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Neutron measurements and the weak nucleon–nucleon interaction

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Abstract. The weak interaction between nucleons remains one of the most poorly-understood sectors of the Standard Model. A quantitative description of this interaction is needed to understand weak interaction phenomena in atomic, nuclear, and hadronic systems. This paper outlines a set of measurements involving low energy neutrons which can lead to significant experimental progress.

1 The physics of the weak NN interaction

Despite nearly 40 years of study, the weak interaction between nucleons is not understood. It is only experimentally accessible through the measurement of small parity-odd amplitudes amid much larger effects of quantum chromodynamics (QCD). The natural scale for the size of parity-odd amplitudes, set by the ratio of the amplitudes for W and Z exchange to those for meson exchange between nucleons, is about 10^{-7}. Although it is clear that the weak NN interaction exists with a size roughly in agreement with dimensional estimates [1,2], the weak NN couplings are basically unknown. It is important to understand low energy weak NN amplitudes for a number of reasons:

(1) NN weak interactions are in principle a new probe of strong QCD. Quark-quark charged and neutral currents have been seen in high energy experiments conducted in the perturbative QCD regime with the expected rates [3], so any deviations at low energy must be due to strong QCD effects. The range of the weak interaction between quarks is much smaller than the nucleon size, and the strong NN repulsion at short distances means that weak interaction dynamics between nucleons must involve meson exchange and soft QCD physics. The weak NN interaction thus samples both short-distance quark-quark correlations in QCD and its chiral symmetry-dominated long-range properties: it is an "inside-out" probe of QCD.

(2) NN weak couplings inferred from measurements in medium and heavy nuclei are inconsistent. The longest-range part of the interaction is dominated by the weak pion-nucleon coupling constant f_π. Measurements of the circular polarization of photons in the decay of ^{18}F [4,5] imply a small value for f_π, while precision PV measurements in p-p and ^{133}Cs [6] seem to imply a large value for f_π [7,8] relative to the estimates of Desplanqes, Donoghue, and Holstein [9].

(3) Knowledge of weak NN couplings can allow for a quantitative interpretation of many PV phenomena in measurements at nuclear and atomic scales, including (a) PV observables in shell model nuclei [10], (b) PV in neutron reactions in heavy nuclei [11,12] analyzed using ideas from quantum chaos and nuclear statistical spectroscopy, (c) the contribution to PV in the ^{133}Cs atom [6] arising from the nuclear anapole moment [13,14], and (d) to PV electron scattering from the virtual photon coupling to an axial current among quarks in the nucleon. A number of experiments (SAMPLE, HAPPEX, PVA4, G0) to measure PV electron scattering in different kinematic regions will be able to isolate different mechanisms and separate out the contribution from q-q weak interactions [15]. Finally, weak NN matrix elements in nuclei bear many similarities with the matrix elements that must be calculated to interpret limits on neutrino masses from double beta decay searches [16]. In all cases, the PV observables open a new window into specific features of many-body states that can only be interpreted if the NN weak interaction amplitudes are known.

(4) Theoretical advances in the description of PV in the NN and few nucleon systems promise to make better contact with QCD in the near future. The valence quark model used by Desplanques, Donoghue, and Holstein (DDH) [9] to calculate effective PV meson-nucleon couplings directly from the Standard Model employed a weak pion coupling constant f_π and six other meson couplings denoted as h^0_ρ, h^1_ρ, h^1_ρ, h^2_ρ, h^0_ω, and h^1_ω, where the subscript denotes the exchanged meson and the superscript indicates the isospin change. A systematic analysis of the weak NN interaction using an effective field theory (EFT) approach and chiral perturbation theory to classify the interaction in a manner consistent with the symmetries of QCD, has appeared very recently [17]. The 5 low energy constants that appear in this new EFT approach connect naturally with the five independent parity-odd S-P NN amplitudes: $^1S_0 \to ^3P_0$,(pp,pn,nn, ΔI=0,1,2), $^3S_1 \to ^1P_1$ (np, ΔI=0), and $^3S_1 \to ^3P_1$ (np, ΔI=1). PV observables in np and pp systems have been calculated [18] and those in few-nucleon systems can be calculated [19] in terms of weak couplings. f_π has been calculated

using QCD sum rules [20] and in an SU(3) Skyrme model [21]. Preparations have been made to calculate the weak NN couplings using lattice gauge theory in the partially quenched approximation [22]. These theoretical efforts set the stage for eventual quantitative predictions of the weak NN interaction directly from the Standard Model and QCD.

Two measurements are planned: a measurement of A_γ in the reaction $\mathbf{n} + p \to D + \gamma$ and a measurement of the parity-odd spin rotation angle ϕ_{PNC} in n-^{4}He. The goal of both of these experiments is to reach sufficient precision to constrain NN weak couplings. These experiments are complementary: n-^{4}He spin rotation is sensitive to a sum of f_π and h^0_ρ: $\phi_{PNC} = -0.97 f_\pi - 0.32 h^0_\rho + 0.11 h^1_\rho - 0.22 h^0_\omega + 0.22 h^1_\omega$) [27] while $\mathbf{n} + p \to D + \gamma$ is sensitive to f_π alone ($A_\gamma = -0.11 f_\pi$) [24]. Furthermore, PV spin rotation in n-^{4}He constrains a linear combination of weak couplings orthogonal to already-measured PV effects in p-^{4}He [23] and ^{133}Cs.

2 Parity-odd gamma asymmetries

The NPDGamma experiment proposes to measure A_γ in the capture of polarized neutrons on protons, $\mathbf{n} + p \to D + \gamma$. The recently commissioned beamline at LANSCE [28] delivers pulsed cold neutrons to the apparatus, where they are polarized by transmission through a large volume polarized ^{3}He spin filter. The neutron beam intensity is measured with a ^{3}He ionization chamber upstream and downstream of the polarizer cell, and again at the end of the beamline with a third ion chamber. A uniform vertical guide field preserves the neutron beam polarization as it is transported to the liquid parahydrogen target. A resonant RF spin flipper whose magnetic field amplitude is varied as a function of neutron time of flight to flip neutron spins of all energies is located upstream of the target. The spin flipper reverses the direction of the neutron spin on successive beam pulses according to a $+--+-++-$ sequence, which cancels time-dependent drifts of detector efficiencies, etc. to 2nd order. The 2.2 MeV γs from the capture reaction are detected in an array of CsI(Tl) scintillators read out by vacuum photodiodes operated in current mode and coupled via low noise I-V preamplifiers to transient digitizers. The current-mode CsI array has intrinsic noise 2 orders of magnitude smaller than the shot noise from the γ signal and has been shown in offline tests to give no false instrumental asymmetries at the 5×10^{-9} level [29]. The pulsed nature of the beam enables the energies of the neutrons to be determined from their time of flight, which is an important advantage for diagnosing and reducing many types of systematic error. This apparatus has been used to conduct measurements of parity violation in several medium and heavy nuclei and has been described in a number of papers [30,31].

A liquid deuterium target could also be used with relatively simple modification to the NPDGamma apparatus. The n-d system is still sufficiently simple that nuclear structure uncertainties do not threaten interpretability of PV measurements in terms of NN weak couplings. The asymmetry $A_\gamma = 0.92 f_\pi - 0.50 h^0_\rho + 0.10 h^1_\rho - 0.16 h^0_\omega + 0.05 h^2_\rho$) [26]. The previous experiment [32] obtained a result consistent with zero: $A_\gamma = 4.2 \pm 3.8 \times 10^{-6}$. The expected size of the PV asymmetry for n-d is about an order of magnitude larger than for n-p because the parity-conserving part of the neutron absorption cross section in n-d is anomalously small, a suppression not present for the E1 gamma ray that the PV component of the weak interaction induces [26]. However, the ground state of liquid deuterium can depolarize the neutrons before capture, dictating a thin, weakly-absorbing target and a higher neutron flux. Systematic effects for this experiment are very similar to those for $\mathbf{n} + p \to D + \gamma$.

3 Parity-odd neutron spin rotation

An experiment to search for parity violation in neutron spin rotation in liquid ^{4}He is also in preparation [37]. A transverse rotation of the neutron spin vector about its momentum manifestly violates parity [33] and can be viewed from a neutron optical viewpoint as due to a helicity-dependent neutron index of refraction. For ^{4}He, the calculated PV neutron spin rotation is $\phi = -0.1 \pm 1.5 \times 10^{-6}$ rad/m using the DDH best values [27]. To measure the small parity-odd rotation, a neutron polarimeter is used to measure the $\hat{y}$ polarization component of a neutron beam initially polarized along the $\hat{z}$ axis and traveling in the $\hat{x}$ direction. The challenge is to distinguish small PV rotations from rotations that arise from residual magnetic fields.

The first measurement by the Washington group achieved a sensitivity of 14×10^{-7} rad/m at NIST [34], a factor of two from the precision needed to provide new information about f_π. No systematic effects were seen at the 2×10^{-7} rad/m level. The apparatus is being rebuilt and upgraded to operate with superfluid helium, which has a much smaller total [35] and small-angle [36] neutron scattering cross section than normal helium and does not support the formation of bubbles. We are also adding more magnetic shielding to lower the residual magnetic field by a factor of 5 from the first experiment [37]. We anticipate a factor of 5 improvement in sensitivity to 3×10^{-7} rad/m. We note that one can also imagine attempting a measurement of neutron spin rotation in liquid parahydrogen, which does not depolarize a low energy neutron beam. The PNC spin rotation in hydrogen has been calculated to be $\phi_{PNC} = -3.12 f_\pi - 0.23 h^0_\rho - 0.23 h^0_\omega - 0.25 h^2_\rho$ [25], which is dominated by f_π.

4 Future prospects for NN weak interaction measurements

Sensitive measurements of the PV gamma asymmetry in n-p and n-D and of the PV spin rotation in n-p and n-^{4}He are technically feasible at existing and/or planned neutron sources. In combination with existing measurements in p-p [38,39,40] and p-^{4}He, the neutron measurements would have a strong impact on our knowledge of the NN weak interaction. A_γ in $\mathbf{n} + p \rightarrow D + \gamma$ and n-p spin rotation are mainly sensitive to f_π. n-^{4}He spin rotation and $\mathbf{n} + D \rightarrow t + \gamma$ systems are sensitive to the rho and omega couplings. With p-p scattering there is accurate information on a linear combination of rho and omega couplings. If the precision of these measurements were set only by the statistical sensitivity achievable at the Spallation Neutron Source, for example, and if the theoretical calculations that relate weak NN couplings to observables are accurate, then 4 of these couplings can be determined to better than 30% accuracy [41].

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