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THE β-RAY SPECTRUM OF RADIO-HELIUM

BY

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When beryllium is bombarded with fast neutrons (of energies greater than about 2 million electron volts), a radioactive isotope of helium, ${}^{6}_{2}\mathrm{He}$, is formed by the process[1,2]:

$$ {}^{9}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{6}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}. \qquad (1) $$

The ${}^{6}_{2}\mathrm{He}$ disintegrates in the following way:

$$ {}^{6}_{2}\mathrm{He} \rightarrow {}^{6}_{3}\mathrm{Li} + \mathrm{e}^{-} \qquad (2) $$

the half-value period being 0.8 ± 0.1 sec.[3] As already pointed out in a preliminary note[4] the results of an investigation of the energy distribution of the β-particles from the radio-helium support the interpretation of the processes of its formation and disintegration indicated by the above formulae. This is discussed more completely at the end of the present paper which also gives a full description of the experiments, in which a special technique had to be used owing to the short half-value period of the radio-helium.

Experimental arrangement.

We used a Wilson expansion chamber constructed by Dr. J. C. JACOBSEN; the arrangement is shown in fig. 1. The

[1] T. BJERGE, Nature **138**, 400 (1936).

[2] T. BJERGE, Studier over kunstig Radioaktivitet med kort Halveringstid, Dissertation, Copenhagen (1938).

[3] T. BJERGE, loc. cit., see also NAHMIAS and WALEN, J. de Phys. et le Rad., **8**, 153 (1937).

[4] T. BJERGE and K. J. BROSTRØM, Nature **138**, 400 (1936).

top glass plate, which has a diameter of 15 cm., rests on a glass ring of 5 cm. height, and the movable bottom is a rubber plate R. The volume beneath R, which contains air or another gas at an adjustable pressure, can be connected suddenly to the evacuated vessel A through a ground cone valve; this makes R fall down upon the brass plate B under the expansion of the gas in the chamber above R. The top plate, the ring and the rubber plate are held

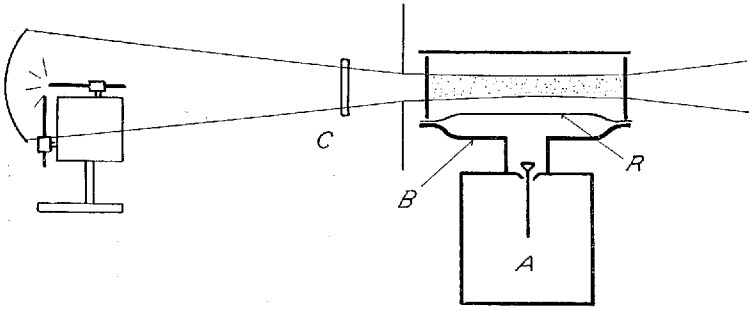

Fig. 1.

firmly against the brass plate B, and the system is made gas-tight by means of rubber washers. The rubber plate R is stiffened by an aluminium (or ebonite) plate, which covers the central part of R so that only a narrow region along the circumference remains soft; this is done by making R of two sheets fused together with the stiff plate between them. Thus the bottom of the expansion chamber is always approximately plane.

The expansion ratio, i. e. the ratio of the volume of the expansion chamber after and before an expansion, can be adjusted by adjusting the pressure in the gas beneath R before the expansion. Air saturated with ether and alcohol vapour was used as gas in the chamber, the bottom of R being covered with a layer of collodium.

The source of light was the positive electrode of a carbon arc with copper-plated "effect" carbons (Siemens Koh-I-Noor, 8 mm.). The beam was concentrated by a spherical mirror as shown in fig. 1. C is a cylindrical lens spreading the light beam in the horizontal plane. The chamber was illuminated for 0.2 sec. just after expansion by opening a shutter and at the same time short-circuiting the series-resistance of the arc (burning on 220 volts D. C.), thus allowing a current of 100 to 200 amperes to pass.

The tracks were photographed by two cameras with double anastigmatic objectives 1 : 4.5, and 12.5 cm. focal length. They were placed 80 cm. above the expansion chamber with a mutual lateral distance of 7.5 cm. Under these circumstances the reproduction will be sufficiently sharp for tracks of any altitude within the illuminated part of the chamber, which has a height of 2 cm. The film material used was mostly Agfa Isochrom or Isopan.

Fig. 2 shows the arrangement for activating the beryllium and bringing it quickly into the expansion chamber. The beryllium layer S was stuck to the outside of a small light brass cylinder by means of shellac. This cylinder was attached to an arm A movable around an axis B and held by a small electromagnet m_1 in such a position that S surrounded the neutron source N (2—300 millicuries of radon mixed vith beryllium powder). When the current in m_1 was broken a spiral spring working on the shaft B would make the arm move so as to bring the beryllium-cylinder into the thin-walled (0.05 mm.) brass tube C inserted in the top plate of the chamber (C had 1.5 cm. diameter and 5 cm. depth); in this position it was held by the electromagnet m_2. The movement was also used to release a falling weight which in due course short-circuited the series-

resistance of the carbon-arc, opened and closed the shutter, and caused the expansion of the chamber.

The β-rays emitted from the beryllium layer were bent into circular paths by a magnetic field produced by two coils M arranged symmetrically above and below the illu-

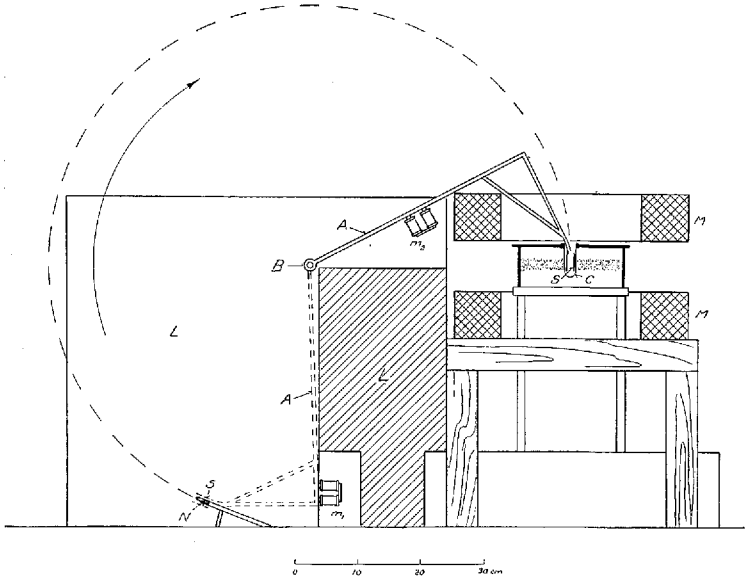

Fig. 2.

minated part of the chamber in approximately the "Helmholtz positions". Each coil had 1200 turns of 1.4 mm. enamelled copper wire wound on a holder of 2 mm. copper plate; the lower coil was supported by a wooden stand, the upper coil was spaced from the lower one by wooden blocks. The magnetic field produced by a 10 amp. current through the coils was measured with a test coil and ballistic galvanometer, the Wilson chamber being removed; it was practically circular symmetric. In Fig. 3 the field is plotted against the distance from the center for a current of 20 amperes.

As a magnetic field of 1500 Ørsteds is suitable for the determination of β-particle energies of a few million e-volts, it was necessary to pass a current of 20 amperes through the coils. Each coil had a resistance of 10 Ohms, so that the total effect developed was about 8 kilowatts; thus it was only possible to feed the coils for a very short time

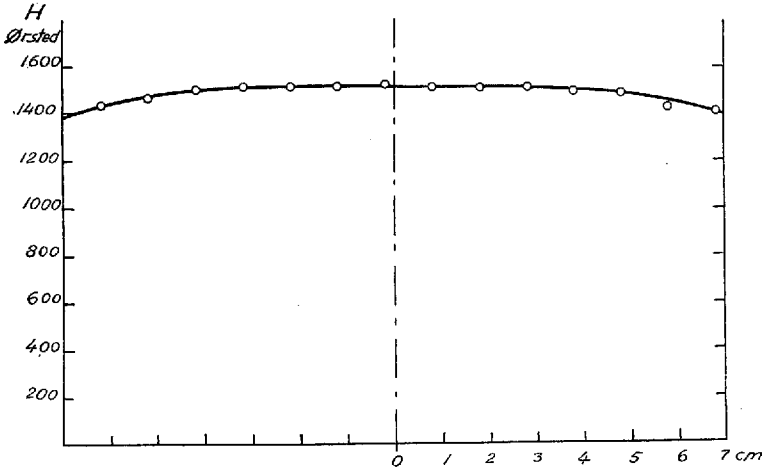

Fig. 3.

at every expansion, because the heating would otherwise very soon disturb the functioning of the Wilson chamber. The switch for the current in the coils was therefore mechanically coupled to the switch starting the movement of the arm, which brought the beryllium sample from the neutron source into the chamber in 0.4 sec. In the course of this time the magnetic field would reach its maximum value within 0.5 per cent, as can be calculated from the self-inductance (1.5 henries) and resistance. After expansion the current was broken by the last switch released by the falling weight mentioned above, and in order to minimize the spark the coils (which were in series) were constantly

shunted with 40 Ohms. In this way the current only flowed for 0.7 sec. at each expansion; further the lower part of the chamber was cooled by surrounding it with a copper-plate cylinder to which was soldered a copper tube cooled by a stream of water, and the top part of the chamber could be air-cooled by a fan. When photographs were taken only at one-minute intervals the chamber would work satisfactorily.

At each expansion the current in the coils was determined; the ammeter used did not come to rest within 0.7 sec., but was adjusted as a kind of "ballistic" instrument.

In order to shield the chamber from the γ-rays from the neutron source the latter was surrounded with blocks of lead (L in fig. 2) except for a slit to allow the passage of the moving arm.

The evaluation of the photographs.

A part of the photographs were, of course, spoiled for various reasons such as fog in the chamber, insufficient illumination, etc. On the more successful 1 or 2 tracks, on an average, are seen starting from the cylinder in the middle of the chamber, as shown by the examples in fig. 4 and 5. The track in fig. 4 was produced by a negative elektron; this is also the case for the track A of fig. 5, but for the track B, which is a closed circle, it is not possible to decide the sign of the electron. The total number of tracks found on the photographs was 120; most of these could unambiguously be ascribed to negative electrons, no one could unambiguously be ascribed to a positive electron, and the number of those which from their appearance

could be either positive or negative was not greater than could be expected if all the particles emitted were negative electrons.

Thus the radioactive substance created by bombardment of beryllium with neutrons (the helium isotope of mass 6) emits negative electrons and there is no sign that it should also emit positive electrons.

The radius of curvature of the tracks was measured

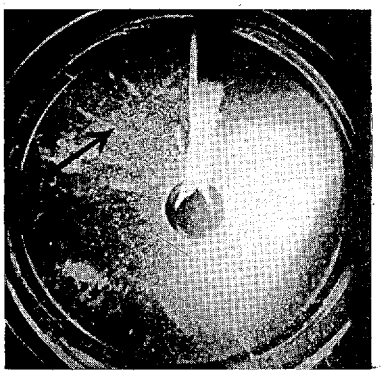

Fig. 4.

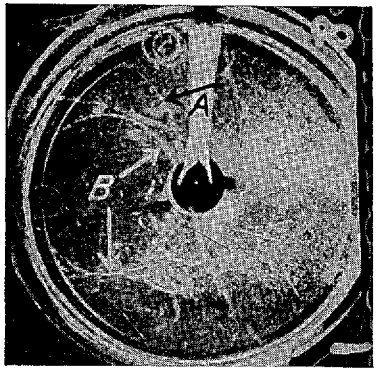

Fig. 5.

by direct comparison of the photograph with a set of concentric circles photographed by the same camera at the same distance. This actually gives the projection of the path on a horizontal plane, but the error introduced by neglecting the vertical component of the velocity will in general not amount to more than one or two per cent of the energy and as the uncertainty in the determination of the energy in our experiments was greater than this, the error was not important. Although in this way the more troublesome method of reprojecting the stereoscopic pictures was not used, the two different aspects of the tracks very often facilitated the evaluation.

The radius of curvature ϱ was multiplied with the corres-

ponding value for the magnetic field H (taken from the curve of fig. 3 using the proper value of the current), and $H\varrho$ was corrected as described below. From $H\varrho$ the energy was deduced, and the 120 particles were divided into energy groups with intervals of 0.5 million e-volts (m. e. v.). In fig. 6 the number of particles in each group is plotted against the energy in m. e. v.

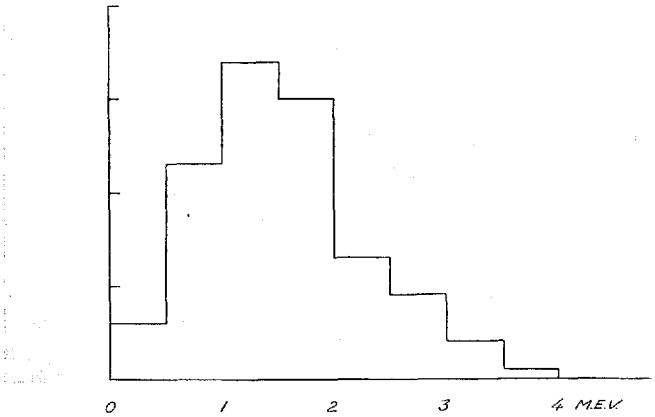

Fig. 6.

The upper limit of the energies is presumably situated between 3.5 and 4.0 m. e. v. The most energetic particle found had 3.6 m. e. v.; on account of the scarcity of particles with energies near the upper limit it is reasonable to assume that the latter is lying somewhat above the maximum energy found for any particle. On the other hand the uncertainty in the determination of the energies of the individual particles, which is shown below to be about 10 per cent, will make the energy spectrum blurred, thus tending to give an increase in the apparent upper energy. Taking these facts into account and judging from the general appearance of fig. 6, we consider the most probable value of the upper energy limit for the β-particles in question to be 3.7 ± 0.5 m. e. v.

Corrections and Uncertainty.

Before reaching the expansion chamber the β-particles have to pass the thin-walled brass cylinder and part of the beryllium layer, and this gives rise to a loss of velocity. The diminution of the quantity $H\varrho$ can be calculated from the formula

$$\frac{\delta(H\varrho)}{\sigma}\cdot\beta^3 = 5.10\cdot\frac{Z}{A}(96.1-\log_e\frac{A}{Z}+\log_e\sigma-\log_e\frac{1-\beta^2}{\beta^2}-\beta^2-2C)^1$$

where σ is the thickness of the layer expressed in cg./cm.^{2}, Z the atomic number, A the atomic weight, β the velocity expressed as a fraction of the velocity of light, and C is a quantity depending on the atomic structure. Putting $C = 41$ this formula seems to be in fairly good agreement with experimental results. For the brass cylinder $\sigma = 5$ cg./cm.^{2}, which gives $\delta_1(H\varrho) = 250$ or 300 Ørsteds·cm. for the β-particle velocities in question. For the beryllium layer $\sigma = 12$ cg./cm.^{2}; on an average the electrons will pass through half of this layer, i. e. 6 cg./cm.^{2}, which gives $\delta_2(H\varrho) = 300 \pm 300$ Ørsteds·cm. The total correction, taking into account that the particles have in general an oblique path through the layers, amounts to about

$$\delta(H\varrho) = 800 \pm 400 \text{ Ørsteds·cm.}$$

The uncertainty 400 Ørsteds·cm. in $H\varrho$ corresponds to an uncertainty in the energy $\Delta_1 E = 0.12$ m. e. v. for particles of energy greater than 1 m. e. v. For slower β-particles $\Delta_1 E$ is smaller.

For a helical path the tangent of which makes an angle α with the horizontal plane, the value found for $H\varrho$ in

[1] Rutherford, Chadwick and Ellis, Radiations from radioactive substances, Cambridge (1930), p. 439.

the way described above gives the horizontal component of the momentum, and the total momentum could be obtained by division with $\cos\alpha$. Energy and momentum being approximately proportional for $E > 1$ m. e. v., the energies found ought to be divided by $\cos\alpha$. With the given dimensions of the illuminated part of the chamber this correction will, however, only in exceptional cases amount to more than a few per cent; considering the fairly large uncertainty in the determination of $H\varrho$, we have, therefore, not carried out the troublesome stereoscopic determination of the paths but left out the correction for their obliquity as unimportant.

Another correction which we have neglected is the correction for the decrease of the magnetic field near the edge of the chamber (see fig. 3). For a path passing this zone the mean radius of curvature (this is what can be measured) will be slightly increased, but the deviation rarely exceeds a few per cent, and the error introduced by neglecting this will counteract the error from neglecting the obliquity. The total effect of leaving out these two corrections will be an uncertainty $\Delta_2 E$ in the energy determination amounting to 2 or 3 per cent.

Besides $\Delta_1 E$ and $\Delta_2 E$ there are the following two sources of uncertainty in the energy determination:

1. The scattering of the β-particles. With air in the chamber the corresponding uncertainty in the mean radius of curvature will, according to genenal experience, amount to 5 or 10 per cent. This gives $\Delta_3 E = 5$ or 10 per cent (for energies > 1 m. e. v.). This is the principal source of uncertainty; it can be considerably reduced by using hydrogen in the chamber instead of air, but the illumination we could obtain was only just sufficient with air

in the chamber and would have been insufficient with hydrogen.

2. The personal factor in evaluating the radius of curvature. Both of us measured all the tracks independently and the results were the same within an uncertainty $\Delta_4 E$ of a few per cent.

Thus the total uncertainty $\Delta_1 E + \ldots \Delta_4 E$ in the energy determination will be about 10 per cent, for the slowest particles perhaps somewhat more.

Discussion.

The maximum energy 3.5 ± 0.5 m. e. v. of the β-particles emitted in process (2) permits calculation of the mass of the ${}^{6}_{2}\mathrm{He}$ atom. Using the atomic masses from table LXXIII in "Nuclear Physics C" by LIVINGSTON and BETHE[1] one has ${}^{6}_{3}\mathrm{Li} = 6.0169 \pm 0.0002$, and hence by reaction (2):

$$ {}^{6}_{2}\mathrm{He} = 6.0169 + 0.0039 = 6.0208 \pm 0.0005. $$

This gives for the energy release in reaction (1):

$$ 9.0150 + 1.0090 - (6.0208 + 4.0039) = -0.0007 \text{ mass units} $$

or

$$ -0.65 \pm 0.5 \text{ m. e. v.} $$

This result is in agreement with the following two facts:

1° — Process (1) is insensitive to surrounding the beryllium sample and neutron source with paraffin, ɔ: slow neutrons are not active in the process.

[1] M. STANLEY LIVINGSTON and H. A. BETHE, Rev. Mod. Phys., **9**, 245 (1937).

2° — OLIPHANT has found that neutrons of energy down to c. 2 m. e. v. are able to produce the radioactivity in question[1]. Such neutrons are emitted in the process

$$ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

in the backward direction from the bombarding beam of deuterons, when the energy of the latter is 0.4 m. e. v. If the incident neutron in (1) has a kinetic energy of c. 2 m. e. v. there will only be 1.2 ± 0.5 m. e. v. as kinetic energy to share between the resulting particles ${}^{4}_{2}\mathrm{He}$ and ${}^{6}_{2}\mathrm{He}$; this however, corresponds to a sufficient mutual repulsion for the particles to penetrate their mutual potential barrier practically instantanously even if the lower value is chosen[2].

This numerical agreement thus supports the interpretation contained in (1) and (2) of the processes of formation and disintegration of a radioactive body when beryllium is bombarded with neutrons. Taking into account the fact that the active body is a gas there are only two other possibilities of an interpretation, viz.:

$$ {}^{9}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{6}_{3}\mathrm{Li} + {}^{4}_{1}\mathrm{H} \qquad (3) $$

with a radioactive hydrogen isotope disintegrating as follows:

$$ {}^{4}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + \mathrm{e}^{-}, \qquad (4) $$

and

$$ {}^{9}_{4}\mathrm{Be} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{5}_{2}\mathrm{He} + {}^{5}_{2}\mathrm{He} \qquad (5) $$

followed by the radioactive disintegration

[1] M. L. E. OLIPHANT, Copenhagen Conference, June 1936 (unpublished).

[2] Compare the remarks on penetrability of potential barriers for α-particles contained in the paper by T. BJERGE, Proc. Roy. Soc., **164**, 243 (1938).

$$^{5}_{2}\mathrm{He} \rightarrow {}^{5}_{3}\mathrm{Li} + \mathrm{e}^{-} \qquad (6)$$

The first of these possibilities can be excluded because the radioactive gas can be conducted through hot copper oxide and afterwards through an air-trap cooled with solid carbon dioxide and alcohol without losing its activity[1]. The second possibility, expressed by (5) and (6), would involve that the energy difference between the $^{5}_{2}$He and the $^{5}_{2}$Li in question should be 3.7 ± 0.5 m. e. v. Now $^{5}_{2}$He might be formed from $^{4}_{2}$He by addition of a neutron, $^{5}_{3}$Li by addition of a proton, and the binding forces are probably small and not very different, so that the energy difference could hardly be much more than the 0.8 m. e. v. due to the mass difference between a neutron and a hydrogen atom. Thus the present experiments should exclude the processes (5) and (6) as an explanation of the radioactivity in question, and only the explanation given by (1) and (2) remains.

This argument we consider to be fairly safe, but as recent experiments have thrown new light upon the existence of a helium isotope of mass 5, a brief discussion of these experiments and their bearing on the present problem may have some interest.

WILLIAMS, SHEPHERD and HAXBY[2] have given evidence for the process

$$^{7}_{3}\mathrm{Li} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{5}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \qquad (7)$$

The mass of the $^{5}_{2}$He determined by means of the range of the homogeneous group of α-particles is found to be 5.0137; this is more than the mass of $^{4}_{2}$He plus a neutron,

[1] T. BJERGE, Studier over kunstig Radioaktivitet med kort Halveringstid, Dissertation, Copenhagen (1938).

[2] J. H. WILLIAMS, W. G. SHEPHERD and R. O. HAXBY, Phys. Rev. **52** 390 (1937).

and accordingly the $^5_2$He splits up into these particles after a mean life of about $5 \cdot 10^{-20}$ seconds (as found from the uncertainty in the energy of the $^4_2$He-group), i. e. long before it can reach a detecting apparatus.

Joliot, and Zlotowski[1], on the other hand, find that on bombardment of deuterium with polonium α-particles protons are released which they explain by the reaction

$$^4_2\mathrm{He} + {}^2_1\mathrm{H} \rightarrow {}^5_2\mathrm{He} + {}^1_1\mathrm{H} \qquad (8)$$

From the proton tracks in a Wilson-chamber the mass of $^5_2$He is found to be 5.0106 which is less than that of $^4_2$He plus a neutron, thus indicating a stable $^5_2$He. One might perhaps assume that in process (7) the $^5_2$He is left in an excited state of about 3 m. e. v. and thus reconcile the results of Williams, Shepherd and Haxby with those of Joliot anb Zlotowski.

Neither of these two $^5_2$He nuclei could, however, be identical with the β-radioactive helium isotope produced by bombarding beryllium with neutrons. The $^5_2$He of Williams, Shepherd and Haxby only exists for about 10^{-20} seconds and is thus excluded. The $^5_2$He of Joliot and Zlotowski has the mass 5.0106 ± 0.0005; if we suppose this $^5_2$He to split up in a process like (6) with the maximum β-ray energy of 3.7 ± 0.5 m. e. v. the resulting $^5_3$Li atom would have the mass 5.0067 ± 0.0007. This would mean, however, that $^6_3$Li, which has the mass 6.0169, would have more mass than $^5_3$Li plus a neutron and would thus be unstable. As a matter of fact, $^6_3$Li is quite stable, and a stable $^5_3$Li has not been found.

Also in the light of the new evidence of the existence

[1] F. Joliot and J. Zlotowski, Comptes rendus **206**, 1256 (1938).

of $^{5}_{2}$He we may, therefore, conclude that the only possibility of explaining that a radioactive helium isotope is produced by bombarding beryllium with fast neutrons is the one expressed by reactions (1) and (2).

The present work was carried out at the Institute of theoretical Physics of the University of Copenhagen. We wish to express our thanks to Professor N. BOHR for his kind interest in the work and to Dr. J. C. JACOBSEN for the loan of the Wilson chamber. Our thanks are also due to the Radium Institute of Copenhagen for the gift of the emanation.

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