IMAGING
WITH MAGNETIC NEUTRONS

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Spin-polarized neutron imaging is a nondestructive magnetic method that provides a number of advantages over two-dimensional magnetic imaging techniques with garnet films or scanning techniques (for magnetic fields outside of the sample). The method is applicable to very different environmental setups, including both low- and high-temperature investigations, and samples can be investigated from almost any viewing angle.

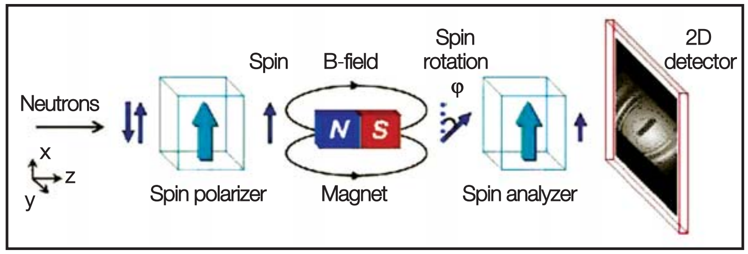

Fig. 1 — Schematic diagram of the setup for imaging magnetic materials on CONRAD. The neutron beam is polarized, allowed to precess around a magnetic field, analyzed, and then detected. Note how the intensity (dark blue arrow) behind the analyzer is smaller than the intensity behind the polarizer.

The technique enables three-dimensional information about the field distribution to 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 time- and space-resolved measurements become possible.

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

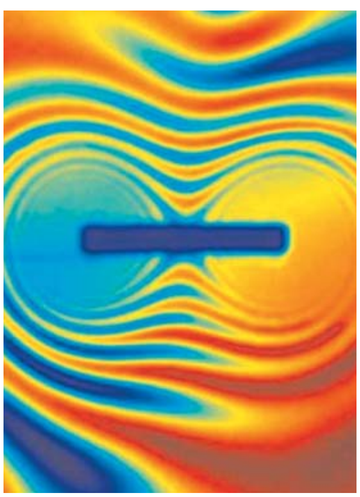

Fig. 2 — A radiograph showing the field lines surrounding a bar magnet. The magnetic field decreases in strength with distance from the magnet. This results in a series of maxima and minima, where the beam polarization is sequentially parallel or anti-parallel, respectively, to the analyzer. Very close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

Magnetic field imaging

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. To overcome this problem, a new imaging technique has recently been proposed by a group of researchers at the Hahn-Meitner Institute (HMI), Berlin, Germany.

This new method, called polarized neutron radiography, is based on 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 in both two and three dimensions.

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 undergoes a Larmor precession around the field.

Polarized neutron radiography

In polarized neutron radiography, a polarized neutron beam, in which all spins point in one direction, traverses the magnetic field of the sample. The result is based on the spatially resolved measurement of the final (cumulated) precession angles of the polarized neutron beam. For monochromatic neutrons with a uniform velocity, the precession angle can be related to the averaged strength of the magnetic field through which the neutrons passed.

A polarization analyzer located behind the sample converts this angle to an intensity that is measured by a two-dimensional, 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.

Experimental studies

Magnetic imaging experiments with polarized neutrons have recently been undertaken on the COld Neutron RADiography and tomography facility (CONRAD) at the HMI. In this setup, a spin filter polarized 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 (Fig. 1).

The key to the image thus formed is that the analyzer transmits only 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 processed.

The maximum intensity will be measured when the beam polarization and the analyzer are aligned perfectly parallel. The minimum intensity will be measured when the beam polarization and the analyzer are aligned perfectly anti-parallel.

This has been demonstrated with a variety of magnetic systems. Figure 2 shows the familiar pattern of field lines surrounding a simple dipole magnet, while Fig. 3 shows the field around a magnet levitating over a cooled YBCO superconductor due to the Meissner effect.

The rainbow color scale (from blue = minimum to red = maximum) in the images is related to the intensity variations induced by the sample, and by the presence of a magnetic field. The decay of the magnetic field strength with distance is indicated by the annular structure of minima (blue) and maxima (red) representing the periodic 2p rotation of the neutron spin.

This imaging method can also be extended into three dimensions by a standard tomographic technique in some instances, as indicated in Fig. 4. This 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.

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Bibliography

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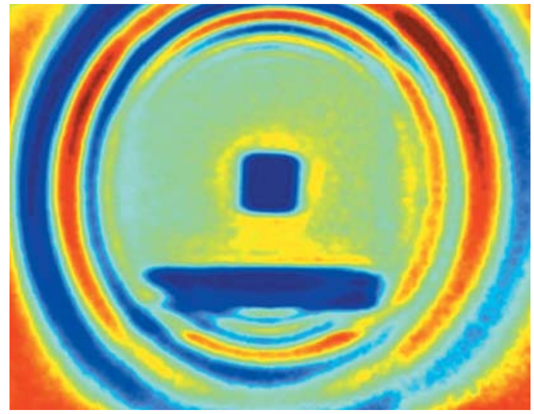

Fig. 3 —A radiograph showing the field lines around a bar magnet levitating over an yttrium-barium-copper-oxide (YBCO) superconductor, a result of the so-called Meissner effect. In its superconducting state, the YBCO expels all magnetic fields and thus repels the permanent magnet.

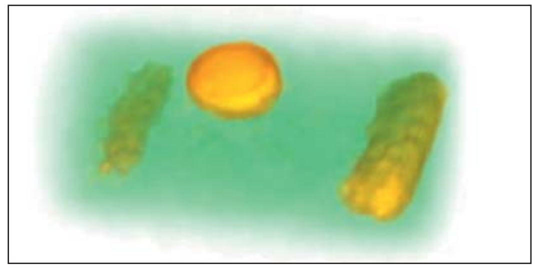

Fig. 4 — A three-dimensional reconstruction of trapped flux (yellow regions left and right) inside a polycrystalline cylinder of lead. When cooled to below its critical temperature in the presence of a weak magnetic field, some flux is present inside due to defects and grain boundaries, and this remains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