Spin-polarized neutron imaging

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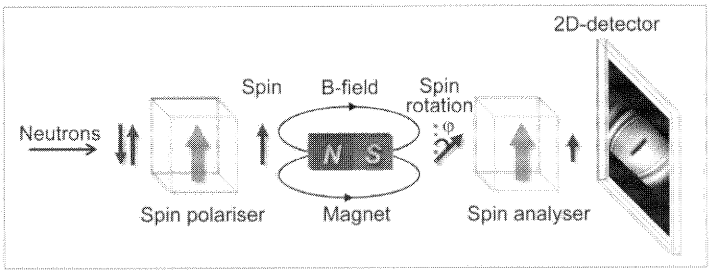

Fig. 1: Schematic diagram of the set-up used for imaging magnetic materials on CONRAD. The neutron beam is polarized, allowed to precess around a magnetic field, analyzed, and then detected. Note how the intensity (dark blue arrow) behind the analyzer is smaller than the intensity behind the polarizer. [1]

Introduction

Conventional approaches for imaging magnetic fields are limited to investigating the surface of a sample and the free space around it; the observation of the spatial distribution of magnetic fields within a bulk sample is not possible. In order to overcome this problem, a new imaging technique has recently been proposed [1,2]. This new method uses neutrons, subatomic particles whose zero net electrical charge allows them to penetrate thick layers of matter, but whose intrinsic magnetic moment makes them highly sensitive to magnetic fields. Utilizing the magnetic interaction of a spin-polarized neutron beam, it is possible to visualize magnetic fields both in free space and in the bulk of solid, massive, opaque samples, revealing the field line distribution both in two and three dimensions [3,4,5].

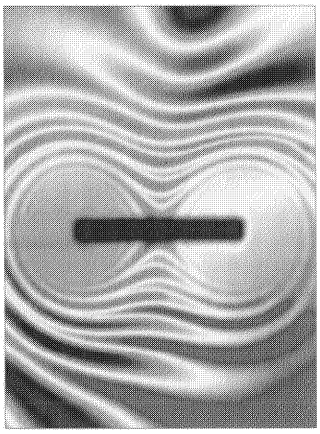

Fig. 2: A radiograph showing the field lines surrounding a bar magnet. The magnetic field decreases in strength with distance from the magnet, resulting in a series of maxima and minima, where the beam polarization is sequentially parallel or anti-parallel, respectively, to the analyzer. Very close to the magnets (where the field is strongest) the field lines are too close together to be resolved spatially [3,4].

Polarized neutron radiography

The neutron is sensitive to magnetic fields due to its magnetic moment, which is anti-parallel to its spin. In the presence of a magnetic field the magnetic moment will undergo a Larmor precession around the field. Polarized neutron radiography is based on the spatially-resolved measurement of the final (cumulated) precession angles of a polarized neutron beam (one in which all spins point in one direction) that traverses the magnetic field of the sample. For monochromatic neutrons (neutrons with a uniform velocity) the precession angle can be related to the average strength of the magnetic field through which the neutrons passed. A polarization analyzer located behind the sample converts this angle to an intensity which is measured by a 2D position sensitive detector. The recorded two-dimensional projection image is then determined by the original intensity modified by a product of the normal absorption contrast and the contrast given by the spin analysis due to the rotation of the polarization vector in the magnetic field [1].

Experiments

Magnetic imaging experiments with polarized neutrons have recently been undertaken on the COld Neutron RADiography and tomography facility (CONRAD) at HZB. The setup used a spin□filter to polarize a neutron beam, which was then allowed to pass through a magnetic sample before being analyzed with a second spin□filter and detected by a position sensitive detector (Figure 1). The key to the image thus formed is that the analyzer only transmits the component of the beam polarization that is parallel to its own polarization axis. As a result, the intensity measured behind the analyzer is the initial beam intensity modulated both by conventional absorption (the magnitude of which can be found from a standard radiograph) and by some sinusoidal function that is directly related to the angle by which the polarization has precessed. The maximum (minimum) intensity will be measured when the beam polarization and the analyzer are aligned perfectly parallel (anti□parallel).
This has been demonstrated with a variety of magnetic systems. Figure 2 reveals the familiar pattern of field lines surrounding a simple dipole magnet. The rainbow color scale (from blue = minimum to red = maximum) used in the images is related to the intensity variations induced by the sample and by the presence of a magnetic field [3,4]. The decay of the magnetic field strength with distance is indicated by the annular structure of minima (blue) and maxima (red) representing the periodical 2ϖ rotation of the neutron spin. For the quantification of the magnetic field an iterative calculation algorithm based on Biot-Savart law was developed [1]. The comparison between calculated and measured images for a dipole magnet levitating over a

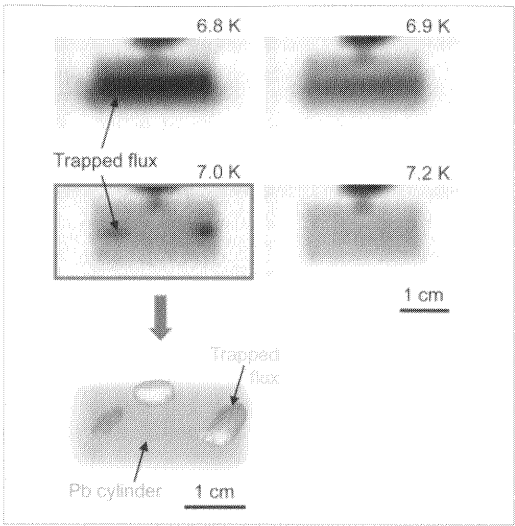

Fig. 4: A three-dimensional reconstruction of trapped flux (yellow regions left and right) inside a polycrystalline cylinder of lead. When cooled to below its critical temperature in the presence of a weak magnetic field, some flux is present inside due to defects and grain boundaries, and this remains trapped even after the field is switched off [1].

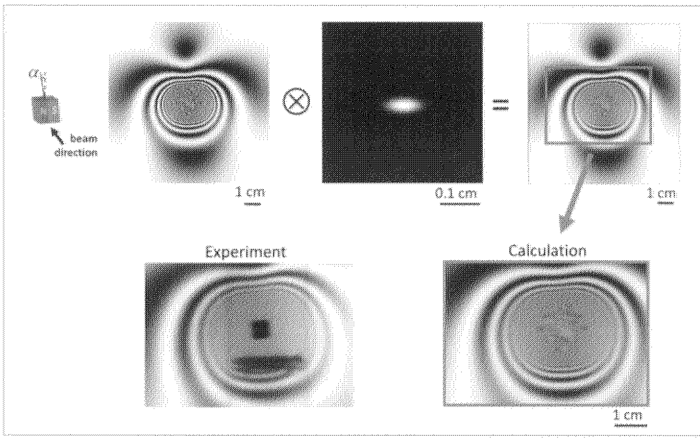

Fig. 3: Comparison of measured and simulated spin polarised neutron radiographies of a dipole levitation over a superconductor: Radiographic image of the levitating dipole (tilted at α=3°) retrieved by a calculation procedure using Biot Savart's law (top) [1]. The corresponding map of the neutron spin rotation in the field was converted into a gray scale image that was convoluted with the resolution function of the instrument. In the central part of the image around the location of the dipole the magnetic field is very strong (up to 1.6 T), causing image artefacts due to the limited sampling of the simulation. Comparison of calculation and experiment (bottom).

superconductor ($YBa_2Cu_3O_7$) is shown in Figure 3. This imaging with spin polarized neutrons can also be extended into three-dimensions using a standard tomographic technique in some instances, as indicated in Figure 4, which shows the distribution of a magnetic field trapped inside a lead cylinder that becomes superconductive when cooled below the critical temperature, $T_c = 7.2$ K [1,2].

Outlook

Spin-polarized neutron imaging is a non-destructive method that provides a number of advantages compared to 2D magnetic imaging techniques using garnet films or scanning techniques (for magnetic fields outside of the sample). The method is applicable to very different environmental set-ups (e.g. for low or high temperature investigations) and samples can be investigated from almost any viewing angle. In this way 3D information about the field distribution can be revealed (even if no mathematical tomographic reconstruction is applied). Measurements are fast because approximately one million pixels are acquired per image within a time-range of several seconds to several minutes. No other method can compete with these advantages even in free space and, as demonstrated, time- and space-resolved measurements become possible.

The presence and controlled application of magnetic fields are essential in many areas of science and technology as well as in fundamental physics. For example, investigations of flux distribution and flux pinning in large superconducting samples [1, 2], the skin effect in conductors [5] or magnetic domain distributions in bulk ferromagnets could be visualized and studied in detail. Finally, the radiographic technique can be extended to tomography in order to investigate and visualize magnetic fields three-dimensionally.

[1] N. Kardjilov, I. Manke, M. Strobl, A. Hilger, W. Treimer, Th. Krist, M. Meißner, J. Banhart, *"Three-dimensional imaging of magnetic fields with polarized neutrons"*, Nature Physics 4, pg. 399-403 (2008)
[2] Nature Physics, press release, www.nature.com/nphys/press_releases/nphys0308.html
[3] I. Manke N. Kardjilov, A. Hilger, J. Banhart, *"Einblicke in Magnetfelder"*, Physik in unserer Zeit 4, July 2008.
[4] N. Kardjilov I. Manke, A. Hilger, M. Dawson, J. Banhart, *"Spin-polarized Neutron Imaging"*, Advanced Materials & Processes, July 2008.
[5] I. Manke, N. Kardjilov, M. Strobl, A. Hilger, J. Banhart, *"Investigation of the skin effect in the bulk of electrical conductors with spin-polarized neutron radiography"*, Journal of Applied Physics 104, 1 (2008).

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