AN INFLUENCE OF HYPOTHETICAL EXTRA-SHORT-RANGE INTERACTION ON THE SCATTERING ANISOTROPY OF COLD NEUTRONS BY NOBLE GASES.

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In order to estimate the influence of a new hypothetical extra-short-range interaction on the scattering of cold neutrons for the experiment proposed in [1] both analytical and Monte Carlo calculations of angular distributions of neutrons with initial velocities of 200 and 20 m/s scattered by argon atoms were carried out.

It was shown that the measurement of scattering anisotropy at $45^0/135^0$ proposed in [1] is not sensitive enough to the parameters of hypothetical extra-short-range interaction. However, the effect of this interaction is more apparent as a suppression of neutron forward scattering if the interval of neutron velocities after scattering is fixed below the initial neutron velocity.

A possibility of obtaining a better constraint on the hypothetical new interaction is discussed in [1] and compared with those usually quoted in the literature. The authors of this paper also argue that one could avoid the influence of the n,e-interaction in the scattering of neutrons by atoms by using very slow neutrons. In fact, the authors of [1] erroneously assume that the n,e-scattering contribution is absent at the transferred momentum $q = 0$. On the contrary the contribution of the n,e-scattering to the total amplitude is maximal actually at small q. However, in this case it does not depend on the scattering angle and in reality it does not prevent from searching for other effects which introduce an anisotropy to the scattering of very slow neutrons by atoms. We carried out calculations with the purpose to specify behavior of the forward – backward scattering anisotropy of neutrons depending on the velocity of neutrons after scattering taking into account parameters of the extra-short-range interaction.

Here we are talking about the description of scattering of mono-energetic neutrons on one-atom gas in view of thermal motion of atoms. In this case, let us remind the distribution of scattered neutrons is described by the expression (see, for example, [2]):

$$f_{Tur}(V_0, V, \theta, A) = \frac{(A+1)^2}{A^2\sqrt{\pi}V_0 B_0} \frac{V^2}{\sqrt{V_0^2 + V^2 - 2V_0 V\cos\theta}} \times \exp\left\{ -\frac{\left(V^2 - V_0^2 \frac{A-1}{A+1} - \frac{2V_0 V\cos\theta}{A+1}\right)^2}{4\left(\frac{A}{A+1}\right)^2 B_0^2 (V_0^2 + V^2 - 2V_0 V\cos\theta)} \right\} \quad (1)$$

where

V_0 is the initial velocity of a neutron,

V is the velocity of a neutron after scattering,

θ is the scattering angle,

A is the atomic weight (number).

$$B_0 = \sqrt{\frac{2kT}{mA}} = 128.9\sqrt{\frac{T}{A}} \text{ [m/s]}.$$

Without going into a detailed discussion on the origin of the extra-short-range interaction we take advantage of the expression for the amplitude of this interaction given in [1]:

$$f_V(\theta) = -A\frac{g^2}{4\pi}\hbar c\frac{2m\lambda^2/\hbar^2}{1+(q\lambda)^2}, \qquad (2)$$

$$q = 2k\sin(\theta/2),$$

which can be rewritten as

$$f_V(\theta) = -A\frac{g^2}{2\pi\hbar c}\frac{mc^2\lambda^2}{\{1+[2k\sin(\theta/2)\lambda]^2\}} \Rightarrow -\frac{A}{2\pi}\frac{939.6\,MeV}{197.3\,MeV\,fm}\frac{(g\lambda)^2}{\{1+[2k\sin(\theta/2)\lambda]^2\}}, \qquad (3)$$

where g is a dimensionless constant, and λ is the size of the interaction region.

The differential cross section of neutron scattering taking into account smallness of a hypothetical interaction and neglecting the n,e-interaction and Schwinger's scattering contributions will be proportional to the expression

$$d\sigma \sim f_N^2 + 2f_N f_V, \qquad (4)$$

and taking into account the thermal motion of gas atoms

$$d\sigma(V_0,V,\theta,A) \sim (f_N^2 + 2f_N f_V)f_{Tur}(V_0,V,\theta,A). \qquad (5)$$

We are interested in the scattering anisotropy of neutrons depending on the initial velocity and the velocity after scattering. The calculations of the following ratio

$$R(V_0,V) = \frac{d\sigma(V_0,V,45^0)}{d\sigma(V_0,V,135^0)} \qquad (6)$$

were carried out analytically and using the Monte-Carlo method for argon gas at room temperature and normal pressure.

The question on the relative signs of amplitudes f_N and f_V is not clear to us. It has an important effect on the distribution of scattered neutrons. From figure 6 of paper [1] one can conclude that the authors assumed the opposite signs for these amplitudes (curves with the f_V taken into account pass below those obtained in the absence of additional interaction). Following this assumption we performed analytical calculations of scattering anisotropy of neutrons by argon at the specified angles using the formula (6) for parameters in a range $g = 0.3\cdot10^{-7} - 0.3\cdot10^{-6}$ and $\lambda = 1-100\,nm$, and also without taking into account additional interaction ($g = 0$). Thus in the expression for amplitude (3) the transferred momentum of a neutron is equal to

$$q = 1.5883\cdot10^5\sqrt{V_0^2 + V^2 - 2V_0V\cos\theta}\ \frac{1}{cm},$$

(dimension of velocity V is [*m/s*]). Known nuclear scattering length $b_N = -f_N = 0.226\cdot10^{-12}\ cm$ and initial velocity of neutrons $V_0 = 200$ m/s were used.

The results of these calculations are shown in Fig. 1. Fig. 2 demonstrates how the velocity and angular resolutions for the initial $V_0 = 20$ and $V_0 = 200\,m/s$ can distort the expected anisotropy of scattered neutrons depending on their final velocity. Fig. 1 shows that the anisotropy curves for the specified values of g only weakly depend on λ and this dependence practically disappears with reduction of the constant g down to $g = 0.3\cdot10^{-7}$. Therefore it is evident that the extraction of λ from the experiment proposed in [1] (especially if one takes into account also the influence of the finite angular and velocity resolutions on the distribution curves) is rather problematic.

Using the algorithm developed in [3,4] the Monte-Carlo calculations for distributions of scattered mono energetic neutrons by atoms of natural argon were also performed depending on the scattering angle and final velocity of neutrons after scattering. Procedure consists of the following steps:

- The vector of velocity for an atom in the laboratory coordinate system is generated;
- The relative velocity (energy) of a neutron - atom is determined and the path of the neutron before collision is generated. Only those events are kept for further analysis where the path is less than the one given, the total cross section is calculated taking into account the scattering cross section, multiplied by the factor V_R / V_0 (V_R is relative velocity), and the capture cross section (independent from the relative velocity and equal to $\sigma_\gamma = \sigma_{0\gamma} / \sqrt{E_0}$, where $\sigma_{0\gamma}$ is the capture cross section at $E = 1\, eV$);
- We determine which process takes place (capture or scattering) taking into account the ratio of scattering cross section and capture cross section;
- If there was a scattering, the transition in the center mass frame is performed and the velocity vector of the neutron in this system is determined, then the new velocity of the neutron in the center of mass frame is generated (either with or without the hypothetical interaction), the transition to the laboratory system is made and the scattering angle of the neutron and the module of its velocity in laboratory system is determined;
- As a result one entry is added to a cell of a matrix 400x90 (400 final velocity intervals of a neutron, 90 intervals for the scattering angle).

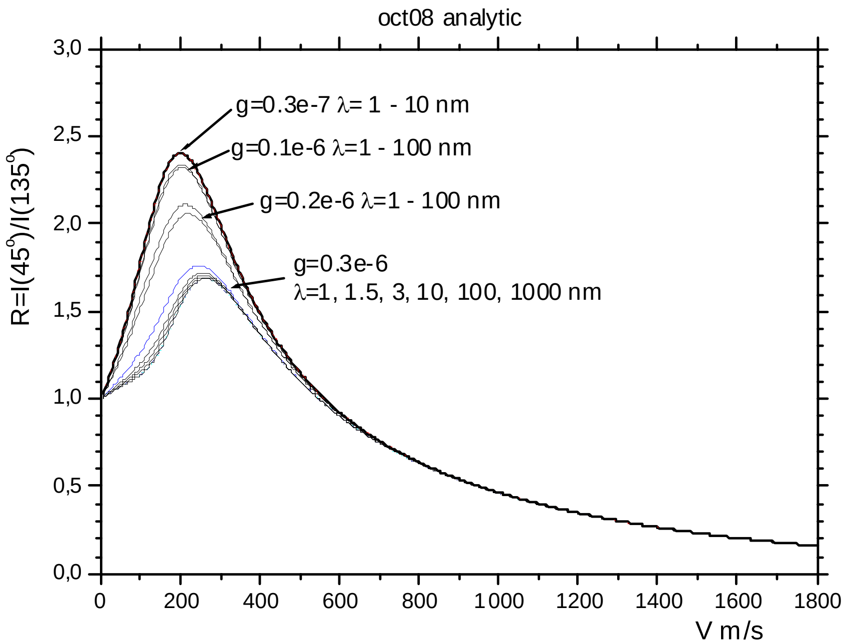

Fig.1. Anisotropy of neutrons (scattered by argon atoms) with initial velocity $V_0 = 200\, m/s$ depending on their final velocity for the parameters specified in the figure.

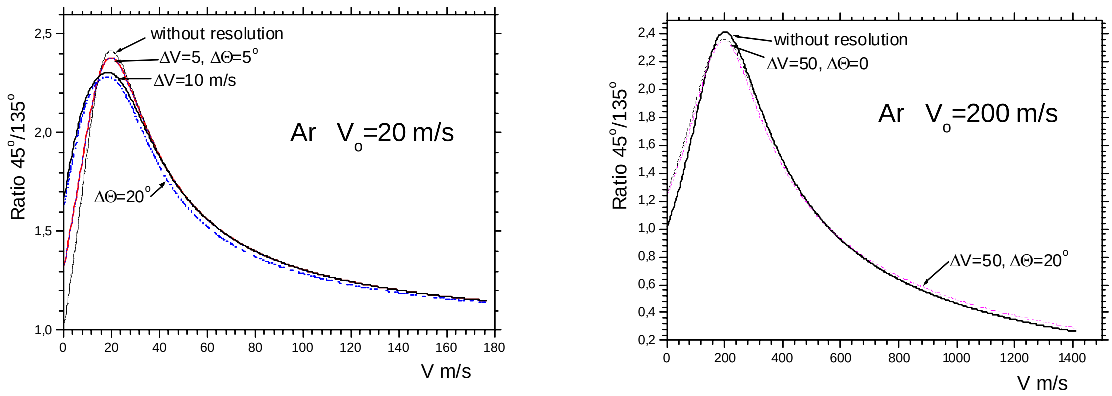

Fig.2. Influence of the velocity and angular resolution on expected distributions of scattered neutrons depending on their final velocity.

After the generation of a given number of neutrons the obtained matrix allows to find the anisotropy of scattered neutrons depending on their final velocity or to find the angular distribution of neutrons for the chosen interval of their final velocities.

Let us consider the procedure of generation for the scattering angle in the center of mass frame. According to (4) we can write that $d\sigma_s \sim b_N^2(1+2f_V/b_N)$ and the amplitude of the hypothetical interaction for argon

$$f_V = 3.033\frac{(g\lambda_{nm})^2}{1+4k^2\lambda^2\sin^2(\theta/2)}[cm],$$

where in the numerator the dimension of λ is in nm, the denominator is dimensionless and f_V itself has dimension cm.

Then the total cross section is proportional to the integral

$$\sigma_s \sim \int_0^\pi b_N^2\left\{1+\frac{2\eta}{b_N[1+\mu\sin^2(\theta/2)]}\right\}\sin\theta\, d\theta \ .$$

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Here $\eta = 3.033(g\lambda)^2$, $\mu = 4(k\lambda)^2$.

$$\sigma_s \sim b_N^2[2+\frac{4\eta}{b_N\mu}\ln(1+\mu)] \qquad (7).$$

The probability of scattering on the angle θ is defined as

$$P(\theta) = \frac{\int_0^\theta d\sigma_s \sin t\, dt}{\sigma_s}$$

$$P(\theta) = \frac{1}{\sigma_s}b_N^2[2\sin^2(\theta/2)+\frac{4\eta}{b_N\mu}\ln(1+\mu\sin^2(\theta/2)] = r \qquad (8)$$

r is a random number, uniform in the interval [0,1]. Since the generation of the angle is carried out in the center of mass frame, the wave number k of a neutron which is included in μ, is also taken in the same frame. The equation (8) was solved with respect to $x = \sin^2(\theta/2)$ using the BISEC code from the JINR library. The scattering angle in the center of mass frame was obtained as $\theta = 2\arcsin\sqrt{x}$. The calculations by the Monte-Carlo method were performed for different sets of values g и λ and for initial velocities $V_0 = 20$ and 200 m/s. To exclude the contribution from the hypothetical interaction the constant g was set to zero. In figure 3 some results of calculations of the scattering anisotropy of neutrons and their comparison with analytical ones using the formula (6) are given.

We can conclude that the results of Monte-Carlo calculations are in good agreement with the analytical ones. Monte-Carlo calculations for different sets of g and λ also confirm that at $g \leq 0.1\cdot 10^{-6}$ it is hardly possible to find a dependence of the anisotropy on the λ value. At the same time obtained as a result of the Monte-Carlo calculations matrices of distribution of scattered neutrons for final velocities and angles (the 400x90 matrices) have allowed to extract angular distributions of scattered neutrons for the chosen intervals of final velocities. An example of such distribution is shown in Fig. 4.

Results of calculations for initial velocity of neutrons $V_0 = 20\, m/s$ are shown in figures 5 and 6.

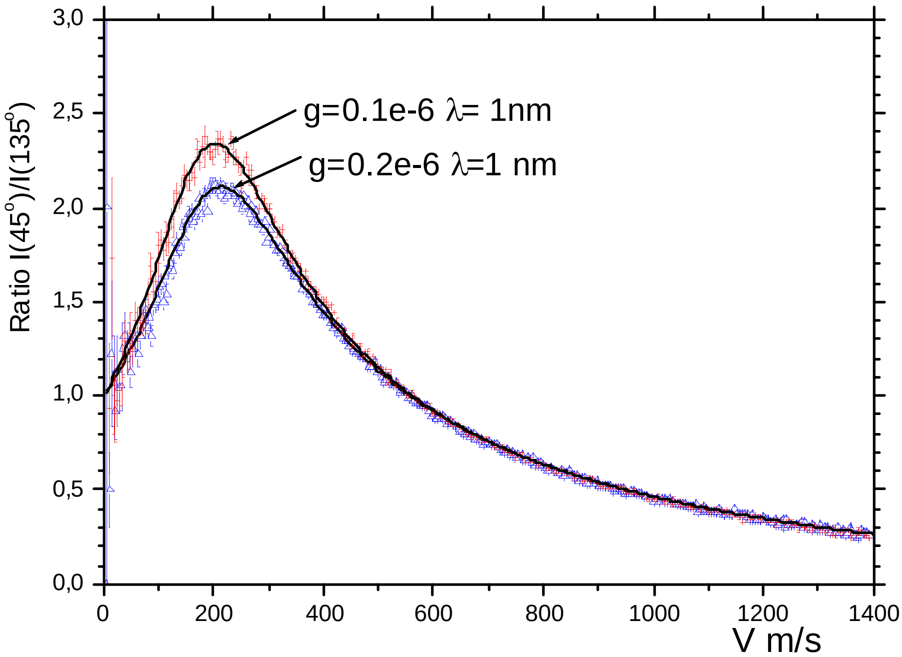

Fig.3. Comparison of some analytical anisotropy (curves) and Monte-Carlo results (points) for argon, $V_0 = 200\ m/s$.

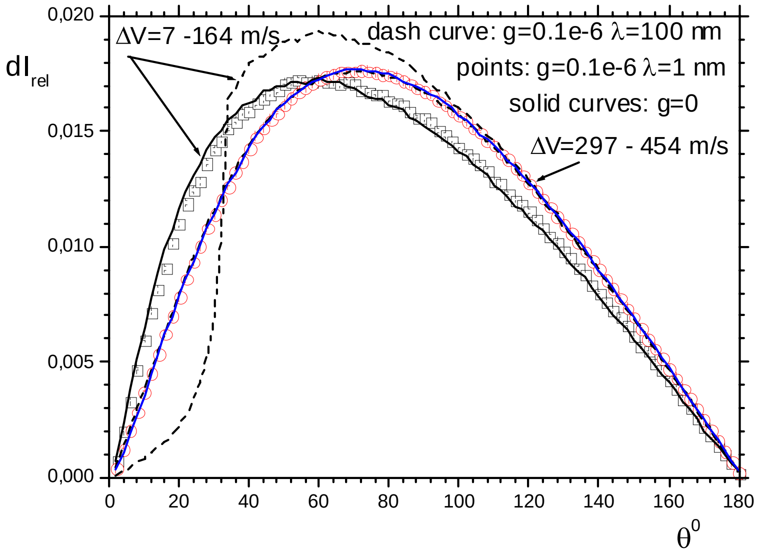

Fig.4. Angular distributions of scattered neutrons with initial velocity $V_0 = 200\ m/s$ for two intervals of final velocities $\Delta V = 7 - 164$: and $\Delta V = 297 - 454\ \ m/s$, calculated by the Monte-Carlo method. Points - $g = 0.1 \cdot 10^{-6}\ \ \lambda = 1\ nm$, solid curves - $g = 0$, dash curve - . $\lambda = 100\ nm$.

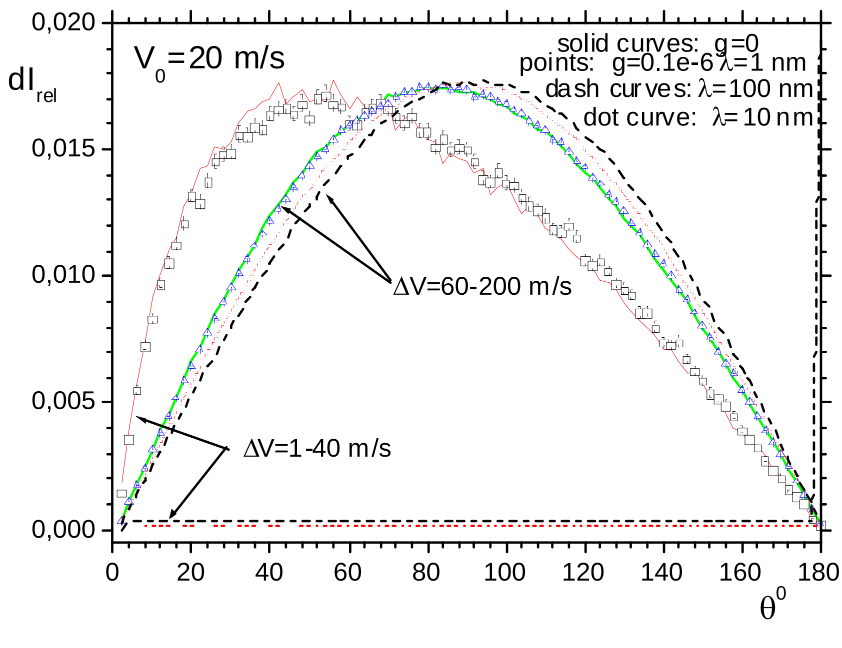

Fig.5. Angular distributions (Monte-Carlo calculations) for neutrons with initial velocity $V_0 = 20\ m/s$ for $g = 0$ (solid curves), $g = 0.1 \cdot 10^{-6}$, $\lambda = 1\ nm$ (points), $\lambda = 10\ nm$ (dotted curves), $\lambda = 100\ nm$ (dashed curves) for the chosen intervals of final velocities $\Delta V = 1 - 40\ m/s$ and $\Delta V = 80 - 200\ m/s$.

Figure 5 demonstrates that the distributions with $g = 0$ and $g = 0.1 \cdot 10^{-6}$ $\lambda = 1\ nm$ practically coincide for both intervals of velocities, but for values $\lambda = 10\ nm$ and $100\ nm$ the scattering of neutrons with $\Delta V = 1 - 40\ m/s$ is simply absent, and in angular distributions for $\Delta V = 80 - 200\ m/s$ a shift of a maximum occurs in the direction of the large angles, which is increased with increase of λ. The effect from the contribution of the extra-short-range interaction for other parameters is shown in fig. 6. Figures 4, 5 and 6 show that contrary to the dependence of neutron scattering anisotropy from the final velocity, the effects due to the presence of the extra-short-range interaction are more apparent in the angular distributions. Thus it is favorable to carry out measurements with even colder neutrons. The proposed technique of calculations of angular distributions allows to estimate expected experimental effects depending on the initial velocity of neutrons and chosen interval of final velocities. Naturally, if a realization of such an experiment becomes possible it is necessary to search for an optimum of V_0 and ΔV to achieve necessary statistics.

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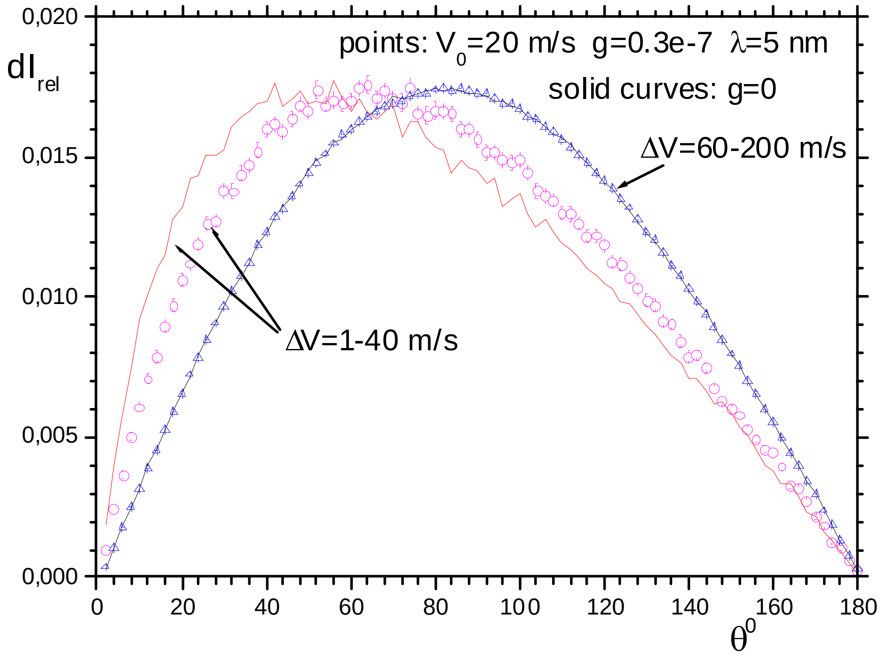

Рис.6. Angular distributions for $V_0 = 20\ m/s$, $g = 0$ and $g = 0.3 \cdot 10^{-7}$ and $\lambda = 5\ nm$ for the same intervals of final velocities as in fig.5.

References

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