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Hadronic parity violation and neutron capture reactions

M. T. W. Gericke
University of Manitoba - Winnipeg, Canada

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Summary. — The hadronic weak interaction remains one of the most poorly understood sectors of the Standard Model; for obvious reasons. On the one hand, the initial and final states involve strongly bound systems of particles, for which the theoretical description (*e.g.* QCD) is insufficient itself and all of the current alternative or hybrid approaches are phenomenological and therefore depend on experimental input. On the other hand, experimental tests are notoriously difficult because the weak interaction observables are suppressed by the strong interaction and very high statistics measurements are needed to reach a meaningful accuracy, which in turn requires tight control of systematic uncertainties. All of this is true for both strangeness-conserving ($\Delta S = 0$) and strangeness-changing ($\Delta S = 1$) non-leptonic interactions. In the former category, new high intensity neutron facilities and the experiments that are proposed or are in preparation there promise sensitivities that could finally see non-zero parity violating (PV) effects in systems that have a theoretically clean interpretation. This paper provides a brief description of the physics issues and various models and introduces a few experimental efforts that are currently underway.

PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS `24.70.+s` – Polarization phenomena in reactions.
PACS `13.75.Cs` – Nucleon-nucleon interactions (including antinucleons, deuterons, etc.).
PACS `25.40.Lw` – Radiative capture.

1. – Theory

The residual (parity violating) hadronic weak interaction between nucleons is induced by quark-quark weak interactions, as described in the Standard Model. At energies below the electroweak scale, the quark-quark weak interaction can be written in a current-current form with pieces that transform under (strong) isospin as $\Delta I = 0, 1, 2$. Although the modification of the relative strengths of the different four-quark operators involved can be calculated in QCD perturbation theory [1,2], this calculation is only valid at scales above the chiral symmetry breaking scale Λ_χ. NN weak processes occurring at energies well below this scale necessarily involve the unsolved non-perturbative limit of QCD and therefore remain one of the most poorly understood sectors of the electroweak theory. The importance of the study of the hadronic weak interaction between nucleons has been outlined in various recent publications [3-6]. For example, the fact that the range for W and Z boson exchange between quarks is small compared to the nucleon size, suggests that a high precision measurement of non-zero PV effects (or the lack thereof) is sensitive to quark-quark correlations in nucleons (*e.g.* in their normal bound state form). Precision measurements of PV observables in few nucleon systems therefore provide a probe for non-perturbative QCD. Related to this are the unresolved puzzles in the strangeness-changing non-leptonic weak decays of hadrons, which includes the unexpected $\Delta I = 1/2$ channel amplification in kaon decays and the anomalously large PV asymmetries in non-leptonic weak decays of hyperons for which the dynamics is still not fully understood [7]. The hadronic weak interaction between nucleons is primarily sensitive to quark-quark neutral currents at low energy, as the charged currents ($\Delta I = 1$) are suppressed in NN processes by $V_{us}^2/V_{ud}^2 \simeq 0.1$. So an observation of these unexpected isospin dependences in nuclon-nucleon and few nucleon systems in the $\Delta S = 0$ sector would show that these dynamical puzzles are present for all light quarks (rather than just the strange quark) and would therefore imply a non-trivial QCD dynamical phenomenon of general interest [3].

Calculations of strangeness changing and conserving hadronic weak interaction processes and observables have been carried out for a long time [8], resulting in the so-called weak meson exchange model, where the weak interaction is modelled as a process in which the three lightest mesons (π, ρ, and ω) couple to one nucleon, via the weak interaction, at one vertex and to the second nucleon, via the strong interaction, at the other vertex. An attempt to calculate the weak meson-nucleon couplings of the HWI from the Standard Model using a valence quark model for QCD was first made by Desplanques, Donoghue, and Holstein (the DDH paper [9]) in 1980. The so-called DDH "reasonable ranges" and "best values" for these couplings have been a *de facto* benchmark for comparison with experiment. An experimental program was outlined and the calculations specifying the relation between the corresponding observables and the weak coupling constants was carried out by Adelberger and Haxton in 1985 [10]. In recent years however, this framework has come under increased scrutiny. As pointed out in [4], for example, "the effects of chiral symmetry breaking on the value of h_π^1, which are not included in the DDH treatment, may be anomalously large" [11].

New efforts to calculate parity violating NN observables, starting from (χ PT based) effective field theory, are being undertaken, but experimental input is needed to relate them to modern NN potentials. In pion-less effective field theory (relevant for the experiments discussed here), five independent amplitudes are generated ($\lambda_t, \lambda_s^{I=0,1,2}, \rho_t$), corresponding to the PV mixing of partial waves ${}^3S_1(I=0) \leftrightarrow {}^1P_1(I=0)$, ${}^1S_0(I=0,1) \leftrightarrow {}^3P_0(I=0,1)$, and ${}^3S_1(I=0) \leftrightarrow {}^3P_1(I=1)$, respectively [3]. The challenge lies in finding feasible few nucleon experiments which can measure the various observables with high enough accuracy and together over-constrain the theoretical couplings. It is now possible to make such measurements due to the availability of new, high intensity neutron facilities, such as the SNS. Another recent effort now also explores the possibility of calculating the weak amplitude on the lattice [12].

2. – Experimental efforts

In this section I want to briefly introduce a few recent experimental efforts and some general design issues that all such experiments have to face. Although experiments can

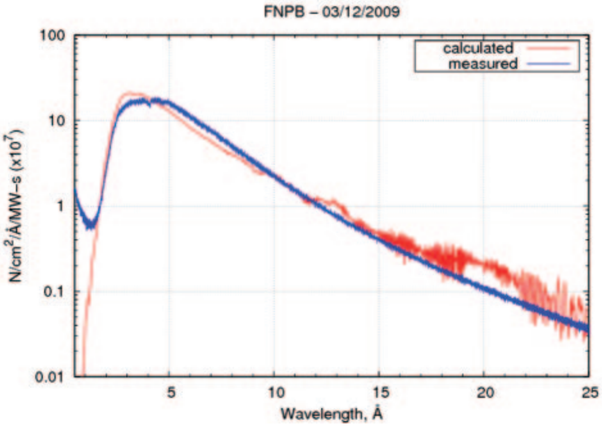

Fig. 1. – Full spectrum of cold neutrons at the SNS FNPB in 2009, running at 750 kW (accelerator).

in principle be carried out at any neutron source, including both reactors and accelerator driven spallation sources, I restrict the discussion here to those experiments that are carried out at spallation sources. The primary advantage of running at neutron spallation sources is that one has all information about the neutron energy (due to the pulsed nature of the the accelerator), by way of the time-of-flight method. This is limited only by detector and DAQ resolution. Figure 1 shows the measured neutron flux spectrum (one pulse) on flight path 13 at the Fundamental Neutron Physics Beam (FNPB) line at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL), compared to a simulation. Knowing the neutron energy as it passes into the experimental apparatus is an important feature, aiding in the suppression of many neutron energy dependent systematic effects.

In general, there are four important components to most hadronic PV neutron experiments. Referring to the numbering in fig. 2, these include 1) a set of neutron beam monitors, 2) a polarizer (helium 3 or supermirror), 3) a spin flipper or rotator, and 4) a target and detector assembly. The components are usually in close proximity to each other to avoid backgrounds and other effects associated with beam divergence. Although fig. 2 shows the setup at the FNPB this sort of layout is common to most hadronic PV experiments.

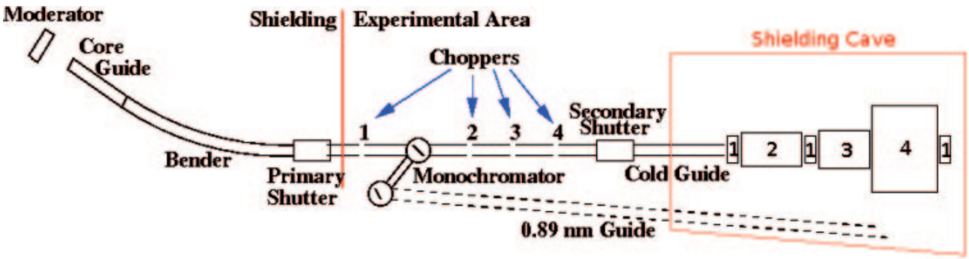

Fig. 2. – Schematic of the SNS fundamental cold neutron physics beam (FNPB) line and the typical experimental setup including three beam monitors 1), a polarizer 2), a spin flipper or rotator 3) and a target-detector assembly 4). The distance from the moderator (cold neutron source) to the experimental area is about 15 m.

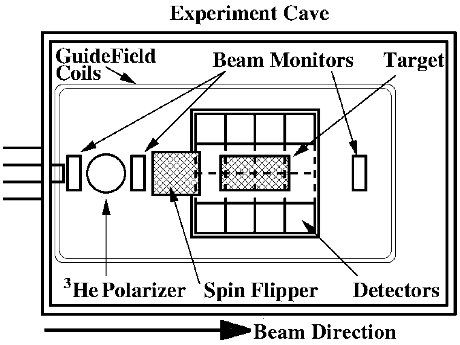

Fig. 3. – Schematic of the NPDGamma experimental setup.

Like all parity violating experiments, neutron experiments need an observable with an amplitude (a scalar quantity) that is an inner product of a polar vector and an axial vector. Since it is relatively easy to produce polarized neutron beams and since the polarization can be reversed or rotated with high efficiency ($\simeq 99\%$) the commonly used axial vector is the neutron spin. To maintain the neutron spin, experiments have to be operated in a magnetic holding field. Systematic effects and backgrounds can be expected from processes such as Stern-Gerlach steering of neutrons, parity allowed asymmetries (associated with scattering), asymmetries and backgrounds from capture or transmission through materials other than the intended target, in flight neutron beta-decay and nuclear beta decay [13].

2˙1. *NPDGamma*. – The NPDGamma experiment has been designed to make the world's first significant measurement of parity violation in the np system. NPDGamma measures the directional asymmetry in the number of outgoing photons after radiative capture of polarized cold neutrons on protons. The only experimentally known fact about this asymmetry is that it is smaller than $\approx 2\times10^{-7}$, as obtained from the first phase of the NPDGamma measurements at LANL ((2006 result $(-1.1\pm2.1\,\text{stat.}\pm0.2\,\text{sys.})\times10^{-7}$) [13]) and the only other measurement of this observable ($A_\gamma = (0.6 \pm 2.1) \times 10^{-7}$) [14]. The theoretically predicted size of the asymmetry is ($\approx 5 \times 10^{-8}$) [9, 11, 6] and the aim of the experiment is to measure it to 20% combined statistical and systematic error during a second run at the SNS. The NPDGamma layout (as installed at LANL) is shown in fig. 3 and includes beam monitors, a helium 3 polarizer system, a spin flipper, a liquid hydrogen target, and a 48 element CsI(Tl) detector array. A more detailed description of

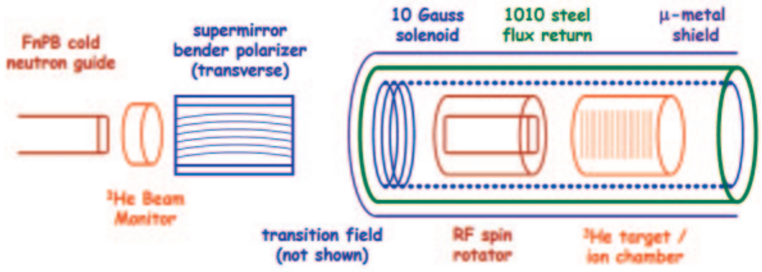

Fig. 4. – Schematic of the n3He experimental setup.

the physics and the setup of the NPDGamma experiment itself can be obtained from [13] and references within. The experiment has been installed and commissioned and is scheduled to begin data production in December 2011, a the FNPB.

2˙2. *n3He.* – The n3He experiment is currently in the development and construction phase and aims to make a measurement of the parity violating asymmetry A_p of the correlation between the longitudinal polarization of incoming cold neutrons ($\vec{\sigma}_n$) and the outgoing momentum of protons ($\vec{k}_p$) after nuclear breakup in the reaction $\vec{\mathrm{n}} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{T} + 765\,\mathrm{keV}$. The theoretical prediction for the size of the asymmetry is in the range of ($\approx -9.44 \times 10^{-8}$) to ($\approx -2.48 \times 10^{-8}$) [15], which was calculated using chiral two- and three-body strong interaction potentials with both DDH and EFT models for the weak potentials. The experiment has been approved to run at the SNS FNPB after the conclusion of the NPDGamma experiment and aims to measure the asymmetry to 1×10^{-8}.

The layout of the experiment is shown in fig. 4 and consists of the same beam monitors and supermirror polarizer that are used for the NPDGamma experiment, a spin rotator to flip the longitudinal polarization of the neutron beam, and a multiwire ion chamber serving as the target and the detector. The chamber is filled to one atmosphere with helium 3 and a small amount of carrier gas (*e.g.* nitrogen) and therefore absorbs all of the neutrons in the beam. The electrons produced by the proton from the above mentioned reaction ionize the gas and are detected by sense wires distributed uniformly throughout the chamber. In this way, the average number of forward going protons can be detected and measured as a function of neutron spin.

2˙3. *Neutron spin rotation.* – An experiment measuring the parity violating neutron spin rotation in helium 4 has recently been completed at the National Institute for Standards and Technology (NIST) in Gaithersburg, Maryland, with a result of $\mathrm{d}\phi/\mathrm{d}z = (1.7 \pm 9.1(\mathrm{stat.}) \pm 1.4(\mathrm{sys.})) \times 10^{-8}$ [16]. The theoretical prediction for this observable, within the DDH framework, is in the range of $\pm 1.5 \times 10^{-}6$ [9].

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