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Neutron Interferometry in NPI Řež

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Recently a new non-dispersive phase difference method was developed for the high accuracy measurement of the neutron coherent scattering length which achieves an accuracy in the determination of b_c of even better than 10^{-4}, i.e. at the level of 10^{-5}. This method was used for the high accuracy measurement of the coherent scattering length of Si. The experiment has been done on the neutron interferometer installed at 10 MW reactor in Řež. Our results are in a very good agreement with the results obtained from the measurements carried out at the HMI Berlin and at NIST Gaithersburg.

KEYWORDS: neutron interferometry, scattering length

§1. Introduction

The neutron interferometric facility installed at the beam line HC8 at 10 MW reactor in Řež is a non-dispersive setting of a double monochromator and an interferometer crystal placed on a vibroisolated foundation. The interferometer crystal (conventional LLL-type) manufactured at the Atominstitut Wienna features 70% interference pattern visibility for the 220 reflection (neutrons wavelength of 0.1 nm). A new sample holder permits to position, rotate in a horizontal plane and tilt the sample in both beams inside the interferometer (Fig. 1). This instrument was used for the high accuracy measurement of the coherent scattering length of Si. The phase acquired by the transmission of the neutron wave through a sample can be measured in a neutron interferometry experiment with an accuracy of about 10^{-4} or even better. However, looking in the well-known tables of neutron scattering lengths[1)] one should note that the most accurate up to present values (the accuracy of about 0.03%) have been determined either by the dynamical diffraction (Pendellösung oscillations) method for silicon[2)] or by the gravitational spectrometer for natural Pb and Bi,[3)] but not by a neutron interferometry method. The main obstacle that has been met by neutron interferometry is the dispersion problem.[4–7)] The phase shift acquired by a neutron wave that propagates through a sample inserted in the dispersive geometry (see Fig. 2) is proportional to the neutron wavelength λ: $\Phi = Nb_c\lambda t_{eff}$, where N is the atom density in the sample and t_{eff} is the effective thickness of the sample traversed by the neutron beam. Therefore, one must know the precise value of the mean wavelength λ, which then defines the accuracy of the determination of b_c from the measured value of Φ. As a solution of this problem, the non-dispersive sample geometry was proposed,[6,7)] where the sample was installed parallel to the lattice planes of the interferometer crystal (see Fig. 2). In this case the effective thickness $t_{eff} = t_0/\sin\theta_B$, where t_0 is the thickness of the sample, and using the Bragg law $\lambda = 2d\sin\theta_B$ (θ_B is the Bragg angle, d - the lattice spacing) one obtains $\Phi = 2Ndb_ct_0$

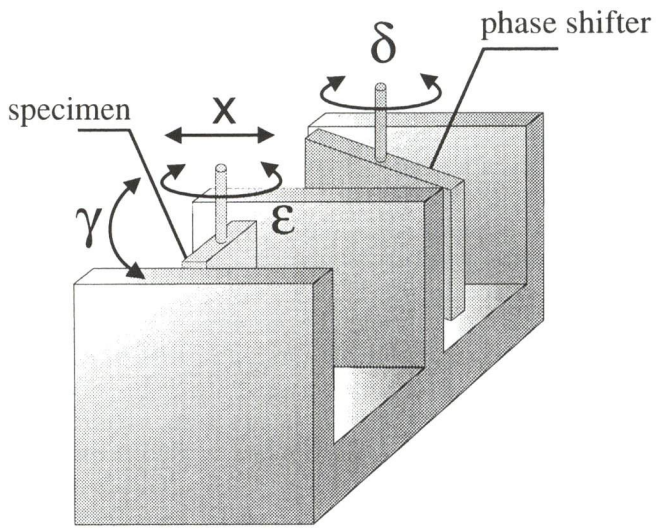

Fig. 1. Neutron interferometer in NPI Řež.

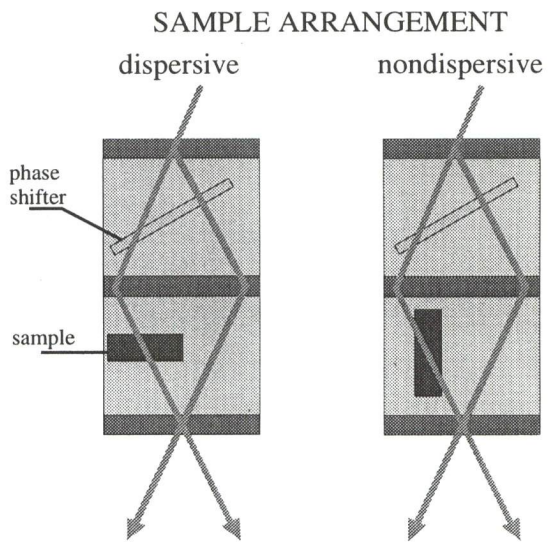

Fig. 2. Dispersive and non-dispersive setting of the sample in a neutron interferometer.

so that the phase shift is λ-independent. However, now the very precise orientation of the sample relative the crystal planes of the interferometer is required. To overcome this obstacle a new non-dispersive phase difference method was developed[8] which achieves an accuracy in the determination of b_c of even better than 10^{-4}, i.e. at the level of 10^{-5}. This method was used for the high accuracy measurement of the coherent scattering length of Si.[9]

§2. Non-Dispersive Measurement of Neutron Scattering Length

Let us consider a sample that is placed in one of the beams of the interferometer, so that to be nearly parallel to crystal planes of the interferometer crystal (Fig. 3). For a small declination angle ε of the surface of the sample from the Bragg planes of the crystal and for the sample placed in beam I and II[8] the effective thickness $t_{eff} = t_0/\sin(\Theta_B \pm \varepsilon)$ and acquired phase shifts are,

$$\Phi_I = 2dNb_c t_0 \frac{\sin(\theta_B)}{\sin(\theta_B + \varepsilon)} \tag{2.1}$$

$$\Phi_{II} = -2dNb_c t_0 \frac{\sin(\theta_B)}{\sin(\theta_B - \varepsilon)} \tag{2.2}$$

Expanding these expressions for a small $\varepsilon \ll 1$, one obtains:

$$\Phi_I = 2Nb_c t_0 \{1 - \varepsilon\cot(\theta_B) + \frac{\varepsilon^2}{2}[1 + 2\cot^2(\theta_B)]\} \tag{2.3}$$

$$\Phi_{II} = -2Nb_c t_0 \{1 + \varepsilon\cot(\theta_B) + \frac{\varepsilon^2}{2}[1 + 2\cot^2(\theta_B)]\} \tag{2.4}$$

The basic idea of the proposed method is not to adjust the sample relative to the interferometer trying to get $\varepsilon \approx 0$, but to record the interference patterns for both positions of the sample in the interferometer for a set of positive and negative values of ε. Then from eqs. 2.3 and 2.4 one obtains:

$$\Phi_I - \Phi_{II} = 2dNb_c t_0 \{2 + \varepsilon^2[1 + 2\cot^2(\theta_B)]\} \tag{2.5}$$

$$\Phi_I + \Phi_{II} = -4dNb_c t_0 \varepsilon\cot(\theta_B) \tag{2.6}$$

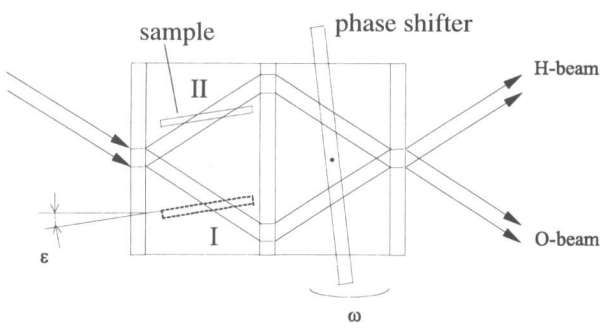

Fig. 3. Experimental arrangement.

Fitting the dependence of the phase difference $\Phi_{II} - \Phi_I$ to a parabolic function of ε (eq. 2.5), one can define the minimum of this parabola, which corresponds to the parallel position of the sample and crystal planes. Then the neutron scattering length, b_c, can be calculated by the value of $(\Phi_I - \Phi_{II})_{min}$ as

$$b_c = \frac{(\Phi_I - \Phi_{II})_{min}}{4dNt_0} \tag{2.7}$$

and does not depend on the wavelength λ.

Thus, an aim of the experiment is to determine phase shifts Φ_I and Φ_{II}, introduced by a sample placed in the beams I and II of the interferometer, for different angles ε between the sample and crystal planes of the interferometer. However, the neutron interferometry method does not allow the direct detection of the total phases $\Phi_I(\Phi_{II})$, but only their fractions $\varphi_I(\varphi_{II})$ with $0 < \varphi_{I,II} < 2$, so that $\Phi_I = \varphi_I + 2\pi n_1$, $\Phi_{II} = -\varphi_{II} - 2\pi n_2$, with n_1, n_2 integers. Fitting the experimental data to a sinus-like theoretical dependence one can determine phase shifts φ_I and φ_{II}, measured for different angles δ of the surface of the sample in respect to the interferometer crystal (here δ is a physically measured value in contrast to ε which is a model one). Carrying out such measurements with a small step for δ, which allows to follow 2π multiple variations of $\Phi_I(\Phi_{II})$, one can define $\Phi_I - \Phi_{II} = f(\delta)$. Then fitting this function to δ^2 (eq. 2.5), we can determine the value of δ_{min} ($\varepsilon = 0$), which corresponds to the parallel alignment of the surface of the sample and the crystal planes of the interferometer. Because in this case phase shifts introduced in both of beams of the interferometer are equal (so that $\Phi_I = |\Phi_{II}|$ and $n_1 = n_2$), we obtain:

$$b_c = \frac{(\varphi_I - \varphi_{II})_{min} + 4\pi n_1}{4dNt_0} \tag{2.8}$$

Therefore, in order to determine b_c from eq. 2.8 one should define the number of integer oscillations n_1 for the parallel position of the sample and crystal planes. This can be done using a knowledge of b_c from preliminary low accuracy experiments by a method described in ref.10.

§3. Experiment

The experiment has been done on the neutron interferometer installed at the beam line HC8 at 10 MW reactor in Řež. The measurement of the coherent scattering length of Si has been performed by a non-dispersive phase difference method described above. In this method interference patterns are measured by rotating the phase shifter for three positions of the sample - outside the interferometer and in the beams I and II (Fig. 4) in dependence on the declination of the surface of the sample from the Bragg planes of the interferometer crystal. As can be seen from Fig. 5 the phase shift produced by the sample inserted in one of the beams of the interferometer depends nearly linearly on the angle of misalignment according with eqs. 2.3 and 2.4. The difference between the phase shifts produced by successively inserting the sample in beams I and II, respectively only weakly depends on the declination angle in the vicinity

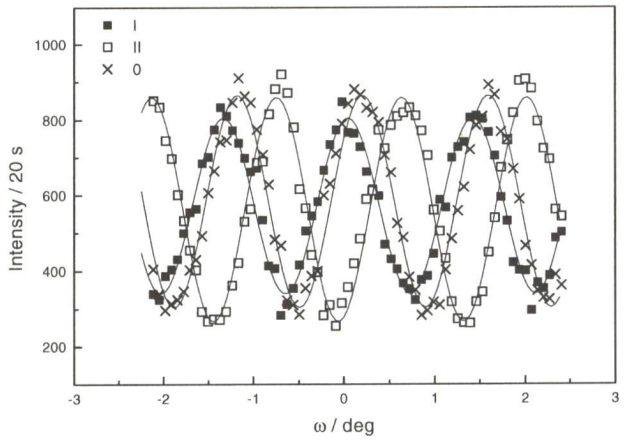

Fig. 4. Interferograms taken at the three positions of the sample - outside the interferometer, in the beams I and II.

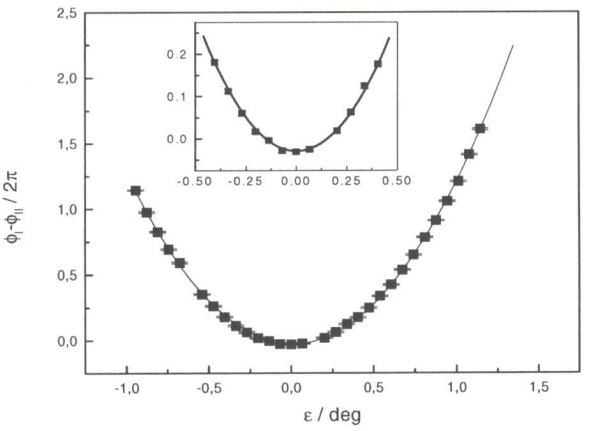

Fig. 6. Phase differences $\Phi_I - \Phi_{II}$ for different angular positions of the sample. Solid line is the fit according to eq. 2.5.

of the vertex of the parabola (Fig. 6). From a quadratic fit according eq. 2.5 one can determine the phase shift difference modulo 2π corresponding to the minimum of this curve. The total phase shift can be determine by procedure described in ref.10. In our case of a Si plate of a thickness of 3.0055(1) mm we obtained the value of 477.3392(75) *rad.* Using the crystal lattice constant of silicon $a = 0.543102\ nm$ and a correction factor due to the displacement of air by the sample we obtain the value for $b_c = 4.1511(2)\ fm$.

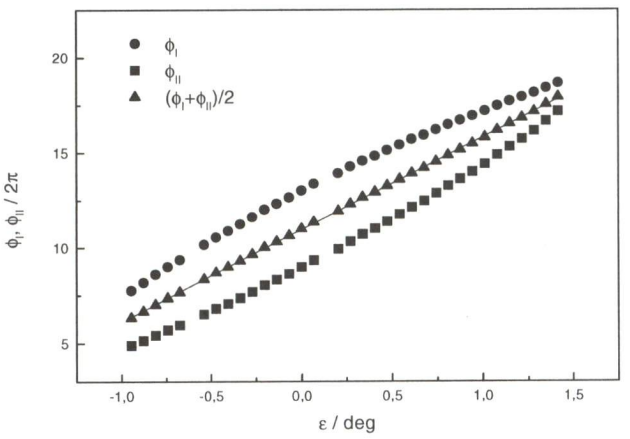

Fig. 5. Phases Φ_I and Φ_{II} and sum of the phases $\Phi_I + \Phi_{II}$ for different angular positions of the sample.

§4. Summary

From the Table I it is evident that the result of this experiment is in a very good agreement with the results obtained from the measurements carried out at the HMI Berlin and at NIST Gaithersburg.[9] It proves that phase shifts can be measured at our instrument with a relative uncertainty of 0.002%.

TableI. Precise measurements of coherent scattering length of Si at different facilities.

Facility	wavelength (nm)	thickness (mm)	b (fm)
NIST	0.27	3.00527(15)	4.15041(21)
HMI	0.198	3.00527(15)	4.15102(21)
NPI	0.106	3.0055(1)	4.1511(2)

Acknowledgements

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