Material and Life Science Experimental Facility

Japan Atomic Energy Agency
High Energy Accelerator Research Organization

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Materials and Life Science
Investigated by Neutrons and Muons

The world most intense pulse neutron and muon sources
Mysteries of materials and life become into sight by MLF

Japan Proton Accelerator Research Complex (J-PARC) consists of the world most intense proton accelerators and experimental facilities. Materials and Life Science Experimental Facility (MLF) located in the center of the J-PARC site is an experimental facility aiming to promote materials and life science using the world most intense neutron and muon beams generated from 1MW pulsed proton beam (3GeV, 25Hz, 333μA) given by the accelerator.

MLF, which is administrated as one of the experimental facilities of J-PARC which is the collaborative project between Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK), provides domestic and overseas users opportunity to perform not only academic researches but also industrial applications.
**Static Structures**

Neutrons have the properties of waves as well as particles. They can probe crystal structures by detecting interference of scattered neutrons from periodic alignment of atoms (Bragg diffraction) similar to the case of X-rays.

**Dynamical Behaviors**

The mass of a neutron is comparable with a hydrogen atom. When neutrons are scattered by atomic nuclei, they can exchange energy with them. Observation of energy changes of neutrons before and after the scattering reveals the dynamical behavior of atoms and molecules.

**Magnetic Structures**

Neutrons are small magnets with spin 1/2, and affected by the magnetic field inside a material. Observation of scattered neutrons reveals magnetic structures or magnetic field distributions in materials.

**Transmission Imaging**

Neutrons go through materials without destruction due to their moderate properties and low interaction with atoms. The advantages of neutron imaging are to observe light atoms and/or molecules such as hydrogen atoms, water molecules, and so on.

**Elements Sensitivity**

Neutrons are suitable to distinguish elements, especially light atoms or isotopes, due to their ability to interact with nuclei. They work well to observe a motion of water molecules in fuel cells, find the production area of ancient materials, and so on.

**Fundamental Physics**

Precise measurements of the neutron lifetime, electric dipole moment, and scattering length of atoms reveal the secret of the universe. New physics beyond the standard model of particle physics can be discovered with neutrons.

**Static Structures**

Positively charged muons observe states of the material once it is implanted and stops at a position between atoms. Negatively charged muons stop very close to atomic nuclei to form an artificial muonic atom. Employing the magnetic features of muons, we can clarify materials and life from very near the microscopic point of view.

**Dynamical Behaviors**

A muon has spin angular momentum of 1/2 and acts as a small magnet. Once it is implanted into matter, the muon spin starts to precess due to the magnetic field from surrounding nuclei and electrons. By measuring the distribution of positions emitted because of the muon decay, we know the magnetic structure and field distribution within the matter and can therefore investigate magnetic materials and superconductors.

**Magnetic Structures**

Since muons only interact with matter via the weak and electromagnetic forces, they can penetrate deep into a substance. We can observe the states within a matter and composition elements just like X-rays are used to look through the human body.

**Transmission Imaging**

We can investigate the composition of a material by investigating characteristic X-rays emitted by the electrons running around a nucleus. The characteristic X-rays emitted by the negative muons running around a nucleus have higher energies and can therefore penetrate deeper into matter.

**Elements Sensitivity**

Muonic atoms, which have a negative muon running around the nucleus, tell us about the structure of the nucleus. In addition, muonic atoms of hydrogen isotopes trigger muon catalyzed fusion; it could become our future energy source.
Neutrons and muons are produced by collision between the protons accelerated to near the speed of light and the nucleus of the target material.

Production of Neutrons and Muons

3 GeV Proton Synchrotron
The proton synchrotron, which comprises the electromagnets to accelerate the protons from the linear accelerator, is arranged in a ring. This synchrotron accelerates protons to 3 GeV (about 5% of the speed of light).

3 GeV proton beam transport line
The 3 GeV proton beam in ultrahigh vacuum beam-ducts is transported to MLF through an underground tunnel about 100 m long.

Muon Target
The target to produce muons which decay to muons. The target, being made up of carbon, is surrounded by a copper radiator for heat generated with proton irradiation.

Muon Beam Extraction
The 3 GeV proton beam is focused on the muon target located at M3 tunnel, upstream of the neutron target. From the muon target, four muon beam lines, D line, U line, S line and H line are installed to extract intense pulsed muons.

Neutron Target
The target truck for producing neutrons. The mercury target cooling system cycles mercury, allowing the heat from the proton collisions to be removed.

MLF Experimental Hall
The neutron beamlines covered with the radiation shields extend from the deep blue neutron target station in the light center of the photo to lower left.
Spallation neutron source

Production of Neutrons by Protons

The spallation neutron source consists of the following components to produce neutron beams from the proton beam:
- 3-GeV proton beam transport line to transport the intense proton beam from the accelerator to the neutron source
- Mercury target to produce neutrons by proton beam irradiation
- Beryllium and iron reflectors to reflect escaping neutrons back into the center of neutron source
- Liquid hydrogen moderator to reduce the neutron energy to suitable levels for material researches

The functions of these components enhance each other, and then the world's brightest neutron beam is produced.

Process to produce a neutron beam

1. Proton beam injection
2. Spallation reaction
3. Extinction of a neutron beam
4. Slowing-down of neutrons
5. Reflection of neutrons
6. Neutron

- A 3-GeV proton beam irradiates the mercury target.
- Protons collide with mercury nuclei, and spallation reactions are initiated. Then neutrons are ejected from the nucleus.
- Most of the neutrons are reflected back into the moderator.
- The energy of neutrons gradually decreases by repeated collisions with hydrogen in the moderator.
- Neutrons having suitable energy for material research are produced, and are delivered to neutron instruments in the experimental hall.

Core of neutron source station

1. Reflector
   Beryllium and outer iron blocks reflect escaping neutrons to enhance the neutron beam intensity.
2. Moderator
   Circulating liquid hydrogen reduces the neutron energy down to almost the level before the reflector.
   Three kinds of moderators (coupled, decoupled, and poisoned) provide unique neutronic performances.
3. Mercury target
   The mercury target consists of a mercury container containing circulating mercury and a safety shell having a helium layer contained by a cooling water layer.

Neutron source station

Helium cryogenic system
Hydrogen circulation unit
Target trolley
Neutron beam shutter
Shielding blocks

3-GeV proton beam transport line

The 300 m long 3-GeV proton beam transport line consists of dipole magnets to bend the proton beam, quadrupoles to converge/diverge the proton beam, and steering poles to fine-tune the proton beam trajectory. A hundred and eight magnets line up precisely, transport the proton beam from the 3-GeV proton synchrotron to the mercury target.

Intensity comparison of worlds' spallation neutron sources

- J-PARC: 600 kW, 11 x 10^17
- SNS: 1.4 MW, 5.9 x 10^17
- ISIS 2nd target: 48 kW, 4.0 x 10^16

Remote handling devices

Activated components are maintained by remote handling using manipulators. The pictures on the right show an actual mercury target replacement.
Neutron Detection

Since neutrons do not have electric charges and do not interact with electrons in atoms, they interact directly with nuclei. Neutrons are, therefore, measured through nuclear reactions. Only a few kinds of nuclei interact well with neutrons and can be used for neutron measurements.

In MLF gas detectors containing $^7$Li and scintillation detectors utilizing $^7$Li or $^8$B nuclei are employed for neutron measurements. Gas detectors count electric pulses generated through gas ionization caused by secondary charged particles which are produced as a result of nuclear interaction of neutrons with $^7$Li. Scintillation detectors measure optical signals generated through energy deposition by secondary charged particles which are produced as a result of nuclear interaction of neutrons with $^7$Li or $^8$B nuclei.

Gas Detectors

A neutron interact with a $^3$He nucleus. A proton (p) and a triton (t) are generated.

$^3$He + neutron $\rightarrow$ p (5.76 MeV) + t (1.17 MeV)

The secondary particles p and t ionize the gas in the detector.

Scintillation Detectors

A neutron interact with $^7$B. An alpha particle and a $^7$Li nucleus are generated.

$^7$B + neutron $\rightarrow$ alpha (2.78 MeV) + $^7$Li (2.02 MeV)

The secondary particles alpha and $^7$Li generates light pulses through excitation of phosphors.
The accelerators at J-PARC deliver a high intensity proton beam to neutron and muon targets at MLF. Pulsed proton beam produces pulsed neutron and muon beams at each target.

**Investigation with NEUTRONS**

Neutrons are both particles and waves. The wave length of a neutron is inversely proportional to its velocity and the energy of a neutron is proportional to the square of its velocity. When the wave length of a neutron becomes comparable to the distance between atomic or molecular in the material scattered neutrons interfere with each other, which is caused by the wave characteristic of neutrons. Like X-ray or electron beams, we can study microscopic internal structures of materials using this phenomenon.

Neutrons spawned at the neutron target have a large distribution in their energy. Distribution in energy means distribution in velocity. All neutrons in a pulse fly out from the target within very short period, however, a neutron with higher energy arrives at the sample faster and a neutron with lower energy arrives later. There is wide spread in the arrival time.

By measuring the flight time of the neutrons we can calculate the velocity of neutron, if we know the flight path length precisely. That means we can measure the energy and the wave length of a neutron by measuring the time of flight of a neutron.

This is the time-of-flight method.

**Elastic Scattering**

Elastic neutron scattering gives structural information of matter composed of atoms or molecules. Matter waves of scattered neutrons superpose and the waves interfere constructively or destructively by reflecting the inner structure of matter. The resulting wave reflects intensity of neutrons with a wavelength ($\lambda$), measured on the detector set at a scattering angle ($2\theta$). The structure of matter is analyzed by using the intensity distribution.

The magnetic structure of magnetic substance is also analyzed by elastic neutron scattering because the intensity distribution of scattered neutrons depends on the orientation and magnitude of magnetic moment of magnetic atoms in the magnetic substance. Measuring scattered neutrons over a wide range of scattering angle gives information of hierarchical structure or higher ordered structure of protein molecules, soft matter etc.

**Inelastic Neutron Scattering**

In inelastic neutron scattering experiments, we analyze change of neutron energy before and after it has scattered at a sample. Neutrons, which are injected into the sample, interact with the motion of atoms, molecules and spins in the sample. Some of neutrons get energy from motion in the sample and some of neutrons give their energy to the sample to create motions in it.

Changes in the energy of the neutrons cause changes in the velocity of the neutrons. Neutrons, which receive energy from a sample, increase their speed. On the other hand, neutrons, which give energy to a sample, lose their speed. We can measure these changes by using the time-of-flight method.

Exchange of energy is governed by the law of conservation of momentum and energy. We can get microscopic information about the dynamics of microscopic atoms, molecules and spins inside the sample by inelastic neutron scattering.

The nature of a matter is determined by the electronic states of the atoms composing the material. Electrons have spin angular momentum, with the properties of a small magnet. We investigate the magnetic field from the electron spins and look into the states of electrons. The represented experimental technique using muons, muon spin rotation, relaxation, and resonance ( \(\mu\)SR) detects the magnetic fields inside the matter with an ultra high sensitivity. We understand the state of electrons through the measurement of the internal field, and thereby clarify the nature of materials.

**Investigation with MUONS**

**Muon Spin Rotation, Relaxation and Resonance (\(\mu\)SR)**

Muons implanted into the same stop at unoccupied positions between the atoms, and start to precess because of the magnetic field from the surrounding electrons. After the short average life of 2.2 microseconds the muon decays into a positron. At the time of decay, a positron is preferentially emitted in the direction of the muon spin due to the “Parity violation of weak decay.” By measuring the positron distribution and its time dependence, we know how the muon spin polarization evolves in the matter, what kind of magnetic field is present and the state of surrounding electrons.

Each muon changes its spin orientation because of the internal field. After finding the sample average, the initial muon spin polarization is lost as a function of time. By measuring the time evolution of muon spin polarization, we investigate the electronic states within the matter.

Neutrons and muons provide unique information which may not be available from other experimental techniques. Such information is sometimes indispensable to answer questions about the mysteries of materials and life. This is why these probe particles are used in a wide range of fields ranging from basic science to industrial applications.

J-PARC/MLF is contributing to the realization of a better life for you through solving mysteries of Nature and expansion of the industries.