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Yu. A. Alexandrov

SOME PRINCIPAL PROBLEMS IN PHYSICS AND LOW-ENERGY NEUTRON PHYSICS

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Александров Ю. А. E3-2004-164
Некоторые принципиальные вопросы физики и нейтронная физика низких энергий

Рассмотрены некоторые принципиальные вопросы, связанные с внутренней структурой элементарных частиц, в частности нейтрона, полученные в нейтронной физике низких энергий.

Первый вопрос касается зарядового радиуса нейтрона $< r_E^2 >^{1/2}$, связанного с величиной длины рассеяния нейтрона на электроне a_{ne}, измеряемой при низких энергиях. Достигнутая в настоящее время точность измерений позволяет не только говорить о величине $< r_E^2 >$, но и определить ее дираковскую и фолдиевскую части. Знак первой части оказывается прямым образом связанным с фундаментальной теорией Юкавы, объясняющей происхождение ядерных сил. Одно из популярных экспериментальных значений дираковской части (из величины $a_{ne} = (-1{,}32 \pm 0{,}03) \cdot 10^{-16}$ см) противоречит теории Юкавы.

Второй вопрос также имеет отношение к пространственной протяженности нуклона. В середине 1950-х гг. было введено понятие деформируемости, т. е. поляризуемости нуклона в электромагнитном поле. Приводятся положительные доводы об экспериментальном обнаружении электрической поляризуемости нейтрона уже в нейтронных опытах 1957 г., т. е. ранее, чем в опытах по определению поляризуемости протона (1960 г.).

Наконец, третий вопрос касается поисков магнитного заряда нейтрона. Обсуждается опыт (Финкельштейн, Шалл, Цалингер, 1986 г.), свидетельствующий с большой точностью об отсутствии такого заряда у нейтрона. Данный дифракционный эксперимент базировался на концепции существования аномально малой эффективной массы нейтрона, обуславливающей высокую чувствительность эксперимента. Существование изолированного магнитного заряда (монополя Дирака) в природе объяснило бы факт квантования электрического и магнитного зарядов (Дирак, 1931 г.).

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Alexandrov Yu. A. E3-2004-164
Some Principal Problems in Physics and Low-Energy Neutron Physics

The questions connected with internal particle (e. g. neutron) structure obtained at low-energy neutron physics are discussed.

The first question deals with the charge neutron radius $< r_E^2 >^{1/2}$ connected with the value of neutron–electron scattering length a_{ne} determined at low neutron energies. At present, the obtained accuracy allows us to speak not only about the value of $< r_E^2 >$ but also on the segmentation of $< r_E^2 >$ into Dirac and Foldy addenda. The sign of the Dirac addendum is connected directly with the fundamental Yukawa theory explaining the origin of nuclear forces. One of the popular experimental values of the Dirac addendum (from $a_{ne} = (-1.32 \pm 0.03) \cdot 10^{-16}$ cm) contradicts the Yukawa theory.

The second question also concerns the subject of the structure of the neutron, namely its deformation. The notion of deformation (polarizability) of the nucleon in electromagnetic field was introduced in the mid-1950s. The reasons are given in favor of the opinion that the neutron polarizability was observed for the first time in neutron experiments as far back as 1957, i. e. earlier than proton polarizability was detected (1960).

Finally, the third question deals with the search for a magnetic charge of the neutron. A beautiful experiment (Finkelstein, Shull, Zeilinger, 1986) testifying with high accuracy the absence of a magnetic charge of the neutron is discussed. This diffraction experiment was based on the concept of anomalous small effective mass of the neutron providing greatly enhanced sensitivity. The existence of an isolated magnetic charge in the nature would explain the quantization of electric and magnetic charges (Dirac, 1931).

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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INTRODUCTION

Physics is a single whole, therefore the answers to some principal questions should be sought for not only in high energy physics, but also in other fields of physics, e. g. in low-energy neutron physics. Especially since the accuracy of experiments in neutron physics is frequently much higher. In the opinion of Prof. Blokhintsev the division into high and low energy physics is incorrect. Some high-energy physics specialists sometimes do not pay attention to very accurate low-energy physics experiments bringing to light significant questions of fundamental physics.

It is well known that the history of science not only implies the accumulation of new facts and concepts but also the history of human lives. The people who developed the foundations of modern physics were not merely physicists. The majority of them belonged to the entire human culture. Bohr, Heisenberg, Laue, Einstein, and Erenfest could play different musical instruments brilliantly. Luis de Broiglie was a historian, Schrödinger, Planck, Sommerfeld, and others wrote poetry. Schrödinger, in addition, was a philosopher and a theologist. Heisenberg was a mountain climber. In addition, he, like Laue, Pauli, and Schrödinger, knew the classical languages. Otto Han, who discovered uranium fission, sang in a choir, in his young years, conducted by Planck, who in addition gave lectures on musical theory at a university, and who had dreamt of becoming a pianist when he was young. The list could be easily continued.

Therefore fundamental questions of physics have to concern not only physicists but other representatives of human culture, many interesting people who made useful things for humanity.

I would like to talk about the results relating to the spatial structure of one of the ultimate particles, one that is present in our bodies as well as in the surrounding universe — namely, the neutron. The results I am going to present, follow from a number of experiments carried out in the area of low-energy neutron physics of about several hundred eV and lower.

What is the structure of the neutron? Today, it is known that the neutron is a non-point particle. It has an inner structure. What is this structure? Physicists have been dealing with this problem for many years. I became interested in the problem in the early 1950s, in the days of my long gone youth. At that time, in Obninsk near Moscow, we were not occupied with fundamental research, but were participating in starting the city's Atomic Power Station (1954). But thanks to one of my teachers, Prof. D. I. Blokhintsev, we were involved in science. I could talk long about that time and tell many interesting things. But I will only talk about the thing that still intrigues me: what is the structure of the neutron?

In Obninsk, in the 1950s, many interesting investigations were performed. Among them, the so-called Schwinger small-angle neutron scattering due to the electromagnetic interaction between the moving magnetic moment of the neutron and the Coulomb fields of nuclei was found for the first time (1956), the concept of electric neutron polarizability at heavy nuclei scattering was introduced (1955-56s), and there, the first experimental studies of these phenomena were carried out.

I would like to say a few words about some properties of the neutron as elementary particle.

1. ON THE NEUTRON–ELECTRON INTERACTION

When the first evaluations of neutron–electron $(n-e)$ interaction were made in the early 1930s of the last century, Fermi and Marshall [1] began more accurate measurements of this interaction, which were made only in the late 1940s and later. Between the neutron and the electron an interesting type of interaction can exist. It arises as a consequence of the Yukawa meson theory of nuclear forces. Owing to the virtual dissociation of a neutron into a proton and a π^- meson , the neutron is surrounded by a meson cloud of size of order $\hbar/(m_\pi c) \approx 1.4\cdot 10^{-13}$cm and the electric field can be expected to be present in the immediate vicinity of the neutron. When a neutron approaches an electron at fairly short distances, electrostatic interaction forces must arise between them. These forces affect the $n-e$ scattering length a_{ne}. This problem was first apparently solved by Fried [2] and then later in more detail by Foldy [3] in the 1950s. Foldy showed that the experimentally measured interaction between the neutron and the electron, the $n-e$ scattering length a_{ne}, consists of two parts: a magnetic term containing the neutron anomalous magnetic moment, this term can be calculated theoretically, and an intrinsic term which arises from the spatial distribution of the neutron into a proton and a π^- meson.

The problem was solved by Foldy on the basis of the generalized Dirac equation and for $k = 2\pi/\lambda \to 0$ the $n-e$ scattering length takes the form:

$$a_{ne} = 2Me/(\hbar^2)[\varepsilon_1 + \mu_n e\,(\hbar/(2Mc))^2], \tag{1}$$

where ε_1 describes the radial extent of the distribution of intrinsic electric charge in the neutron. The term containing μ_n (anomalous magnetic moment of the neutron) is the Foldy contribution due to zitterbewegung that is the relativistic effect of the «trembling» of Dirac particles. In the Foldy study

$$\varepsilon_1 \sim 1/6 r^2 \rho_{\rm in}(\mathbf{r}) dV = e/6 < r^2_{\rm in} >_N, \tag{2}$$

where $\rho_{\rm in}(\mathbf{r})$ is the neutron intrinsic electric charge density and $< r^2_{\rm in} >_N$ is the neutron mean squared intrinsic charge radius.

Foldy writes: «We employ the corresponding symbol rather than an equal sign here, since there is some ambiguity in relating the relativistic coefficients to the physical extension of a static charge distribution. The indicated correspondence is perhaps the most reasonable one».

However in the limiting case of low energies (at such exactly energies the value a_{ne} is determined experimentally) one can show (see below) that

$$\varepsilon_1 = e/6(< r^2_{E,\rm in} >_N), \tag{3}$$

i. e. we have an equality and not proportionality symbol and then one can obtain

$$a_{ne} = 2Me/(\hbar^2)[e/6(< r^2_{E,\rm in} >_N) + \mu_n e(\hbar/(2Mc))^2]. \tag{4}$$

From Eq. (4) one can find for the neutron

$$< r^2_{E,\rm in} >_N = 3\hbar^2/(Me^2)(a_{ne} - a_F), \tag{5}$$

where $a_F = \mu_n e^2/(2Mc^2) = -1.468 \cdot 10^{-13}$cm is the length corresponding to the Foldy interaction.

The sign of the first member in Eq. (4) (see also Eq. (5)) defined by the sign of value $< r^2_{E,\rm in} >_N$, depends on the scattering length a_{ne} measured in the experiment. In principle, the sign of mean square charge radius $< r^2_{E,\rm in} >_N$ of a particle in general, neutral, having no charge, can be positive as well as negative. This sign must be determined by the charge sign, located on the periphery. Since the expected distribution of electric charge in the neutron has a negatively charged «tail», the value $< r^2_{E,\rm in} >$ must be negative. The total neutron charge is equal to zero, however, the value $< r^2_{E,\rm in} >$ in accordance with relation (2) must be negative.

Using Eq. (5) the magnitude and sign of $< r^2_{E,\rm in} >$ can be obtained from the measured value of a_{ne}. However since a_{ne} and a_F are quantities of the same order of magnitude, very precise measurements are necessary to find $< r^2_{E,\rm in} >$. Numerous experiments were began in 1947 and are continued to the present day. Sometimes some physicists ask whether there have been no precise measurements of a_{ne} for 55 years? From the viewpoint of experimenters the answer will be positive. A lot of experiments contradict the most well-developed ideas based on the Yukawa theory about the structure of the neutron and I will try to confirm this statement.

Let us begin with the form factors. The structure of the nucleon as well as of nuclei is described using form factors. Contrary to the atom, the electric charge distribution in the case of nuclei will not be identical to the nuclear mass distribution. Moreover, in the case of an isolated nucleon the latter undergoes strong recoil. These phenomena are the main reason for impossibility to determine the nucleus or nucleon structure in the ordinary way.

As you know, the nonrelativistic Rutherford expression for spinless point particles gives the effective scattering differential cross section

$$(d\sigma/d\Omega)_{\rm Ruth} = z^2 Z^2 e^4/(16E^2 \sin^4\theta/2), \tag{6}$$

where E is the kinetic energy of the incident particle.

If the target particle is not a point particle, it can be shown that Eq. (6) will be

$$(d\sigma/d\Omega) = ((d\sigma/d\Omega)_{\rm Ruth} |F(q^2)|^2, \tag{7}$$

where $F(q^2)$ is the form factor and q^2 is the squared four-momentum transfer $[q^2 = (p_f - p_i)^2 = (p_{fe} - p_{ie})^2]$, where p_i, p_f, p_{ie}, p_{fe} are the initial and final four-momenta of the proton and electron. The spatial components of the four-momentum coincide with the particle momentum P, and the time component is iE/c, where E is the particle energy.

For the elastic scattering of a point electron on a spin-1/2 particle of finite size, there is the Rosenbluth formula [4] (1950):

$$d\sigma/d\Omega = (d\sigma/d\Omega)_0 \{(F_1^2 - (q\hbar/2Mc)^2[2(F_1 + \mu_k F_2)^2 \tan^2(\theta/2) + \mu_k^2 F_2^2]\}, \tag{8}$$

where $(d\sigma/d\Omega)_0$ is the differential cross section for the electron elastic scattering on a point charge $[(d\sigma/d\Omega) \neq (d\sigma/d\Omega)_{\rm Ruth}]$, M is the mass of particle target, μ_k is the anomalous magnetic moment, $F_1(q^2)$ is the Dirac form factor describing the spatial charge distribution and the associated normal magnetic moment, $F_2(q^2)$ is the Pauli form factor associated with the spatial distribution of the anomalous magnetic moment.

Later in 1962, Sachs [5] derived linear combinations of the form factors F_1 and F_2 convenient for working with experimental data. There are the charge form factor

$$G_E(q^2) = F_1(q^2) + \mu_k (q\hbar/2Mc)^2 F_2(q^2) \tag{9}$$

and the magnetic form factor

$$G_M(q^2) = F_1(q^2) + \mu_k F_2(q^2). \tag{10}$$

Since (9) and (10) are linear combinations F_1 and F_2, it is impossible to show which set is more fundamental, F_i or G_i. But Eq. (8) is written more simply as in the former, there is no cross term involving G_E and G_M like F_1F_2. Moreover G_E and G_M describe the distribution of the total charge and the total magnetic moment.

It is useful for purely illustrative purposes to have a clear interpretation of the form factors. This is possible in Breit coordinate frame (three-momenta of the initial and final protons are equal in magnitude and opposite in direction, and the corresponding energies are the same). In the Breit frame the spatial distribution of the electric charge density

$$\rho(\mathbf{r}) = e/(2\pi)^3 \int G_E(q^2)\exp\,(-i\mathbf{qr})d\mathbf{q} \tag{11}$$

or

$$G_E(q^2) = 1/(e) \int \rho(\mathbf{r})\exp\,(i\mathbf{qr})d\mathbf{r}. \tag{12}$$

If G_E = const, it follows from (11) that $\rho(r) \sim e\delta(r)$, where $\delta(r)$ is the delta function. The q dependence of G_E characterizes the deviation of the charge distribution from a point one. However, each value of q corresponds to a particular reference frame and so the spatial structure of the nucleon specified by (11) and (12) is rather complicated. Only in the nonrelativistic case ($\hbar q \ll Mc$) when the change of the nucleon at rest can be neglected, the spatial image of the nucleon becomes well defined. In this case the Breit system coincides with the system of the nucleon at rest, the nucleon can be considered at rest during the collision and there is no trouble with Fourier transforms (11) and (12).

Since the total charge of the nucleon is

$$Q = \int \rho(\mathbf{r})d\mathbf{r}, \tag{13}$$

from (12) and (13) we find that $Q = eG_E\ (0)$. For the proton we find from (9)

$$G_{EP}(0) = F_{1P}(0) = 1 \text{ and } G_{EN}(0) = F_{1N}(0) = 0 \tag{14}$$

for the neutron.

If the particle have no charge, this only implies that G_E (0) = 0. The particle is truly neutral when the form factors are zero for all q^2. If it is not so, a particle can emit virtual photons and possesses a charge distribution.

In the limiting case of very low energies Eq. (12) can be expanded in a series to the power of q^2 $[G_E(q^2) = 1 - 1/6 < r_E^2 > q^2 + \ldots]$. From this series follows that

$$< r_E^2 >= 1/(e) \int \rho(\mathbf{r}) 4\pi r^2 dr = 6(dG_E/dq^2)_{q2=0} \tag{15}$$

or

$$< r_E^2 >= 6\,(dF_1/dq^2)_{q^2=0} + \frac{3}{2}\mu_k(\hbar/Mc)^2. \tag{16}$$

The second term in Eq. (16) is of a magnetic nature associated with the zitterbewegung of a particle satisfying the Dirac equation and having anomalous magnetic moment (Foldy term). As for the first term it arises from the nuclear internal structure. This term is called the Dirac radius and we can write

$$< r_{E,\text{in}}^2 >_N = 6\,(dF/dq)_{q^2=0}. \tag{17}$$

The total mean squared electric radius of the particle is

$$< r_E^2 >=< r_{E,\text{in}}^2 > + < r_F^2 > . \qquad (18)$$

For the neutron $< r_F^2 >_N = -0.1268 \cdot 10^{-26}$ cm^2.

Using Eqs. (15), (16), (17) and Eq. (4) we can write that

$$(dG_E/dq^2)_{q^2=0} = 14.41\, a_{ne}, \qquad (19)$$

where a_{ne} is in 10^{-13} cm.

Therefore the study of the $n - e$ scattering gives information about the value of $(dG_E/dq^2)_{q^2=0}$. This information can be also obtained (and also on $< r_{E,\text{in}}^2 >$) from the electron–deuteron scattering experiments, but large experimental uncertainties make this insufficiently accurate (see Fig. 1).

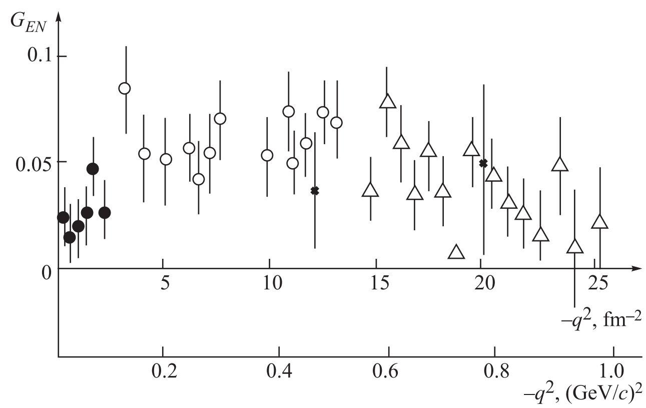

Fig. 1. Dependence of the neutron electric form factor on q^2

Now several words about the propriety of Eq. (4) (or Eq. (5)) which has been questioned (see, e. g. Ref. [6]). This question has been discussed in several papers [7, 8] and the validity of Eq. (4) at low energies has been established. This conclusion follows, for example, essentially from Eq. (9), differentiation of which allows one to obtain Eq. (4) directly (see, e. g., [7]), because $a_{ne} = Me^2 < r_E^2 >_N /(3\hbar^2)$ in the first Born approximation.

The differential cross section for the coherent scattering of slow neutrons with a wavelength of the order of the size of atom is described by the relation

$$\sigma(\theta) = |a + Zf(\sin\theta/\lambda)a_{ne}|^2, \qquad (20)$$

where a_{ne} is the coherent nuclear scattering length and $f(\sin\theta/\lambda)$ is the atomic form factor. Estimates show that the ratio $Za_{ne}f/a$ may be of the order of 10^{-2} (for usual heavy atoms) and so a_{ne} can be measured.

But sometimes this ratio may exceed the value of 0.2–0.5, if the value of a is very small.

The results of measurements of the $n-e$ scattering length performed from 1947 to 1999 are given in the Table. From the Table it follows that the value of $< r^2_{E,\text{in}} >^{1/2}_N$ (see Eq. (5)) is small, apparently less than 10^{-14} cm. It should be noted that if $< r^2_{E,\text{in}} >^{1/2}_N$ for the neutron is the same as for the proton ($0.83 \cdot 10^{-13}$ cm), a_{ne} would be of the order of 10^{-15} cm, i. e. roughly 6–8 times larger than the values given in the Table.

Table. Results of $n-e$ measurements

Authors, year	Method	Magnitude of effect	$-a_{ne}$, 10^{-16} cm
W. Havens et al., 1947–1951	Total neutron cross section on Pb and Bi	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.5\%$	1.91±0.36
D. Hughes et al., 1952–1953	Total neutron reflection from Bi to O_2 mirror	$\Delta\theta/\theta \approx 50\%$	1.39±0.13
E. Melkonian et al., 1959	Total neutron cross section on Bi	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.5\%$	1.56±0.05
V. Krohn, G. Ringo, 1966–1973	Neutron scattering on noble gases	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 0.5\%$	1.33±0.03
L. Koester et al., 1976–1995	Total neutron cross section and atomic scattering length on Bi, Pb, ^{208}Pb	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.2\%$	1.32±0.03
Yu. Alexandrov et al., 1974–1985	Neutron diffraction on a ^{186}W single crystal	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 20\%$	1.60±0.05
Yu. Alexandrov et al., 1985	Total neutron cross section on Bi	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.2\%$	1.55±0.11
S. Kopecki et al., 1994–1997	Total neutron cross section on ^{208}Pb and on Bi	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.2\%$	1.33±0.03±0.03 1.44±0.03±0.06
T. Enik et al., 1995	Total neutron cross section on ^{208}Pb	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.2\%$	1.67±0.16
A. Laptev et al., 1988–1999	Total neutron cross section on ^{208}Pb and joint analysis of ^{208}Pb and C	$\Delta\sigma_{ne}/\sigma_{\text{tot}} \approx 1.2\%$	1.78±0.25 1.75±0.27

From the Table it also follows that the experimental results of a_{ne} can be divided into two groups. The result of the first one $< a_{ne} >= -1.58(3)\cdot 10^{-16}$ cm leads (according to Eq. (5)) to $< r^2_{E,\text{in}} >_N < 0$ which is in accordance with the Yukawa theory. The result of the second one ($< a_{ne} >= -1.30(3) \cdot 10^{-16}$ cm) leads to $< r^2_{E,\text{in}} >_N > 0$ which contradicts the Yukawa theory. Most probably the last group of experimental data is incorrect. My opinion is that the Yukawa theory cannot be refuted at large distances (of the order of $\hbar/(m_\pi c) \approx 1.4 \cdot 10^{-13}$ cm).

The discussion of experiments cited in the Table one can find in Ref. [9].

In conclusion of this section I would like to give some calculations.

In Ref. [10] the following formula used to analyze the experimental data was obtained:

$$\begin{aligned} y = \sigma_{\rm tot}(E')/4\pi - b^2_{\rm coh} = \\ = a^2_{ne}(Z-F)^2 - 2a_{ne}b_{\rm coh}(Z-F) - f^2 + 2a_{ne}fF + 2/3\pi k'Rfb_{\rm coh} - \\ - (\Sigma_1 - \Sigma)[b_{\rm coh} - a_{ne}(Z-F) + \pi k'Rf/3] + \\ (\Sigma_1)^2/4 - \Sigma_1\Sigma/2 + \Sigma_2/4, \quad (21) \end{aligned}$$

where $f = \dfrac{M\alpha_n}{R}\left(\dfrac{Ze}{\hbar}\right)^2$ is the scattering amplitude due to the electric polarizability of the neutron, $F = Z/2\int\limits_0^\pi f(\sin\theta/\lambda)\sin\theta d\theta$ is the atomic form factor integrated over angles, E and E' are the neutron energies at which $\mathrm{b}_{\rm coh}$ and $\sigma_{\rm tot}$ are measured, Σ, Σ_1, and Σ_2 are described by the parameters of resonances.

In my opinion this formula is more convenient for the analysis of experimental data.

For ^{208}Pb the value of $y \approx 0.01 \cdot 10^{-24}$cm^2/sr. At a neutron energy less than 2 keV the value $p_1 b_{\rm coh} < 10^{-4} \cdot 10^{-24}$cm^2/sr $(p_1 = \Sigma_1 - \Sigma)$, $p_2 < 6 \cdot 10^{-6} \times$ $\times 10^{-24}$cm^2/sr (p_2 is the combination of Σ, Σ_1, and Σ_2).

The value of $2a_{ne}b_{\rm coh}(Z-F) = 1.62 \cdot 10^{-2} \cdot 10^{-24}$ cm^2/sr, thus one can neglect by resonance scattering for ^{208}Pb and Eq. (21) takes the form (neglecting also by the polarizability terms of the order of $10^{-4} \cdot 10^{-24}$ cm^2/sr):

$$y = \sigma_{\rm tot}(E')/4\pi - b^2_{\rm coh}. = -2a_{ne}b_{\rm coh}(Z-F) + a^2_{ne}. \quad (21a)$$

From Eq. (21a) one can obtain excluding $b_{\rm coh}$:

$$a_{ne} = \frac{1}{4\pi}\left[\sqrt{\sigma_{\rm tot}(E'_1)} - \sqrt{\sigma_{\rm tot}(E'_2)}\right] / [F(E'_1) - F(E'_2)]. \quad (22)$$

Using Eq. (22) one can obtain from experimental data of the paper [11] the following data of a_{ne} (see the table on the next page).

These results suggest that the value of $\sigma_{\rm tot}$ at E = 1970 eV found in [11] is incorrect. Taking $\sigma_{\rm tot}$(1970) to be 11.525$\cdot 10^{-24}$cm^2 (instead of 11.479(3)$\cdot 10^{-24}$cm^2 as found in [11]) one can find $a_{ne} = -1.59(15) \cdot 10^{-16}$cm and $a_{ne} = -1.61(29) \cdot 10^{-16}$ cm which is apparently close to the true value.

$\sigma_{\text{tot}}(1.26 \text{ eV})$	$-1.58(30) \cdot 10^{-16}$ cm	$\sigma_{\text{tot}}(5.19 \text{ eV})$
$\sigma_{\text{tot}}(5.19 \text{ eV})$	$0.10(29) \cdot 10^{-16}$ cm	$\sigma_{\text{tot}}(1970 \text{ eV})$
$\sigma_{\text{tot}}(1.26 \text{ eV})$	$-0.26(15) \cdot 10^{-16}$ cm	$\sigma_{\text{tot}}(1970 \text{ eV})$

2. NEUTRON ELECTRIC POLARIZABILITY

Now I would like to tell you about neutron polarizability - a problem, which appeared about 50 years ago, and about the influence of neutron polarizability on neutron scattering by heavy nuclei at relatively low energies of neutrons (less than 10 MeV).

Among other things, the first experimental search for the neutron polarizability influence on the character of neutron scattering was initiated at the Institute of Physics and Power Engineering (IPPE), Obninsk.

One of the great successes in physics of the 1950s were the famous experiments by Hofstadter carried out at the electron accelerator of Stanford University (USA). Hofstadter was the first who shown experimentally that proton was not a point particle. In this connection physicists were wondering if there are other natural phenomena indicative for nucleon space structure. In the middle of the 1950s this question was considered independently by three groups of physicists: in the USA by Klein (1955) [12], in Russia by Baldin (unfortunately the first paper was published in 1960 [13]) and by Alexandrov and Bondarenko (1956) [14]. In all of the mentioned papers the notion of nucleon polarizability was introduced (independently). I would like to tell you about the research initiated by the third group in Obninsk.

The phenomenon of polarizability implies a deformation of spatially extended nucleon in electric or magnetic field. In the case of electric field E the neutron acquires electric dipole moment $d = \alpha E$, where α is the coefficient of electric polarizability, and obtains additional potential energy

$$V(r) = -dE = -\alpha(Ze)^2/(2r^4). \tag{23}$$

I discussed with Prof. Blokhintsev the possibility of such a phenomenon inherent exactly to the neutron as far back as 1954, after that he sanctioned the experimental search for this effect in neutron scattering. At that time the first fast reactor in Europe was started in Obninsk. With Dr. Bondarenko we made a decision to search for the influence of neutron polarizability on small-angle neutron scattering. The angles of scattering can be estimated using correlation $\theta \leqslant \lambda\!\!\!^{-}/R$. At $\lambda\!\!\!^{-} \cong 4.6 \cdot 10^{-13}\text{cm}\,(E = 1 \text{ MeV})$ and $R \cong 2 \cdot 10^{-11}$ cm it is possible to obtain $\theta \cong 1.5°$.

As a result of first measurements in 1955 [14] carried out in Obninsk on lead at neutron energies of 2–3 MeV, the so-called Schwinger scattering was discovered. The following data [15, 16], obtained in Obninsk at small-angle megaelectronvolt neutron scattering by the nuclei of Pu, U, Bi, Pb, Sn and Cu, were processed using the optical model of nucleus supplemented by the Schwinger potential. The results are shown in Fig. 2 [16], where dashed curves represent

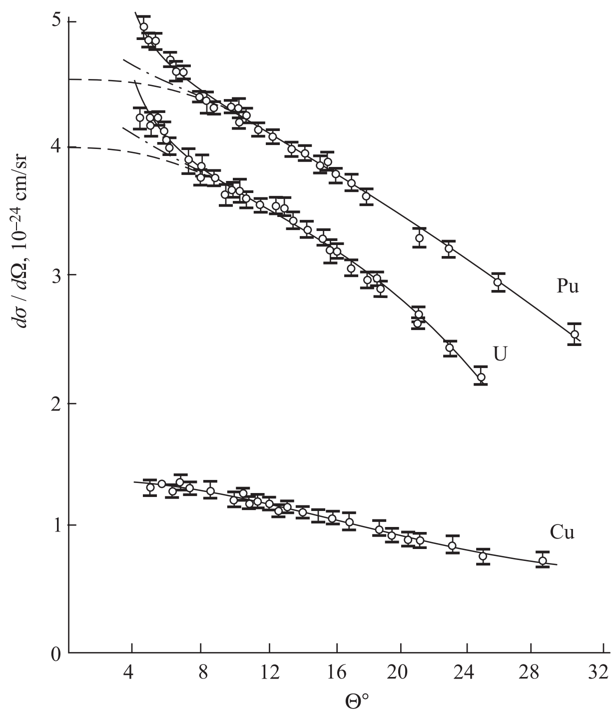

Fig. 2. Angular distributions of neutrons in the elastic scattering on Pu, U, and Cu

purely nuclear scattering, dotted-dashed curves represent nuclear scattering supplemented by the Schwinger potential. Thus, as long ago as 1957 the additional scattering for the plutonium and uranium nuclei in the region of small angles was observed, which could not be explained by nuclear and Schwinger potentials only. Later similar additional scattering of megaelectronvolt neutrons was observed in many works (Obninsk — up to 1989, Gatchina, USA, Italy, etc.).

It was natural to explain the obtained results by the contribution of scattering caused by neutron polarizability using potential (23) and the value of $\alpha \approx 10^{-40}$ cm^3 was obtained [16].

The information about the value of α can be also obtained by studying neutron scattering on heavy nuclei at the energies less than 300 keV. Such a kind of experiments has been started since 1960. Among them the experiment of 1966 should be mentioned. It was performed at FLNP (Dubna) using the time-of-flight method on lead at the pulsed reactor IBR in the neutron energy region from 0.6 to 26 keV. As a result, the value $\alpha \leqslant 6 \cdot 10^{-42}$ cm^3 was obtained [17]. This value remained record breaking up to 1986 that is about for 20 years.

Later the measurements of angular distribution of neutrons and of total cross sections were performed at FLNP in cooperation with Garching (Germany), in Gatchina as well as in Austria, USA, England and other countries. However, in all these works the estimations of α-neutron value are less by a factor of 100 than the value 10^{-40} cm^3, namely, they are in the region 10^{-42} cm^3. Thus, there was a serious deviation between the results obtained in the megaelectronvolt neutron region and that obtained in the region of energies lower than 300 keV. Attempts to describe theoretically in a single manner these two groups of data fail. The value of the electric polarizability coefficient of the neutron obtained from one group is two orders of magnitude larger than the value obtained from the second group of data. Therefore it is quite reasonable to assume that an additional long-range interaction (besides nuclear and Schwinger) participates in the scattering of neutrons on nuclei.

This contradiction remained unexplained for 45 years. I think, the explanation was found due to two more factors, apart from the factor of time, of course. The first one was pointed out in 1959 by Blokhintsev, Barashenkov and Barbashov in the article [18] published in the journal UFN: «...Perhaps there are effects of interaction between the neutron and the electron shell of heavy nuclei». The second one is a possible existence of long-range action (forces of the Van der Waals' type, r^{-6}) in hadron interactions to which Sawada (Japan) [19] paid and pays special attention (in 2000 one of the paper of Sawada was entitled as «Proposal to observe the strong Van der Waals force in the low-energy neutron – Pb scattering»). However such experimental data on the small-angle scattering of neutrons with energy of 0.5–10 MeV by heavy nuclei are already available. The measurements were conducted by physicists in Obninsk (1956-90), in Gatchina (1963-99), etc. Apropos, as I know, the first work discussing possible existence of long-range hadron interactions belongs to Prof. Wilkinson (1961, The Rutherford Jubilee International Conference).

Possible existence of an additional potential of neutron scattering on nuclei with a longer range than that of the usual nuclear potential is discussed below. It may be due to Van der Waals forces.

In 1999 it was shown in the work by Pokotilovsky [20] and in his work made in cooperation with his colleagues [21] that at neutron energies 0.5–10 MeV the changes in differential cross section of neutron scattering on the isotope ^{208}Pb in the region of small angles caused by potential (23) with the value

$\alpha = 1.5 \cdot 10^{-40}$ cm^3 were the same as those caused by the Van der Waals potential

$$U(r) = -U_R(R/r)^6 \tag{24}$$

(R is the radius of nucleus) when choosing constant $U_R \approx$ 250–350 keV. The constant U_R has not been calculated in the works by Pokotilovsky's group but it has been defined by selection, by means of «hands» to achieve the best agreement between the calculations and experiment. The constant U$_R$ was not related to neutron polarizability spatially.

The scattering amplitude for $n = 6$ has the form

$$f_{n=6} = \frac{2MU_R R^3}{\hbar^3}\left[\frac{\sin x}{4x} + \frac{\cos x}{12} + x\frac{\sin x}{24} - x^2\frac{\cos x}{24} + \frac{x^3}{24}\int_x^\infty \frac{\sin t}{t}dt\right], \tag{25}$$

where M is the neutron mass and $x = qR = 2kR\sin(\theta/2)$.

As is shown in [20] a long-range potential at n = 5, 6 or 7 at low energy ($x \ll 1$) practically is not observed. The result of optical model calculations with addition of both $\sim r^{-6}$ and $\sim r^{-4}$ (neutron polarizability potential) for the ^{208}Pb isotope is shown in Fig. 3 [21]. The calculations are conducted at energies of

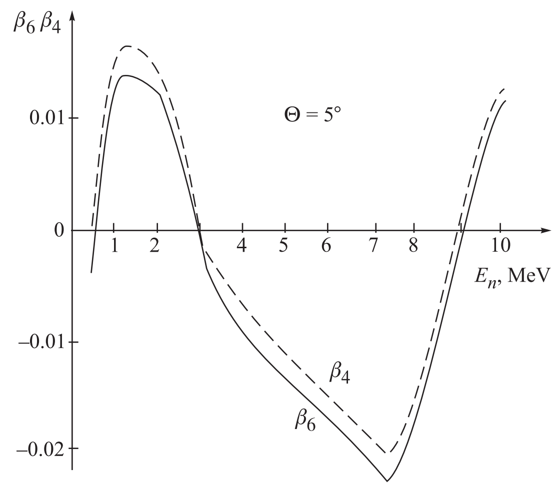

Fig. 3. Energy dependence of relative effects of Van der Waals potential (β_6) and the potential due to polarizability (β_4) on the neutron scattering

0.5–10 MeV and under the choice of the constant U_R = 300 keV. As you see the energy dependence of relative effects on the Van der Waals potential (β_6) and the potential due to polarizability (β_4) with the value $\alpha = 1.5 \cdot 10^{-40}$cm^3 is approximately the same. An analogous picture can be obtained in the interval of small angles from 3 to 15°. However, it was desirable to calculate the constant U_R and see how it is related to neutron polarizability that is to the value α. These calculations were performed by your obedient servant, that is by me, in 2001. I told about these calculations in Dubna (ISINN-10) and in Sarov at the International Conferences [22, 23]. It should be noted that they are not undoubtedly precise yet. However, at the present situation it is enough to be sure that there are no considerable errors that would change the neutron value α by the factor of 100, since this is the difference between the values 10^{-42} cm^3 and 10^{-40} cm^3 which were obtained at low (<300 keV) and high (0.5–10 MeV) energies.

Let us evaluate the constant U_R of the Van der Waals attraction forces analytically [24] (this evaluation has not been made in [20, 21]). These forces arise in the second approximation of perturbation theory and are due to the electric dipole–dipole interaction. The dipole–dipole interaction in the perturbation operator is [25]

$$V = \frac{e^2}{r^3}[\mathbf{r}_1\mathbf{r}_2 - 3\frac{(\mathbf{r}_1\mathbf{r})(\mathbf{r}_2\mathbf{r})}{r^2}], \tag{26}$$

where $\mathbf{r}$ is the distance between the nuclei of atoms, $\mathbf{r}_1$ is the distance from the first electron to the first nucleus, and $\mathbf{r}_2$ is the distance from the second electron to the second nucleus.

This approximation is rather good if the following conditions are fulfilled:

$$r_1/r < 1 \text{ and } r_2/r < 1. \tag{27}$$

If one looks for the energy values as a series of $E = E^{(0)} + E^{(1)} + E^{(2)}$ +..., one can show (see [25]) that the approximation correction to E will be

$$E_n^{(2)} = \sum_m \frac{|V_{mn}|^2}{E_n^{(0)} - E_m^{(0)}}, \tag{28}$$

where

$$V_{mn} = \int \Psi_n^{(0)} V \Psi_m^{(0)} dq \tag{29}$$

and $\Psi^{(0)}$ are the eigenfunctions of the main unperturbed operator of the system. The first approximation is absent because the mean values of the dipole moments are equal to zero (spherical symmetry of charge density distribution). Using (26), (28) and (29) one can derive an expression for the Van der Waals interaction energy which is valid for two multielectron atom [25]

$$U(r) = \frac{6}{r^6} \sum_{n,n'} \frac{\langle n\,|d_{z1}|\,0\rangle^2 \langle n'\,|d_{z2}|\,0\rangle^2}{E_n - E_{01} + E_n' - E_{02}}, \tag{30}$$

where $\langle n\,|d_{z1}|\,0\rangle^2$ and $\langle n'\,|d_{z1}|\,0\rangle^2$ are the squares of the matrix elements of the first and the second atom dipole moments, E_{01} and E_{02} are the ground state energies of the atoms, and E_n and E'_n are the excited state energies of the atoms.

This is a sufficiently good formula if the condition $r_1/r < 1$ and $r_2/r < 1$ holds.

Next, let us use Eq. (30) to estimate the Van der Waals interaction energy between the neutron and the scattering atom. For the neutron, whose size, as is known, is smaller than of the proton (proton radius is about $0.8 \cdot 10^{-13}$ cm), the condition $r_1/r < 1$ holds sufficiently well. For the atom, the situation is not so good, however, but it is quite acceptable as we shall see further.

Taking into account the fact that the first excited state of the nucleon is the nucleon plus π meson it is possible to assume that $E_1 - E_{02} = \mu c^2$, where μ is the meson mass, and only to take into account this term in summation over n' (the others are negligible). Since $\mu c^2 \gg E_n - E_{01}$ and the polarizability of the systems is $\alpha = 2\sum\limits_n \frac{<n|d|0>^2}{E_n - E_0}$ (see [25]), Eq. (30) takes the form

$$U(r) = -\frac{3}{2r^6}\alpha_n \sum_n \Delta E_n^A \alpha_n^A, \tag{31}$$

where α_n is the neutron polarizability coefficient, $\Delta E_n^A = E_n - E_{01}$ is the excitation energy of the nth electron in the atom, and α_n^A is the polarizability of the nth electron that exists in the bound state in the atom.

Equation (31) that shows that the van der Waals interaction energy is proportional to the product of polarizabilities of the two systems, is universal, i. e. it does not depend on the internal structure of the interacting systems and it holds for atoms, hadrons, and elementary particles of the other types. It only depends on the validity of general principles, such as Lorentz invariance, electromagnetic current conservation, analyticity and unitarity (see, e. g. [26]). We shall continue using Eq. (31) in what follows.

The value of ΔE_n^A in Eq. (31) can be taken equal to the binding energies of the corresponding electrons in the atom. For uranium, binding energies change from 115.6 keV (K-shell) to a value of about 1 keV and smaller for N-, O- or P-shells. The values of α_n^A for the electrons in a compound atom should be known. At present, however, there is no rigorous theory for their calculation as yet. In the first approximation they can be set equal to the values of electron polarizabilities in the atom by using for estimation an atom model as a linear oscillator vibrating with the frequencies $\omega_k = E_k/\hbar$, where E_k is the energy of electrons moving in the atom. Since in such a model, $\alpha_k = \dfrac{e^2}{m\omega_k^2}$ for the constant

($\omega = 0$) applied field, we have in the classical approximation [27]

$$\alpha_k^A(\theta) = N_k(\theta)\frac{e^2\hbar^2}{mE_k^2}, \tag{32}$$

where m is the electron mass and $N_k(\theta)$ is the number of electrons in the atom having the energy E_k. Information about E_k can be obtained by equating them to the binding energy of the corresponding electrons in the atom.

Equation (32) can be verified on the example of hydrogen atom. For them, as it is known from [25], $\alpha_H = 4.5\,a_B^3$, where $\alpha_B = \hbar^2/(me^2) = 0.529 \cdot 10^{-8}$ cm. Substituting this value into the formula for α_H we obtain $\alpha_H = 6.66 \cdot 10^{-25}$ cm. Equation (32) yields $\alpha_H = 6.06 \cdot 10^{-25}$ cm if $E_H = 13.5$ eV.

The results of the Thomas–Fermi model calculations [28] and of Eq. (32) are approximately equal for tin atom and the difference between the results of analogous calculations for uranium atom does not exceed 1.5 times.

The special distribution of electrons in the atom can be determined from the angular distribution of small-angle scattered neutrons. In the first approximation the distance of the neutron trajectory going through the atom from the nucleus, ΔR, is related to the scattering angle as $\Delta R \approx ƛ/\theta$. Knowing ΔR and using the Thomas–Fermi model for the atom, it is possible to determine the number of electrons N_i participating in the investigated process, i. e. of those that are at a distance smaller than ΔR from the nucleus. The distributions of electrons over shells and their binding energy in the atom can be found in [29, 30]. Then according to Eq. (32) one can calculate the values of $\alpha_K^A(\theta)$ for each scattering angle.

Next, we estimate U_R. Note that the constant U_R determining the strength of the Van der Waals interaction can, in principle, be estimated for any chosen ΔR. It is better, however, to choose $\Delta R \gg R$. In this case, the validity of the Van der Waals interaction will not be doubted. To compare with U_R in [20, 21], we can follow their authors and extrapolate potential (24) to the point at R equal to the radius of the nucleus. For $r = R$, the potential $U(r) = -U_R$ and comparing Eq. (31) with Eq. (24) it is possible to obtain the sought equation for the constant U_R of the Van der Waals interaction (for n = 6):

$$U_R(\theta) = -\frac{3}{2R^6}a_n\sum_n \Delta E_n^A a_n^A, \tag{33}$$

where R is the radius of the nucleus in the atom (for uranium $R = 9.4 \cdot 10^{-13}$ cm).

The sought constant U_R can be obtained by the operation of averaging over the scattering angles from 3 to 15° (this small-angle range interval was taken into account in [21]):

$$U_R = \int U_R(\theta)\sin\theta d\theta / \int \sin\theta d\theta. \tag{34}$$

Carrying out the calculations numerically, it is possible to obtain U_R = 210 keV for uranium, for the neutron energy 1 MeV and for the neutron polarizability $\alpha = 1.5 \cdot 10^{-42}\text{cm}^3$. Thus, the neutron polarizability was first detected in small-angle neutron scattering experiment as early as 1957 in Obninsk, i. e. earlier than proton polarizability was observed in the $\gamma - p$ scattering experiment (1960).

In conclusion it should be emphasized that similar to Hofstadter experiments that prove the nucleon to have a spatial structure, the notion of deformation (polarizability) of the nucleon and its discovery in the experiment do not only lead to a new important physical property but are also of fundamental philosophic importance.

3. MAGNETIC NEUTRALITY OF THE NEUTRON

At present, an interest in magnetic monopoles has grown especially in connection with the grand unified theories. However, Dirac already discussed this question in 1931 [31] and in 1948 [32]. The existence of magnetic isolated charge was also discussed by Gilbert (1600) and by Ampere (1800s). They gave negative answers to the existence of magnetic charge.

In 1873 the equations of electromagnetic field were created by Maxwell. These equations confirmed the Ampere's hypothesis on the molecular currents

$$\begin{aligned} \operatorname{div} \mathbf{E} = 4\pi\rho_e, \quad -\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \operatorname{rot} \mathbf{B} = \frac{4\pi}{c}\mathbf{j}_e, \\ \operatorname{div} \mathbf{B} = 0, \quad -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} - \operatorname{rot} \mathbf{E} = 0, \end{aligned} \tag{35}$$

where ρ_e is the density of electric charge (the source of electric field E), j_e is the density of electric current (the source of magnetic field H). If we could write $4\pi\rho_m$ instead of 0 in the left column of equations and $4\pi/cj_m$ in the right one, we would have a total symmetry of equations (ρ_m and j_m are the densities of magnetic charge and magnetic current). «It would be surprising if the nature does not use this chance» — wrote Dirac [31]. One of the main results of Dirac's work (1931) is the relation

$$e_m = n\,\frac{\hbar c}{2e} = n\,68.5e, \tag{36}$$

where $\alpha = e^2/(\hbar c) = 1/137$ (the fine structure constant). This relation indicates the quantization of both magnetic and electric charges, that is very important conclusion. Equation (36) was also obtained by Fermi in 1950 [33] and by Efinger in 1969 [34]. Thus, if at least one magnetic monopole exists in the nature, then the electric charge became a quantized charge.

The value, which is analogous to the fine structure constant α for magnetic monopole is

$$\alpha_m = e_m^2/(\hbar c) \approx 34, \tag{37}$$

which is comparatively large value.

Now we can discuss the question of magnetic monopole ionization. The electric field for magnetic monopole moving with velocity v is

$$E = \frac{e_m}{b^2}\frac{v}{c}, \tag{38}$$

where b is the distance between monopole and atom.

The effect of ionization is proportional to the squared electric field E and the ratio

$$\text{(monopole effect) /(electron effect)} = (e_m/e)^2(v/c)^2 \approx (68.5)^2 = 4692, \text{if}\, v \approx c. \tag{39}$$

This strong effect was discovered in cosmic rays in the 1947–48, and Fermi and Teller thought that this effect was connected with monopoles, but in reality it was heavy nuclei from cosmos.

The first experimental search for magnetic monopoles was initiated by Malkus (1951) [35]. The author analyzed the monopole beam passing through a magnet of length L = 100 cm at magnetic field B = 250 Gauss. The result of this experiment was negative. The tracks of monopoles were not found.

The best experiment was performed by Finkelstein, Shull and Zeilinger [36]. This experiment was based on the effective mass concept of the neutron predicted by dynamical diffraction theory. This concept of the Bragg-diffracting neutron was developed by Zeilinger et al. They showed that in perfect crystals the effective inertial mass of the diffracting neutron is many times smaller than normal and hence in the presence of external force F the neutron trajectory must exhibit a deflection many times larger than normal. In this case the Newton's second law is

$$a = \frac{F}{m} \pm \frac{F}{m}(1-\Gamma^2)^{\frac{3}{2}}\frac{\Delta_0}{d_{(hkl)}}, \tag{40}$$

where Δ_0 is the pendellosung length (part of mm), $\Gamma = \tan\Omega/\tan\theta_B$, Ω is the angle between the neutron propagation direction and (hkl) planes, θ_B is the Bragg angle for this reflection, effective mass $m^* = md_{(hkl)}/\Delta_0$ and for the Si(220) reflection $m^*/m = \pm 4.72 \cdot 10^{-6}$. The «±» sign indicates that the neutron can have either positive or negative mass. These two signs are associated with two wave fields in the crystals α and β, respectively (see Fig. 4). The top view of the experimental arrangement is shown in Fig. 4. Deflection of a neutron beam is proportional to $1/m^*$. Monochromatic radiation ($\lambda = 2.46$Å$, \Delta\lambda/\lambda$ = 1%) from a graphite monochromator was filtered through graphite. The aluminum wedge angle was chosen to separate the α and β wave fields by a distance equal to their individual widths. The aluminum wedge angle was chosen to separate the α and β wave fields by a distance equal to

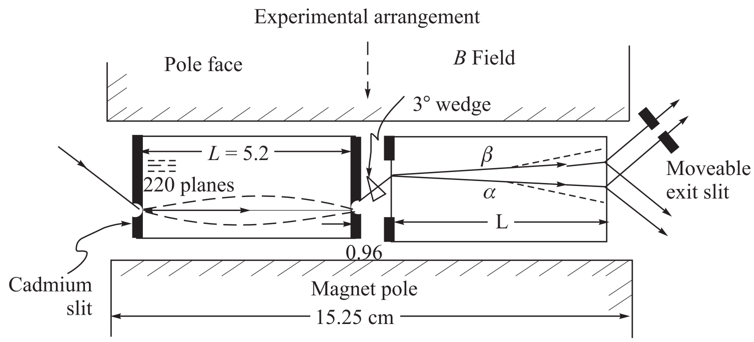

Fig. 4. Top view of the MIT (USA) experiment. The dashed lines illustrate the effect of a force on the neutron trajectories inside the crystal

their individual widths. The 3° wedge was used. The difference in intensity was recorded at the reversal of magnetic field. The upper limit on the neutron magnetic monopole charge has been established as

$$e_m = (0.28 \pm 0.72) \cdot 10^{-27} \text{cgs units.} \tag{41}$$

In conclusion I would like to give some results of the calculation. The experiment [36] discussed above has been performed at MIT (USA). A similar method can be used not only for the estimation of magnetic but of electric neutron charge as well. Now the best experimental estimation of the latter was obtained at ILL (Grenoble) ($q_n < 1.5 \cdot 10^{-21} e$) (1988). Using the MIT method one can improve this estimation up to several tens of times making use of the MIT reactor even.

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141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@pds.jinr.ru
www.jinr.ru/publish/