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Neutron Microscope with Phase Contrast

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The usual phase-contrast imaging methods demand that the object be illuminated by spatial coherent waves, which involves a significant decrease in luminosity. But, neutron phase contrast imaging may also be achieved by the so called Neutron Optical Spin Rotation effect in which spatial coherency of the initial wave is not needed. A simple neutron microscope based on this idea is proposed to demonstrate the possibility of phase contrast imaging with UCN.

KEYWORDS: ultracold neutrons, neutron microscope, phase contrast

§.1. Introduction

Remarkable progress in neutron microscope engineering and realization has been achieved in the last decade. This is mainly related to the creation of intense sources of ultracold neutrons (UCN). Such neutrons display an unique capability for reflecting specularly from the surface of many materials at any incidence angle. It is essential that the neutron velocity should be lower than the limiting velocity $V_{\lim}$ for the material. So the use of UCN makes it possible to design mirror focusing systems as for usual optics. The principal distinction is the influence of gravity on the neutrons passing through the optical system. This influence involves special aberrations appearing in a neutron image. This problem has now been mostly solved.[1-3] Neutron imaging of special "white and black" objects has been demonstrated in several experiments. However, the most "realistic" objects must be more or less transparent to neutrons with only the phase structure of transmitted waves changing at interaction with the object. This means that solution of the problem of phase contrast imaging is the critical point for the future of neutron microscopy.

§.2. Neutron-matter interaction and the origin of the contrast

Unlike for light and electron optics, neutron wave propagation in material is defined predominantly by the strong neutron-nucleus interaction. As this takes place, the neutron capture and up-scattering processes lead to neutron beam attenuation while passing through the object. This forms a basis for object structure visualization. But the possibility exists in neutron microscopy to obtain a contrast with different origin. This contrast is related to the distinction between the limiting velocities for different materials. So in this case, a special spectral cut-off contrast is realized.[2]

Besides, as in light optics, neutron wave propagation in a material can be described by using an index of refraction. In the absence of magnetic interaction, it is given by the formula:

$$n^2 = 1 - \frac{\lambda^2}{\pi}\sum \rho_i b_i \qquad (1)$$

where λ is the incident neutron wavelength, ρ_i is the i-th type of nucleus density, and b_i is the coherent scattering length for bound atoms of type "I". So it is possible to try to get a phase contrast like in usual optics. But the usual phase-contrast methods demand that the object be illuminated by spatial coherent waves, which involves a significant decrease in luminosity. That is why the possibility of realizing the phase contrast method in neutron microscopy was initially conceived as a distant prospect.

But as was proposed previously, neutron phase contrast imaging may also be realized using the so-called Neutron Optical Spin Rotation effect.[4,5] Polarized neutrons must be used for the realization of this idea but spatial coherency of the initial wave is not needed. This concept has the advantage of higher luminosity and makes it possible to realize phase contrast at the present time in using modern UCN sources.

§.3. Phase contrast and Neutron Optical Spin Rotation

To realize the idea of phase-contrast imaging, it is needed to prepare a polarized neutron beam with spins to be oriented perpendicular to the magnetic field B. For a static magnetic field, the neutron wave function has the form:

$$\Psi = \frac{1}{\sqrt{2}}\begin{pmatrix} e^{ik_+x} \\ e^{ik_-x} \end{pmatrix}; k_\pm = k\left(1 \mp \frac{\mu B}{E}\right)^{1/2} \qquad (2)$$

Here μ is the neutron magnetic moment, k and E are wave number and kinetic energy of the incident neutron, respectively. Such a transversely polarized neutron beam may be considered as a coherent superposition of states with spin projections parallel and antiparallel to the field. The wave numbers of these two states are different and their interference in space leads to a Larmor precession pattern.[6] The precession angle is defined by the phase difference between up and down components of the spinor (Eq.(2)). An additional phase difference will arise when the neutron passes a sample. This effect results from the difference between k_+ and k_- and wave dispersion in matter. It was called the Neutron Optical Spin Rotation (NOSR). The value of the angle of NOSR is obtained as:

$$\varphi = \frac{\mu B}{E} \cdot \frac{1}{n} \cdot kd(1-n). \qquad (3)$$

Eq.(3) contains the factor

$$\Phi = kd(1-n) \tag{4}$$

which has the same form as the phase difference arising between coherent beams in the usual scheme of a neutron interferometer. Such a phase difference Φ also provides a basis for phase-contrast imaging in an optical microscope with the object illuminated by spatial coherent waves. So the NOSR effect causes the full precession angle φ to be different for a transparent but optically non-homogenous sample. This fact provides a basis for phase-contrast imaging in neutron microscopy. It only needs the conversion of the variation in angle φ into the intensity variation over the neutron image. It is worth noting that the angle φ is inversely proportional to the third power of the neutron velocity. Thus it is appropriate to use cold and ultracold neutrons to get a bigger effect.

It is evident from comparing Eq.(3) and Eq.(4) that abandonment of coherent sample illumination involves a substantial decrease in the phase-contrast effect. But nevertheless, this method gives us the possibility to obtain phase-contrast images for microscopic objects at the present time.

In the first papers[4,5] concerned with this problem, a neutron spin-echo technique was proposed to observe the neutron phase contrast. This technique allows the angle φ to be separated from the Larmor precession angle when using a wide neutron energy spectrum. Recently, the results of the first spin-echo experiment with a sample placed in one of the Larmor precession fields was published.[7] Cold neutrons (λ =5.7Å) were used in this experiment.

§.4. Phase contrast in a neutron microscope

Further development of this idea consists in combining the static spin flipper and the precession path where the specimen is located.[8] The requirements for monochromatization of an incident neutron beam may be insignificant in the case of a small precession angle. Therefore, it is not necessary to use the spin-echo technique. Then, such a device may be designed in the form of a mini-device which satisfies the problems of neutron microscopy.

To realize this idea, the thin-film flipper was proposed. This flipper consists of two parallel, closely spaced current-carrying foils (Fig.1).

If a current flows along these foils in the opposite directions in each other, then a static homogeneous magnetic field will be formed in the space between the foils. This flipper should be placed in a weak external guide field oriented normally to the flipper field. Neutrons with an initial polarization along the guide field will pass non-adiabatically through the first current-carrying foil and enter a region in which the field is perpendicular to the original spin direction. The neutron spin $\boldsymbol{S}$ begins to precess around the flipper field $\boldsymbol{B}$ direction. The magnitude of the field and the distance between the foils may be varied to get a specified Larmor precession angle φ_L for neutrons passing through the flipper. After passing, also nonadiabatically, through the second foil, the neutron will enter the guide field again.

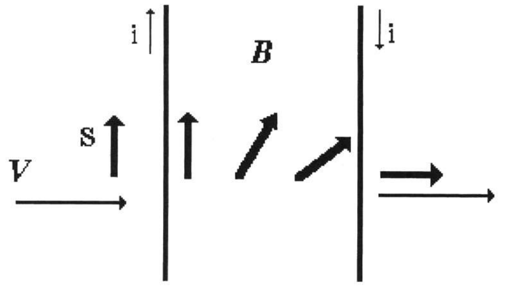

Fig.1. The spin-flipper scheme; B: magnetic field, V:neutron velocity, S: neutron spin, i: foil current.

If the initial polarization of the neutron beam is equal to P_0 then after passing through the flipper, it will be $P = P_0\cos(\varphi_L)$. If a sample to be investigated is placed in the gap between the foils, then the total angle of precession will vary. In this case, the polarization will be given by $P = P_0\cos(\varphi_L+\varphi)$, where the angle φ is defined by the neutron-optical characteristics of the sample and is described by Eq.(3). So the presence of a sample causes a change in beam polarization. The use of an analyzer makes it possible to convert this change into a change in an intensity. This is a basis for phase-contrast imaging.

It can be seen that the rate the polarization P changes with φ depends on the value of φ_L. It is best to choose angle φ_L so that a maximum phase-contrast sensitivity is attained. The sensitivity is conveniently defined as a minimum change in Φ (Eq.(4)) which can be practically measured for the object to be investigated.

When using polarized neutrons, it is possible to derive the sensitivity for different measuring conditions. When neutrons with only one spin component (up or down) are detected, the maximum sensitivity will be reached if φ_L satisfies the equation:

$$\cos(\varphi_L) = \pm(\sqrt{1+r} - \sqrt{r})^2; r = \frac{N_b}{N} \tag{5}$$

where N is the quantity of neutrons in an imaged element, (not including background); N_b is the background for this imaged element. The plus or minus sign depends on which component (up or down) is used. If the initial polarization is taken as P_0=1, then the sensitivity (≅ 99% CL) is given by:

$$\Delta\Phi \geq \frac{3}{\sqrt{N}} \cdot \frac{E}{\mu B} \cdot \frac{1}{(\sqrt{1+r} - \sqrt{r})}. \tag{6}$$

But it seems more attractive to detect two different images at a time, using two position-sensitive detectors. In this case, the neutron beam is split into two components by an analyzer (Fig.2).

Under these conditions, the polarization can be taken as a measured value at an image point. Then the maximum of phase-contrast sensitivity will be reached at $\varphi_L = \pi/2$ and is given by:

$$\Delta\Phi \geq \frac{3}{\sqrt{N}} \cdot \frac{E}{\mu B} \cdot \sqrt{1+4r}. \tag{7}$$

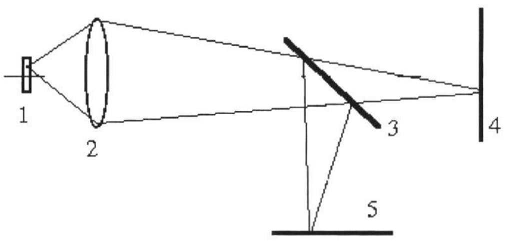

Fig.2. The scheme of a phase-contrast neutron microscope; 1 : spin-flipper with object placed inside, 2 : objective, 3 : analyzer-splitter for neutron beam, 4, 5 : 2D-detector.

This scheme is more preferable, because the procedure of setting the maximum sensitivity does not depend on the background and it is always defined by the condition $\varphi_L = \pi/2$. This condition means that the polarization after the flipper, without the sample, must be zero. Besides, the quantitative characteristics of the image are insensitive to incident neutron flux fluctuations. It can be also seen from Eqs.(6) and (7) that in this case the sensitivity is higher by about 10%. Computer simulation has been performed for this scheme under the conditions of a wide neutron spectrum and divergent beam with a deviation from the axis of up to 30°. These conditions are close to reality. It was shown that in this case, the effect coincides with the effect for collimated monoenergetic neutron beam.

The phase-contrast imaging method proposed here must be compared with the usual imaging method based on attenuation of the neutron beam passing through the sample. In this situation, the variation in image intensity is defined by the well-known formula:

$$f = f_0 \exp(-\rho\sigma d) \equiv f_0 \exp(-X). \qquad (8)$$

Here f and f_0 are the intensity of the incident and transmitted beam respectively, ρ the atomic density, σ the cross section for the reactions which are responsible for neutron beam attenuation, and d the sample thickness. If the sample is very thin, then the value X in Eq.(8) is much less than unity. In this case, the sensitivity ($\cong 99\%\ CL$) will be given by:

$$\Delta X \geq \frac{3}{\sqrt{N}}\sqrt{1+r}. \qquad (9)$$

§.5. Phase-contrast neutron microscope - Is it possible today ?

At the moment the UCN-source at the Institute Laue-Langevin (France) offers the best conditions for neutron microscope operation. The ultracold neutron flux at this source is $n = 3.3\cdot10^4$ neut./cm^2 sec with $V_z < 7.0$ m/sec. [9] Using the existing neutron microscope,[2] it is possible to detect about $3\cdot10^3$ neutrons passing through an object element of $10\times10\ \mu m^2$ during 10 days of exposure. If the value of r is taken as 0.2, which was observed in the previous experiments, then according to Eqs.(7) and (9), the sensitivity to the object element visualization will be given by:

$$\Delta\Phi \geq 350 rad \qquad T = 10 days$$
$$\Delta X \geq 0.06 \qquad S = 10\times10\mu m^2 \qquad (10)$$

For reference, the values of Φ and X are tabulated in Table 1 for different chemical elements with a sample thickness of $d = 1\ \mu m$. Only a few elements with optical potentials E_{lim} of less than 130neV are presented. The neutron velocity was taken as V=6.0m/s ($E \cong 2\cdot10^{-7}$eV) and the value of the magnetic field $B = 10G$.

Values of D_X and D_Φ presented in the last two columns are the sample thicknesses such that Eq.(10) is fulfilled. So, they are the limiting thicknesses for visualization under the conditions mentioned above. It can be seen from the Table that the sensitivity of the phase-contrast imaging method is considerably higher then the sensitivity of the usual method when working with transparent objects. At present, it is possible to observe phase-contrast images for micron-sized objects. We believe that the further development in UCN-sources will result in extensive studies in neutron microscopy.

Table 1. Contrast properties of some elements. ($d = 1\mu m$, V = 6.0m/s, $B = 10G$)

El. (m/s)	V_{lim} (neV)	E_{lim}	X 10^{-4}	Φ (rad)	D_x (μ)	D_Φ (μ)
Al	3.24	54.9	3.7	14.9	162	23.5
Si	3.27	55.9	3.7	15.2	162	23.0
Cr	3.80	75.5	182	21.3	3.3	16.4
Zn	4.33	98.1	20.3	29.0	29.5	12.1
Ge	4.35	99.0	30.2	29.3	19.9	11.9
Mo	4.34	98.5	51.0	29.2	11.8	12.0
Ag	3.92	80.4	989	22.9	0.6	15.3
In	2.79	40.7	1637	10.8	0.4	32.4
Sn	3.38	59.7	4.9	16.4	122	21.3
Ta	4.32	97.6	337	28.8	1.8	15.8
W	3.86	77.9	327	22.1	1.8	15.8
Au	4.73	117.0	1902	36.2	0.3	9.7
Pb	3.97	82.4	1.6	23.6	375	14.8
Si^{28}	3.25	55.4	3.9	15.0	154	23.3
Si^{29}	3.48	63.3	2.3	17.5	261	20.0
Si^{30}	3.44	62.0	2.5	17.0	240	20.6
Ag^{107}	4.43	102.5	1206	30.7	0.5	11.4
Ag^{109}	3.29	56.6	2354	15.4	0.3	22.7

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1) A. Steyerl, W. Drexel, T. Ebisava, et.al.: *Rev. Phys. Appl.* 23 (1988) 171

2) S.S. Arzumanov, S.V. Masalovich, et.al.: *JETP Letters* 52(7) (1990) 369

3) A.I. Frank: *Neutron Optical Devices and Applications* (1992), SPIE Vol.1738, p.323

4) A.I. Frank: *Voprosy Atomnoy Nauki y Techniki, ser. Obschaya y Yadernaya Fiz.* 3(36) (1986) 69

5) V.G. Baryshevskii, S.V. Cherepitsa and A.I. Frank: *Phys. Lett.* A153 (1991) 299

6) F. Mezei: *Neutron Interferometry*, ed. U.Bonse and H.Rauch (Clarendon Press, Oxford, 1979) p.265

7) M. Hino, N. Achiwa, et.al.: *Physica* B 213&214 (1995) 842

8) S.V. Masalovich: *Sov. Phys. Tech. Phys.* 37(2) (1992) 205

9) "The Yellow Book", *Guide to Neutron Research Facilities at the ILL*, ed. K. Ibel (Institute Laue-Langevin, Grenoble, France - April, 1994) p.38