

High-precision neutron spectrometry, using diffraction focusing. Test experiment

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Abstract. The effect of double-crystal neutron focusing, using Laue diffraction in large perfect crystals was studied. The observed effect allows reach the angular resolution better than $0.03''$, that is $\sim 10^{-2}$ of the Bragg reflection width. This fact makes it possible to create a new ultra-precise method for neutron spectrometry combining the spin-echo small angle neutron scattering with Laue diffraction.

1. Introduction

This work was motivated by the preparation of new experiment [1] to verify the electrical neutrality of the neutron by a new method, based on spin interferometry technique SESANS (spin-echo small angle neutron scattering), see [2]. The principle of such interferometer is described in [1], where it is shown that this technique allows, in general, to improve the modern precision of the neutron electric charge measurement [3]. However, for this purpose high magnetic fields, large neutron wavelengths of a few tens angstroms, and the several meters dimensions of the setup are required [1]. That makes practically unreachible the requirements to uniformity and stability of magnetic fields. It should be noticed that increasing the accuracy of the neutron electric charge measurements is an extremely difficult task. The attempts taken over the last 20 years trying to improve the constraint on the neutron electric charge, using, for example, ultracold neutrons [4], have not given any results.

2. Neutron diffraction

As shown in [1] the method can be significantly improved using the neutron Laue diffraction in a perfect crystal. The idea is as follows.

There is a well-known effect of diffraction inhancement when a small variation of the incident neutron beam direction within Bragg width (a few arc seconds) results in a significant change within the Bragg angle (a few tens degrees) of the neutron flux density direction inside the crystal (see. Fig.1).

The direction of the neutron flux density in the crystal can be described by the angle Ω (measured from the crysallographic plane, i.e. from the direction of neutron flux density along



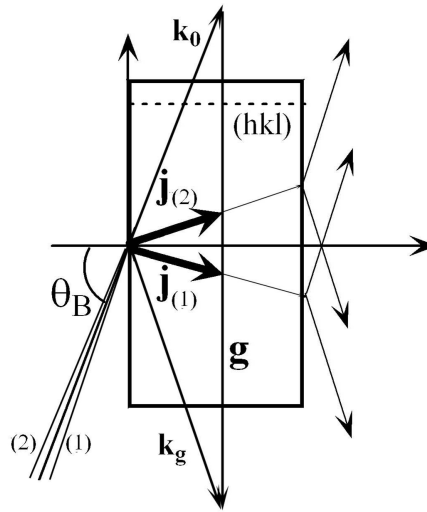


Figure 1. Fig. 1. Symmetric scheme of the neutron Laue diffraction in a perfect crystal. $\mathbf{j}_{(1)}$ and $\mathbf{j}_{(2)}$ are neutron flux density in a crystal for the two directions of the incident beam, slightly different within the Bragg (Darwin) width, \mathbf{g} – reciprocal lattice vector.

the plane for exact Bragg condition) equal to

$$\Omega = \Delta\theta \cdot \frac{E}{v_g} \cdot 2 \sin^2 \theta_B, \quad (1)$$

where θ_B is the Bragg angle, $\Delta\theta$ is the deviation from the exact Bragg condition, E is the neutron energy and v_g is the amplitude of g -harmonic of the periodic neutron-crystal interaction potential. This effect was used in the measurement of neutron refraction by the prism in the double-crystal diffraction pattern [5]. A similar effect for a neutron flux density deflection can be observed also due to variation of the neutron energy, because angular deviation from the Bragg condition directly depends on the change in neutron energy:

$$\Delta\theta = \frac{\Delta E}{2E} \tan \theta_B, \quad (2)$$

where θ_B is the Bragg angle, ΔE is the the change of neutron energy. This feature was used for measurements of neutron refraction in the magnetic field [6].

The two-crystal scheme of Laue diffraction with two crystals placed in magnetic fields of opposite directions was considered in [1]. In this scheme, the crystals are used as “amplifiers” of a neutron refraction in the magnetic field. So the magnitude of the effect caused by the influence of an external force acting on a neutron in such scheme is about $K_g = E/v_g$ times greater than that for standard techniques SESANS. Value K_g for the cold neutron diffraction are $\sim 10^5$, because $E \sim 10^{-2}$ eV and $v_g \sim 10^{-7}$ eV.

However, it is more convenient to use the scheme of experiment based on the effect of the diffraction focusing in Laue diffraction [7]. The experimental scheme is shown in Fig. 2. In such geometry a part of the diffracted beam will be focused on the exit surface of the second crystal [8] so the intensity distribution as well as the neutron polarization distribution at the entrance surface of the first crystal will be reproduced at the exit surface of the second crystal.

We can choose the positions of the coils in such a way (Fig. 2) to make the angles of the neutron spin rotation in the coil K1 equal to those in the coil K2, but those angles will have opposite signs for any neutron trajectory, and so the total angle of rotation will be zero. Calculations of the coils for the geometry under consideration were performed in [9]. The presence of external force acting on a neutron between the crystals will lead to the change of neutron direction and to the focus shift [8]. Due to such a shift a neutron spin will turn by the angle ϕ_x , because some difference arises of the neutron path lengths in opposite magnetic fields. It is easy to show that this angle, corresponding to the focus shift by the value x , will be equal to

$$\phi_x = \frac{2\mu B}{\hbar} \cdot \frac{2x \tan \theta_0}{v}, \quad (3)$$

where v is the neutron velocity, B is the value of magnetic fields in the coils K1 and K2, θ_0 is the angle between the direction of neutron velocity and the normal to the coil boundary, Fig. 2.

If a neutron changes its direction in the region (1), Fig. 2, by the angle α , the shift of the neutron beam spot at the exit surface of the second crystal will be equal to

$$x_\alpha = \frac{\alpha}{\gamma_B} L \tan \theta_B = 2\alpha L \sin^2 \theta_B \frac{E}{v_g}, \quad (4)$$

where γ_B is the Bragg width, L is the crystal thickness, θ_B is the Bragg angle. The action of an external force F_n at a distance l will change the direction of the neutron velocity by the angle $\alpha = F_n l / (2E)$ and the shift of the beam focus spot at the exit of the second crystal will be

$$x_F = \frac{F_n l}{v_g} L \sin^2 \theta_B. \quad (5)$$

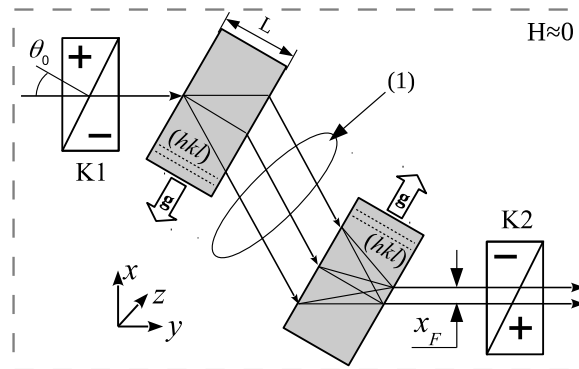


Figure 2. Fig. 2. The idea of the experiment using neutron Laue diffraction. K1, K2 are the coils with the magnetic field B , the signs “+” and “−” correspond to the directions of the magnetic field

The main parameter, which limits the angular resolution of the method, is the spot size of a spatially focused neutron beam. The beam spreading over the surface of the second crystal by the value of Δx will lead to the spreading of angles of neutron spin rotation after the passage the coil K2 by the value of $\Delta \phi$, see (3). To observe the spin rotation effect the condition $\Delta \phi < 2\pi$ should be satisfied.

Physical limit of spatial resolution in the double-crystal diffraction pattern is determined by the value [7]:

$$x_w = \frac{\xi_g \tan \theta_B}{2\pi} = \frac{V}{4F_g d} \quad (6)$$

where $\xi_g = \pi V / (2F_g d \tan \theta_B)$ is the extinction length, V is the volume of the crystal unit cell, d is the interplanar spacings, F_g is the structure factor. The values of x_w for cold neutron diffraction are usually of $(10 - 50)\mu\text{m}$. For instance, for the (220) plane of silicon $x_w = 26\mu\text{m}$. Such spatial resolution allows to use the magnetic fields up to 1 kGs. As a result, for the silicon crystals with the plane (220) and 10 cm thicknesses, value of the electric field $E_0 = 100\text{ kV/cm}$ in the area (1), see. Fig. 2, and $l = 1\text{ m}$, the neutron spin rotation angle (due to presence of the neutron electric charge e_n) will be, see. (3) and (5)

$$\phi_e \simeq 1 \cdot 10^{18} e_n \quad (7)$$

for the Bragg angle $\theta_B = 70^\circ$, e_n is in units of electron charge. Thus, for accuracy to measure the angle of the neutron spin rotation at the level of $\sigma(\phi_e) \sim 10^{-5}$, we can expect the sensitivity to measure the neutron charge at the level of $\sim 10^{-23}$ of the electron charge, which is two orders of magnitude better than the modern constraint [3].

3. Experiment

As the first stage of this project we study the effect of diffraction focusing in double-crystal scheme of Laue diffraction. The experiment was carried out at the reactor WWR-M (PNPI NRC KI, Gatchina). We investigated Laue diffraction in crystals of silicon with the sizes $110 \times 110 \times 100\text{ mm}^3$ and the working crystallographic plane (220) ($d = 1.92\text{ \AA}$, $F_g = 32 \cdot 10^{-13}\text{ cm}$, $v_g = 5 \cdot 10^{-8}\text{ eV}$). Scheme of the experiment is shown in Fig. 3. Crystal silicon together with the rotating platform placed in an thermostatic volume. The stability of the crystal temperature was 10^{-2} K/day . The distance between the crystals were fixed. Therefore, we had two spots from the direct and forward beam, Fig. 3. An example of the experimentally measured intensity distribution over the exit face of the second crystal is shown in Fig. 4.

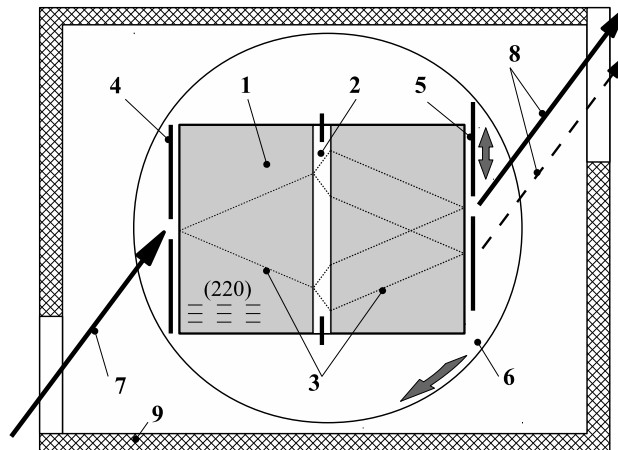


Figure 3. Fig. 3. Experimental scheme. 1 is silicon single crystal, 2 is the gap between the crystals with an additional collimating slit, 3 is example of neutron trajectory in the crystal, 4 is the entrance slit, 5 is the movable exit slit, 6 is the turning table, 7, 8 are incident and outgoing neutron beams, 9 is the thermostat

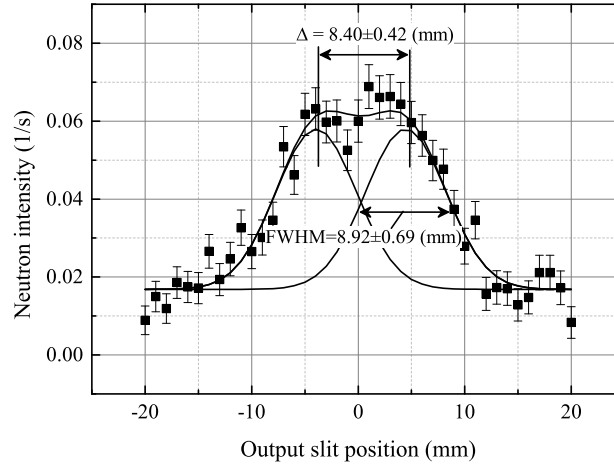


Figure 4. Fig. 4. The intensity dependence on the exit slit position. The sizes of the entrance and exit slits were 4 mm, $\theta_B = 68^\circ$. The aperture of the beam in the region (2), see Fig. 3 is equal to 110 mm.

The splitting into two components coincided with the calculated value. Spatial line width was 8.9 mm, which was slightly more than the expected value (~ 6 mm). Apparently, this is due to imperfection of the used crystal, because the reduction of the beam aperture between the crystals, see area (2) in Fig. 3, reduces the width of the line, see Fig. 5. The estimated own spatial resolution obtained from Fig. 5 was $W_m < 3$. Unfortunately, the low luminosity of the experiment allows us to give only an upper limit for the W_m .

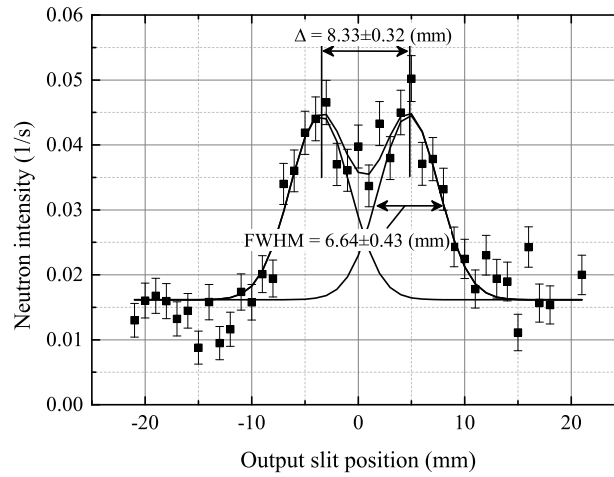


Figure 5. Fig. 5. The intensity dependence on the output slit position. The sizes of the entrance and exit slits were 4 mm, $\theta_B = 68^\circ$. The aperture of the beam in the region (2), see Fig. 3 is equal to 56 mm.

In the present experiment the value of the beam displacement along exit surface (4) is determined by angular deviation of the neutron in the following way:

$$x_\alpha = 2 \cdot 10^7 \alpha \text{ [mm]}. \quad (8)$$

So, the spatial resolution $W_m < 3$ mm corresponds to the angular one $\alpha_W < 1.5 \cdot 10^{-7} = 0.03''$.

4. Conclusion

The effect of double-crystal neutron focusing was studied. The possibility to create a setup with the spatial resolution better than 3 mm, which corresponds to an angular resolution of $0.03''$ was demonstrated. Numerical calculations show that the statistical sensitivity to measure a neutron electric charge can be $\sigma(e_n) \simeq 1.5 \cdot 10^{-21}$ of the electron charge for 100 days of statistics accumulation for the value of the electric field $E_0 = 100 \text{ kV/cm}$ and the cold neutron fluxes achievable at high flux reactors, such as HFR ILL (Grenoble, France), or PIK reactor under construction (Gatchina, Russia). Further improvement may give approximately two orders better sensitivity, because in principle the spatial resolution of the proposed experimental scheme can be about two orders better, see. (6). More detailed experimental test at the high flux cold neutron beam should be carried out to answer the question about the experimentally achievable sensitivity.

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