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Measurement of the total cross sections of ultracold neutrons with noble gases and search for long-range forces

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The comparison of results of cross section measurements by the different methods can provide useful information on existence of long-range interaction. The total neutron cross sections of He, Ne, Ar, Kr and Xe were measured using a method of ultracold neutrons. Measurements with ultra cold neutrons confirm the discrepancy between coherent cross-section of scattering for He measured by a neutron interferometer and scattering cross-section measured by the transmission method. The discrepancy makes up 5.3 standard deviations.

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1. Introduction. There are different methods search for long-range forces in the interaction of elementary particles [1–3].

An experimental search of additional terms in the scattering amplitude can be based on the fact that a long-range interaction gives contribution to the scattering amplitude either at small transferred momentum or at small scattering angles.

Paper [4] suggests reconsidering an approach to the method of a small angle scattering and passing to registration of small recoil energy instead of small angles of scattering. A new approach suggests using gas of ultracold neutrons (UCN) as a target that collides with the flux of atoms being in the same trap.

This article presents the first results of an experimental search of long-range forces as it was proposed in the papers [4, 5]. The measurement of the total cross sections of ultracold neutrons with noble gases was carried out. A comparison of the scattering amplitude from interferometer measurements $f(0)$ with the amplitude obtained by the UCN method is presented.

If long-range forces do exist, then measurements with an interferometer are most sensitive to their manifestation, since they measure scattering amplitude at zero angle. Measurements of total cross-section with UCN are also sensitive to long-range forces since they can take account of recoil energy up to 10^{-7} eV. However, the UCN method turns out to be insensitive to energy transmission less than 10^{-7} eV. Finally, scattering cross-section measurements at energy ~ 1 eV might prove to be insensitive to long-range interaction as it results in scattering at very small angles.

Comparison of three results of measurements can provide useful information on existence of long-range interaction.

2. Experimental method. The probability of UCN storage in a trap is the sum of probability of UCN losses:

$$\tau_{\rm stor}^{-1\,\rm total} = \tau_n^{-1} + \tau_{\rm stor}^{-1\,\rm gas} + \tau_{\rm stor}^{-1\,\rm walls}, \qquad (1)$$

where τ_n^{-1} is the neutron decay probability, $\tau_{\rm stor}^{-1\,\rm gas}$ is the probability of UCN losses due to interaction with gas atoms and $\tau_{\rm stor}^{-1\,\rm walls}$ is the probability of UCN losses due to interaction with the trap walls.

The probability of UCN losses caused by neutron interaction with gas atoms can be measured as difference of UCN storage probability in a trap with gas density n_A and with zero gas density:

$$\tau_{\rm stor}^{-1\rm gas}(n_A) = \tau_{\rm stor}^{-1\,\rm total}(n_A) - \tau_{\rm stor}^{-1\,\rm total}(n_A = 0). \qquad (2)$$

Now let us calculate the magnitude of value $\tau_{\rm stor}^{-1\,\rm gas}(n_A)$ taking into account an additional contribution made by the long-range interaction. The probability of UCN losses induced by collision with gas atoms can be written as follows:

$$\tau_{\rm stor}^{-1\,\rm gas}(n_A) = \int\limits_{E_{\rm min}}^{\infty} d\Phi(E_A) \int\limits_{\varepsilon_{\rm min}}^{E_A[4M/(M+1)^2]} d\sigma(\varepsilon) + $$
$$ + n_A V_{2200} \sigma_{\rm capt}^0 = n_A \bar{V}_A \sigma_A^{\rm total}, \qquad (3)$$

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where $d\Phi(E_A)/dE_A$ is a flux of atoms incident on an ultra cold neutron, $d\sigma/d\varepsilon(\varepsilon)$ is a differential cross section depending on the recoil energy, $\sigma^0_{\rm capt}$ is the capture cross section reduced to neutron velocity $V_{2200} = 2.2 \cdot 10^5\,{\rm cm{\cdot}s^{-1}}$, $\sigma^{\rm total}_A$ is the total cross section which consists of scattering cross section ($\sigma_{\rm scat}$) and capture cross section ($\sigma^0_{\rm capt}$): $\sigma^{\rm total}_A = \sigma_{\rm scat} + \sigma^0_{\rm capt} V_{2200}/\bar{V}_A$. (The scattering cross section ($\sigma_{\rm scat}$) takes account of a nuclear and long-range interaction.) $E_{\rm min}$ is minimum energy of atoms after colliding with which a neutron is able to escape the trap $E_{\rm min} = E^{\rm trap}_{\rm UCN}(M+1)^2/4M$, $\varepsilon_{\rm min}$ is minimum recoil energy when UCN escape from the trap. To simplify, the UCN initial energy is equal to zero $\varepsilon_{\rm min} = E^{\rm trap}_{\rm UCN}$, $E_A \cdot 4M/(M+1)^2$ is maximum neutron recoil energy. The flux of atoms is

$$d\Phi(E_A)/dE_A = \frac{n_A \bar{V}_A}{(kT)^2} E_A \exp\left\{-\frac{E_A}{kT}\right\}, \qquad (4)$$

where n_A is the number of atoms in cm^{-3} at temperature T, $\bar{V}_A$ is the average velocity of atoms of mass $m_n M$ at temperature T, $\bar{V}_A = 4(kT/2\pi m_n M)^{1/2}$.

The gas density $n_A[{\rm cm}^{-3}] = 2.687 \cdot 10^{19} P_A[{\rm atm}] \times 273/T[{\rm K}]$, where P_A is an experimentally measured gas pressure. Finally, we can write formula $\sigma^{\rm total}_A = (\tau_{\rm stor} n_A \bar{V}_A)^{-1}$ for calculation of total cross section from experimental data.

3. Experimental set-up. The experiment has been carried out using the test beam of the UCN facility PF2 of the ILL reactor. The scheme of installation is shown in Fig. 1. The apparatus consists of UCN spectrometer with valves for filling and emptying a neutron guide system, UCN detectors and a vacuum system. The UCN spectrometer is a vertical cylinder with diameter 60 cm and height 200 cm. It was made from copper with the inner surface coated by beryllium. The critical velocity of this coating is 6.8 m/s.

For measuring the total cross section of UCN interaction with gas the detector (5) is applied to measure the number of UCN in the trap after different holding time with the closed valve (4). Measuring UCN storage time at different gas pressure, we can determine the total cross section of UCN interaction with atoms.

At the beginning of measurement cycle UCN enter the trap (2) through the input UCN guide at the opened valve (1) and the closed valve (4). After filling the trap during 150 s, the valve (1) is closed and UCN are kept in the trap during the given holding time $t_1 = 10$ s or $t_2 = 70$ s. Then the valve (4) is opened and neutrons reach UCN detector (5). During the measurement cycle the absorber (3) is placed in the top position at distance "h" from the trap bottom in order to restrict the spectrum of neutrons being stored.

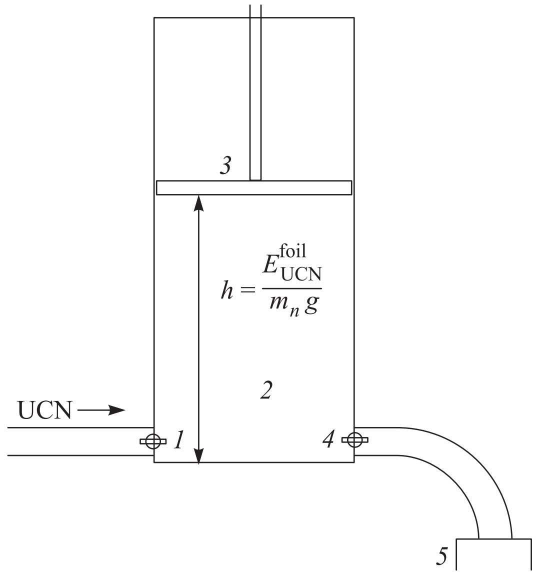

Fig. 1. Experimental set-up: *1* – the entrance valve, *2* – UCN trap with critical energy trap UCN E, *3* – the absorber for formation of UCN spectrum, *4* – the exit valve, *5* – the UCN detector

The measurement of UCN storage time in the trap $\tau_{\rm stor}$ is a conventional procedure. It consists of measurements of the number of UCN in the trap $N(t_1)$ at the moment t_1 after closing the entrance valve (1) and the number of UCN in the trap $N(t_2)$ at the moment t_2. The storage time $\tau_{\rm stor}$ is determined according to the formula $\tau_{\rm stor} = \ln[N(t_1)/N(t_2)]/(t_2 - t_1)$.

The typical UCN storage time in the spectrometer is about 68 s.

The experiment used noble gases He, Ne, Ar, Kr, Xe, produced by the MESSER firm. Gases were kept in vessels at high pressure with gas purity no less than 99.995% (Table 1). The system of gas filling was made up of a reducer, a leak with a fine adjustment, an adapting pipe and lock valves.

Pressure of noble gases was measured with a sensor of absolute pressure CERAVAC CTR 100 produced by Leybold. The sensor upper limit is 10 torr, the instrument error depends on the measured pressure and is within 0.002–0.02 torr.

An experimental hall of the reactor ILL (D level) is equipped with a system of detecting and stabilizing the air temperature. The experiment made use of records of temperature sensors in the reactor hall.

4. Results of measurements. Before making measurements a spectrometer had been pumped out for a few days. The attained vacuum was $2 \cdot 10^{-5}$ mbar. According to the measurements made with a mass spectrometer produced by the Hiden firm the remaining vac-

Table 1

The total cross sections of noble gases measured by the UCN storage method

Gas	Gas purity, %	$\bar{V}_{\text{gas}}$, m/s	$(P\tau)_{\text{gas}}$, mbar·s	σ_{tot}, barn
He	99.995	1255	418 ± 1.8	0.782 ± 0.004
Ne	99.999	558.4	273 ± 3.7	2.69 ± 0.04
Ar	99.995	396.8	242 ± 2.3	4.27 ± 0.04
Kr	99.999	274.2	7.2 ± 0.2	208 ± 6
Xe	99.998	219.0	7.31 ± 0.14	256 ± 5

uum contained mainly air and water. Such a composition of remaining gases is typical for non-heated vacuum systems.

After closing the valve of vacuum pumping out the spectrometer pressure started increasing slowly in correspondence with the linear law. As shown in Fig. 2, the rate of pressure increase in the spectrometer is $\sim 2 \cdot 10^{-3}$ mbar/h.

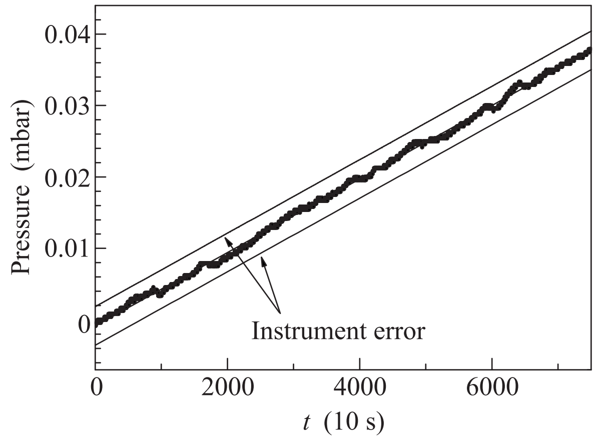

Fig. 2. Increasing of pressure in spectrometer after closing of pumping line

One can account for this fact both by some leakage outside the spectrometer and by processes of desorption from the internal surfaces of the vacuum volume. Probability of UCN losses after closing the valve of vacuum pumping out has also increased in correspondence with the linear law. (Fig. 3).

The gases under study filled the spectrometer as soon as the valve of vacuum pumping out was closed. The procedure of gas filling took no more than ten minutes, which was immediately followed by the program of measuring storage time of UCN in the spectrometer. The procedure of measuring storage time continued on average about 20 h. As a result, for each of the gases and the chosen pressure one could measure time dependence of probability of UCN losses in the vessel filled with gas. The time was measured from the moment of the spectrometer closing. Measurement results for He are given in Fig. 3. In order to eliminate influence of leak-in gases, one obtained probability of losses in the gas vessel from the linear extrapolation using the method of the least squares by the zero time (by the moment of vessel closing).

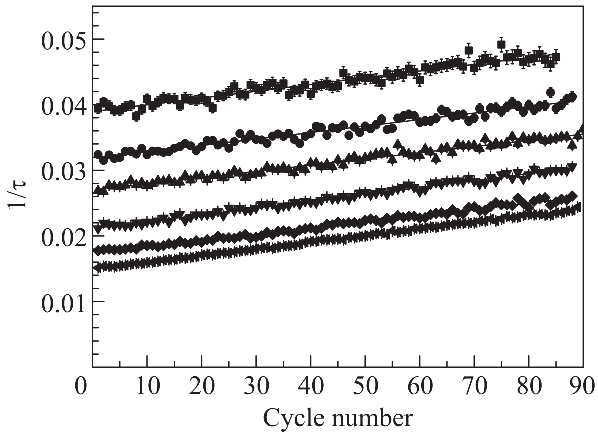

Fig. 3. Probability of UCN losses versus number of measurement cycle for different pressures of helium: left triangles - 0 mbar, diamonds – 1 mbar, down triangles – 2.5 mbar, up triangles – 5 mbar, circles – 7 mbar, squares – 10 mbar

Probability of UCN losses in the spectrometer versus pressure of different gases under investigation is shown in Fig. 4.

The total probability of UCN losses in a trap is the sum of partial probabilities of UCN losses:

$$\tau_{\text{stor}}^{-1\,\text{total}} = \tau_n^{-1} + \tau_{\text{stor}}^{-1\,\text{walls}} + \tau_{\text{stor}}^{-1\,\text{gas}}, \qquad (5)$$

where τ_n^{-1} is the neutron decay probability, $\tau_{\text{stor}}^{-1\,\text{walls}}$ is the probability of UCN losses due to interaction with the trap walls and $\tau_{\text{stor}}^{-1\,\text{gas}}$ is the probability of UCN losses due to interaction with gas atoms.

The last term of the total probability can be rewritten as follows:

$$\tau_{\text{stor}}^{-1\,\text{gas}} = p/(P\tau)_{\text{gas}}, \qquad (6)$$

Table 2

The calculation of coherent cross section from the total cross sections of noble gases for the UCN storage method

Gas	$\sigma_{\rm tot}$, barn	$\sigma_{\rm capt}$, barn	Admixtures	$\sigma_{\rm incoh}$, barn	$\sigma_{\rm coh}$, barn
He	0.782 ± 0.004	0	0.013	0	0.769 ± 0.004
Ne	2.69 ± 0.04	0.15 ± 0.02	0	0.008 ± 0.009	2.53 ± 0.04
Ar	4.27 ± 0.04	3.74 ± 0.05	0	0.220 ± 0.005	0.32 ± 0.06
Kr	208 ± 6	201 ± 8	0	0.01 ± 0.14	7.2 ± 10
Xe	256 ± 5	240 ± 12	0	0	16 ± 13

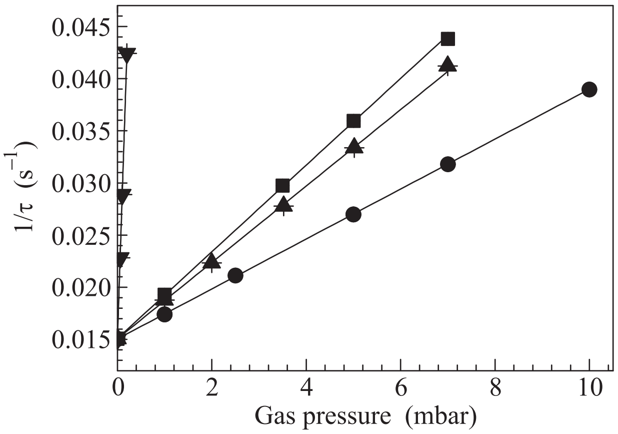

Fig. 4. Probability of UCN losses versus gas pressure for different gases: circles – helium, squares – argon, up triangles – neon, down triangles – krypton

where $(P\tau)_{\rm gas}$ is parameter determining UCN losses due to interaction with gas atoms and p is the gas pressure.

Thus the values of parameter $(P\tau)_{\rm gas}$ of the gases under study were obtained as a result of linear extrapolation by the least squares method of the data given in Fig. 4. Parameter $(P\tau)_{\rm gas}$ is equal to the inverse slope coefficient. Independent of the gas pressure term is the sum of the neutron decay probability and the probability of UCN losses due to interaction with the trap walls. Values of these summarized probabilities for different gases are in good agreement within statistical accuracy.

Using the obtained values $(P\tau)_{\rm gas}$ the total cross sections for different gases were calculated using formula:

$$\sigma_{\rm tot} = [(P\tau)_{\rm gas}/2.687 \cdot 10^{19} \cdot 273/T_{\rm gas} \cdot \bar{V}_{\rm gas}]^{-1}, \quad (7)$$

where $2.687 \cdot 10^{19}$ is the number of gas atoms in $1\,{\rm cm}^3$ at pressure 1 atm (1 atm = 1.01325 bar = 760 Torr) and temperature $T = 273\,{\rm K}$, $\bar{V}_{\rm gas}$ is an average velocity of gas atoms at temperature $T_{\rm gas}$, $(P\tau)_{\rm gas}$ is parameter defining UCN losses due to interaction with gas atoms. The temperature of gas atoms $T_{\rm gas} = 297 \pm 1\,{\rm K}$.

The values $(P\tau)_{\rm gas}$ obtained by the linear extrapolation method and calculated according to the formula (7) of the magnitudes of total cross-section of UCN interaction with noble gases are shown in Table 1. The same table presents data on gas purity and values of average velocity of gas atoms at $T_{\rm gas} = 297 \pm 1\,{\rm K}$.

One can compare coherent cross sections of noble gases measured by the transmission, UCN storage and neutron interferometer method [6]. Making the comparison we have to take into account the correction for incoherent scattering cross section (see Table 2) and we have to recalculate the bound cross section to the scattering cross section on the free atom. The results of the comparison are shown in Table 3.

In this Table the coherent cross sections $\sigma^*_{\rm coh\_free}$ measured by the transmission method is equal to $\sigma^*_{\rm coh\_free} = \sigma_{\rm scat\_free} - \sigma_{\rm inc\_free}$. The total scattering cross section $\sigma_{\rm scat\_free}$ is taken from Ref. [7]. Incoherent scattering cross section $\sigma_{\rm inc\_free} = [M/(M+1)]^2\sigma_{\rm inc}$, the bound incoherent cross section $\sigma_{\rm inc}$ is taken from Ref. [8]. $\sigma^{**}_{\rm coh\_free} = 4\pi[M/(M+1)]^2 b_c^2$, where b_c is taken from Ref. [6]. The value $b_{\rm free\_nucl} = \sqrt{\sigma^*_{\rm coh\_free}/4\pi}$.

5. Conclusions. UCN storage method is successful for the measurement of the total cross section of He. But the accuracy of scattering cross section of noble gases with large capture cross section is determined by the accuracy capture cross sections.

One can see that the values measured by the UCN storage method are in good agreement with the values of transmission method. But the values measured by the transmission and UCN storage method, except for a neon case, are less than the similar values obtained from a neutron interferometer data.

The difference between the results of the transmission method (or UCN storage method) and neutron interferometer measurements cannot be explained by the $n{-}e$ scattering because the $n{-}e$ scattering length is much smaller than the experimental discrepancy. More over, taking into account $n{-}e$ scattering only increase this discrepancy.

The presented discrepancy is likely to be due to a systematic experimental error. To clarify the problem

Table 3

Comparison of coherent cross sections of noble gases measured by the transmission or UCN storage method with neutron interferometer method

Gas	Transmission method [7] UCN storage method (this work)	Neutron interferometer [6]	$\sigma^{\rm TM}_{\rm coh\_free} - \sigma^{\rm INT}_{\rm coh\_free}$, $\sigma^{\rm UCN}_{\rm coh\_free} - \sigma^{\rm INT}_{\rm coh\_free}$, barn	Comments
He	0.773 ± 0.009 0.769 ± 0.004	0.855 ± 0.016	-0.082 ± 0.018 (4.5σ) -0.086 ± 0.016 (5.3σ)	The result is confirmed by UCN measurements
Ne	2.42 ± 0.03 2.53 ± 0.04	2.44 ± 0.04	-0.02 ± 0.05 (0.4σ) 0.09 ± 0.06 (1.6σ)	Future improvement of accuracy
Ar	0.424 ± 0.008 0.32 ± 0.06	0.51 ± 0.01	-0.086 ± 0.012 (7σ) -0.19 ± 0.07	The accuracy of UCN measurements is not enough because of capture cross section
Kr	6.19 ± 0.17 7.2 ± 10	6.94 ± 0.11	-0.75 ± 0.20 (4σ) 0.26 ± 10	

new measurements are to be made the scattering lengths by means of interferometer. Finally, if there is some chance that the observed difference is caused by long-range forces it could be tested by means of the method of measuring the flux of above-barrier neutrons. This method is also sensitive to the long-range forces.

As a result of measurements carried out in this work the total neutron cross sections of He, Ne, Ar and Kr were measured using a method of a ultracold neutrons. Ultra cold neutron measurements confirmed the existence of discrepancy between coherent cross-section of scattering for He measured by a neutron interferometer and scattering cross-section measured by the transmission method. The discrepancy is 5.3 standard deviations.

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