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TO SEMI-CENTENARY ANNIVERSARY OF DISCOVERING THE SCHWINGER SCATTERING AND STARTING THE FIRST WORKS ON NEUTRON POLARIZABILITY

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К 50-летию экспериментального обнаружения нейтронного
швингеровского рассеяния и первых работ о нейтронной поляризуемости

Теория нейтронного швингеровского рассеяния была предложена и развита Швингером в 1948 г., однако экспериментальное обнаружение явления состоялось лишь в 1956 г., несмотря на многократные попытки. В настоящее время швингеровское рассеяние следует учитывать во многих прецизионных экспериментах, например при изучении электромагнитного взаимодействия нейтронов с ядрами. С помощью швингеровского рассеяния можно измерять степень поляризации первичного пучка даже при энергиях частиц порядка 1 ГэВ.

Понятие нейтронной поляризуемости было введено после известных опытов (1953–1954) Хофштадтера как дополнительное явление, подтверждающее пространственную структуру нуклона. Впервые нейтронная поляризуемость была обнаружена в нейтронных опытах при рассеянии на малые углы в 1957 г., однако серьезное противоречие между результатами мега- и килоэлектронвольтной области энергий стало понятным лишь в 2001 г.

Показано также, что проведенные к настоящему времени эксперименты по рассеянию мегаэлектронвольтных нейтронов на малые углы тяжелыми ядрами не подтверждают идею $(n+3)$-мерной гравитации.

Работа выполнена в Лаборатории нейтронной физики им. И. М. Франка ОИЯИ.

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Alexandrov Yu. A. E3-2006-142

To Semi-Centenary Anniversary of Discovering the Schwinger
Scattering and Starting the First Works on Neutron Polarizability

The theory of neutron Schwinger scattering was proposed and developed by Schwinger in 1948, but despite multiple efforts, the experimental discovery of this phenomenon was made eight years later. Currently, Schwinger scattering should be accounted for in many precise neutron experiments, for example, while studying the electromagnetic interaction of neutrons with nuclei. By means of Schwinger scattering it is possible to measure the degree of polarization of the initial beam even at particle energies of 1 GeV order.

The concept of neutron polarizability was introduced as additional natural phenomenon indicating the nucleon space structure after the first Hofstadter's experiments (1953–1954). The neutron polarizability was detected in a small-angle neutron scattering experiment in 1957. However, the serious contradiction between the results obtained in megaelectronvolt and kiloelectronvolt neutron energy ranges was explained only in 2001.

It is also shown that existent small-angle neutron experiments at megaelectronvolt energy by heavy nuclei do not confirm the idea of $(n+3)$-dimensional gravity.

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

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INTRODUCTION

The first report, dedicated to 40-year anniversary of discovering the proton radioactivity, was presented by V. A. Karnaukhov in autumn 2005 in JINR. At that time it was recommended to make such presentations regularly, referring to both the core of the topic and its history.

In this paper I'm going to tell about the experimental discovering of the so-called Schwinger scattering (1956), as well as about first works relating to the neutron electric polarizability (1956–1957). This announcement presents interest for both elder and younger generations of physicists. It is important to acknowledge that valuable and remarkable works are, as a rule, performed at comparatively young age (for example, well-known physicists Bohr, Einstein, Mössbauer, Kapitsa and many others).

1. SCHWINGER NEUTRON SCATTERING

Well, what is Schwinger neutron scattering? In contrast to the short-acting nuclear forces it is induced by far-acting between magnetic momentum μ_n of a moving neutron and the Coulomb field of a nucleus. For the first time in 1948 Schwinger theoretically calculated it [1] and suggested using it for obtaining the polarized megaelectronvolt neutrons.

As a main diffraction maximum is concentrated in $\theta \leqslant \lambda/R$ angles range, and R is large enough, at the neutron energy of 1 MeV order, the Schwinger scattering will be observed in the small-angles range (< 5–7°) and for heavy nuclei it will occur comparable to cross section of nuclear scattering. Using Born approximation, Schwinger had obtained the following expression for an amplitude of scattering:

$$f(q) = f_0(q) + \frac{1}{2} i(\boldsymbol{\sigma} \cdot \mathbf{n})\mu_n \cot\frac{\theta}{2}\left(\frac{\hbar}{Mc}\right)\left(\frac{Ze^2}{\hbar c}\right)[1 - f(q)], \qquad (1)$$

where $f_0(q)$ is an amplitude of nuclear scattering, $q = 2k\sin\theta/2$, θ angle of scattering, $\mathbf{n}k^2\sin\theta = [\mathbf{k}\times\mathbf{k}_0]$, $\mathbf{k}$ is a wave vector, $f(q) = \dfrac{4\pi}{Z}\displaystyle\int_0^\infty \frac{\sin qr}{qr}\rho(r)r^2 d^3r$ is an atomic form factor, and differential cross section of scattering:

$$\sigma(\theta) = |f_0(\theta)|^2 + \gamma^2\cot^2\theta/2 + 2\gamma\,\mathrm{Im}\, f_0(\theta)\cot(\theta/2)(\mathbf{n}\mathbf{P}_0), \qquad (2)$$

where $\gamma = (1/2)\mu_n \left(\frac{\hbar}{Mc}\right)\left(\frac{Ze^2}{\hbar c}\right)$, and $\mathbf{P}_0$ is a vector of falling neutron polarization.

In the case of unpolarized neutrons, the third term in the expression (2) is zero and only first two terms remain.

In consequence of the spin-orbital interaction, induced by the movement of magnetic momentum of neutron in Coulomb field of the nucleus, the scattered neutrons appear to be highly polarized. Polarization equals:

$$\mathbf{P} = \mathbf{n}\frac{2\mathrm{Im} f_0(\theta)\gamma \cot\theta/2}{|f_0(\theta)|^2 + \gamma^2 \cot^2\theta/2.} \tag{3}$$

Thus, it results from the interference between the amplitude of Schwinger scattering and an imaginary part of nuclear scattering amplitude. The polarization value may reach 90–100 % for heavy nuclei and neutron energies of 1 MeV order.

After 1948 multiple attempts to discover the given scattering were undertaken (USA, Canada, Great Britain and others). However, as a rule, they were unsuccessful because of the absence of powerful neutron sources and necessity of beam hard collimation.

First successful experiments [2] were carried out in Obninsk Physics-Energy Institute (PEI) in 1955–1956. It is notable that at that period of time a series of works was carried out in Obninsk. They were of fundamental importance and related to the basic physics. Unfortunately, there is almost nothing written about them in the famous book of Yu. Stavissky «We are from Obninsk» (published in 2002). Prof. D. I. Blokhintsev – the director of PEI in the 50s, despite the very complicated technological problems connected to starting (1954) and then to operating the first atomic power station (APS), — was able to create an atmosphere allowing employees of the Institute to elaborate on the fundamental physics, if they wished so. Such physicists as G. I. Marchuk (future president of AS USSR), B. B. Kadomtsev (future academic, working in Kurchatov Institute later on), A. S. Davydov (author of the famous books «Quantum mechanics» and «Theory of an atomic nucleus»), V. F. Turchin (author of the book «Slow neutrons») and many others had originated from Obninsk. M. A. Markov and Ya. A. Smorodinsky had rather often attended the seminars in PEI. It is impossible not to remember V. A. Malykh (the greatest technologist, creator of thermo-emitting elements for first APS and ceramics technology), he didn't get higher education but, nevertheless, he had become Doctor of Technical Sciences, Lenin Prize laureate, Hero of the Socialistic Labor and died at the end of the 60s, and I. I. Bondarenko — an eminent scientist and an extremely good-willing person. It is a pity he had untimely died at the beginning of the 60s.

Well, now on the scattering of fast neutrons (with the energy of 1 MeV order) at heavy nuclei. A successful experimental work was accomplished by PEI scientists Yu. A. Alexandrov and I. I. Bondarenko in 1955. It came as a consequence of starting the first fast neutron reactor in USSR and Europe of that time period, which was a sufficiently powerful source of the necessary neutrons. The reactor was put into operation in May 1955 and measurements of the small-angle neutron scattering had started at once. The power of reactor was 100 KW, it had an active zone of only 13 cm in diameter and was cooled by mercury. In the direct vicinity of the active zone a steel collimator was placed which had a slit size of 4×1 cm and a length of 1 m (see Fig. 1). It is proper to pay honor to D. I. Blokhintsev and to the scientific leader on fast reactors A. I. Leipunsky

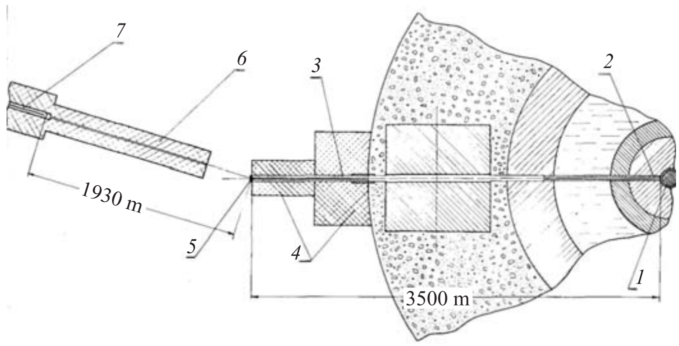

Fig. 1. Apparatus for measurements of the small-angle neutron scattering. *1* — reactor active zone; *2, 3* — steel collimators; *4, 6* — paraffin shielding; *5* — target; *7* — detector

who sanctioned the laying of the collimator. The reactor had not been operating for long. It took less than a year for mercury to destroy casings of plutonium elements, so plutonium appeared in mercury. However, by the end of 1955 the main work on small-angle neutron scattering was performed and immediately sent to print. Unfortunately, it was published only after publication of English work [3] (January, 1956) and appeared in print only in the second half of 1956. In the English work neutrons from the cyclotron beryllium target were used. Their energy amounted to about 100 MeV, but the cross section of scattering at small angles was not measured.

Currently, regarding results of Obninsk work. They are presented in Fig. 2. The cross section for lead well coincides with Schwinger calculations. The discovered phenomenon the authors [2] had called «Schwinger scattering».

Several words on neutron detectors. First measurements, presented in Fig. 2, have been carried out using a scintillation detector ZnS in plexiglas. An average

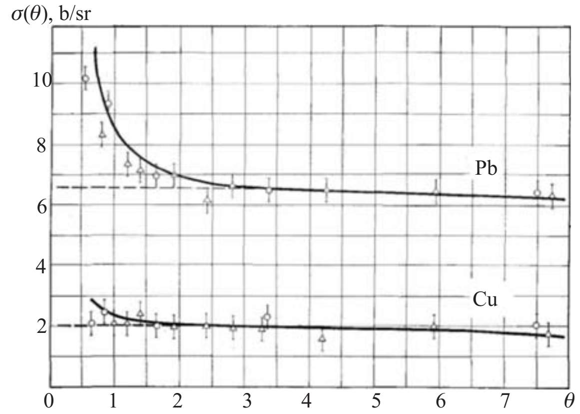

Fig. 2. First results of the small-angle neutron scattering distributions measurements

of measured neutron energy was about 3 MeV. During farther measurements a cylindrical helium chamber was applied (^{4}He has a resonance in the scattering cross section at 1.2 MeV neutron energy). A cylindrical hydrogen chamber was also applied. The neutrons of head-on collisions were extracted by means of radiotechnical method (by the shape of pulse rise-up portion). They were analyzed by energy. Thus, it was possible to extract neutrons with the energy of 0.5 to 15 MeV.

Afterwards, in the range of the thermal neutron energy Schwinger scattering was observed by Shull (1963) at vanadium and by Alexandrov and collegues (1979) at tungsten.

After 1956 Schwinger scattering had been investigated in many laboratories of the world (Gatchina, Kurchatov Institute, USA, Italy and others). In this regard it is proper to mention the work of Dukarevich and Dyumin (Gatchina, 1963). It was Dyumin's PhD thesis. Neutrons ($E = 14.2$ MeV) of deuterium–tritium reaction were used. It was not necessary to collimate them because alpha-particles, produced in reaction, were undergoing collimation. Their coincidences with the neutrons were registered. Measurements have been carried out at W, Pb, Bi, Th and U nuclei in the interval of angles from 3 to 20°.

In Kurchatov Institute Schwinger scattering was investigated by Gorlov, Lebedeva and Morozov, starting in 1957, whereas in Obninsk by Anikin, Kotukhov and Soldatov (up to 1990 [4]). In Obninsk work at analyzing the experiments an optical model of nucleus was used with an addition of Schwinger potential. Measurements were performed at Cu, Pb, U nuclei in the interval of angles 2–24° and at the neutron energies of 0.6 to 15 MeV.

At last, here are several words on the work of Italian physicists (1973–1980) [5]. The given work was accomplished at the neutrons of $^7\mathrm{Li}(p,n)^8\mathrm{Be}$ reaction, which had 2.5 MeV energy. The scattering had been investigated in the interval of angles from 2.1 to 9.1°. The scheme of the experiment is presented in Fig. 3. In order to detect the neutrons, a position-sensitive scintillation spectrometer was used. It had a length of 80 cm and was 3 cm in diameter. An important feature of this work is that a simultaneous measurement was performed in it for all angles at once. A place of neutron registration was determined by the time of light signals arriving at the photomultipliers. The neutron scattering was studied at In, Ho, Hg, Bi, U nuclei. Some of the results of the experiment are presented in Fig. 4. Works of Obninsk physicists, as well as Italian experiments, do not exclude a hypothesis of the supplementary small-angle neutron scattering at heavy nuclei besides Schwinger scattering (see below).

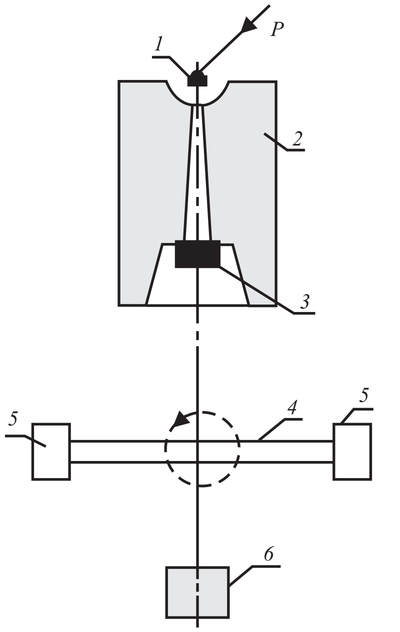

Fig. 3. Scheme of Italian experiment. *1* — lithium target; *2* — shielding; *3* — scatterer; *4* — position-sensitive spectrometer; *5* — photomultiplier; *6* — neutron direct beam detector

In which experiments and calculations is it necessary to account for Schwinger scattering and when is it proper to apply it?

1) First of all, it is necessary to take it into account in all precision experiments, for example, at studying the electromagnetic interaction of neutrons with nuclei.

2) With Schwinger scattering assistance it is possible to obtain polarized neutrons and other baryons with the energy of about several MeV and higher.

3) It is possible to measure lengths of neutron scattering.

4) It is possible to measure the degree of available particles polarization (even if their energy is of several GeV order).

5) It is possible to measure the unknown magnetic moments of hyperons and antihyperons (suggestion of L. Lapidus – JINR, 1973).

6) In some cases, Schwinger scattering should be taken into account at calculating the nuclear reactor shielding.

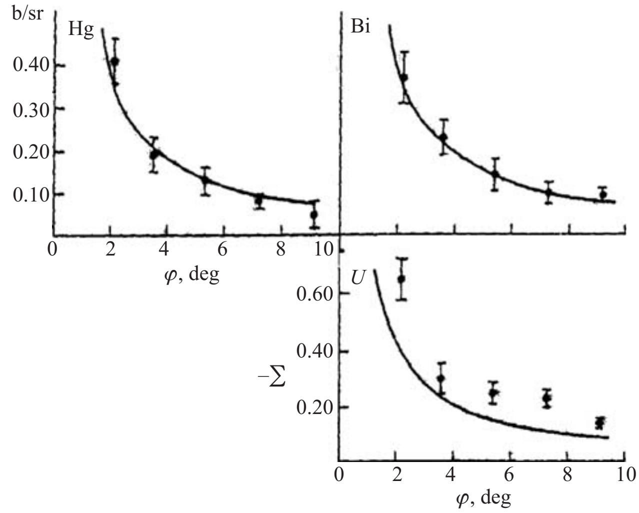

Fig. 4. Results of Italian experiment

2. THE ELECTRIC POLARIZABILITY OF NEUTRON

In order to understand the importance of the given problem a person ought to travel in time to the beginning of the 50s. At Stanford in 1952–1953 Hofstadter, for the first time, experimentally showed using the scattering of electrons with the energy of about some hundreds MeV that a proton had a space internal structure. In this regard, the following question arose in front of physicists: whether there is another phenomenon verifying the space structure of nucleon in nature. Both in Russia and the USA the corresponding works were taken; at the same time, they were completely independent from each other.

In the USA in 1955 a work of Klein [6] was published, where he discussed an amplitude of photon scattering at the nucleon and talked about the possibility of nucleon polarizability, i. e., about nucleon deformation in the field of electromagnetic forces. An analogous problem was considered in Moscow by the group of Baldin. At the conference in Venice in 1957 he reported on this theme, however, his first publication appeared only in 1960 [7]. A little later the problem of nucleon polarizability in Moscow was taken up by Petrunkin and Lvov, and in PINP (Gatchina) by Shekhter.

At PEI (Obninsk) in 1954–1956 Alexandrov and Bondarenko were considering the question on neutron scattering in Coulomb field of nuclei. At that time, an idea of electric polarizability of neutron was introduced [2]. Due to that a neutron is a system, which, according to Yukawa theory, includes opposite virtual electric charges, in Coulomb field a neutron should come to having the directed electric dipole moment d, whereas in Hamiltonian of neutron and nucleus interaction the following additional term appears:

$$V(r) = dE = -\alpha E^2/2 = -\frac{\alpha Z^2 e^2}{2r^4}, \qquad (4)$$

where α is a coefficient of electric polarizability of the neutron.

Due to that the main diffraction maximum has to be at the scattering angles $\theta \leqslant \lambda/R$, θ will be of the order of or less than 3° at $\lambda = 4.6 \cdot 10^{-13}$ cm ($E = 1$ MeV) and $R = 10^{-11}$ cm values. Exactly, at such angles it is proper to search for possible display of neutron electric polarizability at neutron scattering on heavy nuclei.

As I have already mentioned, the experiments studying the neutron small-angle scattering were started in 1955 and their first result appeared to be the discovery of Schwinger scattering. The experiments have been further continued and in 1957 the work [8] by Alexandrov was published. It concerned with finding anomalies for Pu and U in the small angles area at the neutron energy of about 1.5 MeV, consisting in faster growth of the cross section than it is required by the nuclear and Schwinger scattering theory (see Fig. 5). These results were also reported at the Conference on nuclear reactions at small and intermediate energies (November, 1957). By that time Barashenkov, Stakhanov and Alexandrov published the work [9], containing the calculated expression of

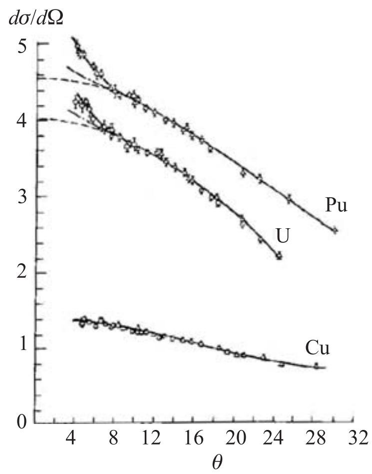

Fig. 5. Angular distribution of neutrons in the elastic scattering on Pu, U and Cu

the scattering amplitude caused by the neutron electric polarizability:

$$f(\theta) = \frac{\alpha M}{2R}\left(\frac{\text{Ze}}{\hbar}\right)^2 x\left\{\frac{\sin\, x}{x^2} + \frac{\cos\, x}{x} + si(x)\right\}, \tag{5}$$

where $x = 2kR\sin\theta/2$, $si(x) = \int\limits_x^{\infty}\frac{\sin x}{x}dx$, and $k = 2\pi/\lambda$ is a neutron wave number.

Total differential cross section of unpolarized neutron scattering will have the following form:

$$\sigma(\theta) = |f_0(\theta)|^2 + \gamma^2\text{cot}^2\theta/2 + |f(\theta)|^2 + 2(\theta)\text{Re}\, f_0(\theta). \tag{6}$$

It is important to note that the contribution of the cross section caused by neutron polarizability into total scattering cross section is very small. For lead this value is $\Delta\sigma = 0.13\alpha\sqrt{E} = 1.3$ mb at $E = 100$ eV and $\alpha = 1$ (10^{-42} cm^3 in units).

In Obninsk rather many physicists-theoreticians had been studying the theoretical questions related to the neutron electric polarizability, namely, Kaprov, Usachev, Agranovich, Konobeev, Stavinskij, Odintsov and others. A great role in the experiment and theory development was played by investigations lead out by communities of the Frank Laboratory of Neutron Physics JINR and Garhing Laboratory (Germany) (see, e. g., [10]), FLNP JINR and PINP (joint works with G. Petrov's group), FLNP JINR and INP (Řež, Czech Republic), as well as by works carried out in the USA, Austria, Germany and also, certainly, Obninsk (Anikin, Kotukhov up to 1990 [4]). However, all analyzes of the experimental data obtained in the megaelectronvolt neutron energy region resulted in neutron polarizability coefficient value being equal $\alpha = 10^{-40}$ cm^3.

Starting with approximately 1960 it became known that the value α may be successfully found in the region of neutron energies less than 300 keV. If the differential cross section of neutron elastic scattering is presented in the form of Legandre polynomials expansion:

$$\sigma(\theta) = \frac{\sigma_s}{4\pi}[1 + \omega_1\cos\theta + \omega_2 P_2(\cos\theta) + \ldots], \tag{7}$$

where $\sigma_s = 4\pi\sin^2\delta_0/k^2$ is total cross section of scattering, so for nuclear scattering a coefficient may be obtained at $\cos\theta$:

$$\omega_1 = \frac{6\sin\delta_1\cos(\delta_0 - \delta_1)}{\sin\delta_0} \approx \frac{6\delta_1}{\delta_0} \sim (kR)^2 \sim E, \tag{8}$$

i. e., at low energies the asymmetry of nuclear scattering increases linearly with the increase in neutron energy.

Accounting for the scattering induced by the neutron polarizability brings to appearing of scattering of the interferential term in the cross section. In this case ω_1 will contain an additional term proportional to the root from the neutron energy:

$$\omega_1 = aE + b\sqrt{E}, \tag{9}$$

where $b \sim \alpha$.

In 1966 in FLNP JINR at the IBR-30 reactor the investigation on scattering at lead was carried out in the range of neutron energies from 0.6 to 26 keV and in the angles range from 30 to 150° [11]. Yu. Alexandrov, G. Samosvat, J. Sereeter, Tsoj Gen Sor were the authors of this work. Processing the results of this work resulted in conclusion that value $\alpha < 6{\cdot}10^{-42}$ cm^3. This estimation had stayed unsurpassed during 20 years.

Thus, there is a sharp contradiction between the results obtained in megaelectronvolt and kiloelectronvolt areas of neutron energies. Besides, the experiments of Goldansky et al. on γ–p scattering in photon energy range of about 100 MeV gave $\alpha = 10^{-42}$ cm^3 value for a proton. Accordingly, the available contradiction had been unexplained for 40–45 years. Several factors are known to contribute to the explanation of this contradiction. So, in 1959 D. Blokhintsev, V. Barashenkov and B. Barbashov supposed the existence of yet unaccounted for and unknown interaction between neutron and atoms to be possible, as they suggest in an article published in UPN-journal. Starting with 1960s D. Wilkinson (England) and T. Savada (Japan) believed that there was a long-range interaction between hadrons. Here, I would like to cite a statement of V. Agranovich (expressed in 1957–1958 in PEI Obninsk): «. . . at the small-angle scattering of fast neutrons an additional interaction may occur, which is caused by a phenomenon of polarizability of electron covering by a transiting neutron. Rough estimations of the interaction potential value show that it is a little less than Schwinger scattering. More accurate calculations appear to be difficult and were not as yet carried out». This expression appeared to be prophetic. It is cited on in my PhD thesis (1958) (to my shame, I had not paid proper attention to it during several decades).

In 1999 Pokotilovsky with co-workers presented in [12] (see also [13]) that at the neutron energy from 0.5 to 10 MeV in the interval of angles from 3 to 15° the effect from the polarizability potential ($\sim 1/r^4$) at $\alpha = 10^{-40}$ cm^3 and from Van der Waals potential [$V_R = U_R(R/r)^6$] is identical for lead, if constant U_R is chosen to be equal 250–350 keV for better description of the experimental data. Pokotilovsky had not considered the connection between constant and polarizability value. The calculations of differential cross section of the neutron scattering were performed by the optical model of nuclear scattering with the addition of both potentials $\sim 1/r^4$ and $\sim 1/r^6$. Moreover, the Van der Waals potential will not practically appear at the low energies ($E \leqslant 300$ keV).

In 2001 your obedient servant performed the analytical estimation of U_R value and established its connection with the neutron polarizability. It is known that Van der Waals forces occur in the second approximation of the perturbation theory and are caused by the electric dipole–dipole interaction. Since I had reported on the calculation method and its results three times at International conferences (ISINN-9, Dubna, 2001; 51st International Meeting on nuclear spectroscopy and atomic nucleus structure, Sarov, 2001; International conference on the selected problems of modern physics, Dubna, 2003) and these data are furthermore published in article [14], here only the final expression for the constant U_R is presented:

$$U_R(\theta) = \frac{3}{2R^6}\alpha \sum_i \Delta E_i^A \alpha_i^A(\theta), \tag{10}$$

where R is radius of the nucleus (for the case of uranium $R = 9.4 \cdot 10^{-13}$ cm); $\Delta E_i^A = E_i - E_{0i}$ is the excitation energy of the $i\mathrm{th}$ electron in atom; $\alpha_i^A(\theta)$ is the polarizability of $i\mathrm{th}$ electron in atom; θ is the angle of scattering.

In order to estimate U_R (10) value, it is possible to accept ΔE_i^A to be equal to the binding energies of the corresponding electrons in an atom. For uranium the binding energies are changing from 115.6 keV (K-shell) to the value of 5–6 eV order (P-shell).

It is necessary to know the values $\alpha_i^A(\theta)$ for electrons in a complex atom. However, at present there is no strict theory for their calculation. In the first approximation they may be considered to be equal to values of electron polarizability in an atom, accepting the atom model in the form of a linear oscillator to be used in estimation process. In similar model we'll have (see, e. g., [15]):

$$\alpha_i^A(\theta) = N_i \frac{e^2\hbar^2}{mE_i^2}, \tag{11}$$

where m is mass of an electron, and N_i — number of electrons in atom, having energy E_i. The information on E_i values may be obtained by equating them with binding energies of the corresponding electrons in the atom. Electron spatial distribution in the atom may be found out from the angular distribution of scattered neutrons in the small-angle range. The value of the neutron trajectory distance from the atom's center, passing through an atom, in the first approximation is connected to the value of scattering angle as $\Delta R = \lambda/\theta$. Knowing ΔR (for uranium at energy of falling neutrons of 1 MeV order it changes depending on the scattering angle in the small-angle range from $3.5 \cdot 10^{-9}$ to $1 \cdot 10^{-11}$ cm), it is possible to determine the number of electrons participating in the considered process, their arrangement by coverings and their binding energy in the atom. Then, according to the formulas (10) and (11), it is possible to calculate $\alpha_i^A(\theta)$ and $U_R(\theta)$ values for each scattering angle.

The correctness of the formula (11) may be checked. Thus, for the hydrogen atom it is known that $\alpha_H = 6.66 \cdot 10^{-25}$ cm^3. According to formula (11), it is possible to get $\alpha_H = 6.06 \cdot 10^{-25}$ cm^3 if E_H is accepted to be $E_H = 13.5$ eV. The calculations presented in work [16], carried out using Thomas–Fermi model, may serve as further examples. So, for an atom of tin there is practically no difference between results obtained by means of such calculations and according to formula (11), and regarding uranium the difference does not exceed 1.5 value.

The sought U_R value may be obtained by conducting an averaging procedure $U_R(\theta)$ by the scattering angles (3–15° according to work [12]):

$$U_R = \frac{\int\limits_{\theta_1}^{\theta_2} U_R(\theta) \sin\theta \, d\theta}{\int\limits_{\theta_1}^{\theta_2} \sin\theta \, d\theta}. \tag{12}$$

Conducting the above-mentioned procedures, it is possible to get an estimation $U_R = 210$ keV for uranium at the neutron polarizability value $\alpha = 1.5 \cdot 10^{-42}$ cm^3 (the value of the proton electric polarizability is, as it is known, $\alpha_p = (1.17 \pm 0.08 \pm 0.07) \cdot 10^{-42}$ cm^3). The potential $\sim 1/r^4$, certainly, will also work, but using Van der Waals potential at the neutron energy of megaelectronvolt order seems to be more adequate.

The obtained U_R value is close to the real one (let's remind that $U_R = 300$ keV for ^{208}Pb isotope). More thorough approach to determining the neutron polarizability by the above-stated method, i. e., developing the necessary theoretical questions, will apparently be realized in future. For the present it is proper to note that despite its extremely small value the neutron electric polarizability had already been observed in experiments on the fast neutron small-angle scattering by heavy nuclei in 1957, that is, in a year or two after appearing of a hypothesis about it and earlier than the proton polarizability in the experiments on γ–p scattering.

3. CHECKING THE IDEA OF MULTIDIMENSIONAL GRAVITY THEORY

In conclusion I would like to note that the work [17] considering the idea of possible existence of $(n + 3)$-dimensional gravity, was published in 2004. The case when $n = 0$ corresponds to the usual Newtonian triple dimensional gravity. In work [17] it is suggested to check the fairness of $(n + 3)$-dimensional approach ($n = 1, 2, 3, \ldots$) by conducting experiments with neutrons, in particular, on the neutron small-angle scattering by heavy nuclei. The variant of $n = 1$

is rejected because the calculation of the limit distance R_c, inside which the $(n + 3)$-dimensional approach may operate, exceeds the size of the solar system. So, it would not be stable. At $n = 2$, –$R_c = 3$ cm, at $n = 3$, –$R_c = 8 \cdot 10^{-6}$ cm, and at $n = 4R_c = 10^{-8}$ cm. Thus, the proposed idea may be fair for distances less than fractions of a centimeter. In the framework of the suggested theory the attracting force between two bodies of m_1 and m_2 masses may be written as:

$$F = \frac{m_1 m_2 G_n}{r^{n+2}}, \tag{13}$$

where $G_n = G$ is known Newton gravitational constant (if $n = 0$), or in the form of the interaction potential:

$$V(r) = \frac{m_1 m_2 G (R_c)^n}{(n+1) r^{n+1}}, \tag{14}$$

where $(R_c/R_e)^n = (c^2/\eta^2)(G_F/G)$, $G_F = (1.166 \cdot 10^{-5}\ \text{GeV}^{-2})(\eta c)^3$ is Fermi's constant, and

$$R_e = [G_F/(\eta c)]^{1/2}.$$

The amplitude of gravitational elastic neutron scattering at nuclei may be written as:

$$A_g(E, \theta) = i/(k) \sum (2L + 1) \delta P_L(\cos\theta), \tag{15}$$

where $\delta = \dfrac{m_1 m_2}{(n+1) b^n \hbar v} G(R_c)^n$, and $b = (L + 1/2)\eta/(m_1 v)$.

Perhaps, the most suitable opportunity to discover the $(n + 3)$-dimensional gravity is to observe the small-angle scattering of neutrons with energy of 1 MeV order by the heavy nuclei. As it is indicated above, such experiments were majorly carried out 40–50 years ago. At that time, the additional contribution, explained by the influence of neutron electric polarizability, was discovered besides nuclear and Schwinger scattering.

Table 1.

$V(r)$, eV	$\alpha = 2.6 \cdot 10^{-40}$	$n = 1$	$n = 2$	$n = 3$	$n = 4$
	0.34	$2 \cdot 10^{-3}$	$3.7 \cdot 10^{-9}$	$7 \cdot 10^{-15}$	$9 \cdot 10^{-21}$

Let's see what kind of scattering is caused by $(n + 3)$-dimensional gravity. After all it will also be long-ranging. By the present it is well established that at the neutron energy of 1 MeV order and at their scattering onto the angles of 1 degree order at the even–even nucleus the additional contribution makes a value of $0.6 \cdot 10^{-24}$ cm^2 order. Using the formulas (4) and (14) it is possible to compare values of the interaction potentials at the $E = 1$ MeV. The comparison results are presented in the table below:

It is seen from Table 1 that the $(n+3)$-dimensional gravity is hardly acceptable even at $n = 1$.

It is also possible to calculate the additional contribution into the scattering cross section

$$d\sigma/d\Omega = |f_0(\theta) + A_g(E,\theta)|^2 \approx |f_0(\theta)|^2 + 2|f_0(\theta)||A_g(E,\theta)|. \qquad (16)$$

Accepting $f_0(\theta) = 0.7 \cdot 10^{-12}$ cm (see, e. g., [14]) for nuclear scattering, it is possible to get (see Table 2) for

$$\Delta\sigma = 2|f_0(\theta)|\,|A_g(E,\theta)|(\text{at}\,\theta \approx 4^\circ):$$

Table 2.

$\Delta\sigma$, b	$\alpha = 2.6 \cdot 10^{-40}$	$n = 1$	$n = 2$	$n = 3$
	0.6	$1 \cdot 10^{-4}$	$3.6 \cdot 10^{-9}$	$4.2 \cdot 10^{-12}$

Therefore, from the presented calculations it may be concluded that there are not as yet available any experimental proves of fairness of the idea on the $(n + 3)$-dimensional gravity. In any case the existent experiments on small-angle neutron scattering do not support this idea.

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