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Study of Electromagnetic Structure of the Neutron by Neutron Interferometry Method

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The problem of the determination of the neutron-electron scattering length and following from it the question about the sign of the mean square intrinsic charge radius of the neutron is a subject of active studies and discussions last years. A new experimental approach and a new model-independent method of the evaluation of the neutron-electron scattering length from the data obtained in neutron transmission and neutron interferometry experiments are proposed.

KEYWORDS: Fundamental Properties of the Neutron, Neutron Interferometry

1. The mean square electrical radius of the neutron and its polarizability

One of fundamental problems of nuclear physics is the electrical structure of the neutron. The characteristic of such a structure is an electrical charge distribution inside it - the mean square electrical radius of the neutron and its polarizability, i.e., the induced electrical dipole moment that appears in the external field.

The problem of determination of the neutron-electron scattering length a_{ne} and following from it the question about the sign of the mean square intrinsic charge radius of the neutron $\langle r_{in}^2 \rangle_n$ has been a subject of active studies and discussions for some years[1-5]. This value is a characteristic of the electrical charge distribution inside the neutron:

$$\langle r_{in}^2 \rangle_n = \rho(r) \cdot r^2 \cdot d^3r \Big/ \rho(r) \cdot d^3r \qquad (1)$$

It can be determined by the neutron-electron interaction amplitude a_{ne} and the Foldy parameter a_F [2]:

$$\langle r_{in}^2 \rangle_n = \frac{3\hbar^2}{Me^2}(a_{ne} - a_F) \qquad (2)$$

Thus, for an experimental determination of $\langle r_{in}^2 \rangle_n$ one has to measure a_{ne} and compare its value with the Foldy parameter.

In spite of the relative weakness of neutron - electron interaction producing only small effects when compared to those due to strong nuclear interaction, they can be detected because of the interference between neutron waves, scattered at a nucleus and at atom electrons, that allows an experimental determination of the mean square electrical radius of the neutron and its polarizability. Certainly, these effects are most pronounced in the neutron, where the parameters in question can be obtained from the energy dependence of the total neutron cross section $\sigma_{tot}(E)$ measured in neutron transmission experiments and $\sigma_{tot}(0)$. Values of the amplitude of the neutron-electron interaction amplitude a_{ne} obtained in experiments on neutron transmission [4, 19, 5]

$$a_{ne} = -(1.309 \pm 0.024)\ 10^{-3}\ \text{fm}$$
$$a_{ne} = -(1.309 \pm 0.024)\ 10^{-3}\ \text{fm} \qquad (3)$$
$$a_{ne} = -(1.577 \pm 0.034)\ 10^{-3}\ \text{fm}$$

result in fatal uncertainty in the determination even of the sign of the mean square electric charge radius of the neutron.

At present it is commonly accepted, that this difference is connected with methods of the data treatment, because both groups have used practically the same set of experimental data [1, 3]. It should be noted, that experiments on neutron diffraction on a monocrystal of ^{186}W [6] have resulted in $a_{ne} = -(1.60 \pm 0.05) \cdot 10^{-3}$ fm, so that the difference of values of a_{ne} is significant. Therefore, a new method of evaluation of experimental data is required, which is discussed in the next chapter.

At present experiments aiming at an increase of the accuracy of the determination of the neutron-electron scattering amplitude a_{ne} and the polarizability α_n of the neutron are in progress in both Berlin and Prague[7]. The values of a_{ne} and α_n can be obtained from energy dependence of the coherent scattering cross section $\sigma_{coh}(E)$ over a rather wide energy range E = 0 - 200 keV. This cross section can be defined as the potential part of the total neutron cross section $\sigma_{tot}(E)$, which can be experimentaly measured. However, to do this $\sigma_{tot}(E)$ should be corrected for incoherent scattering, absorbtion and resonance contributions for all isotopes, contained in the sample.

At thermal energies the total cross section is also strongly influenced by solid state effects (connected with the aggregate state of the sample), which can be evaluated only with a limited precision [8]. These corrections are small and defined with reasonable accuracy in the electron-volt region, but are very large and uncertain for very low

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energies ($E \sim 0$). Therefore, it is proposed to obtain $\sigma_{coh}(0)$ from the neutron scattering length b_{coh} measured by thermal neutrons ($E \sim 10^{-3}$ eV).

Because of the Z-dependence of a_{ne} (Z - the nuclear charge), these measurements have to be carried out on atoms of heavy elements. The lead isotope ^{208}Pb is particularly interesting, because its nucleus has only two resonance levels [9] that significantly contribute to the total neutron cross section. For these reasons we aim to carry out the precise measurements to an accuracy of about 10^{-4} both of $\sigma_{tot}(E)$ (by the method of resonance detectors[10]) and of b_{coh} (by the neutron interferometry method[7]) on a highly enriched ^{208}Pb sample. All these experiments will be carried out with the same sample: such an approach will allow us to eliminate uncertainaties resulting from possible contaminations in the sample.

2. The determination of a_{ne} from neutron interferometry and transmission experiments.

The problem of the analysis of experimental data, obtained in neutron transmission experiments and aimed at the determination of the neutron-electron interaction amplitude a_{ne}, has been widely discussed during recent years.[1, 11, 12] At present it is commonly accepted that the basic cause of contention between the two groups (see Eq. (3)) is the procedure used to account for the resonance scattering contribution .

The experiments in question are usually carried out with isotopically enriched samples of heavy elements, such as Pb or Bi. The measured value is the total neutron cross section $\sigma_{tot}(E)$ (E - the neutron energy), whereby one can obtain the coherent scattering cross section σ_c making corrections to absorption, incoherent, spin-orbit and solid-states effects:

$$\sigma_s(k) = \sigma_{tot}(k) - \sigma_a - \sigma_{inc} - \sigma_{LS} - \sigma_{sol} \quad (4)$$

Using

$$\sigma_a(k) = \frac{4\pi}{k}\mathrm{Im}\, a_c(k) \quad (5)$$

one can obtain the real part of the coherent scattering length $a_c(k)$:

$$a_c(k) = \sqrt{\frac{\sigma_s(k)}{4\pi} - \frac{\sigma_a \cdot k}{4\pi}} \quad (6)$$

On the other hand, the coherent scattering length $a_c(k)$ is connected with the real part of the coherent scattering amplitude:

$$a_c(k) = -\mathrm{Re}\, f(k) = \frac{1}{2k}\sum\nolimits_1 - \frac{\delta}{k}\cdot\left(1 - \frac{1}{2}\sum\nolimits_2\right) \quad (7)$$

Here δ is the total phase of all scattering processes:

$$\delta = \delta_0 + \delta_{ne} + \delta_{pol} = kR'e(k) + ka_{ne}Z[F(k) - h(k)] + ka_{pol}\cdot g(k) \quad (8)$$

where R' is the nuclear potential radius, $F(k)$ - the angular averaged atomic form factor [9], a_{pol} - the neutron's electric polarization length; ($R_N = 1.2027A^{1/3}$ - heavy nuclei charge radius)

$$e(k) = 1 - \frac{(kR')^2}{6} + \frac{(kR')^4}{120} + \ldots$$

$$h(k) = 1 - \frac{(kR_N)^2}{5} + \frac{2\cdot(kR_N)^4}{135} + \ldots$$

$$g(k) = 1 - \frac{\pi(kR_N)}{3} + \frac{(kR_N)2}{3} - \frac{4\cdot(kR_N)^4}{135} + \ldots$$

are the effective range correction and averaged nuclear form factors, respectively. The summation in Σ_1 and Σ_2 are performed over all known resonances with energy E_j ($\Delta E_j = E - E_j$) and momentum k_j:

$$\Sigma_1 = \sum_i \frac{k}{k_i}\frac{g_i\Gamma_{n_i}\Delta E_i}{\left(\Delta E_i^2 + \frac{\Gamma^2}{4}\right)} \qquad \Sigma_2 = \sum_i \frac{k}{k_i}\frac{g_i\Gamma_{n_i}\Gamma_i}{\left(\Delta E_i^2 + \frac{\Gamma^2}{4}\right)} \quad (9)$$

Substituting (8) to (7) and separating E - independent terms, one can obtain Eq.(10): (*see below*)

The first two terms in this expression are E-independent and their sum is in fact the coherent scattering length $a_c(0)$:

$$\frac{1}{2k}\sum\nolimits_1 + \left[R_j'\cdot e(0) + a_{pol}\cdot g(0)\right] = a_c(0) \quad (11)$$

Now, substituting (11) to (10) we come to the final expression (Eq. (12), *see below*) whereby one can evaluate a_{ne}. The traditional way of the data processing is to extract the contribution of the isotope with the highest abundance, i.e., to insert isotopic corrections into (12): to do this one needs to use table data on R' and resonance parameters for all isotopes of the sample. The results of our calculations made for the neutron scattering length value b_c = 9.488 fm and the values of σ_{tot} for E = 1.26 eV taken from Ref. 11 are presented in Table 1.

$$a_c(k) = \frac{1}{2k}\sum\nolimits_1 + \left[R'\cdot e(k) + a_{ne}Z[F(k) - h(k)] + a_{pol}\cdot g(k)\right]\cdot\left(1 - \frac{1}{2}\sum\nolimits_2\right) = \quad (10)$$
$$= \frac{1}{2k}\sum\nolimits_1 + \left[R'e(0) + a_{pol}g(0)\right] + \left\{R'\left(e(k) - e(0)\right) + a_{ne}Z[F(k) - h(k)] + a_{pol}\left(g(k) - g(0)\right)\right\}\cdot\left(1 - \frac{1}{2}\sum\nolimits_2\right)$$

$$a_c(k) = a_c(0) + \left\{R'\left(e(k) - e(0)\right) + a_{ne}Z[F(k) - h(k)] + a_{pol}\left(g(k) - g(0)\right)\right\}\cdot\left(1 - \frac{1}{2}\sum\nolimits_2\right) \quad (12)$$

Table 1. Results of calculation of a_{ne} according to Eq. (12) for different sets of R' for enriched sample of ^{208}Pb

Ref.	^{204}Pb < 0.02 %	^{206}Pb 0.64%	^{207}Pb 2.06%	^{208}Pb 97.3%	$a_{ne,\,mfm}$
14	9.75(5)	9.6(2)	9.7(1)	9.83(6)	1.301
15	9.5	9.46	9.3	9.8	1.459
16	9.55	9.52	9.5	9.78	1.383
17	9.4	9.76	9.52	9.86	1.340
17	9.3	93483	9.429	9.476	1.416

One can see a significant instability in such a method: the use of different sets of R' proposed by different authors, results in significant difference in a_{ne}.

We have developed a new model-independent method[18] of the experimental data processing. The idea is to avoid the use of the procedure discussed above that aims to obtain a result for *the single isotope*, but to carry out calculations for *the sample as a whole*; the details of this method are presented below.

Again, we use the relations discussed above (Eqs. (4-12)), but now they are referred to the j-th isotope of the sample under the study.Thus, one can write: Eq.

$$a_c(k) = -\mathrm{Re} f(k) = \frac{1}{2k}\sum_1^j - \frac{\delta}{k}\cdot\left(1-\frac{1}{2}\sum_2^j\right) \quad (13)$$

In these sums Σ_1^j and Σ_2^j parameters of all resonance are related to the j -th isotope.

Following the above procedure, one can obtain: (Eq. (14), *see below*)

where $a_c^j(0)$ is the coherent scattering length of the j -th isotope:

$$a_c^j(0) = \frac{1}{2k}\sum_1 + \left[R_j'\cdot e(0) + a_{pol}\cdot g(0)\right] \quad (15)$$

In order to get the bound scattering length, one has to multiply both parts of (Eq. 15) by $\frac{A_j+1}{A_j}$.

Now let us consider the sample, that has an isotopic abundance c_j:

$$\sum_j c_j = 1 \quad (16)$$

Making the summation over both parts of Eq.(14) with the weights c_j, we obtain: (Eq. (17), *see below*)

Finally, using

$$b_c^j(0) = \frac{A_j+1}{A_j} a_c^j(0) \quad (18)$$

we come to the expression for the neutron-electron interaction amplitude: (Eq. (19), *see below*)

Let us consider this formula. The first term in the numerator is the coherent scattering length of the sample and can be expressed as Eq. (20) (*see below*)

The second term in the numerator is the neutron scattering length b_{coh} *of the sample*, that it is measured by the neutron interferometry experiment, i.e., it *has not been corrected* for the isotope composition value.

The third term in the numerator can be calculated and its contribution to the a_{ne} is rather small, in order of 10^{-5}-10^{-6} in our case, with the exception of the point E = 1970 eV, where it is of about 10^{-4}. Thus, this approach allows us to extract the value of a_{ne} from the set of experimental values principally *without* any isotopic corrections (it should be noted however that the isotopic composition of the sample is considered to $\sigma_{tot}(k)$, Eq. (20)). Calculations carried out by Eq. (19) for the same input data set as have been used for calculations by Eq. (12) result in $a_{ne} = 1.413\cdot10^{-3}$ fm and is independent on the choice of sets of R'.

$$a_c^j(k) = a_c^j(0) + \left\{R_j'\left(e(k)-e(0)\right) + a_{ne}Z[F(k)-h(k)] + a_{pol}\left(g(k)-g(0)\right)\right\}\cdot\left(1-\frac{1}{2}\sum_2^j\right) \quad (14)$$

$$\sum_j \frac{A_j+1}{A_j} c_j a_c^j(k) = \sum_j \frac{A_j+1}{A_j} c_j a_c^j(0) + a_{ne}Z\cdot[F(k)-h(k)]\cdot\sum_j c_j\frac{A_j+1}{A_j}\left(1-\frac{1}{2}\sum_2^j\right) + \sum_j c_j\frac{A_j+1}{A_j}\left\{\left\{R_j'\left(e(k)-e(0)\right) + a_{pol}\left(g(k)-g(0)\right)\right\}\cdot\left(1-\frac{1}{2}\sum_2^j\right)\right\} \quad (17)$$

$$a_{ne} = \frac{\left\{\sum_j c_j\frac{A_j+1}{A_j}a_c^j(k) - \sum_j c_j b_c^j(0) - \sum_j c_j\frac{A_j+1}{A_j}\left[\left\{R_j'\left(e(k)-e(0)\right)+a_{pol}\left(g(k)-g(0)\right)\right\}\cdot\left(1-\frac{1}{2}\sum_2^j\right)\right]\right\}}{Z\cdot[F(k)-h(k)]\cdot\sum_j c_j\frac{A_j+1}{A_j}\cdot\left(1-\frac{1}{2}\sum_2^j\right)} \quad (19)$$

$$a_c^{sample}(k) = \sqrt{\frac{\sigma_{tot}(k)-\sigma_a-\sigma_{inc}-\sigma_{LS}-\sigma_{sol}}{4\pi}} - \frac{\sigma_a\cdot k}{4\pi} \quad (20)$$

3. The accuracy of the determination of a_{ne} from experimental data.

Now we have to make an important remark, concerning the accuracy of the determination of a_{ne}. Results of calculations carried out by the proposed method are stable (practically independent) under variations of nuclear parameters (R', Σ_1 and Σ_2). At the same time the accuracy of a_{ne} is mainly defined by the accuracy of experimental values - $\sigma_{tot}(k)$ and b_{coh}. This fact is illustrated by Fig. 1, where the dependence of a_{ne} on the accuracy of b_{coh} is presented. One can see, that already a standard deviation from b_{coh} = 9.494(29) of the ^{208}Pb enriched sample (the best accuracy obtained up to the present [7]) results in such large deviation of a_{ne}, that it covers the range from a_{ne} = - 1.09×10^{-3} fm to a_{ne} = - 1.88×10^{-3} fm. Considering this, the rather high accuracy on a_{ne} reported in [11] of 5 % based on b_{coh} of 9.50(6) fm seems strange indeed.

The error in the result of experiment[7] is mainly connected to the uncertainty of the effective wavelength λ used for the calculations of b_C. Therefore, at the next experiment we are going to use an advanced method allowing us to monitor the neutron wavelength during the interferometrical measurement with the aim to achieve an accuracy of about 0.01 %.

Our understanding is that the error bar of the value of a_{ne} that has been obtained from the presently available total neutron cross sections and neutron scattering length values should be significantly increased. This fact may go some way to lessen the conflict between the two reported evaluations of a_{ne}; a conflict that should be resolved by the high accuracy measurements currently under way.

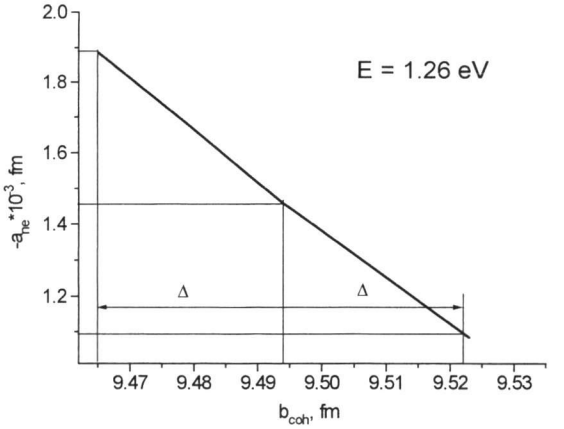

Fig. 1. Dependence of a_{ne} vs. b_{coh}. Δ is the standard deviation of the present day data.

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Note added in proof

In oral disscussions at this Symposium a new approach to this problem was mentioned [19, 20], which is to cancel the Foldy term in Eq. (2), so that $\left\langle r_{in}^2 \right\rangle_n \sim a_{ne}$ and is certainly negative. Discussions of this theoretical question is out of the scope of the present article.

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