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Polarized neutrons at pulsed sources in Dubna

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Abstract

The evolution of investigations with polarized neutrons using pulsed neutron sources with short and long pulses in Dubna is discussed. Some peculiarities of the use of long-pulse neutron sources are investigated.

Keywords: Polarized neutrons; Pulsed neutron sources; Magnetism; Surfaces; Multilayers

1. Introduction

On June 23, 1960 in Dubna of Moscow Region at the Joint Institute for Nuclear Research (JINR) a research reactor of the new type, the fast pulsed reactor (IBR) started to operate [1]. The main advantage of such a reactor is the possibility of generating an intense pulsed neutron flux at a small average power. In the last years before its shutdown in 2000 this reactor was operating without reactivity modulation as a photonuclear source with a multiplying target (booster) at a mean power of 10 kW, neutron density in the pulse 5×10^{14} n/cm^2/s, pulse width 4.5 μs for resonance neutrons and a repetition rate of 100 pps. In 1984 the new IBR-2 pulsed reactor with a rotating neutron reflector was commissioned in Dubna. It generates a record thermal neutron flux in a pulse of 10^{16} n/cm^2/s with a frequency of 5 Hz at a mean power of 2 MW and a thermal neutron pulse length of 320 μs. In the years from 2007 to 2010 the IBR-2 reactor will be upgraded and the new reactor IBR-2M will be operating for 20–25 years without major modification.

This paper is a brief review of investigations in nuclear and condensed matter physics with polarized neutrons at high flux pulsed sources with a large neutron pulse width and it contains an analysis of advantages and disadvantages of different experimental techniques. One of them, reflectometry with polarized neutrons, is discussed in greater detail.

2. Polarized neutrons investigations in Dubna

One of the brightest and most promising ideas in neutron physics born in Dubna is the use of polarized neutrons and polarized nuclei for investigation purposes. Beginning from 1961, on the

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initiative of F.L. Shapiro, there have been developed methods of neutron polarization using a dynamically polarized proton target. The polarization of nuclei in the target is achieved by its cooling to a temperature of the order of 10^{-2} K in a dilution refrigerator. Also, pioneering experiments to study super-fine interaction effects in compound states of nuclei were conducted [2]. At present, the methods are used to study the violation of fundamental symmetries in neutron resonances [3]. Such experiments are definitely to be carried out with pulsed neutron sources because they require spectral analysis of resonance neutrons. The preferable neutron pulse length is around 1 μs.

In 1964 Baryshevsky and Podgoretsky [4] predicted the effect of nuclear neutron precession (nuclear pseudomagnetism). There are three types of experiments to observe neutron precession: (1) pseudomagnetic resonance, (2) direct measurement of the angle of rotation of the neutron polarization vector and (3) paramagnetic neutron resonance of the first order. The first two experiments were performed by the Abragam group [5]. The experiment on paramagnetic neutron resonance of the first order predicted by Baryshevsky and Podgoretsky has not been performed yet. All experimental measurements of nuclear pseudomagnetism (nuclear neutron precession) were only carried out for thermal neutrons ($2<\lambda<4$ Å) far from resonance. It is theoretically predicted that close to neutron resonance precession changes its character considerably and its sign even changes. This has not been studied experimentally yet. To carry out this experiment, a pulsed source is preferable.

A general phenomenon at interfaces of magnetic media is spatial neutron beam splitting. This phenomenon was predicted and calculated in 1978 [6]. The relation to the problem of polarization of ultra-cold neutrons (UCN, discovered in Dubna in 1968) was pointed out by Ignatovich [6]. With reflectometry this effect was unexpectedly verified experimentally as noted in Ref. [7]. Experiments to observe the splitting were performed in FLNP of JINR at the IBR-2 reactor [8]. Since then several experiments of the kind have been performed as summarized in Ref. [9].

In 1980, Korneev proposed a spin-flipper with an extended working area for a polychromatic polarized neutron beam [10]. The working cross-section of such a spin-flipper has the form of a slit aligned to the neutron beam from a reflecting polarizer. The whole cross-section of the neutron beam is exploited resulting in an increase of luminosity.

Recently, it was shown that in the case of polarized neutrons, it is possible to register standing waves without using nuclear reactions [11]. Our investigations show that enhanced neutron standing waves in a particular spin state is generated in the area of the total reflection. Recently, it was shown that enhanced standing waves can be used to create a phase difference shift of neutron spin states in spin-echo devices [12].

3. Instrumentation with polarized neutrons at IBR-2

At present three instruments with polarized neutrons are in operation at the IBR-2 reactor.

Spectrometer REMUR, started to operate in 2002, is a new spectrometer with polarized neutrons which was constructed in the process of the modernization of the first spectrometer for condensed matter investigations with polarized neutrons at IBR-2, the spectrometer of polarized neutrons SPN [13]. The spectrometer REMUR is mostly used as a reflectometer but has an option for small-angle scattering experiments. A detailed description of the spectrometer REMUR will be published somewhere else. In the following section we will note some of its specific characteristics.

Reflectometer REFLEX was proposed in 1992 [14] as a reflectometry complex of two TOF reflectometers each of them reflecting two neutron beams simultaneously. At present one of these reflectometers, REFLEX-P, with polarized neutrons and a Korneev spin-flipper is operating [15]. This reflectometer has a high resolution due to a long flight path and adapted angular resolution. Tests to study inelastic processes in off-specular reflection have been performed on this spectrometer.

Spectrometer Kolkhida was built to carry out investigations of nuclear neutron precession at the IBR-2 pulsed reactor. It consists of an experimental complex of a polarized neutron spectrometer and a polarized nuclear target installation [16]. The Co (92%)–Fe (8%) single crystals are used for neutron polarization and polarization analysis. Nuclear polarization is done in a dilution cryostat equipped with a superconducting solenoid.

4. Reflectometry at IBR-2

Reflectometry with polarized neutrons has been intensively developing at the IBR-2 reactor since some time ago. Studies in scientific areas like superconducting films [17], thin magnetic layers [18] or magnetic multilayers [19] have been performed. New developments in off-specular scattering have also been undertaken and are discussed in Refs. [20–22].

Below we will discuss some essential features of reflectometry at a pulsed source.

- The high flux reactor IBR-2 with a peak thermal neutron flux of $10^{16}\,\mathrm{n/cm^2/s}$ and a low pulse repetition rate of 5 Hz provides best use of neutrons in the wide available wavelength band $1<\lambda<14$ Å with a high wavelength resolution of $\Delta\lambda/\lambda \approx 0.02$–$0.001$ is exploited. In future, cold sources will bring further improvement. At present, a wavelength and a time average flux of $2\times10^5\,\mathrm{n/cm^2/s}$ and background count rate of 0.1 n/cm/s are obtained with linear-sensitive detector at sample position.
- The polarization efficiency achieved on REMUR is shown in Fig. 1 (curve 1). A focusing stack-type analyser (Fig. 1, curve 2) and resonant spin-flippers (with an efficiency better than 99%) with a broad active cross-section ($50\,\mathrm{cm^2}$) are utilized in order to provide polarization analysis over the full off-specular angular range.
- The resolution in momentum transfer q is a combination of the resolution of the wavelength and the angular resolution and is, in a simplified presentation, given as

$$\left(\frac{\Delta q}{q}\right)^2 = \left(\frac{\Delta\lambda}{\lambda}\right)^2 + \left(\frac{\Delta\theta}{\theta}\right)^2,$$

where $\Delta\theta/\theta$ is the generalized angular resolution in relative units. The electronic time resolution of the reflectometer τ, which has to be added to the wavelength resolution, is small compared to the pulse length of the IBR-2 $\Delta t = 320\,\mu\mathrm{s}$ and is neglected: $\tau \ll \Delta t \approx T\Delta\lambda/\lambda$, where T is the flight time of neutrons from reactor to detector corresponding to the distance L. On REMUR we have $L = 34$ m and as a result, for $\lambda = 14$ Å, the wavelength resolution is $(\Delta\lambda/\lambda)_{\min} \approx 1\times10^{-3}$.

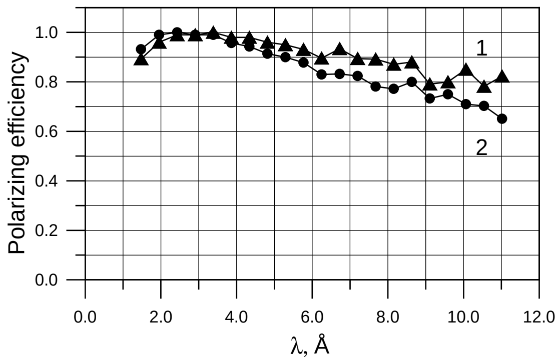

Fig. 1. Polarising efficiency of polarizer (curve 1) and analyser (curve 2) as a function of neutron wavelength for spectrometer REMUR.

The angular resolution $\Delta\theta$ is determined by the slit system forming the beam, the foot print of the sample and the resolution of the detector. In the most frequently used set-up an angular resolution of $\Delta\theta/\theta \sim 0.03$ is used to match the wavelength resolution for 1 Å (using a scattering angle θ of ~ 10 mrad).

Thus, layered structures with a total thickness of about 3000 Å can be investigated with a standard resolution set-up. Measuring at a second position of the scattering angle θ allows the investigation of thin-layered structures or thin-layered structures within a thicker film.

- It should be noted that in the time-of-flight set-up the beam geometry and the orientation of the sample within the beam are fixed except for the second scattering angle measuring position. So, shielding can be optimized and no corrections due to varying illumination of the sample are necessary.

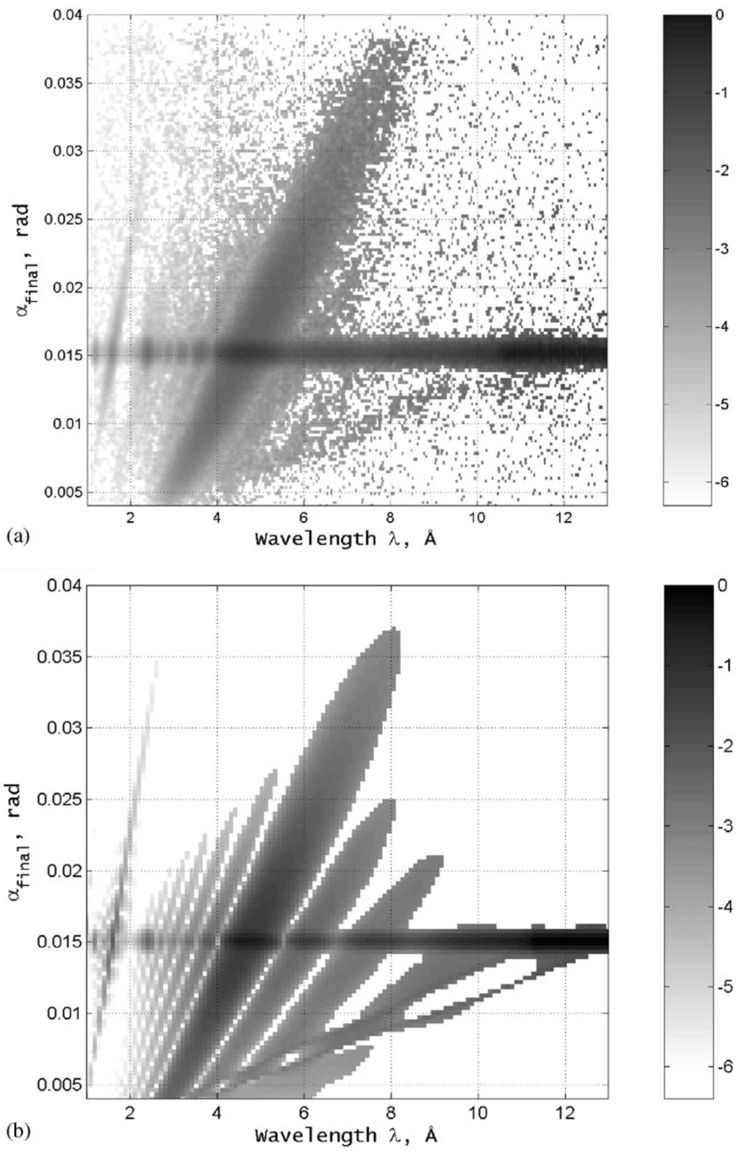

Fig. 2. (a) Intensity map of specular and off-specular scattered neutrons (spin-down) from the Fe/Cr multilayer at $H = 0.428\,\mathrm{kG}$ as a function of λ and α_{final}, the neutron wavelength and outgoing scattering angles, respectively; incident angle $\alpha_{\mathrm{i}} = 15\,\mathrm{mrad}$. The strong intensity along the horizontal line at $\alpha_{\mathrm{i}} = 15\,\mathrm{mrad}$ corresponds to the specular reflection. Off-specular scattering in the form of 1/2 and 3/2 order Bragg sheets crosses the specular line around 4.5 and 1Å, respectively, and is determined by the domain structure of the multilayer. Yoneda scattering appears at the specular line at the critical wavelength $\lambda = 12.5\,\text{Å}$ and interferes with the Bragg sheet scattering for smaller wavelengths. Off-specular scattering through the total thickness oscillations arises to conformal interfacial roughness; (b) result of the supermatrix calculation with the model of noncollinear domains [21].

- A linear position-sensitive detector is used on REMUR for off-specular scattering studies. Off-specular scattering can be recorded around the specular line up to the horizon and further to the direct beam [20–22].

Off-specular scattering from a magnetic Fe/Cr multilayer film is shown in Fig. 2 as an example of studies performed on REMUR (see for details Ref. [21]). The presentation of the measured intensity as a function of the outgoing angle and wavelength demonstrates clearly that the direct beam is separated from the specularly reflected beam on the detector and that the detector can be even positioned aside the direct beam. In this geometry, overloading of the detector due to too high neutron flux of the direct beam can be avoided. This is a unique advantage of the TOF-technique of particular necessity in the region of small momentum transfers around critical edges.

However, more intensity is needed when finer effects of interference between the various types of off-specular scattering, e.g. Bragg sheet scattering and roughness scattering, appear near the horizons but also within the full off-specular plane. New effects are predictable, which will also allow describing less model-like samples in detail. Having a better resolution will be necessary in the vicinity of the reflectivity line in order to study the off-specular scattering on larger objects. Thus, higher intensity and better resolution are needed in future. A Larmor precession reflectometer with Fourier analysis will be constructed to meet these requirements [23].

5. Conclusion

In conclusion it should be said that the pulsed reactors of Dubna provide us with unique experience of using pulsed neutron sources with a medium pulse length. In particular, the IBR-2 reactor has characteristics close to the long-pulse target of ESS in project. A pulse length of 320 μs is compatible with good resolution for reflectometry and small-angle scattering experiments and moderate resolution for diffractometry and inelastic scattering. At the same time, the use of advanced techniques allows achieving of resolution equal to that in short-pulse sources for diffractometry as well. The high-resolution Fourier diffractometer at the IBR-2 reactor has the spatial resolution $\Delta d/d = 5 \times 10^{-4}$ with a record neutron flux at sample position [24]. Further improvements are expected with the use of cold sources and the implementation of Larmor precession devices for reflectometry [23] and small-angle scattering [25].

The experience of the exploitation of the booster is also interesting for future neutron sources as the use of multiplying targets increases the neutron flux by a factor of 10–100 with the same accelerator.

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