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Abnormally large neutron polarizability or long-range strong-interaction potential at fast neutron scattering by heavy nuclei?

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Abstract. It is shown that the discrepancy between the results obtained for different neutron energy ranges, when neutron polarizability is derived from the neutron scattering data, can be removed if one assumes that at the fast neutron scattering a strong-interaction long-range potential of Van der Waals ($\sim r^{-6}$) or Casimir-Polder ($\sim r^{-7}$) is observed. This strong-interaction long-range potential has possibly some experimental confirmation in the elastic p-p scattering.

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There is a strong contradiction between the magnitudes of the neutron electric polarizability α_n obtained from the experiments on elastic scattering by heavy nuclei of neutrons in different energy ranges: $\alpha_n \leq (1$–$2) \times 10^{-3}\,\text{fm}^3$ from the experiments at neutron energies $E_n \leq 40\,\text{keV}$, and $\alpha_n \geq 10^{-1}\,\text{fm}^3$ from scattering of neutrons in the energy range from $\simeq 0.5$ to several MeV. The first results do not contradict the modern theoretical models [1]: $\alpha_n \sim 1 \times 10^{-3}\,\text{fm}^3$, 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} potential:

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

where Ze is a nuclear electric charge, R is the 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 for in the internal region this potential is indistinguishible from the nuclear one.

The scattering amplitude in Born approximation for the potential (1) has the following form:

$$f_{\text{pol}} = \alpha_n \left(\frac{Ze}{\hbar}\right)^2 \frac{m}{2R} \left[\frac{\sin x}{x} + \cos x - x\int_x^\infty \frac{\sin t}{t}\text{d}t\right], \tag{2}$$

where m is the neutron mass, $x = qR$, and q is the neutron scattering vector. In the limit $x \ll 1$

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

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

The neutron angular distribution

$$\sigma(\theta) = \frac{\sigma_t}{4\pi}\left[1 + \omega_1 P_1(\cos\theta) + \omega_2 P_2(\cos\theta) + \cdots\right] \tag{4}$$

contains

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

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

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

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

$$\sigma_s(k) = \sigma_0 + ak + bk^2 + \cdots \tag{6}$$

Precise measurements of the total neutron cross-sections and the coherent scattering length of Pb and Bi

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[5] yielded

$$\alpha_\mathrm{n} = (0.8 \pm 1.0) \times 10^{-3}\,\mathrm{fm}^3. \quad (7)$$

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

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

The reconsideration of experiments [6,7] performed in [8] has led the authors of this works to the conclusion that only the upper limit for the electric polarizability of the neutron can be inferred from these measurements: $\alpha_\mathrm{n} \leq 2 \times 10^{-3}\,\mathrm{fm}^3$.

The stringent limit follows from the latest measurement [9] in which it was established: $\alpha_n = (0.0 \pm 0.5) \times 10^{-3}\,\mathrm{fm}^3$.

On the other hand, in the 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 [10], the measured cross-sections are systematically greater than the calculated ones at the smallest angles. The authors [10] 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 [11] showed that the great variety of data on neutron scattering in the MeV energy range (total cross-sections, angular distributions and especially small-angle scattering) have better discription (in the sense of χ^2 value) if, in addition to the short-range Woods-Saxon potential of general form and the Schwinger interaction, the neutron electric polarizability term with a factor as large as $\alpha_\mathrm{n} \simeq (1\text{–}2) \times 10^{-1}\,\mathrm{fm}^3$ is included into the potential of neutron-nucleus interaction. This value of the neutron electric polarizability is two orders of magnitude higher than the value expected from reasonable calculations [1] and the measurements in the keV energy range. This value of neutron polarizability gives the potential $\simeq 0.2$ MeV at the surface of the Pb nucleus which may be compared with depth of the Woods-Saxon potential well of $\simeq 50$ MeV. In their analysis authors [11] used the most general neutron-nucleus interaction consisting of two Woods-Saxon potentials with up to 14 free parameters.

What is the way to reconcile these two contradicting results? It is possible that some more refined model of the neutron-nucleus interaction accounting for the Schwinger term and reasonable neutron polarizability is able to describe the data in the MeV energy range. However, it might be possible, as was proposed in [12], 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 for the existence of a long-range component in the strong interaction between hadrons was discussed previously using different approaches. Some theoretical aspects of strong long-range interaction between hadrons were analyzed by many authors (see for example [13] and references therein) without any final firm conclusion about the existence and strength of these forces. Irrespective of theoretical predictions which are very indeterminate, the bounds on the magnitude of this interaction may be obtained from experiments involving a variety of techniques. On the other hand, there are long-standing persistent indications on the existence of a strong attractive potential of the r^{-n} form with n between 6 and 7 ($n = 6.08$ as the latest value, and magnitude $\simeq 200$ MeV at $r = 1$ fm, see [14] and referencies therein) which follow as a result of the sophisticated analisys of elastic p-p scattering in the 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 cited low-energy neutron scattering experiments these potentials could not be observed. The reason for that is in the fact that, as was shown, the only signal of the long-range r^{-4} interaction at low energies ($x \ll 1$), which distinguishes it from a short-range one, and which was searched for in these experiment, is the term in the neutron-nuclei cross-section proportional to k. The potentials $\sim r^{-6}$ and $\sim r^{-7}$ at $x \ll 1$ yield characteristic terms in the scattering amplitude with higher degrees in k which are very small at low energies to be observed in cited experiments.

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

$$\begin{aligned} &U(r) = -U_R\left(\frac{R}{r}\right)^n, \quad U_R > 0, \text{ for } r > R;\\ &U(r) = 0, \quad \text{for } r < R, \end{aligned} \quad (9)$$

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

$$f_5 = \frac{2mU_RR^3}{\hbar^2} \times\left[\frac{\sin x}{3x} + \frac{\cos x}{6} - x\frac{\sin x}{6} - \frac{x^2}{6}\int_x^\infty \frac{\cos t}{t}\mathrm{d}t\right], \quad (10)$$

$$f_6 = \frac{2mU_RR^3}{\hbar^2}\left[\frac{\sin x}{4x} + \frac{\cos x}{12} - x\frac{\sin x}{24} - x^2\frac{\cos x}{24} + \frac{x^3}{24}\int_x^\infty \frac{\sin t}{t}\mathrm{d}t\right], \quad (11)$$

and

$$f_7 = \frac{2mU_RR^3}{\hbar^2}\left[\frac{\sin x}{5x} + \frac{\cos x}{20} - x\frac{\sin x}{60} - x^2\frac{\cos x}{120} + x^3\frac{\sin x}{120} + \frac{x^4}{120}\int_x^\infty \frac{\cos t}{t}\mathrm{d}t\right], \quad (12)$$

In the limit $x \ll 1$, these amplitudes are

$$f_5(x \ll 1) = \frac{2mU_RR^3}{\hbar^2}\left[\frac{1}{2} - \left(\frac{11}{36} - \frac{\ln\gamma}{6}\right)x^2 + \frac{1}{6}\ln x \cdot x^2 + O(x^4)\right], \quad (13)$$

$$f_6(x \ll 1) = \frac{2mU_R R^3}{\hbar^2} \times \left[\frac{1}{3} - \frac{1}{6}x^2 + \frac{\pi}{48}x^3 + \frac{1}{80}x^4 + O(x^6)\right], \quad (14)$$

and

$$f_7(x \ll 1) = \frac{2mU_R R^3}{\hbar^2}\left[\frac{1}{4} - \frac{1}{12}x^2 + \left(\frac{137}{720} - \frac{\ln(\gamma)}{120}\right)x^4 - \frac{1}{120}\ln x \cdot x^4 + O(x^6)\right], \quad (15)$$

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 $x^2 \ln x$. 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 $x^4 \ln x$. The short-range potential yields only even terms of x. For a potential of the form $\sim r^{-2n}$ the expansion of the Born amplitude yields the single odd term $\sim x^{2n-3}$, for a potential of the form $\sim r^{-(2n+1)}$ the non-even term is $\sim x^{2(n-1)} \ln x$.

These terms are more than two orders of magnitude lower than the linear term in the expasion of Born amplitude for r^{-4} potential and $x = 0.2$ ($E_\mathrm{n} \simeq 20\,\mathrm{keV}$ for neutron scattering on heavy nuclei) at the same value of the long-range potential at the nuclei boundary U_R. Therefore, in the low-energy experiments ($x \ll 1$), it was practically impossible to recognize the presence of the long-range potential of the form $\sim r^{-n}$ with $n \geq 6$, even if its amplitude at the nuclei boundary is as large as two orders of magnitude greater than the potential due to neutron polarizability (1) with $\alpha_\mathrm{n} \simeq 10^{-3}\,\mathrm{fm}^3$.

The scattering amplitudes in the first Born approximation (3) and (10)–(12) for $n = 4$–7 generally behave similarly in the range $x < 5$, where the amplitudes are not small, differing only by the factor which does not change significantly. The same is true for the several first Born scattering phases for these potentials in the MeV neutron energy range. It means that it is possible that large potential of the r^{-4} type inferred from fast neutron scattering in [11] may be in fact the potential r^{-n} with $n = 6$ or $n = 7$ but of correspondingly larger magnitude at $r = R$.

The optical model calculations of the differential cross-sections of neutron scattering on heavy nuclei in the energy range 0.5–10 MeV [15] demonstrated that the effects of additional long-range potentials with $n = 4$–7 on neutron cross-sections are very close if to fit appropriately the value U_R of the potentials at the nuclei boundary. For example the value $U_R \simeq 200\,\mathrm{keV}$ for the neutron polarizability potential inferred from experiments [11] must be changed to $U_R \simeq 300\,\mathrm{keV}$ for the long-range potential with $n = 6$ to achieve close similarity of their effects on cross-sections with difference in the limits of several per cent.

The experimental situation concerning strong long-range forces between hadrons was discussed in [13]. It turned out that if to parametrize these potentials in the form $U(r) = c(1\,\mathrm{fm/r})^n$, the most stringent restriction followed from measurements of radiative transitions in antiprotonic atoms: $c \leq 100\,\mathrm{MeV}$ ($n = 6$), and $\leq 600\,\mathrm{MeV}$ ($n = 7$). Other experiments (Cavendish or Eötvös-type experiments, hyperfine structure of molecular hydrogen) give much weaker bounds on long-range potentials with $n = 6$ or 7.

Experiments on neutron-nuclei scattering in thermal energy range (as well as neutron optics experiments) are very insensitive to these potentials. With $U_R = 300\,\mathrm{keV}$ and neutron energy $E_\mathrm{n} = 100\,\mathrm{meV}$ it follows from the above expression (14) that the contribution of the term x^3, specific for van der Waals potential, is $\simeq 10^{-10}$ of the neutron-nucleus amplitude.

At an energy $\simeq 20\,\mathrm{keV}$ the contribution of the term $\sim x^3$ is about $3\times10^{-3}\,\mathrm{fm}$, and the contribution of the term $\sim x^4 \ln x$ (the long-range potential with $n = 7$) is $\simeq 10^{-4}\,\mathrm{fm}$, the effects being significantly below the limits of detectability in the present experiments.

Better confirmation or more strict constraints for the existence of strong long-range neutron-nucleus interaction requires detailed computations with the most flexible nuclear optical potential and inclusion of long-range potentials of the r^{-n} type with different n. This complicated procedure must establish what kind of a long-range potential is able to satisfy better the description of the whole set of data on fast neutron-nucleus scattering.

Besides this approach, used in [11] to infer the long-range contribution to neutron-nucleus interaction, two ways are possible to determine the long-range potential explicitly using the characteristic k-dependence of the scattering amplitude described above. Both follow from the long search for the electric polarizability of the neutron [2–9]. One way is the very precise measurement of the angular distribution, the second one, the measurement with millibarn precision of the total cross-sections of neutron scattering by different (light and heavy) nuclei in the energy range up to several hundred keV. No such data are available now.

Analysis shows that the task of reliable inferring the small admixture of strong long-range interaction even from very precise neutron scattering data is dauntingly difficult. However in view of importance of this question for the theory of strong interaction it is worthwhile persuing it, as well as finding more crucial experiments for distinguishing the strong long-range component in nucleon-nucleon and nucleon-nucleus interaction.

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