Measurement of parity-violating neutron capture
gamma asymmetries at low-energies


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A sensitive measurement of parity-violating (PV) observables in few-nucleon systems can shed light on our current understanding of the hadronic weak interaction at low momentum transfers. Theoretical models describe the nucleon-nucleon weak interaction at low energies with 6 parameters that need, in principle, to be determined in the same number of independent experiments. In this context, a series of experiments with cold neutrons are being proposed and developed. Particularly, experiments that aim to measure the parity-violating asymmetry in the distribution of the gamma-rays emitted in the capture of polarized neutrons by protons and deuterium, will be discussed in this paper.

Keywords: Hadronic weak interaction; parity-violation observables; few nucleon systems; fundamental neutrón physics.

La medición de observables provenientes de la violación de paridad en sistemas de pocos nucleones puede ayudar a mejorar nuestro entendimiento actual de la interacción débil hadrónica. Los modelos teóricos describen la interacción débil nucleón-nucleón a bajas energías mediante 6 parámetros que necesitan ser determinados en el mismo número de experimentos independientes. En ese contexto una serie de experimentos con neutrones fríos están siendo propuestos y desarrollados. Particularmente se describirán en este trabajo, experimentos que buscan medir la asimetría, que viola paridad, en la distribución de los rayos gamma emitidos en la captura de neutrones fríos polarizados en protón y deuterio.

Descripciones: Interacción débil hadrónica; observables de la violación de paridad; sistemas de pocos nucleones; física fundamental con neutrones.
1. Introduction

Leptonic and semi-leptonic weak processes are well understood through the electroweak theory since in those QCD effects are small and can be parametrized in terms of currents with different tensor structures and couplings that can be determined from experiments. However, for purely hadronic weak processes the scenario is not as clear. The dynamics of the quarks in bound systems is dominated by momentum transfers that place the hadronic weak interaction in the non-perturbative regime of QCD, which at present makes impossible a first principle calculation of the nucleon-nucleon (NN) weak interaction.

The traditional way to describe the NN weak interaction has been the one-meson-exchange potential introduced by Desplanques, Donoghue and Holstein (DDH) in 1980 [1]. The range of the gauge bosons that mediate the weak interaction is only 0.02 fm, however the hard-core repulsion in the NN interaction keeps the nucleons much farther apart. The way to overcome this issue in the DDH model is to describe the weak interaction between nucleons as mediated by the exchange of light mesons. The meson-exchange potential of this formalism is a linear combination of terms, each involving the exchange of a $\pi$, $\rho$ or $\omega$ meson with isospin exchanges of 0, 1 or 2. Because QCD has not been solved for bound systems, the six meson-nucleon weak couplings ($f_1^\pi, h_0^\rho, h_1^\rho, h_2^\rho, h_0^\omega,$ and $h_1^\omega$) in the DDH potential cannot presently be calculated from first principles and need to be determined from experiments. Because of the PV nature of the weak interaction, that experimentally isolates it from the much stronger effects of the other interactions, a good number of PV observables have been measured in nuclear systems. However, the lack of knowledge of the wave functions of the nuclear states involved complicates the extraction of the weak couplings from these measurements. For this reason, it has been established that few-nucleon systems are the most suitable to study in order to obtain the DDH coupling constants.

Recent developments describe the NN weak interaction at low energies using an effective field theory (EFT) approach [2], which classifies the interaction in a manner that is consistent with the symmetries of QCD, and unlike the DDH model, does not assume any particular dynamical mechanism. In this framework, the PV effects in two-nucleon systems have been parameterized, at low energies, by five independent amplitudes for the S-P transitions $^1S_0 \rightarrow ^3P_0$ ($p-p, p-n, n-n, \Delta I=0,1,2$), $^3S_1 \rightarrow ^1P_1$ ($n-p, \Delta I=0$), $^3S_1 \rightarrow ^3P_1$ ($n-p, \Delta I=1$), and one long-range one-pion-exchange parameter that is proportional to the DDH coupling constant $f_1^\pi$.

Although the EFT has an equivalent number of coupling parameters as the DDH formalism, the EFT couplings are in principle calculable in lattice gauge theory. However to test the EFT predictions, the measurement of PV observables in two- and few-nucleon systems is still of central importance.

In this paper, we will describe two experiments that will measure the PV asymmetry in the distribution of the gamma-rays emitted in the capture of polarized cold neutrons by protons (NPDGamma), and deuterium (NDTGamma). These experiments are part of a program in the area of fundamental neutron physics whose goal is to improve our understanding of the hadronic weak interaction by measuring PV observables in few-nucleon systems [3].
2. The NPDGamma Experiment

NPDGamma is an experiment that will measure the asymmetry with respect to the neutron polarization direction of the gamma-rays emitted in the capture of cold neutrons by protons. The expected asymmetry is \(\sim 10^{-7}\) and the goal is to measure it to a precision of \(10^{-8}\). The measurement of this asymmetry is important to determine the pion contribution in the weak interaction between nucleons \(f_\pi^2\). Because the pion is the lightest meson and thus has the longest interaction range, it can be expected to carry the largest contribution in the weak interaction between nucleons compared to contributions of heavier mesons, dominating particularly the \(\Delta f=1\) part of the hadronic weak interaction in the DDH model.

NPDGamma ran in 2006 at the Los Alamos Neutron Science Center (LANSCE) of Los Alamos National Laboratory. The experiment was carried out at the flight path 12 (1FP12) of the Lujan Center at LANSCE. This flight path was constructed and commissioned by the NPDGamma collaboration for this experiment.

A scheme of the experiment is shown in Fig. 1. Neutrons at LANSCE are produced by spallation when a high energy (800 MeV) pulsed proton beam, with 20 Hz repetition rate, hits the tungsten spallation target. Neutrons are moderated by their passage through cold liquid hydrogen and are transported to the experimental room with a \(m=3\) Ni-Ti multilayer supermirror guide. The brightness of the moderator measured at 1FP12 has an approximate Maxwell-Boltzmann distribution with maximum of \(1.253 \times 10^8 \text{ncm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{meV}^{-1} \mu\text{A}^{-1}\) at 3.3 meV [4]. The pulsed nature of the spallation source allows the determination of neutron energy by time-of-flight. However, the overlap of the slowest neutrons in one pulse and the fastest neutrons of the following pulse can create ambiguity in the time-of-flight to energy correlation. To prevent this, the flight path is equipped with a frame overlap chopper, located approximately half way between the neutron source and the experimental room. The chopper consists of two rotating blades covered with gadolinium oxide, which absorbs the neutron beam when the blades are covering the guide. It is operated so that it blocks the slowest neutrons in each pulse and thus negligible overlap occurs. In the experimental room, race-track coils produce a 10 G homogeneous magnetic field that is present along the whole apparatus (see Fig. 1). The field preserves the polarization of the neutrons and prevents the Stern-Gerlach steering of the beam. When the 1/2-spin neutrons enter the magnetic field region, they distribute equally in the two possible quantum spin states. The neutron beam is polarized by its passage through a \(^3\)He spin filter [5]. The functioning of these filters is based on the large dependence with the relative spin direction of the \(n+{^3}\text{He} \rightarrow p+t+764\text{keV}\) nuclear reaction, which proceeds through a resonant state of zero spin. Therefore, the absorption of neutrons with spin anti-parallel to the \(^3\)He spin is favored while the absorption of neutrons with parallel spin is suppressed. Before reaching the target, neutrons pass through a RF spin rotator, that inverts the neutron polarization in an 8-pulse sequence (\(\uparrow\uparrow\uparrow\uparrow\downarrow\downarrow\downarrow\downarrow\)) to reduce up to second order systematic effects that may produce a false gamma-asymmetry [6].

Hydrogen can have two possible molecular states: ortho-H\(_2\), which has a high neutron scattering spin-flip probability, and para-H\(_2\), in which only non-spin flip scattering and capture can occur for neutron energies below 15 meV. The target is a vessel containing 16 L of liquid hydrogen held at 17 K. These conditions are necessary in order to have most of the hydrogen (99.98%) in the para-H\(_2\) state [7].

Three neutron beam monitors are located along the experimental apparatus and are used to monitor beam fluctuations and to determine, through relative neutron transmission measurements, the neutron beam polarization and the ortho/para ratio in the target. The monitors are parallel plate ion chambers that contain a mixture of \(^3\)He, \(^4\)He and \(\text{N}_2\). Neutrons are detected by the same nuclear reaction that occurs in the spin filters. The energetic charged particles produced \((p\text{ and }t)\) ionize the gas and this ionization is collected by the electrodes to produce a current signal that is later converted to voltage [8].

The gamma-rays produced in the capture of neutrons in the target are counted by an array of 48 CsI detectors, arranged in 4 rings of 12 detectors that surround the target [9,10]. Since the instantaneous neutron and gamma count rates are very high (\(~5 \times 10^7\) gammas/pulse), the detectors, as well as the beam monitors, are operated in current mode.

In the NPDGamma run in 2006 at LANSCE, with approximately 750 hours of good data, the measured up-down gamma asymmetry is \((−1.9±2.0(\text{stat.})±0.2(\text{sys.}))\times10^{-7}\) [11]. The experiment is now being relocated to the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. It will be the first experiment to take place at the recently constructed Fundamental Neutron Physics Beamline (FPNB). The increased neutron flux at the SNS (about 10 times higher than that at LANSCE), along with other improvements in the apparatus, will allow us to determine \(A^{dp}_{\uparrow\uparrow}\) to the goal statistical precision of \(10^{-8}\) with negligible systematic errors.

3. The NDTGamma Experiment

In order to have another linearly-independent equation to determine the weak coupling constants, it has been proposed to measure the gamma-asymmetry in the capture of neutrons on deuterium (NDTGamma experiment). \(\vec{n}\vec{d}\) is the simplest few-body system where reliable theoretical analysis can be performed and where nucleons inside may not have large momenta and S-P transitions still dominate, which is essential for the EFT approach.

The measurement of \(A^{\vec{n}\vec{d}}\) has advantages and disadvantages with respect to the measurement of \(A^{dp}\). On one hand, the asymmetry predicted by the DDH model is one order of magnitude larger than for the \(\vec{n}\vec{p}\) system \((\sim10^{-6})\). On the other hand, the cross section for capture of neutrons in
deuterium is extremely small (only 0.52 mb at $E_n = 25.3$ meV), which represents a challenge for the design of the target since almost any material that could be used as container would have a much larger neutron capture cross section. Shielding is another important aspect to consider for the target, since most neutrons will not be captured and their propagation in the experimental room could create a significant background. In addition to that, considerable neutron depolarization in the target might occur since unlike in the NPDGamma experiment, a target where spin-flip scattering is suppressed is unfeasible. However, the gamma-rays emitted in the $\bar{n} + d \rightarrow t + \gamma$ reaction are circularly polarized, and by measuring their degree of polarization it is possible to infer the average neutron beam polarization at capture. The target for this experiment will be radiatively cooled D$_2$O ice. Oxygen has the advantage of having smaller neutron capture cross section than deuterium (0.19 mb at $E_n = 25.3$ meV), therefore the background created by capture in this material will be small, approximately 14% if the gamma detectors are operated in current mode as in NPDGamma. However, since the instantaneous gamma count rate will be considerably smaller for NDTGamma, the possibility of running the detectors in counting mode to discriminate gammas by pulse-height is being studied.

NDTGamma faces now the challenge of proving that with such a target, neutron polarization will remain large enough at capture to achieve the statistics necessary to measure the asymmetry effect. In the summer of 2008, the collaboration performed a series of test measurements at the 1FP12 of the Lujan Center at LANSCE. The neutron beam, polarized with a $^3$He spin filter, was directed to a room temperature liquid D$_2$O target. The gamma polarization was measured with two gamma polarimeters, located above and below the target (see Fig. 2).

The relationship between the degree of polarization of the gamma-rays ($P_\gamma$) from the capture of neutrons in deuterium, and the average neutron beam polarization ($P_n$) is given by

$$P_n = \frac{P_\gamma}{R^d},$$

where $R^d = 0.42 \pm 0.03$ is the (measured) polarization parameter for the 6.257 MeV gamma-rays from the $\bar{n} + d \rightarrow t + \gamma$ reaction. The gamma polarimeters used to determine $P_\gamma$ consist of solenoids with a copper-nickel-vanadium alloy core, and use the dependence of the Compton scattering cross section with the electron spin to filter out a particular gamma polarization state [12]. The spin direction of the electrons in the polarimeter can be inverted by changing the direction of the magnetic field produced by the solenoid, and thus opposite gamma polarization states can be filtered out in each measurement ($N^+ \text{ or } N^-$). The asymmetry between the measured numbers

$$A = \frac{N^+ - N^-}{N^+ + N^-}$$

is related to the gamma polarization by

$$A = \eta P_\gamma,$$

where $\eta$ is the analyzing power of the gamma polarimeter, which can in principle be calculated, however in practice it is more accurate to measure it using a $^{32}$S target, with a known circular polarization of the capture gamma. Because $^{32}$S is a zero spin nucleus, it will not produce spin-flip scattering of the incident neutrons and the value of $P_n$, determined by the measurement of neutron transmission through the spin filter, can be utilized.

The data analysis of the test measurements is in progress and will be reported in an upcoming publication.

4. Conclusions

The NPDGamma experiment successfully completed its first stage at the Los Alamos National Laboratory, measuring an up-down gamma asymmetry of

$$(-1.9 \pm 2.0 \text{(stat.)} \pm 0.2 \text{(sys.)}) \times 10^{-7}$$


The experiment will begin its second data taking run in 2009 at the FNPB of the SNS in Oak Ridge National Laboratory, where the goal precision of $10^{-8}$ is expected to be achieved. Progress has been made towards the consolidation of the NDTGamma experiment. The test measurements performed in 2008, in addition to new measurements to be performed in the near future, are expected to show the feasibility of the measurement of the gamma-asymmetry in the $\bar{n} + d \rightarrow t + \gamma$ reaction.