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NEUTRON POLARIZABILITY

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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).

The problem of neutron polarizability is closely connected with the name of D.I.Blokhintsev. Among other things, first experimental search of the neutron polarizability influence on the character of neutron scattering was initiated in the Institute of Physics and Power Engineering (IPPE), Obninsk, where Prof. Blokhintsev was director in the 1950s.

One of the great successes in physics of the 1950s were famous experiments by Hofstadter carried out on 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 of nucleon space structure. In the middle of the 50s this question was considered independently by three groups of physicists: in the USA by Klein (1955) [1], in Russia by Baldin (unfortunately first paper in 1960 [2]) and by Alexandrov and Bondarenko (1956) [3]. In all of the mentioned papers the notion of nucleon polarizability was introduced (independently) similar to a certain degree, to the existing notions of atom polarizabilities. Since the influence of neutron polarizability on neutron scattering was considered only by the third group, I would like to tell you about the research initiated by this group in Obninsk.

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

$$V(r) = -dE = -1/2\,(\alpha E^2)\,. \qquad (1)$$

I discussed with Prof. Blokhintsev the possibility of such phenomenon inherent exactly in neutron as far back as 1954, after that he sanctioned the experimental search of this effect in neutron scattering.

At this time the first fast reactor in Europe was started in Obninsk. Together with Dr.Bondarenko we made a decision to search the influence of neutron polarizability on small angle neutron scattering. The angles of scattering can be estimated using the correlation $\theta \leq \bar{\lambda}/R$, where R is the radius of interaction. At $\bar{\lambda} \cong 4.6\mathrm{x}10^{-13}$cm (E = 1 MeV) and at R exceeding the radius of nuclear interaction ($R \cong 2\mathrm{x}10^{-11}$cm) it is possible to obtain $\theta \cong 1.5°$.

As a result of first measurements in 1955 [3], carried out in Obninsk on lead at neutron energies of 2-3 MeV, so-called Schwinger scattering was discovered. This phenomenon was predicted by Schwinger in 1948 but was not found till the mid-50s, despite the efforts of physicists from USA, Canada and other countries. It is the result of interaction between the magnetic moment of moving neutron and the Coulomb field of nucleus.

The following data [4,5], obtained by me 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 on Fig.1 [5], where dashed curves represent purely nuclear scattering, dot-and-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 the 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 (1). In case of the Coulomb field it will be

$$V(r) = -1/2\,(\alpha E^2) = -\,\alpha(Ze)^2/(2r^4) \qquad (2)$$

and the value of polarizability coefficient α obtained during experimental data processing will be about $\alpha \approx 10^{-40}\ \mathrm{cm}^3$ [5].

In 1960 the Goldansky's group measured the α value for proton in the experiment of γ-quantum scattering with the energy from 40 to 70 MeV on hydrogen. It proved to be in the region of 10^{-42}cm^3, that is 100 times less than Obninsk's value. By that time theoretical evaluations of the nucleon α appeared, primarily, in the works by Prof. Baldin. However, all of them led to the value $\alpha \approx 10^{-42}$cm^3 and, thus, were at variance with the Obninsk's value.

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 kind of experiments were started since 1960. Among them the experiment of 1966 should be mentioned. It was performed in 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 $\alpha \leq 6\text{x}10^{-42}$ cm^3 was obtained [6]. This value remained record-breaking up to 1986, which is about 20 years.

Later the measurements of angular distribution of neutrons and of total cross sections were performed by FLNP in cooperation with Garching (Germany), in Gatchina, as well as in Austria - USA, in 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 those obtained in the region of energies lower than 300 keV. 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 [7] : «...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) [8] paid and pays special attention (in 2000 one of the paper by Sawada was entitled as «*Proposal to observe the strong van der Waals force in the low energy neutron - Pb scattering*»). Apropos, as I know, the first work discussing a possible existence of long-range hadron interactions belongs to Prof. Wilkinson (1961, *The Rutherford Jubilee International Conference*).

In 1999 it was shown in the work by Pokotilovsky [9] and in his work made in cooperation with his colleagues [10] that at the 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 the potential (2) with the value $\alpha = 1.5\text{x}10^{-40}$ cm^3 will be the same as those caused by the van der Waals potential

$$V(r) = -U_R(R/r)^6 \qquad (3)$$

(R is the radius of nucleus) when choosing constant $U_R \approx 300$ keV. At the same time the potential (3) will not practically appear in the region of lower energies. The constant U_R was not calculated in the works by Pokotilovsky's group but was defined by selection, by trial method to achieve the best agreement between the calculations and the experiment. The constant U_R was not related to neutron polarizability spatially.

However, it was desirable to calculate the constant U_R and see how it was related to neutron polarizability that is to the value α. These calculations were performed by me, your obedient servant, in 2001. I will not tell you about these calculations in detail. I told about these calculations in Dubna (ISINN-10) and in Sarov on International Conferences [11, 12] last year (see also [13]). It should be noted that they are not undoubtedly precise yet. However, at present, it is enough to be sure that there are no considerable errors that would change the neutron value α by the factor 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 higher (0.5 - 10 MeV) energies.

As a result of calculations in the second approximation of perturbation theory one can obtain:

$$U_R(\theta) = \frac{3\alpha}{2R^6} \sum \Delta E_i \, \alpha_i(\theta) \qquad (4)$$

where $\Delta E_i \approx E_i$ is the binding energy of the i-th electron in atom, α_i is the polarizability of the i-th electron in atom.

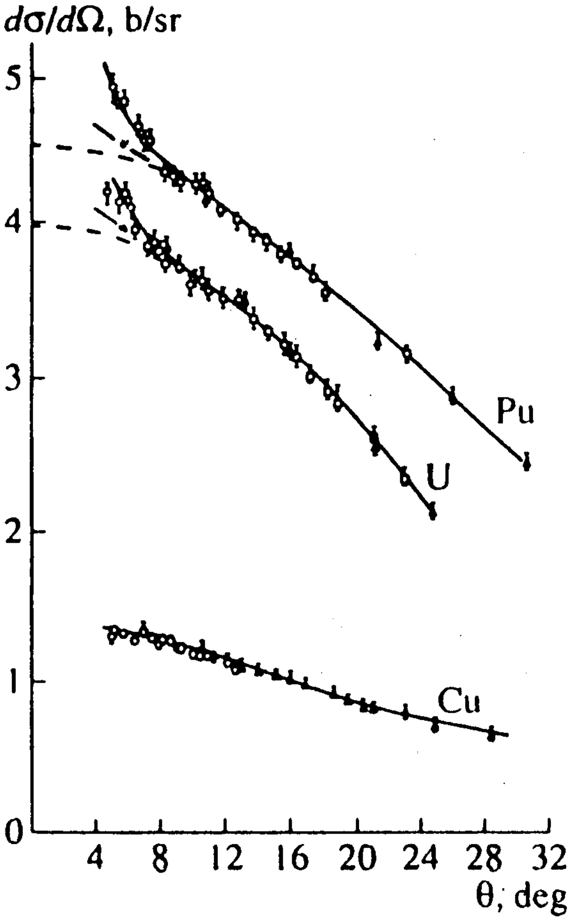

Fig.1. Angular distributions of neutrons in the region of angles 5°-30° in the elastic scattering on Pu, U and Cu. The dashed curve is the purely nuclear scattering $\sigma_0(\theta)$, the dash-dotted curve is $\sigma_0(\theta)$, supplemented by Schwinger potential.

Equation (4), which shows that the van der Waals interaction energy is proportional to the product of polarizabilities of 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 other types. It only depends on the validity of general principles, such as the Lorentz invariance, electromagnetic current conservation, analyticity and unitarity (see, e.g. [14]). We will continue using eq.(4) below.

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 was considered in paper[10]):

$$U_R = \int U_R(\theta) \sin\theta \, d\theta \,/ \int \sin\theta \, d\theta. \qquad (5)$$

It is necessary to know α_i of electrons in a complex atom. At present, however, there exists no strict theory of their calculation. In the first approximation we can accept the model of atom as a linear oscillator and, thus, we have from the book by Blokhintsev [15]:

$$\alpha_i (\theta) = N_i (\theta) \frac{e^2 \hbar^2}{m E_i^2} \qquad (6)$$

where m is electron mass, $N_i(\theta)$ is the number of i-th electron in atom.

It is possible to verify eq.(6) on the examples of some atoms. It is known, e.g., that for hydrogen atom $\alpha_H = 6.66 \times 10^{-25} cm^3$. From eq.(6) one can obtain $\alpha_H = 6.06 \times 10^{-25} cm^3$, if E =13.5 eV . From eq. (6) one can obtain for tin atoms the value of α_{Sn} , which will be approximately equal to the value obtained as the result of the Thomas-Fermi model calculations [16]. For uranium atoms the difference between the results of analogous calculations does not exceed 1.5 times [16].

The spatial 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 $\Delta R \approx \lambda\!\!\!^{-}/\theta$. 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 which are at a distance smaller than ΔR from the nucleus.

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

In conclusion, it should be emphasized, that similar to the Hofstadter experiments that proved 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.

The important role in solution of this problem belongs to Prof. D.I.Blokhintsev and I want to emphasize it in my report.

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Александров Ю. А. E3-2003-118
Поляризуемость нейтрона

Обсуждаются проблема введения понятия поляризуемости нейтрона и роль проф. Д. И. Блохинцева в развитии проблемы поляризуемости. Рассматривается также влияние поляризуемости нейтрона на нейтронное рассеяние частиц тяжелыми ядрами. Приводятся в согласие результаты оценок электрической поляризуемости нейтрона, выполненные в интервалах энергий нейтронов порядка нескольких мегаэлектронвольт и менее 300 кэВ. Приводятся аргументы в пользу мнения о первом экспериментальном наблюдении явления поляризуемости нейтрона в 1957 г. в опыте по рассеянию нейтронов на малые углы тяжелыми ядрами.

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Alexandrov Yu. A. E3-2003-118
Neutron Polarizability

The problem of introducing the notion of neutron polarizability and the role of Prof. D. I. Blokhintsev in the development of this problem are discussed. The influence of neutron polarizability on neutron scattering by heavy nuclei is considered. The results of estimations of electric neutron polarizability in the megaelectronvolt energy region and in the energy region of less than 300 keV are correlated. The reasons are given in favor of the opinion that neutron polarizability was observed for the first time in neutron experiments, namely megaelectronvolt small angle neutron scattering, i. e. in 1957.

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

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