MEASUREMENT OF THE NEUTRON HALF-LIFE


Submitted to JETP editor September 29, 1958

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 directly2,4 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 Sosnovskii reported 8 to 15 min.4 In later work Robson got 12.8 ± 2.5 min3 and Spivak and Sosnovskii 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 Np 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,

\[ T = kJ \ln 2 / N_p, \]

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...
of $\frac{1}{4} \times 10^{-6}$ 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 $\alpha$ 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 $\alpha$.

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, and by the activation of gold targets, applying corrections for the neutron resonance effect.

The absolute number of $\beta$ electrons for Au$^{199}$, gotten by the $4\pi$ counter method, was a supporting measurement for both methods. The neutron den-
sity measurement by activation of gold was car-
rried out with two targets, one of which was pre-
pared by evaporation in vacuum, in the form of a
thin layer of gold (0.06 mg/cm²) on a metallized
collodion film. The other, thicker one (40 mg/
\text{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, respec-
tively.

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 \( \rho \)
and the measured velocity of the gamma rays was
found by an independent experiment. In this experi-
ment the sodium target was placed in a collimated
beam of thermal neutrons, whose density had been
found by the absolute number of decays as de-
scribed above for gold. The relation of the meas-
ured neutron density to the gamma activity of the
sodium target, measured by the same scintillation
counter, gave the value of the constant of propor-
tionality.

In this experiment the correction for the neu-
tron 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, \( q_{\text{abs}} = (98 \pm 1.5) \times 10^{-24} \text{ cm}^2 \)
(reference 7) for \( E = 0.025 \text{ ev} \), and by those in
the absolute measurements with the 4\( \pi \) counter
(\( \pm 0.5 \% \)) and in the relative measurements with
the scintillation counter (\( \pm 0.5 \% \)). The error for
the gold cross-section includes \( 0.5 \times 10^{-24} \text{ cm}^2 \)
for deviation from \( 1/v \).

The results of the neutron density measure-
ments 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 \( \rho = 2.17 \times 10^{3} \text{ neutrons/cm}^3, \pm 1.8 \% \).

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 de-
tector miscounted its activity. Therefore the re-
lation of these pieces to the specific activity of
the central piece was determined. The applica-
tion of this relation to the value of the neutron
density \( \rho \) in the center of the beam gave the
wanted value of the integral of the neutron den-
sity, \( J = (7.68 \pm 0.15) \times 10^4 \text{ neutrons/cm}. \)

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 con-
tained 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 differ-
ence 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 po-
tential 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 \( \text{H}_1^+ \) 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
deay protons.

The count of \( \text{H}_1^+ \) ions fell slowly as the equip-
ment 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 \( \text{H}_1^+ \) ions as the difference
in counts with and without accelerating potential.

Besides this, when the number of \( \text{H}_1^+ \) ions was
large, one could construct — for a chosen multi-
plier — an integral curve for the distribution of
moments and set the discriminator level to a
value corresponding to the plateau of this distri-
bution (Fig. 2, dotted line). In counting the decay
protons, the number of protons and, even more so,
the number of \( \text{H}_1^+ \) ions was not large and the
scheme previously set up (for the \( \text{H}_1^+ \) ions) was
repeated and periodically checked with the aid of
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 $H^+$ 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, $(1.5 \pm 0.5)\%$, 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 $2 \times 10^{-6}$ 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.

<table>
<thead>
<tr>
<th>Neutron beam on</th>
<th>Neutron beam off</th>
<th>Number of decay protons in one min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of counts in 20 min</td>
<td>Number of counts in 20 min</td>
<td>Accelerating voltage on</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>864</td>
<td>290</td>
<td>584</td>
</tr>
<tr>
<td>874</td>
<td>249</td>
<td>625</td>
</tr>
<tr>
<td>917</td>
<td>263</td>
<td>654</td>
</tr>
<tr>
<td>858</td>
<td>290</td>
<td>579</td>
</tr>
<tr>
<td>823</td>
<td>213</td>
<td>610</td>
</tr>
</tbody>
</table>
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 x 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 specific activity of each, which was proportional to 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 \( \Sigma P_i \), this quantity, referred to \( \Sigma P_i \), 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.

The coefficient \( k \) was determined with the help of a computer and found to be \( 7.87 \times 10^{-13} \) cm.

The authors are grateful to Academician I. V. Kurchatov for his continuing interest in the work. We want to express our gratitude to the mathematical group, in the persons of M. R. Shura-Bura, E. S. Kuznetsov, and their co-workers I. G. Kru­tkova, V. N. Toroptseva, and O. B. Moskalev, for their indispensable computer work, and also to the group operating the RFT reactor.

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

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.

Translated by W. Ramsay

200

*The value of \( f \) is calculated from the tables of Dzhelepov and Zyryanova. 8

---