MEASUREMENT OF THE NEUTRON HALF-LIFE

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The half-life of the neutron was measured and found to be equal to 11.7 ± 0.3 minutes.

1. INTRODUCTION

THE free neutron is the simplest beta-emitting nucleus, and a quantitative knowledge of its half-life can give useful information in the explanation of the form of the beta interaction. Interest in this question has increased lately, and demands have arisen for accurate determinations of the half-life of the neutron. However, a more accurate measurement of this important constant involves considerable experimental difficulties, and up to now it has been measured to an accuracy of only 10 — 15%. The present work was undertaken with the goal of significantly improving this accuracy.

Determinations of the half-life of the neutron have been carried out in the U.S.A.[1-3] and in the U.S.S.R.[4] In these works the slow decay protons formed in the powerful neutron beams of a nuclear reactor were accelerated to 10 — 15 kev and were detected either directly[2,4] or by their coincidences with decay electrons.[1,3] In all these cases the accelerating electrode was placed near the beam, and the decay protons were "drawn out" of it by a field. For the determination of the half-life it was necessary to calculate what part of the total number of protons being created in some particular part of the beam were detected in the experiment. However, the result of the calculations was also determined, under the conditions of the experiment, by the spectrum of the decay protons. Experimentally, this spectrum is still insufficiently known,[4,5] and its theoretical form depends strongly on the possible choice of the beta interaction, which is also still insufficiently checked by experiment. Therefore, in experiments with an accelerating electrode alongside the beam the half-life measurements have a systematic uncertainty, connected with the poor knowledge of the proton spectrum, which significantly decreases the accuracy of these experiments.

Such experiments at first produced rather rough estimates of the half-life. Thus Snell, Pleasonton, and McCord gave values from 10 to 30 min,[1] Robson reported 9 to 25 min,[2] and Spivak and Sosnovskiĭ reported 8 to 15 min.[4] In later work Robson got 12.8 ± 2.5 min[3] and Spivak and Sosnovskiĭ 12.0 ± 1.5 min.[4] The latest values were obtained by an arrangement in which the beam was located in the field accelerating the protons, as before; the experiment was set up, however, so that the number of protons picked up by the detector were exactly equal to the number of protons created in a rigorously determined part of the beam. The half-life found in this experiment was free from the uncertainty connected with the proton spectrum.

In the present work the half-life is also determined by directly-measured quantities and by purely geometrical factors which can be accounted for exactly. This was possible thanks to the fact that the decay protons, before coming into the accelerating field, passed through a system of diaphragms. Although the number of protons N_p picked out by these diaphragms was only a small part of the whole quantity formed in the effective part of the beam, these protons enter the accelerating field with small angular dispersion. This allows one to fully focus them on the entrance aperture of the detector with relatively little effort. Therefore, in the formula for the half-life of the neutron,

$$T = kJ \ln 2 / N_p, \qquad (1)$$

where J is the integral of the neutron density over the beam cross-section, the coefficient k depends only on the geometrical conditions of the experiment and the distribution of neutrons in the beam.

2. DESCRIPTION OF THE APPARATUS

The measurements were carried out on a beam of neutrons from the RFT reactor. A longitudinal section of the apparatus is displayed in a schematic diagram (Fig. 1). A well-collimated neutron beam with a diameter of 80 mm passed through the vacuum chamber 1, in which a vacuum

*Deceased.

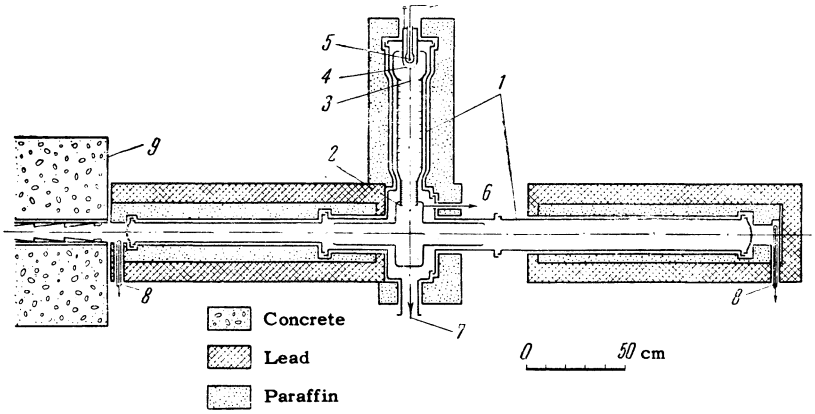

FIG. 1. Schematic diagram of the apparatus. 1 – apparatus shell, 2 – diaphragm, 3 – diaphram with grid, 4 – spherical grid, 5 – proportional counter, 6 – high voltage electrode, 7 – diffusion pump outlet, 8 – monitors, 9 – reactor shield.

of $\frac{1}{2} \times 10^{-6}$ mm is maintained. A hollow electrode 6, which was given a positive potential of 20 kv, was placed in the chamber. The decay protons appearing in the beam opposite to diaphragm 2 (diameter, 78 mm) passed through into this electrode (in which a field existed) and up to grid 3 (diameter, 100 mm). The diaphragm 2 and the grid 3 were distant, respectively, 13.6 and 82.1 cm from the axis of the beam. Beyond grid 3 the decay protons came into a region where the electric field between the grounded spherical grid (3 cm radius) and the high-voltage electrode accelerated them and focussed them onto detector window 5. The accelerating field was very nearly spherical so that the motion of the protons in it could be easily calculated. The calculations showed that a potential of just 10 kv ensured that all the protons passing through diaphragm 3 were collected at the detector window. The characteristics of the focusing system were examined in special trials in which one investigated the dependence of the number of protons both on the size of the charge and on the placement of detector 5 and the dimensions of the entrance window 3. The results of these trials affirmed the calculation and provided full confidence in that, for 20 kv — the potential which was actually used, to assure a better relation to background effects — all the decay protons coming into the focusing field were definitely collected at the detector window.

For the proton count one used a Geiger-proportional counter, whose construction and characteristics are described in detail in reference 4. The counter window (16 mm diameter) was covered by a thin film of collodion (0.07 μ thick), which was backed from the vacuum side by a tungsten grid (wire diameter, 2.5 μ; spacing, 0.5 mm). A second grid (wire diameter, 20 μ, spacing, 0.9 mm) was placed on the other side of the film to shield the effective volume of the counter from charges collected on the film.

Since four grids were placed between the creation point of the decay protons and the counter effective volume, part of the protons were absorbed by them and did not reach the counter. If the counter recorded n_p protons, then

$$n_p = \alpha N_p,$$

where N_p is the quantity of protons hitting counter 3, and α is the transmissivity of all the grids.

Grid 3, covering the entrance window of the focusing system, was made out of wires of 20 μ diameter in a square mesh 4 mm on a side. The geometrical transmissivity of such a grid is close to 0.99. In actuality it was even closer to unity because of the "hanging" of the field onto the relatively coarse mesh. Therefore we did not take into account the absorption in this grid, including it instead in an increase of the error in α. The geometrical transmissivity (for normal incidence) of the spherical grid 4 was 0.913, and those of the grids at the counter window were 0.950 and 0.978. From this, the transmissivity of all grids for normally incident protons was 0.848. The value for the largest possible angles of inclination of the protons from the normal was a bit smaller than this, 0.838. Since the protons were incident on the grids at angles spread between these two extreme values, the value $\alpha = 0.843 \pm 0.006$ was taken for the general transmissivity of all the grids.

3. MEASUREMENT OF THE BEAM NEUTRON DENSITY

The neutron density was determined by the activation of sodium targets, whose cross section follows the 1/v law,[6] and by the activation of gold targets, applying corrections for the neutron resonance effect.

The absolute number of β electrons for Au^{198}, gotten by the 4π counter method, was a supporting measurement for both methods. The neutron den-

sity measurement by activation of gold was carried out with two targets, one of which was prepared by evaporation in vacuum, in the form of a thin layer of gold (0.06 mg/cm^2) on a metallized collodion film. The other, thicker one (40 mg/cm^2) consisted of precisely weighed gold foil.

The absolute number of decays from the thin target, measured by the spherical counter, and the relative activity of both targets, measured by the gamma radiation on a scintillation counter, made possible the determination of the neutron density, after making the corrections for neutron resonance. The corrections were got by the measured cadmium ratio values for gold and the 1/v detector; they were 2.84 and 23.4, respectively.

The determination of the neutron density by activation of the sodium target was made by measuring the intensity of its emitted gamma rays with a scintillation counter; the coefficient of proportionality between the neutron density ρ and the measured velocity of the gamma rays was found by a separate experiment. In this experiment the sodium target was placed in a collimated beam of thermal neutrons, whose density had been found by the absolute number of decays as described above for gold. The relation of the measured neutron density to the gamma activity of the sodium target, measured by the same scintillation counter, gave the value of the constant of proportionality.

In this experiment the correction for the neutron resonance effect in gold was insignificant (0.7%), since the cadmium ratios, measured with thermal neutrons for Na and Au, were 4000 and 150. So one could be confident that the error in the neutron density determined by the sodium activation was fixed only by the errors in the gold cross-section, $\sigma_{abs} = (98 \pm 1.5) \times 10^{-24}$ cm^2 (reference 7) for E = 0.025 ev, and by those in the absolute measurements with the 4π counter ($\pm 0.5\%$) and in the relative measurements with the scintillation counter ($\pm 0.5\%$). The error for the gold cross-section includes 0.5×10^{-24} cm^2 for deviation from 1/v.

The results of the neutron density measurements by the activation of gold and sodium in the center of the same beam in which the half-life measurements were made coincided within limits of $\pm 0.5\%$. These density measurements gave a value of $\rho = 2.17 \times 10^3$ neutrons/cm^3, $\pm 1.8\%$.

The integral of the density J, which enters in relation (1), was determined by the activation of the gold foil, which was placed across the beam, completely blocking it. The foil, therefore, was completely cut to pieces and the scintillation detector miscounted its activity. Therefore the relation of these pieces to the specific activity of the central piece was determined. The application of this relation to the value of the neutron density ρ in the center of the beam gave the wanted value of the integral of the neutron density, $J = (7.68 \pm 0.15) \times 10^4$ neutrons/cm.

4. DETECTION OF THE DECAY PROTONS

As already mentioned, the decay protons were detected with a proportional counter, the end of which was covered by a thin film. The counter was filled with pure carbon tetrafluoride at a pressure of 10 mm of mercury, so that the range of protons with energies about 20 kev was contained within the counter.

The decay protons were counted directly but did not coincide with the number of electrons, so that their number was determined as the difference in count when the accelerating potential was turned on and then off. One had to reckon with the fact that the inclusion of the accelerating potential led to some increase of the count even in the absence of the neutron beam. Investigation of this effect showed[4] that it was caused by the detection of H_1^+ ions coming from the apparatus. Polishing and oxidizing the aluminum high-voltage electrode and other parts, measures prompted by the experience of past work, allowed us to make this effect much smaller than the count of the decay protons.

The count of H_1^+ ions fell slowly as the equipment stood under vacuum, but such ions were always observed in a freshly pumped-out apparatus; using this fact, it was possible to carry out a series of controlled experiments. It was found primarily that the magnitude of the effect depended neither on the degree of irradiation of the apparatus nor on whether the neutron beam passed through the chamber or was shut off from it. This allowed us to determine, for the shut-off beam, the effect of the H_1^+ ions as the difference in counts with and without accelerating potential.

Besides this, when the number of H_1^+ ions was large, one could construct — for a chosen multiplier — an integral curve for the distribution of momenta and set the discriminator level to a value corresponding to the plateau of this distribution (Fig. 2, dotted line). In counting the decay protons, the number of protons and, even more so, the number of H_1^+ ions was not large and the scheme previously set up (for the H_1^+ ions) was repeated and periodically checked with the aid of

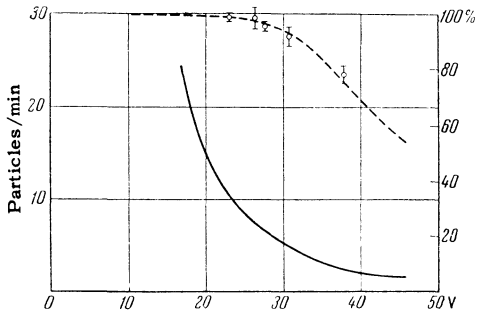

FIG. 2. Integral distribution of pulse amplitudes of H^+ ions – dotted curve; dependence of the background on the discriminator level – solid curve; o – decay protons (control values).

alpha particles from a source (Am^{241}) that could be moved within the vacuum chamber. This was also convenient because it appeared that the integral curves of the momentum amplitude distribution for alpha particles and H_1^+ ions coincided with good accuracy, if for the alpha count the amplifier strength was decreased as necessary.

The gas multiplication factor of the counter was preserved unchanged through the long hours of the experiment by the use of a grid to shield the charges on the film, by stabilizing the supply, by the nature of the gas used, and by the large ballast volume joined to the counter.

Since the measurements were rather lengthy, two extra ionization chambers, their stability controlled by the activation of copper targets, were used to detect fluctuations in beam intensity. The counting procedure for the decay protons is illustrated in the table, where several measurement cycles, each consisting of four short trials, are shown. Twenty-five measurement cycles were carried out, and the decay proton count was found to be 29.6 ± 0.4 protons/min. This value was reconciled with the results of the monitor chambers, with which the beam neutron density was determined. The deviations of the results of the individual cycles are in good agreement with the statistical error for the average values.

The measurements were carried out for discriminator levels somewhat higher than necessary to count all the decay protons, but the background effect correlation was much more favorable for this setting than for a lower discriminator level.

The results obtained, together with some control values measured for large biases are shown in Fig. 2. From this figure it is evident that the extrapolation to zero bias could be done rather exactly, since the error, (1.5 ± 0.5)%, was small. The extrapolated value for the number of protons was $N_p = 30.0 \pm 0.4$ protons/min; taking into account the transmissivity of the grids ($\alpha = 0.843$) we get $N_p = 35.6 \pm 0.54$ protons/min.

As to systematic errors, notice must be taken of the danger involved in the circumstance that the decay protons have to travel a rather long distance, about 80 cm, before they enter the accelerating field. However, loss of protons in this way, by scattering and charge exchanges in collisions with residual gas molecules — pressures were 1 or 2×10^{-6} mm of mercury (measured directly in the chamber) — could take place only for the insignificant soft part of the proton spectrum, even for the worst conceivable cross-section value; the proton loss can hardly have exceeded several tenths of a percent.

Besides, the protons scattered into small angles on the sides of the electrode could hit the aperture of diaphragm 3 and raise the count somewhat, but only if this effect was not compensated for by proton charge exchange during scattering.

The measurements described above were carried out with a large quantity of thin diaphragms placed inside the electrode between diaphragms 2 and 3. We repeated the measurements, using the same accuracy, with the diaphragms removed, when the potential scattering surface for the protons was almost a hundred times greater. The agreement of the results showed that the effect discussed actually did not occur.

5. DETERMINATION OF THE COEFFICIENT k

The value of the coefficient k in formula (1) is determined by the geometrical conditions of the experiment and by the neutron density distribution in the plane perpendicular to the beam axis.

Neutron beam on			Neutron beam off			Number of decay protons in one min
Number of counts in 20 min			Number of counts in 20 min			
Accelerating voltage on	Accelerating voltage off	Decay proton and hydrogen ions	Accelerating voltage on	Accelerating voltage off	Hydrogen ions	
864	280	584	81	47	34	27.5
874	249	625	66	54	12	30.65
917	263	654	80	62	18	31.8
859	280	579	58	58	0	28.95
823	213	610	80	56	24	29.3

To carry out the calculation, involving a numerical integral, the effective volume of the beam was cut up into 900 elements in the form of long parallelopipeds along the beam, each having a transverse cross section in the form of a square, 0.3 × 0.3 cm. The number of decay protons incident on the aperture of the focusing system from the i-th element is proportional to the product P_iL_i, where P_i is the neutron density of the i-th element and L_i its geometrical "weight." The total number of protons incident on the counter from the whole beam volume is proportional to ΣP_iL_i. This quantity, referred to ΣP_i, is the unknown.

The "weights" L_i, which depend only on the geometrical conditions of the experiment, were calculated with an electronic computer.

The neutron density distribution was determined from the activation of a gold foil. For this, the gold foil was cut up into 900 squares, which coincided with the cross sections of the volume elements used for the numerical integration, and the specific activity of each, which was proportional to P_i, was determined. Figure 3 illustrates the neutron density distribution in the beam.

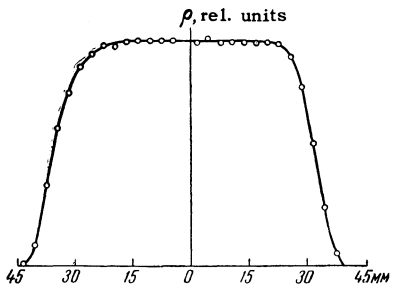

FIG. 3. Neutron density distribution over the beam diameter.

The coefficient k was determined with the help of a computer and found to be 7.87×10^{-13}cm. The value of d depends only insensitively on the form of the density dependence. For example, changing the density distribution by substituting a similar one for a somewhat smaller beam diameter (70 mm) leads to a value $k = 7.84 \times 10^{-3}$ cm. The error in the calculation of k was found to be due, in the main, to the inaccuracy in the given geometry of the apparatus and did not exceed some tenths of a percent.

6. RESULTS OF THE MEASUREMENTS

Substitution of the values of J, N_p, and k in Eq. (1) give for the half life of the neutron the value*

$$T = (11.7 \pm 0.3) \text{ min.}$$

*Here, as in all the other cases, the reduced mean-square error is used.

The reduced lifetime of the neutron is thus fT = 1180 ± 40.*

For tritium, a value fT = 1132 ± 40 (reference 9) was cited in the literature until recently. Not long ago the mass difference for H^3 and He^3 was measured, and from those data it follows that for tritium, fT = 1132 ± 40 (reference 10). Thus it appears that the fT of the neutron and that of tritium are, with good accuracy, identical. If use is made of the conection between the quantity fT and the ratio of the constants G_{GT} and G_F, then comparing the fT of the neutron and of O^{14}, fT = 3103 ± 62 (reference 11), we get

$$G_{GT}^2 / G_F^2 = 1.42 \pm 0.08.$$

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200

*The value of f is calculated from the tables of Dzhelepov and Zyryanova.[8]