9
76	9.4±0.5	41.5±1.0	9.5
77	7.1±0.3	6.8±0.5	8.3
78	21.4±1.0	16.1±0.8	24.0
80	40.4±1.0	30.2±1.0	48.0
82	7.5±0.5	5.0±0.5	9.3

* Lieutenont Colonel, USAF. Research under auspices of Air University, Maxwell Air Force Base, Montgomery, Alabama.

** Captain, USAF. Research under auspices of Air University, Maxwell Air Force Base, Montgomery, Alabama.

† Supplied by the Y-12 plant, Carbide and Carbon Chemicals Corporation, through the Isotopes Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

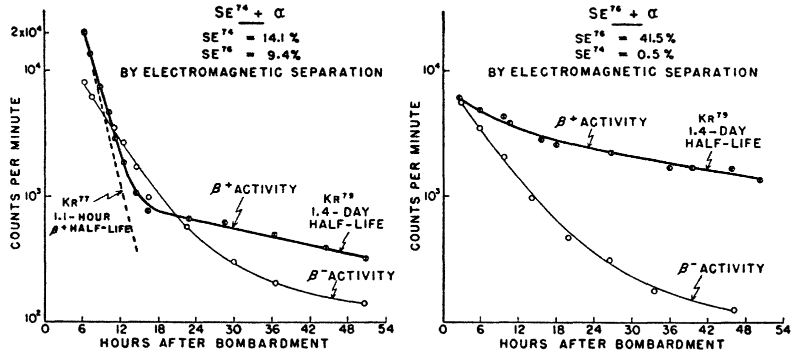

FIG. 1. A comparison of decay curves of separated β^-- and β^+-activity from alpha-particle bombardment of electromagnetically enriched Se^{74} and Se^{76}. The 1.1-hour Kr^{77} β^+-activity appears in the Se^{74} sample but not in the Se^{76} sample.

In order to determine whether the activity was due to a radioactive bromine or krypton isotope, a sample of Hilger selenium, laboratory No. 12006, was bombarded with alpha-particles. The target was prepared as in the first experiment. After bombardment, the radioactive krypton gas was removed by application of low heat to a mixture of the selenium, Na_2CO_3, $NaNO_3$, and KBr, and swept into a glass collector tube to one end of which a 2.0-mil aluminum foil window was attached.

Figure 2 shows the decay separately of β^+- and β^--activity in the krypton gas. A β^--activity of 4.4-hour half-life, and a strong β^+-activity of 1.1-hour half-life were observed. The 1.1-hour activity was thus established as a krypton isotope. Since it had been previously determined that the activity was also produced by alpha-particle bombardment of stable Se^{74}, assignment is made to Kr^{77}.

Figure 3 shows aluminum absorption measurements of the total activity obtained from an alpha-particle bombardment of enriched Se^{74}. Measurements were taken on a Wulf electrometer attached to a Freon-filled ionization chamber. Absorption measurements taken when the activity was in the 1.1-hour Kr^{77} period indicated a beta-end point of 0.74 g/cm^2, corresponding to 1.7 Mev as determined by the Sargent range-energy relation.

Measurements of electromagnetic radiation from the 1.1-hour activity were also taken. For this purpose the sample was placed between the pole faces of an electromagnet and a magnetic field applied of sufficient strength to prevent all beta-particles from entering the ionization chamber. Measurements of activity taken under these conditions were then measurements of the electromagnetic radiation from the sample. Measurements of activity were also taken with a $\frac{1}{4}$-inch aluminum absorber inserted between the sample and the ionization chamber. Since this amount of absorber was sufficient to stop any x-ray radiation present, these measurements were measurements of the gamma-ray activity of the sample.

From such data it was concluded that in the 1.1-hour Kr^{77} period there is gamma-ray activity in addition to that necessary to account for annihilation radiation, and also x-ray activity.

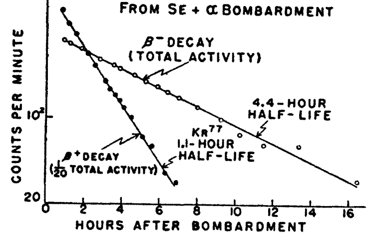

FIG. 2. Decay curves of β^-- and β^+-activity in krypton from alpha-particle bombardment of selenium. This shows that the strong 1.1-hour β^+-activity is a krypton isotope.

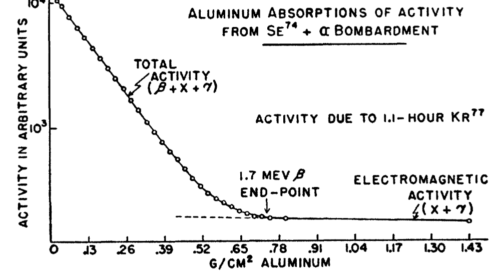

FIG. 3. Aluminum absorption measurements showing the 1.7-Mev positron end point of the 1.1-hour Kr^{77} activity.

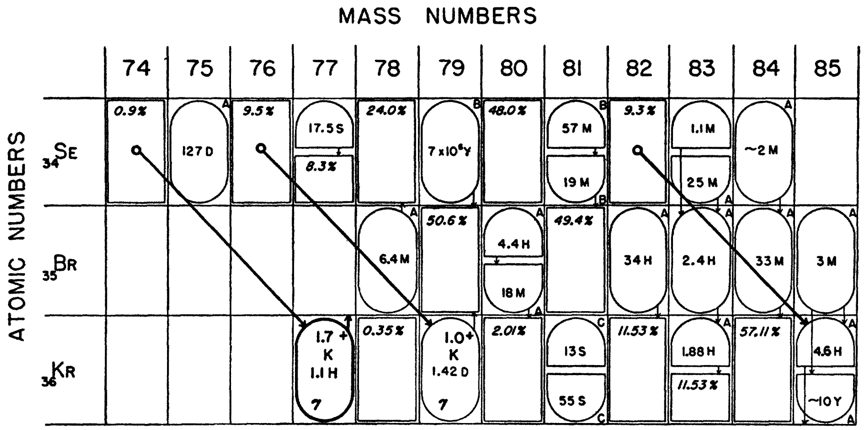

FIG. 4. The Se, Br, Kr section of the periodic table. The new Kr^{77} isotope, new reactions, and characteristic radiations found are shown in heavy lines.

The presence of x-ray activity was shown by subtracting the curve representing gamma-ray activity from the curve representing decay of total electromagnetic radiation. From considerations of the amount of x-ray radiation that would be expected from the "bremsstrahlung" effect, it was concluded that this x-ray radiation is a result of the K-capture process.

The ratio of K-capture processes to positron emissions in Kr^{77} from the $Se^{74}(\alpha, n)$ reaction is computed to be 2.6. This ratio was determined by a computation of saturation intensities and correcting for the relative ionization produced by the different forms and energies of radiation involved.

III. THE 1.4-DAY Kr^{79} ISOTOPE

A krypton activity of 18 ± 2 hours resulting from deuteron bombardment of krypton was first reported by Snell.[1] Assignment of the activity was made to either Kr^{79} or Kr^{81}. The same assignment of a 34.5 ± 1-hour krypton activity was made by Creutz *et al.*,[2] who obtained the period by proton bombardment of bromine. A positron end point of about 0.4 Mev was determined by cloud-chamber measurements. A krypton period of about 33-hour half-life was also reported by Clancy[3] as the result of alpha-particle bombardments of selenium, and assignment of the activity was made to either Kr^{79} or Kr^{81}. Beta end-point energies in the $Kr^{79,81}$ activity of 0.6 Mev (70 percent) and 0.9 Mev (30 percent) from Kr^{78} and Kr^{80} as target nuclei, respectively, have been reported.[4]

The location of the 1.4-day krypton period may be readily made as a result of alpha-particle bombardments of enriched Se^{74} and Se^{76}. Figure 1 shows that in the activity from such bombardments a period of 1.4-day half-life appeared in the Se^{76} sample in considerably larger intensity than in the Se^{74} sample. These curves indicate that the 1.4-day krypton period is formed from stable Se^{76}. If the activity had been formed from stable Se^{78} by alpha-particle bombardment, a smaller intensity of the 1.4-day period would have been expected in the Se^{76} sample than in the Se^{74} sample, since the former contained 16.1 percent of stable Se^{78}, which would produce Kr^{81}, while the latter contained 21.4 percent of Se^{78}. The 1.4-day krypton activity is then assigned to Kr^{79}.

Aluminum absorption measurements of the 1.4-day Kr^{79} activity indicate a beta-end point of 1.0 Mev. Beta-emission was determined to be entirely positrons.

Gamma-ray activity in addition to that produced by annihilation radiation has been observed. X-ray radiation resulting from the K-capture process is also present in the activity. The ratio of K-capture processes to positron emissions in the Kr^{79} activity from the $Se^{76}(\alpha, n)$ reaction is computed to be 50.

[1] A. H. Snell, Phys. Rev. **52**, 1007 (1937).
[2] E. C. Creutz, L. A. Delsasso, R. B. Sutton, M. G. White, and W. H. Barkas, Phys. Rev. **58**, 481 (1940).
[3] E. P. Clancy, Phys. Rev. **60**, 87 (1941).
[4] U. S. Atomic Energy Commission Abstracts of Declassified Documents, Vol. 1, No. 6, MDDC-614L, p. 380.

From the above data the ratio of reaction cross sections for the production of Kr^{77} and Kr^{79} by alpha-particle bombardment of selenium is determined to be 1.4.

IV. THE 4.6-HOUR Kr^{85} ISOTOPE

The 4.6-hour Kr^{85} period was reported by Snell[1] as a result of deuteron bombardment of krypton. The Kr^{85} period was not obtained by Clancy[3] as a result of alpha-particle bombardment of selenium. In the latter bombardments, only a 114-minute krypton period, assigned to the excited level of stable Kr^{83}, and a 33-hour krypton period, assigned to $Kr^{79, 81}$, were observed. The Kr^{85} period was then considered by Clancy to be long or fairly short, and a 4-hour krypton activity obtained from deuteron bombardment of krypton was presumed to be caused by Kr^{87}. The 4.6-hour Kr^{85} activity has been reported by Seelmann-Eggebert and Born[5] as a result of uranium fission by decay of the 3-minute Br^{85} isotope, and also as a result of $Sr(n, \alpha)$ and $Rb(n, p)$ reactions.[6]

A 4.4±0.2-hour half-life of β^--activity appears in Fig. 2, which shows the decay curves of separated β^- and β^+ krypton activity from alpha-particle bombardment of Hilger selenium. This curve indicates that the Kr^{85} isotope is produced by alpha-particle bombardment of selenium.

Figure 4 shows the Se, Br, Kr part of the periodic table. The new Kr^{77} isotope and new reactions found are noted by heavy lines.

ACKNOWLEDGMENTS

The support received from the Ohio State University Development Fund and the Graduate School is gratefully acknowledged. All chemical separations were performed by Mr. H. L. Finston and Mr. R. M. Dyer. The successful technique developed by them for the separation and collection of the radioactive krypton gas used in these experiments is especially worthy of mention.

[5] W. Seelmann-Eggebert and H. J. Born, Naturwiss. **31**, 59 (1943).

[6] H. J. Born and W. Seelmann-Eggebert, Naturwiss. **31**, 86 (1943).

PHYSICAL REVIEW VOLUME 74, NUMBER 7 OCTOBER 1, 1948

On the Angular Distribution in Nuclear Reactions and Coincidence Measurements

C. N. YANG
Department of Physics, University of Chicago, Chicago, Illinois

(Received June 9, 1948)

Theorems concerning the general form of the angular distribution of products of nuclear reactions and distintegrations are derived. These theorems are based only on the invariance properties of the physical process under space rotation and under inversion. The following examples are studied in detail: (i) angular correlation between the electron and the neutrino in β-decay; (ii) angular correlation between a β-ray and a γ-ray emitted in succession by a nucleus; and (iii) angular correlation between two γ-rays emitted in succession by a nucleus.

INTRODUCTION

In the calculation of the angular distribution in nuclear reactions and of the angular correlation in processes involving β- and γ-decay it often happens that many terms cancel out at the end of a laborious computation. The consistency of the occurrence of such cancellation leads one to suspect that some general reasons quite independent of the particular form of interaction are at work. In this paper we shall show that this is indeed the case. In fact, the general form of the angular distribution in many cases can be obtained directly from the theorems derived in this paper.

For nuclear reactions between spinless particles the existence of a limitation on the complexity of the angular distribution for fixed orbital angular momentum of the incoming particles is well known. That the same result holds *with the spin* taken into consideration (for un-