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ON THE FORM OF LONG-RANGE POTENTIAL OBSERVED AT FAST NEUTRON SCATTERING BY HEAVY NUCLEI

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There is a strong contradiction between magnitudes of neutron electric polarizability α_n obtained from the experiments on elastic scattering by heavy nuclei of neutrons in different energy ranges: $\alpha_n \leq 2 \times 10^{-3} fm^3$ from the experiments at neutron energies $E_n \leq 40$ keV, and $\alpha_n \geq 10^{-1} fm^3$ from the measurements with neutrons in the energy range from $\simeq 0.5$ to several MeV. The first results do not contradict to modern theoretical models [1]: $\alpha_n \sim 1 \times 10^{-3} fm^3$, but the second one seems to be excessively large and surpass the expectations by two orders of magnitude.

The measurements of neutron electric polarizability in the low energy range of scattered neutrons is based on the specific form of the Born amplitude for neutron scattering in the r^{-4} polarization potential

$$U_{pol} = -\alpha_n (Ze)^2/2r^4, \text{ for } r > R; \quad U_{pol} = 0 \text{ for } r < R, \qquad (1)$$

where Ze is a nuclear electric charge, R is an electric radius of the nucleus. For simplicity, in what follows, we set long-range potentials equal to zero inside the nuclei, which does not change significantly the results of this consideration. The scattering amplitude in Born approximation for the potential of Eq. 1 has the following form:

$$f_{pol} = \alpha_n \Big(\frac{Ze}{\hbar}\Big)^2 \frac{m}{2R} \Big[\frac{sinx}{x} + cosx - x \int_x^{\infty} \frac{sint}{t}\, dt\Big], \qquad (2)$$

where m is the neutron mass, $x = qR$, and $\vec{q}$ is a momentum transfer vector. In the limit $x << 1$

$$f_{pol} = \alpha_n \Big(\frac{Ze}{\hbar}\Big)^2 \frac{m}{R} \Big[1 - \frac{\pi}{4}x + \frac{1}{6}x^2 + O(x^4)\Big]. \qquad (3)$$

It was shown by Thaler [2] that, due to the linear in q second term in the neutron polarization scattering amplitude, neutron-nucleus differential cross-section, as a result of interference of nuclear and polarization amplitudes, must contain the term linear in the neutron wave vector k. The neutron angular distribution

$$\sigma(\theta) = \frac{\sigma_t}{4\pi}[1 + \omega_1 P_1(cos\theta) + \omega_2 P_2(cos\theta) + ...] \quad (4)$$

contains

$$\omega_1 = -\alpha_n \frac{\pi}{5}\Big(\frac{Ze}{\hbar}\Big)^2 \frac{2m}{a} k, \quad (5)$$

which is linear in k (a is the neutron scattering length).

The measurements of angular distribution of neutrons scattered by heavy nuclei [3] in the energy range of $0.6 - 26$ keV with addition of the earlier measurements [4] in the energy range of $50 - 160$ keV [4] yielded the result $\alpha_n \leq 10^{-2} fm^3$.

It is evident that due to neutron polarizability the total neutron-nucleus cross-section must contain the term linear in k:

$$\sigma_s(k) = \sigma_0 + ak + bk^2 + ... \quad (6)$$

Precise measurements of total neutron cross-sections and coherent scattering length of Pb and Bi [5] yielded

$$\alpha_n = (0.8 \pm 1.0) \times 10^{-3} fm^3. \quad (7)$$

The result of the measurements of the total neutron cross-section by heavy nuclei in the energy range up to 40 keV [6, 7] yielded the value

$$\alpha_n = (1.20 \pm 0.15 \pm 0.20) \times 10^{-3} fm^3. \quad (8)$$

The reconsideration [8] of experiments [6, 7] has led to conclusion that $\alpha_n \leq 2 \times 10^{-3} fm^3$.

On the other hand, in MeV energy range neutron scattering by heavy elements demonstrates significant deviations from optical model calculations with the account of Schwinger (spin-orbit) scattering. For example, in [9], the measured cross-sections are systematically greater than the calculated ones at the smallest angles. The authors [9] did not propose any explanation of this disagreement, and the measurements were not continued.

In a series of experiments and careful optical model calculations, the authors of [10] showed that the great variety of data on neutron scattering in MeV energy range (total cross-sections, angular distributions and especially small angle scattering) have a significantly better discription if the polarization term with the neutron polarizabilty factor as large as $\alpha_n \simeq (1-2)\cdot 10^{-1} fm^3$ is included into the potential of neutron-nucleus interaction. This value is two orders of magnitude higher than the value expected from reasonable calculations [1] and the measured restrictions [5, 6, 7].

What is the way to reconcile these two contradicting results? It is possible that some more refined model of neutron-nucleus interaction accounting for Schwinger term and "reasonable" neutron polarizability is able to describe the data in the MeV energy range. However, it might be possible that some other potential of the $\sim r^{-n}$ type with $n > 4$, for example with $n = 6$ (Van der Waals), or $n = 7$ (Casimir-Polder) influences neutron scattering in the MeV energy range.

A possibility of the existence of a strong long-range interaction between hadrons was discussed two decades ago using different approaches (see, for example, [11] and references therein) with mostly negative result but without any final firm conclusion. On the other hand, there are persistent indications on the existence of a strong potential of the r^{-n} form with n between 6 (Wan der Waals) and 7 (Casimir-Polder) (see [12] and referencies therein) which follow as a result of the sophisticated analisys of elastic $p-p$ scattering in MeV energy range. Similar long-range strong interaction might probably be observed in the neutron-nucleus scattering in the MeV energy range as it is (possibly) observed between hadrons.

It turns out that in the low energy range experiments [3, 5, 6, 7] (more precisely at $x << 1$) these potentials practically cannot be observed. The reason for that is in the fact that the only signal of the long-range interaction at low energies ($x << 1$), which distinguishes them from a short-range one, is a non-even term in the **expansion** of the first order Born amplitude.

The scattering amplitudes for the long-range potentials of the form

$$U(r) = -U_R\Big(\frac{R}{r}\Big)^n, \text{ for } r > R; \quad U(r) = 0, \text{ for } r < R, \tag{9}$$

where R is the radius of the nucleus, in the first Born approximation for n=5,6, and 7 are given by

$$f_5 = \frac{2mU_R R^3}{\hbar^2}\Big[\frac{sinx}{3x} + \frac{cosx}{6} - x\frac{sinx}{6} - \frac{x^2}{6}\int_x^\infty \frac{cost}{t}dt\Big], \tag{10}$$

$$f_6 = \frac{2mU_R R^3}{\hbar^2}\Big[\frac{sinx}{4x} + \frac{cosx}{12} - x\frac{sinx}{24} - x^2\frac{cosx}{24} + \frac{x^3}{24}\int_x^\infty \frac{sint}{t}dt\Big], \tag{11}$$

and

$$\begin{aligned} f_7 \;\; = \;\; & \frac{2mU_R R^3}{\hbar^2}\Big[\frac{sinx}{5x} + \frac{cosx}{20} - x\frac{sinx}{60} - x^2\frac{cosx}{120} + x^3\frac{sinx}{120} + \\ & + \frac{x^4}{120}\int_x^\infty \frac{cost}{t}dt\Big], \end{aligned} \tag{12}$$

In the limit $x << 1$, these amplitudes are

$$f_5(x << 1) = \frac{2mU_R R^3}{\hbar^2}\Big[\frac{1}{2} - \Big(\frac{11}{36} - \frac{ln\gamma}{6}\Big)x^2 + \frac{1}{6}lnx \cdot x^2 + O(x^4)\Big], \tag{13}$$

$$f_6(x << 1) = \frac{2mU_R R^3}{\hbar^2}\Big[\frac{1}{3} - \frac{1}{6}x^2 + \frac{\pi}{48}x^3 + \frac{1}{80}x^4 + O(x^6)\Big], \tag{14}$$

and

$$\begin{aligned} f_7(x << 1) \;\; = \;\; & \frac{2mU_R R^3}{\hbar^2}\Big[\frac{1}{4} - \frac{1}{12}x^2 + \Big(\frac{137}{720} - \\ & - \frac{ln(\gamma)}{120}\Big)x^4 - \frac{1}{120}lnx \cdot x^4 + O(x^6)\Big], \end{aligned} \tag{15}$$

where $\gamma \simeq 1.781$ is the Euler constant. It can be seen that the only non-even power of the x term in the expansion of Born amplitude for the potential $\sim r^{-5}$ is $x^2 lnx$. For the potential $\sim r^{-6}$ the only odd term is x^3 and the term characteristic for long range $\sim r^{-7}$ interaction is $x^4 lnx$. The short range potentials yield only even terms of x. For the potential of the form $\sim r^{-2n}$ the decomposition of Born amplitude yields the single odd term $\sim x^{2n-3}$, for the potential of the form $\sim r^{-(2n+1)}$ the non-even term is $\sim x^{2(n-1)} lnx$. Quantitative estimations for $x = 0.2$ yield the result that these terms are more than two orders of magnitude lower than the linear term in the expansion of Born amplitude for r^{-4} potential. Therefore, in the low-energy experiments ($x << 1$), it is practically impossible to recognize the presence of the long-range potential of the form $\sim r^{-n}$ with $n \geq 5$, even if it is as large as two orders of magnitude greater than the potential due to neutron polarizability (Eq. 1) with $\alpha_n \simeq 10^{-3} fm^3$.

The scattering amplitudes in the first Born approximation (Eqs. 3 and 9-11) for $n = 4 - 7$ generally behave similarly in the transferred moment range $x < 5$ where the amplitudes are not excessively small, differing only by the factor which does not change significantly. The same is true for the first 5-6 Born scattering phases for these potentials in MeV neutron energy range. It means that it is quite possible that large potential of the r^{-4} type inferred from fast neutron scattering in [10] may be in fact the potential r^{-n} with $n = 6$ or $n = 7$ but of larger magnitude at $r = R$.

Better confirmation or rejection of this point of view requires detailed computations with the most flexible nuclear optical potential and inclusion of long-range potentials of the r^{-n} type with different n in order to find out what kind of a long range potential is able to satisfy better the description of all the data on fast neutron scattering. These computations are now in progress.

The tentative calculations of neutron scattering cross-sections in MeV energy range for the Woods-Saxon potential with addition of long-range potentials r^{-n} with different n between 4 and 7 yield low difference in the form of angular distributions and total cross-section.

References

[1] G. Breit and M. L. Rustgi, Phys. Rev., **114**, 380 (1959); A. Kanazawa, Nucl. Phys., **24**, 524 (1960); P. Hecking and G. F. Bertsch, Phys. Lett., **99B**, 237 (1981); H. Krivine and J. Navarro, Phys. Lett., **171B**, 331 (1986); V. Bernard, B. Hiller, and W. Weise, Phys. Lett., **205B**, 16 (1988); R. Weiner and W. Weise, Phys. Lett., **159B**, 85 (1985); G. Bunatyan, Jad. Fiz. **55**, 3196 (1992); Sov. J. Nucl. Phys., **55**, 1781 (1992).

[2] R. M. Thaler, Phys. Rev., **114**, 827 (1959).

[3] Yu. A. Alexandrov, G. S. Samosvat, Z. Sereeter and Tsoi Gen Sor., Pis'ma v ZhETF, **4**, 196 (1966); JETP Lett. **4**, 134 (1966).

[4] M. D. Goldberg, V. M. May, and J. R. Stehn, BNL-400, Second Edition, v.II, 1962.

[5] L. Koester, W. Washkowski and J. Meier, Z. Phys., **A329**, 229 (1988).

[6] J. Schmiedmayer, H. Rauch and P. Riehs, Phys. Rev. Lett., **61**, 1065 (1988).

[7] J. Schmiedmayer, P. Riehs, J. A. Harvey and N. W. Hill, Phys. Rev. Lett., **66**, 1015 (1991).

[8] V. G. Nikolenko and A. B. Popov, JINR Preprint no.E3-92-254, Dubna, 1992; Proc. of the 8th Intern. Symp. on Capture Gamma Ray Spectroscopy, Frieburg, Sept. 20-24, 1993, p.812.

T. L. Enik, L. V. Mitsyna, V. G. Nikolenko, A. B. Popov and G. S. Samosvat, Jad. Fiz., **60**, 648 (1997); Phys. Atom. Nucl., **60**, 567 (1997).

[9] L. Drigo, C. Manduchi, G. Moschini et.al., Nuovo Cim., **13A**, 867 (1973); V. Giordano, C. Manduchi, M. T. Russo-Manduchi and G. F. Segato, Nucl. Phys. **A302**, 83(1978).

[10] G. V. Anikin and I. I. Kotukhov, Jad. Fiz., **12**, 1121 (1970); G. V. Anikin and I. I. Kotukhov, Jad. Fiz., **14**, 269 (1971); G. V. Anikin and I. I. Kotukhov, Atomnaja Energija., **60**, 51 (1986); G. V. Anikin and I. I. Kotukhov, Atomnaja Energija., **60**, 54 (1986); G. V. Anikin and I. I. Kotukhov, Proc of the Ist Intern. Conf. on Neutron Physics, Kiev, 14-18 Sept. 1987, Vol.2, p.139; G. V. Anikin and I. I. Kotukhov, Jad. Fiz., **49**, 101 (1989); I. I. Kotukhov, Dissertation , Fiziko-Enegeticheskii Institute , Obninsk, 1990, (in Russian, unpublished).

[11] G. Feinberg and J. Sucher, Phys. Rev., **D20**, 1717 (1979).

[12] T. Sawada, Int. Journ. Mod. Phys., **A11**, 5365 (1996).

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