# New Measurement of the Charge Radius of the Neutron

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(Received 24 October 1994)

The neutron transmission through a thorogenic liquid $^{208}$Pb sample 2 in. thick has been measured in the neutron energy range between 0.1 and 360 eV at the ORNL neutron source ORELA. Analyzing the shape of the transmission spectra as a function of neutron energy, agreement was found with the predictions by the atomic form factor. With a sensitivity for the mean squared charge radius of the neutron $\langle r_n^2 \rangle$ as high as 3%, a very reliable and also accurate result of $\langle r_n^2 \rangle = -0.113 \pm 0.003 \pm 0.004$ fm$^2$ was extracted. For the neutron-electron scattering length we obtained $b_{ne} = (-1.31 \pm 0.03 \pm 0.04) \times 10^{-3}$ fm.

PACS numbers: 25.40.Dn, 13.40.Gp, 13.60.Fz, 14.20.Dh

High energy lepton scattering by nucleons can be used to obtain nucleon form factors and information on the distribution of valence quarks. Additional knowledge for the neutron can be deduced from neutron-electron scattering where eV neutrons are scattered by electrons bound in diamagnetic atoms. Related experiments reveal information on the low momentum behavior of the electric form factor, i.e., probe the pionic cloud surrounding the core of the neutron.

In the literature neutron-electron scattering is described by its scattering length $b_{ne}$ which is related to the mean squared charge radius of the neutron by $\langle r_n^2 \rangle = c_n b_{ne}$, with $c_n = 3m_e a_0/m_n = 86.387$ fm, where $a_0$ denotes the Bohr radius and $m_n$ and $m_e$ are the masses of the neutron and the electron, respectively. There is a very high confidence that the value of $\langle r_n^2 \rangle$ is negative because of the negative-$\pi$-meson cloud.

Assuming that the neutron behaves like a Dirac particle [1] $b_{ne}$ can be separated into $b_{ne} = b_F + b_I$. The main contribution $b_F$, the Foldy scattering length, is calculated to be $b_F = -1.468 \times 10^{-3}$ fm for the interaction of an electron with a pointlike neutron having the anomalous magnetic moment. The intrinsic scattering length $b_I$ describing the "intrinsic" charge distribution is of minor size. Similarly as for $b_{ne}$ an intrinsic charge radius can be defined as $\langle r_I^2 \rangle = c_n b_I$.

The possibility of determining $b_{ne}$ by measuring the interference of the amplitudes of neutron-electron scattering with the much larger ones of nuclear scattering [2] has found great interest, as shown by the numerous experiments [3–14]. The results of $b_{ne}$ are listed in Table I and show a negative charge radius $\langle r_n^2 \rangle$.

Some of the experiments [3–13] were reviewed by Sears [15], who selected the experiments of Garching [13]

TABLE I. Experimental results of $b_{ne}$ in units of $10^{-3}$ fm.

| Experiments | | | |
|---|---|---|---|
| 1947 [2] | −0.1 ± 1.8 | 1973 [9] | −1.30 ± 0.03 |
| 1951 [3] | −1.9 ± 0.4 | 1975 [10] | −1.60 ± 0.05 |
| 1952 [4] | −1.5 ± 0.4 | 1976 [11] | −1.364 ± 0.025[c] |
| 1953 [5] | −1.39 ± 0.13 | 1976 [11] | −1.393 ± 0.025[c] |
| 1956 [6] | −1.4 ± 0.3 | 1986 [12] | −1.55 ± 0.11 |
| 1959 [7] | −1.56 ± 0.05[a] | 1986 [13] | −1.32 ± 0.04 |
| 1966 [8] | −1.34 ± 0.03[b] | 1992 [14] | −1.38 ± 0.04 |
| This work | −1.31 ± 0.03 ± 0.04 | | |
| **Compilations** | | | |
| Garching-Argonne [8,9,11,13] in Ref. [15] | | | −1.31 ± 0.03 |
| Dubna [10,13] in Ref. [16] | | | −1.59 ± 0.04 |
| Ref. [5] and this work | | | −1.32 ± 0.03 |

[a]To be reevaluated [17].
[b]Value was replaced by the result of Ref. [9].
[c]Value was replaced by the result of Ref. [13].

0031-9007/95/74(13)/2427(4)$06.00  

and Argonne [9] to obtain the very accurate value of $b_{ne} = (-1.31 \pm 0.03) \times 10^{-3}$ fm. In another review [16], Alexandrov has combined his two Dubna experiments [10,12] and obtained a rather different value of $b_{ne} = (-1.59 \pm 0.04) \times 10^{-3}$ fm. The values of Dubna and Garching differ by 5.6 standard deviations. Using Ref. [12] for liquid Bi and the liquid Bi of Ref. [13] a fraction of the discrepancy has been intensively discussed during the last few years [18–21], and the claim has been made that a reason for this difference is the correction for resonances [12,18]. This argument was shown to be unlikely [20], and the Garching value was favored. However, further arguments did not rule out the Dubna value [21]. To be able to resolve the dispute both Refs. [18] and [20] suggested new experiments which would be insensitive to resonance corrections. Some basis for this discussion came probably from the sign of $b_I$ which is negative for the Dubna but positive for the Garching value. Within the approximation of $b_{ne} = b_F + b_I$ some support for the Dubna value has been presented [22]. But it was shown [23] also that the Garching value can be considered to be consistent with the predictions of more accurate models.

In theoretical model investigations, the neutron charge radius $\langle r_n^2 \rangle$ is used (e.g., [24–28]). Outstanding are the calculations with the cloudy bag model [24] predicting a value of $b_{ne} = -1.50 \times 10^{-3}$ fm. But any moderate shifts to more or less negative values could occur since small changes of the pionic distribution may change the value of the charge radius considerably.

Based on the experimental situation we made a new experiment using the approach of Melkonian, Rustad, and Havens [7] for the following reason: This approach should give the most reliable result, if a modern technology for detector and data acquisition systems [29] is applied in an experiment at ORELA at ORNL, where an excellent neutron source is available. Furthermore measurements using thorogenic lead should show extremely low resonance corrections (see Fig. 1) and could give the desired answer [18,20] for some discrepancies of the values of Garching and Dubna.

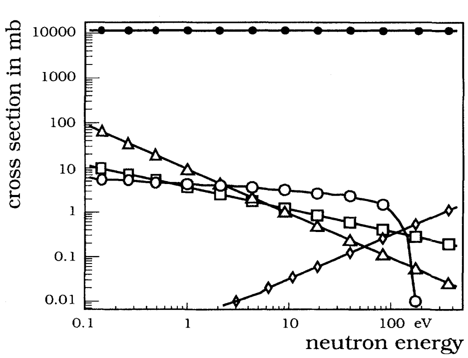


FIG. 1. Cross section and corrections; •, the total Pb cross section; □, absorption; ◇, resonance correction; ∘, background correction; △, condensed matter correction.

Implemented were some improvements: (a) Our neutron time of flight (TOF) setup had a good determination of the neutron energy whereas with the crystal spectrometer [7] there were considerable admixtures of neutrons of higher order reflections. (b) With the TOF setup the geometrical setup was the same for all neutron energies whereas for each energy the geometry had to be modified by changing the scattering angle of the crystal spectrometer. (c) The energy dependent part of the coherent nuclear scattering of our thorogenic liquid lead sample was smaller and therefore easier to be corrected than for the liquid bismuth sample [7]. (d) Our evacuated vessel containing the liquid sample avoided the previous problems [7] of having the liquid sample in a He atmosphere with admixtures of $O_2$ or $H_2$ gases. (e) Using a sample twice as thick as in Ref. [7] the sensitivity of the transmission measurement was increased. In our experiment the contribution of $b_{ne}$ changed the transmission in the energy range from 0.1 to $\simeq$2 eV by up to $\simeq$3%.

Over several years, several periods of experimental work were spent to improve the experimental setup. Best measurement conditions were achieved for a final set of eight runs. Here the accelerator operated with a repetition rate of 100 pulses/s and a pulse width of 10 ns. The TOF geometry was defined mainly by a beam collimator at 8 m with a diameter of 7/8 in. The detector was positioned at 18.08 m. Samples and filters were inserted into the beam at 5, 9, and 10 m. The neutrons were detected with a 1 mm $^6$Li-glass scintillator which was viewed by two photomultiplier tubes (RCA 8854) positioned symmetrically to the beam. The detector signals were fed into a 100 MHz flash-ADC to record both the time and pulse-height information [29]. This allowed an off-line pulse-height discrimination as well as a distinction between the neutrons and the gamma-ray background. The background was evaluated using neutron resonance filters and polyethylene scatterers. In the energy range between 0.1 and 100 eV signal to background ratios of 1500:1 have been achieved. The applied dead-time correction was less than 0.5% for the open beam and 0.1% for the lead sample. Open beam and sample spectra were corrected separately for background, dead time, and overlap. Figure 1 shows some details. Transmission spectra were obtained by the ratio of neutron spectra with and without the sample.

The main point of this work was to obtain a value for $b_{ne}$ from comparing measured and calculated neutron transmission spectra. The calculation of the transmission is explained in Eqs. (1)–(4) below.

The transmission $T(E)$ as a function of the neutron energy $E$ is given by

$$T(E) = \exp[-N\sigma_{\rm tot}(E)], \qquad (1)$$

where $N$ is the sample thickness of 0.154 atoms/b. The total cross section $\sigma_{\rm tot}(E)$ is

$$\sigma_{\rm tot}(E) = \sigma_{\rm coh}(E)S_{\rm coh}(E) + \sigma_{\rm inc}(E)S_{\rm inc}(E) + \sigma_{\rm abs}(E), \qquad (2)$$

with $\sigma_{abs}$, $\sigma_{coh}$, and $\sigma_{inc}$ denoting the absorption, coherent scattering, and incoherent scattering cross section, respectively. Since we used a liquid thorogenic lead sample with the isotopic composition of 0.5% $^{204}$Pb, 25.82% $^{206}$Pb, 1.65% $^{207}$Pb, and 72.54% $^{208}$Pb, the absorption cross section was very small (see Fig. 1). This reduced the systematic uncertainties considerably in comparison to our previous experiment with natural lead [14].

The two functions $S_{coh}(E)$ and $S_{inc}(E)$ describe the condensed matter correction and were approximated by the expressions [30]

$$S_{inc}(E) = \left(\frac{A}{A+1}\right)^2\left(1 + \frac{k_B\theta}{2AE}\right),$$
$$S_{coh}(E) = \left(\frac{A}{A+1}\right)^2\left(1 + \frac{k_B\theta}{2AE} - \frac{C(\theta)}{E}\right), \tag{3}$$

where $k_B$ is the Boltzmann constant and $\theta$ the sample temperature. The numerical value of the parameter $C(\theta)$ depends both on the temperature and on the material of the sample and was determined for lead in separate transmission measurements at various temperatures of the sample. No small angular scattering was required to fit [31] the dramatic transmission pattern down to neutron energies as low as 0.001 eV, and therefore such effects should be negligible above 0.1 eV. For $C(\theta)$ we obtained $0.952 \times 10^{-3}$ eV [31]. Further testing of various methods showed that the estimation of the uncertainty of $C(\theta)$ is less than 5%. Finally the expression for the coherent scattering cross section in first Born approximation is

$$\sigma_{coh} = 4\pi[b_c(E) + b_R(E) - b_{ne}(Z - f(Z,E)) + b_p(E)]^2 + \sigma_{LS}(E), \tag{4}$$

where $\sigma_{LS}(E)$ denotes the Schwinger cross section, $b_c(E)$ the nucleus coherent scattering length [32] including the effective range correction, $b_R(E)$ the energy dependent contribution of the resonance scattering [33] (see Fig. 1), and $b_p(E)$ the contribution caused by the polarizability of the neutron [29]. The atomic form factor $f(Z,E)$ as given by x-ray scattering [34] and integrated over $4\pi$ produces the energy dependence of the $b_{ne}$ contribution. We characterize this energy dependence by $Z - f(Z, 0.1\text{ eV}) \simeq 42$, $Z - f(Z, 2\text{ eV}) \simeq 71$, and $Z - f(Z, 100\text{ eV}) \simeq 81$.

Using the method of least squares the transmission data were fitted for each run separately taking $b_{ne}$ and a value for the normalization as independent parameters (see Fig. 2). The values of $b_{ne}$, its errors, and the weighted mean are listed in Table II as obtained by fitting the data in the energy range from 0.1 to 360 eV. The major contribution to the systematic uncertainty is caused by the condensed matter correction. As this correction decreases rapidly with increasing neutron energy (see Fig. 1) we fitted the transmission data for various energy ranges. The results are listed in Table III and are in agreement within statistical uncertainties.

For the final result we used the fit over the energy range of 0.1 to 360 eV and obtained for the charge radius

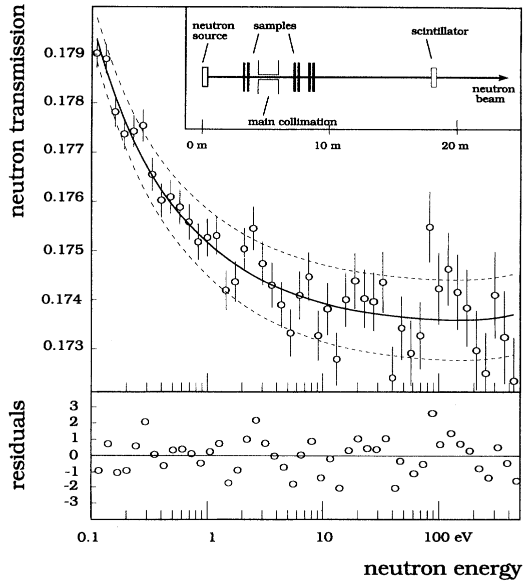


FIG. 2. Transmission of run 402. Open circles: measured data. Solid line: fit by $b_{ne}$ and by normalization. Broken lines: 1 standard deviation from the fit; since the broken lines include the uncertainties of both $b_{ne}$ and normalization, less than 30% of points are outside. The inset shows the experimental arrangement.

$\langle r_n^2 \rangle = -0.113 \pm 0.003 \pm 0.004$ fm$^2$. The two uncertainties denote the statistical and systematic uncertainty, respectively. The major part of the systematic uncertainty (0.003 fm$^2$) can be ascribed to the uncertainty of the condensed matter correction. The remaining parts came from uncertainties in background and dead-time corrections as well as from the resonance contribution.

Our results for $b_{ne}$ are shown in Table I. Compared to the compilations we agree with the value of Garching, but disagree with the value of Dubna. As Ref. [5] agrees with our value, we present in Table I, last line, a new compiled value, assuming that our systematic uncertainty can be approximated by a standard deviation of $0.02 \times 10^{-3}$ fm. Summarizing the experiment we obtained the following:

(a) A very low and reliable background correction (see Fig. 1) was achieved by optimizing experimental condi-

TABLE II. Results of $b_{ne}$ for the various runs.

| Run number | $b_{ne}$ ($10^{-3}$ fm) |
|---|---|
| 390 | $-1.335 \pm 0.168$ |
| 395 | $-1.351 \pm 0.072$ |
| 396 | $-1.303 \pm 0.075$ |
| 401 | $-1.359 \pm 0.069$ |
| 402 | $-1.388 \pm 0.087$ |
| 415 | $-1.261 \pm 0.092$ |
| 417 | $-1.190 \pm 0.077$ |
| 420 | $-1.270 \pm 0.083$ |
| Mean value | $-1.308 \pm 0.029$ |

TABLE III. Results of $b_{ne}$ for various energy ranges with statistical and systematic uncertainties.

| Energy | $b_{ne}$ ($10^{-3}$ fm) |
|---|---|
| 0.100–360 eV | $-1.308 \pm 0.029 \pm 0.030$ |
| 0.150–360 eV | $-1.306 \pm 0.035 \pm 0.025$ |
| 0.230–360 eV | $-1.335 \pm 0.043 \pm 0.020$ |
| 0.330–360 eV | $-1.272 \pm 0.052 \pm 0.015$ |
| 0.480–360 eV | $-1.305 \pm 0.065 \pm 0.010$ |

tions. (b) To determine a value for $b_{ne}$ the validity of the condensed matter correction was verified for the energy range between 0.1 and 360 eV. (c) For the first time the shape of the energy dependence of the contribution of $b_{ne}$ to the transmission was examined and showed its dependence on the atomic form factor. (d) The value of $b_{ne} = (-1.31 \pm 0.03 \pm 0.04) \times 10^{-3}$ fm obtained depends only on the energy dependence of the transmission and not directly on its absolute value.

We thank the ORELA staff for providing us with the best experimental conditions. We thank also H. Leeb for valuable help and D.C. Larson and H. Rauch for their support. This research was sponsored by the Office of Energy Research, Division of Nuclear Physics, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and was supported by the Austrian Fonds zur Forderung der Wissenschaftlichen Forschung under P-8489 and P-9802.

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