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# TEST OF THE FAST THIN-FILM FERROMAGNETIC SHUTTERS FOR ULTRACOLD NEUTRONS

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Покотиловский Ю. Н., Новопольцев М. И., Гельтенборт П. Е3-2008-139
Испытание быстрых тонкопленочных ферромагнитных затворов для ультрахолодных нейтронов

Проведены испытания двух типов тонкопленочных ферромагнитных затворов для ультрахолодных нейтронов. Первый тип основан на отражении нейтронов от последовательности тонких ферромагнитных слоев с противоположной намагниченностью. Второй тип основан на преломлении нейтронов в размагниченной ферромагнитной фольге.

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Test of the Fast Thin-Film Ferromagnetic Shutters for Ultracold Neutrons

Test of thin-film ferromagnetic shutters of two types for ultracold neutrons has been performed. The first type is based on neutron reflection from the sequence of successively placed thin ferromagnetic layers with oppositely directed magnetization. The second one is based on neutron refraction in ferromagnetic foils inserted in the beam.

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

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Experiments on further test of thin-film ferromagnetic shutters for ultracold neutrons are described. The previous experiments on the shuttering of ultracold neutrons by means of similar devices are described in [1–5].

1. The idea of very slow neutron shutters is based on the phenomenon of neutron reflection from the sequence of successively placed (deposited) thin ferromagnetic layers with the oppositely directed magnetization. Such a sequence represents a potential barrier for neutrons of any polarization when the neutron energy $E < E_{\rm up} = \frac{\hbar^2}{2m}4\pi Nb + \mu B$ (the closed state). When all the layers are magnetized in one direction by application of external magnetic field, the neutrons of one polarization with the energy $E > E_{\rm low} = \frac{\hbar^2}{2m}4\pi Nb - \mu B$ pass through the shutter (the open state). The neutron energy range where the effect of shuttering may take place is between these two values.

The shutters are thin multilayered films of ferromagnetic (iron, permalloy) with the thickness of $\sim 10^3$Å, deposited at the surface of thin Si plates; technological details are described in [4, 5].

The main possible application of such shutters may be very high resolution time-of-flight spectrometry of very slow neutrons. The resolution in this case is restricted by the magnetic field switching time and the neutron pass time through the multilayered shutter. At an overall thickness of the shutter of 2 $\mu$m and a neutron velocity in the medium of 2 m/s the neutron pass time through the shutter is 1 $\mu$s. With the opening time of a shutter of 10 $\mu$s and a flight path of 1 m and a neutron energy of 100 neV the energy resolution is about $10^{-2}$ neV. However, there is a quantum mechanical restriction for the energy resolution originating from the uncertainty relation $\Delta E \Delta t \geqslant \hbar/2$:

$$\Delta E \geqslant \left( \frac{2\hbar^2 E^3}{mL^2} \right)^{1/4}, \qquad (1)$$

where $E$ is the neutron energy, $m$ is the neutron mass and $L$ is the flight path.

At the same flight path $L = 1$ m and $E = 100$ neV the uncertainty relation restriction of Eq. (1) is $1.6 \cdot 10^{-2}$ neV.

Our goal in this work was to further investigate the properties of these shutters, not studied previously.

**The Long-Time Stability of Ferromagnetic Shutters.** Some of the samples of thin-film many-layered shutters were manufactured long ago (more than 15 years ago). The positive result consists in the fact that the investigation showed no change in the properties — the UCN transmission in the open and closed states compared with the measured ones just after production. It is important from the practical point of view and means that the long-time interdiffusion between adjacent oppositely magnetized layers is insignificant.

**The Neutron Energy Dependence of Transmission in Open and Closed States.** In the most preferable mode of application such shutters are supposed to work with the quasi-monochromatic spectrum of incident neutrons, therefore, it is necessary to determine the neutron energy range where the shuttering efficiency — the open/closed ratio — has the maximum value. Figure 1 presents the open/closed ratio for the two-layered shutter sample, measured with the mechanical time-of-flight spectrometer.

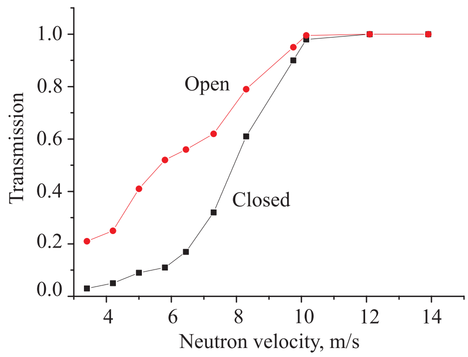


Fig. 1. Neutron transmission in the open and closed states of the shutter as a function of the neutron velocity for the two-layered shutter

**The Manufacture Problems.** Our previous experience of the manufacturing of the multilayered thin-film shutters by successive thermal evaporation showed that when attempting to produce shutters with the number of ferromagnetic layers larger than four, the neutron transmission through shutters decreased. The probable cause of this phenomenon is that the deposition of the next layers deteriorates the properties of the preceding ones. Therefore, in the present experiment we tried to use the stacks of separate two- and four-layered shutters: each at its own substrate with the number of layers not larger than four. The result was that coefficients of transmission in open and closed states did not follow exactly the law of the product of transmission for separate shutters that could be in the case of absence of any adiabatic neutron spin rotation in the space between the shutters. The cause of this could be some adiabatic neutron spin rotation due to small magnetic field normal to the plane of shutters. The other reason was that we did not have in our disposal identical shutters: some of them were prepared from isotopic mixtures of Fe and Ni, some from natural ones so that the neutron effective energy range of their work was different. Nevertheless, the shuttering capability increased significantly with an increase of the number of shutters — up to $\sim 40$ for three two-layered shutters (Fig. 2). We hope that with the stack of 5–10 two-layered identical separate shutters it is possible to reach the stopping coefficients on the order of $10^{-3}$, which is sufficient for some practical application.

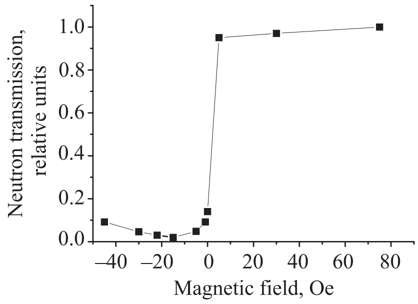


Fig. 2. Transmission of the stack of two shutters as a function of the applied magnetic field

**The Measurement of the Shape of Ultracold Neutron Pulse after Thin Ferromagnetic Shutter.** The scheme of the measurement is shown in Fig. 3. Incident ultracold neutron beam from neutron guide *1* is modulated with thin ferromagnetic shutter *2*. Open and closed states of the shutter are produced by pulse magnetic coil *5* and direct current coil *6*. Neutrons transmitted through the shutter are absorbed in thin scintillation neutron detector *3* consisting of $^6$LiOH layer and thin ZnS(Tl) scintillator. Thin ferromagnetic shutter *2* and the $^6$LiOH radiator of the scintillation detector *3* were tightly pressed together with no gap between them. The light pulses were registered by PMT, *4* is the long ($\sim 60$ cm)

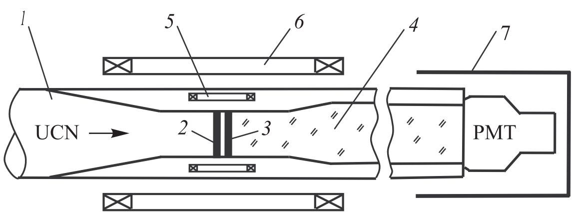


Fig. 3. Scheme of the measurement of the form of neutron pulse after pulsed transmission of the thin-film ferromagnetic shutter: *1* — UCN guide, *2* — thin-film ferromagnetic shutter, *3* — scintillating neutron detector, *4* — PMT, *5* — pulse magnetic coil, *6* — direct current magnetic coil, *7* — magnetic shielding

plexiglass light guide, *7* is the magnetic shielding of the PMT. The measured forms of «neutron pulse» in the case of magnetic pulse widths 250 and 100 $\mu$s are shown in Figs. 4 and 5.

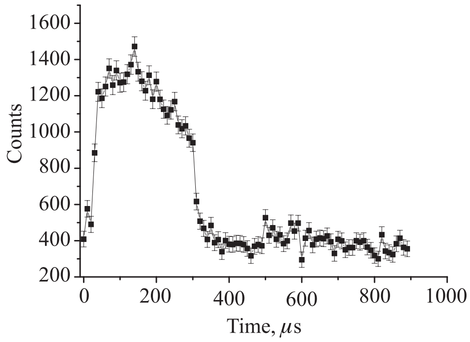


Fig. 4. The measured form of neutron pulse in the case of the magnetic pulse width 250 $\mu$s

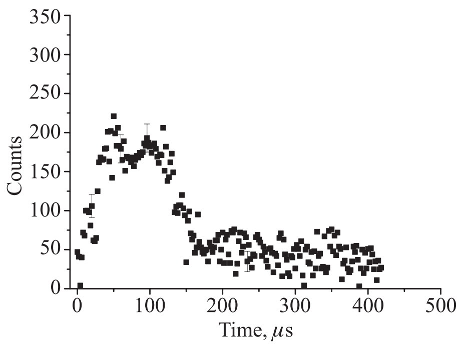


Fig. 5. The measured form of the neutron pulse in the case of the magnetic pulse width 100 $\mu$s

2. The second type of possible ferromagnetic shutter [6] is based on the neutron refraction and diffraction in a non-magnetized ferromagnetic medium (closed state) and significant decreasing of such a scattering in the state of magnetic saturation (open state). As is well known, slow neutrons on traversing ferromagnetic medium experience small angle scattering on magnetic inhomogeneities. They are either diffracted or refracted depending on how large the phase difference is of the neutron wave travelling the same distances in an inhomogeneity and in

homogeneous medium. The refraction index $n$ for the neutron wave travelling in the magnetic medium is

$$1 - n^2 = \frac{\lambda^2 N \bar{b}}{\pi} \pm \frac{\mu B}{E}, \tag{2}$$

where $N$ is the atomic density of the medium, $\bar{b}$ — the mean neutron coherent scattering length, $\mu$ — the magnetic moment of the neutron, $B$ — the magnetic induction value in the medium, $E$ and $\lambda$ — the energy and the wavelength of the neutron, respectively. Signs «+» and «–» stand for the parallel and antiparallel orientations of the neutron spin with respect to the $\vec{B}$ direction. The difference in phases of the neutron waves scattered on the inhomogeneities having opposite directions of magnetization is

$$\phi = 2\pi \frac{\delta}{\lambda} \frac{\mu B}{E}, \tag{3}$$

where $\delta$ is the inhomogeneity size along the direction of neutron propagation. At $\phi \ll 1$ the diffraction dominates, in the opposite case, the refraction does. The characteristic angle of diffractive scattering $\alpha \sim 2\lambda/\delta$, the characteristic angle of neutron deflection on refraction by a single inter-domain interface $\Delta\theta = \frac{\mu B}{E} \cot(\theta)$, here $\theta$ is the grazing angle of the neutron wave incident on the interface (it is assumed here that $\theta > \theta_{\text{crit}} = (2\mu B/E)^{1/2}$, the critical angle of total reflection). In a typical ferromagnetic traversed by slow neutrons it is the refraction that should play the main role in the small-angle magnetic scattering. If the ferromagnetic is non-magnetized it can be assumed that neutron deflections are uncorrelated and the angular broadening of the beam is proportional to $(\tau/\delta)^{1/2}$, where $\tau$ is the thickness of the sample, $\delta$ is the mean domain size. The experimental data [7, 8] favor this assumption. The simple model of sharp inter-domain boundaries [8] led to the expression for the total width at half maximum of the angular distribution of transmitted neutrons:

$$\Gamma_\theta = \frac{4.7 \mu B}{E} \left( \frac{\tau}{2\delta} \right)^{1/2}. \tag{4}$$

This formula yields $\Gamma \sim 0.3$ for very cold neutrons with the velocity 10 m/s, at $\tau = 20$ $\mu$m, $\delta = 5$ $\mu$m, and $B = 2 \cdot 10^4$ G.

Investigations [9] have shown that the real situation is not so simple, as the refraction depends on the character and thickness of inter-domain boundaries. Thus, expression (4) gives an approximate estimate on the broadening. In various experiments a significant decrease has been observed in the angular broadening of the transmitted neutron beam under the action of an external magnetic field applied to ferromagnetic sample. By exploring this fact and the method of pulsed magnetization and demagnetization of foils from magnetically soft materials it is possible to realize the pulsed modulation of very cold neutron beam.

We tested several materials as possible candidates: rolled armco-iron foils, two types of permalloy, and the electrotechnical steels. Significant effect of magnetic scattering in the non-magnetized sample in comparison with the magnetized one was observed in the case of iron but in all cases the effect of neutron scattering on crystalline inhomogeneities prevailed. In addition, we tested several types of amorphous ferromagnetic foils: amorphous iron, the amorphous alloy $^{58}Ni_{0.62}$ $Nb_{0.38}$, the alloys $Co_{24}Fe_{56}Si_{15}P_5$, $Fe_{78}Co_{8.1}B_{13.9}$ and industrial alloy EK-97 (Russian production). In all the investigated cases we encountered significant non-magnetic scattering due to the crystalline inhomogeneities. In the best case $n\sigma$ for 10 m/s neutrons transmission through 20 $\mu$m foil exceeds 5. This result shows that application of polycrystalline ferromagnetic to modulate very slow neutron beam is inefficient.

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