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DIFFERENTIAL NEUTRON SPECTROMETRY IN THE VERY LOW NEUTRON ENERGY RANGE. NEUTRON CROSS SECTIONS FOR Zr, Al, POLYETHYLENE AND LIQUID FLUOROPOLYMERS

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1 Introduction

Ultracold neutrons (UCN) with energy below ~ 0.25 μeV, which can be contained for a long time in closed volumes, have found well known applications in the investigations of fundamental properties of the neutron[1]. The examples of applications of very low energy neutrons (with energies up to several μeV) for investigation in condensed matter physics are rather scarce (see for example the reviews[2, 3]) in spite of very high energy and momentum resolution: $\sim$1 nev and $\sim 10^{-3}$ Å^{-1} or better respectively. This high resolution comparable with the neutron spin-echo method[4] opens up the obvious new possibility in investigations of supermolecular structure and dynamics due to very high sensitivity of very low energy neutrons to scattering on the objects of the size 10-1000 Å. The latter is especially interesting in soft matter, polymer and biological science, where slow motion of large molecules and clusters is one of very interesting and poorly investigated domains.

The only reason for such a modest scale of application of very low energy neutrons in condensed matter research is low intensity of neutron flux in this energy range.

The best (and now the only) source of neutrons in neV energy range - ILL UCN turbine[5] yields $\sim$ 50n/(cm^{2}s neV) in the maximum of the neutron spectrum in vicinity 750 neV (v$\approx$ 12m/s).

Last years brought hope for significant progress in the intensity of very low energy neutron beams. It is connected with possible use of the most effective cold moderators: solid deuterium or solid deuterocarbons at low temperatures $\sim$ 5-10 K for production of very cold neutrons[6, 7, 8, 9]. It will increase interest to the use of very cold neutrons in condensed matter studies.

2 Spectrometers

We tested two different time of flight very low energy neutron spectrometers. Both ones have standard scheme but with modifications accounting the strong influence of gravity on motion of neutrons in this energy range. The first one contained the chamber for samples, the neutron collimators, the mechanical chopper, the horizontal mirror neutron guide in flight path, and the neutron detectors: gas-filled and of the scintillation type. This spectrometer was used for total neutron cross sections measurements and for the investigation of properties of thin film ferromagnetic shutters[10] and interferential thin film structures in transmission mode.

The second one consists of the large horizontally placed position sensitive gas filled annular detector (8 rings) with diameter ~600 mm, the vertically positioned vacuum neutron flight path chamber (neutrons move along parabolic trajectories in the Earth gravitational field with the vertical axes of parabolas coincident with the axes of the neutron coordinate detector), the sample units, the neutron monochromators (thin film interferential filters), the collimators of the incident neutron beam and the corresponding electronics. This spectrometer is used for total and differential neutron cross section measurements with the ultimate goal to measure double differential neutron cross sections $\mathrm{d}^2\sigma/\mathrm{d}\Omega d\epsilon$.

The mechanical and thin film ferromagnetic choppers of the neutron beam were used, the latter in the pseudorandom mode. The test included the investigation of properties of position sensitive gas filled low pressure proportional neutron detector with different gases: enriched $^{10}BF_3$ and the mixture ^3He and CF_4, the optimization of the neutron collimators and the measurements of differential cross section for several samples. On-line control of the amplitude spectra from all rings of the detector

was performed during the measurements. Investigation of the background in conditions of low intensity neutron flux was also important.

Detailed description of the spectrometers will be published elsewhere. Here we present only the results of the measurements of neutron cross sections obtained in the course of setting going the spectrometers.

All the measured samples are relevant to the experiments in UCN physics and therefore present some practical interest. The foils of Zr and Al are used as the entrance windows for UCN detectors and energy filters in some specific UCN spectrometers[11]. They serve also as the exit windows in UCN sources. Polyethylene is used as an "ideal" UCN absorber in gravitation UCN spectrometers and for the calibration of UCN losses in the storage chambers. Liquid fluoropolymers are used for covering the walls of UCN storage chambers[12].

3 Cross sections

Some results of the measurements are shown in the Figs. 1-5. Figs. 1-3 show results of the tentative measurements of very low energy scattering on polycrystalline metal foils which present typical example of inhomogeneous medium for neutrons. The transmission of slow neutrons through highly inhomogeneous medium was studied previously by A.Steyerl[13]. It was demonstrated that transmission as a function of neutron wave length permits to deduce characteristic parameters of inhomogeneities, in particular their size and density. Our measurements were performed at the larger wavelengths, up to $\sim 10^3$ Å, where sensitivity to the scattering on inhomogeneities and clusters is increased significantly.

It is known that in the Born approximation the differential macroscopic cross section of elastic scattering for neutrons trans-

mitting through an isotropic inhomogeneous medium has the form[14]:

$$\frac{d\Sigma_{el}}{d\Omega} = \frac{1}{\pi}(\frac{m}{\hbar^2})^2 \int_0^\infty G(\rho)\frac{sin(q\rho)}{q\rho}\rho^2 d\rho, \quad (1)$$

where m is the neutron mass, q=$|\vec{k'} - \vec{k}|$ is the neutron wave vector change, and G($\vec{r},\vec{r'}$)=< δU($\vec{r}$) δU($\vec{r'}$) >, ($\rho = |\vec{r'} - \vec{r}|$) is the correlation function of fluctuations of the local neutron-medium interaction potential.

The latter is

$$U = \frac{\hbar^2}{2m}\sum_i 4\pi N_i b_i, \quad (2)$$

where N_i is atomic density and b_i is coherent scattering lengths of nuclei of the medium, so that $\delta U(\vec{r}) = U(\vec{r}) - <U(\vec{r})>$.

The total cross section after integration over solid angle with account of the solid angle of the neutron detector is:

$$\Sigma_{el}(k) = 2(\frac{m}{\hbar^2})^2 \frac{1}{k^2}\int_0^\infty G(\rho)[cos(2k\rho \cdot sin\theta_0) - cos(2k\rho)]d\rho, \quad (3)$$

where $2\theta_0$ -is the acceptance angle of the neutron detector.

For exponential correlation function

$$G(\rho) = G(0)e^{-\rho/\rho_0}, \quad (4)$$

where ρ_0 is the correlation length, we have the expression

$$\Sigma_{el}(k) = 2(\frac{m}{\hbar^2})^2 \frac{G_0\rho_0}{k^2}\Big[\frac{1}{1+4k^2\rho_0^2 sin^2\theta_0} - \frac{1}{1+4k^2\rho_0^2}\Big] \quad (5)$$

for total cross section, and two expressions for differential cross section:

$$\frac{d\Sigma_{el}}{dq} = \frac{16 sin^2\frac{\theta}{2}}{q}(\frac{m}{\hbar^2})^2 \frac{G_0\rho_0^3}{1+q^2\rho_0^2}, \quad (6)$$

and

$$\frac{d\Sigma_{el}}{dq} = \frac{4}{k^2}(\frac{m}{\hbar^2})^2 \frac{G_0 q\rho_0^3}{1+q^2\rho_0^2}, \quad (7)$$

at θ=const and k=const respectively.

This formalism was used for the interpretation of the measurements of total and differential cross sections for the samples of the metal foils. For example for Zr foil the following parameters for the model of Eqs. 4-5 were found from the total cross section measurement: G(0)=1.7±0.11 neV^2, ρ_0=840±95 Å. From the fitting according to Eqs. 6-7 of data on differential cross section the result is somewhat different: G(0)=8.0±3.0 neV^2, ρ_0=450±75 Å. It is seen that tested model of Eq. 4 does not describe properly the spatial inhomogeneity of polycrystal metal. The reliable test of more refined models is hardly possible in view of not sufficient statistical precision of present measurements. But it is seen that the when combining the total and differential cross section measurements it is possible to reveal more details about the large scale structure of material than if to apply an analisys of only one of them.

Fig. 4 shows the total cross section for polyethylene film. At this level of precision it shows no visible deviation from 1/v law, but our tentative measurement of differential cross section demonstrates some elastic scattering due to inhomogeneities of density even for this highly incoherent substance with very small strength of coherent scattering (U≈-9 neV). The fit of the total cross section data according

$$\sigma = \sigma_0 + a \cdot \lambda', \tag{8}$$

where λ' is the neutron wave length in the substance (corrected for the Fermi potential of the sample), gives: $\sigma_0 = (96 \pm 18)$b, a=(2.073 ± 0.043)b/Å. This cross section is the sum of energy independent elastic incoherent scattering, and the capture and upscattering cross section, both proportional to the wave length. It follows that with account of the neutron capture, extrapolated to the thermal point upscattering contribution is $\sigma_{ups,extr} = 2.073 \cdot 1.8 - (0.334 \cdot 2/3) = (3.51 \pm 0.08)$b/atom of the (CH_2)-complex or (5.56 ± 0.1)b/H atom.

Liquid fluoropolymer Fomblin[12] has the chemical formula $CF_3(C_3F_6O)_n(OCF_2)_mOCF_3$,

with m/n=20-40, molecular weight ~3000. Total cross section is shown in the Fig. 5. The fit according to Eq. 8 yields: $\sigma_0 = (5.33 \pm 2.6)$ b, a=$(7.1 \pm 0.67) \cdot 10^{-2}$ b/Å.

The low temperature liquid fluoropolymer POM-310[2] is the mixture of complex fluoropolyoximethylenes with the general formula $CF_3O(CF_2O)_n(CF_2CF_2O)_m(OCF_2CF_2O)_l\ CF_3$

with n:m:l=65.8:3.1:0.2 and molecular weight 4883. The fit of the total cross section for this substance according to Eq. 8 yields: $\sigma_0 = (6.1 \pm 2.5)$ b, a=$(6.15 \pm 0.62) \cdot 10^{-2}$ b/Å.

The values of the energy dependent (proportional to the wave length) inelastic part of the cross sections for liquid fluoropolymers do not coincide with the the similar results of the measurements of total cross section for these substances at the wave length 20 Å(the measurements were performed in this work in the wave length range 1-20 Å, and in the temperature range 10-300 K) if to extrapolate both ones to the same energy according 1/v law. The values obtained in[17] at 20 Å at room temperature are two times larger. Two effects may contribute to this difference: possible existence of very low energy excitations in these substances, and significant dependence of coherent inelastic upscattering on the incident very low energy neutron wave length. The latter may be very probable in substances with very large parameters of space order like liquid polymers.

[2]The investigated substances were produced by the Perm' branch of the Russian Scientific Center "Applied Chemistry"

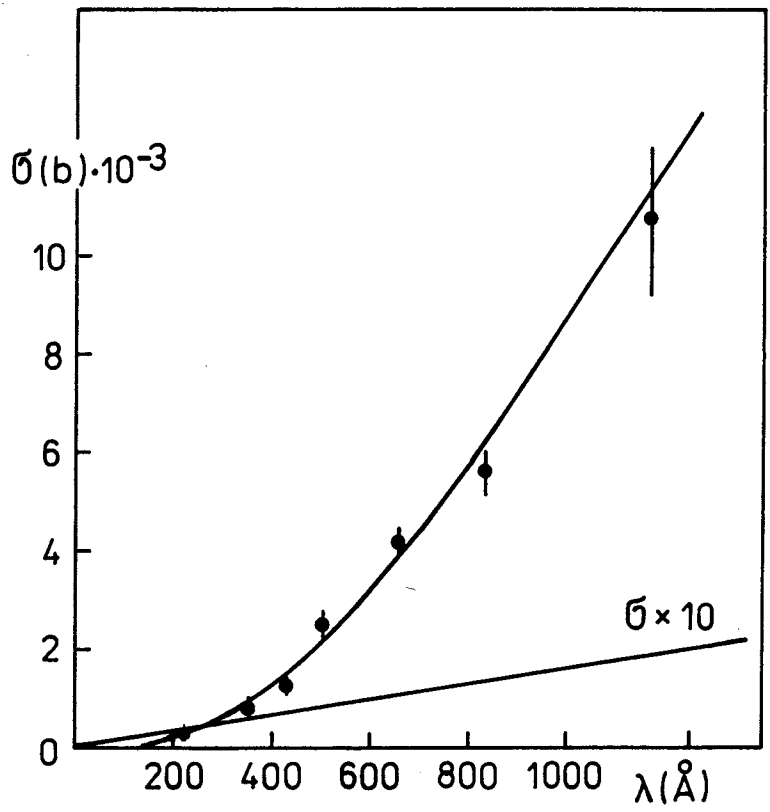

Fig. 1. Total cross section for Zr (GoodFellow, 50 mkm, 99.8% purity, not annealed). The straight line σ is the result of extrapolation of the cross section for Zr σ_{tot}=1.45 b at the energy 1 mev[16]. The curve through the experimental points is result of fitting according to Eq. 8.

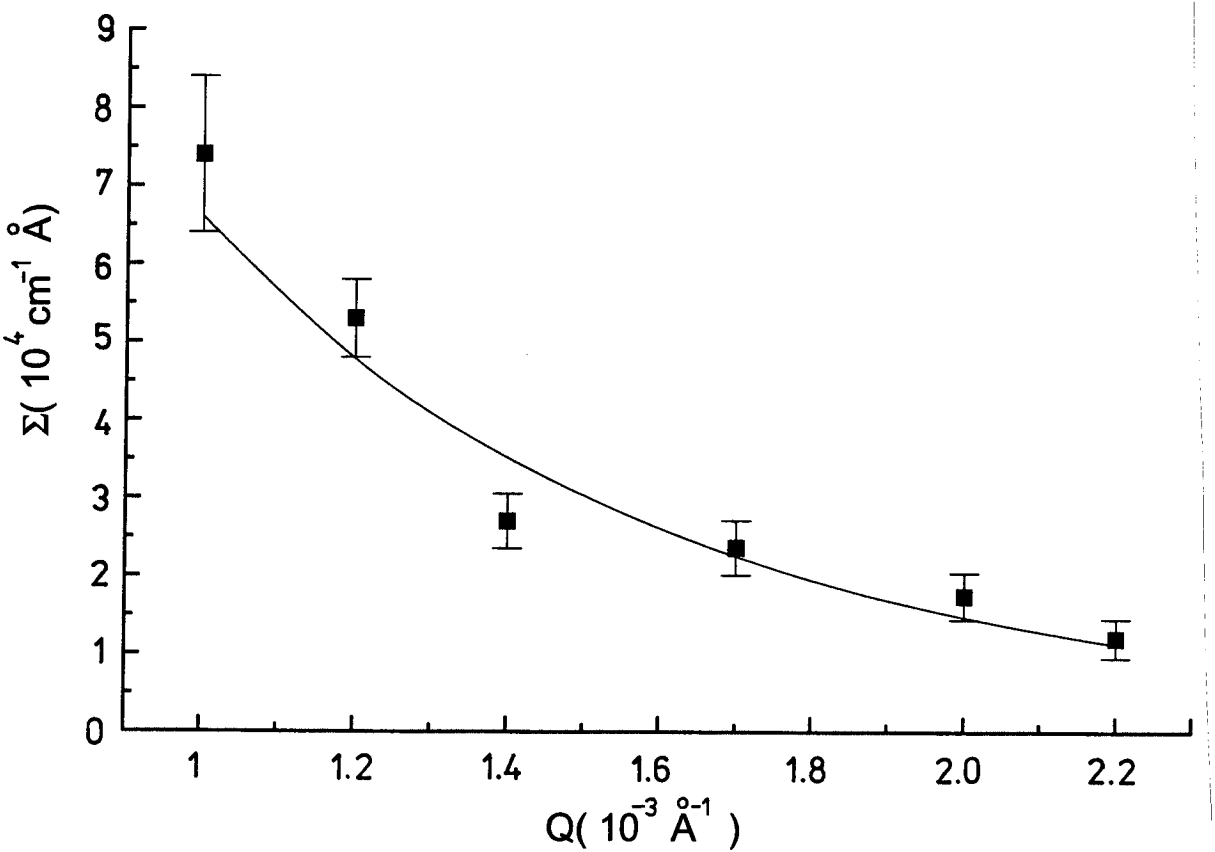

Fig. 2. Differential cross section for Zr.The curve through the experimental points is resut of fitting according to Eq. 7.

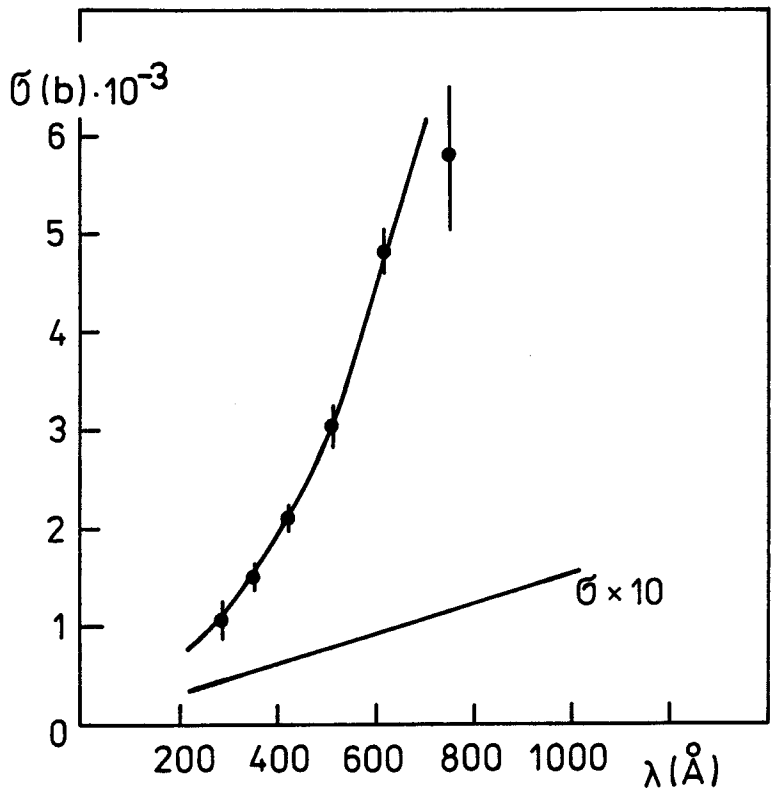

Fig. 3. Total cross section for Al (GoodFellow, four foils with total width 48 mkm, 99.99% purity, not annealed). The straight line is the result of extrapolation of cross section for Al σ_{tot}=1.8 b at the energy 0.6 mev[16]. The curve through the experimental points is result of fitting according to Eq. 7.

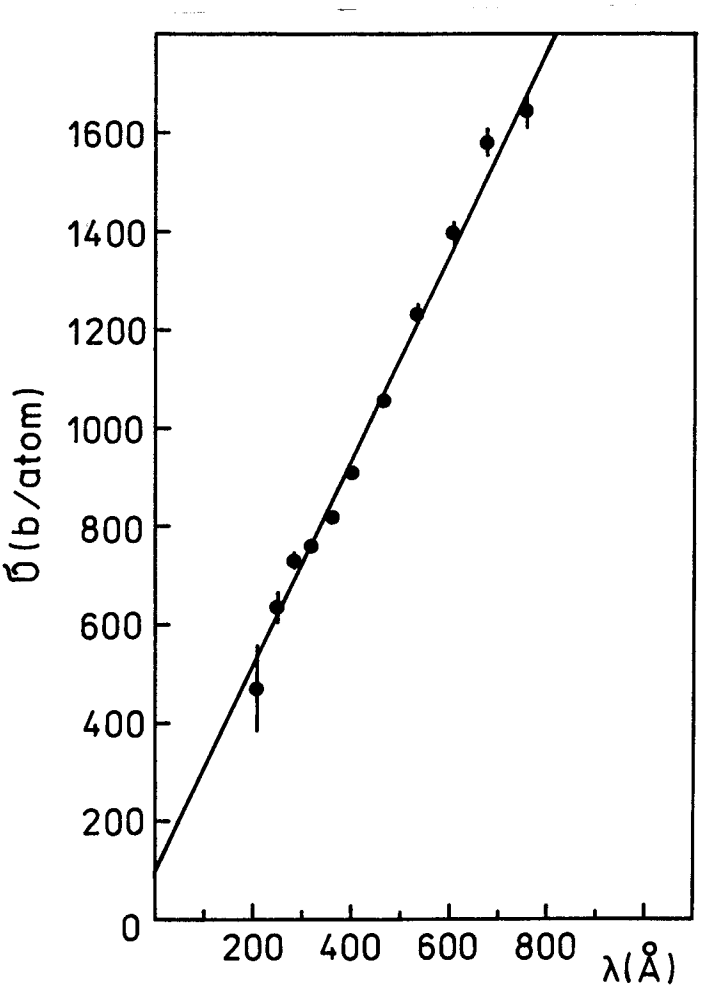

Fig. 4. Total cross section for polyethylene film, the thickness 7.88 mg/cm^2. The straight line is the result of the least squares fit according to Eq. 8.

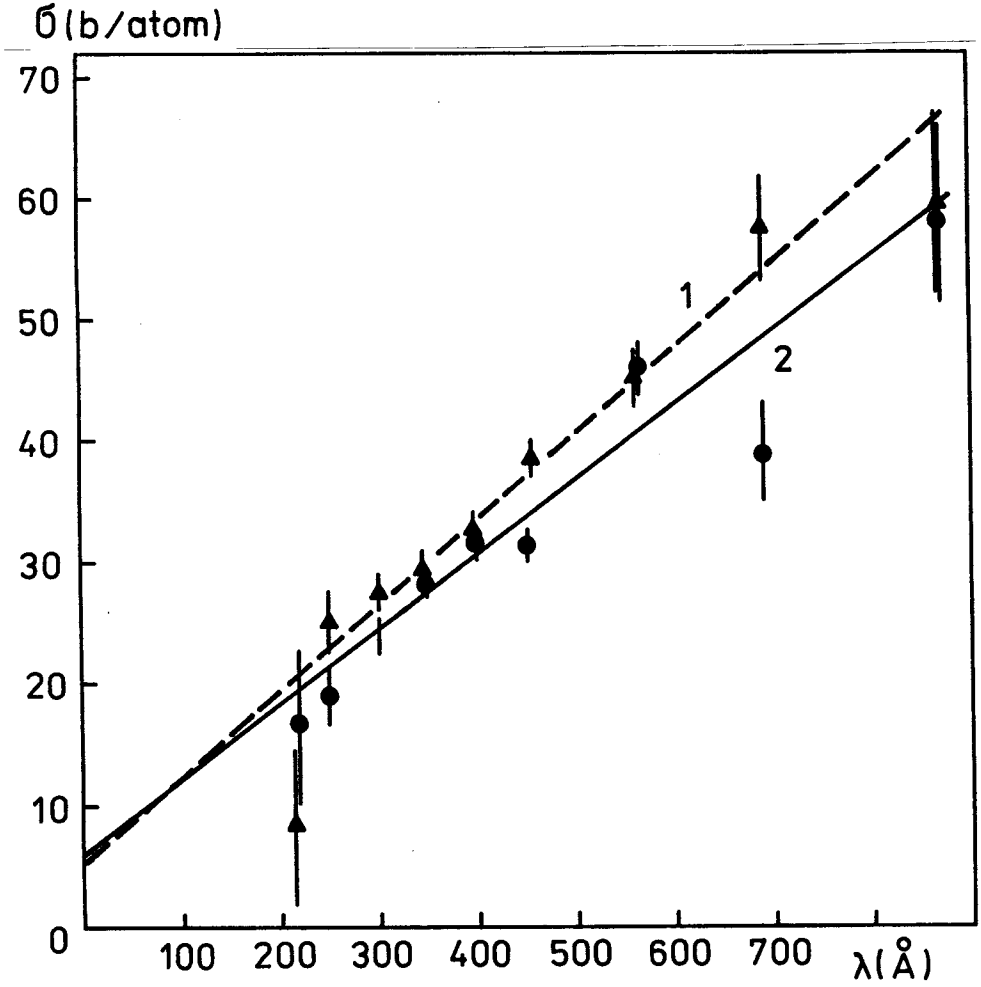

Fig. 5. Total cross sections for Fomblin (Ausimont[15]) (1, triangles), and low temperature liquid fluoropolymer POM 310 (2, circles), the thickness 0.38 g/cm^2. The straight lines are the result of the least squares fit according to Eq. 8.

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Дифференциальная спектрометрия нейтронов в области очень низких энергий. Сечения для Zr, Al, полиэтилена и жидких фторполимеров

Представлены некоторые результаты измерений, полученные при испытаниях времяпролетных нейтронных спектрометров в диапазоне энергий 0,05–2,5 мкэВ. Измерения полных и дифференциальных сечений были проведены для нескольких образцов веществ, представляющих интерес для физики ультрахолодных нейтронов: Zr, Al, полиэтилена и жидких фторполимеров.

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Pokotilovski Yu. N. et al.
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Differential Neutron Spectrometry in the Very Low Neutron Energy Range. Neutron Cross Sections for Zr, Al, Polyethylene and Liquid Fluoropolymers

Some results of the test of the time-of-flight neutron spectrometers in the energy range (0.05–2.5) μeV are described. The measurements of total and differential cross sections were performed for several substances relevant to the experiments in the physics of ultracold neutrons: Zr, Al, polyethylene and liquid fluoropolymers.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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