DET KGL. DANSKE VIDENSKABERNES SELSKAB
MATEMATISK-FYSISKE MEDDELELSER, BIND XXIII, NR. 12

DEDICATED TO PROFESSOR NIELS BOHR ON THE OCCASION OF HIS 60TH BIRTHDAY

ON THE RECOIL OF THE NUCLEUS IN BETA-DECAY

BY

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KØBENHAVN
I KOMMISSION HOS EJNAR MUNKSGAARD
1945

Printed in Denmark
Bianco Lunos Bogtrykkeri

Introduction.

It has long been known that in a β-transformation the energies of individual β-particles vary over a wide range (1), from zero to a well defined upper limit (2) characteristic of the element in question. Experiments performed by ELLIS and WOOSTER (3) and by MEITNER and ORTHMANN (4) showed that the observed variation in energy of the β-particles cannot be ascribed to any secondary process outside the nucleus. Since both the mother and the daughter substances must be assumed to have a definite energy content, which is the same for the individual atoms, the difference in energy between the individual β-particles apparently shows a lack in conservation of energy in a β-transformation. PAULI then suggested that in a β-transformation two particles are emitted and that the available energy, which may be identified with the upper limit of energy for the β-particles, is shared between them. The new particle, *i. e.* the neutrino, must have a small rest mass and zero charge. With the help of a number of additional assumptions, FERMI (5) developed a theory which in a general way accounted for the experimental results including the energy distribution of the β-particles and the empirical relation between lifetime and transformation energy.

The direct experimental evidence for the emission of neutrinos is entirely negative (6), (7), no indication having been obtained of any ionization which could be attributed to such particles in their passage through matter. Hence, the only possibility remaining is to look for an effect on the emitting nucleus itself. The question here is, whether the recoil of the nucleus in a β-transformation corresponds to the momentum gained from the β-particle alone or to the resultant momentum of the β-particle

and the neutrino. Considerable experimental difficulties may here be expected in view of the smallness of the recoil energy.

In experiments on the β-recoil from ThB, DONAT and PHILIPP (8) found an efficiency amounting to a few per cent of that obtained in α-recoil. This low efficiency, which may reasonably be attributed to spurious surface effects, may illustrate the difficulties which are to be expected from an attempt to determine the recoil energy. If only a few per cent of the recoil atoms were able to leave the surface, a quantitative determination of the energy of the individual recoil atoms, if it could be carried out, would probably be of minor interest.

LEIPUNSKI (9) was the first to make an attempt to measure the recoil energy in a β-transformation. He determined the number of recoil atoms from ^{11}C which were able to pass through a retarding electric field, thus supposing that they were charged. Without exact knowledge of the experimental conditions it is difficult to decide whether this has been the case. It should generally be expected that the recoil atoms leave the surface as neutral atoms if the radioactive material rests on the surface of a metal. The same applies to LEIPUNSKI's experiments where a negative ion of ^{11}B was formed by the emission of the β-particle.

The disturbing influence of surface effects was avoided by CRANE and HALPERN (10) who worked with ^{38}Cl in a cloud chamber. They observed that frequently a cluster of droplets was formed at the beginning of a track, a phenomenon which they ascribed to ionization and dissociation of the gas in the chamber by the recoil atom. In similar experiments with ^{32}P, where the maximum energy of the β-particles is much smaller than for ^{38}Cl, no such clusters could be found. A direct determination of the recoil energy from the number of droplets was difficult, since the energy expanded per droplet is not known with certainty and may probably be considerably smaller than the energy expanded per ion by fast particles. CRANE and HALPERN interpreted their results as an indication of the existence of a neutrino. The main support for this interpretation was the observation that clusters of many droplets at low energy of the β-particles were found just as frequently as at high energy; this

would not have been the case if only the β-particle was emitted, conservation of momentum being assumed.

ALVAREZ, HELMHOLTZ and WRIGHT (11) exposed *in vacuo* a clean surface to a vacuum distilled layer of cadmium with period 6.7 hours formed by the Ag (d, 2n) Cd reaction. On this clean surface the daughter substance formed by K-capture from the cadmium was found. The passage of the active silver from one surface to another was ascribed either to a recoil following K capture (emission of an X-ray or a neutrino) or to a change in the surface binding of the atom during K capture.

Experimental Method.

For a quantitative determination of the recoil energy the active element should be a gas at a pressure which is so low that the mean free path is large compared to the dimensions of the vessel. Then the recoil atoms must necessarily be charged before their collision with the walls of the vessel, and the recoil energy can be determined by a retarding electric field. If the daughter substance formed in the transformation is radioactive, the number of recoil atoms passing through the retarding field can be simply determined.

In Table I, the active isotopes of krypton and xenon which are formed by the fission of uranium or otherwise are listed as far as they have been identified at present (12), (13), (14). Some constants in the table were redetermined in this work. As it results also from the table, GLASOE and STEIGMAN (15) have found that the active deposit from the gases consists entirely of ^{88}Rb, if a sample of uranium is left for about 3 hours after irradiation with neutrons before the inert gases formed by fission are driven off. The figures in Table I further show that, if the inert gases are collected about 5 minutes after a short irradiation, the active deposit collected during the next 5 minutes will mainly consist of ^{89}Rb. In this case, the separation is not as complete as with ^{88}Rb, since both ^{88}Rb and ^{138}Cs will be present to some extent. Unfortunately, the decay constants of ^{88}Rb and ^{89}Rb are nearly identical, so that a determination of the amount of ^{89}Rb

Table 1.

$$^{81}\mathrm{Kr} \xrightarrow[34.5\ \mathrm{h.}]{0.4\ \mathrm{MeV}} \mathrm{Br}$$

$$^{82}\mathrm{Kr} \xrightarrow[113\ \mathrm{m.}]{\gamma = 0.5\ \mathrm{MeV}} \mathrm{Kr}$$

$$^{85}\mathrm{Kr} \xrightarrow[4.6\ \mathrm{h.}]{0.8\ \mathrm{MeV}} \mathrm{Rb}$$

$$^{87}\mathrm{Kr} \xrightarrow[75\ \mathrm{m.}]{4\ \mathrm{MeV}} \mathrm{Rb}$$

$$^{88}\mathrm{Kr} \xrightarrow[2.7\ \mathrm{h.}]{2.4\ \mathrm{MeV}} \mathrm{Rb} \xrightarrow[17.8\ \mathrm{m.}]{5\ \mathrm{MeV}} \mathrm{Sr}$$

$$^{89}\mathrm{Kr} \xrightarrow[\sim 3\ \mathrm{m.}]{4.5\ \mathrm{MeV}} \mathrm{Rb} \xrightarrow[15.4\ \mathrm{m.}]{3.8\ \mathrm{MeV}} \mathrm{Sr} \xrightarrow[55\ \mathrm{d.}]{1.5\ \mathrm{MeV}} \mathrm{Y}$$

. . . . . .

$$^{133}\mathrm{Xe} \xrightarrow[5\ \mathrm{d.}]{0.3\ \mathrm{MeV}} \mathrm{Cs}$$

$$^{135}_{135}\mathrm{Xe} \xrightarrow[9.4\ \mathrm{h.}]{10\ \mathrm{m.}} \mathrm{Cs} \xrightarrow{?}$$

$$^{137}\mathrm{Xe} \xrightarrow[3.8\ \mathrm{m.}]{4\ \mathrm{MeV}} \mathrm{Cs}\ ?$$

$$^{138}\mathrm{Xe} \xrightarrow[18\ \mathrm{m.}]{?} \mathrm{Cs} \xrightarrow[33\ \mathrm{m.}]{?} \mathrm{Ba}$$

$$^{139}\mathrm{Xe} \xrightarrow[45\ \mathrm{s.}]{?} \mathrm{Cs} \xrightarrow[7\ \mathrm{m.}]{?} \mathrm{Ba} \xrightarrow[87\ \mathrm{m.}]{1\ \mathrm{MeV}} \mathrm{La}.$$

present can only be performed if the amount of ^{89}Sr (half period = 55 days) can be measured; this, however, can only be done with fairly strong sources. For these reasons, it was decided to work with ^{88}Kr, although a few experiments have also been made with ^{89}Kr.

The experimental method is schematically demonstrated in Fig. 1. A metal box with one end consisting of a wire gauze was placed in a vessel containing the inert gases obtained from uranium fission. Two metal plates, I and II, which were placed at equal distances from the wire gauze and the opposite end of the box, were kept at a positive potential relative to the box. After

the inert gases had been kept in the apparatus for a suitable time, the amount of active deposit collected on I and II was measured. The difference between these activities was due to recoil atoms starting from the interior of the box and having sufficient energy to surmount the potential difference between the box and the plates. When the potential difference between the box and the plates was varied in separate experiments, the energy distribution of the recoil atoms could be determined.

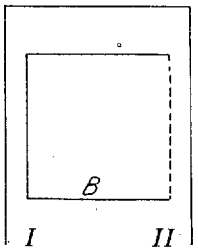

Fig. 1.

By this method the energy of a β-particle cannot be determined simultaneously with that of the corresponding recoil atom; it is possible only to compare the energy distribution of the recoil atoms with that of the β-particles. The limitations of the method will be discussed later in connection with the results.

The main part of the apparatus (Fig. 2) was a rectangular box B_1 made of sheet copper, one side of the box being closed by a brass wire gauze. The box was divided into a number of smaller partitions by means of cross-walls, the purpose of which was to limit the free paths of the recoil atoms and thus to reduce the influence of the residual gases in the apparatus. The box with the wire gauze was placed, electrically insulated, inside a second box B_2 also made of sheet copper. The active deposit from the inert gases was collected on aluminium foils, F_1 and F_2, attached to the inner sides of B_2. For measurements of the activity of the deposit the aluminium foils were removed from the apparatus and wrapped around a cylindrical counter.

The difference between the activities of the aluminium foils, which determines the number of recoil atoms with energy higher than the potential difference between the outer and the inner box, was of course proportional to the total amount of inert gas present in the apparatus. For the comparison of different experiments, this latter quantity which varied somewhat from one experiment to another, had to be determined in some arbitrary unit. For this purpose the arrangement in the lower part of Fig. 2 was used.

A circular brass disc D was placed in the bottom wall of a

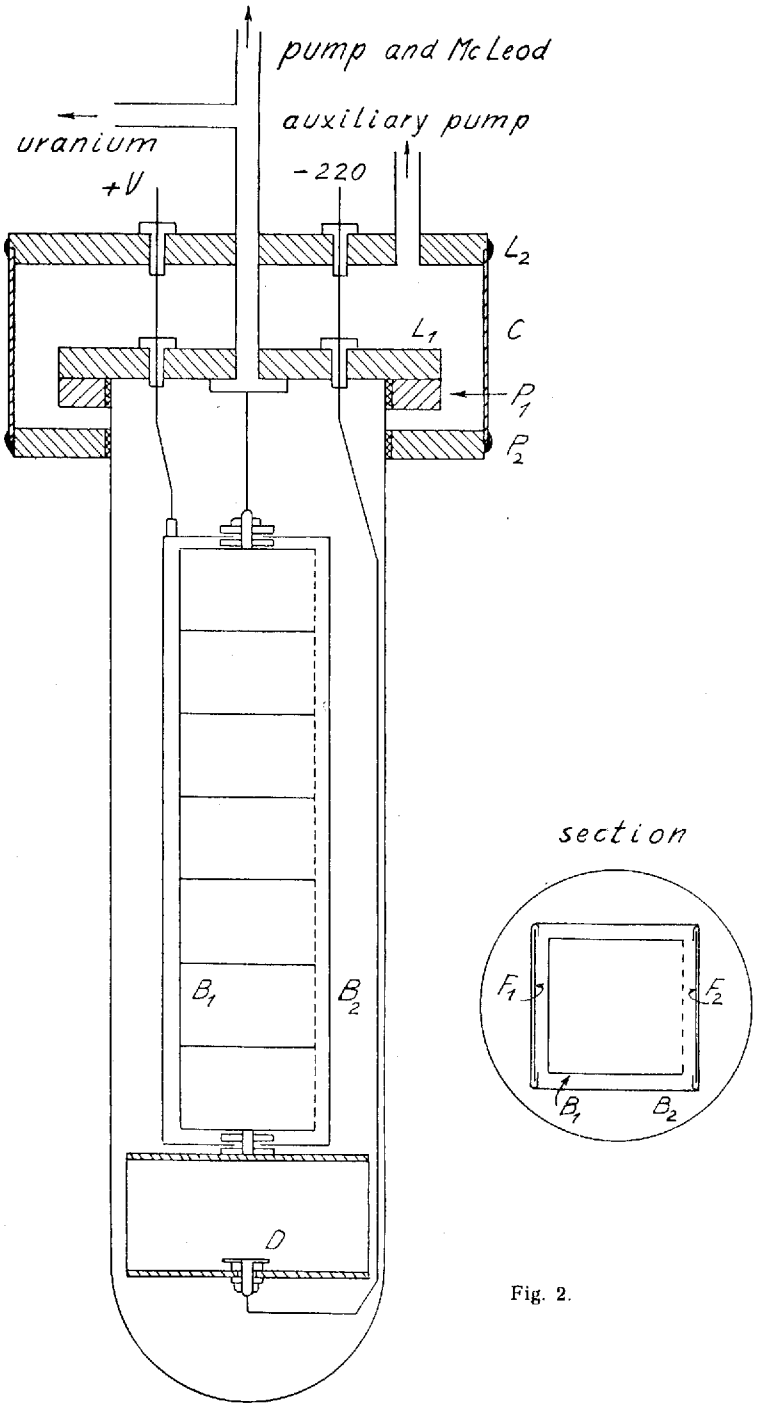
pump and McLeod
auxiliary pump
uranium
+V
-220
L_2
C
L_1
P_1
P_2
B_1
B_2
D
section
F_1
F_2
B_1
B_2

Fig. 2.

brass cylinder, electrically insulated and kept at a potential of —220 volts relative to the cylinder. The activity of the disc, determined under standard conditions,, was used as a measure of the total amount of ^{88}Kr present. The constancy of the counters used was checked before and after each measurement by irradiation with a γ-ray source placed in a standard position.

The metal parts of the apparatus were housed in a pyrex tube, diameter 8 cm. and length 30 cm., provided with brass flange and lid. The wires leading to the different parts of the apparatus were brought in through insulating plugs in the lid. It was found that the wax joints gave rise to a slight increase in pressure of about 10^{-4} mm. per hour. In order to eliminate this, an arrangement with a double lid was used (Fig. 2). Two brass flanges, P_1 and P_2, were waxed to the pyrex tube with sealing wax, the inner lid, L_1, rested directly on P_1. Connection between P_2 and the outer lid L_2 was made by a brass cylinder C fitting looscly around P_2, the joints being tightened by Apiezon Q. The tube leading to the pump, was hard soldered through both L_1 and L_2; the space between L_1 and L_2 was connected to a separate pump. To dismount the apparatus after air had been let in, it was only necessary to remove C. With this arrangement, the rise in pressure during an experiment, which usually lasted about 45 minutes, was less than 10^{-5} mm. The uranium was placed in a glass bulb which was connected to the main part of the apparatus by a long glass tube, so that the uranium could be brought in between the coils of the cyclotron magnet. In the glass tube a U-tube and a stopcock H were placed. The apparatus was evacuated by a single-stage mercury diffusion pump and an oil pump. The pressure was read on a McLeod gauge.

The uranium was used in an emanating form obtained by precipitating a mixture of $UO_2(NO_3)_2$ and $FeCl_3$ with ammonia; after washing, the precipitate was dried at room temperature and powdered. In the state in which the uranium was used in the experiments, it gave off large amounts of water vapour and other gases when placed under vacuum. When the pyrex tube containing the main part of the apparatus was cooled in liquid air, most of these gases were condensed, a residual pressure of about 10^{-4} to 10^{-3} mm. remaining. As far as could be determined, this

residual pressure was proportional to the number of neutrons used in the irradiation, the other conditions being constant. This observation indicates that the gases causing the residual pressure were produced by decomposition of the uranium precipitate by neutrons and thus gives some idea of the chemical nature of these gases, which is of interest in connection with a discussion of the possibilities of the recoil atoms losing energy during their passage through the apparatus. The condensation of the gases actually was carried out in two steps, the U-tube being cooled in solid carbon dioxide and the pyrex tube in liquid air. The gases passing through the U-tube, in which mainly the water vapour was condensed, had a pressure of roughly 0.1 mm. which, as mentioned above, was reduced to 10^{-4} to 10^{-3} mm. by cooling the pyrex tube in liquid air. When the condensation was made in one step, cooling also the U-tube in liquid air, it was found that a considerable part of the krypton gas was retained by the gases condensed on the walls of the U-tube, the activities obtained being much larger after condensation in two steps.

The general course of an experiment was as follows. After the apparatus had been assembled and evacuated, the uranium was irradiated with neutrons from the cyclotron for 15 to 30 minutes. About 3 hours after the irradiation, Dewar beakers with solid carbon dioxide and liquid air were placed around the U-tube and the pyrex tube containing the main part of the apparatus, and the stopcock H was opened. The copper box B_2, inside which the active deposit from the krypton gas was collected, was closed on all sides except for a hole in the bottom, so that the gaseous mixture before entering B_2 had to pass along the wall of the pyrex tube. On a single occasion, the pressure inside the box was further controlled, while the gases were let in, by placing a hot wire gauge consisting of a 4 μ platinum wire, length 3 cm., inside the box. The wire was placed as one arm in a Wheatstone bridge, and the changes in resistance were recorded by a galvanometer during the admission of the gases. No increase in pressure beyond 10^{-3} mm. could be observed.

The stopcock H was left open for about 1 minute and the apparatus was then left to itself for 30 minutes. Subsequently, the gaseous mixture was removed by the pump before air was let in, the voltage difference between B_1 and B_2 being maintained.

The pumping had to be performed rather thoroughly, because the deposit collected with air in the apparatus was distributed in a way completely different from that obtained at low pressure. A number of experiments were actually wasted before the importance of this precaution was realized.

The amount of ^{88}Rb on the aluminium foils was determined by wrapping the foils around cylindrical counters and counting

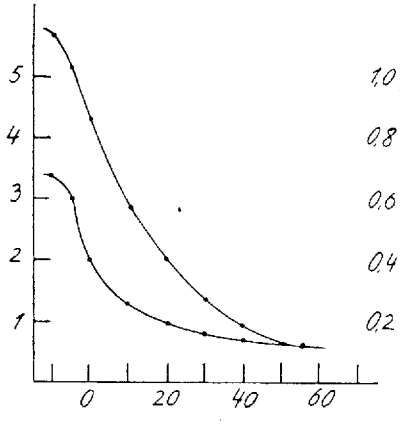

Fig. 3a.

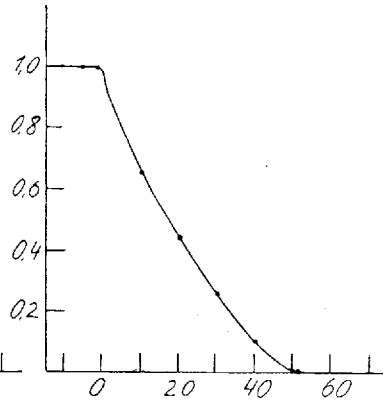

Fig. 3b.

Abscissa: retarding potential X in volts. Ordinate: Fig. 3a, activities of collecting foils. Fig. 3b, fraction of recoil atoms with energy greater than X.

for 36 minutes. The activity of the brass disc D was measured simultaneously by a third counter. In Fig. 3a are shown the amounts of ^{88}Rb on the aluminium foils, referred to a standard activity of D, as a function of the voltage. The total number of counts in each experiment was about 1000 times the figures given as ordinate, so that the statistical errors are fairly small. Other measurements with higher voltages showed that up to 900 volts the activities of the foils were equal and decreased steadily with increasing voltage.

Fig. 3b shows the difference between the curves in Fig. 3a, the difference at zero voltage being taken as unity. This, then, shows the fraction of the total number of recoil atoms starting from the interior of the copper box and having sufficient energy to surmount the potential difference in question.

From Fig. 3a the upper limit of the energy of the recoil atoms from ^{88}Kr is found to be 51.5 ± 2 eV. Before this result can be discussed in relation to the β- and γ-rays emitted from ^{88}Kr, a number of possible sources of error must be taken into consideration.

Experimental Errors.

The upper limit of energy of the recoil atoms can be determined rather accurately; a further result would be the distribution of energy for the recoil atoms, obtained by differentiating the curve in Fig. 3b. Due to an instrumental error, which will now be discussed, the measured energy distribution must be subjected to a considerable correction.

Suppose a positively charged particle starts from a point within a homogeneous electric field between two parallel electrodes with kinetic energy E in a direction making an angle θ with the direction of the field. The path of the particle will be a parabola, and it is easily shown that, if the particle is just able to reach the positive electrode, the potential difference between its starting point and the positive electrode will be $X = E \cos^2\theta$. If N particles start from a point within the electric field in all directions, the number of particles starting in directions making angles between θ and $\theta + d\theta$ with the direction of the electric field is $N \sin\theta d\theta$. If the energy is determined by variation of the field, as is the case in the present experiment, then, since $dX = -2E \sin\theta \cos\theta d\theta$, an apparent energy distribution will be found, in which the number of particles with energy between limits X and $X + dX$ is

$$N(X)\,dX = \frac{N}{2}\,\frac{1}{\sqrt{EX}}\,dX \quad \text{(Fig. 4, curve I).}$$

In the experimental arrangement the space inside B_1 may to a good approximation be considered field – free (cf. later), so that the present considerations apply to the passage of the recoil atoms through the field between the wire gauze and the aluminium foil. If the recoil atoms are regarded as being divided into homo-

geneous groups with energy E, where E lies between O and a maximum value, then in the measured energy distribution each of these groups will be spread out into a band of energies ranging from O to E, as shown in Fig. 4. It results from this that in the measured energy distribution the number of recoil atoms with small energies has been much exaggerated.

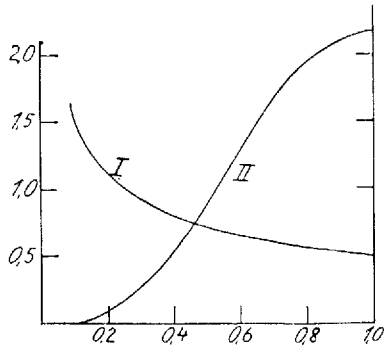

Fig. 4.

The distribution curve I in Fig. 4 is changed considerably when the geometry of the apparatus is taken into account. Fig. 5, which is a two-dimensional representation of the main part of the apparatus, shows that recoil atoms starting in a direction which makes an angle θ with the direction of the electric field can only be emitted from part of the space inside B_1 if they are to reach the collecting foil. The passage of the recoil atoms through the wire gauze acts in the same direction because the free opening of the wire gauze decreases to zero when θ approaches $\frac{\pi}{2}$. As a result, the measured energy distribution for a homogeneous group of recoil atoms cannot be represented by curve I in Fig. 4, but is more correctly represented by curve II. The lower part of this curve is fixed by the finite thickness of the wires of the gauze, the free opening of the gauze actually becoming zero for an angle θ somewhat less than $\frac{\pi}{2}$. A further estimate of the shape of the curve was obtained from a rough determination of that part of the space inside B_1 from where recoil atoms can be emitted, forming an angle θ with the direction of the electric field.

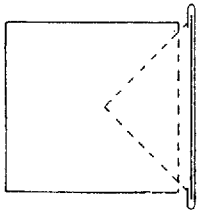
Fig. 5.

An accurate determination of the distribution to be expected is rendered extremely difficult by the irregularities of the electric field at the edges of the copper box. Even if the distribution was known accurately, a correction of the results shown in Fig. 3b could hardly be carried out unambiguously. The only method

would be to assume a suitable energy distribution for the recoil atoms and to compare the resulting corrected distribution with the experimental results. In the light of a later discussion it may, however, be unnecessary to perform the correction in question. For the moment, it suffices to state that

1) the upper limit for the energy of the recoil atoms is unaffected,
2) the true energy distribution of the recoil atoms should be represented by a curve which, in Fig. 3b, would lie everywhere above the measured points.

In comparison with the correction which has been discussed, other possible sources of error are of minor importance. Among these, the influence of the gas in the apparatus should primarily be considered. As mentioned above, during the collection of ^{88}Rb the pressure was 10^{-3} to 10^{-4} mm., measured with a McLeod gauge. The gases were probably formed by decomposition of the uranium hydroxide by neutrons and may thus be expected to have small molecular weights (hydrogen, oxygen, etc.), while no heavy molecules were present. In a determination of the density of the gas, it must be taken into account that the pressure was measured at room temperature while the pyrex tube with the main part of the apparatus was cooled in liquid air. As is well known, a difference in temperature between two communicating vessels is equivalent to a difference in the number of molecules per cc. in the ratio of the square root of the absolute temperature. A measurement of the temperature of the copper box by a thermojunction showed that the cooling of the copper box took place so slowly that in the experiments its temperature probably never has been below 0° C. This difference from the temperature of the McLeod gauge is so small that the influence on the density of the gas can be neglected.

The energy losses which occur when ions of the alkaline metals pass through gases have been studied by various observers. It has been generally found that inelastic collisions are rare; thus, only energy losses due to elastic collisions need to be considered. To determine the loss of energy in a collision between a recoil atom and a molecule of the gas, let M and V be the mass and the velocity of the recoil atom and m the mass of the

molecule, which is supposed to be at rest before the collision. The centre of gravity of the system moves with the velocity $\frac{M}{M+m} \cdot V$; relative to the centre of gravity the two molecules move with velocities $\frac{m}{M+m} \cdot V$ and $\frac{M}{M+m} \cdot V$. In Fig. 6, which represents the two molecules at the moment of impact, let these latter quantities be given by AB and DE; after the impact, the velocities relative to the centre of gravity will be BC and EF. If A'B is the velocity of the centre of gravity, the velocity of M after the impact is A'C, or

$$\overline{A'C}^2 = V_1^2 = \left[\frac{M^2+m^2}{(M+m)^2} - \frac{2Mm}{(M+m)^2}\cos 2\varphi\right] \cdot V^2.$$

The probability that φ is within limits $d\varphi$ is proportional to $\sin 2\varphi \, d\varphi$, and the mean value of V_1^2 is

$$V_1^2 = \frac{\int V_1^2 \sin 2\varphi \, d\varphi}{\int \sin 2\varphi \, d\varphi} = \frac{M^2+m^2}{(M+m)^2} \cdot V^2.$$

Finally, the mean value for the loss of energy is

$$\frac{1}{2} M (V^2 - V_1^2) = \frac{1}{2} MV^2 \cdot \frac{2Mm}{(M+m)^2}$$

or half that occurring in a head-on collision. For a rubidium ion colliding with a molecule of oxygen the mean loss of energy is thus 26 %.

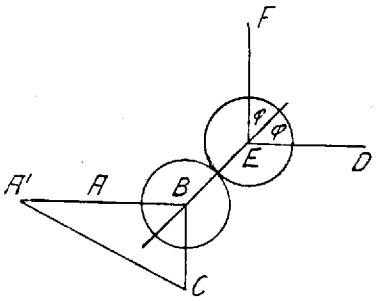

Fig. 6.

The evidence as regards the number of collisions suffered by alkaline ions during their passage through gases is somewhat conflicting. SCHMIDT (17) has determined the mean free path for K^+ ions with energies 25 and 200 volts in a large number of gases. For the gases which come into consideration here, SCHMIDT found values for the mean free path ranging from 8 cm. to 24 cm. referred to a pressure of 10^{-3} mm. In similar experiments,

DURBIN (18) found values which generally were about twice as large. If x is the mean distance traversed by a recoil atom in the apparatus, and λ is the mean free path, the probability that a recoil atom will traverse the distance x without collision is $e^{-\frac{x}{\lambda}}$. With $x = 2$ cm., which roughly is the mean distance traversed by a recoil atom before it collides with a wall, and $\lambda \sim 20$ cm., this is about 0.9, *i. e.* 10 % of the recoil atoms would lose energy due to the residual gas in the apparatus. Considering the somewhat discordant evidence concerning the value of the mean free path, and since the chemical composition of the gaseous mixture in question is practically unknown, the figures found for the energy loss can only be taken as a rough approximation. The effect of an energy loss of this order of magnitude would be to shift slightly downwards the curve in Fig. 3b; this effect, however, would probably be only just detectable. The result of these considerations is in good agreement with the experience gained from our experiments. Measurements with the same retarding potential and with pressures ranging between 10^{-3} and 10^{-4} mm. actually gave always the same results.

A further effect to be considered is the collision of the recoil atoms with the metal walls of the apparatus. Up to now it has been assumed that the rubidium atoms always remain attached to the wall after the first impact. If this was not the case, the atoms which leave the wall would probably be neutral and thus would give rise to a more or less uniform distribution of ^{88}Rb over the walls. Such an effect, if present, might change the observed energy distribution of the recoil atoms, especially near the upper limit of energy.

In the experiments, it was found that the activity of the foils continued to decrease with increasing retarding potentials up to 900 volts, the activities of the two foils being equal. This shows clearly that the contribution due to neutral recoil atoms is insignificant.

It should further be mentioned here that a very similar result was obtained by COMPTON and his co-workers (13) for the accomodation coefficient of ions. From purely classical conceptions, COMPTON concluded that, if an ion with mass M collides with a wall built up from atoms with masses m, the ion will always

remain attached to the wall, if $M > m$. In COMPTON's experiments, the ions had energies of the order of 100 volts and, accordingly, his results should apply directly to the present case. It is somewhat uncertain how low the energy of the ion can be before the forces between the atoms of the wall come into play. Recoil atoms with an energy of the order of 1 Volt may probably be present, in which case the accomodation coefficient may be below 1. However this may be, the fact that the activities of the collecting foils continued to decrease with increasing retarding potential shows definitely that the number of neutral recoil atoms must have been small.

In obtaining the energy distribution in Fig. 3b as the difference between the activities of the two collecting foils, it was supposed that the space inside the copper box was field-free. In order to test this assumption more closely, a model of the apparatus was made in 6-fold enlargement and the field inside the box was mapped out by a small flame connected to an electrometer. Inside the wire gauze, in front of one of the openings, the potential was about 2 % of the potential of the collecting electrode, and decreased nearly linearly with the distance from the gauze. This means that the potential difference between the collecting foil and the interior of the box is slightly smaller than that between the foil and the wire gauze or, in other words, that the observed energy limit of the recoil atoms is somewhat too high. The correction is, however, so small that it hardly needs consider ation.

β- and γ-rays from ^{88}Kr.

The upper limit of energy for the β-particles from ^{88}Kr has been determined by WEIL (19) to 2.3 MeV. by an expansion chamber in a magnetic field. The β-spectrum was found as the difference between the spectrum obtained from ^{88}Kr in equilibrium with ^{88}Rb and that obtained from ^{88}Rb alone. In his note, WEIL does not state how he has eliminated the β-particles from ^{87}Kr (T = 75 min.), which probably have been present, and the β-particles from ^{85}Kr (T = 4.6 hours) which certainly have been present in his experiments. To remove any doubt as to which of the krypton isotopes the upper limit of 2.3 MeV. belongs,

WEIL's determination was checked by absorption measurements. The result obtained for ^{88}Kr was 2.4 MeV. and is thus in good agreement with WEIL's value. Since the measurements, however, were complicated by the presence of both ^{85}Kr, ^{87}Kr and ^{88}Rb, the work will be considered in greater detail.

An approximate determination of the relative amounts of ^{85}Kr, ^{87}Kr and ^{88}Kr present in the gaseous mixture from uranium can be obtained from FLAMMERSFELD's (20) results for the amounts of different mass numbers formed in the fission process, on the supposition that the total amount of the mass numbers 85, 87 and 88 formed during the fission process has been transformed into isotopes of krypton at the time when the measurements were made. This must be approximately the case, since all the isobars with nuclear charges smaller than 36 have short periods. With this assumption, FLAMMERSFELD's figures give for the relative activities of ^{85}Kr, ^{87}Kr and ^{88}Kr after a short irradiation the ratio 0.39:1.9:1.0. If the gaseous mixture is left for 15 hours, the ratio is changed into $1{,}9:2{,}0\cdot10^{-2}:1{,}0$, so that now the mixture contains mainly ^{85}Kr and ^{88}Kr. As ^{85}Kr has an upper energy limit of 0.8 MeV., its β-particles can be absorbed completely by 0.3 g./cm.^{2} of aluminium. The activity due to ^{88}Rb, the daughter substance from ^{88}Kr which has a very penetrating β-radiation, was determined by observations of the growth in activity of ^{88}Kr freed from Rb.

The arrangement used for the irradiation of the uranium was similar to that employed in the main experiment, except that the gases were removed from the uranium by a Toepler pump and stored over mercury in a glass crucible. A U-tube in the pump line was cooled by solid CO_2 to remove water vapour. The gases were pumped off immediately after the irradiation and left in the glass crucible for 15 hours. Subsequently, the gases were transferred to a cylindrical brass cell with a thin aluminium window, which was placed below a counter. A cotton plug in the connecting tube served to retain any rubidium which might be carried along together with the gas. With an aluminium absorber of suitable thickness ($>$ 0.3 g./cm.^{2}) placed above the cell, the rise in activity due to the formation of ^{88}Rb was followed, the measurements being continued for about 1 hour. From this rise, the activity at the moment when the gas was let into the

cell could be determined. The thickness of the absorber being more than 0.3 g./cm.^{2}, this initial activity was due to ^{88}Kr alone. The measurements were performed with a number of different absorbers, different experiments being compared by measuring the activity of ^{88}Kr + ^{88}Rb in equilibrium through a standard absorber.

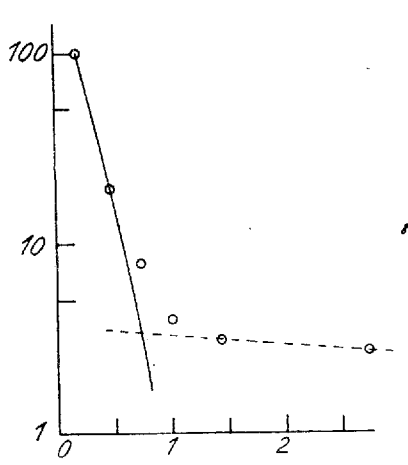

Fig. 7 a.

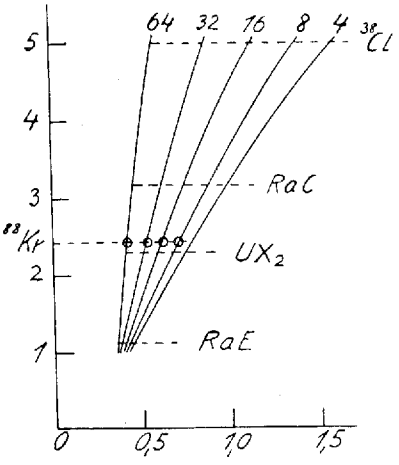

Fig. 7 b.

Abscissa: thickness of absorber in g Al per cm^2. Ordinate: Fig. 7a number of β-particles from ^{88}Kr, Fig. 7b upper limit of energy in MeV.

The results are shown in Fig. 7 a, where the activity of ^{88}Kr measured through an aluminium absorber, thickness 0.3 g./cm.^{2}, has been put equal to 100. The absorption curve for the β-particles (full curve) was obtained by subtracting the γ-ray activity (dotted line) from the measured activities. The measurements show that the range of the β-particles in aluminium is about 1.1 g./cm.^{2}, but the existence of a γ-radiation makes an exact determination of the range difficult. Therefore, an attempt was made to obtain the range by means of an interpolation method.

For this purpose, absorption curves for the β-particles from ^{38}Cl, RaC, UX_2, and RaE were measured, using the same arrangement as with ^{88}Kr. The activity measured through an aluminium absorber, thickness 0.3 g./cm.^{2}, was taken as unity. In Fig. 7 b the curves marked 64, 32, etc. were obtained by deter-

mining for each element mentioned the thickness of absorber which gave an activity of 0.64, 0.32, etc. The points for ^{88}Kr were found in the same way from the absorption curve in Fig. 7 a. These points lie on a horizontal line, giving for the upper limit of energy the value of 2.43 MeV. It is doubtful, however, whether the result is as accurate as might appear from the number of figures which can be read from the curves. Although the method consists in an interpolation between absorption curves for elements for which the upper limit of energy has been fairly well determined, the difference in shape of the β-spectra due to the emission of γ-rays might probably affect the result. On the other hand, the smoothness of the curves in Fig. 7 b indicates that the complexity of the β-spectra cannot be of great influence, probably because the absorbers used transmit only the high-energy part of the β-spectra, for which the shape remains almost unaffected by the presence of a γ-radiation. For the later discussion, the upper limit of energy will be taken as 2.4 MeV; the agreement with WEIL's result is satisfactory.

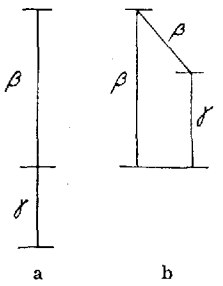

Fig. 8.

An investigation of the γ-rays from ^{88}Kr is complicated by the presence of ^{87}Kr and ^{88}Rb which both emit γ-rays. As already shown in connection with the measurements of the β-spectrum, the influence of ^{87}Kr could be sufficiently eliminated by performing the measurements on sources which had been left for about 15 hours after the irradiation. The relative amount of ^{85}Kr actually increases at the same time, but fortunately, this element does not emit any or at least only a weak γ-radiation.

The main problem to be considered in relation to the energy of the recoil atoms is whether the emission of a β-particle with energy 2.4 MeV. leads to the ground state of ^{88}Rb, in which case the level scheme might be represented as in Fig. 8 b or, if it is followed by a γ-radiation, as in Fig. 8 a. A distinction between these possibilities can be obtained by a determination of the number of β-γ-coincidences. If the β-spectrum is simple (level scheme Fig. 8 a), the number of coincidences per β-particle is independent of the energy of the β-particle and will thus remain constant when absorbers are placed in the path of the β-particle

while, for a complex β-spectrum, the number of β-γ-coincidences under the same circumstances will decrease.

In the measurements on γ-rays, the cell which had been used for the absorption measurements was placed between two counters. One of the counters recorded the β-particles, the other the γ-radiation. The β-counter was provided with a thin mica window, the γ-counter was screened by 2 mm. of lead; aluminium absorbers could be placed between the cell and the β-counter.

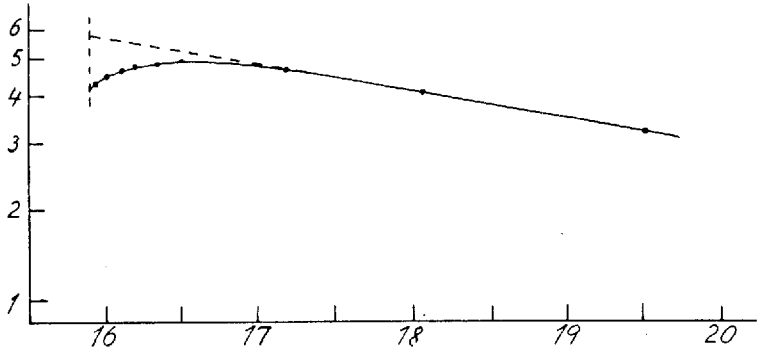

Fig. 9.

Abscissa: time in hours after irradiation. Ordinate: number of β-particles from $^{85}Kr + {}^{88}Kr + {}^{88}Rb$.

The counters were connected to a Rossi stage to record β-γ-coincidences.

As in the experiments described previously, the number of β-particles increased for about an hour due to the formation of ^{88}Rb, and then decreased (Fig. 9). In the present case, the rise in β-activity was relatively small since, at the beginning of the experiment, the β-activity was due both to ^{88}Kr and ^{85}Kr. The γ-activity remains nearly constant for about 30 minutes, then decreasing with a period of 2.7 hours. From the particular shape of the decay curve, the relative intensities of the γ-rays from ^{88}Kr and ^{88}Rb can be determined approximately. This, however, is of minor interest for the present problem, since the number of β-particles and β-γ-coincidences due to ^{88}Rb alone can be determined directly. The amount of ^{88}Rb present was determined as the difference between the number of counts obtained by extrapolating the decay curve for the gaseous mixture in equilibrium

with ^{88}Rb backwards to the moment when the mixture was let into the cell, and the number of counts from the gas alone (Fig. 9).

The counting of β-γ-coincidences was commenced when the gas was let into the cell and was continued for about 4 hours. It was to be expected that, due to the γ-rays from ^{88}Rb, an increase in the number of coincidences would occur together with the growth of ^{88}Rb. A quantitative determination of the increase was, however, difficult in view of the small number of coincidences which could be obtained with the sources available. The number of coincidences from ^{88}Rb alone was determined in a separate experiment, in which the same cell as had been used in the main experiment was activated with ^{88}Rb, the gaseous mixture being removed before the measurements were made. Some uncertainty still remains concerning the correction for the presence of ^{88}Rb, since indications were found that the location of ^{88}Rb on the inner wall of the cell was not the same in different experiments.

Table 2, which refers to the same experiment as Fig. 9, gives the number of counts per minute obtained with a source of ^{85}Kr + ^{88}Kr + ^{88}Rb in equilibrium and the correction in the number of β-γ-coincidences due to ^{88}Rb. The amount of ^{88}Rb (1400 counts per minute, without absorber) was found from the decay curve in Fig. 9.

Table 2.

Absorber	^{85}Kr + ^{88}Kr + ^{88}Rb			^{88}Rb	Difference
	β	γ	β-γ-coinc.	β-γ-coinc.	
0 g./cm² Al.....	5600	32	1.4 ± 0.2	0.33 ± 0.1	1.1
100 —	2380	32	0.41 ± 0.06	0.22 ± 0.06	0.2
200 —	1450	32	0.05 ± 0.05	0.09 ± 0.05	~0

The figures in the last column of Table 2 show that the number of β-γ-coincidences decreases rapidly with increasing absorber thickness and has practically disappeared with an absorber of 0.2 g./cm.². The reduction in the number of β-particles from ^{88}Kr due to this absorber is unknown, since the absorption could only be determined for absorbers with thicknesses greater

than 0.3 g./cm.²Al. If, however, the β-spectrum of ^{88}Kr was elementary (level scheme of the type in Fig. 8 a), about 40 per cent of the β-particles would be transmitted through an absorber of 0.2 g./cm.². This is quite incompatible with the observed decrease in the number of coincidences. It may thus be concluded that the transformation, in which a β-particle with energy 2.4 MeV. is emitted, leads to the ground state of ^{88}Rb.

This result is supported by more indirect evidence. Actually, a transformation energy of 2.4 MeV. for ^{88}Kr, which has an even number of protons and an even number of neutrons, is surprisingly high. From the formulae given by BOHR and WHEELER (18) for the energy content in nuclei a value of about 1.5 MeV. ensues, depending somewhat on the choice of the constants. Hence, the conclusion is obtained that the emission of γ-rays from ^{88}Kr does not change the upper limit of energy of the recoil atoms; the energy distribution is, however, changed in the direction of an increasing number of recoil atoms with small energies due to the complexity of the β-spectrum. This evidence cannot be traced further, since the details of the level scheme in Fig. 8 have not been determined. A detailed knowledge of the level scheme would, however, not be of much interest so long as the correction for the change in energy distribution due to the passage of the recoil atoms in oblique directions through the retarding field cannot be evaluated quantitatively.

Discussion.

If a β-particle with kinetic energy E_β is emitted from a nucleus with mass M, the recoil energy X is determined from

$$X_\beta \cdot 2Mc^2 = E_\beta^2 + E_\beta \cdot 2mc^2,$$

or, with M = 88,

$$X_\beta = 6.10\ E_\beta^2 + 6.24\ E_{\beta_1} \ldots\ldots \quad (1)$$

where X_β is expressed in eV, and E_β in MeV. For a neutrino with zero rest mass and kinetic energy E_ν, the recoil energy is

$$X_\nu = 6.10 \cdot E_\nu^2 \ldots\ldots \quad (2)$$

in the same units as in (1). For $E_\beta = 2.4$ MeV., (1) gives $X_\beta = 50$ eV. in close agreement with the measured value. This shows that, if a neutrino is emitted together with a β-particle of maximum energy, the kinetic energy of the neutrino must be small, or that, apart from the rest mass of the electron and the neutrino, the energy release in a β-transformation is determined by the upper limit of energy of the β-spectrum.

This has usually been assumed. The experimental evidence, however, which has mainly been derived from the branch products of the radioactive series, is rather conflicting, especially in regard of the energy emitted in the form of γ-rays (25), (26).

In view of the estimated errors in the measurements of the recoil energy and of the upper limit of energy of the β-spectrum, the largest possible difference between the measured value of X_β and that obtained from (1) may be fixed at $\Delta X = 2$ eV.; this value sets a limit to the energy of a neutrino emitted together with a β-particle with the maximum energy. If p, p_β, and p_ν are the momenta of the recoil atom, the β-particle, and the neutrino, respectively, then $p = p_\beta + p_\nu$, if the electron and the neutrino are emitted in the same direction. This point, however, will be discussed later. Since $p^2 = 2MX$, we have

$$2\,Mc^2X = \left[\sqrt{E_\beta^2 + 2\,mc^2\,E_\beta} + E_\nu\right]^2, \text{ or approximately}$$

$$X = 6\,(E_\beta + E_\beta^2) + 6\,E_\nu^2 + 12\,E_\nu\sqrt{E_\beta + E_\beta^2}$$

with the same units as in (1), and finally

$$\Delta X = 6\,E_\nu^2 + 12\,E_\nu\sqrt{E_\beta + E_\beta^2} \sim 6\,E_\nu^2 + 34\,E_\nu.$$

For $\Delta X = 2$ eV., this gives $E_\nu \sim 0.06$ MeV.

The agreement between the measured and the calculated values of the recoil energy actually is much better than assumed here. The value for X_β found from (1), corresponding to $E_\beta = 2.43$ MeV., is 51.2 eV., while the measured value is 51.5 eV. In view of the errors to be expected, it appears appropriate to consider such a close agreement fortuitous.

The evidence for or against the emission of a neutrino must be obtained from the energy distribution of the recoil atoms. If

no neutrino is emitted, the energy distribution of the recoil atoms is simply obtained from the β-spectrum. The Fermi distribution is given by

$$W(p)dp = \text{const. } p^2 \left[\sqrt{m^2c^2 + p_m^2} - \sqrt{m^2c^2 + p^2}\right]^2 dp, \quad (3)$$

where $W(p)dp$ is the number of β-particles with momentum between limits dp, and pm is the upper limit of p. With the kinetic energy E_β as independent variable, the expression changes into

$$W(E_\beta)\,dE_\beta = \text{const.} \cdot (E_\beta + mc^2)(E_{\beta m} - E_\beta)^2 \sqrt{E_\beta^2 + 2mc^2 E_\beta}\, dE_\beta, \quad (4)$$

where $E_{\beta m}$ is the upper limit of E_β. If momentum is conserved during the emission of the β-particle, and no neutrino is emitted, we have $p^2 = 2MX$, and the energy distribution of the recoil atoms is given by

$$W(X_\beta)\,dx_\beta = \text{const.} \sqrt{X_\beta}\left[\sqrt{m^2c^2 + 2MX_{\beta m}} - \sqrt{m^2c^2 + 2MX_\beta}\right]^2 dX_\beta, \quad (5)$$

where $X_{\beta m}$ is the upper limit of X_β.

The constant is determined by the condition $\int W(X_\beta)\,dX_\beta = 1$. To compare the distribution given by (5) with the experimental results, a curve showing $W(X_\beta)$ as a function of X_β was constructed (Fig. 10). From this differential distribution the probability that a recoil atom has an energy greater than X_β or $\int W(X_\beta)\,dX_\beta$ was obtained by numerical integration. The result is shown in Fig. 11, curve III, where curve I is the experimentally determined energy distribution from Fig. 3b. As shown previously, the curve representing the true energy distribution, if it could be determined, would lie everywhere above the measured points. The result is thus clearly that the number of recoil atoms with energies near the upper limit is much larger than can be accounted for by recoil from the β-particles alone.

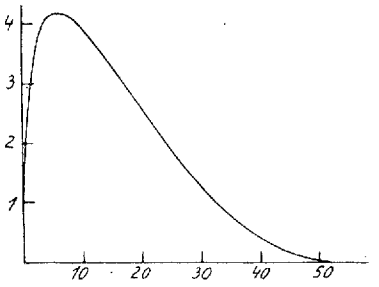

Fig. 10.
Abscissa: recoil energy X in eV.
Ordinate: number of recoil atoms with energy between limits dX.

It has here been assumed that the β-spectrum is simple. According to the level scheme in Fig. 8, the transformation energy can be emitted either in a single β-transformation or it can be divided between a β- and a γ-ray. In the latter case, no further experimental evidence is available at present, but the

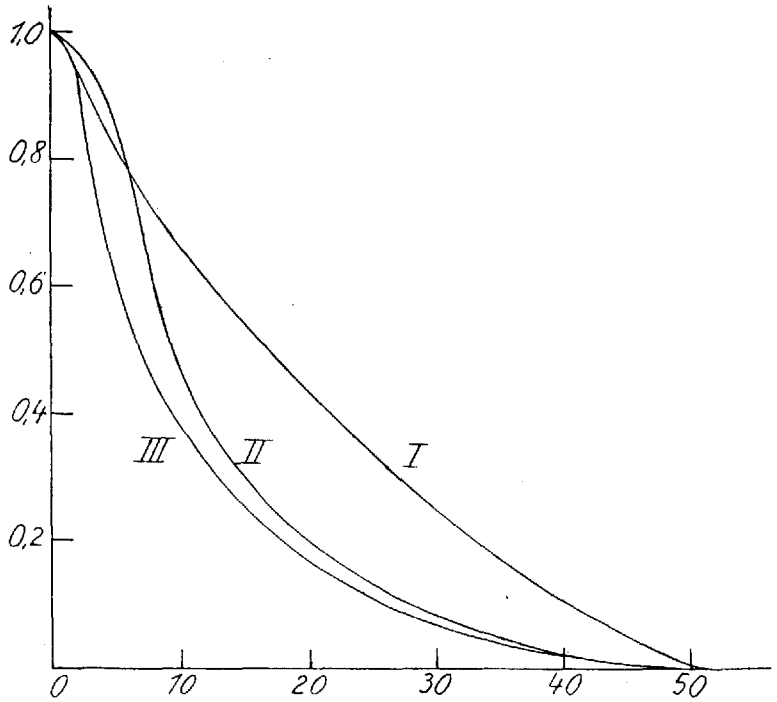

Fig. 11.
Abscissa: recoil energy X in eV. Ordinate: fraction of recoil atoms with energy greater than X.

only possibility which must be taken into account with respect to the recoil energy is that in which the γ-ray energy is emitted in a single quantum.

If p_β and p_γ denote the momenta due to the emission of the β- and the γ-ray separately, the total momentum is given by

$$p^2 = p_\beta^2 + p_\gamma^2 - 2\, p_\beta p_\gamma \cos\varphi,$$

where φ is the angle between the directions of p_β and p_γ, or

$$X = X_\beta + X_\gamma - 2\sqrt{X_\beta X_\gamma}\cos\varphi, \qquad (6)$$

where

$$p^2 = 2\,MX,\ p_\beta^2 = 2\,MX_\beta,\ p_\gamma^2 = 2\,MX_\gamma = \left(\frac{E_\gamma}{c}\right)^2.$$

Assuming for p_β the Fermi distribution, the probability that X_β is within the limits of dX_β is given by (5). If there is no correlation between the directions of p_β and p_γ, the number of recoil atoms for which φ is within limits $d\varphi$ is proportional to $\sin\varphi\,d\varphi$, so that the combined probability that X_β is within the limits dX_β and φ within the limits $d\varphi$ is given by

$$W(X_\beta, \varphi)\,dX_\beta d\varphi = \text{const.}\,W(X_\beta)\,dX_\beta \sin\varphi d\varphi.$$

Introducing here $\sin\varphi\,d\varphi = \dfrac{dX}{2\sqrt{X_\beta X_\gamma}}$ from (6), we obtain

$$W(X, X_\beta)\,dX dX_\beta = \text{const}\,W(X_\beta)\,dX_\beta \frac{dX}{\sqrt{X_\beta \cdot X_\gamma}}. \qquad (7)$$

When X is constant, X_β must be within the limits g_1 and g_2 determined from (5) by putting $\cos\varphi = \pm 1$,

$$g_1 = X + X_\gamma - 2\sqrt{XX_\gamma} \geqq 0$$

$$g_2 = X + X_\gamma + 2\sqrt{XX_\gamma} \leqq X_{m\beta}.$$

The energy distribution for the recoil atoms is now given by

$$W(X)\,dX = \text{const.} \cdot \int_{g_1}^{g_2} \frac{W(X_\beta)}{\sqrt{X_\beta \cdot X_\gamma}}\,dX_\beta \cdot dX \qquad (8)$$

together with the condition $\int_0^{X_m} W(X)\,dX = 1$, where

$X_m = X_{\beta m} + X_\gamma + 2\sqrt{X_{\beta m} \cdot X_\gamma}$ is the upper limit of X.

For a numerical test, some arbitrary assumption must be made regarding the way in which the energy is divided between the β-and the γ-radiation. The figures in Table 3 indicate that for various possible combinations of β- and γ-ray energy the upper limit of energy for the recoil atoms varies but slightly.

Table 3.

β	γ	X_m
0.4 MeV.	2.0 MeV.	46.3 eV.
1.0 —	1.4 —	48.5 —
2.0 —	0.4 —	51.1 —

The energy distribution for the case in which the β-energy is 1.0 MeV. has been calculated from (7) by the same procedure as that used previously. Primarily, a curve showing W(X) as a function of X was constructed; from this differential distribution the probability that a recoil atom has an energy greater than X was found by numerical integration. The result appears from Fig. 11, curve II. The difference between this curve and the distribution corresponding to a simple β-spectrum is small, especially as regards the number of recoil atoms with energy near the upper limit. A combination of the distribution in Fig. 11, II and Fig. 11, III in the (unknown) branching ratio of the level scheme (Fig. 8b) would again give very nearly the same result.

It has here been assumed that no correlation exists between the directions of p_β and p_γ. According to HAMILTON (22), however, a correlation occurs for light nuclei and high energies in the case of forbidden transitions. For the Fermi interaction, HAMILTON gives the angular distribution of the γ-ray as $W(\theta) = 1 - \frac{9}{13}\cos^2\theta$, or that the γ-ray is mainly emitted in a direction perpendicular to that of the β-particle. It is doubtful whether HAMILTON's result applies to the γ-rays from ^{88}Kr. If it does, the change in the energy distribution for the recoil atoms will be in the direction of a smaller number of recoil atoms with energies near the upper limit.

To sum up, we may now conclude that in the experimentally determined energy distribution the number of recoil atoms with energies near the upper limit is much larger than can be accounted for by the momentum due to the emission of β- and γ-rays.

When the emission of a neutrino is assumed, the calculated energy distribution of the recoil atoms is changed; to obtain a comparison with the experimental results, additional assumptions

must be made about the rest mass of the neutrino and about the angular distribution of the neutrino relative to the direction of the electron (22). For a qualitative discussion of the matter, the following possibilities for the angular distribution may be considered:

1) The electron and the neutrino always emitted in the same direction.

2) The angular distribution $1 + \frac{v}{c} \cos \varphi$.

3) The angular distribution $1 - \frac{v}{c} \cos \varphi$.

4) The electron and the neutrino always emitted in opposite directions.

In 2) and 3), v is the velocity of the β-particle and φ the angle between the β-particle and the neutrino. The rest mass of the neutrino will be assumed to be equal to zero. Although a rest mass different from zero might probably come into consideration, the accuracy of the experimental results is hardly sufficient to justify such a detailed discussion, especially because the recoil energy is mainly determined by the energy distribution just mentioned. As an example, the energy distribution will now be calculated with the angular distribution $1 + \frac{v}{c} \cos \varphi$.

If p_β and p_ν are the momenta due to the emission of the β-particle and the neutrino separately, then

$$p^2 = p_\beta^2 + p_\nu^2 + 2\, p_\beta\, p_\nu \cos \varphi, \quad \text{or}$$

$$2\, Mc^2 \cdot X = E_\beta^2 + 2\, mc^2 E_\beta + E_\nu^2 + 2\, E_\nu \sqrt{E_\beta^2 + 2\, mc^2}\, E_\beta \cos \varphi,$$

where E_β is the energy of the β-particle and E_ν that of the neutrino. Putting $E_\nu = E_m - E_\beta$, we get

$$\left.\begin{aligned} X = \frac{1}{2\, Mc^2} \Big(E_\beta^2 + 2\, E_\beta\, mc^2 + (E_m - E_\beta)^2 + 2\,(E_m - E_\beta) \\ \sqrt{E_\beta^2 + 2\, E_\beta\, mc^2} \cos \varphi\Big) = A\,(E_\beta) + B\,(E_\beta) \cos \varphi. \end{aligned}\right\} \quad (9)$$

For a fixed value of E_β, the number of recoil atoms for which φ is within the limits of $d\varphi$ is proportional to

$$W(\varphi)\,d\varphi = \sin\varphi\left(1+\frac{v}{c}\cos\varphi\right)d\varphi = \sin\varphi\,\frac{\sqrt{E_\beta^2+2E_\beta mc^2}}{E_\beta+mc^2}\cos\varphi\,d\varphi;$$

the combined probability that E_β is within limits dE_β and φ within limits $d\varphi$ is

$$W(E_\beta)\,dE_\beta \cdot W(\varphi)\,d\varphi,$$

where $W(E_\beta)$ is given by (4). Introducing here $\cos\varphi = \frac{X-A}{B}$ and $dX = -B\sin\varphi\,d\varphi$, the expression can be transformed into

$$W(E_\beta, X)\,dE_\beta\,dX = \text{const}\cdot[(E_{\beta m}-E_\beta)(E_\beta+mc^2)+Mc^2X$$

$$-\frac{1}{2}(E_\beta^2+2E_\beta mc^2+(E_{\beta m}-E)_\beta^2)]\,dE_\beta\,dX,$$

where $W(E_\beta\ X)\,dE_\beta\,dX$ is the number of recoil atoms with energies between limits dX originating from the emission of β-particles with energies between limits dE_β. The total number of recoil atoms with energies within limits dX is now obtained by integrating over the region of $\mathfrak{E}_\beta$, which contributes to the recoil energy X, or

$$W(X)\,dX = \text{const}\cdot\int_{g_1}^{g_2} W(E,X)\,dX\,x\,dE,$$

where g_1 and g_2 are determined from (9) as the values of E_β corresponding to $\cos\varphi = \pm 1$.

Fig. 12 shows $W(X)$ as a function of X. By a numerical integration of this differential distribution, the probability that a recoil atom has an energy greater than X was found. The result is shown in Fig. 13, curve III, where curve I is the experimentally determined distribution. It is apparent that agreement is obtained with the experimental results insofar as the calculated curve is now above the measured points. The same result would of course be obtained if it was assumed that the neutrino is always emitted in the same direction as

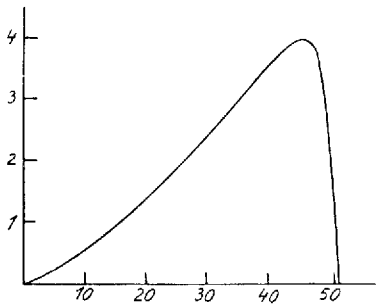

Fig. 12.
Abscissa: recoil energy X in eV.
Ordinate: number of recoil atoms with energy between limits dX.

the β-particle since, in the latter case, the number of recoil atoms with energies near the upper limit would be still larger.

A similar calculation made under the assumption that the angular distribution is $1 - \frac{v}{c}\cos\varphi$ gives the result in Fig. 13,

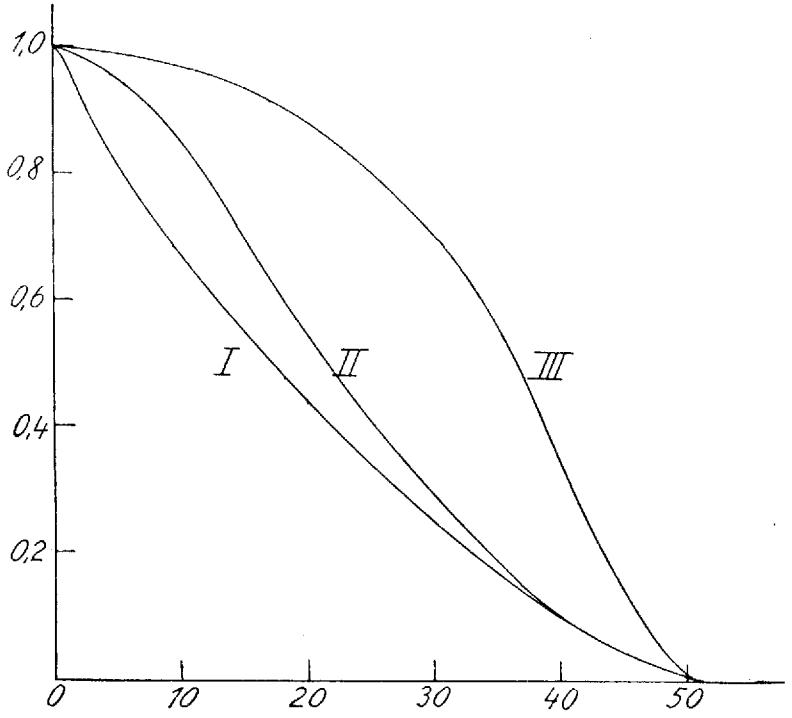

Fig. 13.

Abscissa: recoil energy X in eV. Ordinate: fraction of recoil atoms with energy greater than X.

curve II. It is seen that the energy distribution of the recoil atoms is shifted in favour of smaller energies and that, for energies near the upper limit, the calculated curve now is slightly below the measured points.

To account in a qualitative way for the experimental results, it seems thus necessary to assume that the neutrino is emitted mainly in the same direction as the β-particle. A further comparison, aiming at the distinction between the angular distributions

quoted as (1) and (2), would claim a higher accuracy of the experimental results than has been obtained here. For an improvement of the experimental results it would primarily be necessary to correct for the shift in the energy distribution due to the passage of the recoil atoms in oblique directions through the retarding field, *i. e.* to obtain an exact determination of the curve in Fig. 5, II. This correction which is inherent in the use of a gas as a radioactive source, can be evaluated if the apparatus is changed in such a way as to eliminate irregularities of the retarding field. A further complication is that caused by the emission of γ-rays; here serious difficulties in obtaining quantitative results are to be expected. In fact, a complete level scheme has hardly been established for any γ-ray transition and, in the present case, the matter is further complicated by the circumstance that ^{88}Rb cannot be obtained free from other radioactive elements.

As mentioned previously, a few experiments have been made with ^{89}Kr, the procedure being the same as with ^{88}Kr, except for the changes which were made necessary by the difference in period. The upper limit of energy for the β-particles was found to be 4.5 MeV., using the same method as for ^{88}Kr. The determinations of the recoil energy are as yet incomplete; the results show that the upper limit of energy is considerably higher than for ^{88}Kr.

After the completion of the work, a paper by J. S. ALLEN (24) came into our possession. This author has worked on ^{7}Be which by a special evaporation process was deposited in a very thin layer on platinum. ALLEN was able to observe recoil atoms with an energy of about 40 eV. and he attributed these atoms to the emission of neutrinos in the transformation

$$\begin{cases} {}^{7}\mathrm{Be} + e_k \rightarrow {}^{7}\mathrm{Li} + \nu + 0.85 \text{ MeV.} \\ \text{or} \begin{cases} {}^{7}\mathrm{Be} + e_k \rightarrow ({}^{7}\mathrm{Li})^{x} + \nu + 0.40 \text{ MeV.} \\ ({}^{7}\mathrm{Li})^{x} \rightarrow {}^{7}\mathrm{Li} + \gamma + 0.45 \text{ MeV.} \end{cases} \end{cases}$$

ALLEN's method is more direct than that used in the present work, since no β-particles are emitted from ^{7}Be, but at the same time the difficulties caused by surface effects are obvious. If the value of 0.85 MeV. for the energy difference between ^{7}Be and ^{7}Li is accepted as correct, an unexplained discrepancy of about 25 % remains between the calculated and the observed recoil

energies. In the interpretation of ALLEN's results, an uncertainty which, however, may not be serious is caused by the emission of γ-rays from ^{7}Li. An attempt was made to demonstrate the emission of γ-recoil atoms by a coincidence method; it failed, however, which is somewhat surprising, since about one-tenth of the total number of disintegrations should be accompanied by the emission of γ-rays.

The experiments were performed at the Institute of Theoretical Physics, Copenhagen. Our thanks are due professor NIELS BOHR for the facilities kindly placed at our disposal, Mr. N. O. LASSEN for his help in the work with the cyclotron, and Mr. B. MADSEN for the construction of the counters.

Summary.

The upper limit of energy for the recoil atoms from ^{88}Kr has been determined to 51.5 ± 2 eV. in close agreement with the value to be expected from the upper limit of energy of 2.4 MeV. for the β-particles. From the energy distribution of the recoil atoms it is concluded that a neutrino is emitted and that the neutrino probably is emitted mainly in the same direction as the β-particle.

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Indleveret til Selskabet den 24. Juli 1945.
Færdig fra Trykkeriet den 21. September 1945.