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MAXIMUM AND MEAN  
ENERGY OF THE RECOIL NUCLEUS  
IN THE BETA-DECAY OF  $\text{KR}^{89}$

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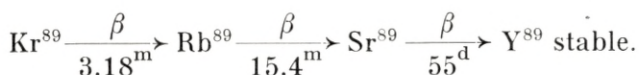
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## Introduction.

The maximum and the mean energy of the recoil in the  $\beta$ -decay of  $\text{Kr}^{89}$  have been measured.

The decay of  $\text{Kr}^{89}$  and its daughter substances can be summarized in the following scheme<sup>(1, 2)</sup>:



$\text{Kr}^{89}$  is much more shortlived than  $\text{Kr}^{88}$  which has a half-life of  $166^{\text{m}}$ <sup>(3)</sup>. Consequently, although the same experimental methods have been used as in the investigation of the recoil in the  $\beta$ -decay of  $\text{Kr}^{88}$ <sup>(4)</sup>, a number of experimental problems has to be considered much more closely for the experiments with  $\text{Kr}^{89}$  than for those with  $\text{Kr}^{88}$ . Therefore it is the intention in this article to give a rather detailed account of some methods which are used in this work and are applicable to other shortlived inert gases.

The  $\beta$ -spectrum of  $\text{Kr}^{89}$  is complex<sup>(2)</sup> and just as in the case of  $\text{Kr}^{88}$ <sup>(3, 5)</sup> this brings about some uncertainty in the interpretation of the results with respect to the angular correlation for the angle  $\theta_{\beta\nu}$  between the directions of emission of the electron and the neutrino. However, some tentative conclusions will be drawn in the last section of the paper.

## The Maximum Energy.

The principle of the method is the same as in the measurement of the maximum energy of the recoil in the  $\beta$ -disintegration of  $\text{Kr}^{88}$ .

Fig. 1 illustrates the vacuum system. An evacuated container, U, is filled with uraniumhydroxide, mixed with a small portion

of ammonium carbonate. The container is placed between the coils of the cyclotron magnet, as close to the beryllium target as possible. The container is surrounded by a few centimeters of paraffin. U is connected to the other parts of the apparatus through a stopcock  $S_1$ . The pumps are connected to the system by a second stopcock  $S_2$ .  $L_1$ ,  $L_2$  and  $L_3$  are liquid air traps.

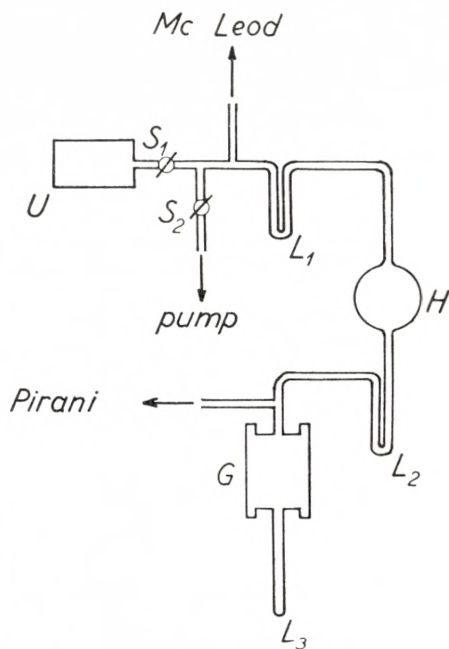


Fig. 1. The vacuum system for the measurement of the maximum recoil energy.

After the cyclotron irradiation is stopped,  $S_2$  is closed and  $S_1$  is opened. Due to the presence of the dissociation products of the ammonium carbonate the liquid air traps work as pumps and the radioactive inert gases are pumped off from the uranium and collected in the main apparatus. The bulb H is introduced in order to slow down the flow of gas passing through the liquid air trap  $L_1$ . The pressure in the system is controlled by a Pirani and a McLeod manometer. G is the main apparatus. It is shown in more detail in Fig. 2. The apparatus has axial symmetry about the line a-a, of course apart from the two tubes leading to the uranium-container and to the liquid air trap  $L_3$  respectively. The central box, G, is closed by flanges, one of which carries

a wire gauze which covers the area close to the symmetry axis a-a. G is continued by isolating flanges C which are sealed to G. The flanges C carry two metal plates D and the two collectors A and B. A potential difference  $V$  is maintained between the central box G and the collector system A-B-D. The two plates

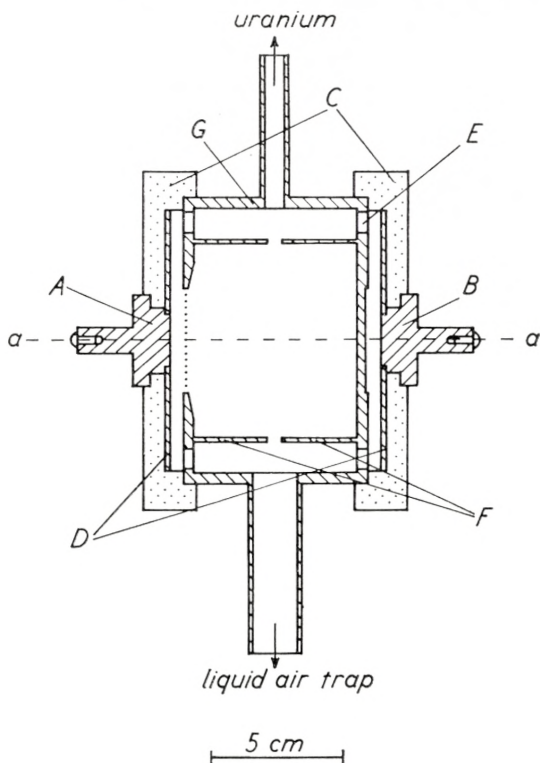


Fig. 2. The main apparatus for the measurement of the maximum recoil energy.

D are connected by a metal wire which is not shown in the figure. The potential difference  $V$  is taken from a battery of dry cells which is connected between A and some point of G. At the same time  $V$  is measured by a voltmeter connected between B and some other point of G. This arrangement ensured that no part of the system A-B-D was electrically insulated from the others and consequently all parts of the system had the correct potential.

It is very important to ensure a rapid and free passage of the gas to all parts of the instrument when operating with

short lived gases. Therefore, a large number of holes E connect the spaces between D and G with the interior of G. During the experiment the  $\beta$ -disintegrations of the short lived gas takes place everywhere in the apparatus. Some recoils hit the collector plates A and B. The electron work function of the metal surface of the collector used is smaller than the ionization potential of rubidium. Consequently, a recoil atom that is reflected from these surfaces is almost certain to be neutral. From the average energy measurements it may be concluded that neutral recoil atoms are very rare and that they play no measureable role in these experiments. Consequently, we may conclude that when a recoil nucleus hits a metal surface in the apparatus it is collected on this surface. The number of recoils accumulated on A and B can be determined by the radioactive decay of Rb<sup>89</sup>. The radioactivity of the plates is measured after the main experiment by dismantling the collectors A and B and carrying them to a counter. The activity  $N_B$  on B is due to those recoils produced in the space between B and G which are able to surmount the potential difference between the point where they are created and B. The activity  $N_A$  on A equals  $N_B$  plus a certain number  $N_I$  of recoils coming from the interior of G. It is desirable that all the recoils  $N_I$  originate in field free space. Therefore, the shields F are introduced in the apparatus to prevent recoil particles created between D and G from passing through the holes E into the interior of G and out through the wire gauze towards plate A.

The main apparatus G is completely surrounded by cadmium shields in order to prevent the slow neutron flux from the cyclotron from generating any activity in the material of the collectors.

The general course of an experiment is as follows. After the apparatus has been assembled and evacuated, the uranium is irradiated with neutrons from the cyclotron for 3 minutes. Let us call that instant of time when the cyclotron was stopped  $t = 0$ . The stopcock  $S_1$  has been closed since the start of the cyclotron irradiation and the liquid air traps are immersed in liquid air. Between  $t = 0$  and  $t = 1^m$  the stopcock  $S_2$  has been closed and at the time  $t = 1^m$   $S_1$  is opened and closed again at  $t = 3^m$ . During this interval of time  $L_1$  acts as a pump in the way described above and the main apparatus is filled by gases ori-

ginating from the fission process at a pressure of  $\sim 10^{-3}$  mm Hg. The pressure in the apparatus as close as possible to G is read on the Pirani manometer. The result is shown in Fig. 3. The potential  $V$  is kept at 1000 volts until the pressure in G is constant. This happens at  $t = 3^m$  and at  $t = 3^m.25$  the potential  $V$  is lowered to the value desired in the experiment in question and

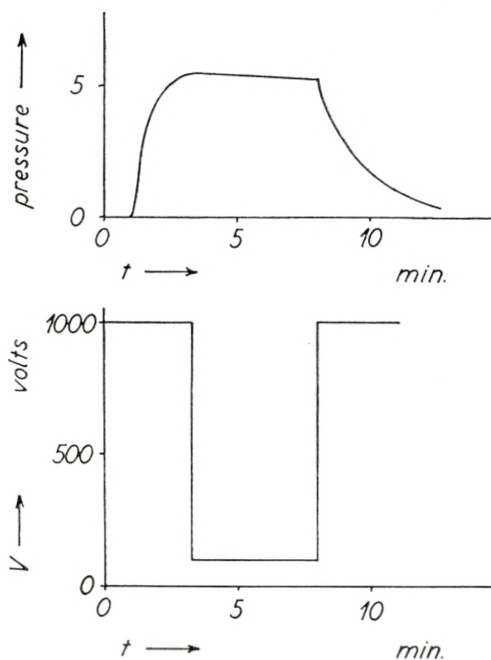


Fig. 3. The pressure and the potential difference  $V$  as a function of time during the course of an experiment.

kept at this value until  $t = 8^m$  and at this time it is raised again to 1000 volts. At the same time the gas is pumped off and afterwards the experiment is interrupted and the collector plates A and B are dismantled and carried to the counters. Here the ratio  $N_A/N_B$  is determined. The result is plotted as a function of  $V$  in Fig. 4.

During the intervals of time when  $V = 1000$  volts very few recoils can reach the plates A and B due to the strong repulsive force from these plates. Furthermore to the first approximation the few recoils reaching the plates A and B during this interval

of time give the same contribution to  $N_A$  as to  $N_B$  the difference being due to concentration differences between the spaces close to A and B. These concentration differences arise from the non-static situation during the inlet of the radioactive gas, and the application of the strong repulsive potential is a very important precaution when working with short lived activities where the time used for the inlet of the gas is of the same order of magnitude as the life-time of radioactive gas.

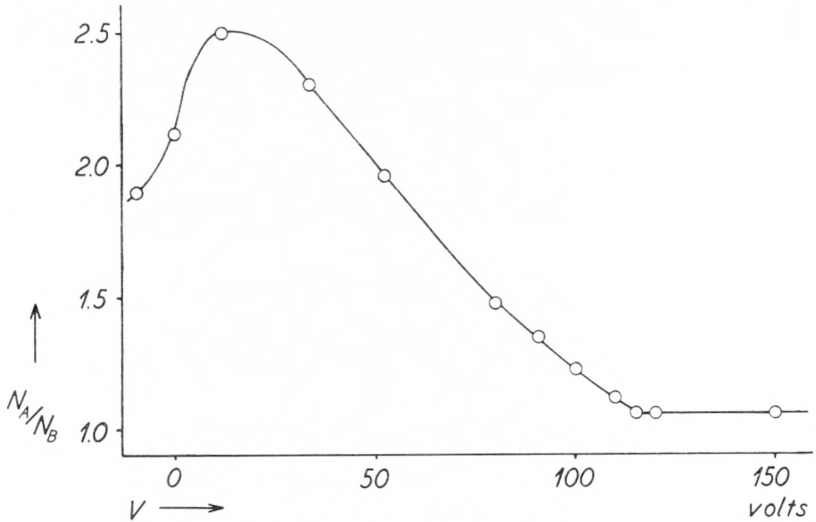


Fig. 4.  $N_A/N_B$  as a function of  $V$ .

During the interval of time from  $t = 3^m.25$  until  $t = 8^m$  the main experiment goes on. The pressure is constant and the differences in concentration of the radioactive gas may be neglected. It is noticed that  $N_A/N_B$  is constant and equal to 1.05 for  $V > 115$  volts. This result means that above this voltage no recoils can surmount the potential difference between G and A and we may conclude that the maximum recoil energy equals  $115 \pm 5$  eV. Due to a small inaccuracy in the mechanical construction of the apparatus the volume between A and G was 4% bigger than the volume between B and G. This is in agreement with the above mentioned value 1.05 of  $N_A/N_B$  for  $V > 115$  volts.

Of course it is important to examine the purity of the  $Rb^{89}$  activity on the collectors. First of all we cannot avoid contamina-



tions of  $\text{Rb}^{88}$  from the decay of  $\text{Kr}^{88}$ . However, the maximum energy of the recoils of  $\text{Kr}^{88}$  is considerably lower than the maximum energy of the  $\text{Kr}^{89}$  recoils. Consequently this impurity has no influence on the measurement of the maximum energy. For the mean energy the contamination of  $\text{Rb}^{88}$  gives rise to an important correction. This is the reason for the examination of this particular point described in the next section. The half-lives of the krypton isotopes with mass number higher than 89

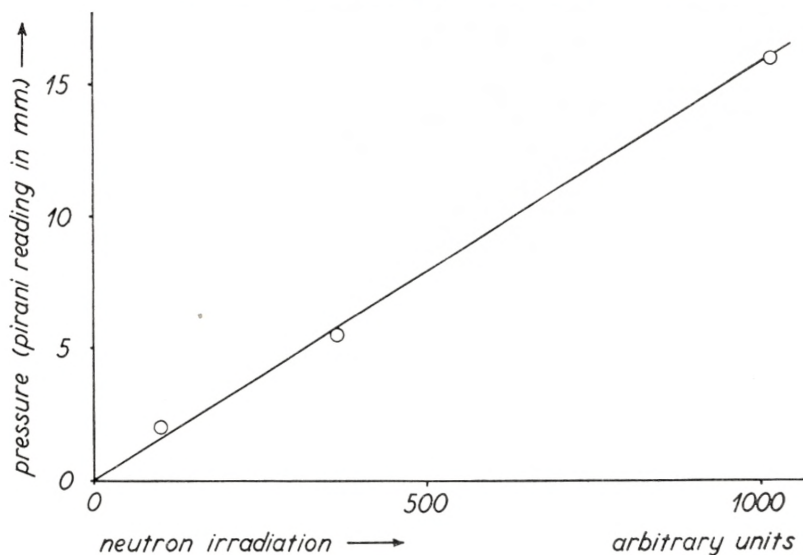


Fig. 5. Minimum pressure obtainable in the apparatus as a function of the total neutron irradiation in terms of the cyclotron beammeter reading.

are very short and consequently contaminations from daughter substances from these isotopes are excluded. Impurities from  $\text{Xe}^{188}$  and  $\text{Xe}^{139}$  might however occur, but the liquid air traps together with the  $\text{CO}_2$ ,  $\text{NH}_3$  and  $\text{H}_2\text{O}$  dissociation products from the ammonium carbonate remove all traces of Xenon. This was checked by following the decay curve of the activities of the plates A and B and was further controlled by some measurements carried out in connection with the average energy determination. The decay curves of the collector plates did not show the slightest sign of impurities of a  $7^m \text{Cs}^{139}$  or a  $33^m \text{Cs}^{138}$  isotope.

The experiments were carried out at a pressure of  $10^{-3}$  mm Hg. We have to notice an important point in this connection.

With the present method for obtaining the radioactive gases it is not possible to obtain as low a pressure as one might want to and at the same time get sufficient radioactive material. Fig. 5 shows the minimum pressure obtainable after different neutron irradiations. It is seen that the minimum pressure is proportional to the irradiation.

However, the pressure  $10^{-3}$  mm Hg is not unreasonably high. This will be illustrated in one of the following sections in connection with some experiments carried out during the investigation of the mean energy. In these experiments the influence of the pressure on the average energy is measured directly. It is concluded from the results that only a small fraction of the recoils has suffered collisions with the residual gas molecules in the experiments described in this section. Consequently the maximum energy cannot be influenced by the pressure in the apparatus.

### **Relative Yield of Daughter Substances from $\text{Kr}^{88}$ and $\text{Kr}^{89}$ , Half-Life of $\text{Kr}^{89}$ , Relative Fission Yields of $\text{Kr}^{88}$ and $\text{Kr}^{89}$ .**

We have mentioned that the rubidium activity on the collector plates consists of a mixture of  $\text{Rb}^{89}$  and  $\text{Rb}^{88}$ . The half-lives of these activities are practically the same namely  $15.4^m$  and  $17.8^m$  respectively. Consequently the ratio of the contributions from  $\text{Rb}^{89}$  and  $\text{Rb}^{88}$  cannot be determined very accurately from an analysis of the decay curve of the activity on the collector plates. Therefore an apparatus was designed for the determination of the ratio of the activity of  $\text{Rb}^{89}$  to the activity of  $\text{Rb}^{88}$  deposited on the surface of a field free space. A diagram of the vacuum system is shown in Fig. 6.

The system U- $\text{S}_1$ - $\text{S}_2$ -pump-McLeod- $\text{L}_1$  is the same as that described in the previous section. From this point and further on the apparatus has been augmented by a complete system of bulb H, liquid air trap  $\text{L}_2$  and main apparatus M. The liquid air trap  $\text{L}_3$  has been left out and some stopcocks  $\text{S}_3$  and  $\text{S}_4$  have been introduced. The main apparatus is shown in more detail in Fig. 7. It consists simply of a box A closed with a flange C. In the center of C is placed a small disk B. When the apparatus is opened the disk can be unscrewed and carried to the counter.

The general course of an experiment is as follows. The system is assembled and evacuated and irradiated with neutrons. The

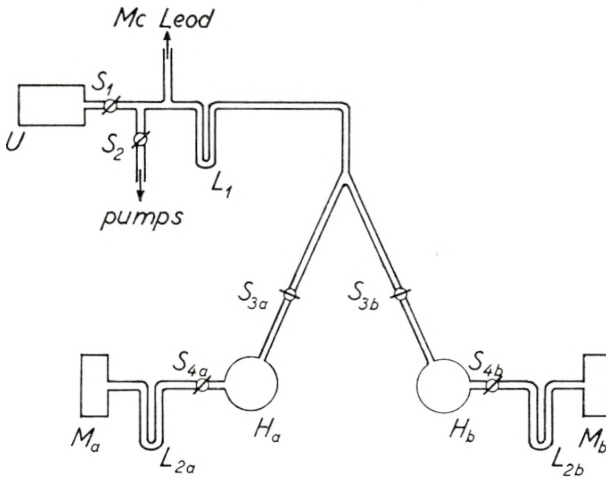


Fig. 6. The vacuum system for the determination of the relative yield of mass numbers 88 and 89.

cyclotron irradiation lasts 3<sup>m</sup>. Again let us call that instant of time when the cyclotron was stopped  $t = 0$ . The stopcocks  $S_1$ ,  $S_2$  and  $S_4$  are supposed to be closed, the stopcocks  $S_3$ , however, are open. The liquid air traps are cooled by liquid air. At the time  $t = 1^m$  the stopcock  $S_1$  is opened and at the time  $t = 2^m$  it is closed again. During this interval of time the bulbs  $H$  are filled with gas from the uranium container. Soon after this the stopcocks  $S_3$  are closed and  $S_2$  is opened. This means that equal amounts of gas are enclosed in the two bulbs  $H$  and that the volume between  $S_1$  and  $S_3$  is evacuated. At a certain time  $t_0$  the stopcock  $S_{4a}$  is opened and the gas in the bulb  $H_a$  is let into the main apparatus  $M_a$ . The pressure in a system very similar to  $M_a$ , namely the average energy apparatus described in the following section, is shown in Fig. 8 with  $t_0 = 4^m$ . At the time

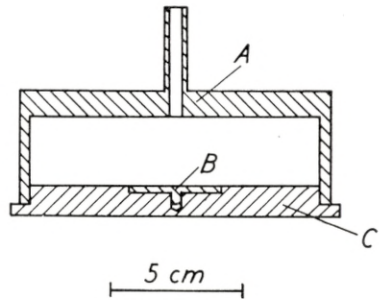


Fig. 7. The figure shows the main apparatus used for the determination of the relative yield of  $Kr^{88}$  and  $Kr^{80}$ .

$t = t_0 + 4^m$  the stopcock  $S_{3a}$  is opened and the gas is pumped off. At the time  $t = t_0 + 5^m$  the vacuum in  $M_a$  is opened and a

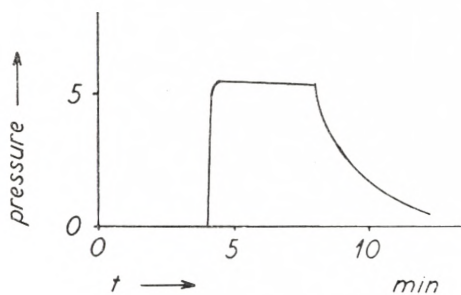


Fig. 8. Pressure curve showing the gas inlet and outpumping in the average energy apparatus.

large amount of air is allowed to flow through the apparatus so that all traces of radioactive gas are removed from the system.  $M_a$  is opened, the plate  $B_a$  is unscrewed and brought to the counting equipment and the radioactivity  $N_a$  of this plate is measured from the time  $t = t_0 + 10^m$  and until  $t = t_0 + 50^m$ . The shape of the decay curve is followed during this interval of time. At the

time  $t'_0 = t_0 + 54^m$  exactly the same procedure is carried through with the system labelled b. The result is the activity  $N_b$  on plate  $B_b$ . The volumes of the corresponding parts of the instruments a and b are equal within the accuracy necessary in this experiment.

The ratio

$$J_{Rb^{89}}/J_{Rb^{88}} = (N_a - N_b \exp(\lambda_{Kr^{88}} \cdot 54^m))/N_b \exp(\lambda_{Kr^{88}} \cdot 54^m) \quad (1)$$

is plotted as a function of  $t_0$  in Fig. 9. The exponentials  $\exp(\lambda_{Kr^{88}} \cdot 54^m)$  take into account the decay of  $Kr^{88}$  between the starting times  $t_0$  and  $t'_0$ . The time variation of the curve in Fig. 9 is given by the expression

$$J_{Rb^{89}}/J_{Rb^{88}} = \text{const} \cdot \exp(-(\lambda_{Kr^{89}} - \lambda_{Kr^{88}}) t_0) \quad (2)$$

and from the knowledge of  $\lambda_{Kr^{88}}$ <sup>(4)</sup> and the curve in Fig. 9 it is possible to find the half-life of  $Kr^{89}$ . The result is  $3.14^m$  in agreement with the result from measurements on mass separated krypton isotopes<sup>(2)</sup>.

One can also estimate the relative fission yield of mass numbers 88 and 89 from this measurement. It can be shown that the rubidium activity  $A_R$  on the collector plates is connected with the yield  $y_K$  of the corresponding  $Kr$ -isotope by the following expression

$$A_R = \left. \begin{aligned} & y_K \lambda_R (1 - \exp(-\lambda_K T)) \exp(-\lambda_R t) \cdot \\ & \cdot \int_{t_0}^{t_1} P(t) \exp(-(\lambda_K - \lambda_R) t) dt; \end{aligned} \right\} \quad (3)$$

here  $\lambda_R$  and  $\lambda_K$  are the decay constants of the rubidium and the krypton isotope respectively,  $T$  is the time interval used for neutron irradiation,  $t_1$  is the instant of time when the experiment is interrupted and  $P(t)$  is the pressure function as shown in Fig. 8

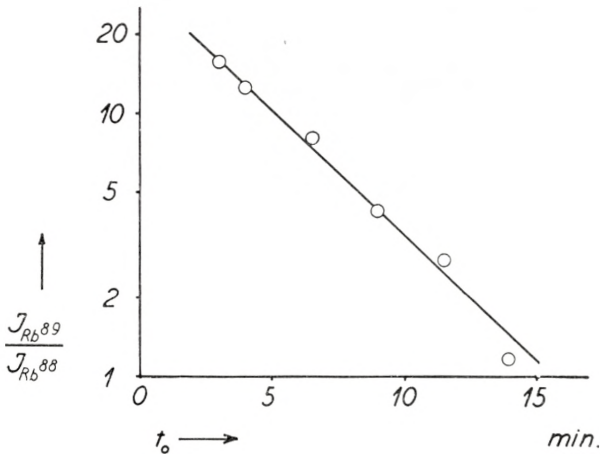


Fig. 9.  $J_{Rb^{89}}/J_{Rb^{88}}$  as a function of  $t_0$ .

normalized in some way which, however, does not matter because we are interested in relative fission yields only. The expression (3) is valid for  $t \gg t_1$ . An evaluation of the numerical data gives

$$y_{89}/y_{88} = 1.5 \pm .2. \quad (4)$$

All predecessors of our two krypton isotopes are very short lived<sup>(6)</sup> compared with the time intervals  $t_0$  used in the determination of the curve in Fig. 9. Also our two krypton isotopes lie rather close to the stable isotopes and it can be assumed that the main part of the primary fission products have  $Z > Z_{Rb} = 37$  so that (4) may be taken as a representative of the fission yields of mass numbers 88 and 89.

For the following experiments it is of some importance to notice that the inevitable contamination of  $Kr^{88}$  in the present

experiments for  $t_0 = 4^m$  amounts to 8.0 % when measured by the  $\text{Rb}^{88}$  activity in the standard manner discussed above.

### The Mean Energy.

The principle of the method is again the same as has been applied to  $\text{Kr}^{88}$  before.

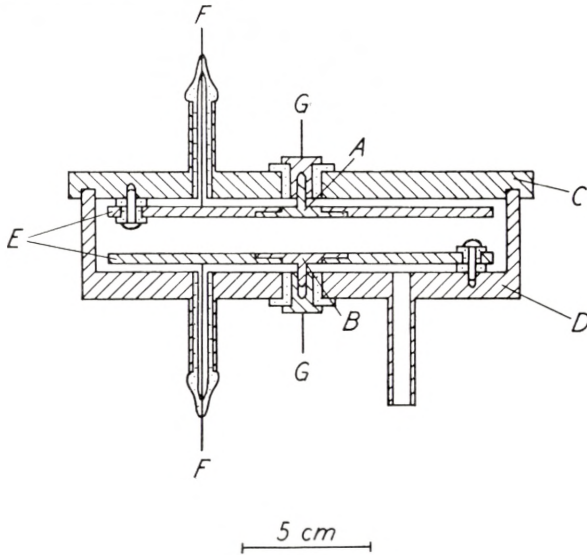


Fig. 10. The main apparatus for the measurement of the average energy.

The vacuum system consists simply of one of the systems shown in Fig. 6 and applied in the experiment described above. The system labelled *b* is left out and also the stopcock  $S_{3a}$  is left out. The main apparatus is of course changed and the average energy apparatus is shown in Fig. 10. It consists of a metal box *D* with a lid *C*. Isolated from this box are placed two metal plates *E* which form a plane parallel condenser. The central part of the plates, *A* and *B*, can be removed and carried to the counters. An electrical potential difference  $V$  is applied across the condenser. The voltage  $V$  is connected between the wires *F-F* and measured between *G-G*. Consequently, a current is drawn through the plates and all parts of the condenser plates have the correct potential.

When  $Ve \gg E_R^{\max}$  the ratio of the number of recoils collected on the positive plate  $N_+$  to the number collected on the negative

plate  $N_-$  gives a direct measure of the mean value of the energy  $E_R$  divided by the charge  $z_R$  of the recoils. This connection is expressed by the following formula<sup>(7)</sup>

$$\langle E_R/z_R \rangle = 6VN_+/(N_+ + N_-), \quad (5)$$

where  $\langle \rangle$  denotes the average value.

For singly charged recoil atoms the method gives directly

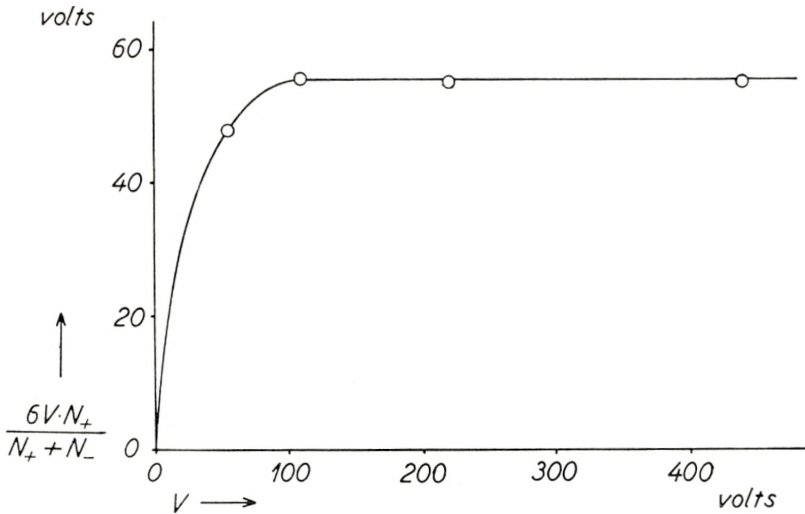


Fig. 11.  $6VN_+/(N_+ + N_-)$  as a function of  $V$ .

$\langle E_R \rangle$ . In the case of  $\text{Kr}^{88}$  the  $\beta$ -decay is sometimes followed by internal conversion<sup>(5)</sup> and consequently also by Auger effect. The result is a rather high charge on some of the recoils. Also, for theoretical reasons<sup>(8)</sup>, it might be expected that already the  $\beta$ -emission itself might give rise to some ionization of the electron shells of the recoiling atom. This means that (5) cannot in general be taken as a measure of  $\langle E_R \rangle$ .

The general course of an experiment is exactly the same as for the measurement of the relative yields of  $\text{Rb}^{88}$  and  $\text{Rb}^{89}$ . It is furthermore specified by putting  $t_0 = 4^m$ . The activity of the plates is measured in the standard way described above so that the contamination of  $\text{Rb}^{88}$  to the activity is well known.

The results for the expression  $6VN_+/(N_+ + N_-)$  are shown in Fig. 11. For potential differences  $V$  below  $E_R^{\text{max}}$  the curve in Fig. 11 lies below  $\langle E_R/z_R \rangle$  and for  $V \rightarrow 0$  it goes towards zero.

The connection between the shape of the curve in Fig. 11 and the recoil energy distribution will be discussed elsewhere<sup>(7)</sup>. However, we shall mention that the expression  $6VN_+/(N_+ + N_-)$  deviates from  $\langle E_R/z_R \rangle$  for  $V$  slightly smaller than  $E_R^{\max}$  only to higher order in the difference  $E_R^{\max} - V$ . This means, that even if  $V$  is 5–10 volts below the maximum energy of 115 volts the results are not affected within the accuracy of these experiments and consequently we may use the measurements at  $V = 110$  volts and higher values of  $V$  for the determination of  $\langle E_R/z_R \rangle$ .

The result is seen to be  $\langle E_R/z_R \rangle = 55.6$  eV for the natural mixture of  $\text{Kr}^{88}$  and  $\text{Kr}^{89}$  measured in the standard way discussed above consisting of 92%  $\text{Kr}^{89}$  and 8%  $\text{Kr}^{88}$ . With the value  $\langle E_R/z_R \rangle = 29$  eV for  $\text{Kr}^{88}$  we get

$$\langle E_R/z_R \rangle_{\text{Kr}^{88}} = 58 \pm 2 \text{ eV.} \quad (6)$$

It has already been mentioned that the pressure in the experiments was  $\sim 10^{-3}$  mm Hg. A series of average energy measurements were carried out at various pressures. Higher pressures than  $10^{-3}$  are obtained by letting a small amount of air leak into the uranium container before the cyclotron irradiation was started. The results for  $\langle E_R/z_R \rangle$  as a function of the pressure are shown in Fig. 12. It is found empirically that the correction has the following form as a function of the pressure  $p$  and the potential difference  $V$ :

$$\Delta \langle E_R/z_R \rangle = -28 p/V, \quad (7)$$

where  $V$  is measured in volts and  $p$  in mm Pirani deflection (1 mm Pirani deflection  $\sim 0.6 \cdot 10^{-3}$  mm Hg).

The results given in Fig. 11 have been corrected for the influence of the pressure by means of the expression (7). The corrections are smaller than 1%.

The order of magnitude of the effect (7) seems to be reasonable. The mean free path for alkali ions at a pressure of  $\sim 10^{-3}$  mm Hg is of the order of 20 cm<sup>(9)</sup>. This is of interest for the measurement of the maximum energy and it leads to the conclusion that only a few per cent. of the particles reaching plate A



in the maximum energy apparatus suffer collisions. Consequently the determination of the maximum energy is not influenced by the pressure.

We have mentioned above that possible effects from  $\text{Xe}^{138}$  or  $\text{Xe}^{139}$  are very small. To establish this fact further some experiments were carried out with  $t_0 = 1^m, 8^m$  and  $27^m$ . In the experi-

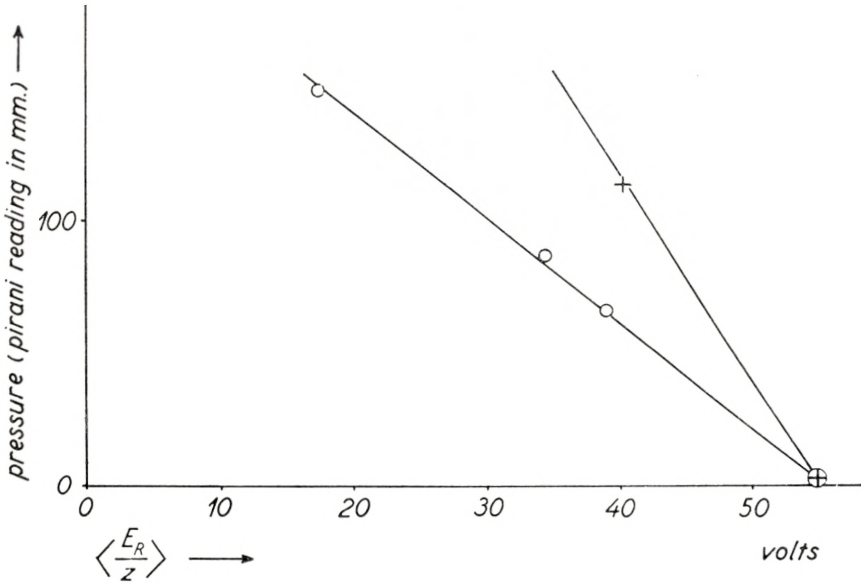


Fig. 12.  $\langle E_R/Z_R \rangle$  as a function of the pressure. The points  $\circ\circ$  correspond to  $V = 110$  volts and  $++$  corresponds to  $V = 220$  volts. The straight lines represent formula (7) for  $V = 110$  volts and  $V = 220$  volts respectively.

ment with  $t_0 = 1^m$  the stopcock  $S_1$  was open during the cyclotron irradiation. From these experiments it can be concluded that any effect from  $\text{Xe}^{138}$  or  $\text{Xe}^{139}$  in the standard experiment with  $t_0 = 4^m$  is less than  $2\%$ . Consequently we can neglect all effects on the average energy measurement from these Xe-isotopes.

At last we may mention an experiment carried out at  $V = 0$ . This experiment gave the result that  $N_+ = N_-$ . The accuracy is limited to  $1\%$  for statistical reasons. From this experiment it can be concluded that the contact potential difference between the plates A and B is negligible.

### Conclusions.

The only important conclusion which can be drawn from this experiment is a further establishment of the relation between the maxim recoil energy and the maximum  $\beta$ -energy. Assuming that the neutrino leaves the nucleus with zero momentum when the  $\beta$ -particle has its maximum energy we find that the maximum recoil energy  $115 \pm 5$  eV corresponds to a maximum  $\beta$ -energy of  $3.9 \pm .1$  MeV. This is in good agreement with the energy found from absorption measurements on isotope separated krypton<sup>(2)</sup> leading to  $E_{\beta}^{\max} = 4.0$  MeV. From this result we may conclude that the group of  $\beta$ -rays having  $E_{\beta}^{\max} \cong 4$  MeV leads to the ground state of Rb<sup>89</sup>.

The result  $\langle E_R/z_R \rangle = 58 \pm 2$  eV cannot be used for an exact determination of  $\langle E_R \rangle$  since  $\langle 1/z_R \rangle$  is unknown. (In rough estimates one may neglect a possible slight correlation between  $E_R$  and  $z_R$ .) However, we can find a lower limit of  $\langle E_R \rangle$  since  $\langle 1/z_R \rangle$  is smaller than unity. Calculations by Winther<sup>(8)</sup> show that for the  $\beta$ -decay  $\text{He}^6 \rightarrow \text{Li}^6$  one would expect that  $\langle 1/z_R \rangle = 0.95$ . In our case we may assume that the ionization is even larger since the effect is supposed to increase with  $Z$ . Also internal conversion processes following the  $\gamma$ -ray emission might lower the  $\langle 1/z_R \rangle$  value. Thus we put  $\langle 1/z_R \rangle < 0.95$  and we get  $\langle E_R \rangle > 60$  eV.

The  $\beta$ -decay of Kr<sup>89</sup> is complex<sup>(2)</sup> and probably consists of two spectra one with  $E_{\beta 1}^{\max} = 3.9$  MeV and another one with  $E_{\beta 2}^{\max} \cong 2$  MeV. It is known that the decay is followed by  $\gamma$ -rays, and since we have concluded that the 3.9 MeV group leads to the ground state of Rb<sup>89</sup> we may assume that the 2 MeV group is followed by a 1.9 MeV  $\gamma$ -ray. According to formula (8) of reference 10 we find the average value of the recoil energy after the combined action of the  $\beta$ -decay and the  $\gamma$ -ray emission simply by adding the average energies obtained in each single process. The average energy from the  $\beta$ -disintegrations alone depends on the angular correlation between the directions of emission of the  $\beta$ -particle and the neutrino. If we assume a spherically symmetrical neutrino emission we find an average recoil energy of 18.8 eV corresponding to  $E_{\beta 2}^{\max} = 2.0$  MeV. The recoil from the  $\gamma$ -ray emission gives  $E_{R\gamma} = 21.7$  eV if we make the assumption that the energy

is carried away by a single  $\gamma$ -ray. If several quanta are emitted the energy is even lower. The final result is  $\langle E_R \rangle_2 \ll 41$  eV. Furthermore, this result is quite insensitive to possible uncertainties in the maximum energy of the low energy group.

We still get a lower limit for  $\langle E_R \rangle_1$  if we take the lower limit 35% for the branching ratio of the low energy group. This gives after a simple calculation  $\langle E_R \rangle_1 > 72$  eV.

The assumption of a  $(1 + v_\beta/c \cdot \cos \theta_{\beta\nu}) p_R^2$  angular correlation together with  $E_R^{\max} = 115$  eV would yield  $\langle E_R \rangle = 89$  eV. This correlation is the most strongly forward neutrino emission probability for 1. forbidden spectra. The symmetrical neutrino emission would give  $\langle E_R \rangle_1 = 65$  eV and the correlation  $(1 - v_\beta/c \cos \theta_{\beta\nu})$  which corresponds to a strongly backward neutrino emission gives  $\langle E_R \rangle_1 = 46$  eV. Due to the incompleteness in the knowledge of the decay scheme the lower limit 72 eV is subjected to some uncertainty and must be taken with all due reservation. Nevertheless it seems to be safe to conclude that it would be difficult to fit the results with the assumption of a backward neutrino emission. It should be added that a forward neutrino emission would also in general be expected if the  $\beta$ -decay is forbidden as seems to be the case for  $\text{Kr}^{89}$  judging from the ft-value.

We wish to thank Professor N. BOHR for his interest in our work and we are also indebted to Professor J. C. JACOBSEN. The present experiments represent a continuation of the work on  $\text{Kr}^{88}$  carried out by Professor J. C. JACOBSEN and one of us.

### Summary.

Experiments on the energy of the recoil nucleus in the  $\beta$ -decay of  $\text{Kr}^{89}$  are described. This maximum energy was found to be  $115 \pm 5$  eV, in good agreement with the previously measured maximum  $\beta$ -energy. The average value of the recoil energy divided by the charge of the recoil atom was determined as  $58 \pm 2$  eV. In connection with the latter experiment the relative yield of mass numbers 89 and 88 in the fission of uranium was

measured, with the result  $y_{89}/y_{88} = 1.5 \pm .2$ . At the same time the half-life of  $\text{Kr}^{89}$  was determined as  $3.14^m$ .

The results support a forward neutrino emission with respect to the direction of emission of the  $\beta$ -particle, in agreement with the assumption that the decay is forbidden.

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