Magnetic Field Imaging using Polarized Pulsed Neutrons at J-PARC

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Neutron Imaging

neutron technique to observe the internal structure of materials in real space by taking an image of neutron transmission.

Origin of contrast

- Attenuation by Absorption or Scattering
- Change in Polarization, ...

→ Imaging of magnetic field

Usage of pulsed neutrons

- Energy dependence can be obtained efficiently and precisely by TOF method.
- Wide energy range neutrons can be available.

Suitable for the “Energy-resolved neutron imaging”
Magnetic Field Imaging

A change in the neutron spin is detected as a change in polarization

Change of neutron spin direction in a magnetic field

\[ \frac{d}{dt} S_\alpha(t) = \frac{g\mu_N}{\hbar} [S(t) \times B(t)]_\alpha, \quad \alpha = x, y, z \]

Spin rotation angle by Lamor precession

\[ \varphi = \omega_L t = \frac{\gamma_L}{\nu} \int_{\text{path}} B ds \]

\[ \omega_L = \frac{g\mu_N}{\hbar} B = \gamma_L B \]

Rotation angle apparently depends on the neutron velocity.

Study of wavelength dependence gives more information.

Usage of polarized neutrons

HZB group
Magnetic Field Imaging with Pulsed Neutrons

Usage of polarized pulsed neutrons

Advantage 1. Wavelength dependence can be obtained with good resolution and efficiency.
   ➔ Path integrals of magnetic field can be evaluated.

Advantage 2. Wide wavelength range is available.
   ➔ Short wavelength neutron is good for large magnetic field.
   Long wavelength neutron is good for small magnetic field or sensitive measurements.

Pulsed neutrons are suitable for magnetic imaging technique.

We performed magnetic field imaging experiments using polarized pulsed neutrons at J-PARC
   ➔ Obtaining wavelength dependence of polarization with high efficiency
   ➔ Quantitative treatment of magnetic field
Experimental Set Up

Beam Line: BL10  
(Beam Power: 16kW, 120kW)

Polarizer/Analyzer:  
  Stacked Bent Magnetic Super Mirrors

Spin Flipper: AFP type  
  (RF field: 173kHz, ~20G)

Sample: Solenoid Coil (diameter: 5mm)

2D detector: 5 inch-PSPMT  
  (scintillator: ZnS(Ag)/LiF 0.25mm-t)  
  ($\Delta x, \Delta y$=~1mm, $\Delta t$=0.5msec)

Beam Size: 20mm(H) x 10mm(W)  
Exposure Time: ~30 min. for one measurement (50,000 pulses)
BL10 NOBORU as a Test Port

Neutron Beam-line for Observation and Research Use (NOBORU)

A primal mission of NOBORU is to study neutronic performance of JSNS. The experiments aim at contribution for stable operation, design validation and integrity check of JSNS.

NOBORU is also expected as a test port to accommodate R&D activities and trial users to bring out new research activities.

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Beam-line Number: BL10 (decoupled moderator)
L1 (moderator-sample distance): 14.0 m
Maximum Beam Size: 100 mm x 100 mm
Experimental Cave: 2.5 m(W) x 3.5 m(L) x 3.0 m(H)

Cold Neutron Flux at Sample Position: 4.8 x 10^7 [n/s.cm²]
Neutron Peak Intensity at 10 meV: 1.5 x 10^{12} [n/eV.s.cm²]
Neutron Pulse Width at 10 meV: 33 [μs]
Available Bandwidth: 9 Å (possible to shift)
Obtained Polarization

Neutron Intensity Distribution (S.F. = OFF)

Neutron Intensity Distribution (S.F. = ON)

Distribution of Polarization

Polarization degree: about 95% @ λ>6Å

Oscillation is due to the inhomogeneity in efficiency of Spin Flipper.

K. Sakai

\[ P = \frac{N_{OFF} - N_{ON}}{N_{OFF} + N_{ON}} \]
Visualization of magnetic field

Decrease of polarization was seen at the position of the solenoid.

→ We can know where the magnetic field is.
Using TOF method, we can get series of images by a couple of measurements (S.F. on/off).
Quantification of the magnetic field strength

\[ \frac{P_i}{P_0} \propto \cos \phi \]

\[ \phi = \gamma B t = \gamma B \frac{L \lambda}{3956} \]

For \( I > 0.6A \), fitting by a sinusoidal function can be done successfully.

By fitting the wavelength dependence of polarization with sinusoidal function, the path integrals (BL) can be evaluated.

\[ B = 2.2 \text{mT/A} \]

\[ BL_{\text{min}} < 4 \times 10^{-6} \text{[Tm]} \]

Polarized pulsed neutrons can be used for the quantification of magnetic field.
Magnetic field direction can be also analyzed by the wavelength dependence of polarization.

Tilt angle $\alpha$ of magnetic field can be evaluated from the oscillation amplitude and the offset of oscillation center.

$|\alpha| = 47.1 \pm 1.8 \text{deg.}$

$|\alpha| = 48.6 \pm 1.9 \text{deg.}$
3D magnetic field analysis

Quantitative treatment of magnetic field strength was confirmed for a simple example.

To understand the magnetic field vectorially, neutron spin analysis is necessary.

Tuning neutron spin direction three-dimensionally by XY direction coils and solenoids (Z direction) and analyze it.

Combination with the CT technique

Three-dimension for magnetic field vector
Three-dimension for spatial distribution → total analysis of magnetic field
Testing 2D magnetic field analysis

Setup for 2D analysis

guide field by permanent magnet
sample
New Imaging Beam Line at J-PARC

A new beam line dedicated to the pulsed neutron imaging was proposed to J-PARC. “Energy-Resolved Neutron Imaging System (ERNIS)”

Evaluate the physical quantities of materials, and Visualize them in real space. stress, texture, microstructures, chemical composition, temperature, ...

Magnetic field in/outside of materials or space is also regarded as an important object for our pulsed neutron imaging study. → Neutron polarization/analysis is a key technique.
Summary

We have performed magnetic field imaging experiments using polarized pulsed neutrons at BL10 of MLF in J-PARC.

The possibility of quantitative analysis of magnetic field using polarized pulsed neutrons was confirmed.

Application to magnetic materials or super-conducting materials will start this year.

Three-dimensional full spin analysis for the reconstruction of magnetic field vector is under the test.

Sufficient resolutions both in spatial and time are necessary.

Detector selection is a difficult problem.

Introduction of the CT technique is planned.
Thank you for your attention