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FEATURE STORY

A backdoor to new physics

[Neutron, Electric Dipole Moment]

The Neutron Optics and Physics group at KEK (NOP) is preparing to begin the research and development of an experiment to measure the neutron electric dipole moment. The result may answer one of the most fundamental questions about the universe. To make this measurement, the group proposes an innovative

The NOP group members gather in front of their beamline at J-PARC: (Back left) two physicists from KEK, Dr. Kenji Mishima and Dr. Tamaki Yoshioka, and two PhD students from the University of Tokyo, Hidehiko Otono (front left) and Hideyuki Oide.

Current cosmology tells us that our universe started out from ‘nothingness’. When our universe first burst into existence, there were equal numbers of particles and antiparticles. Yet today, our universe is almost entirely composed of matter, with just a very little bit of antimatter.

Physicists have proposed several mechanisms to explain how this matter-antimatter asymmetry came about. Recently, they found physical evidences for one such mechanism: violation of charge conjugation-parity (CP) symmetry. CP symmetry says that the laws of physics must stay the same when a particle is swapped with its antiparticle (charge conjugation) and then takes mirror image (parity operation) of its physical properties such as spin. In 2001, both the Belle experiment at KEK and the BaBar experiment at SLAC succeeded in providing experimental evidence for mechanism of CP symmetry violation in B meson decay.

The outstanding problem with the CP violation is that size of this known violation is too small to explain the large matter/antimatter asymmetry in our visible universe. So particle accelerators around the world are working to increase the energy of the collisions to look for additional, hidden CP violations. Interesting candidates for additional CP violation includes those in new exotic physics such as in theories of supersymmetry (SUSY).

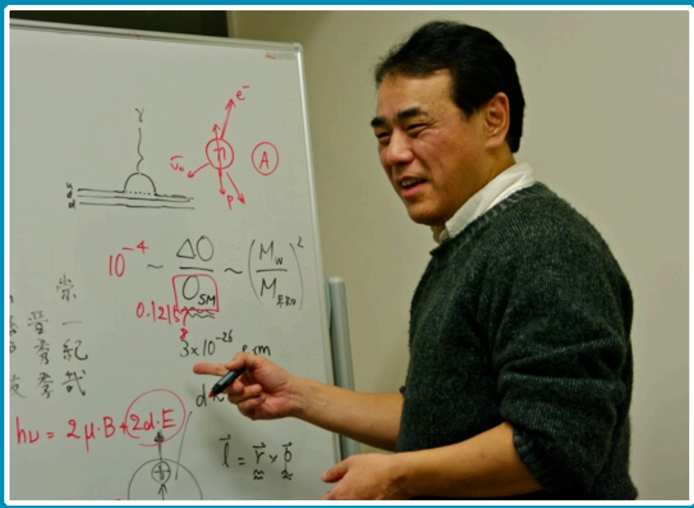
However, colliding particles at high energy isn’t the only way to search for CP violations. In the indirect CP violation search, physicists use a more fundamental symmetry in the laws of physics, CPT symmetry. The CPT symmetry says that the laws of physics should be unaltered when charge conjugation, parity, and time reversal are applied simultaneously.

This means that one can look for violation of time reversal symmetry to deduce violation of CP symmetry. If time reversal T symmetry is broken, then unbroken CP operation cannot restore the CPT symmetry. Because the CPT symmetry must be preserved at all time, T symmetry violation automatically implies CP symmetry violation. This method—looking for CP violation by means of time reversal violation—is called indirect CP violation search.

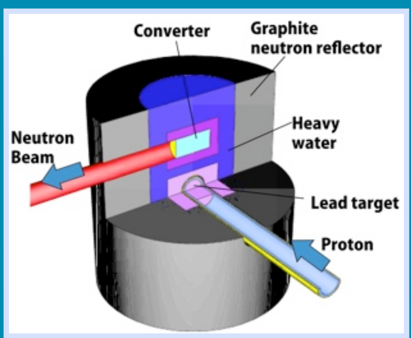
Neutron electric dipole moment

The Neutron Optics and Physics (NOP) group at the Japan Proton Research Complex (J-PARC) is a collaboration of seven universities and research institutions in Japan including KEK. The mission of the group is to perform research on a number of topics in fundamental physics using neutron beams. One of the main objectives of NOP is to search for CP violation indirectly by measuring the size of the electric dipole moment of neutrons.

An electric dipole moment is a slight asymmetry in the distribution of electric charges inside neutrons. Since neutrons are electrically neutral particles, they have an equal amount of positive and negative charge inside. However, the positive and negative charges may not be evenly distributed. For example, there may be more positive charges on one side, and more negative charges on the other. This asymmetry is called an electric dipole moment, and means that neutrons can be affected just a little by the presence of a powerful electric field. The world's most advanced neutron experiment at Institut Laue-Langevin (ILL) has shown that the value cannot be larger than 10^{-26} e centimeters.



The leader of Neutron Optics and Physics (NOP) group at KEK Prof. Hirohiko Shimizu explains the theory behind the neutron electric dipole moment experiment.



A schematic picture of the ultracold neutron source with a converter, in which cold neutrons are slowed to become ultracold neutrons.

"The neutron electric dipole moment is the most promising probe for new physics. With this tool, theoretical predictions of models beyond the Standard Model are experimentally testable," explains the NOP group leader Prof. Hirohiko Shimizu of KEK.

The uncertainty principle of quantum mechanics states that the elementary particles which make up a neutron—an up quark and two down quarks—can spontaneously transform into much heavier particles for a brief periods of time. Those heavier particles may be either known particles from the Standard Model, or exotic new particles from theories beyond the Standard Model. Either way, these short-lived heavy particles can occasionally interact with external particles like photons.

"In order to prove the existence of new particle, we need to be able to measure a moment on the order of 10^{-31} e centimeters," says Shimizu. However, some supersymmetric models predict a moment of 10^{-27} ecentimeters, meaning that just one order of magnitude improvement in the measurement will prove or disprove some models.

Since neutrons have a small magnet-like property called spin, they precess in the presence of a magnetic field. If physicists apply an alternating electric field in addition to a static magnetic field, the interaction of the electric field and the electric dipole moment causes the neutrons to precess at a faster rate. "Spin causes neutrons to precess a few times per second, while the electric dipole moment increases that by something like one precession in 100 years," says Shimizu. "To measure this tiny difference, we need to produce and store as many neutrons as possible."

Ultracold neutron source

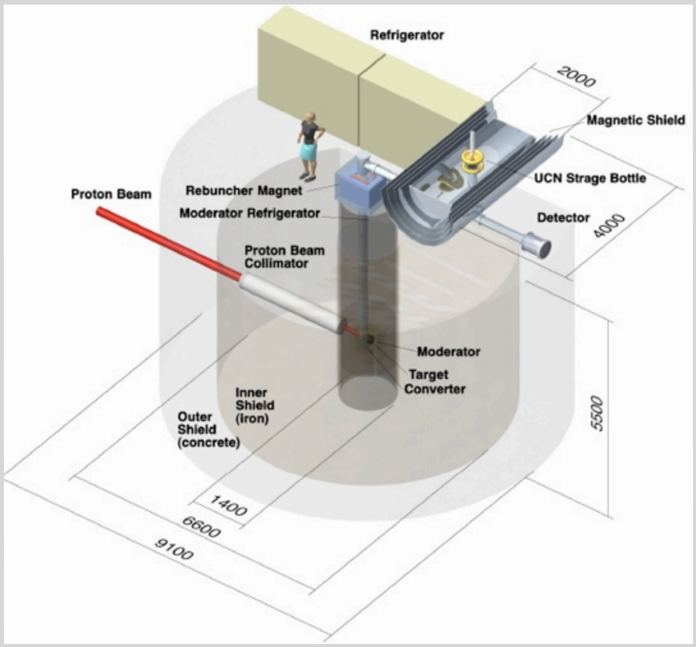
The NOP's proposed neutron electric dipole moment beamline will produce high intensity pulsed beam of cold neutrons from protons provided by a linac at J-PARC. The resulting cold neutrons are then slowed, transforming them into ultracold neutrons by a converter. Ultracold neutrons are very slow neutrons, moving at the speed of just a few meters per second. The team estimates that the system produces several thousands neutrons per cubic centimeter per pulse. The ultracold neutrons are then guided to the storage cell.

As the neutrons travel to the storage cell, the neutron pulse smears out as some particles travel faster while some travel slower. To reduce the velocity differences, physicists use the spin property of neutrons. When a varying external magnetic field of a particular type is applied to the neutrons, the spin of the neutrons flips, releasing energy from the neutrons, and slowing the faster neutrons. This makes the neutron bunch much denser. Additionally, the slowest neutrons are cut out of the bunch by a shutter before entering the storage cell. This combination of magnetic field and shutter is called a neutron rebuncher. The team found that repeating this process ten times would multiply the number of neutrons in the cell by roughly three times.

Neutron storage

The gist of effective neutron storage is to produce ultracold neutrons and let them

(From left) Dr. Takashi Ino, Dr. Kaoru Taketani, Dr. Tamaki Yoshioka, and Dr. Kenji Mishima from KEK gather around their neutron guides with supermirrors on the inner surfaces to guide slow neutrons. They are the four members who constructed BL05.



A schematic view of the ultracold neutron source at J-PARC. This source is used for the neutron electric dipole moment experiment.

bounce around inside of a small volume. The challenge is to make the cloud of neutrons as dense as possible.

“The neutrons in the storage cell are moving around randomly and behave like a gas, so when compressed, the temperature rises, making them move faster,” explains Shimizu. “Faster neutrons will simply penetrate through the container.”

At ILL, about 10 ultracold neutrons per cubic centimeter enter the storage container. This means that, ideally, their 20-litter volume can hold a total of 200,000 ultracold neutrons. An alternative to increasing density is to make the volume larger. However, neutron precession can be disturbed by very small magnetic fields. Using a larger volume is not practical since a larger cell requires a larger magnetic shield.

For this reason, neutron laboratories from around the world are trying to increase storage density, rather than increase storage volume. Both the Paul Scherrer Institut (PSI) in Switzerland and the National Laboratory for Particle and Nuclear Physics (TRIUMF) in Canada aims to hold neutrons of the order of several thousands per cubic centimeters. That's a two-digit improvement. “Our group at KEK is aiming for at least two-digit improvement, and possibly more. This would increase the sensitivity of the device by a factor of at least ten,” says Shimizu.

Neutron guide

The NOP team has just launched into the research and development of the neutron electric dipole moment experiment using a neutron beamline called BL05. BL05 produces cold neutrons from protons provided by a 3 GeV proton synchrotron at J-PARC, and sends them to three beamline branches. The R&D is conducted at an experimental station installed on one of the branches.

Accelerator scientists generally use magnets to skew and focus beams of charged particles. For electrically neutral neutrons, however, that is not possible. To prevent dispersion of neutron beams during transport to an experimental station, the team introduced a neutron guide with specially designed mirrors on the inner surfaces to reflect neutrons away from the guide walls and contain them inside the guide. This was one of Shimizu’s previous contributions to the neutron science.

Each mirror is itself a work of art. Because neutrons are electrically neutral, they easily penetrate ordinary substances, undisturbed by the electrons and protons in everyday matter. To reflect them back, the guide uses special mirrors with fine granularity film coating for the inner surface. Even though neutrons are undisturbed by electric charges in atoms, they still experience nuclear potential due to nucleus. The potential is very small at 10^{-4} eV, but tightly spaced nuclei can form a potential to reflect back slow-moving neutrons. This specially fabricated mirror is called a supermirror.

Doppler shifter

For their R&D work, the team proposes to take a step further and use this supermirror to convert as many cold neutrons as possible to ultracold neutrons. Cold neutrons move at a speed of 1,000 meters per second. The current supermirror technology only allows reflection of neutrons moving slower than 42 meters per second. Any neutrons moving faster than that can escape the container. In practice, this means that significant portions of neutrons are lost before they can be used in the experiment.

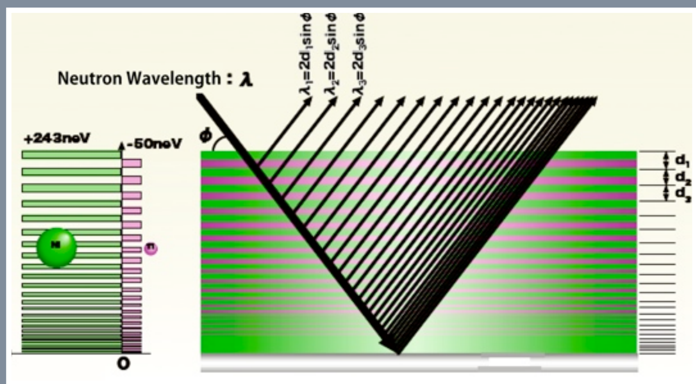
“We know that there are a sufficient number of neutrons which travel at under 200 meters per second being produced at BL05,” says Shimizu. “We need a supermirror that can reflect back those neutrons.”

He says a supermirror that could reflect neutrons with a speed under 100 meters per second would be sufficient. Simple kinematics says that if the mirror is in motion at 100 meters per second away from the neutron source, those neutrons moving at 200 meters per second would come to complete halt when they hit the mirror. Neutrons moving less than 200 meters per second would be slowed. The team therefore has designed a clever turbine of supermirrors that rotates at a few Mach speed in vacuum to move the mirrors away at 100 meters per second. They call this turbine a Doppler shifter.

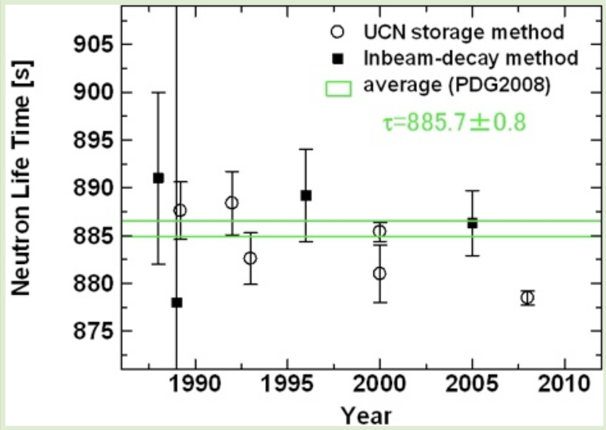
Supermirror

The big challenge is to create a supermirror that can reflect back neutrons moving at 100 meters per second. The current supermirror consists of ten thousand layers of 5-nanometer thick films. The new mirror will require between 100 thousand to a million layers of 2-nanometer thick films.

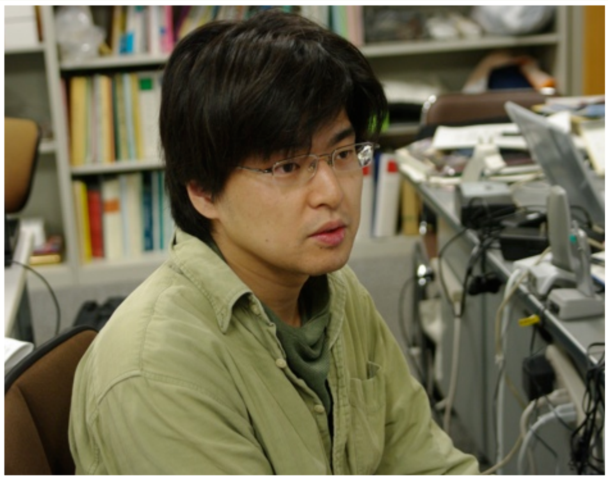
The enabling technology is called ion beam spattering. Nearly a decade ago, the neutron team from Kyoto University and the Institute of Physical and Chemical Research Laboratory (RIKEN) first used ion beam spattering to form films for the first neutron supermirror. Now, the technology has become standard in neutron experiments worldwide.



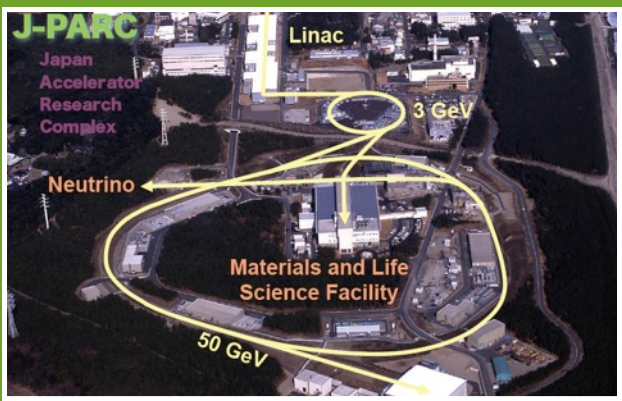
A supermirror consists of layers of thin films to create effective potentials with finely spaced nuclei so as to prevent neutrons from passing through.



The neutron lifetime is very difficult to measure. Depending on the experimental methods, past experiments have reported different values for the lifetime.



Sohei Imajo is a PhD student from Kyoto University working on Doppler shifter.



At J-PARC, the 3 GeV synchrotron proton ring provides proton beams to the neutron experimental hall at the Materials and Life Science Facility. The proposed electric dipole moment experimental station will be built at the end of the linac.

Over the past few years, Europe has caught up with the technologies required for supermirror production. However, Japan still holds the strongest technological base in these technologies, and is best positioned to advance the frontier further. Shimizu says that his team's goal is to create a mirror which can reflect neutrons with velocities up to 119 meters per second.

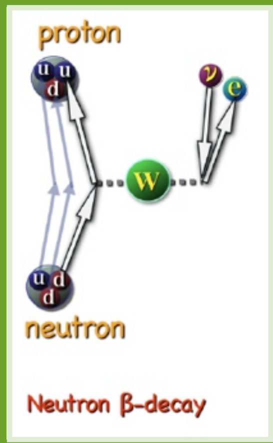
Neutron decay measurement

At another BL05 experimental station, the NOP group at KEK is now starting the first phase of the project: neutron decay time. About 15 minutes after its birth, a neutron decays into a proton, an electron, and an antineutrino. Many laboratories report that the lifetime to be around 886 seconds. One laboratory in Russia, Petersburg Nuclear Physics Institute (PNPI), reports it to be at 879 seconds, one percent less than the world's average. PNPI, however, has the best experimental sensitivity. The team's aim is to determine the precise lifetime of a neutron.

According to Shimizu, the research and development for the neutron electric dipole moment experiment will benefit from the physics of the neutron decay experiment. An observable called spin-electron asymmetry in neutron decay can explore some of the same physics as the neutron electric dipole moment. Although the measurement will not be as precise as that for the electric dipole moment, the team thinks that the result will help refine the dipole moment experiment setup.

"By determining the lifetime of the neutron, we can answer some very fundamental questions in physics. For example, we will improve our understanding of fundamental properties of the Standard Model, and of the composition of elements during the nucleosynthesis phase of the early universe," says Hidetoshi Otono, a PhD student at the University of Tokyo.

"We will hopefully put a period to the long debate over the lifetime of neutrons sometime this year," says Dr. Tamaki Yoshioka of KEK. He and Dr. Kenji Mishima of KEK have been working on the proposal for the neutron electric dipole moment experiment.



A neutron decays into a proton, an electron, and an antineutrino via a W boson.

What's impressive is that just a handful of physicists completed the designs and actual construction of the beamline in less than three years. "We are conducting processes that would have normally taken more than ten years," says Shimizu. "In the 25 years since KEK produced the world's first neutron beam from an accelerator, there has been little neutron science at KEK. We are now trying to make up for those 25 years.

The team has successfully applied their innovative ideas about neutron optics using supermirrors. In the very low energy, clean background, high quality neutron beamline at J-PARC, their physics endeavor now starts with unprecedented experimental sensitivity. Mishima who has worked on the project since its inception three years ago says, "Finally, we are at this moment of beginning that we have long waited for. We are looking forward to presenting the world with new conclusive results."

Related Link:
Neutron Optics and Physics

Paper:
Design of neutron beamline for fundamental physics at J-PARC BL05 (Nuclear Instruments and Methods in Physics Research Section A, Volume 600, Issue 1, p. 342-345.)

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