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Current Perspectives

Radiography and tomography with polarized neutrons

Wolfgang Treimer [a,b,*]

[a] University of Applied Sciences, Beuth Hochschule für Technik Berlin, Department Mathematics Physics & Chemistry, Luxemburgerstr. 10, D-13353 Berlin, Germany
[b] Helmholtz Zentrum für Materialien und Energie, Department G – GTOMO, Hahn-Meitner-Platz 1, D-14109 Berlin, Germany

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ABSTRACT

Neutron imaging became important when, besides providing impressive radiographic and tomographic images of various objects, physical, quantification of chemical, morphological or other parameters could be derived from 2D or 3D images. The spatial resolution of approximately 50 μm (and less) yields real space images of the bulk of specimens with more than some cm^3 in volume. Thus the physics or chemistry of structures in a sample can be compared with scattering functions obtained e.g. from neutron scattering. The advantages of using neutrons become more pronounced when the neutron spin comes into play. The interaction of neutrons with magnetism is unique due to their low attenuation by matter and because their spin is sensitive to magnetic fields. Magnetic fields, domains and quantum effects such as the Meissner effect and flux trapping can only be visualized and quantified in the bulk of matter by imaging with polarized neutrons. This additional experimental tool is gaining more and more importance. There is a large number of new fields that can be investigated by neutron imaging, not only in physics, but also in geology, archeology, cultural heritage, soil culture, applied material research, magnetism, etc. One of the top applications of polarized neutron imaging is the large field of superconductivity where the Meissner effect and flux pinning can be visualized and quantified. Here we will give a short summary of the results achieved by radiography and tomography with polarized neutrons.

1. Introduction

The applications of neutron radiography and tomography (shortly imaging) cover a large number and quite different research disciplines, that are all tasked with investigating the composition of samples under special conditions such as temperature, pressure, magnetic or electric fields, etc. and possibly under additional boundary conditions, which influence the measuring process. The information one obtains from these experiments can always be distinguished into two large classes, real space data (e.g. images,) and reciprocal space data (scattering pattern, scattering curves). Both can be transformed into images or graphs, whereas both presume a (lot of) theory that predicts and describes the information originally collected. Each light microscope provides real data information, i.e. images from the surface of a sample. On the other hand, radiography, computer tomography (CT) or nuclear magnetic resonance yield images from the bulk of a body. But one realizes the difference between images delivered by a microscope and the ones recorded with a CT instrument: both methods deliver real space images but the data acquisition and treatment are quite different. A similar situation occurs for neutron radiography and tomography, where a number of different imaging techniques have already been realized. The applicability of neutron imaging depends on the sample and on the specific technique, which must be used to obtain the wanted information.

The different neutron imaging techniques are extensively described in many publications (e.g. [1,5,6,16,17,18,23,24,34,35,39–42,50–52, 54–56]; however, some basic principles will be given here with emphasis on those that use polarized neutrons.

This rather new tool of neutron scattering has lead to a number of different techniques, which use absorption-, phase- and spin-based interactions of the neutron with the samples. Combinations of these interactions are often wanted and one can distinguish neutron radiography (R) and tomography (CT) into the following topics:

White beam and monochromatic neutron radiography (R) and tomography (CT):

- Absorption R/CT (white beam).
- Time resolved R/CT (white beam).
- Energy selective R/CT (monochromatic neutrons).
- Bragg-edge R/CT (monochromatic neutrons).

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* Corresponding author at: University of Applied Sciences, Beuth Hochschule für Technik Berlin, Department Mathematics Physics & Chemistry, Luxemburgerstr. 10, D-13353 Berlin, Germany. Tel.: +49 304 5042 428; fax: +49 304 5042 220.
E-mail address: treimer@helmholtz-berlin.de

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Phase-based based neutron radiography (T) and tomography (CT) are

- Diffraction enhanced R/CT.
- Phase contrast R/CT.
- Phase grating R/CT.
- Interferometer R/CT.
- Refraction contrast R/CT.
- Ultra-small angle scattering R/CT.

Spin based radiography and tomography with polarized neutrons combines, absorption (attenuation) and phase based interactions, i.e. with the option of polarized neutrons enormously enlarges the field of applications. Additionally new techniques are emerging that reach higher resolution and flexibility such as the Larmor Labeling neutron imaging, which uses the Larmor precession of the neutron spin in magnetic fields (see e.g. Ref. [9])

Investigations of matter by thermal and cold neutron beams are very popular, especially if magnetism comes into play. Neutrons have some very specific properties that make them superior to other probes such as X- or gamma rays, electrons, protons, molecular beams, light and laser if one wants to investigate not only surface but also the bulk of a sample. The interaction of (thermal and cold) neutrons with matter is described by the nuclear interaction potential, given by the special isotope-differentiating scattering lengths and there is no dependency on the atomic number. The low attenuation of neutrons by most elements, with some exceptions, allows for investigating large samples (in comparison to electrons or X-rays). The spin interaction with the magnetism of a sample together with their low velocities (for time of flight measurements) make thermal and cold neutrons a unique probe for condensed matter research. The interaction of neutrons with magnetically ordered matter includes the interaction with the nuclei (coherent scattering length b_c) and with the electronic magnetic moments of incompletely filled 3d-. 4d-, 4f- and 5f-shells (see e.g. [31]). The interaction with magnetic fields H is described by the neutron spin (and the resulting magnetic moment μ) and the Larmor frequency $\omega_L = \gamma_L H$, with γ_L the gyromagnetic ratio of the neutron. One can determine the number of spin rotations in a magnetic field modulo 2π and thus calculate "back" the amount of H if the path length of the neutrons in H is known (see below).

The investigation of samples with respect to their magnetic properties therefore benefits from polarized neutron beams. The knowledge of the initial and final states of the neutrons, i.e. the detection of the polarization after the transmission of neutrons through a sample, is a valuable information and determines contrast of an image (Fig. 1). In this field last few years witnessed the development of new polarizers/analyzers (e.g. the so-called benders based on supermirrors), which combine high transmission with high polarization.

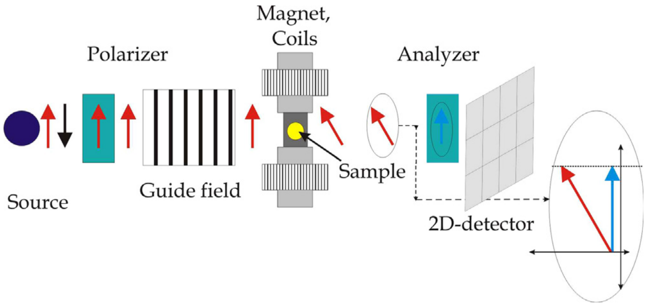

Fig. 1. Layout of an instrument for imaging with polarized neutrons: neutrons from a source are polarized and guided to the sample, which e.g. depolarizes the beam, which is spin-analyzed and then 2D-detected.

2. Theoretical background

2.1. General remarks

Principally there are two different optical geometries for neutron imaging. The first method uses the pin hole technique, i.e. the neutron beam is collimated by an entrance aperture D and a long flight path L of approximately 5 m up to more than 10 m. The better the collimation – here given as the L/D ratio – the better is the spatial resolution at the 2D detector (see Fig. 2). With such a setup one can use the whole white neutron spectrum (0.05–1.5 nm) and thus an intense beam for strong-absorbing or time-resolved radiography or tomography. This can be a disadvantage for wavelength dependent radiographies and tomographies that appear smeared and blurred at the 2D detector; however very often the absorption contrast by some details in a sample is the important information, which is to be visualized. Using a high neutron flux (e.g. 10^7–10^8 neutrons/cm^2) one must be aware of sample activation issues, which may even "destroy" it.

The pin hole technique is easily explained, as shown in Fig. 2. The L/D is the inverse beam divergence and determines the spatial distance of two points at a given distance l_d. If the distance l_d of two points in a sample to the detector is e.g. enlarged, i.e. the detector is placed at $l_d + x1$ or $l_d + x2$, then at a certain distance l_d the points in the image cannot be distinguished from each other as shown in Fig. 3.

The second "kind" of neutron imaging uses a single crystal or a double crystal monochromator, the latter maintains the flight direction of the neutron beam while selecting the wavelength [53]. In the case of a single or double monochromator crystal (often pyrolytic graphite) a main wavelength and a certain wavelength band is Bragg reflected (thus selected) depending on the divergence of the incident neutron beam and the mosaic spread of the monochromator. The selected wavelength band defines the momentum resolution $\Delta Q/Q$ ($Q = (4\pi/\lambda)\sin(\theta)$), the L/D ratio defines the spatial resolution, and both must be adapted and optimized to the imaging problem to be solved [57,58].

In the case of a crystal monochromator the circumstances are a little bit more complicated, than for the pin hole technique, because the simple law of $L/D = l/d$ does not hold any more [57]. The crystal monochromator can be seen as consisting of many "pin holes" (mosaic blocks). From each of these a beam is reflected with the divergence of the incident beam. Under certain boundary conditions it is possible to optimize D and L with respect to the given mosaic spread and gain neutron intensity because L can be reduced and at the same time the spatial resolution can be improved, as shown by Fig. 4. One sees that despite decreasing L, P1 and P2 can be better resolved on the detector screen. This technique is very successfully applied to radiography and tomography especially with polarized neutrons [59,61,62].

In the case of a double crystal monochromator two graphite crystals are operated in the "parallel arrangement" [53]. The first crystal selects a wavelength band out of the incident neutron beam and the second one reflects it back to the initial direction. So one can continuously change the wavelength between e.g. 0.2 nm and 0.62 nm, depending on the wavelength distribution of

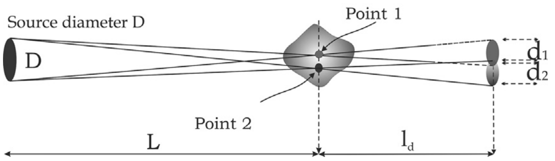

Fig. 2. Pin hole geometry: D=diameter of the aperture, L=distance of D from two points, l_d=distance of the points from detector (screen), and d_1 and d_2 blurred images of point 1 and point 2 respectively (see text).