Status of experiment for n,e-scattering length extraction from the anisotropy of slow neutrons scattered by noble gases

T.L.Enik, L.V.Mitsyna, V.G.Nikolenko, S.S.Parzhitski, A.B.Popov, I.M.Salamatin, G.S.Samosvat

Frank Laboratory of Neutron Physics
Joint Institute for Nuclear Research, 141980 Dubna, Moscow region Russia

Abstract

The experimental installation for measuring the angle anisotropy of neutrons scattered by noble gases in energy region from a few meV up to 1 eV with use of time-of-flight method is in progress and briefly described in the paper. The testing results for the control unit of stepping motor, which rotates the turn-table with neutron detectors and gas sample, and for electronics on a base of personal computer and multi-channel time encoder connected by USB-line are presented. The calculations of the corrections for efficiency variation of detectors in dependence on direction of recorded neutrons scattered forward or backward with taking into account the thermal motion of gas atoms are shown. For natural argon and xenon an analysis of pseudo- experimental data by the Monte Carlo method was also done, and it demonstrates the possibility of obtaining the n,e-scattering length b_{ne} with the accuracy 2% at 10^8 event set in each of energy intervals (about 100 time channels) in energy region of scattered neutrons 0.005 – 1 eV.

1. Introduction.

Investigation of the n,e- interaction continued for a long time. This problem is important today because there is a dozen of most precise experimental b_{ne} values with errors <5% obtained by different methods [1-3], which differ by ~ 5 standard deviations in spite of declared by authors enough high accuracy and give different estimates of the mean square charge radius of neutron. Besides, there is intrigue in the fact, that all known experimental b_{ne} values are scattered around the so-called Foldy scattering length ($b_F = -\mu e^2 / Mc^2 = -1.468 \cdot 10^{-3}$ fm) in the interval ±10% of this value. The possibility of b_{ne} and b_F values equality signifies a non-trivial phenomenon, namely the charge distribution of a neutron interacts with outside charge owing to the neutron magnetic moment only. Thus, further investigations of this problem are desired.

2. Experimental installation.

In [4] we called attention to a possibility of the b_{ne} value extraction from energy dependence of scattering neutron anisotropy in their elastic scattering by noble gases. In comparison with Krohn and Ringo experiment [5] application of the time-of-flight method allows simpler taking into account corrections, which are dependent on neutrons energy. In experiment at thermal reactor [5] these corrections for atoms form-factors and for counters efficiencies had to be averaged over whole neutron spectrum.

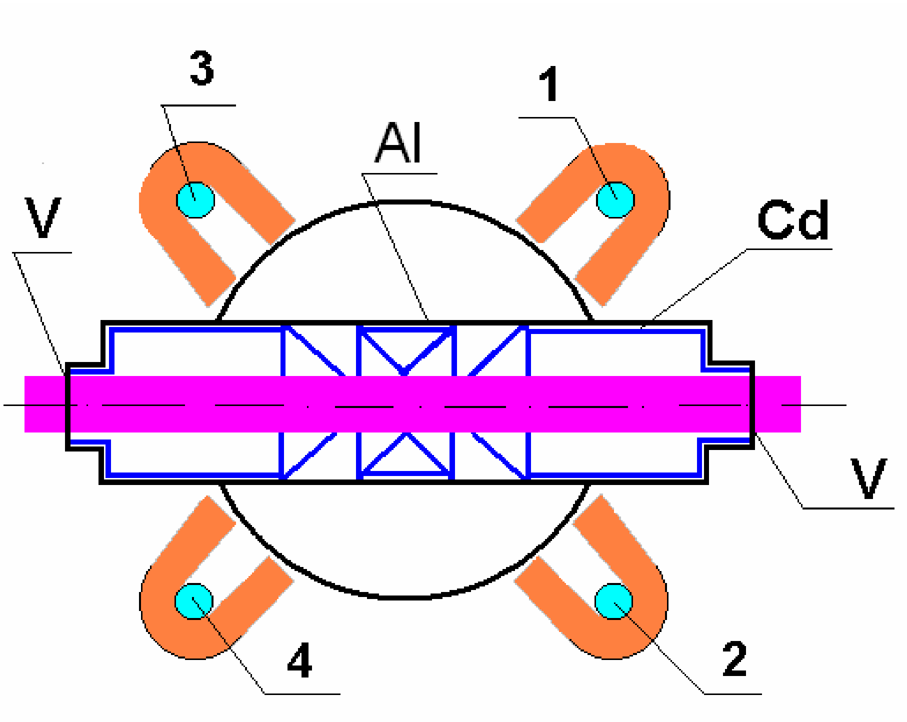

Fig.1. The installation scheme: 1,2,3,4 – ^{3}He- counters in borated polyethylene shielding fixed to the round turn-table.

The experimental installation (Fig.1) represents the turn-table and fixed on it the chamber with noble gas-sample and four ^{3}He-counters (with gas pressure ~10 at. and sizes Ø3×18 cm). Neutron counters are situated at the angles 45^0 and 135^0 relative to the beam axis and at the distance 30 cm from volume of neutron scattering. The scattering volume is confined by cadmium collimators, which also separate the scattering angles range. The turn-table rotates at $\pm180^0$ by a stepper motor with control block 8SMC1-USBh-B1-1MC, which is operated by PC. The 8-channel time encoder [6] is connected to the computer USB-2 port and registers signals from the neutron detectors and two monitor counters, which control a relative neutron flux in the beam. The program was worked out, which realizes interchange of detectors positions at adjusted parameters, exposition in each of positions and information reservation in 8 spectrums (for each ^{3}He-counter in two positions). The control of data storage stability relative to monitor reading is provided by this program, and handy visualization of current and collected information is also realized by it. After testing of the installation with a neutron source we plan to try it at the IREN beam with vanadium (instead of gas sample). Unfortunately, attained state of IREN doesn't allow us to carry out the measurements with gases, so it is expedient to use our installation at IBR-2 reactor.

3. Physical basis of the experiment.

Neglecting Schvinger scattering at low neutron energies and taking into account thermal motion of gas the differential cross section of neutron elastic scattering at the angle θ can be written as

$$\sigma(V_0,\theta,A) = b_N^2[1+2\frac{b_{ne}}{b_N}Z\,f(q)]F_s(V_0,\theta,A)\ , \qquad (1)$$

where V_0 is the initial neutron velocity, b_N is nuclear scattering length, q is the wave number of momentum transfer, $f(q)=[1+3(q/q_0)^2]^{-1/2}$ is the atom form factor, q_0 is a Hartry- Fock constant for a given gas with atom number A.

$$F_s(V_0,V,A) = \frac{(A+1)^2}{A^2\sqrt{\pi}V_0B_0}\int_0^\infty \frac{V^2}{\sqrt{V_0^2+V^2-2V_0V\cos\theta}}\times$$

$$\times\exp\left\{-\frac{(V^2-V_0^2\frac{A-1}{A+1}-\frac{2V_0V\cos\theta}{A+1})^2}{4(\frac{A}{A+1})^2B_0(V_0^2+V^2-2V_0V\cos\theta)}\right\}dV, \qquad (2)$$

$B_0=\sqrt{\frac{2kT}{mA}}=128.9\sqrt{\frac{T}{A}}$ [m/s], V is the neutron velocity after scattering.

For each of counters a measuring anisotropy of neutrons scattered at angles θ_1 and θ_2 is determined as a ratio of scattering intensities $I(E,\theta)$:

$$R(E) = \frac{\sigma(E,\theta_1)}{\sigma(E,\theta_2)} = \frac{I(E,\theta_1)}{I(E,\theta_2)}C(E), \qquad (3)$$

where $I(E,\theta)$ are the scattering intensities of neutrons. The correction coefficient $C(E) = \varepsilon(\theta_2)/\varepsilon(\theta_1)$ for efficiency variation of neutron registration at different angles is used just for b_{ne} value extraction.

The experimental success is determined by the accuracy of obtained intensities ratio at neutron scattering forward ($\theta_1\sim 45^0$) and backward ($\theta_2\sim 135^0$), which is measured alternately at turning the installation at 180^0 relative to the beam axis and is calculated by the formula of the geometrical mean

$$R = \left(\frac{N_{1f}N_{2f}N_{3f}N_{4f}}{N_{3b}N_{4b}N_{1b}N_{2b}}\right)^{1/4},$$

where N are corrected counts, numbers determine counters, and counters positions (at forward or backward scattering) are indicated by letters f and b.

4. The energy loss effect on registration efficiency and measured anisotropy at elastic scattering of neutrons.

Seemingly, the main difficulty in this experiment is in correct calculation of the energy loss, which is happened at scattering of a neutron: it is necessary to know the counters efficiencies ratio $C(E)$ with the accuracy $\Delta C\sim 10^{-4}$ in order to obtain b_{ne} value with systematic uncertainty notably less than statistical one.

Using the Monte Carlo method [7] the calculations of the neutron scattering anisotropy were carried out for two gas scatterers (argon and xenon) in geometry, which is shown in Fig.2, and at initial energy of neutrons from 0.001 eV to 10 eV. If neutrons scattered backward (at angle 135^0) the analogous geometry was used. In these calculations the neutron counter represented a ring with thickness 3 cm, a distance from the center of scattering volume to the detector center was 30 cm, and the capture cross section was presumed to be zero to reduce a counting time.

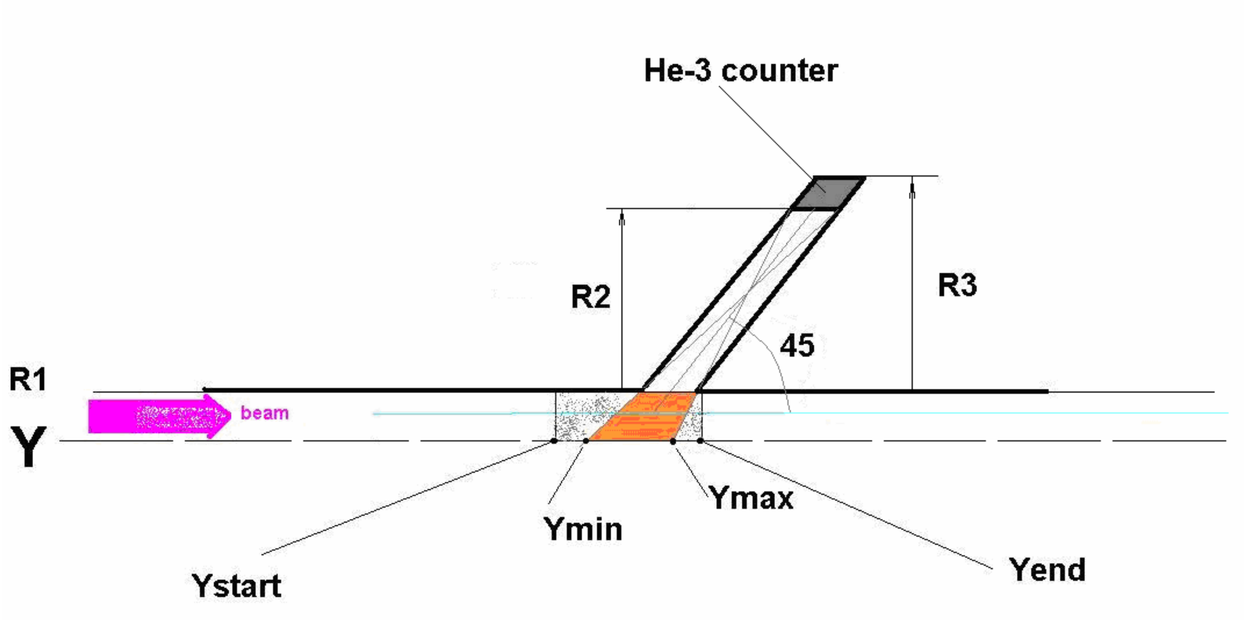

Fig.2. The scheme for Monte Carlo calculations for neutrons scattered forward. The calculating parameters: radius of the falling neutron beam R1=2 cm, inner radius of detector ring R2=21.213 cm, outer radius of detector R3=24.213 cm.

We have an interest in energy distribution difference of neutrons scattered forward and backward and in evaluation of their efficiency registration (ratio of counts of neutrons absorbed in the counter and ones fallen to the counter).

In Fig.3 the energy distributions of neutrons after scattering at atoms of xenon are shown. Scattering angle dispersions in a given geometry for forward and backward scattering are $41.4^0 \div 52.2^0$ and $127.8^0 \div 138.6^0$ correspondingly. In the event that the initial neutron energy is more than thermal one, the energy distribution of neutrons scattered backward moves essentially to smaller energies, so the efficiency of neutron registration is higher than for neutrons scattered forward. If the neutron energy less than thermal one, quite the contrary, the energy distribution of neutrons scattered backward moves to bigger energies, and efficiency of their registration can be less than for neutrons scattered forward.

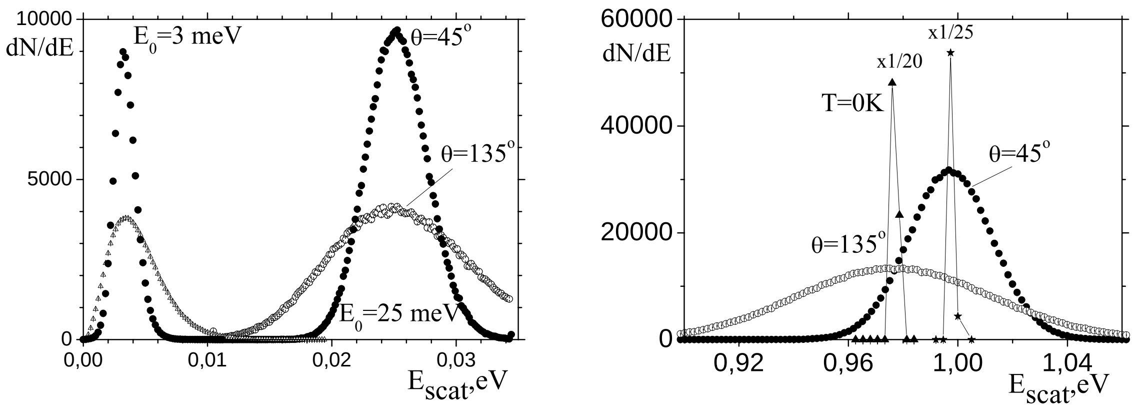

Fig.3. Distribution of neutrons with initial energies 0.003 eV, 0.025 eV and 1 eV scattered by krypton. In the right picture the distributions of neutrons scattered by immovable gas ($T=0^0K$) are shown also (narrow peaks).

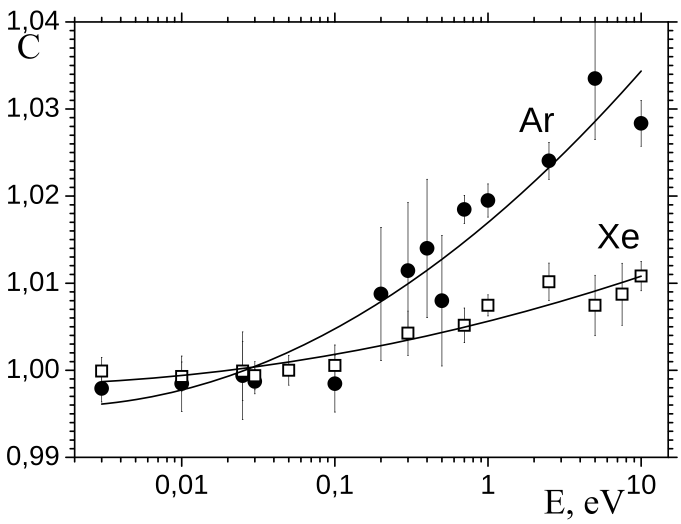

Fig.4. The corrections $C(E)=\varepsilon(135^0)/\varepsilon(45^0)$ obtained from Monte Carlo calculations for intensities of neutrons scattered forward and backward by argon and xenon.

The obtained results showed that widths of energy distributions of scattered neutrons are determined mainly by thermal motion of gas, and scattering angle dispersal within preliminary $\pm 5^0$ at fixed atoms would give narrow distributions. The efficiency of ^{3}He-counter with gas pressure 10 at decreases with a neutron energy growth from 100% (at meV) to 20% (at 10 eV). At the energies more 0.1 eV the efficiency of registration for neutrons scattered backward becomes slightly higher than for neutrons scattered forward. It is more notably in scattering by argon, because its atoms are light more than atoms of xenon. In Fig.4 the corrections $C(E)$ are presented, which must be taken into account for obtaining the true $R(E)$ values. Unfortunately, these insignificant variations of efficiencies have a profound effect on desired scattering anisotropy $R=I(45^0)/I(135^0)$, what the Fig.5 demonstrates.

In Fig. 5 the open points are the results of calculating the R without corrections for efficiency, squares are improved R values after correction for efficiencies variations of forward and backward scattered neutrons registration. Curves in Fig.6 are the analytical calculations (see [7]) taking into account scattering angles range in considered geometry. In all calculations $b_{ne}=-1.32\cdot 10^{-3}$ fm. A satisfactory fit of analytical and Monte Carlo calculations is worthy of note.

Completed calculations showed that even for the very heavy noble gas, which is available for measurements of elastic scattering anisotropy for slow neutrons, the introducing of corrections for efficiency variation is necessary in principle, if we use ^{3}He-counter with gas pressure 10 at as a detector. Just taking into account of these corrections allows obtaining the correct $R(E)$ values in the neutron energy region more than 0.1 eV. As it is shown in our papers, to ensure a wishful accuracy of the b_{ne} value (2 – 3%) this energy region is very important. Besides, we made the inference that taking into account the thermal motion of gas is urgent: the calculated efficiencies for immovable gas in the energy region more than 1 eV, for example, in case of xenon differ from «veritable» efficiencies by 0.07 – 0.17%, and for argon this difference is about 0.5%.

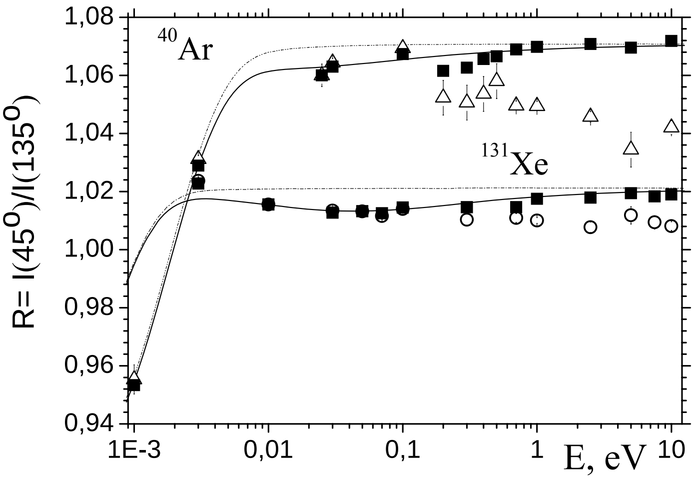

Fig.5. The scattering anisotropy dependence on neutron energy for argon and xenon: open circles and triangles are calculations without correction for efficiency, squares are the calculations with this correction. Solid curves are analytical calculations with taking into account b_{ne} value, dashed curves are ones with b_{ne}=0.

5. The results of pseudo-experimental data analysis.

For argon and krypton with using the formulas (1) – (3) the pseudo-experimental $R(E)$ values were simulated with accidental dispersion within the limits of two standard deviation 2σ (at $\sigma = 2\cdot10^{-4}$) for $b_{ne}=-1.32\cdot10^{-3}$ fm and known b_N values for these gases. Then these data were fitted in different energy regions at fixed b_N value and free parameters of normalization constant α and b_{ne} value. The results of data fitting for argon and xenon in the energy region 0.01 – 1.0 eV are shown in Fig.6 and Fig.7, where at chosen conditions the accuracy about 2% was achieved.

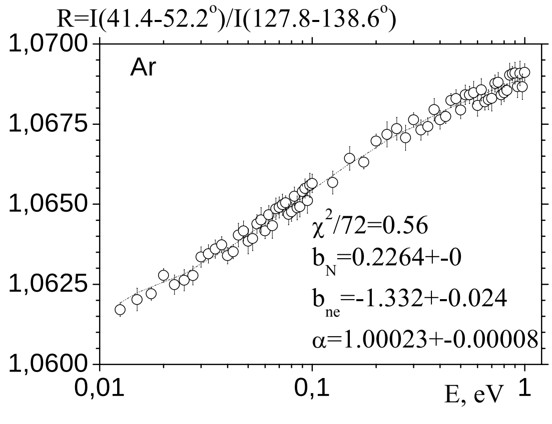

Fig.6. The result of fits for argon. Open points are pseudo-experimental data, dashed curve is the fitting curve.

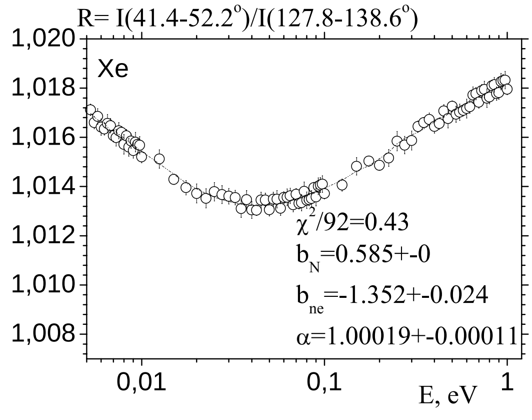

Fig.7. The result of fits for xenon. Open points are pseudo-experimental data, dashed curve is the fitting curve.

Naturally, influence of different fixed b_N value on extracted b_{ne} value was assayed. Its modification by ±1% leads to change of b_{ne} value by ±1.5%, but scattering cross sections for noble gases in thermal energy point were measured with accuracy <1% as long ago as 1966 by Krohn and Ringo. The energy region expansion up to 100 eV raises the statistical accuracy of extracted b_{ne} value, but the necessity of fixing of b_N value remains valid.

6.Conclusions.

Thus, we came to a conclusion, that it is necessary to calculate the corrections for variations of efficiency in real geometry of the experimental installation taking into account the thermal motion of gas atoms. Using the LIT JINR cluster possibilities allows us to obtain a necessary accuracy of these corrections. The coincidence of analytical and Monte Carlo calculations can permit to avoid the bulky Monte Carlo calculations in some geometry configurations, but this fact demands additional investigations. At last the possibility of obtaining the b_{ne} value with the accuracy not worse than 3% is shown. For that in measurements of $R(E)$ value the 10^8 statistics for ~ 100 points in the neutron energy range below 1 eV must be collected.

References.

1. S.Kopecky, J.A.Harvey, N.W.Hill et al., Phys.Rev., **C56** (1997)2229.
2. Yu.A.Alexandrov, Phys. Part. And Nuclei, **30**(1997)72.
3. A.B.Popov, T.Yu.Tretyakova, In: XV International Seminar on Interaction of Neutron with Nuclei, Dubna, 16–19 May 2007, JINR E3-2008-26 (Dubna, 2008)66.
4. G.G.Bunatian, V.G.Nikolenko, A.B.Popov, G.S.Samosvat, T.Yu.Tretyakova, Z.Phys., **A359**(1997)337.
5. V.E.Krohn, G.R.Ringo, Phys.Rev., **148**, 1303(1966); Phys.Rev., **D8**(1973) 1305.
6. V.N.Shvetsov, N.V.Astakhova, N.A.Gundorin, Sh.S.Zeynalov, L.B.Pikelner, I.M.Salamatin, K.M.Salamatin, P.V.Sedyshev, V.I.Smirnov, Abstracts of ISINN-17, JINR E3-2009-50 (Dubna,2009)57
7. V.G.Nikolenko, A.B.Popov, Eur.Phys.J., **A34**(2007) 446