The NPDGamma Experiment

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Nuclear interactions between nucleons (protons and neutrons) involve both the strong and weak forces. Because the strong nuclear force is 10 million times stronger than the weak nuclear force, the weak force between nucleons is difficult to study and is not well understood. A tool for separating the two is the parity symmetry because the strong force preserves this symmetry and the weak force breaks it. The NPDGamma Experiment (Figure 1) is designed to study the weak force acting between neutrons and protons by observing violation of the parity symmetry in the capture of neutrons by protons, which results in the production of a deuteron (hydrogen-2 nucleus) and a gamma ray: $n + p \rightarrow d + \gamma$. Parity symmetry requires that the probability of the gamma ray being emitted in the direction of the neutron spin axis is equal to the probability of its being emitted in the opposite direction (Figure 2). Although the weak interaction between nucleons is fundamentally due to the exchange of *W* and *Z* bosons between quarks, nucleons are such complicated objects that computing the weak-interaction dynamics between them is impossible in the foreseeable future. One of the main problems with carrying out such a computation is that the quarks interact through the strong force. Consequently, the weak interaction must be calculated in the framework of an effective model of the strong interaction. Measurement of parity violation in the two-nucleon system provides an important test of theoretical calculations of the weak interaction in the nonperturbative quantum chromodynamic (QCD) regime.

Figure 1. The NPDGamma Experiment at LANSCE
The neutron beam enters from the left via a neutron guide enclosed by the stainless steel pipe, and the neutrons are polarized in the helium-3 polarizer (blue). Also shown is the array of 48 CsI detector crystals (right side). The reddish brown coils surrounding the apparatus generate a magnetic field to preserve the neutron polarization.

In one model of the weak force between nucleons, the force is carried by mesons traveling between the two. The NPDGamma experiment measures the contribution of the longest-range meson, the pion. This contribution has never been directly measured; it has only been inferred from effects in more-complicated systems, which have produced contradictory interpretations. Values of the weak pion–nucleon coupling have been extracted from two types of experiments. Interpretation of parity violation measurements of fluorine-18 gives an upper limit on this coupling that is significantly smaller than the value predicted by theory. Contradicting this result is a measurement of the anapole moment of cesium-133, which has been interpreted to give a value for the weak pion–nucleon coupling that is several times larger than the theoretical prediction. In contrast to both of these experiments, NPDGamma measures this effect in the two-nucleon system, so it is free from the uncertainties inherent in a nuclear many-body calculation.

In the NPDGamma experiment, when a neutron is captured to form a deuteron (the nucleus of a deuterium atom also called heavy hydrogen), a 2.2-million-electron-volt (MeV) gamma ray is emitted in the process to conserve energy. As mentioned above, parity symmetry requires

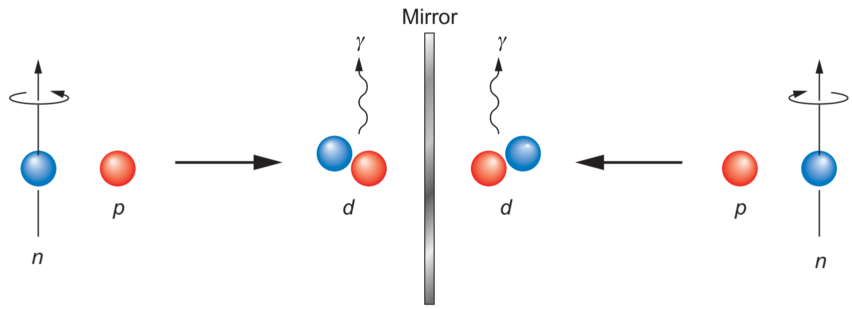

Figure 2. Parity Violation in the NPDGamma Experiment
Parity violation in the experiment is illustrated by comparing the reaction to its mirror image. In the reaction (left), a spin-polarized neutron combines with a proton to form a deuteron and a gamma ray. The gamma is shown being emitted in a preferential direction compared to the neutron spin axis. When the process is viewed in a mirror (right), the neutron appears to be spinning in the opposite direction, but the gamma ray is emitted in the same direction. The neutron spin direction can be restored by flipping the mirror image from top to bottom, but then the preferential direction for gamma-ray emission is reversed. This example shows that, if there is a preferential direction for gamma-ray emission relative to the neutron spin axis, then parity (mirror image) symmetry is violated.

that the probability of the gamma ray being emitted in the direction of the neutron spin axis is equal to the probability of its being emitted in the opposite direction (Figure 2). If there is any difference (asymmetry) in the two probabilities, it is due to the weak force, and the size of the difference is proportional to the relative contribution of the weak force compared ~~to~~ with the strong force to this process. This effect is expected to be small, approximately 50 parts per billion (ppb). The ultimate goal of NPDGamma is to measure parity violation in neutron-proton capture with a precision of 10 ppb.

The NPDGamma experiment, shown conceptually in Figure 3, starts with a beam of cold neutrons produced at LANSCE. The neutrons are guided by reflection from highly polished, specially prepared surfaces to the experimental cave, where they are spin-polarized in preparation for the measurement. The neutrons pass through a 30-liter liquid hydrogen target, where approximately 60 percent of the neutrons are captured by the protons inside the hydrogen atoms. The 2.2-MeV gamma rays from those reactions are detected in cesium iodide (CsI) crystals surrounding the target.

The neutrons have to be spin-polarized, that is, they must have all their spins pointing in the same direction, so that we can tell the relative probability of the gammas being emitted parallel and antiparallel to the spin direction. The method of neutron polarization used by the NPDGamma experiment relies upon the spin dependence of the interaction of neutrons with helium-3 nuclei. Both neutrons and helium-3 nuclei have spin ½. When the spins of a neutron and a helium-3 nucleus are oriented in opposite directions, the probability of the helium-3 capturing the neutron is very high. When the spins are oriented in the same direction, the probability is thousands of times lower. If the unpolarized neutrons pass through enough polarized helium-3, the neutron beam becomes polarized in the same direction. The helium-3 nuclei are polarized by shining circularly polarized laser light on a glass cell containing helium-3 atoms and a small amount of rubidium. The rubidium atoms with spin in one direction preferentially absorb the laser light, which leads first to polarized rubidium atoms. Collisions between the rubidium and helium-3 atoms transfer the polarization to the helium-3 nuclei. This polarization technique was perfected by the NPDGamma team.

The 48 gamma-ray detectors surrounding the liquid-hydrogen target are cubes of crystalline CsI measuring 15 centimeters on a side (Figure 4). When gammas strike the crystals, flashes of blue light are produced by a process called scintillation. This light is viewed by vacuum photodiodes, which convert the light to an electrical current. This current is converted to a voltage and amplified in specially designed low-noise electronics. The detector electronics are so quiet that "noise" in the electrical signals is actually due to the statistical fluctuations in the number of gammas arriving at a given time. Finally, the signals from many events are digitized and stored in computers. The low-noise electronics have also been developed by the NPDGamma team.

Because the detector sensitivities can never be matched accurately enough to detect a 50-ppb difference in the rates between different detectors, a technique called neutron spin reversal is employed. The neutrons are produced by the LANSCE accelerator in pulses spaced 50 milliseconds apart. Each pulse of neutrons starts with spins polarized in the vertical direction (up) by passing through the helium-3 cell. An asymmetry of approximately 2 percent is seen between the top and bottom CsI detectors because of differences in detector sensitivity. On the next pulse, a neutron spin flipper can be energized to rotate the spins by 180º (down). While the 2 percent asymmetry caused by

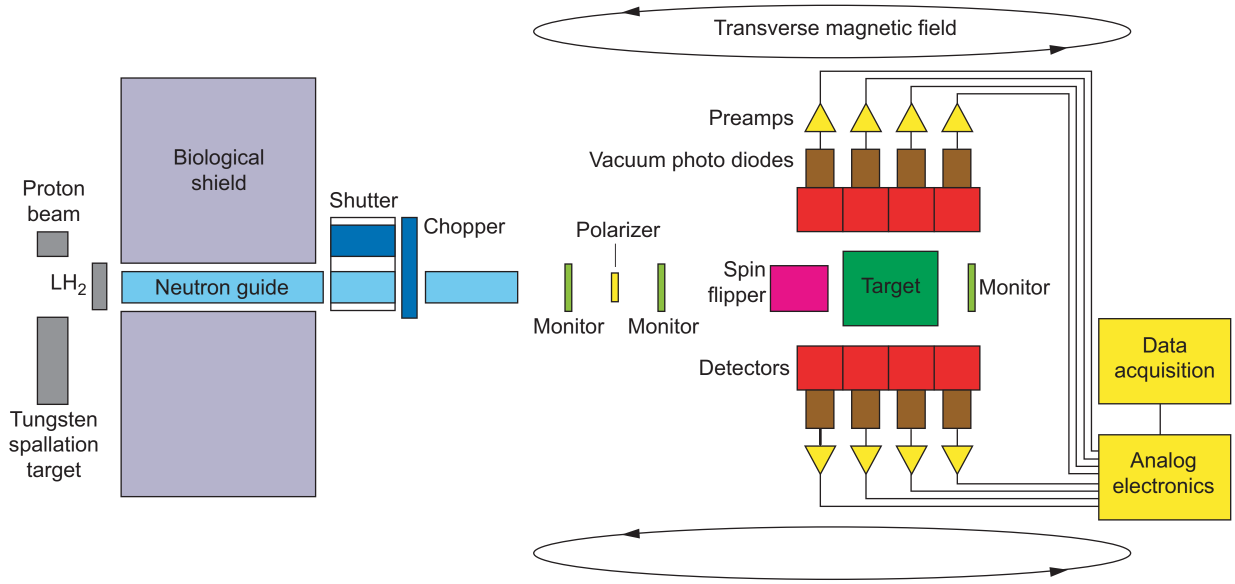

Figure 3. Conceptual Drawing of the NPDGamma Experiment
This drawing shows the major components of the NPDGamma Experiment. Neutrons are produced by the LANSCE proton beam striking a tungsten spallation source and are slowed to low energies by a cold hydrogen moderator. They are guided to the experiment and polarized by passage through a helium-3 polarizer. A spin flipper can periodically reverse the polarization of the neutrons before they are captured by the liquid hydrogen target. CsI crystals surround the target to detect the gamma rays produced in the NPDGamma reaction.

Figure 4. CsI Crystal for Detecting Gamma Rays
The photo shows one of 48 CsI crystals used to detect gamma rays in the NPDGamma experiment. Each crystal is approximately 15 cm on a side.

detector sensitivities remains the same, the 50-ppb asymmetry expected from parity violation reverses sign. Subtracting the asymmetries from the two pulses cancels the first (instrumental) effect and enhances the second (physics) effect.

In an attempt to measure such a small physics effect, many instrumental effects must be considered and minimized. These include parity violation from neutron capture on materials other than hydrogen, changes in beam properties or detector sensitivities with spin reversal, and electronic noise due to the operation of the spin flipper. All those effects have been considered in the design of the NPDGamma experiment and careful controls have been demonstrated to reduce these effects to less than 10 ppb. ■