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The Induced Radioactivity of Potassium

D. G. HURST* AND H. WALKE†

Radiation Laboratory, University of California, Berkeley, California

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The paper reports a study of certain induced radioactivities associated with potassium. It is shown that the half-life of K^{42} is 12.4±0.2 hours. In addition to the well-established deuteron and slow neutron reactions K^{42} is also formed by the reactions $Sc^{45}+n^1\rightarrow K^{42}+He^4$ and $Ca^{42}+n^1\rightarrow K^{42}+H^1$. This last appears to have a relatively small probability. No evidence was found for the reaction $Ca^{44}+H^2\rightarrow K^{42}+He^4$. Fast neutron irradiation of potassium yields active chlorine and A^{41} by the transmutations $K^{39 \text{ or } 41}+n^1\rightarrow Cl^{36 \text{ or } 38}+He^4$; $K^{41}+n^1\rightarrow A^{41}+H^1$. There was no indication of the presence of A^{39} in the activated samples. Alpha-particle bombardment of chlorine yields K^{38} according to the reaction $Cl^{35}+He^4\rightarrow K^{38}+n^1$. This isotope of potassium decays with a half-life of $7.7_5\pm0.1_5$ minutes, emitting positrons having a maximum energy of about 2 Mev and gamma-rays which may be annihilation radiation only. K^{38} is also obtained by deuteron bombardment of calcium thus: $Ca^{40}+H^2\rightarrow K^{38}+He^4$.

I. INTRODUCTION

BY irradiating potassium with slow neutrons Fermi and his co-workers[1] obtained an active substance which they showed by chemical tests was not isotopic with chlorine, argon or calcium, and which had a half-life of about 16 hours. Since the naturally occurring isotopes of potassium are

Mass Number	39	40	41
Abundance (percent)	93.4	0.01	6.6

the only radioactive isotope of potassium (excluding K^{40}) which can be formed by slow neutron capture is K^{42} which then decays by emitting electrons to form the stable Ca^{42}. Hence the period of 16 hours was assigned to this isotope. G. von Hevesy[2] obtained, by fast neutron activation of scandium, a radioactive isotope which decayed to half-value in 16 hours and which behaved chemically like sodium. This he supposed to be K^{42} produced from Sc^{45} by the emission of an alpha-particle after the absorption of the neutron.

Indications obtained by one of us[3] that the accepted value of 16 hours is incorrect led us to measure the half-life of K^{42}. It seemed worthwhile at the same time to search for other activities which one would expect to be associated with potassium. It is the purpose of the present paper to report our results.

The activating particles used in these investigations were deuterons, alpha-particles and neutrons produced in the Berkeley cyclotron[4] under conditions already described.[3] The activities were measured with quartz fiber electroscopes of the type developed by Lauritsen.

II. POTASSIUM (42)

(a) Period

The samples used in determining the period of K^{42} were prepared either by deuteron or slow

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* 1851 Exhibition Scholar from McGill University, Montreal, Canada.

† Commonwealth Fund Fellow.

[1] Fermi, *et al.*, Proc. Roy. Soc. **A149**, 522 (1935).

[2] von Hevesy, Nature **135**, 96 (1935).

[3] Walke, Phys. Rev. **51**, 439 (1937).

[4] Lawrence and Cooksey, Phys. Rev. **50**, 1131 (1936).

neutron bombardment of potassium salts. The agreement between the results obtained by the two methods proves that the deuteron activation was due to the reaction

$$K^{41}+H^2\rightarrow K^{42}+H^1. \qquad (1)$$

After bombardment with 5.5 Mev deuterons the target material, either KCl or KF, was dissolved in water and potassium cobaltinitrite was precipitated. Fig. 1A shows the decay of the activity of such a precipitate. The decay of a sample of K_2CO_3 after irradiation with slow neutrons is shown in Fig. 1B. From such graphs we conclude that the half-life of K^{42} is 12.4±0.2 hours. In a thick target the yield of K^{42} in reaction (1) is of the order 2×10^7 deuterons per active atom. A weak gamma-ray accompanies the decay.

The energy spectrum of the electrons has already been determined by Kurie, Richardson and Paxton.[5]

(b) The formation of K^{42} from scandium

Hevesy and Levi[6] have reported the formation of K^{42} according to the reaction:

$$Sc^{45}+n^1\rightarrow K^{42}+He^4, \qquad (2)$$

in which scandium is bombarded with fast neutrons. They activated a sample of scandium oxide with a radon-beryllium source and after dissolving the irradiated oxide in HCl added sodium chloride, which was subsequently recovered by evaporation and ignition after the precipitation of scandium as hydroxide by carbonate free ammonia. The sodium chloride was found to decay with a period of 16 hours, this being ascribed to the presence of K^{42}.

In the present experiments a sample consisting of two grams of Sc_2O_3 (which had been shown by deuteron activation to be free from potassium) was bombarded for several hours with fast neutrons. It was then dissolved in HCl and a little KCl was added followed by perchloric acid and ethyl alcohol. The precipitated potassium perchlorate was found to be active decaying to half-value in 12.4±0.2 hours. The decay curve is shown in Fig. 1C. It is thus clear that the radioactive potassium isotope observed is K^{42} produced by reaction (2).

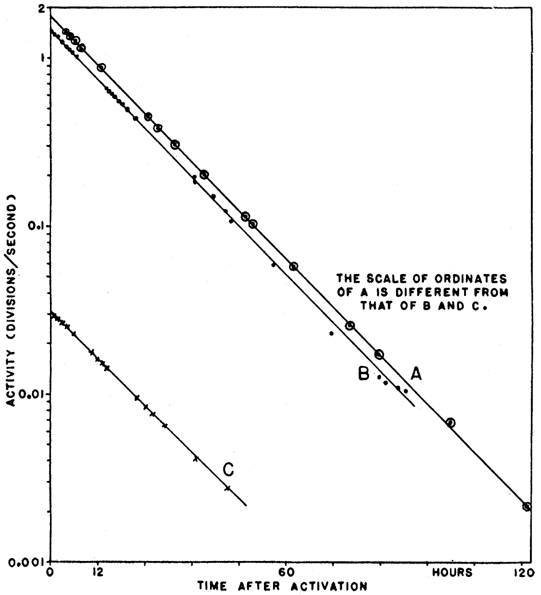

FIG. 1. Decay curves of K^{42} formed by different methods: (*A*) deuteron bombardment of potassium (as potassium fluoride); (*B*) slow neutron irradiation of potassium (as potassium carbonate); (*C*) fast neutron irradiation of scandium (as scandium oxide).

(c) The formation of K^{42} from calcium

Hevesy and Levi[7] have also reported the production of K^{42} by the transmutation:

$$Ca^{42}+n^1\rightarrow K^{42}+H^1, \qquad (3)$$

the half-life given being 16 hours.

In a previous repetition of their work[3] on calcium carbonate it was shown that the results obtained were consistent with the presence of a small amount of sodium or magnesium contamination as the weak activity observed decayed with the characteristic period of Na^{24}.

Recently, however, a very pure sample of calcium hydroxide, free from sodium and potassium, was strongly irradiated with fast neutrons for about ten hours. From the activated sample potassium was precipitated as perchlorate and was found to be weakly radioactive.

The experimental observations of its decay made during the first sixteen hours after separation from the calcium lie on a straight line with a half period of 12.5 hours. Measurements con-

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[5] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).

[6] Hevesy and Levi, Det. Kgl. Danske Videnskabernes Selskab Math-Fysiske Meddelelser **14**, 5 (1936).

[7] Hevesy and Levi, Nature **135**, 580 (1935).

tinued for three days, however, disclosed the presence of a very weak long period of undetermined value, which may well be due to contamination or less probably to a heavier isotope of potassium. However, the earlier portion of the decay curve suggests the presence of K^{42} and it, therefore, appears not unlikely that reaction (3) has been detected.

III. Fast Neutron Irradiation of Potassium

Those reactions which might be expected to take place when potassium is bombarded with fast neutrons are, in addition to that in which K^{42} is formed, as follows:

$$K^{39,\,40,\,41}+n^1\rightarrow A^{39,\,40,\,41}+H^1,$$
$$K^{39,\,40,\,41}+n^1\rightarrow Cl^{36,\,37,\,38}+He^4.$$

Of the isotopes which could thus be produced A^{40} and Cl^{37} are stable; A^{41} has the half-life of 110 minutes;[8] A^{39} is absent from the mass spectrum of argon and hence is probably unstable; and either Cl^{36} or Cl^{38} has a half-period 37.5 minutes.[9] In the present experiments KF, K_2CO_3, KNO_3 and K metal were irradiated with fast neutrons. The KNO_3 was stated to have not more than 0.001 percent chlorine contamination. The decay curves of the activities show the presence of several periods, including that of K^{42}. Such a curve is shown in Fig. 2. After correcting for the activity due to K^{42} a composite curve is obtained. When there is sufficient residual activity as in the example shown, the later points can be considered to lie on a straight line of half-life 110 minutes corresponding to A^{41}. This activity can be then extrapolated to zero time and subtracted, and after this has been done the resulting points lie on a straight line of half-life 37.5 minutes.[10]

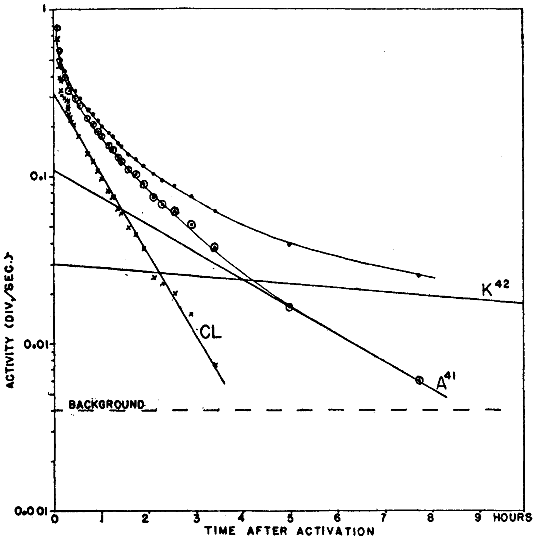

FIG. 2. The activity of potassium fluoride after irradiation with fast neutrons for 45 minutes. The sample was wrapped in cadmium and placed two or three cm behind the beryllium target, which was bombarded with about 15μa of deuterons. The original points are shown by dots. (Some of the early observations are omitted.) Observations later than any on the diagram enable the K^{42} line to be drawn. Subtraction of this from the original points yields the encircled points. Through the last two of these a line is drawn having a slope corresponding to a half-life of 110 minutes. This is subtracted and the resulting points are indicated by crosses. If these points are collinear the resolution is complete; and it will be seen that, except for the first few minutes (where, as explained in the text, the short period is due to O^{19} formed from the fluorine) they follow the line marked Cl which corresponds to a half-life of 37.5 minutes. Thus we may conclude that the total activity is due to K^{42}, A^{41} and active chlorine.

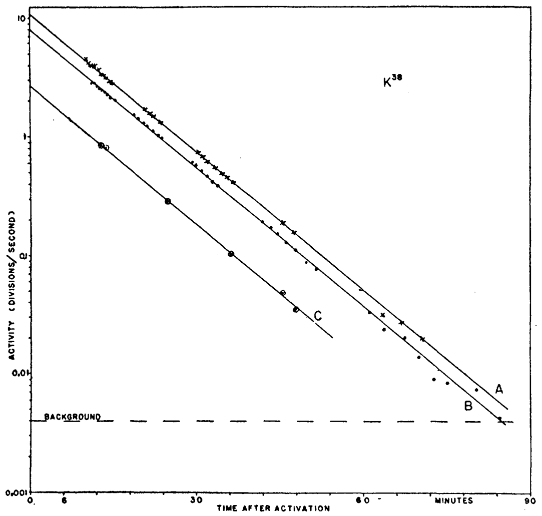

FIG. 3. Decay curves of K^{38}. *A* is the activity of potassium precipitated from lithium chloride after bombardment with 0.12μa of 11 Mev α-particles for 50 min. *B* is the activity of potassium precipitated from sodium chloride after bombardment with 0.1μa of 11 Mev α-particles for 50 min. *C* is the activity of potassium precipitated from lithium chloride after bombardment with 0.1μa of 11 Mev α-particles for 11 min.

In several cases part of the irradiated sample was dissolved in a dilute solution of potassium

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[8] Snell, Phys. Rev. **49**, 555 (1936).

[9] Unpublished. Slow neutron activation of $PbCl_2$ and NH_4Cl.

[10] The short period in Fig. 2 is of the order 1 minute and is probably due to O^{19} formed from F^{19} in the reaction:

$$F^{19}+n^1\rightarrow O^{19}+H^1.$$

The half-life of O^{19} is 40 sec. This short period was not found in K metal, K_2CO_3 or KNO_3.

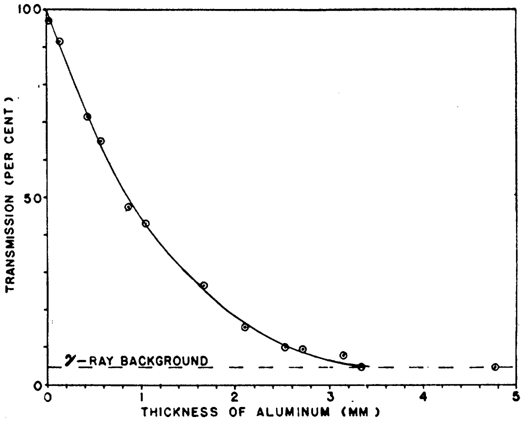

FIG. 4. Absorption in aluminum of the positrons from K^{38}. The upper limit is at 3.4 to 3.5 mm aluminum and corresponds to a maximum energy of 2 Mev.

chloride and the chlorine was precipitated by the addition of silver nitrate. The activity of the silver chloride was found to decay with a single half-life of 37.5 minutes. The magnitude of the initial activity agreed with that of the 37.5 minute period found by resolving the composite curve. These results justify the statement that the chlorine isotope of period 37.5 minutes and A^{41} are produced by irradiating potassium with fast neutrons. There is no evidence of the formation of A^{39}. However, this isotope would not have been detected if it had a short or a very long half-life; nor could it have been observed if its period were nearly equal to one of the known periods of the composite decay curve. Madsen[11] was unable to detect active chlorine in potassium after irradiation with fast neutrons and suggested that this indicated that Cl^{38} is the known active chlorine isotope. In view of the present detection of A^{41} and active chlorine and the failure to observe A^{39}, it is clear that Madsen's argument, based on relative abundances, is not valid.

IV. POTASSIUM(38)

(a) Alpha-particle bombardment of chlorine

The usual alpha-particle reactions in which the bombarding particle is absorbed by a nucleus and a proton or neutron emitted suggest that K^{38} will be produced by bombarding chlorine with alpha-particles according to the reaction:

$$Cl^{35}+He^4\rightarrow K^{38}+n^1;\quad K^{38}\rightarrow A^{38}+e^+$$

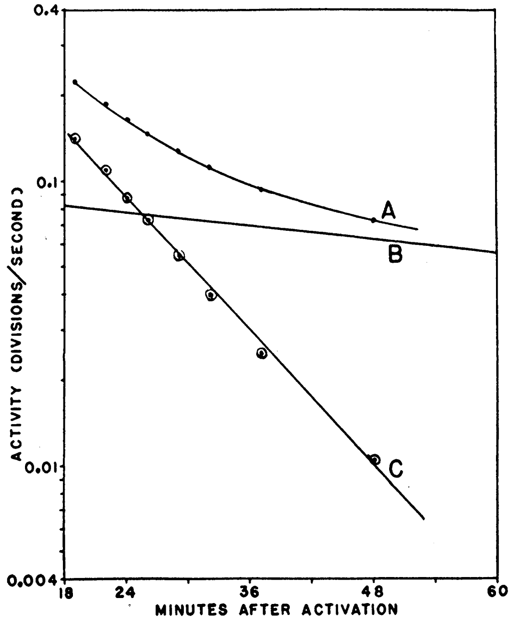

FIG. 5. Curve *A* is the activity of potassium perchlorate precipitated from a solution containing calcium which had been activated with deuterons. Some active scandium came down with the potassium and its activity, as obtained from later observations, is given by *B*. When the points of *A* are corrected by *B* the result is the line *C* corresponding to a half-life equal to that found for K^{38}; hence this isotope is produced by deuteron bombardment of calcium.

and that other argon and potassium isotopes formed will be stable. (We include K^{40} in this category.) Accordingly a search was made for this active potassium in lithium chloride bombarded with 11 Mev alpha-particles. After bombardment the lithium chloride was dissolved in a dilute solution of potassium chloride and the potassium was precipitated as potassium cobaltinitrite. The precipitate had a strong activity decaying to half-value in $7.7_5\pm0.1_5$ minutes as shown in Fig. 3. The particles emitted were positrons having a maximum energy as determined by Feather's rule from the thickness of aluminum required to stop them of 2 Mev. A gamma-ray was also present. The absorption curve in aluminum of the emitted radiations is shown in Fig. 4. Substitution of sodium chloride for the lithium chloride yielded the same isotope. The initial activity corresponds to 2×10^6 alpha-particles per active atom.

Pollard, Schultz and Brubaker[12] have observed the emission of neutrons from chlorine under

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[11] Madsen, Nature **138**, 722 (1936).

[12] Pollard, Schultz and Brubaker, Phys. Rev. **51**, 140 (1937).

bombardment with alpha-particles from Ra C and Th C′. They ascribe these to the formation of K^{40} from Cl^{37} thus:

$$Cl^{37}+He^4\rightarrow K^{40}+n^1.$$

In view of the present results, however, it seems highly probable that they were detecting the formation of both K^{38} and K^{40}.

(b) The formation of K^{38} from calcium

In a previous paper[3] results obtained by one of us in a study of the radioactivities induced in calcium by deuteron bombardment were reported. It was noted that a weak activity was observed in the potassium fraction separated chemically from the irradiated metal. It was suggested that this might be due to contamination, though it was thought, in view of the fact that the half-period did not agree with that of any well-known contaminant, that it might be due to K^{38} formed thus:

$$Ca^{40}+H^2\rightarrow K^{38}+He^4;\quad K^{38}\rightarrow A^{38}+e^+.$$

Following the production of K^{38} by bombarding chlorine with alpha-particles, a search was made for this isotope in irradiated calcium. It has a sufficiently short half-life to have been unobservable in the previous experiments on account of the time needed for the chemical separation adopted.

Calcium metal was, therefore, bombarded with deuterons for half an hour and, following solution in HCl and the addition of inactive KCl, potassium was precipitated by means of perchloric acid and ethyl alcohol. In consequence the precipitate was contaminated with radioactive scandium.[3] However, on correcting for this it was found that K^{38} was present, the decay curve corresponding to a half-period of 7.6 ± 0.2 minutes. This curve is reproduced in Fig. 5.

The decay of this precipitate was measured until its corrected intensity was less than the natural leak of the electroscope, but no evidence was obtained of the 12.4 hour period of K^{42}. The expected reaction

$$Ca^{44}+H^2\rightarrow K^{42}+He^4;\quad K^{42}\rightarrow Ca^{42}+e^-$$

would thus appear to be rather improbable.

V. CONCLUSION

In conclusion we wish to thank the staff of the Radiation Laboratory for their cooperation, and especially Professor E. O. Lawrence for his interest and encouragement. The investigation has been aided by grants to the laboratory from the Research Corporation, the Chemical Foundation and the Josiah Macy, Jr. Foundation.

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The Disintegration of High Energy Protons

G. NORDHEIM, L. W. NORDHEIM,
Purdue University, Lafayette, Indiana

J. R. OPPENHEIMER AND R. SERBER
University of California, Berkeley, California

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The coupling between light and heavy particles assumed in the Fermi theory of β-decay makes it possible for high energy protons in passing through matter to transfer a considerable fraction of their energy to electrons and neutrinos. If we suppose that this coupling is a maximum for relative energies of the light and heavy particles of the order $\hbar c/R$, with R the range of nuclear forces, and is small for much higher relative energies, the most important process which occurs, for sufficiently energetic protons, can be pictured as a sort of photodisintegration of the proton by the contracted Coulomb field of a passing nucleus, the proton changing into a neutron and emitting a positron and a neutrino. With a coupling of the type described, and of the magnitude required by the proton-neutron forces, processes involving more than one pair of light particles will be relatively rare. The cross section for the disintegration of a proton of energy E is found to be of the order

$$2\pi(\hbar/Mc)RZ^2\alpha^2\ln^2(E/Mc^2),$$

and is very small, even for heavy nuclei. The mean energy given to the positron per disintegration is of the order

$$2(\hbar c/R)(E/Mc^2)/\ln(E/Mc^2).$$

The positrons emitted in these disintegrations can account in order of magnitude for the incidence of showers observed under thick absorbers.