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Time-of-flight Fourier Spectrometry with UCN

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Abstract. The report presents the first experience of using a time-of-flight Fourier spectrometer of ultracold neutrons (UCN). The description of the spectrometer design and first results of its testing are presented. The results of the first experiments show that the spectrometer may be used for obtaining UCN energy spectra in the energy range of 60÷200 neV with a resolution of about 5 neV. The application of TOF Fourier spectrometry technique allowed us to obtain the energy spectra from the diffraction of monochromatic ultracold neutrons on a moving grating. Lines of 0, ±1 and ±2 diffraction orders were simultaneously recorded, which had previously been impossible to be done by other methods. These results have made it possible to make a comparison with the recent theoretical calculations based on the dynamical theory of neutron diffraction on a moving phase grating.

1. Introduction

The UCN spectrometry has been successfully developing for a number of decades. Over the past fifteen years a number of experiments with the gravity UCN spectrometer with interference filters have been performed [1-5]. In this method the range of energies to be measured is limited by mgH, where m is the neutron mass, g is the free fall acceleration and H is the maximum possible distance between both filters. In practice, the energy range did not exceed 20-30 neV. In particular, the effect of neutron energy quantization in UCN diffraction by a moving grating was observed for the first time using such a spectrometer [2]. Later this effect was used to test the weak equivalence principle for the neutron [5].

The continuation of this research [6] and recent theoretical results [7] have brought us to the understanding of the need for more detailed investigation of UCN spectra in diffraction by a moving grating. The problem is that the energy range of the resulting spectrum is of the order of 100 neV, which is comparable with the UCN initial energy. At the same time, it is desirable that the energy of the spectral lines could be measured with an accuracy of 1÷1.5 neV. The gravity UCN spectrometry with interference filters appears to be unsuitable for these purposes.

As it follows from simple estimations, the classical TOF method is not suited for this task either, because the ratio of the initial time pulse duration to the pulse repetition period cannot exceed the ratio of the necessary resolution to the width of the time-of-flight spectrum. In our case this ratio is of the order of 10^{-2}. Such losses in luminosity are absolutely unacceptable.

It is likely that the solution of the problem is the use of any correlation time-of-flight methods. It may be the correlation spectroscopy with pseudo-random flux modulation [8-16] or Fourier spectroscopy with periodic or quasiperiodic flux modulation [17-25]. Having compared the two approaches, we have chosen the Fourier TOF spectroscopy [26]. The point is that we had a UCN

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spectrometer with periodic flux modulation [6], which could be relatively easily transformed into a TOF Fourier-spectrometer. On the other hand, the use of pseudo-random flux modulation was bound to lead to a dramatic loss of intensity, as its realization would severely limit the beam cross-section, which in our case had a shape of a ring. Such a UCN Fourier spectrometer was built and further on we report the first experience of its using.

2. Principle of the Time-of-flight Fourier spectroscopy

Let the aim of the measurement be the distribution of times *I(t)* that neutrons spend for the flight along the known path length. This time-of-flight spectrum is evidently related to the velocity distribution. The spectrum might be directly measured, if neutrons would be generated in an ideally narrow δ-like time pulse. In the general case, the detector response is

$$Z(t) = \int_0^\infty I(t')\theta\left(t-t'\right)dt' , \tag{1}$$

where $\theta(t)$ describes the time dependence of the initial flux. If the initial flux is modulated harmonically, then

$$Z(t) = \int_0^\infty I(t')\sin\left[\omega\left(t-t'\right)\right]dt' . \tag{2}$$

Each small part of the time spectrum contributes its harmonic to the detector count rate and the phase shift of this harmonic relative to the modulation phase is defined by the time of flight and modulation frequency. Since the time spectrum may be represented by a Fourier expansion

$$I(t) = \int_0^\infty R\left(\omega\right) sin\left[\omega t - \varphi\left(\omega\right)\right] d\omega \ . \tag{3}$$

$Z(t)$ in equation (2) can be interpreted as a Fourier-harmonic of the initial spectrum. For the reconstruction of the initial spectrum in an ideal case, it is necessary to find functions $R(\omega)$ and $\varphi(\omega)$ in an infinitely large range of frequencies ω.

Since there was a device at our disposal with a fairly stable low-frequency beam modulator of periodic operation, we decided that at the initial stage of the work the measurement with a discrete set of frequencies ω_k would be acceptable. Then the results of the measurement are the amplitudes R_k and phases φ_k of the count rate oscillation for all frequencies ω_k. Having a rather large amount of such data, it is possible to reconstruct the initial time-of-flight spectrum in any time interval

$$I_{\exp}(t) = \frac{\pi}{2}\sum_k R_k \sin\left(\omega_k t + \varphi_k\right) \ . \tag{4}$$

3. Experimental setup and measurement procedure

The experiment was performed at the PF2 source of the Institute Laue-Langevin (Grenoble, France). The spectrometer is a slightly modified version of the device described in [6]. It is shown in Figure 1. Ultracold neutrons are fed to the entrance chamber through the UCN neutron guide and, after a number of reflections, fall down the annular channel with the lower section closed by a monochromator, which is a five-layer Ni-Ti interference filter [27, 28]. To suppress the background of neutrons with energies higher than the effective potential of nickel, the filter-monochromator is combined with a multilayer “superwindow” filter [27]. In the experiments with a moving grating (see [6] for details) the latter was placed directly below the monochromator. It could be rotated by a motor. The neutron flux with the spectrum formed by the combination of two filters and transformed by the moving diffraction grating (if the latter is used) enters the spectrometric part of the device. It comprises a Fourier-chopper, vertical neutron guide, and detector. The Fourier chopper consists of a rotating rotor and stator. The rotor is a 2-mm-thick titanium disc of about 40 cm in diameter with twelve radial slits (see Figure 2). The stator is a titanium diaphragm with only one slit. It is placed at the inlet section of the vertical neutron guide.

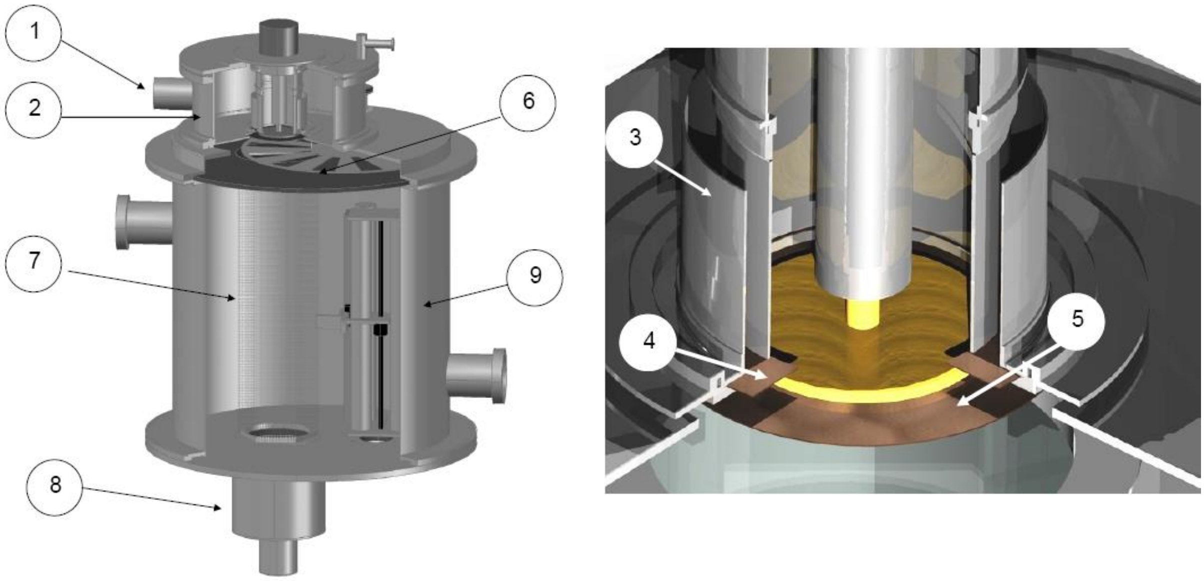

Figure 1. Time-of-flight Fourier spectrometer: general view (on the left) and its upper part (on the right): 1 - feeding guide, 2 - entrance chamber, 3 - annular channel, 4 - filter-monochromator, 5 - grating, 6 - rotor of the Fourier modulator, 7 - vertical glass guide, 8 - detector, 9 - vacuum vessel.

The rotor is driven by a stepper motor located outside the vacuum volume and connected to the rotor via a toothed belt and magnetic coupling. The rotation frequency of the rotor may reach 1800 rpm, which corresponds to a modulation frequency of 360 Hz. For the use of the electronic control system an infrared sensor and a small slot at the periphery of the rotor are used. Stability of the rotor rotation frequency is of the order of 10^{-4}. UCNs passing through the modulator come to the vertical neutron guide formed by six 95x680 mm float glass plates and reach the scintillation detector.

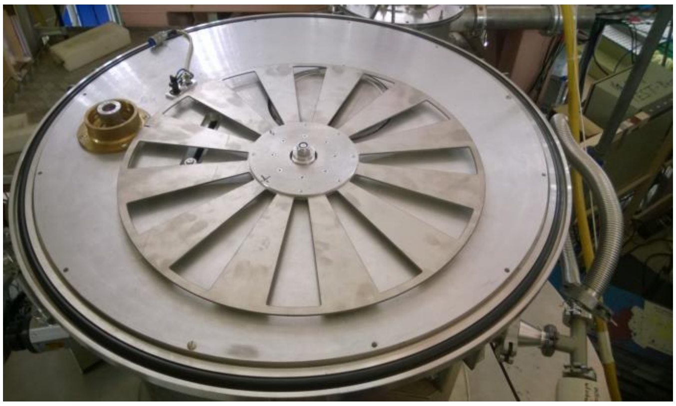

Figure 2. Rotors for the Fourier chopper.

The measurement system registered the time of arrival of pulses from the sensor of the chopper and from the detector and these data were recorded sequentially to a file. The modulation frequency f_k ranged from 6 to 360 Hz with a step of 6 Hz and upon reaching the maximum value decreased again.

Due to the vertical orientation of the spectrometer and the effect of the Earth's gravity the neutron time of flight does not linearly depend on the initial velocity. Sometimes for the correct interpretation of the results it was necessary to recalculate TOF spectrum to the energy scale. In addition to the relation between TOF and energy given by the equation

$$E = \frac{M}{2}\left(\frac{H^2}{t^2} - gH + \frac{g^2 t^2}{4}\right), \tag{5}$$

where M is the neutron mass, g is the free fall gravity acceleration and H is the difference in height between the Fourier modulator and detector. The latter was 72.5 cm. It was also necessary to take into account the nonlinear relation between the widths of energy and time channels on the abscissa axis. The relation between N_t and N_E values, which were proportional to the number of counts in time and energy channels, is given by

$$N_E = N_t\left[M\left(\frac{H^2}{t^3} - \frac{g^2 t}{4}\right)\right]^{-1}. \tag{6}$$

4. Test measurements with neutron interference filters

To test the spectrometer, three neutron interference filters (NIFs) [27, 28] were used. Filter 1 is a five-layer filter with alternating layers of NiMo and TiZr. It has a narrow transmission line. Filter 2 is a nine-layer filter with alternating layers of the same materials. It has a wide transmission line. Filter 3 is a five-layer filter with alternating layers of Ni(N) and TiZr. It was characterized by the splitting of the transmission line (see details in [27, 28]). The time-of-flight spectra measured by the spectrometer are shown in Figure 3.

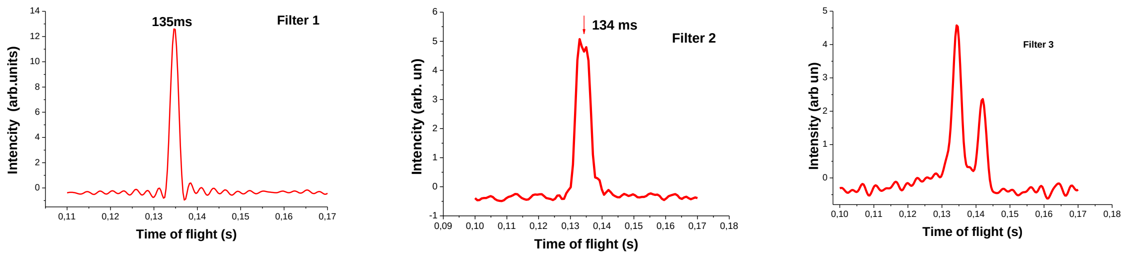

Figure 3. Time-of-flight spectra measured by the Fourier spectrometer. Energy spectra formed by filters 1-3 in combination with filter “superwindow”.

These spectra demonstrate that TOF UCN Fourier spectrometer have a resonable resolution and may be used for physical measurements.

5. Energy spectra of UCN diffracted by a moving grating

As in our previous works [2, 4], the diffraction grating was prepared on the surface of a silicon disc of 150 mm in diameter and 0.6 mm in thickness. Radial grooves (see Figure 4) were made in the peripheral region of the disc, which is a ring with an average diameter of 12 cm and a width of about 2 cm. The widths of the grooves are proportional to the radius and this proportionality ensures a constant angular distance between the grooves equal to a half period. The angular period of the structure is exactly known to be $\alpha = 2\pi/N$ with $N = 94500$. The design depth of the grooves of 0.144 mkm was chosen to ensure a phase difference $\Delta\varphi = \pi$ between the neutron waves passing through the neighboring elements of the grating. The grating was manufactured by Qudos Technology Ltd.

The grating was examined using an atomic force microscope. Two fragments of the grating positioned at different distances from the center were scanned and the image of one of these is shown in Figure 5. Subsequent analysis has shown that the real grating parameters are quite satisfactory agreement with the designed values.

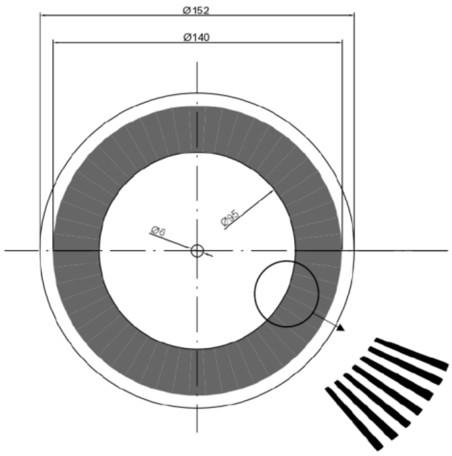

Figure 4. Diffraction grating: dimensions and orientation of grooves.

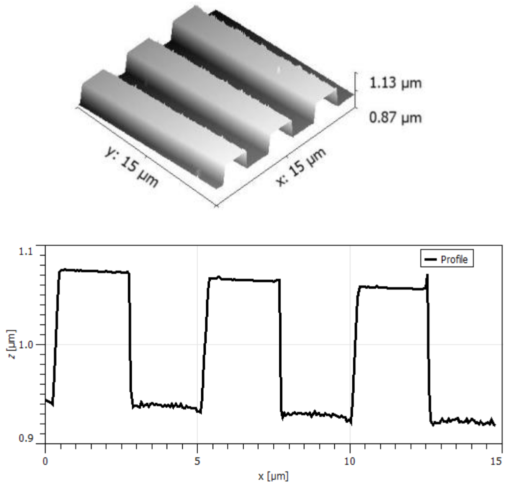

Figure 5. 3D image of the grating fragment obtained with an atomic force microscope.

Energy spectra of UCN passing through the grating were measured both for the grating at rest and for the grating rotating at frequencies of 1500, 3600 and 4800 rpm. With the fixed/specified number of grooves N the expected value of the energy splitting is $\Delta E = 2\pi\hbar Nf$, where f is the rotation frequency. Time-of-flight spectra reconstructed in accordance with (4) were then recalculated into the energy scale using eqs. (5), (6).

These spectra were compared with the results of calculation based on the dynamical theory of diffraction [7]. In these calculations the normal component of the neutron velocity at the surface of the grating was taken to be V_z = 4.67 m/s (energy of 114 neV), which corresponds to the position of the maximum of the monochromator transmission spectrum measured earlier by the time-of-flight method. The distribution of the velocity V_z was assumed to be a Gaussian with the degree of monochromatization $\Delta V_z / V_z = 0.0175$, where ΔV_z is FWHM of the distribution. The dependence of the resolution on the time of flight was neglected. The poorly known spectrum of horizontal velocities was also assumed to have a Gaussian distribution with a zero average value and FWHM equal to 3 m/s.

Figure 6 shows the TOF spectrum of UCN passing through the stationary grating and its corresponding energy spectrum. In addition to the main peak one can also clearly see a small peak at an energy of 255 neV. Apparently, this is a peak at the energy slightly higher than the value of the potential significantly suppressed by the transmission of the “superwindow”.

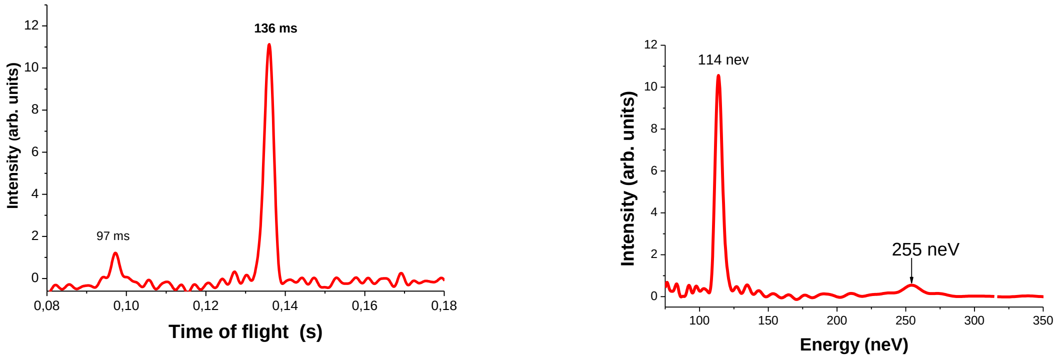

Figure 6. TOF spectrum (on the left) and energy spectra of UCNs passing through the stationary grating (on the right).

Figure 7 illustrates the main results of the experiment. The obtained time and energy spectra measured at three rotation velocities of the grating are displayed together with the results of the calculation. The absolute normalization of spectra was done for better visualization purposes.

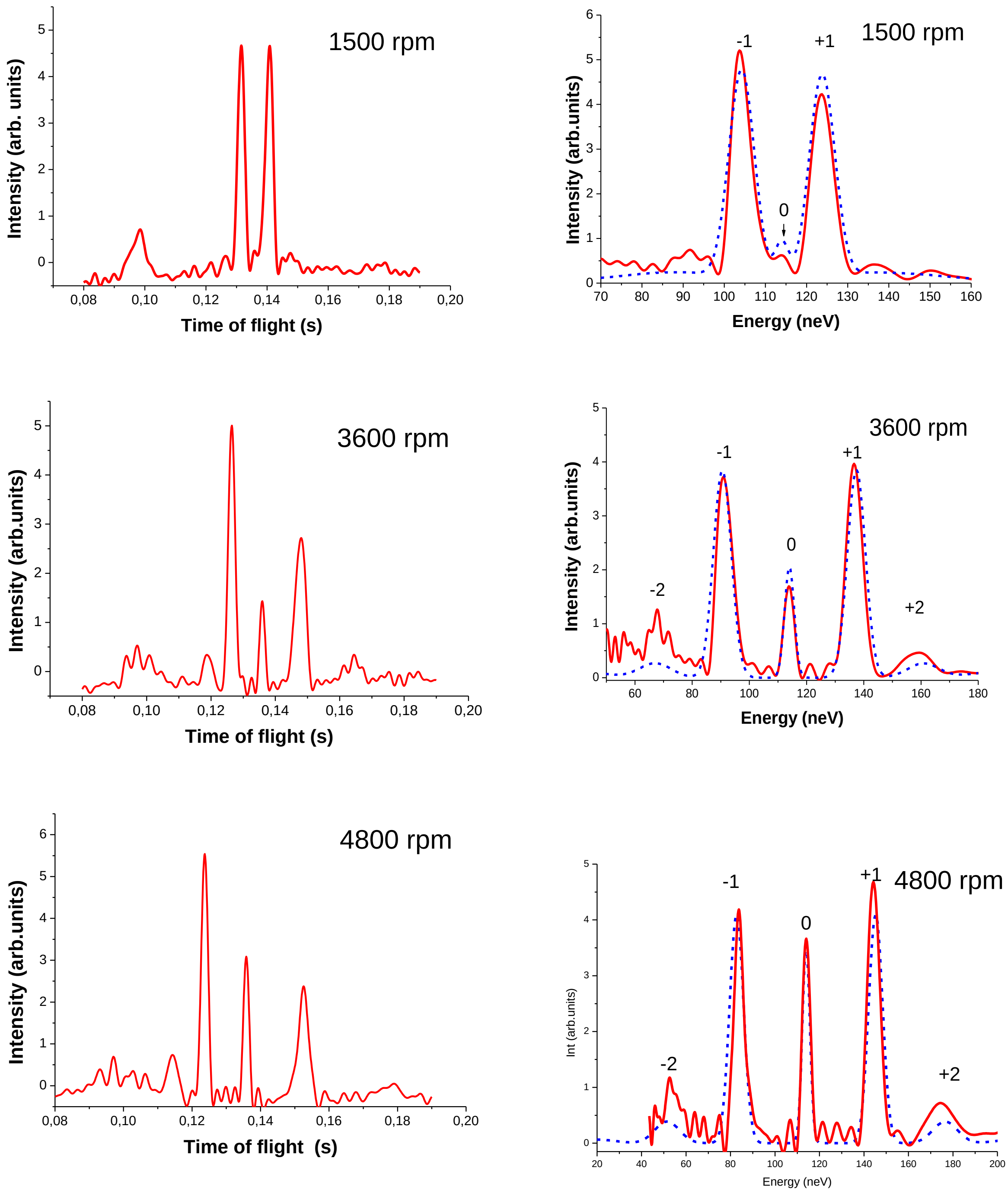

Figure 7. Time-of-flight (on the left) and energy (on the right) spectra of neutrons diffracted by a moving grating measured at different rotation frequencies. Lines of 0, ±1 and ±2 diffraction orders are clearly seen. Experimental (red solid line) and theoretical (blue dotted line) spectra are shown.

The obtained results demonstrate that using this method it is possible to detect spectra with the energy range comparable with the UCN initial energy. That permit us to compare the intensities of lines of five diffraction orders with predictions of the dynamic theory of neutron diffraction [7]. The experimental data were found in a good agreement with this theory.

6. Conclusion

We reported on the development of the time-of-flight UCN Fourier spectrometer designed mainly for studying the non-stationary phenomenon of neutron diffraction by a moving grating. This device is a modification of the gravity spectrometer [6] and therefore the first tests of the new device were carried out in the regime of the discrete spectrum of beam modulation and off-line data processing. This regime is not optimal, but it made it possible to obtain the first results in a relatively short time. The results of the test have shown that this device allows UCN energy spectra to be measured in the energy range of 60 ÷ 200 neV with the resolution of the order of 5 neV.

UCN spectra appearing in the experiments on neutron diffraction by a moving grating were measured using the time-of-flight Fourier spectrometer. In spite of the fact that the first measurements were made with not very high statistics, the results allow for a reliable comparison with the theoretical prediction. The obtained data testify that the experiment is in rather satisfactory agreement with the theoretical predictions based on the multiwave dynamical theory of neutron diffraction in the approximation of slowly changing amplitudes [7].

The activities on further improvement of the device will be aimed at increasing its luminosity. In addition, the spectrometer will be modified for using a continuous spectrum of modulation frequencies, which will improve the parameters of the device.

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References

[1] Frank A I, Bodnarchuk V I, P. Geltenbort P et al. 2003 *Phys. Atom. Nuclei* **66** 1831
[2] Frank A I, Balashov S N, Bondarenko I V et al. 2003 *Phys. Lett.A*, **311** 6
[3] Frank A I, Geltenbort P, Kulin G V and Strepetov A N 2003 *JETP Letters*, **78** 188
[4] Frank A I, Geltenbort P, Kulin G V et al. 2005 *JETP Letters* **81** 427
[5] Frank A I, Geltenbort P, Jentschel M et al., 2007 *JETP Letters*, **86** 225
[6] Kulin G V, Frank A I, Goryunov S V et al. 2015 *Nucl. Instr. Meth*. A **792** 38
[7] Bushuev V A, Frank A I and Kulin G V arXiv:1502.04751v1 [physics.optics]
Bushuev V A, Frank A I and Kulin G V 2015 *JETP* **148** (in press)
[8] Cook-Yahrborough H E 1964 in: *Instrumentation Techniques in Nuclear Pulse Analysis, Washington DC* 207
[9] Mogilner A I, Shalnikov O A and Timochin L A 1966 *Sov.J.Techn. Phys*. **2** 22 (in Russian)
[10] Sköld K 1968 *Nucl. Inst. Meth*. **63** 114
[11] Gordon J, Kroo N, Orban G, et al. 1968 *Phys. Lett*. A **26** 122
[12] Kroo N, Cher L 1977 *PEPAN* **8** 1412
[13] Cser L, Ferenczy F, Kroó N, Rubin Gy et al. 1981 *Nucl. Insr. Meth*.,**184** 431
[14] Freudenberg U, Glaser W 1986 *Nucl. Instr. Meth.* A **243** 429
[15] Gutsmiedl E, Golub R, Butterworth J 1991 *Physica B: Condensed Matter* **169** 503
[16] Novopoltsev M I and Pokotilovski Yu N 2010 *Instr. and Exp. Tech*. **53** 635
[17] Hiismäki P, Trunov VA, Antson O et al. *1985 in Proc. Conf. on Neutron Scatt. in the Nineties,*

Julich, Germany,. (Vienna: IAEA, 1985) 453
[18] Virjo A 1969 *Nucl. Instr. and Meth*. A, **73** 189
[19] Colwell J F, Lehinan S R, Miller Jr. P H and Whittemore W L 1969 *Nucl. Inst.Meth*.A **76** 135
[20] Nunes A C, Natans R and Schoenborn B P 1971 *Acta Cryst*. A**27** 284
[21] Pöyry H, Hiismäki P, Virjo A 1975 *Nucl. Inst.Meth* **126** 421
[22] Pöyry H 1978 *Nucl. Instrum. Methods* **156** 499
[23] Schröder J, Kudryashev V A, Keuter J M et al. 1994 *Neutron Res*. **2** 129
[24] Aksenov V L, Balagurov A M 1996 *Phys.Uspechi*, **39** 897
[25] Maayouf R M A, Abdel-Latif I, El-Kady A, El-Shafey A, Khalil M, El-Shaer Y 1997 *Nucl. Inst.Meth A* **398** 295
[26] Kulin G V, Kustov D V, Frank A I et al. 2014 *JINR Communication P3-2014 -72* (in Russian).
[27] Bondarenko I V, Bodnarchuk V I, Balashov S N 1999 *Phys. Atom. Nuclei*. **62** 721
[28] Bondarenko I V, Balashov S N, Cimmino A et al. 2000 *Nucl. Instr. Meth.* A **440** 591