Installation of the High Resolution Chopper Spectrometer (HRC) at the Japan Proton Accelerator Research Complex (J-PARC).

Using neutrons to see waves in a solid

[Neutron Chopper, Spin Wave, Fermi Chopper, T0 Chopper]

In March 2010, construction was mostly completed on a new neutron spectrometer at the Japan Proton Accelerator Research Complex (J-PARC); the new device is the High Resolution Chopper Spectrometer (HRC). The HRC will explore the hidden motion of atoms within solid materials. Read here about how the HRC pushes the boundaries of neutron spectroscopy, and how the state-of-the-art equipment the HRC team developed has made this possible.

The atoms within a solid are not entirely still. They vibrate. They also interact with each other. This means that an excitation in one atom can be transmitted to its neighbors, then transmitted to their neighbors, and so on. This moving collective excitation is called a wave.

There are several different types of excitation which can travel through a solid in waves. For example, take lattice vibration in the crystal structure of a solid. The vibrational excitation in a lattice gives rise to wave modes, called phonons. Phonons play a crucial role in determining the physical properties of solids. Another example is a spin wave. Each atom in solid sometimes acts like a tiny magnet, and this characteristic is called spin. The excitation of spin states can also cause waves. The quantized modes of a spin wave are called magnons.

“Both lattice waves and spin waves are the result of atomic interactions," explains Prof. Shinichi Itoh of KEK, the leader of the High Resolution Chopper Spectrometer (HRC) group. “By looking at how waves propagate, we can infer something about the interactions among the atoms in a material, and about the

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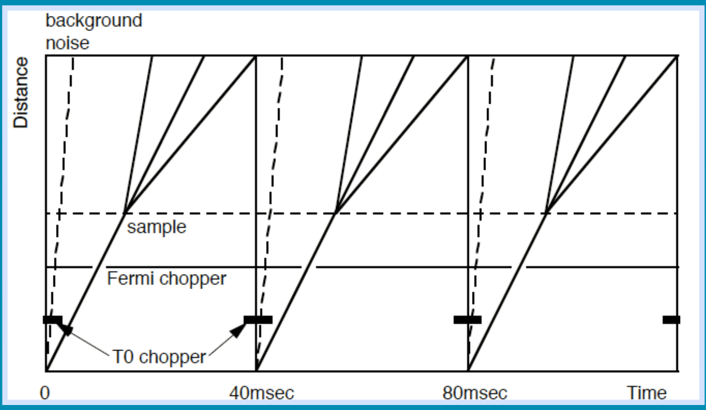


Neutron pulses are generated every 40 milliseconds. The Fermi chopper allows neutrons with the desired energy to pass, but blocks the rest. The monochromatic neutrons hit the sample, and interact inelastically with atoms in the sample. After passing through the sample, high energy neutrons travel faster, while low energy neutrons travel slower. Scientists can calculate the energy of the neutrons which have interacted with the sample by measuring the time-of-flight of the neutrons. Very high energy neutrons penetrate through the Fermi chopper, causing a large amount of background noise during the earlier part of each time-of-flight measurement. The T0 chopper shuts out such high energy neutrons.

physical structure of the material."

The purpose of the new HRC, which is located at the Japan Proton Accelerator Research Complex (J-PARC), is to measure how waves propagate in solids. It will do so with high resolution, and it has the ability to observe waves with a wide range of energy and momentum. Specifically, the HRC is expected to produce high resolution measurements at energy levels up to a thousand times greater than that of conventional neutron spectrometers installed at research reactors. Additionally, the HRC will be able to make measurements of spin waves on both crystalline samples and powder samples. Ordinary neutron spectrometers are limited to just crystalline samples.

Built in a collaborative effort between KEK and the University of Tokyo, the HRC is the result of the team's persistence, and their commitment to precision engineering. In particular, KEK Neutron Science Division (KENS) and KEK Mechanical Engineering Center (MEC) have worked together on major improvements to several experimental devices, including large-area aluminum windows, the T0 (pronounced 't-zero') chopper, and the Fermi chopper.

How a neutron chopper works

Neutron scientists produce neutrons by bombarding the neutron target with J-PARC's high intensity pulsed proton beam. The generated high energy neutrons are moderated to give the lower energy neutrons. Neutrons in each pulse, whose energies ranging from milli-eV to GeV, travel inside neutron mirror guide at different speeds.

The job of neutron choppers is to remove the portion of a neutron beam which has neutrons with unwanted energy, so that only neutrons with the desired energy reach the sample. When monochromatic neutrons (neutrons with the same energy) hit a sample, they interact with the atoms in the sample inelastically, either transferring energy to the atoms, or taking energy from the atoms. Those neutrons that come out at higher energy travel faster, while those neutrons that come out at lower energy travel slower. By measuring the time-of-flight (TOF) to the detectors, scientists can calculate the amount of energy transferred from the neutrons to the sample.

In standard neutron scattering, momentum is also transferred either to or from the atoms in the sample. In general, the scattering angle is related to the momentum transfer, which is inversely proportional to the wavelength of the neutrons. This means that for monochromatic neutrons, such as those that come out of the choppers, the momentum transfer can be directly calculated from the angle of scattering. The scattering angle is measured by the detector.

Knowing both energy transfer and momentum transfer of each neutron detected, scientists can produce a map of the number of neutrons on an energy-momentum space. A Fourier transform of the momentum transfer gives spatial information about the atomic structure of the sample. On the other hand, the energy transfer gives information about how strongly neutrons interacted with the atoms. Neutrons interact differently with different types of atoms.

Neutron spectroscopy gives information which complements that given by other spectroscopy methods, such as X-ray spectroscopy. Because neutrons are electrically neutral, they do not interact electrically with the electron clouds surrounding the nucleus. This means that they directly interact with nucleus of the sample atoms, energetically exciting or relaxing them. Neutrons also have spin, which allows them to interact magnetically with the electrons and nucleus of atoms in the samples.

For example, in water molecules (H2O), the amount of energy transfer for vibrational mode is unchanged as a function of momentum transfer. This implies that the vibrations of atoms are local, that they do not spread out in the form of excitation waves. Within each molecule, the hydrogen atoms and the oxygen atom can oscillate with respect to each other, but do not cause any change in global structure.

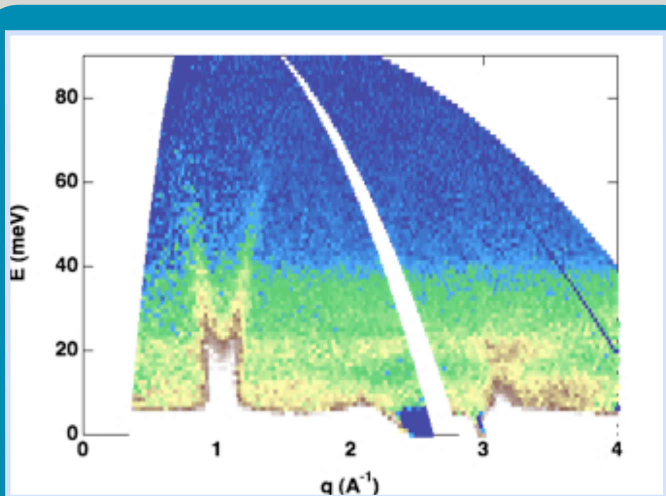
On the other hand, when looking at spin waves in a one-dimensional magnet, a plot of energy transfer versus momentum transfer shows clear evidence of spin waves propagating through the magnet.

High resolution, high energy, and the first Brillouin zones

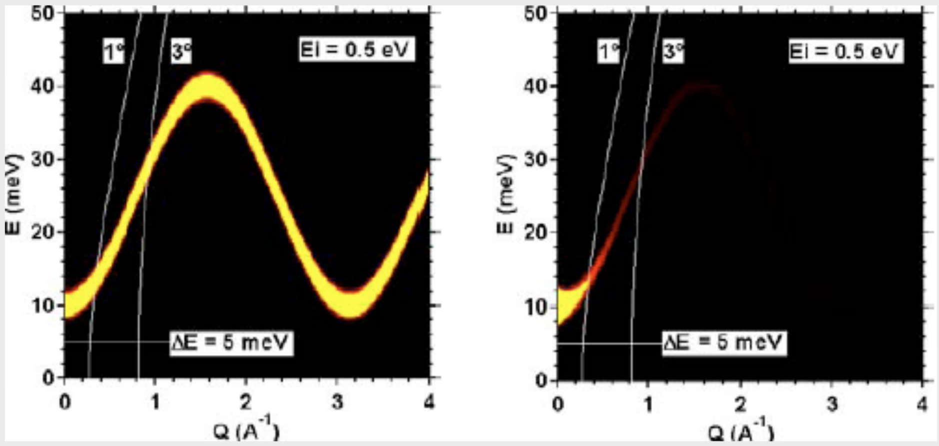
The primary goal of the HRC team is to achieve the highest energy resolution in chopper neutron spectroscopy. Currently choppers have an energy resolution of a few percent with respect to the incoming neutron energy. The HRC aims for a 1 percent energy resolution at an energy level of one eV.

The chopper device used in the HRC, called a Fermi chopper, was originally used in the KENS at KEK. This chopper achieved an energy resolution of just 5 percent when at KENS. "At J-PARC, the high intensity proton beam, the sharp neutron pulses, and the longer neutron flight distance allowed for higher resolution," explains Itoh. "We now are working on reducing background noises. Currently, the energy resolution is 2 percent, but we hope to improve this to 1 percent at high energies."

However, this is just the beginning. The dream of the HRC team is to access what is called the first Brillouin zone, a space the size of a single



A spin wave in a one dimensional anti-ferromagnet, plotted on an energy transfer (vertical) vs. momentum transfer (horizontal) plane. The image was obtained by HRC.



Right: an example of the spin wave spectrum from a single crystalline sample plotted on an energy transfer (vertical) vs. momentum transfer (horizontal) plane. Left: When the sample is not a single crystal, the spectrum from the high momentum transfer region is lost. Thus, for non-crystalline powder samples, it is critical to gain access to the low momentum transfer region, called the first Brillouin zone. The HRC aims to access the first Brillouin zone in the near future.

cell in a periodic medium. Generally, in order to observe spin waves by inelastic neutron scattering, the sample must be a single crystal with a mass of some tens of grams. Growing such a large crystal is very difficult at best, and impossible for many materials. Samples that cannot be crystallized can only be accurately observed with a spectrometer that has a resolution that allows scientists to access the first Brillouin zone. For a powder sample, spin wave signals get smeared out in higher momentum region due to the random orientation of crystals. By accessing the first Brillouin zone, scientists can observe spin waves that still remain intact.

To access the first Brillouin zone, scientists need to obtain energy and momentum distribution of neutrons that are scattered at very small angles. This is challenging, because the small angle region is close to the neutron beam's center where there is severe background noise. To cope with this, the HRC setup allows a longer distance between the sample and the detectors for scattering angles within ten degrees in both horizontal and vertical directions. This is so that the team can closely explore the low scattering angle regime.

"We have a setup that can measure neutrons at scattering angles of down to 0.5 degrees," says Itoh. "This will allow us to look at a wide range of powder samples, including some ferromagnetic materials. For example, spintronics is an emerging technology that utilizes both the spin and electric charge of electrons, but it is impossible to grow a single crystal of the ferromagnetic materials required in spintronics. Having access to the first Brillouin zone will help us to explore the dynamic structures of such materials."

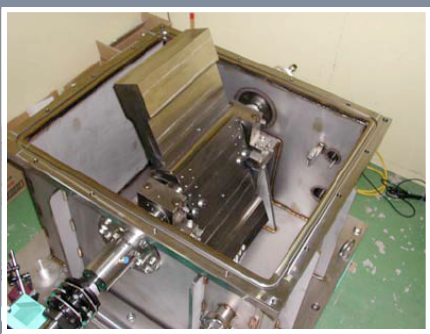
The team's ultimate goal is to explore the very high energy region, from sub eV to more than one eV. This is an unexplored region both for neutron spectroscopy and for basic neutron science. "In addition to the eV extension of molecular and material neutron spectroscopy, there are theoretical predictions which have yet to be tested," says Itoh. "However, these advancements will require a one megawatt proton beam, so it will be a while before we can explore this."

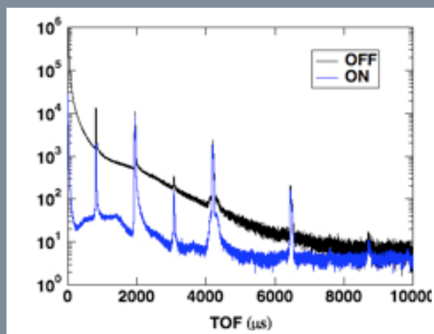
Designing an ultrafast T0 chopper

Designing and developing the high resolution spectrometer required very high precision engineering. Since 2002, the HRC team has worked with KEK's MEC to conduct the development and rigorous testing of the HRC experimental devices.

The most notable result of this collaboration is the T0 chopper. The T0 chopper removes the high energy end of the neutron beam, those neutrons with energies over several eV, and it does this at the very moment of neutron generation (thus the name T0 chopper). Those high energy neutrons would otherwise interact with the internal structures of the spectrometer and cause a large amount of noise. Since high energy neutrons easily penetrate through materials, blocking these neutrons, requires a 120 kilogram metal block. To cut off just the fast moving, high energy neutrons, the block needs to be moved in and out of the neutron path very quickly. This means that the metal block needs to be rotated at 100 hertz, synchronizing with the accelerator at J-PARC. The only rotor in operation in the world achieved only 50 hertz at the time when the team started development.

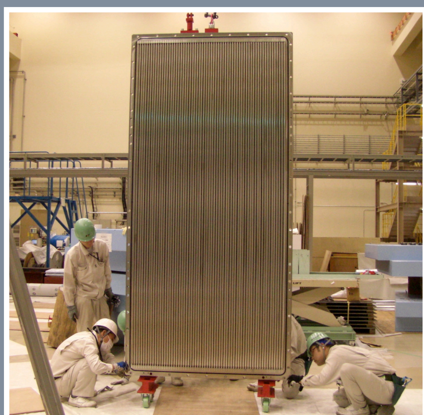
"The gap between 50 hertz and 100 hertz is large in terms of mechanical difficulty. The coaxial parts must be aligned within 10 micrometers, and the rotor timing precision needed to be within 5 microseconds," says


The T0 chopper cuts away unwanted high energy neutrons, those with energy above several eV. The state-of-the-art rotor rotates the 128-kilogram shield at 100 hertz.



The installation of the T0 chopper reduced the background noise by a factor of a hundred.


The HRC team and KEK's Mechanical Engineering Center (MEC) developed the Fermi chopper using magnetic rotor bearing.


An array of 64-piece position sensitive helium-3 detectors.

The HRC team gathers for a group photo during the ceremony to celebrate the completion of the HRC in March, 2010.

Itoh. The completed T0 chopper operated beyond their expectations. The timing was off by less than 1 microsecond. “The T0 chopper pushed the limits of precision engineering in every aspect.”

The installation of the T0 chopper had a great impact. During the beam time, before the T0 chopper had been installed, the background noise was so severe that analysis was impossible. After the installation, however, the background noise was reduced by a factor of one hundred. The successful design of the T0 chopper will also be used at several other neutron beamlines at J-PARC.

The team and the MEC also developed aluminum windows for the vacuum chamber and the Fermi chopper. The 1-meter square aluminum windows, placed in contact with the detectors, which sit just outside of the vacuum chamber, needed to be 1-millimeter thick, and yet be strong enough to endure the atmospheric pressure. The Fermi chopper—not to be confused with the T0 chopper—monochromatizes neutrons using a rotating disc with slits in a cylinder which is 10 centimeters in diameter. The Fermi chopper requires the disc to rotate without friction, for which scientists utilized a magnetic rotor bearing. “We now have in-house technology to build the necessary components of the aluminum windows and the Fermi chopper,” says Itoh.

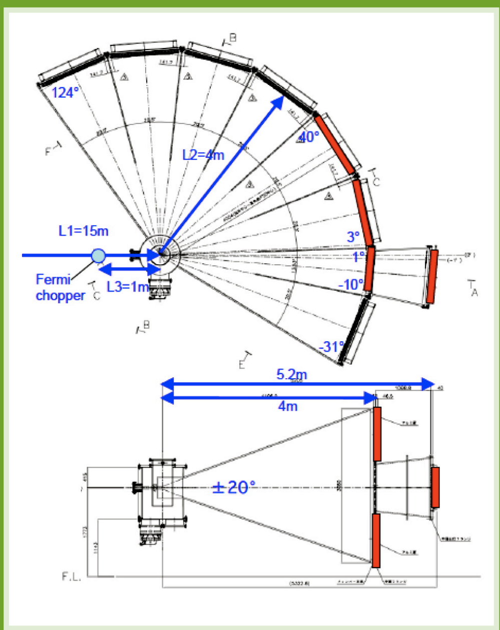
The Helium predicament and prospects

There is in fact a predicament that all members of the neutron experiment community throughout the world find themselves in: a shortage of helium-3. The helium-3 gas detector is the most promising, and best-tested, high precision neutron detector. Due to the security policy currently embraced by the US—the world's sole helium-3 supplier—that inhibits Helium-3 exports for the use beyond security, neutron spectroscopy scientists stand at a crossroad. They can either wait for the policy to change, or develop new detectors.

Many neutron beamlines around the world are affected, and the HRC is no exception. The helium-3 filled detectors for the HRC are supposed to cover the end plate of a fan-shaped vacuum chamber which spreads from minus 31 degrees to plus 124 degrees in the horizontal direction with respect to the beam center. Unfortunately, at this time, the portions of the end plate below minus 10 degrees and above 40 degrees are currently without detectors. This means that only a third of the detector is complete.

However, the HRC team has plans to improve the resolution of the spectrometer, even with the partial lack of the detector sections. First, they are developing a design to reduce noise by installing neutron shields. When the beam hits the walls of vacuum chamber, neutrons are scattered inside the chamber, creating noise. Second, in conjunction with MEC, the team is looking for good materials for the slit used in the Fermi chopper. The slit needs to be made of highly effective shielding material to block the high energy neutrons, and also needs to be as thin and strong as possible to allow for the high frequency rotation.

“Even with the difficulty of the missing detectors, we are making solid steps forward. New data is coming out, and we hope that the cutting-edge science will soon become possible at the HRC,” says Itoh.



Top: the top view of the HRC spectrometer. Bottom: the side view of the HRC spectrometer. The red shows helium-3 detectors already installed.

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