Neutron lifetime obtained from Atomic-Energy-Institute experiment [JETP Lett. 28, 303 (1978)]

P. E. Spivak

I. V. Kurchatov Atomic-Energy Institute
(Submitted 8 February 1988)
Zh. Eksp. Teor. Fiz. **94**, 1–11 (September 1988)

Additional information is presented on the procedure used to measure neutron lifetimes in an Atomic-Energy-Institute experiment. A justification is presented for the corrections to the values, published in a brief communication [JETP Lett. **28**, 303 (1978)], of the neutron density and of the recoil-proton counting rate. Allowance for these corrections leads, on the basis of the data of this experiment, to a neutron lifetime value $\tau_n = 891 \pm 9$ s ($T_{1/2} = 616 \pm 6$ s).

INTRODUCTION

Measurement of the neutron lifetime τ_n by recording the beta electrons or recoil protons calls for knowledge of the efficiency ε with which neutron-decay events can be observed. The possibility of determining ε with an error of several tenths of a percent (close to the neutron-density measurement accuracy) is the main criterion for the choice of the particular experimental procedure. In experiments[1–3] and in new planned measurements[4,5] the efficiency ε is a product of two coefficients—of the effective gathering of the neutron decay products from the observed beam volume by the detector, and of their effective registration by the detector. The difficulties that can be encountered in the determination of these coefficients are well illustrated in Ref. 2.

All the cited experiments, both completed[2,3,6] and planned, differ substantially in apparatus and method, but the observation of the decay products is based on electric or magnetic fields that guide the recoil electrons or protons to the detector.

In contrast to this method, the neutron beam and the recoil protons are transported in the experiment of the Institute of Atomic Energy (IAE) in field-free space. It can be seen from Fig. 1, which shows schematically the experimental setup, that prior to entering the region with the accelerating electric field the decay protons pass through the field-free space between diaphragms D_1 and D_2. The fact that the fields do not influence the proton trajectory from the place where they are generated to their exit from diaphragm D_2, and the 100% efficiency of recording protons that proceed to the detector window after passing through the grids, make it possible to determine the efficiency of detection of neutron-decay events by means of the geometric characteristics of the apparatus and the geometry of the distribution of the neutron density over the beam cross section.

In this experiment the neutron lifetime was determined from the equation

$$\tau_n = \varepsilon \eta Q_s / n_p, \qquad (1)$$

where Q_s is the absolute value of the integrated neutron density (in cm^{-1}) in the beam cross section, ε is the efficiency of observation of neutron-decay events:

$$\varepsilon = \iint \rho(\mathbf{r})\, d\Omega\, ds \Big/ \int \rho(\mathbf{r})\, ds,$$

where $\rho(\mathbf{r})$ are the relative values of the neutron density in beam-cross-section elements with coordinates $\mathbf{r}$ relative to D_1 and D_2, η is the penetrability of the grids placed in the recoil-proton path from the diaphragm D_2 to the detector port, and n_p is the recoil-proton counting rate.

Unfortunately, this experiment, capable of determining each of the coefficients ε and η with 0.3% error, could not be performed, as assumed, with the cold-neutron beam from the "PIK" reactor of the Leningrad Institute of Nuclear Physics, in view of the long-delayed startup of this reactor. The measurements were made with the thermal-neutron beam of the IR-8 reactor of our Institute. This lead to a relatively large error in the determination of the beam neutron density, to the need for introducing a number of corrections and, as a result to a measurement error 2.5 times larger (about 1%) than for measurements with a cold-neutron beam. This circumstance, and the hope of repeating the measurements with a cold neutron beam, which seemed very close to realization, led unfortunately to the decision to publish only a brief communication[1] concerning the experiment with the IR-8. In the more than nine years since that communication, however, only one new measurement of the neutron lifetime was performed by observing the products of its decay,[6] with an error of ± 21 s. At the same time, in the cold-neutron-beam measurements of our Institute it is possible to achieve an error $\delta\tau_n = 3.5$–4 sec, which is close to that expected for measurements of τ_n in the most promising projects.[5] We present therefore here additional data on the methods used to determine the quantities in Eq. (1), as well as a corroboration of the corrections introduced, allowance for which leads, on the basis of the data obtained in the experiment of Ref. 1, to a value $\tau_n = 891 \pm 9$ s ($T_{1/2} = 616 \pm 6$ s).

1. The absolute value of the integrated neutron density Q_s was measured by activation of gold foils. Among the advantages of this method are the high accuracy with which the number of atoms in the target is determined, the well-known cross section for neutron capture by ^{197}Au (Refs. 7 and 8), and also the ease of measuring the ^{198}Au lifetime. For a beam from the active region of the reactor, however, this method of measuring neutron density has the serious shortcoming that it is necessary to take in this case into account the appreciable contribution made to the gold activation by the epithermal neutrons from the resonance capture at a neutron energy 4.8 eV, and the need for introducing a number of related corrections into the results. At the same time, the large epithermal-neutron and γ-ray fluxes, as well as the large beam diameter, made impossible absolute measurements of the neutron density by any other known method. The only neutron-density measurement method that could

 0038-5646/88/091735-06$04.00

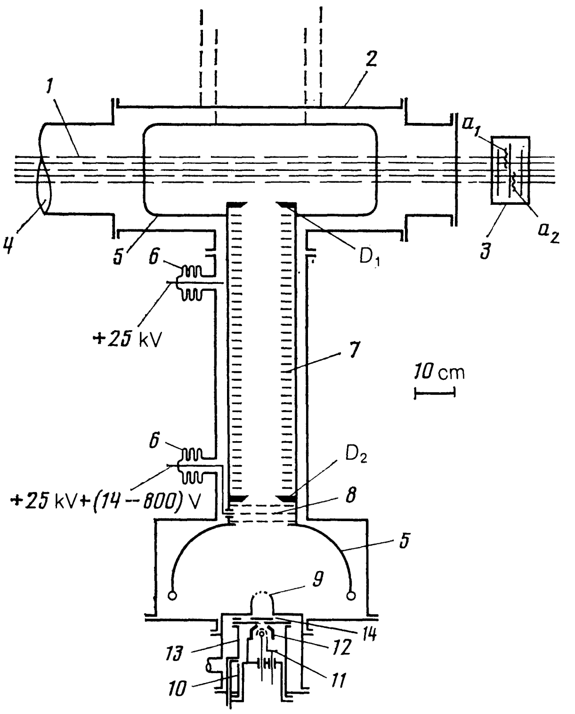

FIG. 1. Schematic diagram of the apparatus for the neutron-lifetime measurement: 1—neutron beam; 2—vacuum chamber; 3—monitor chamber (a_1 and a_2 are ^{233}U layers); 4—channel for passage of extracted neutron beam to a trap and to a vacuum post; 5—electrodes; 6—ceramic insulators; D_1 and D_2—diaphragms; 7—aluminum-foil rings; 8—electrostatic-filter grids; 9—hemispherical grid; 10—detector vacuum chamber; 11—detector gas-filled volume; 12—detector comprising a proportional counter with a drift grid; 13—film-covered detector port; 14—valve separating the volumes of chambers 2 and 10.

be used in this experiment was by gold-foil activation.

The sought neutron density Q_s [cm^{-1}] was obtained from the equation

$$Q_s = C\{[J_0 - J_0(\mathrm{Cd})a]\alpha\beta\}, \qquad (2)$$

where J_0 and $J_0(\mathrm{Cd})$ are the specific activities of the irradiated gold foils, obtained by summing the measured absolute activities of the foil elements, referred to their thickness (in mg/cm^2), and the time of foil irradiation with account taken of the corrections for decay. The designation (Cd) indicates irradiation behind a cadmium screen; C is a proportionality coefficient that contains only universal constants and the activation cross section $\sigma(^{197}\mathrm{Au}) = 98.7$ b (Refs. 7 and 8) for $E_n = 0.0253$ eV; α is the correction for the contribution of the epithermal neutrons to the sought neutron density; β is a correction for the deviation of the gold cross section from the $1/v$ law; a is a correction for the decrease of the flux of epithermal neutrons at the location of the gold foil, owing to their scattering and absorption in the cadmium screen.

To determine the coefficient a, gold foils measuring 1.1×1 cm were placed in the central part of the beam on the neutron-density distribution plateau, and were irradiated behind Cd screens of varying thicknesses (1, 2, and 3 mm). Extrapolation of the specific activities of the foil to zero screen thickness has shown that a screen 1 mm thick decreases the activity by 2.8%, i.e., $a = 1.028 \pm 0.002$.

The coefficient α was obtained from the cadmium ratio $K = Q_s(\mathrm{Cd})$ and was measured using a ^{6}LiF target, a layer of which was deposited on one side of a 0.5×1 cm aluminum foil, facing the window of a proportional gas (CH_4) counter for α particles from the reaction $^6\mathrm{Li} + n \rightarrow \alpha + {}^3\mathrm{H}$. The target was mounted at angle 30° to the beam axis and could be moved together with the counter, at a constant distance (≈ 80 cm) between them, inside the evacuated volume of the chamber in two mutually perpendicular directions relative to the beam axis, in steps of 0.5 cm. The ratio of the particle counting rates, summed over the entire beam cross section area, measured with open and screened beams, is equal to the value of K, or to $K = 38.1 \pm 0.08$ when the coefficient a is taken into account. As a result, the sought coefficient α, which takes into account the contribution of the epithermal neutrons to Q_s, is equal to $K/(K-1) = 1.027 \pm 0.003$.

In this experiment we obtained simultaneously also preliminary information on the neutron-density distribution in the beam cross section. It was found to be in good agreement with the more accurate (described below) measurement of $\rho(\mathbf{r})$, which served as the basis for the calculation of ε.

The coefficient β for the beam from the active zone of the reactor was obtained by a calculation carried out for a Maxwellian spectrum at equilibrium temperature 60° C to which a Fermi distribution is "joined." The calculation yielded $\beta = 0.978 \pm 0.002$.

The absolute values of the activities of the irradiated foils were obtained by the $4\pi\beta\gamma$ coincidence method. The gold foils, covering the 9-cm neutron-beam diameter, measured 11.5×11.5 cm. Naturally, a foil of this size could not be placed in the $4\pi\beta$ counter of the apparatus. To measure its activity the foil had to be cut into elements with maximum dimensions not larger than 2 cm. The foils were therefore cut into one hundred 1.15×1.15 cm elements. (Cutting the foil with the aid of a special stencil did not result in a weight loss exceeding 10^{-3} %.)

Dividing the foil into elements excluded the possibility of appearance in the specific activity J_0 of a systematic error, brought about by the uneven thickness of the foil. As will be shown below, it made it also possible to obtain the density distribution of the neutrons in the beam cross section.

Determination of the integrated specific activities of the foils [J_0 and $J_0(\mathrm{Cd})$] called for an accurate and laborious procedure: division of the foils into elements, weighing the elements, and measuring their intensities. The latter was performed using a precision $4\pi\beta\gamma$ setup developed in the author's laboratory and calibrated with the aid of auxiliary apparatus[9] that made possible, without substantial loss of accuracy, rapid measurements of the activities of a large number of foil elements.

As seen from Eq. (2), the resultant error δQ_s depends on the contribution of the systematic errors of the values of three coefficients. From what has been said above concerning the values and errors of these coefficients, one could hope this contribution not to exceed the error of $J_0 - J_0(\mathrm{Cd})$. Nonetheless, to verify the absence of some unaccounted-for corrections or of incorrectly determined values in the curly brackets of Eq. (2), a control experiment was performed.[10] In this experiment we compared the density ratio of the neutrons of the beam from the active zone of the reactor and the beam of cold neutron with energy limit $6\cdot 10^{-2}$ eV (Ref. 11), obtained from the ratio of the specific activities of the gold foils and from the ratio of the counting rates of the α particles from the target with ^{6}Li. The measurement showed

TABLE I.

Source of error	Error, %
Possible procedural error revealed by the result of a control experiment	0.5
Error in the measurement of the absolute value of the difference between the specific activities J_0 and $J_0(\mathrm{Cd})$	0.6
Error in the knowledge of the cross section for gold activation	0.2

these ratios to be equal within a measurement error $\pm 0.5\%$. Since $J(\mathrm{Cd}) = 0$ for gold foil activated by a beam of cold neutrons, and the error in the deviation from the $1/v$ law is $\beta = 0.9985$, this result offers evidence that the possible procedural error in the determination of Q did not exceed $\pm 0.5\%$.

Table I indicates the sources and values of the errors in the measurement of the neutron density Q_s.

Two corrections must be introduced in the value $Q_s = (1.0025 \pm 0.0065) \cdot 10^5\ \mathrm{cm}^{-1}$ cited in Ref. 1. One is for the mistaken replacement of $\alpha = 1.027$ by the value $\alpha = 1.024$ which is valid for the central part of the beam. The second correction (0.2%) takes into account the screening of the neutrons in a gold foil 15 mg/cm^2 thick. The corrected value is $Q_s = (1.0075 \pm 0.008) \cdot 10^5\ \mathrm{cm}^{-1}$.

2. The coefficient ε indicative of effective observation of neutron-decay events was obtained by a calculation based on the geometric properties of the channel that separates the recoil protons, and on the form of the distribution $\rho(\mathbf{r})$ of the neutron density in the beam cross section. It suffices to find this distribution in the beam cross section plane along the axis of the diaphragms D_1 and D_2 (at an approximate beam divergence 1° the deviation of its diameter along the central "visible" length was ± 0.2 cm). There was no need to irradiate the foils separately to obtain $\rho(\mathbf{r})$, since this information was contained in the specific activities of the foils irradiated to obtain Q_s. To be able to extract the information, the irradiated foil had to be so oriented that each of its elements could be defined by coordinates relative to the diaphragms D_1 and D_2. To this end, the foil was mounted in a frame equipped with foil-orientation markers. The frame with the oil was placed in a position such that the center of the foil approximately coincided with the point of intersection of the axes of the diaphragms and of the beam collimator. In this position, the distance was measured from some selected point to the foil (say near its center) to the plane of diaphragm D_1. This distance, measured accurate to 0.1 mm, served as the basis for the determination of the foil-element coordinates. To prevent loss of the information on the coordinates of the elements, the procedure for cutting up the foil was accompanied by the elements in numbered cells of the map showing their arrangement in the irradiated foil. The results of measurements of the specific activities of the foil elements, proportional to ρ, have shown that the neutron-density distribution over the beam cross-section diameters took the form of equilateral trapezoids with approximate bases 83 and 95 mm. In addition, the form of the neutron-density distribution at the beam edges was made more precise by cutting sixteen peripheral foil elements into four or two parts each. These measurements have also shown that the integrated neutron density outside a 95 mm diameter is negligibly small.

The value of ε was calculated with a computer by the Monte Carlo method. The scatter of the values of ε, obtained in these calculations at the possible beam-shape variations that could result from the limited number (220) of elements, did not exceed 0.15%. The calculated ε turned out to be $(8.538 \pm 0.024) \cdot 10^{-3}$ cm. The choice of a small solid angle, $\approx 10^{-3}$ of 4π, for the observation the proton recoil was dictated, as will be corroborated below, by the need to satisfy the condition that 100% of the protons be recorded by the detector. The small value of ε notwithstanding, the recoil-proton counting rate was equal to $0.85\ \mathrm{s}^{-1}$, which did not hinder its measurement with high statistical accuracy.

Summarizing the foregoing description of the method used to determine the coefficient ε, it is worth emphasizing that the efficiency could be determined without indirect measurements of the solid angle of the recoil-proton observation, or of the effective volume or length of the beam. The error of ε depended only on the accuracy of the measurements and of the data, incorporated in the program, concerning the base distance from the beam to the diaphragms, the diaphragm diameters, and the neutron-density distribution over the beam cross section.

3. A very important part of the apparatus of this experiment was the monitor chamber. It was placed between the exit diaphragm of the collimator and the port for the entrance of the neutron beam into the vacuum chamber, and it was rigidly secured to them. The central electrode of the chamber was diametrically divided into two parts whose opposite sides, as shown in Fig. 1, were covered with thin uniform ^{233}U layers. Pulses from collector electrodes placed on both sides of the central electrodes were fed to two channels of the electronic circuitry. The diameter of the ^{233}U layer was 90 mm, and the diameter of the collimator exit diaphragm was 78 mm. This construction enabled the chamber to perform two functions. The first was to combine the results of time-separated measurements of the recoil-proton counting rate and of the described activation measurements to yield a single value of the neutron density. The constancy of the counting characteristics of the chamber was periodically checked in the absence of a neutron beam against the counting rate of ^{233}U particles from each section of the chamber. The high long-time stability of the chamber readings made it possible to determine, by measuring the summary fragment counting rate $\approx 2 \cdot 10^3\ \mathrm{s}^{-1}$, the relative values of the neutron density, accurate to several hundredths of a percent.

The second function of the chamber was to monitor the stability of the beam position relative to diaphragms D_1 and D_2. The beam-collimation system design should have ensured constancy of the measured $\rho(\mathbf{r})$, but it had to be recognized that a 1 mm displacement of the beam's "center of gravity" due to a change of its shape or position would cause a 0.25% change of ε. To monitor the beam-position stability the central-electrode diametrical line that separated the ^{233}U layers was perpendicuar to the axis of the diaphragms D_1 and D_2. Control experiment have shown that a 0.2 mm change in the position of the beam's "center of gravity" correspond to a 0.5% change of the ratio of the fragment counting rates from the chamber sections. No such changes were observed during the long duration (more than a year) of the experiment.

4. The efficiency η with which the protons from diaphragm D_2 were recorded in this experiment was likewise determined by a geometric characteristic of the apparatus—the total penetrability of the grids along the path of the protons from the diaphragm D_1 to the detector. This efficiency is equal to the penetrability of the grids if all the protons passing through the grids entering the detector port and are recorded by it with 100% efficiency.

Preliminary calculations and experiments with a $^1H^+$ source were used to choose the optimal detector characteristics: its dimensions, the gas (CH_4) pressure, and the port-film thickness. These experiments have shown that protons accelerated to 25 keV lose about 10 keV on passing through a 25 μg/cm^2 organic (collodion) film. In view of this large energy loss, a satisfactory pulse-amplitude spectral width that did not prevent 100% proton-registration efficiency could be obtained only for small angles of proton incidence on the detector port. Calculations governed by the need for meeting this requirement and for minimizing the diameter of the focal-spot that determines the detector dimensions, the apex angle of the cone with base on the aperture of diaphragm D_2 and with vertex on the beam axis was chosen to equal 6°30′. The distance between the diaphragms and the beam axis was chosen accordingly. Calculations have shown that the maximum proton incidence angle on the detector port was 18° and the focal-spot diameter did not exceed 12 mm.

The recoil-proton pulse-height spectrum (Fig. 2) shows that the fraction of pulses with heights less than one-third of the height at the distribution maximum was 0.1–0.15%. Thus, owing to the small solid angle of the recoil protons, 100% of them were recorded by the detector. At the same time, the proton counting rate $n_p = 0.85\ \mathrm{s}^{-1}$ was also enough, confirming the calculation and experimental results with a $^1H^+$ source, to plot the distribution of the recoil protons over the detector port and to verify that the focal spot diameter does not exceed 11 mm (at a port diameter 17 mm). Entrance of 100% of the protons passing through the grids into the detector and the 100% detector efficiency obviated the need for difficultly obtainable corrections to the proton-registration efficiency; the efficiency was thus equal to the penetrability of the grids.

The penetrability of the grids was measured with a device specially prepared for this purpose, viz., a vacuum chamber containing an α-particle source and an α-particle detector. The necessary displacements of the grids and the source were carried out with a manipulator without breaking the vacuum. The grid penetrability was determined as the ratio of the α-particle counting rates with and without the grids between the source and detector. Leaving out the description of the apparatus and of the measurement procedure (which included also imitation of the angles of recoil-proton incidence on the grids), it should be noted that the accuracy of these measurements was determined not only by the aggregate of the experimental data, which was very large, but mainly by the procedural error, which could be estimated by performing a number of control experiments. The following grid penetrabilities were measured: η_1 of the system of three grids of the electrostatic filter, η_2 of the spherical grid used to focus the recoil protons, and η_3 of the reference grid of the detector-port film. The measurements yielded $\eta_1 = 0.9388 \pm 0.0014$, $\eta_2 = 0.9537 \pm 0.0015$ and $\eta_3 = 0.9764 \pm 0.002$. These data yield $\eta = 0.8742 \pm 0.0026$ for the total penetrability of all grids. (Reference 1 cites a penetrability 0.8716 ± 0.0026 smaller by 0.3%, since the calculations included erroneously the penetrability 0.9735 ± 0.002 of a duplicate grid, which was actually damaged and replaced with the one of penetrability η_3.)

5. Determination of the recoil-proton counting rate called for a thorough investigation of the nature of the background which, as seen from Fig. 2, amounted to ~20% of the effect at a proton-registration efficiency 99.8%). These investigations have shown that, besides the main components of the background due to the γ rays and the fast neutrons, a certain fraction is due to the soft part of a broad spectrum of electrons scattered from the electrode located

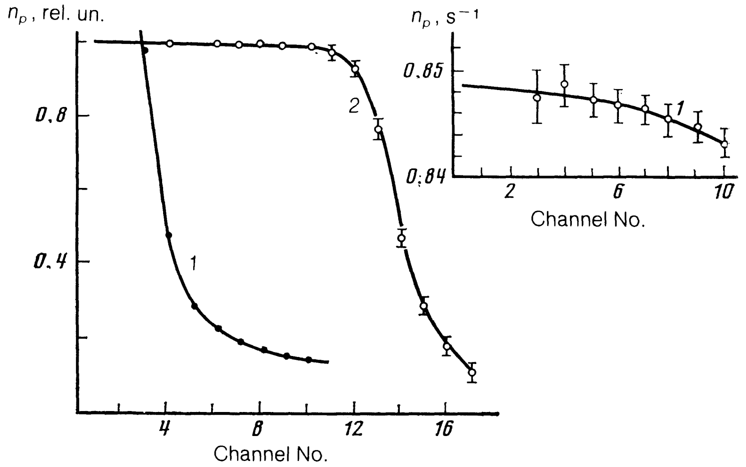

FIG. 2. Integrated pulse-height spectrum: 1—background, 2—recoil protons.

opposite the diaphragm D_1. Registration of the latter by the detector made the largest contribution in the region of small pulse heights, but in view of the multiple scattering of the electrons in the detector, a background was present in the entire significant pulse-height range. A control experiment, in which the beam was blocked by a cadmium screen, has shown that raising the electrode potential from zero to 25 kV changes the background in the region of the second to fourth channels by several percent. The background was therefore measured with an electrostatic filter placed past diaphragm D_2, at a constant potential 25 kV on the electrodes. The background was measured at a threshold potential $+ 800$ V on the central grid of the filter, which retarded the recoil protons, whereas the electrons passing through the filter were accelerated and decelerated in succession without changing the spectrum or intensity.

One more obstacle to the determination of the recoil-proton counting rate could be the $^1H^+$ ions coming from part of the surface of the electrode surface facing electrode D_1, owing to bombardment of the diaphragm by electrons accompanying the neutron beam entering the apparatus. The hydrogen ions passing through the separating channel could cause errors in the measurement of the recoil-proton counting rates, since they were indistinguishable from the latter after acceleration. In a control experiment with the neutron beam blocked by a cadmium screen (producing a 30-fold decrease of the recoil-proton contribution), the hydrogen ions were determined from the difference between the counting rates at zero threshold of the filter and the threshold $+ 14$ V, which calculation of the maximum energy of the $^1H^+$ ions has shown to be more than enough to block them. After outgassing the apparatus to obtain a vacuum of $(3–5)\cdot 10^{-9}$ Torr (to prevent charge exchange of the recoil protons on the path between the diaphragms) and heating the apparatus in an oxygen atmosphere, no hydrogen ions were observable within the limits of experimental error. Nonetheless, to be perfectly sure of total absence of recordable hydrogen ions, the central grid of the filter was always at a potential $+ 14$ V.

As a result of many measurement runs, the recoil-proton counting rate was found to be $0.848 \pm 0.002\ s^{-1}$. Recognizing that 0.36% of protons of energy lower than 14 eV did not pass through the filter, the sought counting rate is $n_p = 0.851\ s^{-1}$. As a control experiment in these measurements (which lasted a net total of 300 hours), we obtained also the counting rate n_p (Cd) for a beam blocked by a cadmium screen. These measurements yielded $n_p/n_p(\mathrm{Cd}) = 37.7 \pm 0.1$. It follows hence that the value of the coefficient α that indicates the contribution of epithermal neutrons to Q_s, is equal to 1.0267 ± 0.003, i.e., agrees within the limit of errors with that previously obtained from measurements of $Q_s/Q_s(\mathrm{Cd})$. (In Ref. 1, owing to an error in the comparison of the ratios $n_p/n_p(\mathrm{Cd})$ and $Q_s/Q_s(\mathrm{Cd})$, an unnecessary 0.3% correction was introduced in n_p. The other correction to n_p (0.25%) to account for the proton loss to reflection from the detector port is likewise unnecessary: it is due to an erroneous interpretation of one of the experiments with a $^1H^+$ source. In fact, the correction for 25-keV protons is appreciably smaller.)

6. The foregoing offered convincing evidence that the proton counting-rate measurements were free of procedural errors connected with the determination of the background. It was impossible in this experiment, however, to avoid completely corrections of the measured recoil-proton counting rate, in view of the influence of the protons on this rate.

One correction may be necessitated by proton scattering from the surface of the electrode between the diaphragms, since $\approx 10^3$ protons/s are incident on the aperture of the diaphragm D_1. However, rings made of thin (20 μm) aluminum foils decreased the scattering surface by a factor 10^3, and it could therefore be assumed that the proton scattering by the walls of the separating channel was negligibly small. The only cause of correction for the admixture of scattered protons to the measured value of n_p was the proximity of the neutron beam to the surface of the cylindrical electrode through which it passed. Part of this surface, opposite diaphragm D_2, served not only as a source of hydrogen ions and electrons (whose influence on n_p was eliminated, as shown above), but was also as a source of recoil protons scattered from the electrode. On the electrode-surface side seen from the aperture of diaphragm D_2 there were incident several thousand protons per second, and that proton fraction reflected in a charged state almost perpendicularly from the surface could pass through the diaphragm D_2.

In the initial design of the apparatus intended for measurements on a beam of cold neutrons, provision was made to move the effective part of the electrode surface to a distance 40–50 cm away (shown by vertical dashed lines in Fig. 1). It was necessary, unfortunately, to forego in the experiment this procedure, which could decrease the effect of the scattered protons on n_p by 20 times, owing to the limited size of the room in which the apparatus for the IR-8 beam was located.

No mention is made in Ref. 1 of the correction to n_p for the admixture of scattered protons, since a preliminary (very crude) estimate raised hopes that the correction would be much smaller than the measurement error, for example the error in the determination of the neutron density. Later, one of the authors of Ref. 1 (Bondarenko) undertook[12] a more precise estimate correction, based on the results of experimental and theoretical investigations of ion scattering from surfaces. His calculations have shown that the correction to n_p ranges from zero to 1%. This estimate agrees with recent results, reported in a diploma paper by Morozov,[13] of a repeated calculation with reference made to more studies. The latter have shown, first, that when the maximum scattering probability in the charged state is chosen the correction to n_p cannot exceed 1.5%, and second, that its most probable value is (0.8 ± 0.35)%. The inaccuracy of the correction was estimated on the basis of the scatter of the experimental data on the scattering probability of protons ($^1H^+$ ions) in the charged state. Introduction of this correction leads to a recoil-proton counting rate $n_p = 0.844 \pm 0.0037\ s^{-1}$.

Table II lists the values, published in Ref. 1, of the quantities that enter in Eq. (1), and their final values after introducing the corrections.

The final value is $\tau_n = 891 \pm 9$ s ($T_{1/2} = 616 \pm 6$ s). The main reason for the large error of the measured τ_n is that the measurements were performed on a beam of neutron from the active zone of the IR-8 reactor.

The proposed repeated measurements of τ_n for a cold-neutron beam will be subject to neither the systematic error 0.35% due to proton scattering nor the systematic error

TABLE II.

Quantities in Eq. (1)	Values published in Ref. 1	Corrections, %	Corrected values
$Q_s \cdot 10^{-5}$ cm^{-1}	1.0025±0.0065	+0.5	1,0075±0.008
$\varepsilon \cdot 10^3$ cm^{-1}	8.538±0.024	–	8,538±0.024
η	0.8716±0.0025	+0.3	0,8742±0.0028
n_p, s^{-1}	0.851±0.002	–0.8	0,844±0.0037

$\pm$ 0.7% in the neutron density. The background, tens of times weaker than in the IR-8 measurements, and the realistic possibility of a more accurate determination of the quantities in Eq. (1), raise hopes of measuring τ_n accurate to 3.5–4 s.

7. The following is a comparison of our results with those by others:

τ_n=918±14 s [Ref. 2], 937±18 s [Ref. 3],

τ_n=891±9 s (present paper),

876±21 s [Ref. 6], 899±11 s [Ref. 14].

(The value of τ_n was obtained in Ref. 14 by measuring the storage time of ultracold neutrons in a vessel coated with heavy-water ice.) The mean-weighted values of $\bar{\tau}_n$ for two groups of data whose values of τ_n agree within the limits of the indicated errors are $\bar{\tau}_n$ 925 $\pm$ 12 s, and $\bar{\tau}_n$ = 892 $\pm$ 7 s.

Obviously, future measurements should be planned with an aim to improve the accuracy of τ_n to 0.3–0.4%. It is realistic to expect this accuracy in the next few years.

Kolebin's group at the Institute of Theoretical and Experimental Physics has proposed[4] and is presently readying an experiment with an intermittent beam of neutrons having a narrow energy interval. This method is used in other projected measurements.[5] It is proposed that in these experiments the neutron density can be measured accurate to 0.2%. In one of them the measurements of τ_n are based on the $4\pi ep$-coincidence method, so that there is no need to know the efficiency. In the other project neutron-beam "trains" pass through a superconducting solenoid and the recoil protons are recorded with 100% efficiency. The prospects of measurements by the method described here have already been discussed. It is possible also that in the nearest few years an accuracy close to 0.3% will be reached also in measurements of the storage time of ultracold neutrons.

[1]L. N. Bondarenko, V. V. Kurguzov, Yu. A. Prokof'ev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 329 (1979) [JETP Lett. **29**, 303 (1978)].

[2]C. Christensen, A. Nielsen, A. Bansen *et al.*, Phys. Rev. **D5**, 1628 (1972).

[3]J. Byrne, J. Morse, K. F. Smith *et al.*, Phys. Lett. **B92**, 274 (1980).

[4]S. M. Kolebin, ITEP Preprint No. 126, 1978. Proc. 6th All-Union Conf. on Neutron Physics, Kiev, 2–6 Oct. 1983. TsNII atominform. 4, 128 (1984).

[5]J. F. Wilkerson, NBS Spec. Publ. Z11. *The Investigation of Fundamental Interactions with Cold Neutrons*, p. 42. J. Byrne, P. G. Dawber, R. D. Scott *et al.*, *ibid.*, p. 48.

[6]J. Last, M. Arnold, J. Dohner *et al.*, Preprint HD-PY 88/01, (1988). Phys. Inst., Univ. of Heidelberg.

[7]F. T. Gould, T. J. Taylor, W. W. Havens *et al.*, Nucl. Sci. Eng. **8**, 453 (1960). J. Als-Nielsen and O. Dietrich, Phys. Rev. **133**, B925 (1964).

[8]W. Dilg, W. Mannhard, E. Steichele, and P. Arnold, Z. Phys. **B264**, 427 (1973).

[9]Ya. Prokof'ev, E. Rogov, and P. Spivak, KIAE (Kurchatov Atom. En. Inst.) Preprint 3632/14, Moscow, 1982.

[10]Yu. A. Prokof'ev, P. E. Spivak, E. V. Rogov, and L. N. Bondarenko, Atom. Energ. **60**, 205 (1986).

[11]M. Zemlyanov, Nucl. Instrum. and Meth. **136**, 425 (1976).

[12]L. N. Bondarenko, KIAE Preprint 3666/2, Moscow, 1982.

[13]I. V. Morozov, KIAE Preprint 50.05/305, Moscow, 1987.

[14]V. I. Morozov, Yu. Y. Kosvintsev, and G. I. Terekhov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 444 (1986) [JETP Lett. **44**, 571 (1986)]. Yu. Yu. Kosvintsev, V. I. Morozov, Yu. N. Panin *et al.*, Proc. Intern. Conf. on Neutron Physics, Kiev, Sept. 1987. TsNII atominform, Moscow (in press).

Translated by J. G. Adashko