I start by reviewing existing $\vec{p}\vec{p}$ measurements with particular emphasis on the recent 221 MeV $\vec{p}\vec{p}$ measurement at TRIUMF which permitted the weak meson-nucleon coupling constants $h_{\rho}^{pp}$ and $h_{\omega}^{pp}$ to be determined separately for the first time. I then review $\vec{n}\vec{p}$ experiments, with specific details of the $\vec{n}\vec{p} \rightarrow d\gamma$ experiment now under preparation at Los Alamos National Laboratory. This experiment will provide a clean measurement of the weak pion nucleon coupling, $f_s$. Finally, I discuss $\vec{e}\vec{p}$ parity violation experiments, particularly the Gzero experiment under way at Jefferson Lab in Virginia. This experiment will measure the weak form factors $G_E^Z$ and $G_M^Z$, allowing the distribution of strange quarks in the quark sea to be determined.

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Key words: parity violation, polarized beams, proton, electron, form factor

1 Introduction

In Vancouver a popular form of Chinese luncheon is “Dim Sum” in which small quantities of a large variety of foods may be tasted. This review is a “Dim Sum” of parity violation experiments. As with a luncheon, my selection is biased by my personal taste and experience. I start with $\vec{p}\vec{p}$ parity violation experiments, concentrating on the the TRIUMF 221 MeV $\vec{p}\vec{p}$ experiment, then discuss $\vec{n}\vec{p}$ parity violation experiments with details of the Los Alamos $\vec{n}\vec{p} \rightarrow d\gamma$ experiment now being installed at LANSCE. Finally, I discuss $\vec{e}\vec{p}$ parity violation experiments, particularly the Gzero experiment at Jefferson Lab. I refer those interested in more background to specific reviews on nucleon-nucleon [1,2] and $\vec{e}\vec{p}$ [3] experiments.

2 $\vec{p}\vec{p}$ Experiments

Figure 1 shows typical $\vec{p}\vec{p}$ parity violation experiments. They scatter a longitudinally polarized beam of protons from a hydrogen target and measure the difference in cross section for right-handed and left-handed proton helicities. The intermediate and high energy experiments use transmission geometry in which the change in scattering cross section is deduced from the change in transmission through the target. Low energy experiments, where energy loss limits the target thickness, use scattering geometry, in which the detectors measure the scattered protons directly. Both types of experiments measure the parity violating longitudinal analyzing power, $A_z = \frac{\sigma^+-\sigma^-}{\sigma^+ + \sigma^-}$, where $\sigma^+$ and $\sigma^-$ are the scattering cross sections for positive and negative helicity.
Table 1. Summary of $\bar{p}p$ parity violation experiments. The long times taken to achieve small uncertainties reflects the time taken to understand and correct for systematic errors. In cases where authors reported both statistical and systematic uncertainties, this table shows the quadrature sum of the two.

| Lab/Energy       | Technical Details                          | $A_\pm (10^{-5})$ | Where Reported                |
|------------------|-------------------------------------------|--------------------|--------------------------------|
| Los Alamos       | scattering 3 atm x 38cm hydrogen gas       | +1 ± 4             | 1974 Phys. Rev. Lett. [4]      |
|                  | 4 liquid scintillators                      |                    |                                |
|                  | scattering 6.9 atm hydrogen gas             | −1.7 ± 0.8         | 1978 Argonne Conference [5]    |
|                  | 4 plastic scintillators                     |                    |                                |
| Texas A&M        | scattering 39 atm x 42cm hydrogen gas       | −4.6 ± 2.6         | 1983 Florence Conference [6]   |
| 47 MeV           | 4 plastic scintillators                     |                    |                                |
| Berkeley         | scattering 80 atm hydrogen gas target       | −1.3 ± 1.1         | 1980 Santa Fe Conference [7]   |
| 46 MeV           | He ion chamber around target                | −1.63 ± 1.03       | 1985 Osaka Conference [8]      |
| SIN (PSI)        | scattering 100 atm hydrogen gas annular ion | −3.2 ± 1.1         | 1980 Phys. Rev. Lett. [9]      |
| 45 MeV           | chamber                                     |                    |                                |
|                   | scattering 4 atm hydrogen gas               | −2.32 ± 0.89       | 1984 Phys. Rev. D. [10]        |
|                   | ion chambers                                |                    |                                |
|                   | −1.50 ± 0.22                                |                    | 1987 Phys. Rev. Lett. [11]     |
| Los Alamos       | transmission 1 m liquid hydrogen gas ion    | +2.4 ± 1.1         | 1986 Phys. Rev. Lett. [12]     |
| 800 MeV          | chambers                                    |                    |                                |
| Bonn             | scattering 15 atm hydrogen gas hydrogen ion | −1.5 ± 1.1         | 1991 Phys. Lett. B [13]        |
| 13.6 MeV         | chambers                                    |                    |                                |
| TRUMF            | transmission 40 cm liquid hydrogen ion      | +0.84 ± 0.34       | 2001 Phys. Rev. Lett. [14]     |
| 221 MeV          | chambers                                    |                    |                                |
| Argonne ZGS      | transmission 81 cm water target ion         | +26.5 ± 7.0        | 1986 Phys. Rev. Lett. [15]     |
| 5130 MeV         | chambers                                    |                    |                                |

A roughly historical summary of $\bar{p}p$ parity violation experiments is given in Table 1. The long time taken to acquire measurements at a reasonable selection of energies and with small experimental uncertainties reflects the technical difficulty of these measurements. Running time is dominated by the time required to understand, and correct for, the various sources of systematic error. The time required to get the desired statistical precision is normally small by comparison.

The TRUMF $pp$ experiment [14] is a transmission experiment as shown in the lower panel of figure 1. A 221 MeV longitudinally polarized proton beam was passed through a 400 mm long liquid hydrogen target, which scattered about 4% of the beam. Hydrogen filled ion chambers located upstream and downstream of the tar-
Selected Parity Violation Experiments . . .

![Diagram of pp experiments](image)

**Fig. 1.** Types of $pp$ experiments. The low-energy experiments use scattering geometry, while the intermediate and high-energy experiments use transmission geometry.

**Table 2.** Overall corrections for systematic errors in the TRIUMF parity violation experiment. The table shows the average value of each coherent modulation, the net correction made for this modulation, and the uncertainty resulting from applying the correction.

| Property                  | Average Value | $10^3 \Delta A_z$ |
|---------------------------|---------------|--------------------|
| $A_z^{\text{uncorrected}} (10^{-7})$ | $1.68 \pm 0.29(\text{stat.})$ | |
| $y * P_y (\mu m)$        | $-0.1 \pm 0.0$ | $-0.01 \pm 0.01$  |
| $x * P_x (\mu m)$        | $-0.1 \pm 0.0$ | $0.01 \pm 0.03$   |
| $(yP_y) (\mu m)$         | $1.1 \pm 0.4$  | $0.11 \pm 0.01$   |
| $(xP_x) (\mu m)$         | $-2.1 \pm 0.4$ | $0.54 \pm 0.06$   |
| $\Delta I/I (\text{ppm})$ | $15 \pm 1$     | $0.19 \pm 0.02$   |
| position + size           | $0 \pm 0.10$   |                    |
| $\Delta E(\text{meV at OPPIS})$ | $7-15$        | $0.0 \pm 0.12$    |
| electronic crosstalk      | $0.0 \pm 0.04$ |                    |
| Total                     | $0.84 \pm 0.17(\text{syst.})$ | |

get measured the change in transmission when the spin of the incident protons was flipped from right-handed to left-handed. Although a very good optically pumped polarized ion source [17, 18, 19] was used that minimized the changes in beam properties other than helicity, other beam properties still changed very slightly. These helicity-correlated beam property changes caused a systematic shift in the $A_z$ distribution, and corrections must be made. To do this, the TRIUMF group continuously measured the helicity correlated changes in beam properties and made corrections based on the sensitivities determined in separate control measurements. All the corrections are summarized in Table 2. The importance of accurate corrections is...
Fig. 2. Constraints on the weak meson-nucleon couplings imposed by experiments in the energy range where the meson exchange model is normally used. The bands are based on calculations by Carlson et al. [22] using the AV18 potential [20] and CD-Bonn strong couplings [21]. The contours are 68% and 90% C.L. (Figure modified from [15]).

apparent when one notes that the measured raw $A_z$ actually came half from true parity violation and half from false effects.

Because the range of the W and Z bosons carrying the weak force is so small ($\sim 0.002\, fm$), the low and intermediate energy $\bar{p}p$ results are normally interpreted using meson exchange models, and parameterized in terms of a set of $\pi$, $\rho$, and $\omega$ weak meson-nucleon coupling constants. $\bar{p}p$ experiments are sensitive to the combinations $h^{PP}_{\rho} = h^{(0)}_{\rho} + h^{(1)}_{\rho} + \frac{1}{\sqrt{6}} h^{(2)}_{\rho}$ and $h^{PP}_{\omega} = h^{(0)}_{\omega} + h^{(1)}_{\omega}$. Where the subscript denotes the exchanged meson and the superscript the isospin change.

The value of the couplings can be extracted from the experiments by assuming a realistic model for the strong interaction and adjusting the weak couplings to fit the data. Using the AV18 strong potential [20] and CD-Bonn values for the strong couplings [21], Carlson et al. [22] calculate that

$$
A_z(13.6\, MeV) = 0.059 h^{PP}_{\rho} + 0.075 h^{PP}_{\omega}
$$
$$
A_z(45\, MeV) = 0.10 h^{PP}_{\rho} + 0.14 h^{PP}_{\omega}
$$
$$
A_z(225\, MeV) = -0.038 h^{PP}_{\rho} + 0.010 h^{PP}_{\omega}
$$

where the energies correspond to the most accurate measurements over the low and intermediate energy range [11, 13, 15]. These constraints are shown graphically in
Fig. 2 Note that the low energy results scale as $\sqrt{E}$ and hence constrain essentially the same linear combination of $h_{pp}^\rho$ and $h_{pp}^\omega$. It was only when the TRIUMF result became available that $h_{pp}^\rho$ and $h_{pp}^\omega$ could be separately determined. By adjusting the couplings for the best fit to the data, Carlson et al. [22] estimate $h_{pp}^\rho = -22.3 \times 10^{-7}$ and $h_{pp}^\omega = 5.17 \times 10^{-7}$ compared to the DDH [23] theoretical “best guess” values of $h_{pp}^\rho = -15.5 \times 10^{-7}$ and $h_{pp}^\omega = 3.0 \times 10^{-7}$.

3 $\vec{n}p \rightarrow d\gamma$ Experiments

Unlike the $\vec{p}p$ experiments just discussed, which are sensitive to $\rho$ and $\omega$ exchange, $\vec{n}p \rightarrow d\gamma$ experiments are sensitive almost exclusively to pion exchange, and measure the weak pion-nucleon coupling, $f_\pi$. In an $\vec{n}p \rightarrow d\gamma$ experiment, the incident cold neutrons are polarized vertically and the gamma rays produced by neutron capture in the hydrogen target are expected to be emitted slightly more in the direction opposite to the neutron spin. The up-down asymmetry $A_\gamma \approx -0.11 f_\pi$ provides a clean measure of $f_\pi$ \(^1\) free of nuclear structure uncertainties [24]. Previous measurements at ILL Grenoble gave $A_\gamma = (6 \pm 21) \times 10^{-8}$ [25] and $A_\gamma = (-1.5 \pm 4.8) \times 10^{-8}$ [26], but neither result was accurate enough to impose a significant constraint.

\(^1\) Some authors quote $H_\pi = f_\pi g_\pi \sqrt{\frac{3}{2}}$, where $g_\pi$ is the strong pion-nucleon coupling.
An experiment is now being prepared at Los Alamos to measure the gamma ray asymmetry in $\bar{n}p \rightarrow d\gamma$ with an uncertainty of $\pm 0.5 \times 10^{-8}$ [24]. The expected asymmetry is $A_\gamma \approx -5 \times 10^{-8}$. The apparatus is shown schematically in Fig. 3. Neutrons are produced by an 800 MeV proton beam incident on a tungsten spallation target. The neutrons are cooled in a liquid hydrogen moderator and transported to the experiment through a super mirror neutron guide. The neutrons are polarized vertically by a polarized $^3\text{He}$ spin filter then captured in a liquid para-hydrogen target. The gamma asymmetry is measured by an array of 48 $15 \times 15$ cm$^2$ CsI(Tl) detectors surrounding the target.

The neutron beam is pulsed at 20 Hz, so the energy of the neutrons arriving at the experiment after the 22 m flight path can be determined by time of flight. An RF spin flipper provides a method of rapid spin reversal to control systematic errors. Systematic errors can be further understood and controlled by reversing the $^3\text{He}$ cell direction or the direction of the overall vertical 10 gauss guide field. In addition, different systematic errors have different dependences on time of flight.

The beamline, FP12, is now complete and the experimental cave is scheduled for completion in fall, 2003. Commissioning runs will follow, with the first production data taking anticipated in late 2004 and 2005.

The Gzero experiment [27] at Jefferson Lab scatters a longitudinally polarized electron beam from a 200 mm liquid hydrogen target, and measures the parity-violating longitudinal analyzing power $A_z = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$ where $\sigma^R$ and $\sigma^L$ are the cross sections for right-handed and left-handed electrons, and $P$ is the beam polarization. $A_z$ values ranging from -3 to -35 ppm are predicted. By measuring
this quantity at a range of angles and momentum transfers, the experiment will
determine the weak charge and magnetic form factors $G^Z_{E,M}(Q^2)$ (essentially the
Fourier transforms of the spatial distributions). Because the weak charges of the
quarks are different than the electromagnetic charges (Table 3), one can combine
these weak form factors with the previously measured electromagnetic form factors
$G^{p,γ}_{E,M}$ of the proton and $G^{n,γ}_{E,M}$ of the neutron and extract the strange quark form
factors

$$G^{s,p}_{E,M} = (1 - 4 \sin^2 \theta_W)G^{p,γ}_{E,M} - G^{n,γ}_{E,M} - G^{p,Z}_{E,M},$$

where $\theta_W$ is the weak mixing angle and $G^{p,Z}_{E,M}$ are the proton electroweak form
factors to be measured by Gzero. Figure 4 shows the proton form factors
$G^{p}_{E}$ and $G^{p}_{M}$ taken from a fit to the existing parity conserving data [28]. At low $Q^2$, where
the effective wavelength of the virtual photon probe is very long, the form factors
are simply the proton charge and magnetic moment, 1.00 and 2.79. These form
factors are the sum of contributions from the different quarks; the points on the
graph show the expected error in the Gzero measurement of the strange quark part.

Table 3. Electroweak couplings of up, down, and strange quarks

| quark | electric charge | weak charge |
|-------|-----------------|-------------|
| u     | $\frac{2}{3}$   | $+1 - \frac{2}{3}\sin^2 \theta_W$ |
| d     | $-\frac{1}{3}$  | $-1 + \frac{4}{3}\sin^2 \theta_W$ |
| s     | $-\frac{1}{3}$  | $-1 + \frac{4}{3}\sin^2 \theta_W$ |

The charge and magnetic form factors can be separated by measuring at forward
and backward angles. In each configuration, several values of momentum transfer,
$Q^2$, in the range $0.1 < Q^2 < 1.0$ (GeV/c)$^2$ will be measured. Do do this, the
scattered particles pass through an 8-sector superconducting magnetic spectrometer
and are detected by an array of plastic scintillators arranged in contours of constant
$Q^2$. In the forward configuration protons are detected at $\theta_p = 70^\circ \pm 10^\circ$ (or $\theta_e =
11^\circ \pm 4^\circ$). Over this angular range there is a strong dependence of $Q^2$ on scattering
angle, and only one beam energy of 3 GeV is required for all $Q^2$. In the backward
configuration, electrons are detected at $\theta_e = 110^\circ \pm 10^\circ$. In this case, $Q^2$ is only
weakly dependent on scattering angle, and the beam energy must be changed for
each $Q^2$. Beam energies of 424, 585, and 799 MeV, corresponding to $Q^2$ of 0.3, 0.5,
and 0.8 (GeV/c)$^2$ are presently planned for the backward angles.

To extract $G^Z_{E,M}$ a correction must be made for the small contribution of the
axial form factor, $G^A_{e}$, to the measured $A_z$. Gzero will determine this experimentally
by measuring quasi-elastic back angle scattering from deuterium. By measuring
at both forward and backward angles and with both hydrogen and deuterium
targets, Gzero will be able to determine $G^e_{E}$, $G^s_{E}$, and $G^A_{e}$ separately. As shown in
Table 4 other $\vec{e}p$ experiments have measured, or are planning to measure, various
linear combinations of the form factors.
Table 4. Comparison of $\vec{e}p$ parity violation experiments. Depending on the scattering angle and momentum transfer, the experiments are sensitive to different linear combinations of form factors

| Experiment          | $E_{\text{beam}}$ | $I_{\text{beam}}$ | $\theta_e$ (deg) | $Q^2$ | Target | Observable         |
|---------------------|-------------------|-------------------|------------------|-------|--------|-------------------|
| SAMPLE [29, 30]     | 200 MeV           | pulsed (2.7 mA peak) | 130–160          | 0.1   | LH$_2$ | $G^+_M + 0.44G^+_A$ |
| HAPPEX [31, 32]     | 3.3 GeV           | 75 $\mu$A        | 12.3             | 0.477 | LH$_2$ | $G^+_E + 0.39G^+_M$ |
| (Jlab Hall-A)       |                   |                   |                  |       |        |                   |
| HAPPEX-2 [33]       |                   |                   |                  |       |        |                   |
| He                  |                   |                   |                  |       |        |                   |
| PVA4 [35, 36, 37]   | 854 MeV           | 20 $\mu$A        | 35               | 0.225 | LH$_2$ | $G^+_E + 0.22G^+_M$ |
| (MAMI-Mainz)        |                   |                   |                  | 0.11  |        | $G^+_E + 0.10G^+_M$ |
| G-zero [27, 38]     | 3 GeV             | 35 $\mu$A        | 6-20             | 0.1-1.0 | LH$_2$ | measurements together give $G^+_E, G^+_M$ and $G^+_A$ |
|                     | 424 MeV           |                   | 100–120          | 0.3   | LH$_2$ |                   |
|                     | 576 MeV           |                   |                  | 0.5   |       |                   |
|                     | 799 MeV           |                   |                  | 0.8   |       |                   |
|                     | 424 MeV           |                   |                  | 0.3   |       |                   |
|                     | 576 MeV           |                   |                  | 0.5   |       |                   |
|                     | 799 MeV           |                   |                  | 0.8   |       |                   |

The $G$zero experiment completed a successful commissioning run of the forward angle configuration in fall 2002 and January 2003 and all major systems are now fully operational. Running will continue with an engineering run October to December, 2003, and production running is scheduled to start in 2004.

5 summary

Parity violation experiments provide a way to study effects of the weak interaction in the presence of the much stronger electromagnetic and strong nuclear interactions. The polarized beam experiments I have described use similar experimental techniques and face similar problems controlling systematic errors. The physics addressed by these experiments can, however be quite diverse. $\vec{n}p$ experiments constrain the weak pion-nucleon coupling constant, $f_n$. $\vec{p}p$ parity violation experiments are sensitive to the shorter range part of the nucleon-nucleon force and constrain the combinations $h^{pp}_\rho = h^{(0)}_\rho + h^{(1)}_\rho + \frac{1}{\sqrt{6}}h^{(2)}_\rho$ and $h^{pp}_\omega = h^{(0)}_\omega + h^{(1)}_\omega$. Finally, $\vec{e}p$ parity violation experiments, such as the Jlab Gzero experiment, offer the opportunity to measure the contribution of strange quark-antiquark pairs to the proton charge and magnetism.

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