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# WIDE BAND DEVICES

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## RESUME

Several methods helping to utilize the neutron spectra emitted by pulsed neutron sources with better efficiency are considered (e.g. supermirror neutron guides, multidetectors, wide band polarizers and the method of pseudostatistical modulation). The present status of proposed approaches are reviewed.

Keywords: polarization, pseudo statistical modulation

## INTRODUCTION

No arguments, the future belongs to the pulsed neutron sources. Contemplating the experience collected at the operating pulsed sources (ISIS, IBR-2, LANCE, KENS,IPNS) all operating facilities were constructed according the principle of the most economical use of the emitted by the pulsed source neutrons. The explanation of such an effort is quite obvious. To increase of the luminosity of the source is limited both by technical and financial restrictions. Thus, the efficiency of any facility can be enhanced only by the use of better collection of scattered neutrons.

As any pulsed source emits a quasi-maxwellian neutron spectrum - which often is called as white one - during a very short time (typical pulse width is several microseconds) thus, those methods are effective which utilize the most wide part of this maxwellian spectrum.

After all, there are several parts of a neutron scattering device, efficiency of which can be drastically improved. All these improvements are using the principle of collecting maximum information.

In the following I should like shortly recall some of them without striving for completeness.

## I. NEUTRON TRANSPORT AND DATA COLLECTION

At present time the simplest but not the cheapest way to conduct neutrons from the source to the sample seems to be supermirror neutron guides. Their aperture today achieves the value being comparable with the $3\theta_{critical}$ of natural nickel. Assuming a neutron guide of quasi-quadrangular cross section the gain factor may reach almost one order. The arguments in the favour of this type of neutron guide were all but a common place if their additional advantage, i.e. being able with considerably increased efficiency transport even short wavelength ( $\lambda \geq 1\mathring{A}$) neutrons allowing to install at least two spectrometers at one channel. These guides indeed, have to be curved, so usual at the output port of the guide emits neutron beam without epithermal and gamma-ray con-

tamination. To my knowledge the first supermirror guide is under preparation in the Institute Laue-Langevin in Grenoble.
The increase of the demand for more effective the data collection seems to be even more trivial. Area detectors (position sensitive, or multiwire ones) operates in many laboratories. The tendency to cover more and more bigger section of the $4\pi$ solid angle surrounding the scatter can be observed in this area of activity. A new feature of this activity is manifested in search for new type of detecting principles, e.g. scintillators with high spatial resolution converters. The high spatial resolution makes easier and faster the study of the structure of crystals the unit cell of which comprises hundreds or even thousands atoms (see biological structures).

## II. WIDE BAND POLARIZERS

At present time there are two main streams to construct wide band polarizers: the polarized $^3$He target, and mechanical constructions using synchronously moving polarizing supermirrors.
a.) $^3$He neutron polarization filter method.
The polarization mechanism in the case of a transmission polarizer comes from the spin dependent absorption process with the following cross section

$$\sigma_{\pm} = \sigma_0 \pm \sigma_p \tag{1}$$

where ± denotes the two possible states of the neutron spin. It was shown [1] that the ratio $\sigma_p$ / $\sigma_0$ is just the polarization of $^3$He. In the paper[2] four possible approaches for $^3$He polarization have been mentioned.
1. *Brute force* That is the cooling the nuclear moments down to several mK in the solid phase (25 bar) with a high magnetic field (more than 10 T).
2. *Optical pumping.* The photons transfer angular momentum to atoms by resonant scattering and subsequently to $^3$He nuclei by hyperfine coupling at room temperature.
3. *Pumping pure $^3$He* The optical pumping acts on the pure gas in an exited metastable state. Metastability exchange collisions then transfer the polarization to the ground state.
4. *Pumping Rb/$^3$He mixture.* The $^3$He polarization is produced by using spin transfer from optically pumped Rb vaporized at 200 °C.
Such type of filters would allow a beam of polarized neutrons with a broad wavelength band and can equally serve both for polarizers and analyzers. Unfortunately, at present time because of purely technical reasons the achieved level of polarization is far from the desired one (95%) and the opacity of the filter is too high. As the $^3$He filter has many degree of freedom, the optimization of the quality factor Q = $P\sqrt{T}$ (P - is the polarization, T - is the transmission) can be considerably increased[3].

b.) Mechanical polarizers.

Mechanical polarizing devices are using movable polarizing supermirror system which would allow to tune glancing angles in time so that the total reflection condition is always fulfilled only for one of the neutron spin direction. (The principle of such a construction is shown in Figure 1[4]). In addition, this technical performance gives rise to use the angular region of the total reflection in which the contamination of neutrons with opposite polarization is absent. (See the insert of Figure 1). In order to satisfy this condition it is necessary to operate at large area moderator and to have a collimation angle less than the total reflection angular range. These conditions in practice, e.g. for small-angle scattering are usually satisfied.

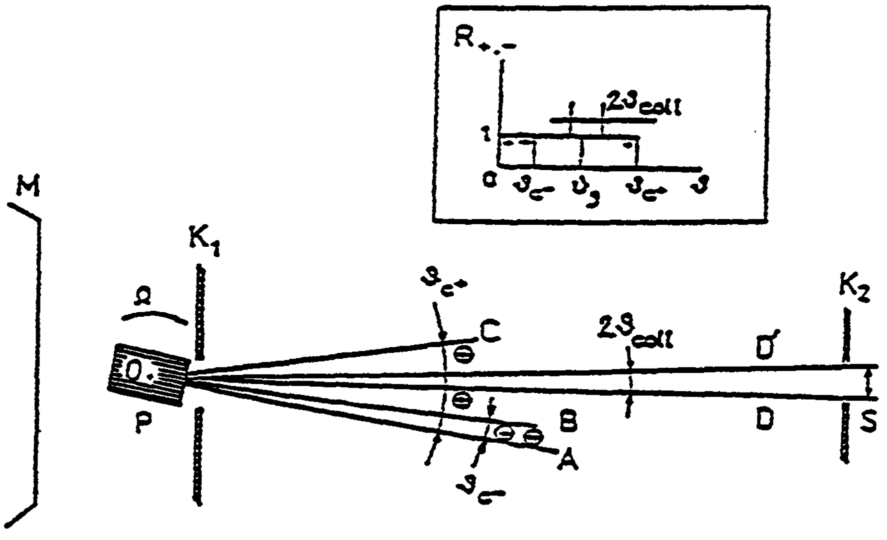

Figure 1. The schematical view of a broad-band polarizing setup for a TOF small-angle neutron scattering instrument. M - the moderator; P - the multimirror polarizing assembly, rotating around the center O with the angular velocity $\Omega$. The neutrons with polarization (+) fill the angular range AOC, while neutrons of mixed polarization (+,-) fall in the angular range AOB. In the angular range DOD′ defined by the collimator K2 only neutrons with polarization (+) do appear. The rotation of P keeps the sample S in the middle of the angle BOC, while the neutron wavelength and the angle AOB and AOC increase in time. The insert shows the idealized reflectivity versus the glancing angle together with the collimation angle DOD′.

This approach can be improved by the use of multiple reflection of the neutrons on the neighboring mirrors plates provided, their both side are covered by polarizing supermirror multilayers (polarizing Soller collimator) and the length of the rotation system is long enough ( e.g. several meters). If the neutron possesses with a velocity component being perpendicular to the plane of the moving mirrors the useful angular range can be considerably decreased (Figure 2a).

Evidently, the motion of the mirror does not affect the reflection process in this way if no movement normal to its plane occurs. This can be achieved when the mirror moves in its on plane. Different ways to arrange of mirrors satisfying to this conditions are shown in Figures 2b and 2c. An intermediate solution can be proposed using a set of coaxial truncated cones with generatrices inclined at an angle to the axis being equal to the "useful angle" $\theta_{us}$ (Figure 2d)[5]. It is worthy of note that the "density" of plates will be in an adequate way to follow the actual wavelength range.

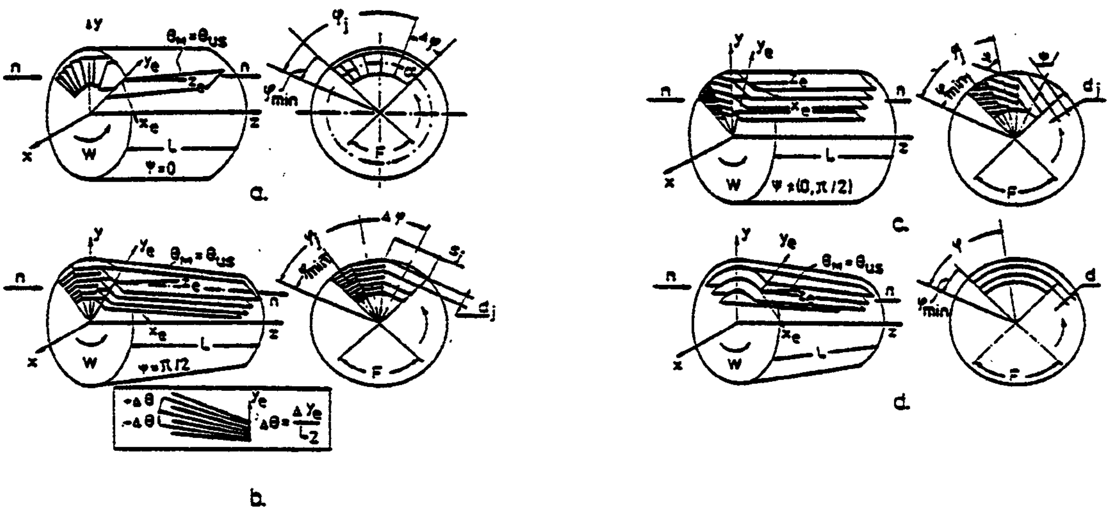

Figure 2. General outlook of various type of wide band neutron polarizing mirror setup.
a.) radialy arranged mirrors; b.) and c.) two different version of the arrangement mirrors moving in-plane. d.) coaxial truncated conical mirrors. L - the length of the mirror setup; W - is the angular velocity of the mirrors; $\psi$ - the tilting angle of the mirrors relating to the axis of the rotation; x,y,z - the coordinates in the laboratory system of coordinates, $x_e,y_e,z_e$ - the comoving coordinates of the comoving reference system; n- the neutron beam.

Unfortunately, the idea of mechanical wide band polarizer never was experimentally tested.
Nevertheless, it can be predicted a disadvantage of such construtions, i.e. they can serve only for polarizers and never can be used with acceptable efficiency for analyzers because they in principle can not be adapted geometrically to the divergent scattered neutron beam.

## III. BEAM MODULATION

The time-of-flight (TOF) method of monochromatization is the greatest advantage of a pulsed source. Experiments aiming the investigation phenomena belonging to the elastic scattering type of measurements are profiting from this potentiality.
Inelastic scattering needs the analysis of the energy change of the scattered neutrons. A smart solution of this task was performed at the ISIS facility. The implementation of a large array of analayzer crystals and detectors provided an instrument of high efficiency and good resolution (the IRIS facility), but at sensitively high cost.
Some times the financial conditions do not allow to build up any similarly sophisticated devices and cheaper and one has to look for simpler solutions.
In the following I should like to discuss an old and almost forgotten approach to the task of the increase of the efficiency of inelastic scattering experiments, i.e. the beam modulation technique using the method of pseudostatistical modulation of the incoming neutron beam.
This method utilizes for the modulation of the beam in time a function a(t). Then the observed number of the scattered neutrons at moment t

$$Z(t) = \int_0^t S(t-t')a(t')dt' + b(t) \tag{2}$$

Here S(t) is the scattering function characterizing the physical properties of the sample. If the function a(t) satisfies the condition

$$C_{aa}(\tau) = n\int_{-\infty}^{\infty} a(t)a(t-\tau)dt = c_1\delta(\tau) + c_2 \tag{3}$$

where $C_{aa}$ is the so called autocorrelation function, and the constants $c_1$ and $c_2$ depends on the duty cycle of the modulator, then the corresponding cross correlation function

$$K(\tau) = \int Z(t)a(t-\tau)dt = c_1S(\tau) + c_2\int_0^T S(\tau)d\tau + c_3 \tag{4}$$

here

$$c_3 = \frac{1}{T}\int_0^T a(t)dt \tag{5}$$

It is well known that the modulation function possesses some characteristic feature of the white noise. In practice, white noise can not be prepare, so its more or less perfect discrete approximation has to be used.
Let us to have a series of elements $a_i$ = either zero or to unit with relation

$$\sum_{i=0}^{N-1} a_i = m \tag{6}$$

and simultaneously

$$\sum_{i=0}^{N-1} a_{i+j} a_{i-k} = C_{aa}(j-k) \tag{7}$$

and

$$C_{aa}(j-k) = \begin{cases} m & \text{if } j-k = 0, \pm N, \pm 2N.. \\ K & \text{otherwise} \end{cases} \tag{8}$$

Or, in another way

$$C_{aa}(j-k) = m(1-c)\delta(j-k) + mc \tag{9}$$

where m - number of unit values in the series, N - is the length of the series and K = m(m-1)/(N-1), c = (m-1)/(N-1) is the duty cycle of the chosen series[6]. Then Eq.(2) can be transformed as

$$Z_n = \sum_{i=0}^{N-1} S_i a_{n-i} + b \tag{10}$$

After some algebraic transformation one gets

$$S_l = \frac{1}{(1-c)m} \sum_{k=1}^{n} (a_{k-l} - c) Z_k - \frac{b}{m} \tag{11}$$

This last expression shows how to obtain from the measured raw data the scattering function. Because of the large value of the duty cycle (almost 50%) the efficiency of the data collection can be characterized by a great gain value in comparison with the use e.g. a Fermi-chopper.
The pseudostatistical method can be applied to a pulsed source too. If the experimental setup is established as it is shown in the Figure 3. the scattered neutrons can be labeled by two indices: i - being proportional to the time elapsed between the neutron pulse and the moment of the registration of the given event, and k - which is the position of the pseudostatistical modulator at the instant of the detection of the scattered neutron.

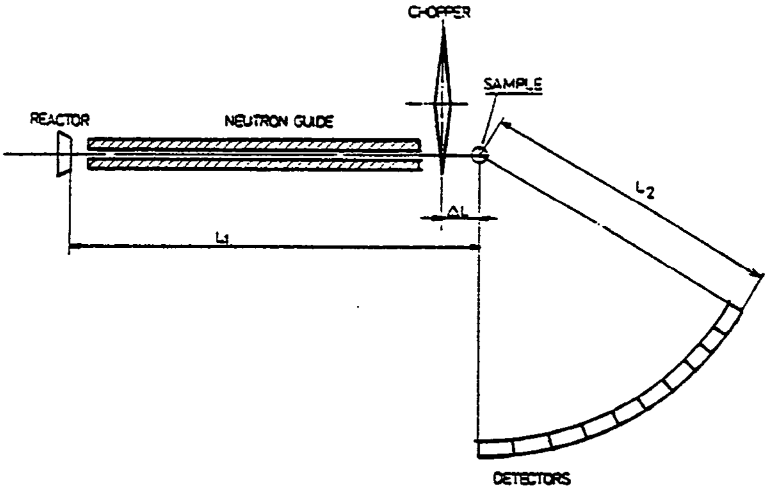

Figure 3. The schematical layout of a pseudostatistical modulation experiment at a pulsed source.

Then the registered spectrum has the form

$$Z_{ik} = \sum_{j=0}^{(N-1)} a_{(k-j)} S_{ij} + b \tag{12}$$

and for each i value the relation (10) is separately valid

$$S_{i\tau} = \frac{1}{m(1-c)} \sum_{k=0}^{(N-1)} (a_{(k-\tau)} Z_{ik} - \frac{b}{m} \tag{13}$$

By the help of the schemes given in Figures 4 and 5 it is easy to interpret the value $\tau$ as the time of flight over the flight path between the sample and the detector. Thus, from the simultaneous knowledge of the total time of flight and the value of $\tau$ the change of the kinetical energy of the scattered neutron can be evaluated.

The above described setup seems to be extremely effective for using it to carry out inelastic experiments at pulsed sources. However, a more detailed analysis of the error matrix makes it evident that the statistical accuracy of each $S_l$ points are equal, and is proportional to the total number of the collected data. From this statement it follows that if S(t) contains several peaks the area of the dominant (as usual elastic) peak determines the error bars. In the most real cases this effect makes hopeless to observe small inelastic effects, like phonons, etc. on the presence of elastic scattering pattern.

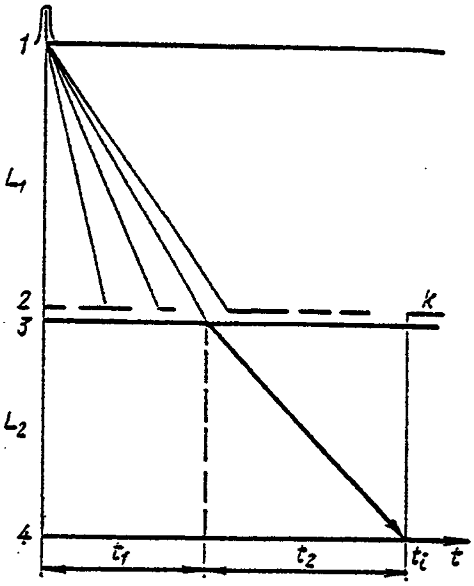

Figure 4. The time-of-flight versus flight path diagram of the pseudostatistical experiment at a pulsed source.

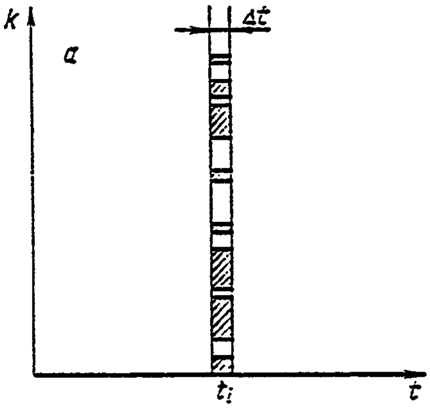

Figure 5a. The count distribution belonging to the position of the pseudostatistical modulator at instant $t_i$. t - is the total time-of-flight; k - is the pseudostatistical sequence. The segments marked with tilted lines correspond to channels filled with neutron count events, the white segments are the empty channels.

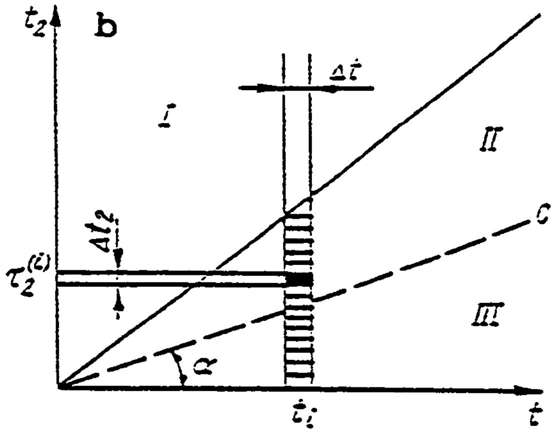

Figure 5b. Schematical view of a time-of-flight segment containing a sharp peak (the dark square) after the cross correlation procedure. c - the position of elastically scattered neutrons; I. - non-physical area; II. - area of the up-scattering; III. - area of the down-scattering;

The only exception would be the case when the physical information is connected with the most intensive peak. The quasi-elastic phenomena satisfy this condition.

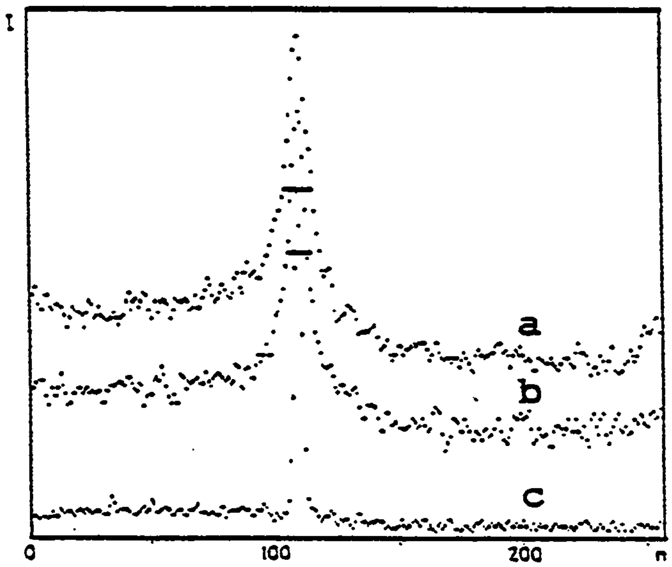

Figure 6. Three typical quasi-elastic spectra. a. - Pure water, b. - 2 mol TMU water solution, c. - sold EBBA liquid crystall. I - the scattered intensity in arbitrary units; n - the time-of-flight on the second flight path in channels (channel-width = 40 $\mu s$). The scattering angle $2\theta=72°$, the wavelength=4 Å.

In fact, in this case all information are concentrated to the most intense peak, which are set along the straight line on the $(t,\tau)$ plane and the quasi-elastic effects over a wide $(Q,\omega)$ range can be simultaneously studied.

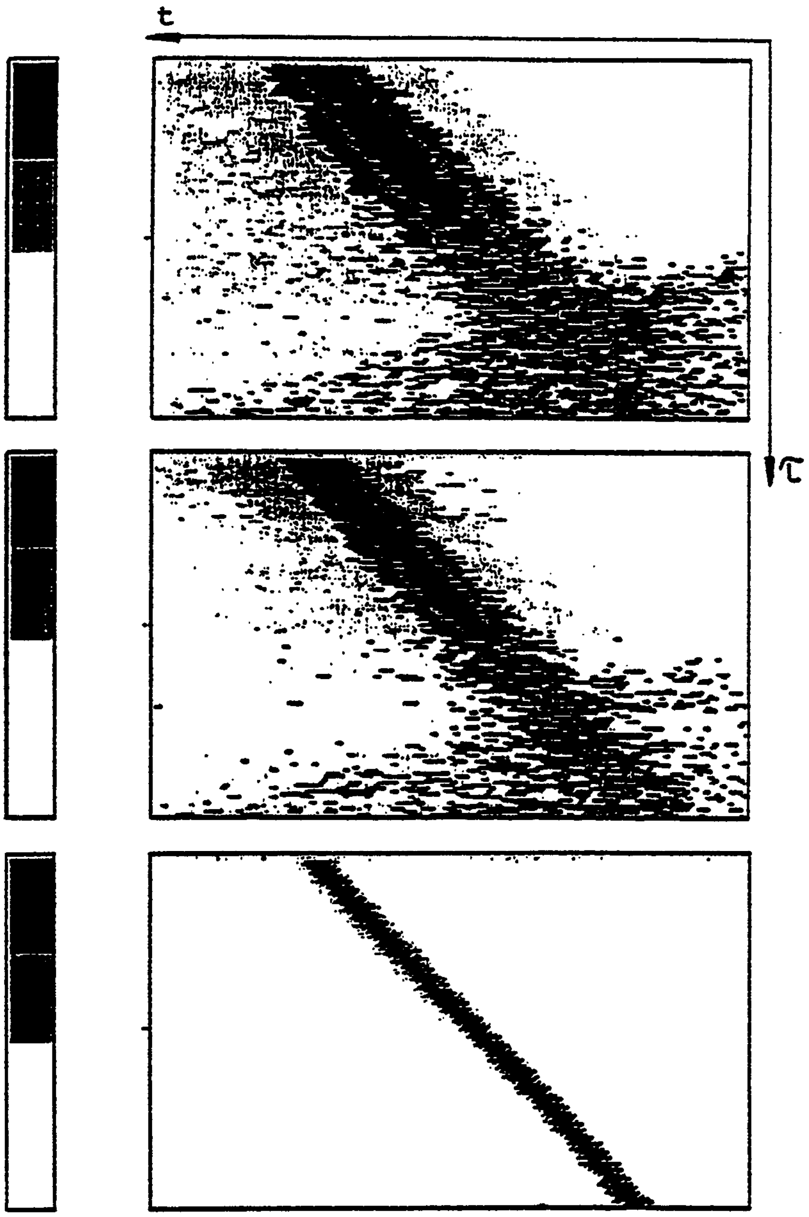

Figure 7. The $(t,\tau)$ intensity level diagrams: pure water (upper box); 2 mol TMU dissolved in water (middle box) and solid EBBA liquid crystal (lower box).

In order to demonstrate the power of the proposed method we carried out quasi-elastic investigation of tetramethylurea (TMU) water solution aiming to investigate the effect of dissolved TMU on the diffusion of the water molecules. The Figures 6 and 7 show the results of the experiment performed at the IBR-2 pulsed reactor.

The broadening of the quasi-elastic peaks takes it origin from the diffusion of the water. It was shown that the presence of TMU causes a considerable slowing down of the motion of the water molecules. The resolution function of the spectrometer was measured by using solid EBBA liquid crystal.

## CONCLUSIONS

In the present paper we made an attempt to draw attention to the importance of the use of wide band instruments. The strong limitation of the increase of the luminosity of the neutron sources can be overcame only by methods of more economical use of the emitted neutrons.

The use of supermirror neutron guides together with two-dimensional multidetectors is obvious.

There are promising endeavours to improve the efficiency of the polarization techniques. The $^3$He filters seems to be more promising than the mechanical polarizers provided their efficiency could be in the future acceptably improved. Otherwise, may be the combination of the two method seems to be realistic. That is, for the polarizer an ensemble of moving supermirror system will be used, whilst, for the analyzer the $^3$He filter has to be utilized.

The old and almost forgotten pseudostatistical modulation method can be revived since this method was proven as a very effective approach to quasi-elastic experiments.

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