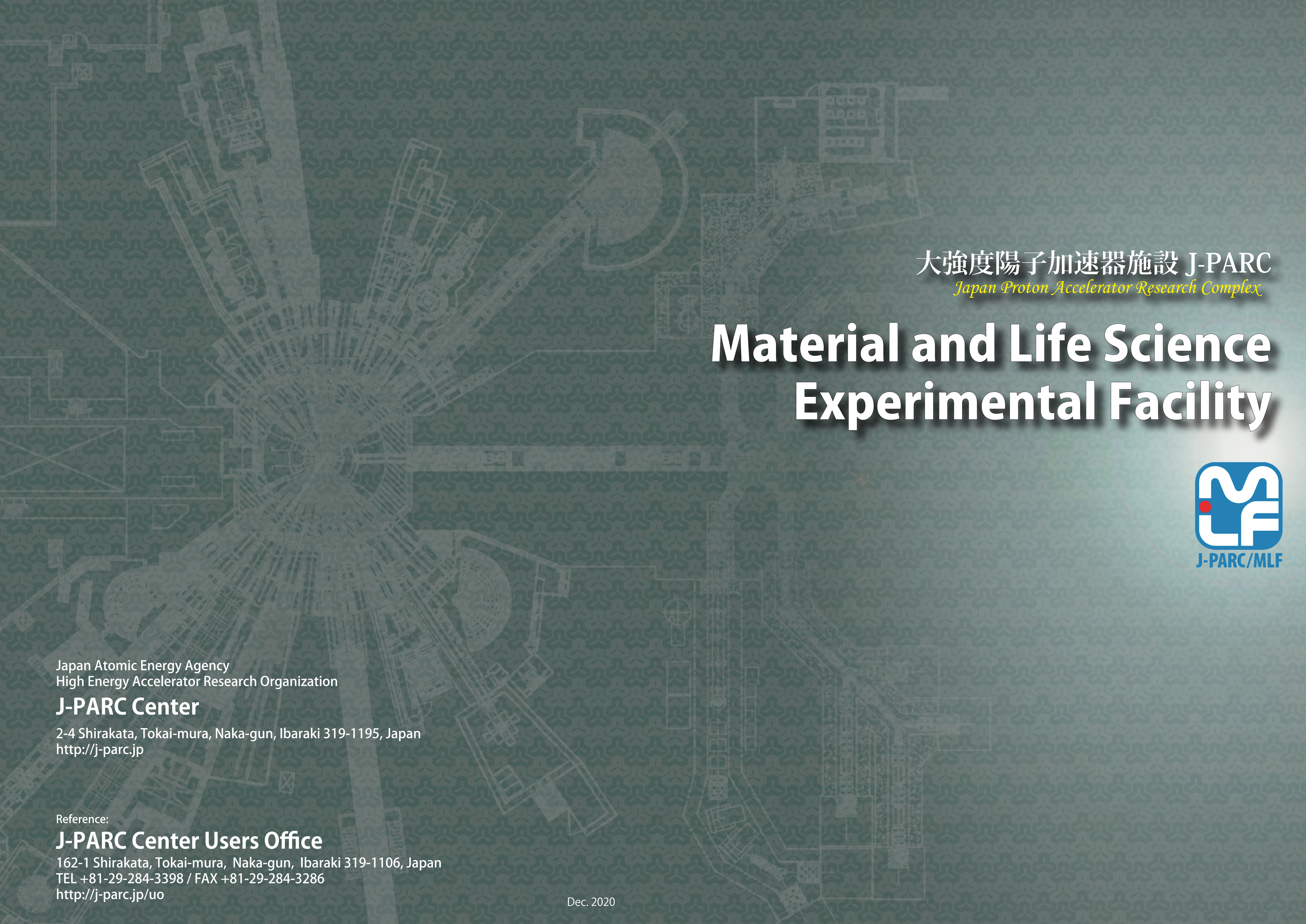


大強度陽子加速器施設 J-PARC

Japan Proton Accelerator Research Complex

Material and Life Science Experimental Facility

J-PARC/MLF

Japan Atomic Energy Agency
High Energy Accelerator Research Organization

J-PARC Center

2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
http://j-parc.jp

Reference:

J-PARC Center Users Office

162-1 Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1106, Japan
TEL +81-29-284-3398 / FAX +81-29-284-3286
http://j-parc.jp/uo

Dec. 2020

Materials and Life Science

Investigated by Neutrons and Muons

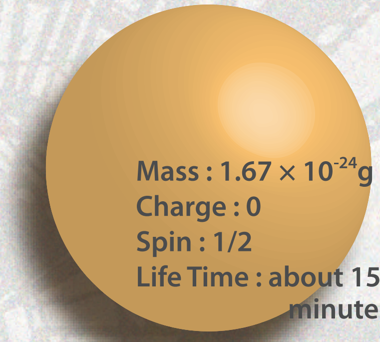
MLF

Materials and Life Science
Experimental Facility

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.

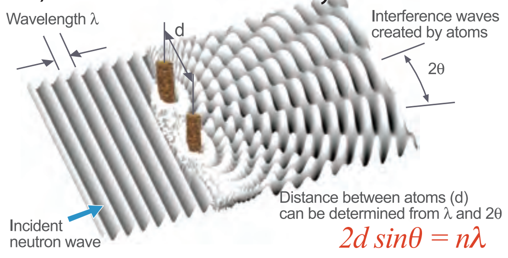
Neutron



Mass : 1.67 × 10^{-24}g
Charge : 0
Spin : 1/2
Life Time : about 15 minutes

Static Structures S

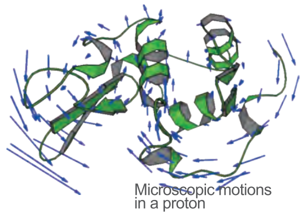
Neutrons have the properties of waves as well as particles. They can probe crystal structures by detecting interference of scattered neutrons from periodic alignment of atoms (Bragg diffraction) similar to the case of X-rays.

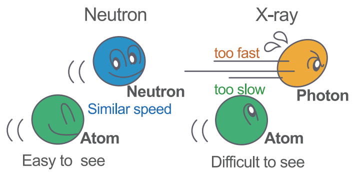


$$2d\sin\theta = n\lambda$$

Dynamical Behaviors D

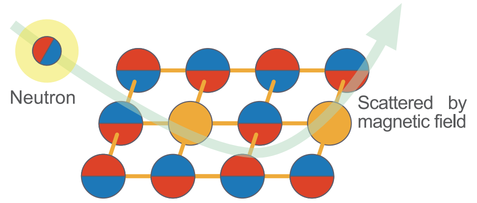
The mass of a neutron is comparable with a hydrogen atom. When neutrons are scattered by atomic nuclei, they can exchange energy with them. Observation of energy changes of neutrons before and after the scattering reveals the dynamical behavior of atoms and molecules.





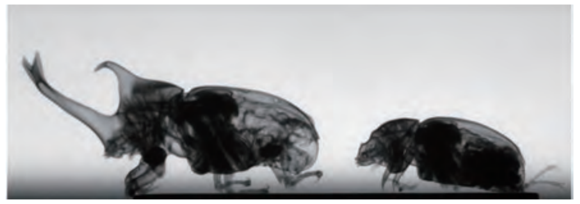
Magnetic Structures M

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.



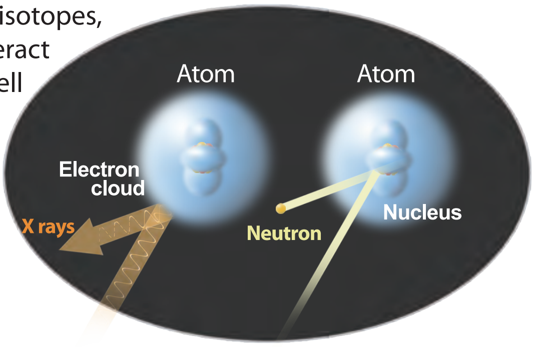
Transmission Imaging T

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 E

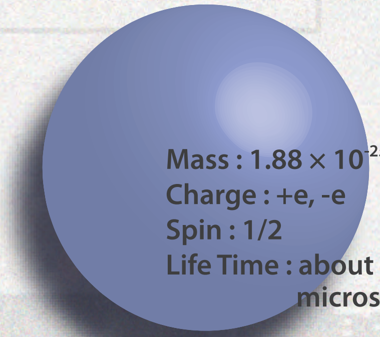
Neutrons are suitable to distinguish elements, especially light atoms or isotopes, due to their ability to interact with nuclei. They work well to observe a motion of water molecules in fuel cells, find the production area of ancient materials, and so on.



Fundamental Physics F

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.

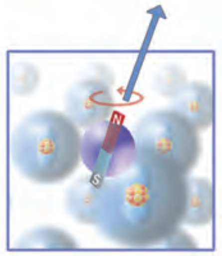
Muon



Mass : 1.88 × 10^{-25}g
Charge : +e, -e
Spin : 1/2
Life Time : about 2 microseconds

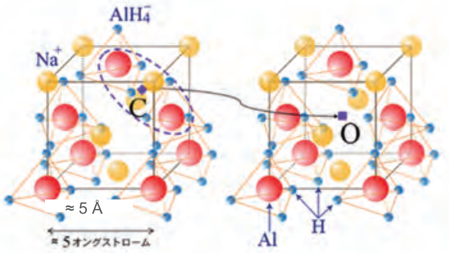
S Static Structures

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.

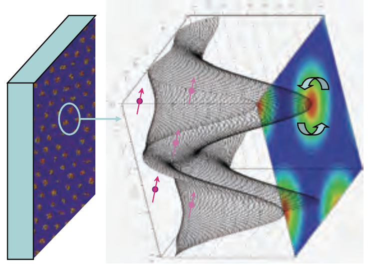


D Dynamical Behaviors

A muon with its own time-range can detect fluctuations of magnetic fields inside the materials. With this feature, one can obtain the information about atomic motions, electric spin fluctuations, propagation of information by electrons inside organic materials. By observing the motion of the muon itself, we can investigate the motion of hydrogen in fuel cells and semiconductors.



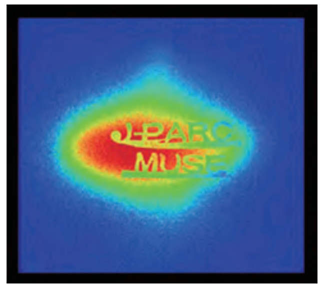
M Magnetic Structures



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 positrons emitted because of the muon decay, we know the magnetic strucure and field distribution within the matter and can therefore investigate magnetic materials and superconductors.

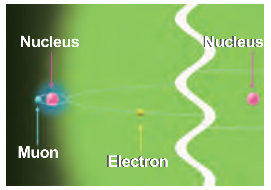
T Transmission Imaging

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.



E Elements Sensitivity

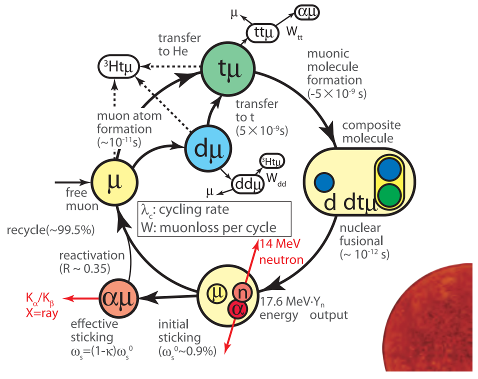
We can investigate the composition of a material by investigating characteristic X-rays emitted by the electrons running around a nucleus. The characteristic X-rays emitted by the negative muons running around a nucleus have higher energies and can therefore penetrate deeper into matter.



Furnish image: Prof. Tsutomu Saito (National Museum of Japanese History)

F Fundamental Physics

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.

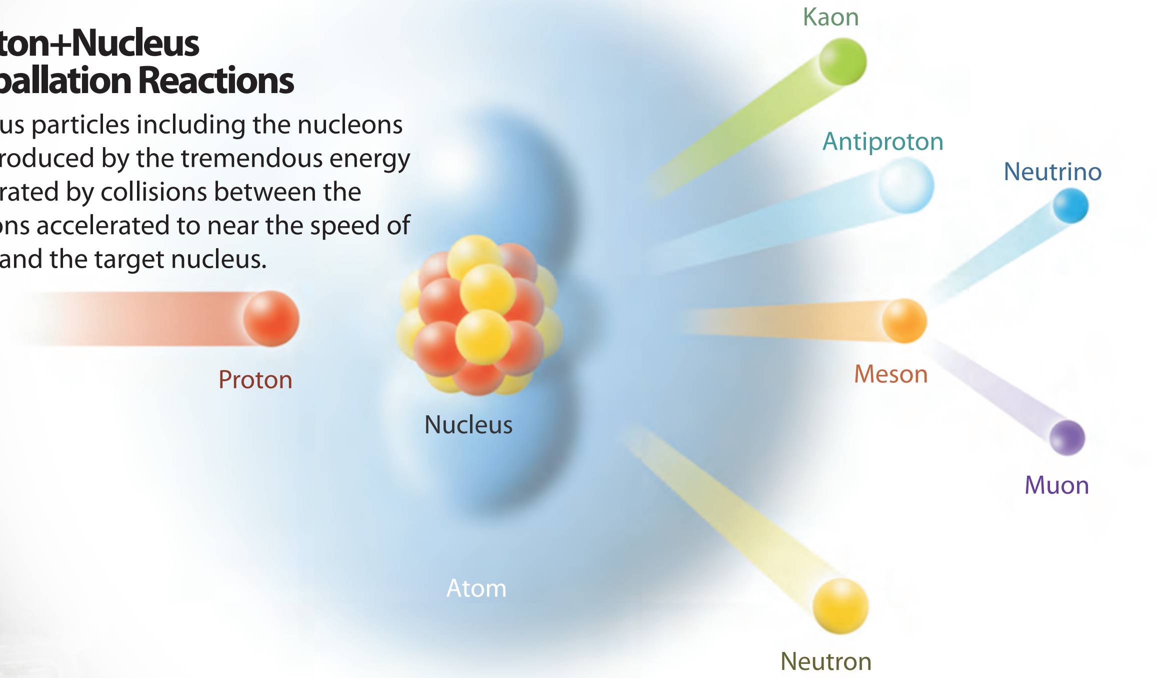


Neutrons and muons are produced by collision between the protons accelerated to near the speed of light and the nucleus of the target material.

Production of Neutrons and Muons

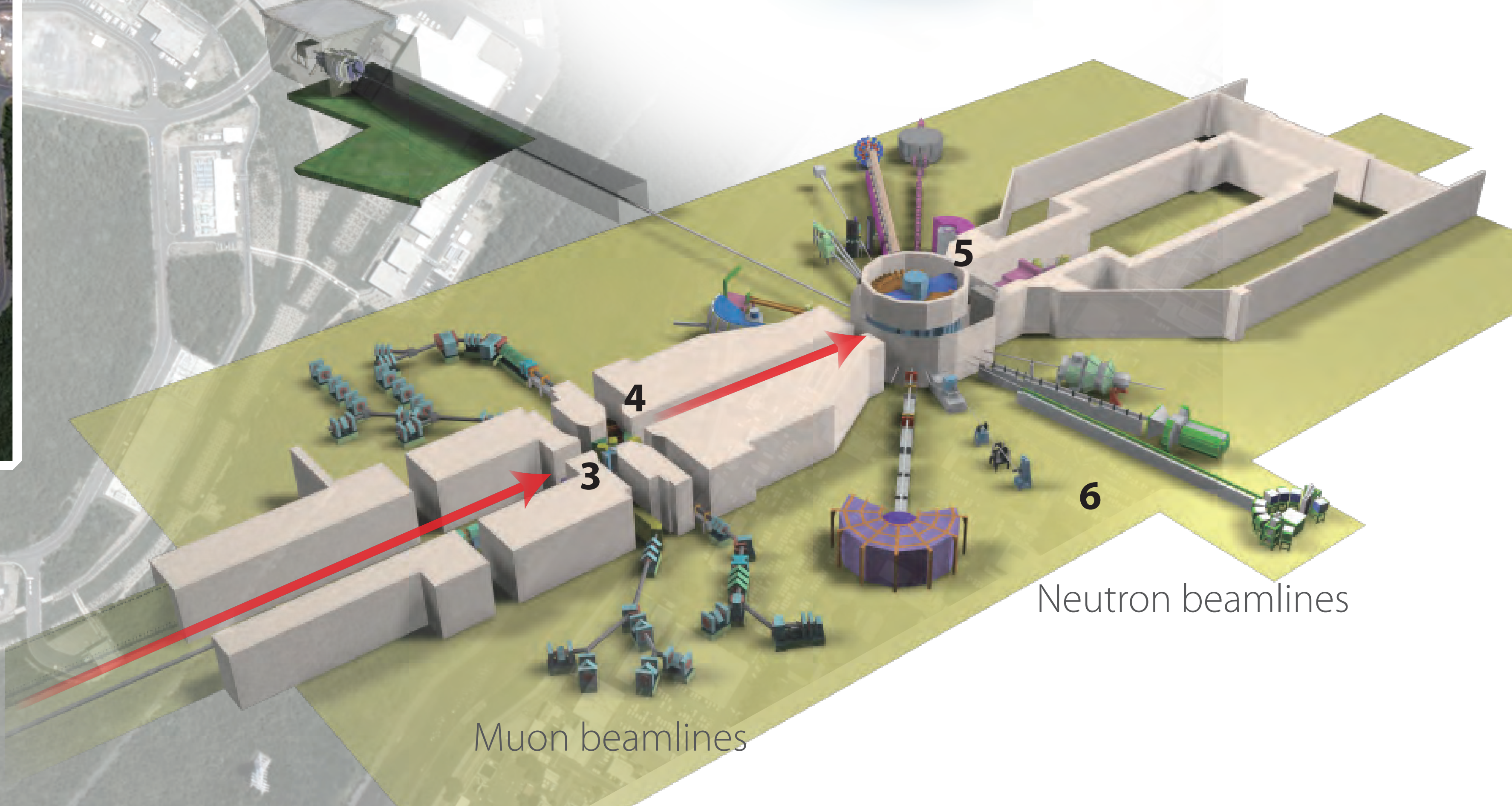
Proton+Nucleus Spallation Reactions

Various particles including the nucleons are produced by the tremendous energy generated by collisions between the protons accelerated to near the speed of light and the target nucleus.



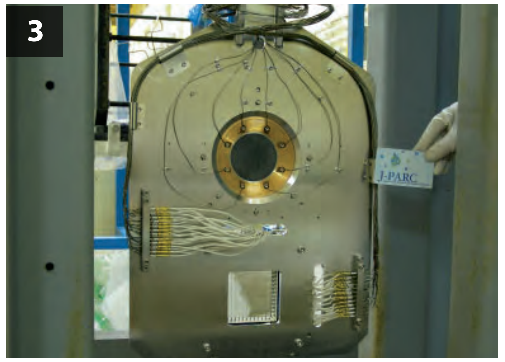
MLF

Various experiments are performed by using the neutrons and muons produced by collision between the accelerated protons and the target.

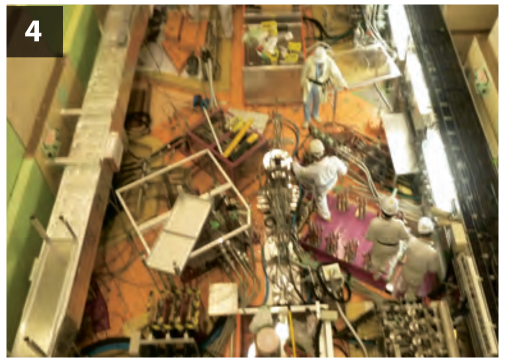


3GeV Proton Synchrotron
The proton synchrotron, which comprises the electromagnets to accelerate the protons from the linear accelerator, is arranged in a ring. This synchrotron accelerates protons to 3GeV (about 97% of the speed of light).

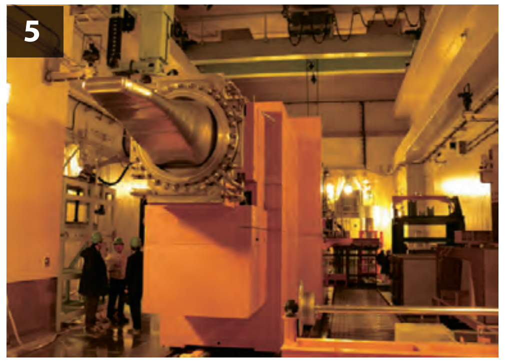
3-GeV proton beam transport line
The 3-GeV proton beam in ultrahigh vacuum beam-ducts is transported to MLF through an underground tunnel about 300 m long.



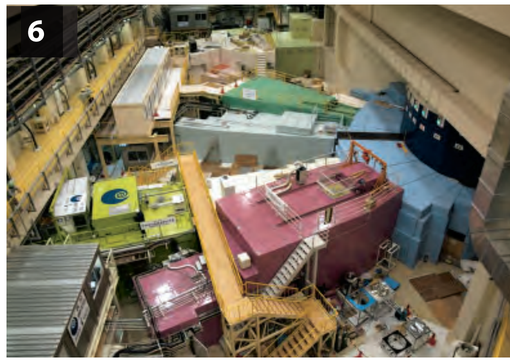
Muon Target
The target to produce π-mesons which decay to muons. The target, being made up of carbon, is surrounded by a copper radiator for heat generated with proton irradiation.



Muon Beam Extraction
The 3-GeV proton beam is focused on the muon target located at M2 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

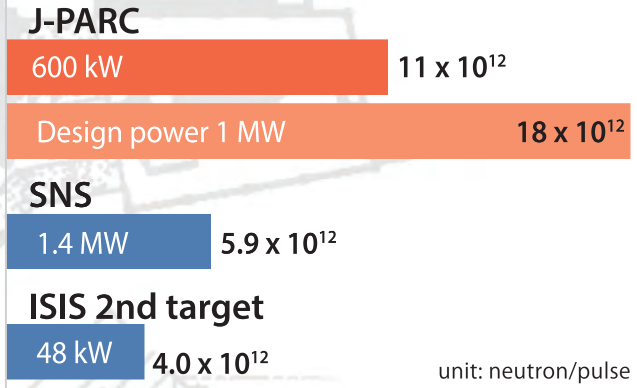
The spallation neutron source consists of the following components to produce neutron beams from the proton beam
- 3-GeV proton beam transport line to transport the intense proton beam from the accelerator to the neutron source
- Mercury target to produce neutrons by proton beam irradiation
- Beryllium 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.

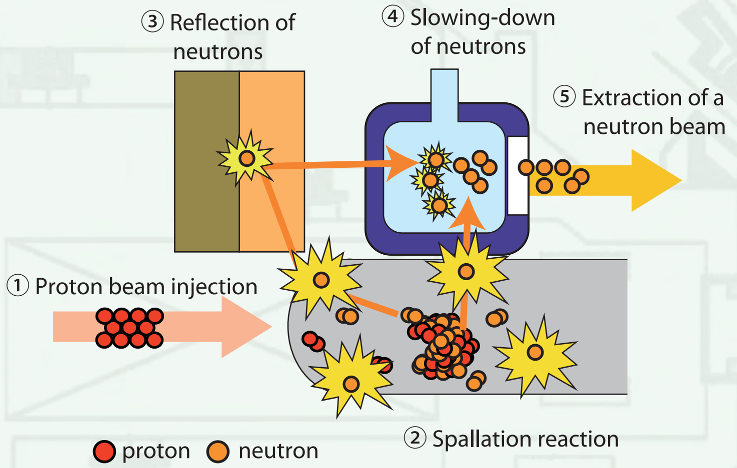
Intensity comparison of worlds' spallation neutron sources

Neutron intensity depends on not only the proton beam power but also the pulse repetition rate and the source design. The figure to the right compares the neutron intensities per pulse of major facilities around the world. J-PARC will provide much higher neutron intensity after achieving the design proton beam power of 1-MW.

SNS; Facility of Oak Ridge National Laboratory in US
ISIS; Facility of Rutherford Appleton Laboratory in UK



Process to produce a neutron beam



① A 3-GeV proton beam irradiates the mercury target.

② Protons collide with mercury nuclei, and spallation reactions are initiated. Then neutrons are ejected from the nucleus.

③ Most of neutrons are reflected by the reflector back into the moderator.

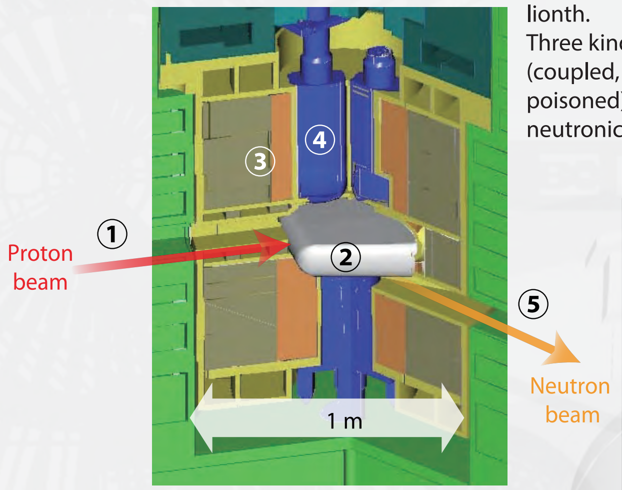
④ The energy of neutrons gradually decreases by repeated collisions with hydrogen in the moderator.

⑤ Neutrons having suitable energy for material research are produced, and are delivered to neutron instruments in the experimental hall.

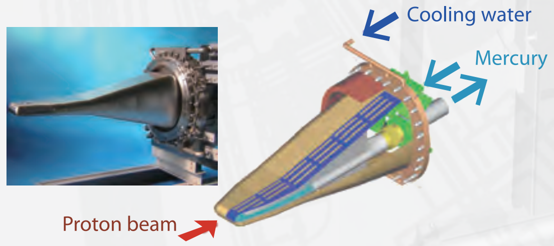
Core of neutron source station

③ Reflector
Inner beryllium and outer iron blocks reflect escaping neutrons to enhance the neutron beam intensity.

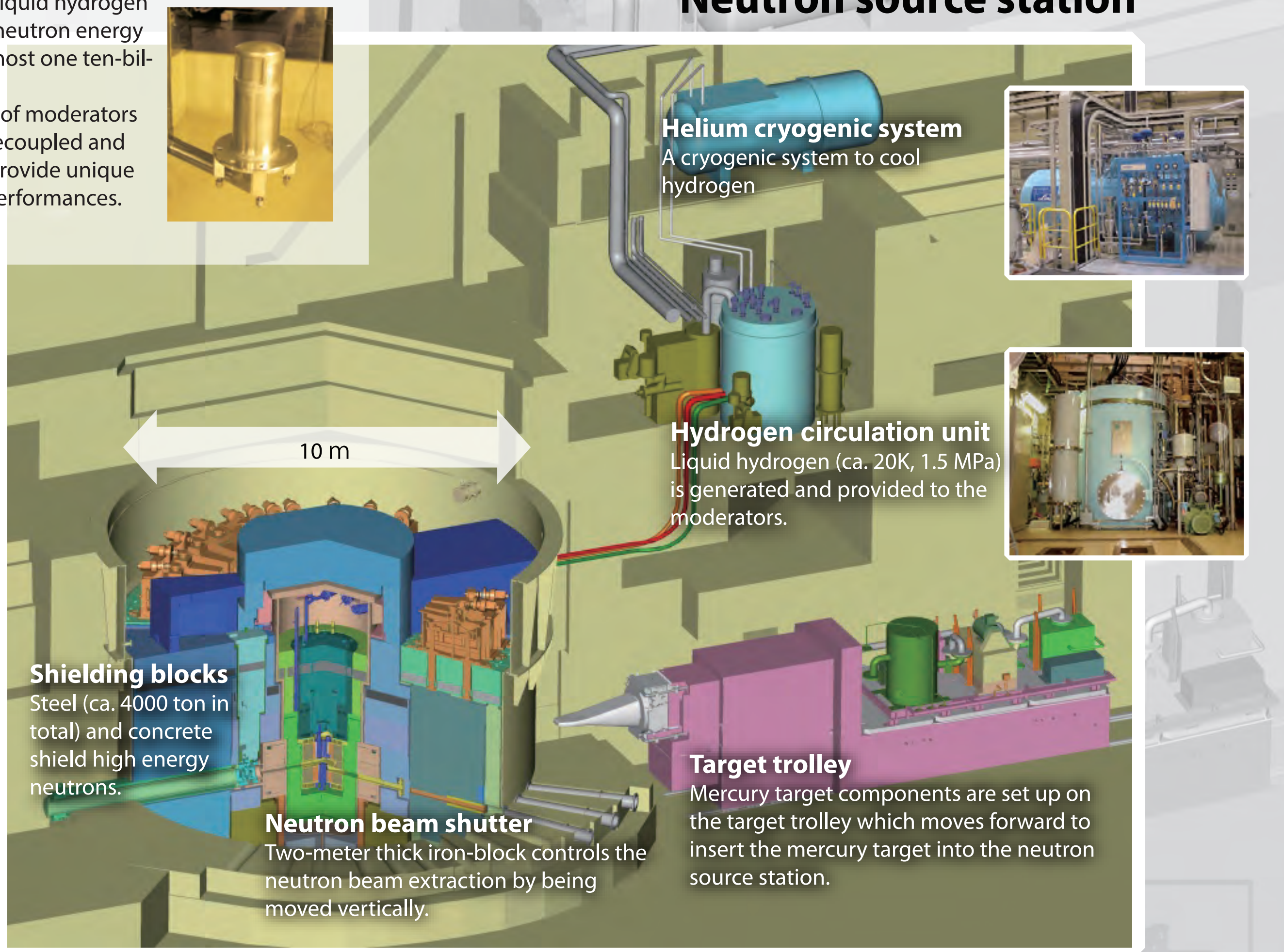
④ Moderator
Circulating liquid hydrogen reduce the neutron energy down to almost one ten-billionth.
Three kinds of moderators (coupled, decoupled and poisoned) provide unique neutronic performances.



② Mercury target
The mercury target consists of a mercury container containing circulating mercury and a safety hull having a helium layer contained by a cooling water layer.



Neutron source station



Helium cryogenic system
A cryogenic system to cool hydrogen

Hydrogen circulation unit
Liquid hydrogen (ca. 20K, 1.5 MPa) is generated and provided to the moderators.

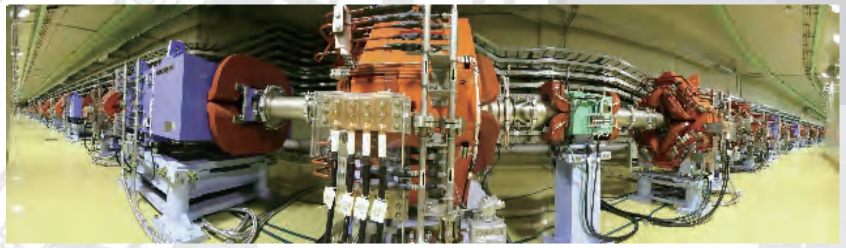
Shielding blocks
Steel (ca. 4000 ton in total) and concrete shield high energy neutrons.

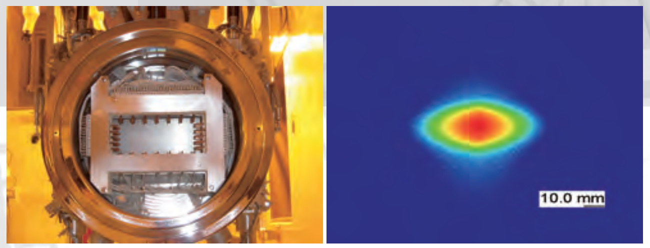
Neutron beam shutter
Two-meter thick iron-block controls the neutron beam extraction by being moved vertically.

Target trolley
Mercury target components are set up on the target trolley which moves forward to insert the mercury target into the neutron source station.

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 ones to fine-tune the proton beam trajectory. A hundred and eight magnets line up precisely, and transport the proton beam from the 3-GeV proton synchrotron to the mercury target.





Left: Proton beam window, which has to sustain the intense proton beam for long periods of time, and separates the accelerator ultrahigh vacuum region and the helium region of the neutron source station.

Right: Measured proton beam shape

Remote handling devices

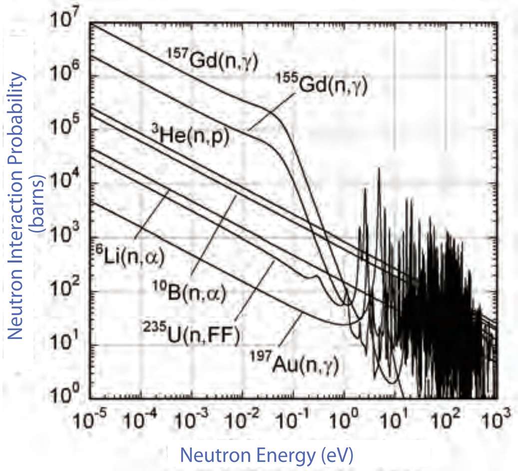
Activated components are maintained by remote handling using manipulators. The pictures to the right shows an actual mercury target replacement.

Neutron Detection

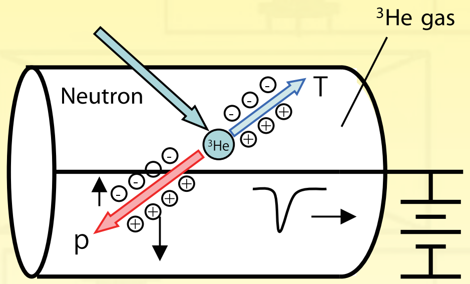
Since neutrons do not have electric charges and do not interact with electrons in atoms, they interact directly with nuclei. Neutrons are, therefore, measured through nuclear reactions. Only a few kinds of nuclei interact well with neutrons and can be used for neutron measurements.

In MLF, gas detectors containing ^{3}He and scintillation detectors utilizing ^{6}Li or ^{10}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 ^{3}He. 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 ^{6}Li or ^{10}B nuclei.

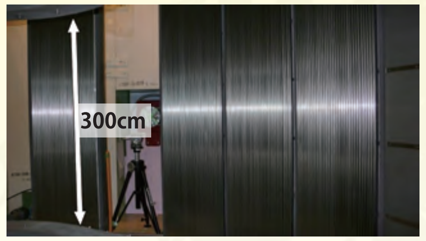
The lower the neutron energy, the more neutron interactions



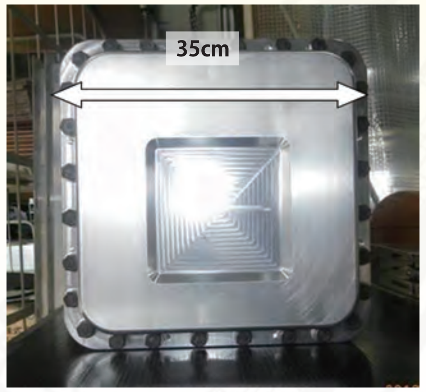
Gas Detectors



A neutron interact with a ^{3}He nucleus. A proton (p) and a triton (T) are generated.
^{3}He + neutron --> p (574keV) + T(191keV)
The secondary particles p and T ionize the gas in the detector.

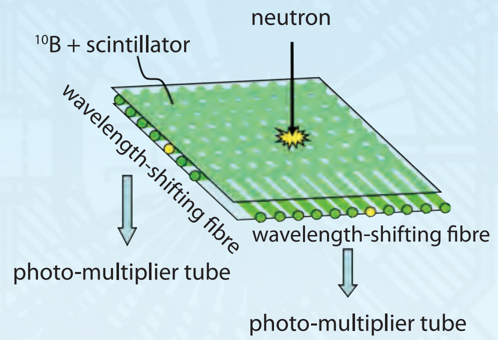


1-d Neutron Gas Detector

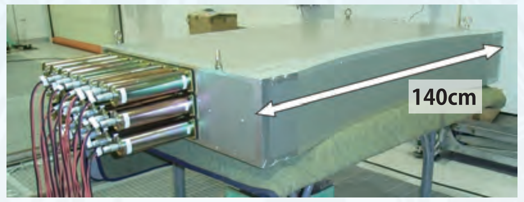


2-d Neutron Gas Detector

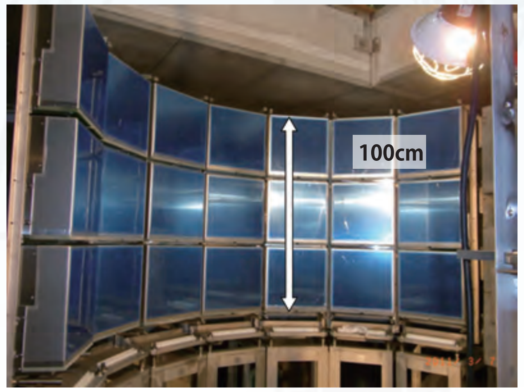
Scintillation Detectors



A neutron interact with ^{10}B. An alpha-particle and a ^{7}Li nucleus are generated.
^{10}B + neutron --> alpha (1.78MeV) + ^{7}Li (1.02MeV)
The secondary particles alpha and ^{7}Li generates light pulses through excitation of phosphors.



1-d Neutron Scintilation Detector

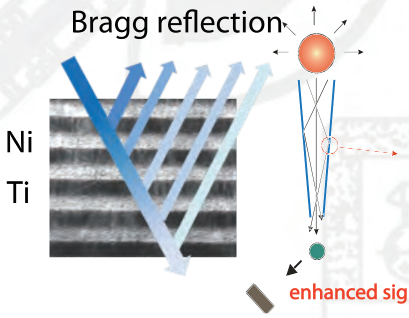


2-d Neutron Scintilation Detector

Neutron Optics for Beam Manipulation

Efficient Transportation of Neutron Beam

Neutron supermirror with high-reflection efficiency

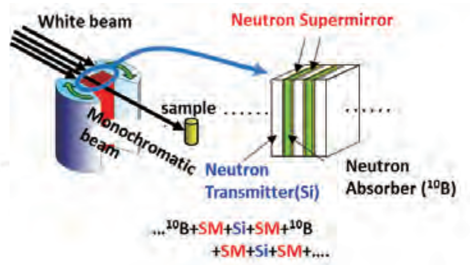


supermirror guide

Neutron supermirrors ranged several meters to about 100 meters transport neutron beam efficiently from the neutron source to experimental instruments.

Novel Fermi Chopper utilizing supermirrors

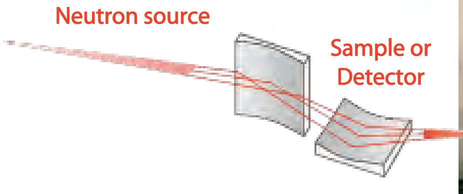
MAGIC Chopper



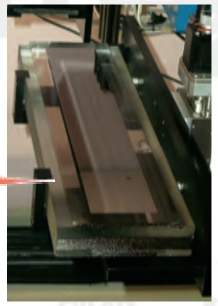
Novel fermi chopper employing supermirrors on the slit position (MAGIC Chopper) is in the process of production, which realize even higher efficiency of inelastic scattering measurements.

Beam Focusing for Nano-scale Science

Focusing supermirror



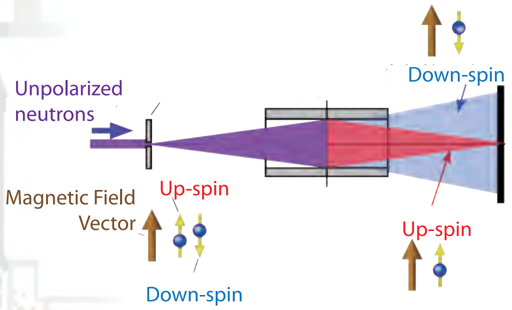
High-performance supermirror with a figure accuracy of nanometer level



1-d elliptic supermirror

Aspheric supermirrors have been developed for wide-band beam focusing onto sample positions and detector positions in order to improve efficiencies of measurements.

Magnetic Neutron Lens

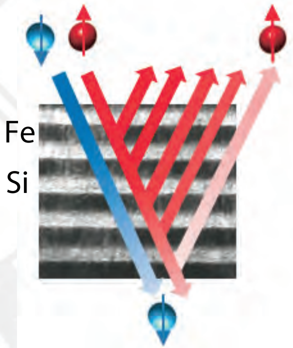


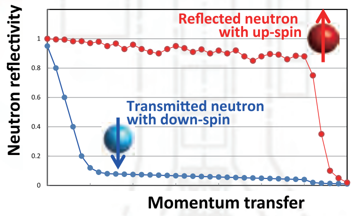
A sextupole magnet for a neutron lens

Magnetic neutron lens have been developed utilizing a magnetic field gradient.

Neutron Polarization for Magnetic, Superconducting Materials Researches

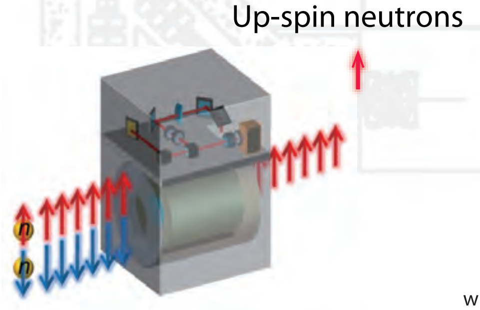
Polarizing supermirrors





Magnetic supermirrors which efficiently polarize wide-band neutrons have been developed by means of distinctly different reflectivity of polarized neutrons (up) and (down) from magnetic multilayers.

Polarized ^{3}He neutron spin filter



A special glass cell which contains ^{3}He gas.

Polarized ^{3}He neutron spin-filters have been developed utilizing distinct difference of absorption probability between up and down-spin neutrons.

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

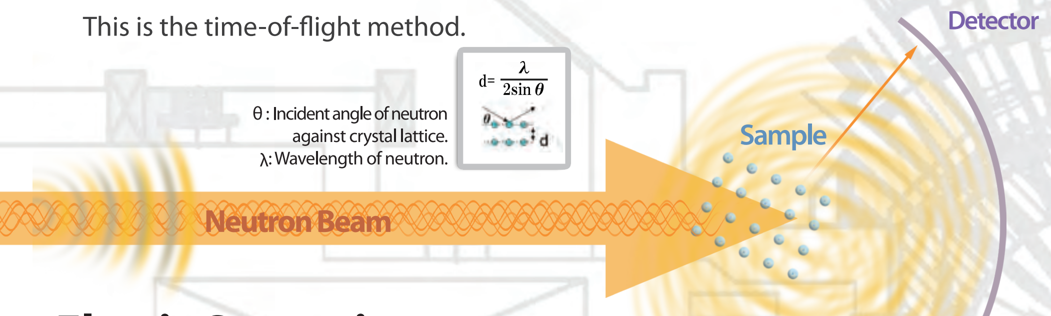
Neutrons are both particles and waves.

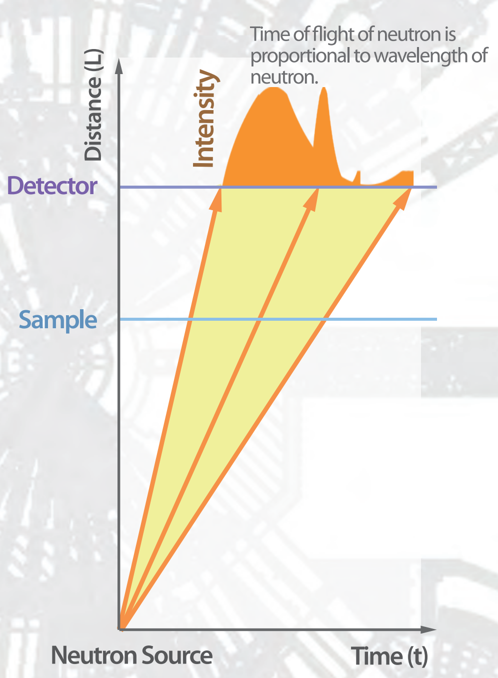
The wave length of a neutron is inversely proportional to its velocity and the energy of a neutron is proportional to the square of its velocity. When the wave length of a neutron becomes comparable to the distance between atoms or molecules in the materials scattered neutrons interfere with each other, 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.

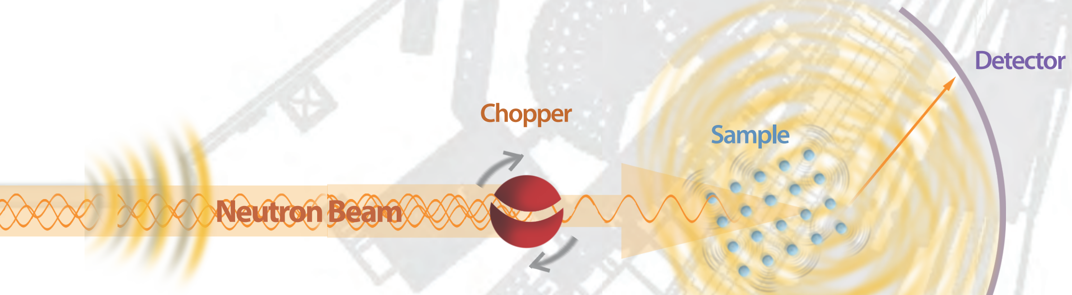


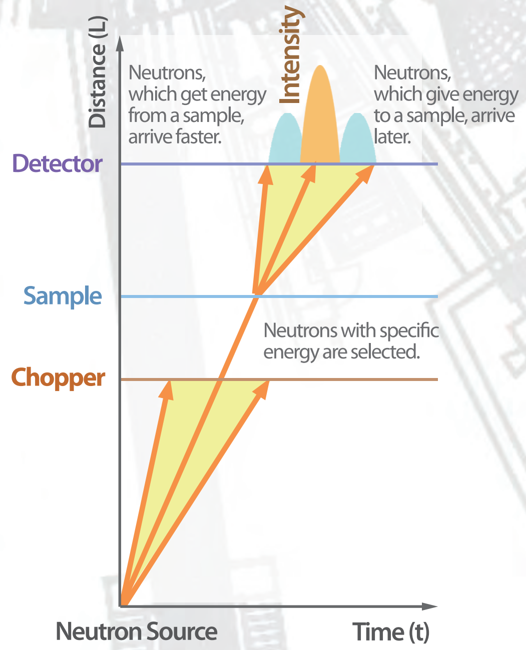


Elastic Scattering

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 (λ), measured on the detector set at a scattering angle (2θ). 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.





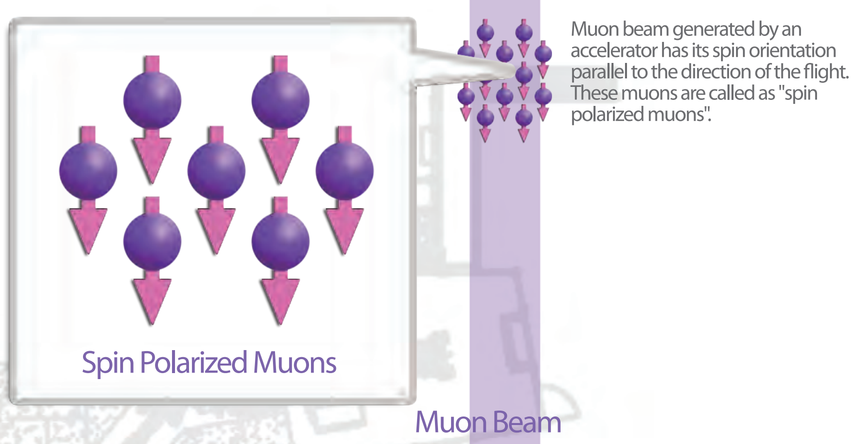
Inelastic Neutron Scattering

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 motions of atoms, molecules and spins in the sample. Some of neutrons get energy from motions 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 scatterings.

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 muon, muon spin rotation, relaxation, and resonance (μSR) 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.



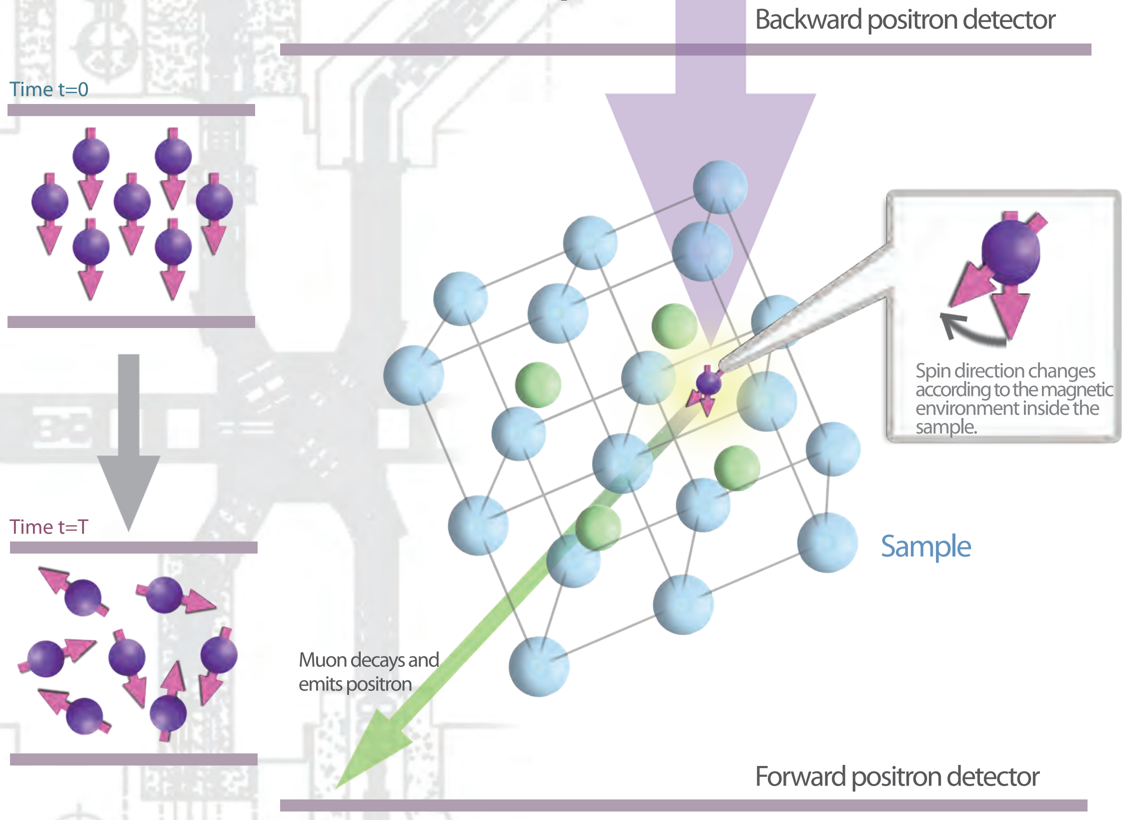
Muon beam generated by an accelerator has its spin orientation parallel to the direction of the flight. These muons are called as "spin polarized muons".

Investigation with MUONS

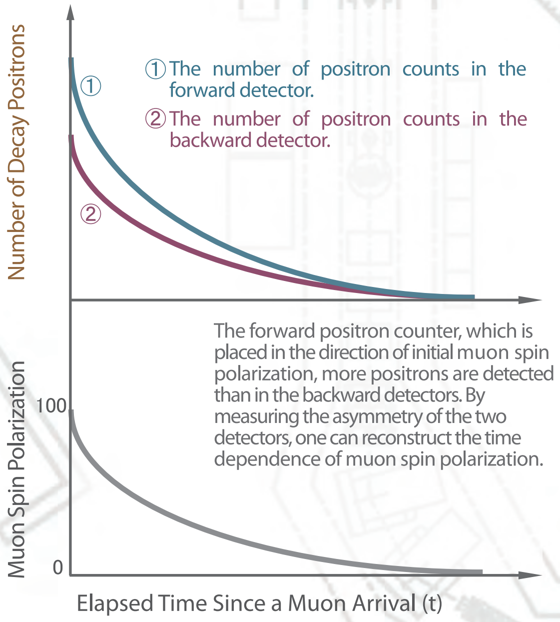
Muon Spin Rotation, Relaxation and Resonance (μSR)

Muons implanted into the samle 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 micro-seconds 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.



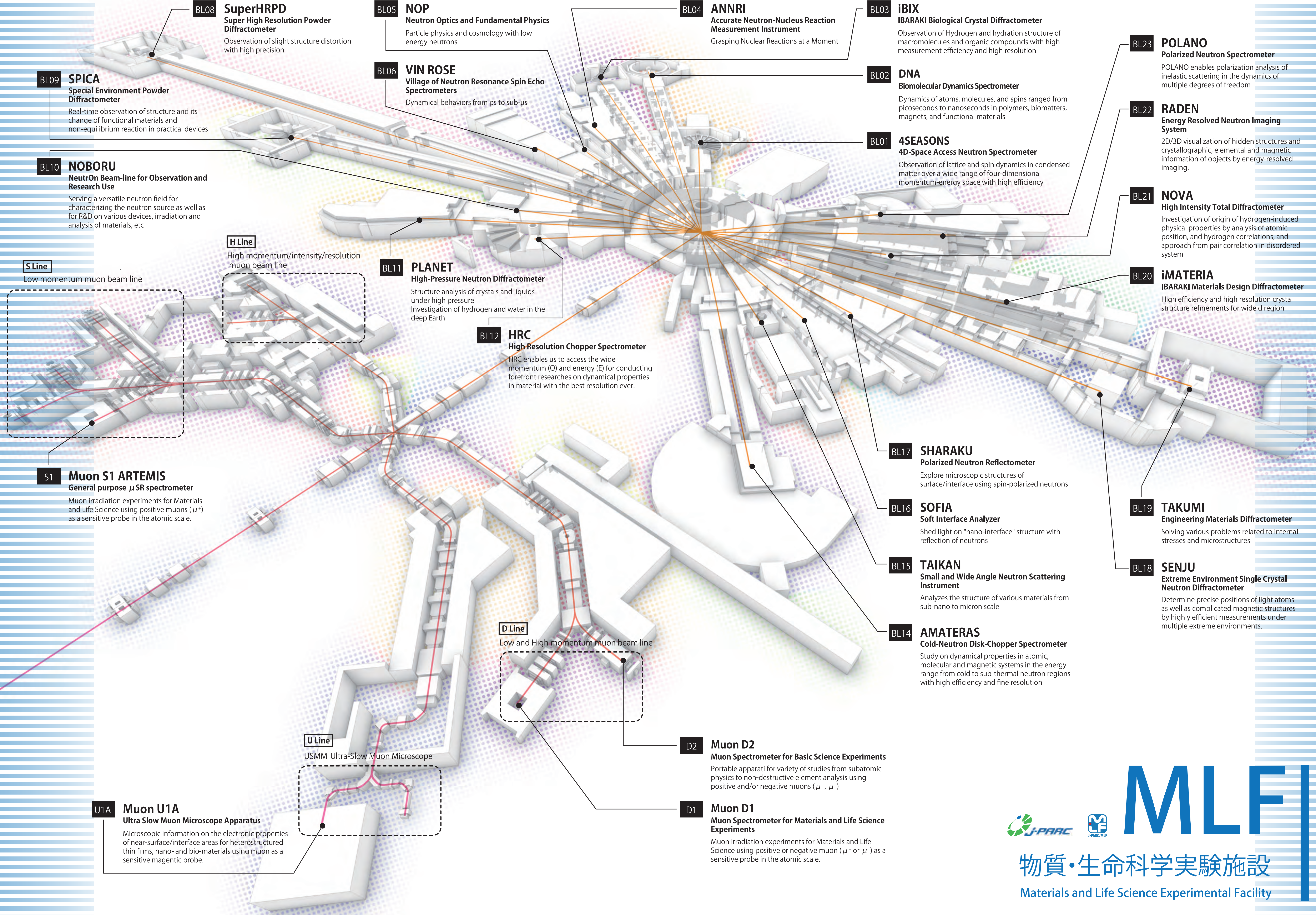
Spin direction changes according to the magnetic environment inside the sample.



The forward positron counter, which is placed in the direction of initial muon spin polarization, more positrons are detected than in the backward detectors. By measuring the asymmetry of the two detectors, one can reconstruct the time dependence of muon spin polarization.

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.



BL08 SuperHRPD
Super High Resolution Powder Diffractometer
Observation of slight structure distortion with high precision

BL05 NOP
Neutron Optics and Fundamental Physics
Particle physics and cosmology with low energy neutrons

BL04 ANNRI
Accurate Neutron-Nucleus Reaction Measurement Instrument
Grasping Nuclear Reactions at a Moment

BL03 iBIX
IBARAKI Biological Crystal Diffractometer
Observation of Hydrogen and hydration structure of macromolecules and organic compounds with high measurement efficiency and high resolution

BL23 POLANO
Polarized Neutron Spectrometer
POLANO enables polarization analysis of inelastic scattering in the dynamics of multiple degrees of freedom

BL09 SPICA
Special Environment Powder Diffractometer
Real-time observation of structure and its change of functional materials and non-equilibrium reaction in practical devices

BL06 VIN ROSE
Village of Neutron Resonance Spin Echo Spectrometers
Dynamical behaviors from ps to sub-μs

BL02 DNA
Biomolecular Dynamics Spectrometer
Dynamics of atoms, molecules, and spins ranged from picoseconds to nanoseconds in polymers, biomatters, magnets, and functional materials

BL22 RADEN
Energy Resolved Neutron Imaging System
2D/3D visualization of hidden structures and crystallographic, elemental and magnetic information of objects by energy-resolved imaging.

BL01 4SEASONS
4D-Space Access Neutron Spectrometer
Observation of lattice and spin dynamics in condensed matter over a wide range of four-dimensional momentum-energy space with high efficiency

BL10 NOBORU
NeutrOn Beam-line for Observation and Research Use
Serving a versatile neutron field for characterizing the neutron source as well as for R&D on various devices, irradiation and analysis of materials, etc

BL21 NOVA
High Intensity Total Diffractometer
Investigation of origin of hydrogen-induced physical properties by analysis of atomic position, and hydrogen correlations, and approach from pair correlation in disordered system

H Line
High momentum/intensity/resolution muon beam line

S Line
Low momentum muon beam line

BL11 PLANET
High-Pressure Neutron Diffractometer
Structure analysis of crystals and liquids under high pressure
Investigation of hydrogen and water in the deep Earth

BL20 iMATERIA
IBARAKI Materials Design Diffractometer
High efficiency and high resolution crystal structure refinements for wide d region

BL12 HRC
High Resolution Chopper Spectrometer
HRC enables us to access the wide momentum (Q) and energy (E) for conducting forefront researches on dynamical properties in material with the best resolution ever!

BL17 SHARAKU
Polarized Neutron Reflectometer
Explore microscopic structures of surface/interface using spin-polarized neutrons

S1 Muon S1 ARTEMIS
General purpose μSR spectrometer
Muon irradiation experiments for Materials and Life Science using positive muons (μ^+) as a sensitive probe in the atomic scale.

BL16 SOFIA
Soft Interface Analyzer
Shed light on "nano-interface" structure with reflection of neutrons

BL19 TAKUMI
Engineering Materials Diffractometer
Solving various problems related to internal stresses and microstructures

BL15 TAIKAN
Small and Wide Angle Neutron Scattering Instrument
Analyzes the structure of various materials from sub-nano to micron scale

BL18 SENJU
Extreme Environment Single Crystal Neutron Diffractometer
Determine precise positions of light atoms as well as complicated magnetic structures by highly efficient measurements under multiple extreme environments.

D Line
Low and High momentum muon beam line

BL14 AMATERAS
Cold-Neutron Disk-Chopper Spectrometer
Study on dynamical properties in atomic, molecular and magnetic systems in the energy range from cold to sub-thermal neutron regions with high efficiency and fine resolution

U Line
USMM Ultra-Slow Muon Microscope

D2 Muon D2
Muon Spectrometer for Basic Science Experiments
Portable apparati for variety of studies from subatomic physics to non-destructive element analysis using positive and/or negative muons (μ^+, μ^-)

U1A Muon U1A
Ultra Slow Muon Microscope Apparatus
Microscopic information on the electronic properties of near-surface/interface areas for heterostructured thin films, nano- and bio-materials using muon as a sensitive magentic probe.

D1 Muon D1
Muon Spectrometer for Materials and Life Science Experiments
Muon irradiation experiments for Materials and Life Science using positive or negative muon (μ^+ or μ^-) as a sensitive probe in the atomic scale.

MLF
物質・生命科学実験施設
Materials and Life Science Experimental Facility