Magnetic measurements (Pt. IV) – advanced probes

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Physics 590B
types of local probes

• microscopic (site-specific)
  – NMR
  – neutrons
  – Mossbauer

• stationary
  – Bitter decoration
  – magneto-optics (Kerr and Faraday effects)

• stationary and scanning
  – Hall probes, micro-SQUID
  – Magnetic force microscope
  – Confocal NV-centers nanoscope

• electron microscopy
  – Lorentz microscopy
  – electron holography

X-Ray Magnetic Circular Dichroism (XMCD)
Spin Polarized Low Energy Electron Microscopy (SPLEEM)
Nuclear Magnetic Resonance (NMR)

NMR spectroscopy is one of the principal techniques used to obtain physical, chemical, electronic and structural information about molecules due to either the chemical shift Zeeman effect, or the Knight shift effect, or a combination of both, on the resonant frequencies of the nuclei present in the sample. It is a powerful technique that can provide detailed information on the topology, dynamics and three-dimensional structure of molecules in solution and the solid state.

Proton NMR Chemical Shifts for Common Functional Groups
Mössbauer spectroscopy (German: Mößbauer) is a spectroscopic technique based on the resonant emission and absorption of gamma rays in solids. This resonant emission and absorption was first observed by Rudolf Mössbauer in 1957 and is called the Mössbauer effect in his honor. Mössbauer spectroscopy is similar to NMR spectroscopy in that it probes nuclear transitions and is thus sensitive to similar electron-nucleus interactions as cause the NMR chemical shift. Furthermore, due to the high energy and extremely narrow line widths of gamma rays, it is one of the most sensitive techniques in terms of energy resolution having the capability of detecting changes of just a few parts per 10^{11}.

In its most common form, Mössbauer Absorption Spectroscopy, a solid sample is exposed to a beam of gamma radiation, and a detector measures the intensity of the beam transmitted through the sample. The atoms in the source emitting the gamma rays must be of the same isotope as the atoms in the sample absorbing them. In accordance with the Mössbauer effect, a significant fraction (given by the Lamb-Mössbauer factor) of the emitted gamma rays will not lose energy to recoil and thus will have approximately the right energy to be absorbed by the target atoms, the only differences being attributable to the chemical environment of the target, which is what we wish to observe. The gamma-ray energy of the source is varied through the Doppler effect by accelerating it through a range of velocities with a linear motor. A typical range of velocities for 57Fe may be +/-11 mm/s (1 mm/s = 48.075 neV).
neutron diffraction

“magnetic” peaks will reflect doubling of the lattice constant
spatially-resolving probes

Figure 1. Diagram comparing the magnetic field sensitivity and spatial resolution of electron microscopy, MFM, Bitter decoration, SHPM, MO imaging and scanning SQUID microscopy.
Figure 2. Diagram comparing the image acquisition time and spatial resolution for five of the techniques described in figure 1.
scanning probes

Laser

4 quadrant photo detector

Cantilever deflection measurement

AFM cantilever

xyz-stage

sample

AFM sample stage
Figure 37. Layer structure of a GaAs/Al$_x$Ga$_{1-x}$As heterostructure (top). Sketch of the corresponding conduction-band edge perpendicular to the layers showing the location of the two-dimensional electron gas (2DEG) (bottom).
Figure 38. Sketch of an idealized 2D Hall probe.

\[ \frac{E_y}{J_{2D}B} = R_H = \frac{-1}{n_{2DE}} \]
scanning Hall probe

Diagram of scanning Hall probe setup:
- Scanner Tube
- Sample
- Tilt Stage
- Hall Probe
- Scan Voltages
- Electronics
- PC
- STM Tip Bias
- Hall Voltage
Figure 41. Electron micrograph of a scanner Hall probe with 0.8 μm spatial resolution.
magnetic fields in superconductors

(a)

(b)
Figure 7. Magnetic field profile at various heights $z$ above an Abrikosov lattice of vortices in an applied field of 10 mT.
Scanning Hall probe images of Vortices, 1997

Scanning Hall probes
YBaCuO film, 1000G

A. Oral et al.
University of Bath
Figure 45. SHPM image of flux vortices in a niobium strip 100 µm wide after cooling to 6.3 K in a field of 0.034 mT (Field 1997).
Figure 46. SHPM image showing finger-like penetration of flux into the niobium strip of figure 45 after ramping the field from zero to 33 mT at 4.5 K (Field 1997).
scanning SQUID
Scanning SQUID Microscopy of half-integer vortex, 1996

Scanning SQUID Microscopy YBaCuO grown on tricrystal substrate

J. R. Kirtley et al.
IBM Thomas J. Watson Research Center
Figure 59. Image of vortices in a YBCO thin-film edge-junction washer SQUID with a scratch running from top left to centre right. Images were recorded after (a) field cooling at a very low field and cycling to (b) 0.06 mT and (c) 0.22 mT at 4.2 K. (d) Image at 4.2 K after cycling to 0.24 mT at 77 K (Kirtley et al. 1995b). [Copyright 1995 International Business Machines Corporation. Reprinted with permission of IBM Journal of Research and Development, Vol. 39, No. 6.]
Magnetic force microscope

The principle of MFM is to measure the change in the interaction force between a magnetized probe and the local magnetic field from the sample.

To achieve this, a ferromagnetic probe attached to a cantilever is scanned across the surface of the sample. The image obtained with the MFM is a space distribution of a particular parameter characterizing the magnetic probe-sample interaction, i.e. interaction force, force gradient.

The most important problem in MFM is to distinguish the topography from the magnetic image. This is achieved using a two-pass method. In the first step the topography is determined by situating the tip close to the surface (under 100 nm) e.g. in contact mode or non-contact mode. In the second step the cantilever is raised to a selected height and the surface is scanned using the stored topography (without feedback). The constant tip-sample separation must be large enough to eliminate Van der Waals forces. This way, the cantilever is influenced only by the long-range magnetic forces.

There are two main approaches to MFM imaging: force mode (or DC mode) and force gradient mode (or AC mode).
magnetic head read/write

Figure 4 Top: A schematic diagram showing an inductive recording head writing domains of in-plane magnetization on a magnetic recording tape. Bottom: An interference micrograph, obtained using electron holography, illustrating the flux distribution both outside (top 25% of image) and inside (bottom
electron microscopy probes

Figure 9. (a) Sketch of an electron trajectory passing by a horizontal flux string containing a single flux quantum. (b) Total change $\Delta \phi$ in phase accumulated by electrons on different trajectories.
Figure 12. Classical response of a beam of electrons incident on a horizontal flux line.

Figure 13. Diagram of an electron microscope designed for investigating vortices in superconductors.
Figure 14. Schematic diagram of the experimental set-up for performing Lorentz microscopy.

Figure 16. Lorentz micrograph of a niobium film at 4.5 K in a field of 10 mT. [Reprinted with permission from Nature (Harada et al. 1992) Copyright 1992 Macmillan Magazines Limited.]
Figure 19. Video frames of regions of vortex lattice in a niobium film at various times after the field was suddenly reduced from 18 to 8.5 mT at 6 K: (a) t = 0 s, (b) t = 0.27 s, (c) t = 0.43 s, (d) t = 0.80 s. Implant defects are located at the black discs and domain boundaries for the vortex lattice are indicated by dotted lines. [Reprinted with permission from T. Matsuda, K. Harada, H. Kasai, O. Kamimura, and A. Tonomura, 1996, Science, 271, 1713. Copyright 1996 American Association for the Advancement of Science.]
Lorentz microscopy

Fe-Pd alloys
Figure 20. Schematic diagram of the experimental set-up for performing electron holography.
Figure 24. Schematic diagram of a real-time electron holography system: YAG, yttrium aluminium garnet; VCR, video cassette recorder.
Figure 22. Interference micrograph of the vortex lattice in a niobium film (phase amplified 16 times) at 4.5 K in an applied field of 10 mT. [Reprinted from Bonevich et al. (1993). Copyright 1993 by the American Physical Society.]

Figure 23. Interference micrograph of a single vortex in niobium at (a) 4.5 K, (b) 7 K and (c) 8 K (phase amplified 12 times). [Reprinted from Bonevich et al. (1994b). Copyright 1994 by the American Physical Society.]
stationary probes

Figure 31. Schematic diagram of a typical Bitter decoration system.
First image of Vortex lattice, 1967

Bitter Decoration
Pb-4at%In rod, 1.1K, 195G

U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
Vortex lattice in high-Tc superconductor, 1987

Bitter Decoration
YBa2Cu3O7 crystal, 4.2K, 52G

P. L. Gammel et al.
Bell Labs
sample edge
Figure 32. (a) Twin layers (dark lines) in a partly detwinned YBCO single crystal as viewed in the optical microscope with polarized light. (b) Bitter decoration image of the same region of the sample. [Reproduced from Grigorieva (1994) by permission of IOP Publishing Limited.]
Magneto-optical imaging: Kerr effect

Kerr

Polar

Longitudinal  Transverse
CeAgSb$_2$
Faraday effect

Faraday-active crystal

\[ \theta_F = \nu d H \]

linearly polarized light

Magnetic field

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Basics of Magnetic Measurements. Part IV (Advanced Probes). Prof. Ruslan Prozorov
magneto-optical imaging: Faraday effect

Figure 49. Sketch of the position of the magneto-optically active layer (MOL) and superconducting sample for (a) high-resolution imaging with europium chalcogenide films and (b) imaging with garnets.
Magneto-optics (Faraday effect)

Magnetooptics (Faraday effect)
Figure 50. Diagram of a typical experimental set-up for performing MO imaging on superconductors.
Existing magneto-optical setup

~ 2.5 K base temperature
~ 2-10 μm spatial resolution
~ 0.5 G field sensitivity
Figure 52. MO image of a Tl-Ba-Ca-Cu-O single crystal in the Meissner state at 76 K with an applied field of 7.2 mT. The sample is about 600 µm wide at its largest point. [Reprinted from Indenbom et al. (1990) with permission from Elsevier Science.]
type-II superconductors

Meissner State  Partial Penetration  Trapped Flux
Magneto-optical studies of a c-oriented epitaxial MgB2 film show that below 10 K the global penetration of vortices is dominated by complex dendritic structures abruptly entering the film. Figure shows magneto-optical images of flux penetration (image brightness represents flux density) into the virgin state at 5 K. The respective images were taken at applied fields (perpendicular to the film) of 3.4, 8.5, 17, 60, 21, and 0 mT.
Topological hysteresis in stress-free lead

tubes suggested by L. D. Landau, J. Phys. USSR 7, 99 (1943)
Similarity to other systems

(a) photochemical reaction
   (irradiation of mercury dithizonate with visible light)
(b) intermediate state in Pb

(a-b) Turing instability in a disk gel reactor
(c-d) intermediate state in pure lead
Topologies of reversible and irreversible regimes
We propose to use NV centers to study magnetic phenomena in individual nano-objects with superior sensitivity and resolution.
Nitrogen vacancy in diamond: paramagnetic ($S=1$) defect with strongly localized electronic states
- $m=0$ state produces high level of red photoluminescence
- $m=\pm 1$ states produce very few red photons.

The sample is illuminated with green light and red light fluorescence is measured. Microwave excitation is used to initialize spin state. Spin rotates in external field changing population of $m=0$ state and leading to the change of red light intensity. Hence, we can measure magnetic field by measuring photoluminescence.

Theoretical limits: resolve picoTesla level magnetic fields in the volume of a single NV center (2x2x2 Å³).

From signal level - limited measurements of macroscopic assemblies to resolution of individual nanoparticles. Study magnetic response at the nanoscale with pico Tesla sensitivity.