Parity Violation and the Nucleon-Nucleon System*

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Abstract

Theoretical and experimental work seeking to understand the phenomenon of parity violation within the nucleon-nucleon system is reviewed.

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1 Introduction

Parity invariance has played a critical role in the evolution of our understanding of the weak interaction. Indeed one could argue that it was the experiment of Wu et al. [1] motivated by the suggestion of Lee and Yang [2] that led to reexamination of the symmetry properties of all interactions and thereby to essentially all of the experiments discussed in this book! Be that as it may, it is clear that this work led in 1958 to Feynman and Gell-Mann’s postulate of the $V - A$ interaction for charged currents [3], which, when combined with Weinberg’s introduction of the neutral current a decade later [4], essentially completed our picture of the weak force. Since that time careful experimental work has led to verification of nearly every aspect of the proposed weak interaction structure

i) in the leptonic sector—e.g. $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e, \tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$;

ii) in the $\Delta S = 0, 1$ semileptonic sector—e.g. $n \rightarrow p e^- \bar{\nu}_e, \Lambda \rightarrow p e^- \bar{\nu}_e$

iii) in the $\Delta S = 1$ nonleptonic sector—e.g. $\Lambda \rightarrow p \pi^-, K^+ \rightarrow \pi^+ \pi^0$.

However, there is one area missing from this itemization—the $\Delta S = 0$ nonleptonic interactions, e.g. $np \rightarrow np$. Obviously there is nothing in the identity of the particles involved to reveal the difference between this weak interaction and the ordinary strong $np \rightarrow np$ process. In fact the weak NN component is dwarfed by the much larger strong NN force but is detectable by the property of parity violation, which it alone possesses.

On the experimental side, the first search for parity violation in the NN interaction was carried out by Tanner [5] in 1957, but it was not until 1967 that convincing evidence was presented for its existence by Lobashov et al. [6], who by using integration methods as opposed to particle counting, was able to find a $(-6 \pm 1) \times 10^{-6}$ signal among the much larger parity conserving strong background in radiative neutron capture from $^{181}$Ta. That this should be the size of a weak parity violating effect is clear from a simple scaling argument relating the parity violating and parity conserving nucleon-nucleon potentials $V_{NN}^{(+)}$ and $V_{NN}^{(-)}$, respectively:

$$\frac{V_{NN}^{(-)}}{V_{NN}^{(+)}} \sim Gm_N^2 \sim 10^{-7}$$

(1)

where $G = 1.01 \times 10^{-5} M_N^2$ is the weak coupling constant.

More than a quarter-century has now elapsed since the Lobashov measurement and many elegant (and difficult) experiments have been performed in this field. Nevertheless, as we shall see, there remain deep and unresolved questions. The reason for this is that while the $\Delta S = 0$ parity violating interaction is simple at the quark level, experiments involve, of necessity, strongly interacting hadrons, and making a convincing connection between an experimental signal and the fundamental Hamiltonian...
which it underlies has proven to be extraordinarily difficult. Lest one underestimate
the difficulty involved, the reader is reminded that in the related $\Delta S = 1$ nonleptonic
sector, the dynamical origin of the $\Delta I = \frac{1}{2}$ rule remains a mystery despite three
decades of vigorous experimental activity[7]. Nevertheless much has been learned in
the process and it is the purpose of this chapter to review the present situation in the
field.

In doing so we are aided substantially by previous workers in this area, and in par-
ticular by the excellent review article prepared nearly a decade ago by Adelberger and
Haxton.[8] Here we primarily summarize progress in experiments and interpretation
since that time.

2 The Parity-Violating NN Potential

In this section we examine the parity-nonconserving NN potential and its relation to
the underlying weak interaction from which it is derived. Since we will be dealing
with low energy processes, we can represent the weak interaction in terms of its local
form—a point interaction of two currents—

$$H_{wk} = \frac{G}{\sqrt{2}}(J^c_\mu J^c_\mu + \frac{1}{2} J^n_\mu J^n_\mu)$$

where, omitting contributions from the heavy (c,b,t) quarks,

$$J^c_\mu = \bar{u}\gamma_\mu(1 + \gamma_5)[\cos \theta_c d + \sin \theta_c s]$$
$$J^n_\mu = \bar{u}\gamma_\mu(1 + \gamma_5)u - \bar{d}\gamma_\mu(1 + \gamma_5)d$$
$$- \bar{s}\gamma_\mu(1 + \gamma_5)s - 4 \sin^2 \theta_w J^{EM}_\mu$$

are the charged and neutral weak currents respectively. Here $\theta_c, \theta_w$ are the Cabibbo
and Weinberg angles while $J^{EM}_\mu$ is the electromagnetic current.[9] One set of rigor-
ous statements which can be made involves the isotopic spin structure of the parity
violating weak Hamiltonian, which can assume the values 0,1,2. In particular the ef-
cective $\Delta I = 2$ Hamiltonian receives contributions only from the product of isovector
charged currents—

$$H_{wk}^{\Delta I = 2} \sim J^c_\mu J^c_\mu.$$ (4)

On the other hand the effective $\Delta I = 1$ Hamiltonian arises from both charged and
neutral currents—

$$H_{wk}^{\Delta I = 1} \sim J^c_\mu J^c_\mu + J^c_\mu J^n_\mu + J^n_\mu J^n_\mu.$$ (5)

Since $J^c_\mu \sim \sin \theta_c$ and $\sin^2 \theta_c \sim 1/25 << 1$, however, we expect that the primary
contribution comes from the product of isoscalar and isovector neutral currents. Fi-
nally, the effective $\Delta I = 0$ Hamiltonian receives significant contributions from both
neutral and charged currents—

$$H_{wk}^{\Delta I = 0} \sim J^c_\mu J^c_\mu + J^c_\mu J^n_\mu + J^n_\mu J^n_\mu.$$ (6)
Now while such relations are easy to write down at the quark level, their implications for the nucleon-nucleon system are much more subtle. The reason is that, because of the heaviness of the W,Z, the low energy weak interaction is essentially pointlike—of zero range. But the nucleon-nucleon interaction has a strong repulsion at small distances so that the probability of nucleons interacting at short range is essentially nil—i.e., there is virtually no direct weak NN interaction. Rather it is known that the ordinary (parity conserving) low energy nucleon-nucleon interaction $V^{(+)}_{NN}$ can be represented to a high degree of precision in terms of a sum of single ($\pi, \rho, \omega$) and multiple meson ($\pi-\pi$) exchanges. We would expect then that its parity-violating counterpart $V^{(-)}_{NN}$ can be represented in like fashion, except that now one meson-nucleon vertex is weak and parity violating, while the other is strong and parity conserving. Consequently, all of the weak interaction physics is contained within the values of these parity violating NNM coupling constants.

Because of the “hard core” associated with the nucleon-nucleon interaction, it is customary to include only mesons of mass less than 800 MeV or so, and our task is further simplified by use of Barton’s theorem, which asserts that exchange of neutral and spinless mesons between on-shell nucleons is forbidden by CP invariance. Therefore only $\pi^\pm, \rho$ and $\omega$ vertices need be considered and the form of the most general parity violating effective Hamiltonian is easily found:

$$\mathcal{H}_{wk} = \frac{f_\pi}{2} \bar{N} (\tau \times \pi)_3 N$$
$$+ \bar{N} \left( h^{0\rho}_{\tau} \cdot \rho^\mu + h^{1\rho}_{\rho_3} + \frac{h^2_{\rho}}{2\sqrt{6}} (3\tau_3 \rho_3^\mu - \tau \cdot \rho^\mu) \right) \gamma_\mu \gamma_5 N$$
$$+ \bar{N} (h^{0\omega}_{\omega} \omega^\mu + h^{1\omega}_{\tau_3 \omega} \gamma_5 N - h^{1\rho}_{\rho_3} \bar{N} (\tau \times \rho^\mu)_3 \frac{\sigma_{\mu\nu} k^\nu}{2\sqrt{6}} \gamma_5 N)$$

We see that there are in general seven unknown weak couplings $f_\pi, h^{0}_{\rho}, \ldots$. However, calculations indicate that $h^{1}_{\rho}$ is quite small and this term is generally omitted, leaving parity violating observables to be described in terms of just six constants. The means by which one attempts to determine these couplings experimentally will be described shortly. However, before doing so we shall examine the theoretical predictions for the size of these vertices from the underlying weak interaction.

### 2.1 Theoretical Calculation of Weak Coupling Constants

One of the first estimates of the weak parity violating vertex constants was provided in the early 1960’s. F.C. Michel estimated the charged current couplings to vector mesons using the so-called factorization approximation, which replaces a sum over a complete set of intermediate states by only the vacuum state contribution—

$$< \rho^+ n | \mathcal{H}_{wk} | p > = \frac{G}{\sqrt{2}} \cos^2 \theta_c < \rho^+ n | V^\mu_{+} A^-_\mu | p >$$
\[ \approx \frac{G}{\sqrt{2}} \cos^2 \theta_c \rho^+ |V_+^{\mu}| \rho^{-} A^- |p> \]  

(8)

The justification for this approximation is basically that it is possible and easy to calculate. There is no reason to believe that it provides anything other than an order of magnitude estimate.

The next major theoretical development occurred in 1970 with the realization that the charged current contribution to pion production could be written using SU(3) symmetry in terms of experimental parity violating hyperon decay amplitudes\[14]\]

\[ <\pi^+ n | H_wk | p> = -\sqrt{2} \tan \theta_c (2 <\pi^+ | \lambda_0 > - <\pi^- | \lambda_0 >) \]  

(9)

Unfortunately, this result is not as convincing as it appears, since it involves a substantial cancellation between \( \Lambda_0 \) and \( \Xi^- \) decay amplitudes and is therefore rather sensitive to possible SU(3) breaking effects\[15].

Three years later McKellar and Pick\[16\] showed how the symmetry SU(6) could be applied to the \( \Delta S = 0 \) parity violating interaction, thereby relating pion and vector meson emission amplitudes. They determined that the vector meson amplitudes predicted via symmetry were of opposite sign and considerably larger than those given by factorization thereby ameliorating an experimental sign discrepancy which existed at that time. However, this approach too was incomplete in that i) there were additional SU(6) couplings which were not predictable from experimental data and ii) because of its non-\( V - A \) character one could not treat the neutral current Hamiltonian in terms of this approach.

A comprehensive calculation which included all previous results and which enabled predictions to be made for all NNM couplings from both charged and neutral current pieces of the weak Hamiltonian was performed in 1980 by Desplanques, Donoghue, and Holstein (DDH)\[17\]. Although additional calculations have been performed during the intervening years\[18, 19\], nearly all are very similar in method and/or yield numerical results which are qualitatively similar to those of DDH, so we shall spend some time summarizing this work.

The basic idea of the work of DDH is use of the valence quark model, within which the nucleon can be constructed in terms of three quark creation operators

\[ |N> \sim b_{q,s} b_{q',s'} b_{q'',s''}|0> \]  

(10)

where we imagine the spins, isospins to be combined to form components of a spin, isospin doublet and the colors to be contracted to form a singlet. Likewise we can construct the vector and pseudoscalar mesons via

\[ |M> \sim d_{q,s} b_{q',s'} |0> \]  

(11)

using quark and antiquark creation operators. The weak Hamiltonian itself has a local current-current structure and involves four quark fields

\[ H_wk \sim \frac{G}{\sqrt{2}} \bar{\psi} O \psi \bar{\psi} O' \psi. \]  

(12)
A generic NNM weak matrix element then is of the form

\[<MN|H_{wk}|N> = \frac{G}{\sqrt{2}} \langle 0| (b_{qs}b_{q's'}b_{q''s''})(b_{qs}d_{q's'}) \bar{\psi}O\psi \bar{\psi}O'\psi (b_{qs}b_{q's'}b_{q''s''})|0> \times R \]  

(13)

where \(R\) represents a complicated radial integral. The vacuum expectation value is tedious to calculate but doable. Thus one finds

\[<MN|H_{wk}|N> \sim \text{known "geometrical" factor} \times R \]  

(14)

which is in the form of a Wigner-Eckart theorem, where the known "geometrical factor" is a Clebsch-Gordan coefficient and \(R\) represents a reduced matrix element, which is identical for all such transitions and may be determined empirically by comparing one such amplitude with its experimental value. In fact when this procedure is followed for the simple charged current Hamiltonian the \(SU(6)_W\) results of McKellar and Pick are exactly reproduced. However, within the quark model based procedure one can treat the neutral current matrix elements on an equal footing. Also, since the \(\pi\)- and \(\rho\)-meson masses are so different it is essential to include \(SU(6)\) breaking effects, and the quark model offers a means of doing this.

While details can be found in ref. 17, the results can be summarized in terms of three different types of reduced matrix elements as shown in Fig. 1. Figure 1a represents the factorization diagrams with the vector or pseudoscalar meson connecting to the vacuum through either the \(V\) or \(A\) current respectively, multiplied by the nucleon-nucleon matrix element of the \(A\) or \(V\) current. The remaining two diagrams are of a different character and correspond to more complicated baryonic intermediate states. Figure 1b can be shown to correspond to the \(SU(3)\) sum rule of Eq. (10). Note that since the hyperon decay amplitudes are themselves proportional to \(\cos \theta_c \sin \theta_c\) the charged current Hamiltonian contribution to pion emission is proportional to \(\sin^2 \theta_c\) and is strongly suppressed. However, this is not the case for the corresponding neutral current contribution, which is of \(O(1)\) and consequently dominates the pion emission amplitude. Finally, Fig. 1c represents the new contribution to the vector/pseudoscalar emission identified by McKellar and Pick.

Despite the understanding gained by connecting the quark model and symmetry based calculations, DDH emphasized that there remain major difficulties in attempts to provide reliable numerical estimates for these weak parity violating couplings. These include uncertainty in

i) the (large) S-P factorization term due to its dependence on the absolute size of the current u,d quark masses;

ii) enhancement factors associated with the renormalization group treatment of the effective weak Hamiltonian;

iii) use of a relativistic vs. a nonrelativistic quark model;
iv) the size of the sum rule contribution to pion emission due to SU(3) breaking;

v) the size of the vector meson vs. pion emission amplitudes due to SU(6) breaking effects;

vi) etc.

Because of all of these unknowns DDH presented their results not as a single number but rather in terms of a range inside of which it was extremely likely that a given parameter would be found. In addition they presented a single number called the “best value” but this is described simply as an educated guess in view of all the uncertainties outlined above. The results of this process are summarized in Table 1.

2.2 Parity Violating Nucleon-nucleon Potential

Before we can make contact with experimental results it is necessary to convert the NNM couplings generated above into an effective parity violating nucleon-nucleon potential. Inserting the strong couplings, defined via

\[
\mathcal{H}_{st} = ig_{\pi NN}\bar{N}\gamma_5 \tau \cdot \pi N + g_{\rho}\bar{N} \left( \gamma_\mu + i\frac{\mu_\nu}{2M}\sigma_{\mu\nu}k^\nu \right) \tau \cdot \rho^\mu N \\
+ \ g_\omega \bar{N} \left( \gamma_\mu + i\frac{\mu_\nu}{2M}\sigma_{\mu\nu}k^\nu \right) \omega^\mu N
\]

(15)

into the meson exchange diagrams shown in Fig. 2
Table 1: Weak NNM couplings as calculated in refs. 17-19. All numbers are quoted in units of the “sum rule” value $3.8 \times 10^{-8}$.

| Coupling | DDH\cite{17} Reasonable Range | DDH\cite{17} “Best” Value | ref. 18 | ref. 19 |
|----------|-------------------------------|---------------------------|---------|---------|
| $f_\pi$  | $0 \rightarrow 30$           | 12                        | 3       | 7       |
| $h^0_\rho$ | $30 \rightarrow -81$       | -30                       | -22     | -10     |
| $h^1_\rho$ | $-1 \rightarrow 0$         | -0.5                      | +1      | -1      |
| $h^2_\rho$ | $-20 \rightarrow -29$     | -25                       | -18     | -18     |
| $h^0_\omega$ | $15 \rightarrow -27$     | -5                        | -10     | -13     |
| $h^1_\omega$ | $-5 \rightarrow -2$       | -3                        | -6      | -6      |

Figure 2: Parity violating NN potential generated by meson exchange.
and taking the Fourier transform one finds the effective nucleon-nucleon potential

\[ V_{PNC}^{\text{eff}} = \frac{f_{\pi} g_{\pi NN}}{\sqrt{2}} \left( \frac{\tau_1 \times \tau_2}{2} \right) \cdot (\sigma_1 + \sigma_2) \cdot \left[ \frac{P_1 - P_2}{2M}, f_{\pi}(r) \right] \]

\[ - g_{\rho} \left( h_{\rho}^0 \tau_1 \cdot \tau_2 + h_{\rho}^1 \left( \frac{\tau_1 + \tau_2}{2} \right)^3 + h_{\rho}^2 \frac{3(\tau_1^3 \tau_2^3 - \tau_1 \cdot \tau_2)}{2\sqrt{6}} \right) \]

\[ \times \left( (\sigma_1 - \sigma_2) \cdot \left\{ \frac{P_1 - P_2}{2M}, f_{\rho}(r) \right\} + i(1 + \chi_{V})\sigma_1 \times \sigma_2 \cdot \left[ \frac{P_1 - P_2}{2M}, f_{\rho}(r) \right] \right) \]

\[ - g_{\omega} \left( h_{\omega}^0 + h_{\omega}^1 \left( \frac{\tau_1 + \tau_2}{2} \right)^3 \right) \]

\[ \times \left( (\sigma_1 - \sigma_2) \cdot \left\{ \frac{P_1 - P_2}{2M}, f_{\omega}(r) \right\} + i(1 + \chi_{S})\sigma_1 \times \sigma_2 \cdot \left[ \frac{P_1 - P_2}{2M}, f_{\omega}(r) \right] \right) \]

\[ - (g_{\omega} h_{\omega}^1 - g_{\rho} h_{\rho}^1) \left( \frac{\tau_1 - \tau_2}{2} \right)^3 (\sigma_1 + \sigma_2) \cdot \left\{ \frac{P_1 - P_2}{2M}, f_{\rho}(r) \right\} \]

\[ - g_{\rho} h_{\rho}^V i \left( \frac{\tau_1 \times \tau_2}{2} \right)^3 (\sigma_1 + \sigma_2) \cdot \left[ \frac{P_1 - P_2}{2M}, f_{\rho}(r) \right] \] (16)

where \( f_{V}(r) = \exp(-m_{V}r)/4\pi r \) is the usual Yukawa form.

Armed now with the form of the parity violating nucleon-nucleon potential one can attempt to calculate the size of parity-violating observables which might be expected in a given experiment. However, before doing so it is useful to examine the general types of experimental signals of parity violation which one might look for.

### 3 Experimental Signals of Parity Violation

#### 3.1 Observables

Parity refers to the behavior of a system under spatial inversion, that is under the mathematical transformation \( r \rightarrow -r \). Under spatial inversion momentum, being proportional to velocity, also changes sign—\( p \rightarrow -p \)—but angular momentum, being an axial vector, does not—\( L = r \times p \rightarrow r \times (-p) = +L \). Likewise spin must transform into itself under a spatial inversion. Thus one generally looks for a parity violating signal by examining a correlation which is odd under spatial inversion, such as photon circular polarization, which has the form \( \sigma \cdot p \).

**a) \( P_{\gamma} \)-circular polarization in \( \gamma \)-decay:** That the presence of non-zero circular polarization is a signal of parity violation can be seen within the context of a simple example. Consider a transition involving emission of electric and magnetic dipole radiation, for which the relevant operators have the form

\[ E1 : \hat{e}_{\gamma} \cdot p \]

\[ M1 : i\hat{e}_{\gamma} \times q \cdot L. \] (17)
Circular polarization involves a linear combination of polarization states orthogonal to the photon momentum and $90^\circ$ out of phase
\[
\hat{q}_\gamma = \hat{z}, \quad \hat{\epsilon}_{R,L} = \sqrt{\frac{1}{2}}(\hat{x} \pm i\hat{y}).
\] (18)

As both $\mathbf{p}$ and $\mathbf{L}$ are tensors of rank one, the Wigner-Eckart theorem guarantees that the $E1, M1$ amplitudes are proportional
\[
<f|\mathcal{O}_{E1}|i> \propto <f|\mathcal{O}_{M1}|i>.
\] (19)

Finally, since $\hat{\epsilon}_\gamma, \hat{\epsilon}_\gamma \times \hat{q}, \hat{q}$ are mutually orthogonal, we see that the simultaneous presence of both electric and magnetic dipole transitions must lead to circular polarization. However, since $\mathbf{p}$ is a polar vector while $\mathbf{L}$ is an axial vector the selection rules are different
\[
E1 : \Delta J = 0, \pm 1; \quad P_i P_f = -1
\]
\[
M1 : \Delta J = 0, \pm 1; \quad P_i P_f = +1
\] (20)

so that clearly a violation of parity invariance is required for the existence of circular polarization.

While nonzero circular polarization is then a clear indication of parity noninvariance, detection of such a signal is made difficult by the fact that there exist no efficient circular polarization analyzers. All such polarimeters are based on the spin dependence of Compton scattering by polarized electrons in magnetized iron. However, even at saturation only $2/26 \sim 8\%$ of the Fe electrons are polarized so this represents an upper bound for the analyzing power of such a polarimeter. In fact, typical values for actual instruments are typically $4\%$ or less.

b) $A_\gamma$-asymmetry in $\gamma$-decay: Because of this limitation, many experiments have instead chosen to polarize the parent nucleus and to look for the existence of a decay asymmetry of the emitted photon with respect to the polarization direction—i.e. a correlation $<\mathbf{J} \cdot \mathbf{q}>$. The difficulty in this case is to provide a large, reversible degree of polarization for the decaying nucleus.

c) $A_z$-longitudinal analyzing power: A third parity violating observable is the longitudinal analyzing power of reactions involving polarized nucleons—
\[
A_Z = \frac{1}{P_Z} \left( \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \right)
\] (21)

where $P_Z$ is the longitudinal polarization and $\sigma_{\pm}$ are the cross sections for right and left handed helicity nucleons respectively—i.e. a correlation $<\mathbf{J} \cdot \mathbf{p}>$. Such measurements are accomplished by rapidly switching the beam helicity. A related, but independent, observable is the analyzing power $A_x$ defined in analogy to Eq. (21). This quantity is measured with beam polarization transverse to the beam momentum, but in the scattering plane.
d) Neutron spin rotation: Propagation of a beam of cold neutrons through a homogeneous sample can be described by an index of refraction, which depends on the forward scattering amplitude of the atoms. Inclusion of the weak interaction adds (coherently) a small parity-nonconserving component to the scattering amplitude, which causes the two neutron helicity states to accumulate different phases in passage through the medium\[13, 20\]. As a consequence, a neutron spin initially transverse (y) to its momentum (z) undergoes a spin rotation in the transverse (xy) plane proportional to the thickness of material traversed, and thus acquires a x-component of polarization. The experimental arrangement [see ref.\[21\] and Fig. 7] makes use of a sample placed between a neutron polarizer (y) and a neutron analyzer (x) at right angle to one another, with the sample placed in between. The sample is placed alternatively before and after a 180° spin rotator, which reverses the x-component of neutron polarization. In this way the method doubles the size of the spin rotation signal and avoids many of the instrumental problems which would have to be dealt with if a comparison were made of counts with sample in place and sample removed.

e) Parity-forbidden decay width: Finally, a fourth type of experiment involves the detection of a process whose very existence would be forbidden were parity to be conserved. An example is the α decay

$$^{16}\text{O}(2^-) \rightarrow ^{12}\text{C}(0^+) + \alpha.$$  \[(22)\]

While the detection of such a signal is a clear indication of parity noninvariance, unlike any of the effects described above, which are interference experiments and consequently depend on the weak matrix element to the first power, the observable here is a rate and is therefore second order in the parity violating weak matrix element. The size of the signal is then very small (B.R.\(\sim 10^{-10}\) for the case above) and must be picked out from a much larger parity conserving background.

No matter which type of experiment one chooses, the very small magnitude of the expected parity violating signal at the weak level involves considerable challenge particular for the NN interaction itself where the effects are of the order \(10^{-7}\). In addition the number of feasible NN experiments is not sufficient to determine the separate weak NN couplings listed in Table 1. Thus many of the experiments listed below involve studies of parity violating effects in complex nuclei.

### 3.2 Experimental Systems

In selecting systems by which to study the phenomenon of nuclear parity violation, one has a number of choices. Certainly the cleanest from a theoretical point of view is the NN system. Indeed experimental phase shifts are known up to hundreds of MeV and beam/target systems are readily available. However, one pays a high price in that the expected signal is in the canonical \(10^{-7}\) range. Thus such experiments are notoriously sensitive to tiny systematic effects. In fact for the np system there still exists no compelling experimental signal.
A second arena is that of few body nuclei, e.g. p-d, p-α scattering and n-d radiative capture. In this case use of Faddeev and other methods provides a relatively believable theoretical base. However, it is by no means as clean as that for the NN processes, and one still is faced with generally tiny experimental effects, which require heroic experimental efforts.

The use of p-shell and heavier nuclei in the study of nuclear parity violation is an alternative route, but it has both positive and negative implications. On the plus side, the nuclear environment offers an enormous assortment of various spin-parity states which can in principle be exploited. Also, one can in some cases use the nucleus as an amplifier, in order to yield parity nonconserving signals much larger than the generic $10^{-7}$ estimated above. However, interpretation of such experiments in terms of fundamental weak interaction parameters requires knowledge of the nuclear wavefunctions at a level considerably more precise than needed for the understanding of more traditional (and parity conserving) nuclear measurements.

An excellent example of the large enhancement that sometimes occurs in complex nuclei is provided by the measurement of the photon asymmetry in the decay of 8⁻ isomer of $^{180}$Hf, which yields a 2% effect

$$A_\gamma = (1.66 \pm 0.18) \times 10^{-2}. \quad (23)$$

An even larger signal is seen in low energy neutron scattering from $^{139}$La, where the longitudinal asymmetry has been measured to be

$$A_L = (9.55 \pm 0.35) \times 10^{-2}. \quad (24)$$

In order to see how such large effects can come about, consider a nucleus having states with identical spins but opposite parity—say $J^+, J^-$—which are very close to one another in energy. Now although we have labelled such states by their spin and parity, in reality neither state is a true eigenstate of parity, because of the presence of the weak interaction. (Spin, of course, is a good quantum number because angular momentum is exactly conserved.) We can calculate the mixing of these presumed close-by levels using first order perturbation theory, yielding

$$|\psi_{J^+} > \simeq |\phi_{J^+} > + \frac{|\phi_{J^-} > < \phi_{J^-} |H_{wk}| \phi_{J^+} >}{E_+ - E_-}$$
$$= |\phi_{J^+} > + \epsilon |\phi_{J^-} >$$

$$|\psi_{J^-} > \simeq |\phi_{J^-} > + \frac{|\phi_{J^+} > < \phi_{J^+} |H_{wk}| \phi_{J^-} >}{E_- - E_+}$$
$$= |\phi_{J^-} > - \epsilon |\phi_{J^+} >$$ \quad (25)

in an obvious notation. Note that we have truncated the sum over all intermediate states down to a single state by the assumption that the two states being considered here are nearly degenerate. We can estimate the size of the mixing parameter $\epsilon$ by
scaling to a typical nuclear level splitting, of the order of an MeV or so. Since this splitting is associated with the strong interaction we estimate

\[ \langle \phi_J^+ | H_{wk}^J | \phi_J^- \rangle \sim \frac{\langle H_{wk}^J \rangle}{\langle H_{st}^J \rangle} \times 1\text{MeV} \sim 1\text{eV}. \]  

(26)

For a pair of levels with a typical—MeV—spacing, we then have

\[ \epsilon = \frac{\langle \phi_J^- | H_{wk}^J | \phi_J^+ \rangle}{E_+ - E_-} \sim \frac{1\text{eV}}{1\text{MeV}} \sim 10^{-6} \]  

(27)

as expected. However, the mixing can be substantially enhanced by selecting two levels which are nearly identical in energy. Thus, for example, for two states which are separated by say 100 eV one might expect an effect of the size

\[ \text{Parity Violating Effect} \sim 10^{-6} \times \frac{1\text{MeV}}{|E_+ - E_-|} \sim 10^{-2} \]  

(28)

and the situation of \(^{139}\text{La}\) falls into this category, involving a narrow p-wave state embedded in a host of nearby s-wave resonances. The case of \(^{180}\text{Hf}\) involves a 501 keV gamma ray, however, and reveals an alternative means by which nuclear enhancement can arise. Since the transition connects 8\(^-\) and 8\(^+\) levels, the transition would be expected to be predominantly electric dipole, with a small magnetic dipole component generated by the presence of parity mixing, and the resultant asymmetry would be of order

\[ A_\gamma \sim 2\epsilon \frac{< M1 >}{< E1 >}. \]  

(29)

However, for \(^{180}\text{Hf}\) the E1 transition is highly retarded, having \(\Delta K=8\) in the Nilsson rotational model, and this selection rule violation accounts for the very large signal.

Despite the obvious experimental advantages to having 1% signals to deal with rather than the generic \(10^{-6}\) effects found in direct NN experiments, the use of complex nuclei does not permit rigorous extraction of the size of weak effects because of the lack of believable nuclear wavefunctions for such heavy nuclei. However, as we shall see below (Sect. 7) sufficiently good wave functions have been established for a number of s-d and p shell nuclei. In addition, for heavy nuclei information has been extracted by use of statistical arguments (Sect. 8).

4 Proton-Proton Interaction

The simplest system wherein the weak parity violating interaction can be studied consists of a pair of nucleons. Since experimental studies of the two-neutron interaction are out of the question for obvious reasons, that leaves either the pp or the pn system, which we shall examine in this and in the following section.
The parity violating pp interaction has been studied by a number of groups by measuring the analyzing power $A_z$ for longitudinally polarized protons. In isospin space, two protons form an isotriplet and therefore the parity nonconserving interaction in this case will involve all the isospin components - $\Delta I = 0, 1, 2$.

Depending on proton energy, measurements on the pp system use one of the arrangements shown schematically in Fig. 3. At high energies, the helicity dependence $A_{z}^{\text{tot}}$ of the total cross section is deduced from the change in transmission through the sample when the spin direction of the incoming beam is reversed, the transmission being measured by the ratio of the beam intensity before and after the sample. At lower energies ($E<50$ MeV) the transmission method is not useful because the large proton energy loss in the sample limits the useable target thickness, so that the attenuation by nuclear interactions is too small to be measured with sufficient accuracy. Instead, one measures the intensity of scattered particles, for both beam helicities, divided by the intensity that passed through the sample. To improve the statistical error, and to reduce certain systematic errors, the detector is arranged to cover all or most of the range in azimuthal angle.

### 4.1 Low energy region

Because of the short range of the PNC interaction, below 400 MeV only low partial waves contribute to the PNC amplitudes, namely the ($^1S_0 \leftrightarrow ^3P_0$) and the $J=2$ transition ($^3P_2 \leftrightarrow ^1D_2$). The two contributions add incoherently:

$$ A_z(E, \theta) = A_{z}^{J=0}(E, \theta) + A_{z}^{J=2}(E, \theta). \quad (30) $$

The relative dependence on energy and angle of each of the two terms can be calculated from the strong interaction phase shifts$^{24, 25}$. The angular dependence of the $J=0$ contribution is isotropic, but the $J=2$ contribution shows a pronounced variation with
Figure 4: Energy dependence of the J=0 \((^1S_0 - ^3P_0)\) and the J=2 \((^3P_2 - ^1D_2)\) PNC transition in pp scattering, calculated from the known strong pp phase shifts. The sign and absolute normalization of the vertical scale for each of the two curves must be determined experimentally. Here the sign and normalization (in units of \(10^{-7}\)) is chosen to correspond to predictions based on the DDH “best” couplings.

angle\[25, 26, 27\]. The energy dependence of the angle-integrated PNC analyzing power \(A^\text{tot}_z\) is shown in Fig. 4. The purpose of PNC experiments is to determine the two unknown absolute normalizations (scale factors) which multiply the \(A^J=0_z\) and \(A^J=2_z\), respectively.

Below about 50 MeV \(A_z\) is governed by the J=0 transition and thus is angle-independent. Consequently, the angular range accepted by the experiment is chosen to optimize statistical and instrumental uncertainties. The pioneering experiment at Los Alamos\[28\] at 15 MeV yielded \(A_z = -(1.7 \pm 0.8) \times 10^{-7}\). Soon thereafter, a group\[29\] working at SIN (Switzerland) reported a result of \(A_z = -(3.2 \pm 1.1) \times 10^{-7}\) for a proton energy of 45 MeV, where the \(A_z\) is near its maximum value. Since \(A_z\) arises almost entirely from the J=0 transition, the factor that relates \(A_z\) at the two energies is known from theory\[25\]:

\[
A_z(45.0 \text{ MeV}) = (1.76 \pm 0.01) \times A_z(15.0 \text{ MeV}).
\]  

Thus the two early results are entirely consistent. The absolute scale depends upon the weak parity nonconserving couplings via

\[
f(^1S_0 - ^3P_0) \approx [h^{pp}_\rho g_\rho(2 + \chi_V) + h^{pp}_\omega g_\omega(2 + \chi_S)]f^T_0,
\]

where

\[
h^{pp}_\rho = h^{(0)}_\rho + h^{(1)}_\rho + \frac{1}{\sqrt{6}}h^{(2)}_\rho \quad \text{and} \quad h^{pp}_\omega = h^{(0)}_\omega + h^{(1)}_\omega
\]

are combinations of parity violating parameters (note that \(f_\pi\) does not enter due to Barton’s theorem) and \(f^T_0\) depends upon the model of the strong NN potential being
employed. With the DDH best values, use of the Reid soft-core potential yields a prediction [see ref. 27 and Table 2]

\[ A_z(45 MeV) = -1.45 \times 10^{-7} \]  

(34)

while use of the Paris potential gives a value about 30% larger.

Work with longitudinally polarized 45 MeV protons at the SIN cyclotron continued for a decade in attempts to eliminate or place accurate limits on a large number of possible systematic errors, many of which in earlier years would have seemed too far fetched to worry about. The final result of these efforts is

\[ A_z(45.0 MeV) = -(1.50 \pm 0.22) \times 10^{-7} \]  

(35)

where the error includes statistical and systematic uncertainties as well as limits on uncertainties in the corrections for instrumental effects. Scattered protons were detected in the angular range \( \theta_{lab} = 23^\circ \) to \( 52^\circ \). Since \( A_z \) is independent of angle, the result can be considered to represent \( A_z \) in the total cross section. However, strictly speaking the total cross section is poorly defined because of Coulomb-nuclear interference at very forward angles, and there is an additional uncertainty from the possible (small) \( J=2 \) contribution. For the total nuclear PNC analyzing power at 45 MeV, the final result is:

\[ A_z^{\text{tot}}(45.0 MeV) = -(1.57 \pm 0.23) \times 10^{-7} \]  

(36)

Agreement with the theoretical expectation (in both magnitude and sign) is excellent and confirms the important role of the nonfactorization contributions to the weak vector meson exchange couplings.

Since the above represents the most accurate result on parity violation in hadronic interactions to date, a brief review of the experiment is of interest. The scattering chamber is shown in Fig. 5. A longitudinally polarized beam of 45 MeV protons is incident on a high pressure (100 bar) hydrogen gas target, and scattered protons are detected in a hydrogen-filled (1 bar) ionization chamber in the form of an annular cylinder surrounding the target. The polarized protons are produced by ionizing polarized atoms prepared by spin separation in an atomic beam device. The polarization of the protons is reversed by inducing suitable radio-frequency transitions between hyperfine states in the neutral atoms. In this way the polarization is reversed without the need for any change in electric and magnetic fields seen by the ions, which might produce a helicity-dependent change in beam properties. The atoms are ionized by electron bombardment inside a solenoid. The protons are accelerated in a cyclotron with their polarization direction transverse. The spin is then precessed, first by a solenoid from the vertical to the horizontal direction, and then from the horizontal transverse direction into the longitudinal direction by a dipole magnet. For testing purposes, the polarization can be precessed into any desired direction by choosing
Figure 5: Scattering chamber used for measurements of $A_z$ near 45 MeV. The drawing shows the gas target T, Faraday cup FC, graphite beam stop C, ion chamber IC formed by foil F and collector CO.

the proper current in the solenoid before the dipole magnet and in a second solenoid after the dipole magnet. Beam current on target was $3 - 4 \mu A$ with $P = 0.83 \pm 0.02$.

Scattered protons are detected by measuring the current in the ionization chamber, \textit{i.e.} this experiment like all others at a similar level of accuracy uses the so-called integral counting technique introduced originally by Lobashov[6], because it is still not feasible to reach the required accuracy by counting individual events. The ion chamber current is integrated during 20 ms intervals, after which the beam properties (beam intensity, beam position, beam diameter, spatial distribution of spurious transverse beam polarization components) are measured during a 10 ms interval, before the polarization is reversed. The initial polarization direction for a group of eight such measurements is chosen at random to reduce periodic noise. Each 60 ms measurement has a statistical error of $3.5 \times 10^{-5}$, as determined from the variance. The beam properties were determined by beam profile monitors in which narrow graphite strips were swept across the beam. Protons scattered by the graphite strips were detected in four detectors, to deduce the various polarization distributions $p_x(y)$, $p_y(x)$ etc. In order to gain information about dependencies not only on variation of transverse polarization with position $(x,y)$ but also with angle, two monitors in different locations along the beam axis are needed to correct the data. It is relatively easy to precess the proton polarization such that, averaged over the beam diameter, the polarization is accurately longitudinal. The real problem is that the polarization vector for different parts of the beam is not perfectly uniform in direction, so that the residual polarization components $p_x$, $p_y$, vary with position within the beam. Particularly dangerous is a fist moment of $p_x$ (or $p_y$) with respect to $y$ (or $x$), \textit{e.g.} a linear variation of $p_x$ with $y$. To understand the problem, look along the beam direction and assume that the left half of the beam has polarization up, the right half polarization down. The
regular (parity-conserving) analyzing power \( A_y \) causes particles on the left to scatter predominantly to the left, and particles on the right to the right. When the beam polarization is reversed, the preferred direction is correspondingly reversed and thus the ion chamber current changes because of geometrical effects. Note that this effect does not vanish even if scattering chamber and beam intensity have perfect axial symmetry. The effects can be brought under control by accurate measurements of the polarization profile and corresponding measurements of the sensitivity of the equipment based on determination of the false effect for different positions and directions of the beam with respect to the symmetry axis of the chamber.

Errors may arise from any change in beam properties which is coherent (i.e., in step with) reversal of the beam helicity, such as small changes in beam position associated with helicity reversal. For reasons of symmetry, one would expect the false effect from coherent beam motion to vanish if the beam is exactly on the effective center of the scattering chamber. However, a very large sensitivity to vertical beam motion (false parity signal of \( 27 \times 10^{-7} \) per \( \mu m \) motion) was observed even when the beam was on the geometric axis of the chamber[31]. The effect was traced to temperature gradients in the high pressure gas target caused by beam heating. After installation of a fast blower system, which rapidly recirculates the target gas, the effect of possible beam motion (measured to be less than 0.2\( \mu m \)) was negligible.

Another interesting question is whether there may be small changes in beam energy when the polarization of the beam is reversed. The changes might result from interaction of the magnetic moment of the polarized hydrogen atoms with magnetic fields in the ion source, but no detailed mechanism has been established. Nevertheless, since calculations showed that already a 1 eV change in beam energy out of 45 MeV would cause an error in \( A_z \) of \( 3 \times 10^{-8} \), a possible energy modulation was investigated. The method principally made use of reversing the phase of the helicity by reversing the precession solenoid in the beam line. This reverses the sign of the true PNC signal but not the sign of the possible energy modulation signal. That energy modulations are not such a remote possibility after all was discovered when, for other reasons, the voltage on an electrostatic lens prior to the cyclotron was modulated. A false signal of \( 100 \times 10^{-7} \) was observed due to energy modulation. The false signal could then be used to test the rejection of the unwanted effect by solenoid reversal. This example suggests that in experiments at the \( 10^{-8} \) level of accuracy all spurious error sources must be investigated even if one knows of no reason why they should be present.

For some error sources no straightforward diagnostic methods exist, so that their investigation may require separate, auxiliary measurements which are comparable in effort to the PNC experiment itself. One such example is the study of the contribution to the ion chamber current from helicity-dependent background, such as background arising from \( \beta \)-decays. The concern is that incident and scattered protons activate various parts of the scattering chamber, and in the process may transfer some of their polarization to the resulting beta emitters, which in turn contribute to the currents in the ionization chamber and the Faraday cup. The effort to study these effects is
considerable, since many possible reactions in different materials are involved, and each has to be studied separately to determine if the combination of activation cross section, polarization transfer to the beta emitter, spin relaxation times, etc. are such that a significant error might result. For discussion of other systematic errors see, e.g., ref. [30, 32, 33].

In view of the many possible sources of error discussed in the literature, one may well ask how one can ever be certain that some additional error source has not been missed. However, by now the assumptions about error suppression have been inspected time and again in a systematic way by several groups working on the problems over more than two decades, so that the likelihood of an effect that has not been thought of is quite remote.

A good check on the correctness of an experimental result of course is obtained from repeating the experiments by another, independent group at a different laboratory, with different equipment, using different tests of systematic errors. For $A_z$ in pp scattering, the group at Bonn [34] has reported a new result at 13.6 MeV, which can be compared directly to the 45 MeV result. At the lower energy, the measured effect is expected to be smaller by a factor $(1.85 \pm 0.01)$, but the smaller magnitude of the effect is offset in part because some of the systematic errors are less dangerous at the lower energy. In particular, all effects associated with the regular, parity-allowed transverse analyzing power are significantly reduced. The experiment used secondary-electron emission monitors to determine the beam position, and employed feed-back devices to stabilize the beam. Their result

$$A_z(13.6 \text{ MeV}) = -(0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$$

(37)

can be compared with the energy-corrected 45 MeV number $A_z = -(0.81 \pm 0.12)$. The results are in excellent agreement.

### 4.2 Higher Energies

A very interesting account of the history of the Los Alamos PNC experiments at 800 MeV energy on targets of H$_2$O and liquid hydrogen, and of the 5.1 GeV experiment on H$_2$O at the Argonne ZGS has been presented in ref. [35]. The total cross section was observed by detecting the change in the fraction of beam transmitted though the sample as the beam helicity is reversed (Fig. 6). The 800 MeV pp experiment used a 1m long liquid hydrogen target. Beam pulses had a 120 Hz repetition rate and an average beam current of 1 to 5 nA. Analog signals from ion chambers (I1, I2) which measure the beam before and after the target are subtracted and digitized to obtain a signal that yields the transmission $T_+$ and $T_-$. With a transmission $T = 0.85$, the quantity $Z = (T_+ - T_-)/(T_+ + T_-)$ had to measured to an accuracy of $10^{-8}$ to reach a sensitivity in $A_z$ to $10^{-7}$. Figure 6 shows the diagnostic equipment which was used to monitor the beam position, intensity, size and net transverse polarization for every pulse. In addition, the variation of transverse polarization across the beam
Figure 6: Experimental setup used for measurements of $A_z$ at 800 MeV by the transmission method. The drawing is schematic and shows the 1 m long LH$_2$ target, and integrating ion chambers I$_1$, I$_2$. An analog difference (I$_2$-I$_1$) is formed before digitizing the signals to reduce round-off errors. The beam polarization is measured by a four-arm polarimeter P$_1$ which detects pp events, while the polarization profile is measured by the scanning target ST and polarimeter P$_2$. Integrating wire chambers W monitored beam position and size for each pulse. Beam position and incident angle were stabilized with signals from split-collector ion chambers S.

One advantage of the transmission method is that the sensitivity to the first moment of transverse polarization is smaller than for a scattering experiment. This is an important advantage because at the higher energies the regular pp analyzing power is large.

The 800 MeV (1.5 GeV/c) result\cite{36}:

$$A_z = (2.4 \pm 1.1) \times 10^{-7}$$

is of roughly the same magnitude but opposite in sign to the results at 45 MeV. The systematic errors are small ($0.1 \times 10^{-7}$), so that the overall uncertainty is governed by the statistical error, which is determined in part by the available beam current, and in part by detector noise due to nuclear spallation reactions in the ion-chamber surfaces.

The theoretical analysis of this measurement is much more complex than that of its lower energy counterparts since the energy is above the pion threshold and inelasticity effects must be taken into account. That the result should be positive
is clear since both S-P and P-D interference terms contribute with a positive sign above 230 MeV. A calculation by Oka\[37\] using experimental phase shifts in order to unitarize Born amplitudes yields a result, using DDH best values, which is about a factor of two above the experimental number. However, this calculation omitted short range correlation effects, which tend to reduce the size of the predicted effect considerably. A crude estimate of such effects made by Adelberger and Haxton\[3\] actually reduced the predicted effect below the experimental number. Subsequent work by Silbar \textit{et al.}\[38\] attempted to model inelasticity effects by including delta degrees of freedom and indicated an additional positive contribution of order $0.9 \times 10^{-7}$. However, this was based upon the DDH “best” value for $f_\pi$ which as we shall see is probably too large. We conclude that although no definitive calculation exists at present, existing calculations seem to agree reasonably well with the experimental value.

The measurement of the helicity dependence of the total cross section of 5.1 GeV (6 GeV/c) protons on a target of H$_2$O at the Argonne zero-gradient synchrotron used a spectrometer to eliminate the helicity-dependent background which would otherwise arise from hyperon decay products. The result\[39\]

$$A_z = (26.5 \pm 6.0 \pm 3.6) \times 10^{-7}$$

is considerably larger than is expected from most theoretical estimates, which tend to give numbers which are positive but which are about an order of magnitude smaller. The discrepancy only increases if one takes into account that the observation is for p − H$_2$O rather than p-N (on account of Glauber corrections, see ref.\[40\]). Of course, at these energies a simple meson-exchange potential model is no longer credible and so other techniques—\textit{e.g.} Regge theory—must be employed. The only credible estimate which has thusfar been able to reproduce the ZGS measurement is a model which involves mixing in the quark wavefunctions to negative parity excited states via quark-diquark interactions in the nucleon\[42\]. Such a model is quite speculative and is certainly not able to be extended to low energies in order to match onto other calculations. For further comments on the analysis of the 6 GeV/c result, see refs.\[35, 42, 43, 44, 45\]. Certainly, a remeasurement of asymmetry in this energy region would be most welcome.

### 4.3 Proposed and Planned Experiments

The low-energy experiments (13.6 MeV and 45 MeV) discussed above yield information only about the $J = 0$ ($^1S_0 \leftrightarrow ^3P_0$) transition. Figure 4 shows that starting at about 100 MeV, the $J = 2$ transition ($^3P_2 \leftrightarrow ^1D_2$) contributes significantly. In order to separate the two contributions, the preferred energy is near 230 MeV, where the $J = 0$ amplitudes cancel. Therefore the contribution to PNC associated with the $J = 2$ ($^3P_2 \leftrightarrow ^1D_2$) amplitude can be measured separately. This would yield an independent determination of the $\rho$ weak coupling constant $h_{\rho}^{pp}$. An experiment in
this energy range, to be carried out at TRIUMF, has been in preparation for some time\cite{19}. Two separate experiments are planned, one detecting the helicity dependence in transmission and one in scattering. The two experiments yield the same information about the weak amplitudes, but they serve as an extremely valuable test of systematic errors because the corrections are bound to have quite different characteristics. The transmission experiment is to use a 40 cm long liquid hydrogen target, with incident and transmitted protons detected by ionization chambers similar to the 800 MeV experiment mentioned above. The distribution of unwanted transverse polarization components is to be determined by beam scanners similar to the 45 MeV experiment. A feedback system is planned to stabilize beam position to 1 $\mu$m. The expected value\cite{25,26} of $A_z$ is about $0.6 \times 10^{-7}$ which is to be measured to an accuracy of $0.2 \times 10^{-7}$ or better. It is to be noted that in this case the angular distribution of $A_z(\theta)$ is far from isotropic.

An experiment near 230 MeV, as well as an extension to 1.5 GeV, is also planned to be carried out with protons extracted from the proton storage ring COSY at Jülich\cite{47}. The beam will be injected and accelerated in the storage ring, which has provision for phase space cooling of the beam. This is expected to result in an extracted beam of high ion optic quality, which in turn should reduce systematic effects associated with changes in beam properties. The possibility to carry out experiments at much higher energies (100 GeV) using the RHIC accelerator now under construction has been discussed \textit{e.g.} by Tannenbaum\cite{48}.

It recently has been pointed out by Vigdor\cite{49} that experiments with internal targets in storage rings may have important advantages over more conventional methods. In particular, it is proposed to arrange precession solenoids in a storage ring in such a fashion that only the longitudinal spin direction is stable, while the transverse components average to zero.

5 Neutron-Proton Interaction

\textit{a) $P_\gamma$ in np-capture:} As previously mentioned, the first clear experimental evidence for parity violation in nuclei was provided in a measurement by Lobashov \textit{et al.}\cite{3}, which detected a nonzero circular polarization [$P_\gamma = (-6 \pm 1) \times 10^{-6}$] of $\gamma$-rays from neutron capture in $^{181}$Ta. The experiment is known for the elegant idea to use a pendulum in vacuum to detect and store the repeated effects of the small periodic signal which resulted in the $\gamma$ detector from the reversal of the magnetic field in the magnetized iron which served as the $\gamma$-ray polarimeter. Later, the same arrangement was used in the first attempt to detect parity violation directly in the NN interaction. The first result\cite{50} was later found to be contaminated with circularly polarized bremsstrahlung caused by polarized electrons from beta decays of fission products in the reactor. A new experiment\cite{51}, which yielded $P_\gamma = (1.8 \pm 1.8) \times 10^{-7}$, was already discussed in a previous review\cite{8}. The new measurement is consistent with the “best value” prediction of $0.57 \times 10^{-7}$ (Table 2). The result is important
in that it removes the earlier significant discrepancy with theory. However, to reach an accuracy sufficient to contribute to the determination of weak coupling constants (e.g., $\pm 0.2 \times 10^{-7}$) is probably not realistic, since the magnitude of the experimental signal to be detected is another factor of 20 smaller on account of the relatively small analyzing power (0.045) of the $\gamma$-ray polarimeter. Experimental results consistent with zero can yield significant constraints on the determination of weak coupling constants in those cases where two coupling constants contribute terms of similar magnitude but opposite sign, but this is not the case for $P_\gamma$.

b) Helicity Dependence in Deuteron Photodisintegration: As an alternative to measuring $P_\gamma$ in np capture, one may choose to study the inverse reaction, i.e. photodisintegration of the deuteron near threshold with circularly polarized photons. The photodisintegration cross section $\sigma^+$ and $\sigma^-$ is measured with incident photons of positive and negative helicity to determine the parity-violating analyzing power $A_L$ defined in Eq. (21) where $P_L$ now refers to the photon circular polarization. Earle et al.\textsuperscript{[52]} accelerated polarized electrons produced by photoemission from GaAs in the Electron Test Accelerator at Chalk River, Canada to energies of 3.2 MeV or 4.1 MeV in order to produce polarized bremsstrahlung in a water-cooled tantalum radiator. The highest energy photons have a circular polarization equal to that of the incident electrons, or about $P_\gamma = 0.35$. The photons are incident on a target of deuterated water. The photoneutrons are thermalized in the target and are detected via the $^{10}$B(n,\alpha) reaction in boron-lined ionization chambers. The ionization chamber current caused by background photons was eliminated by subtracting the current in a second set of chambers, interspersed with the first, but without the $^{10}$B lining.

The effects of changes in electron beam properties (intensity, energy, position, beam size) associated with reversal of the beam helicity were studied in separate test experiments, and corresponding corrections were applied to the data. It is in fact the uncertainty of these corrections, and not statistical uncertainties, which limit the accuracy of the data. The final result, $A_L = (27 \pm 28) \times 10^{-7}$ for bremsstrahlung with an endpoint of 4.1 MeV, and $A_L = (77 \pm 53) \times 10^{-7}$ for an endpoint energy of 3.2 MeV unfortunately are not accurate enough to provide significant constraints on the weak coupling constants. A number of improvements in the experiment were discussed by the authors, suggest that with a major effort their method might be capable of a sensitivity comparable with the theoretical prediction. However, the required factor of 100 reduction in systematic and statistical errors would probably require a group effort of at least a decade.

c) $A_\gamma$ in np-capture: The quantity measured in the above deuteron experiments arises from the $\Delta I = 0, 2$ mixing effects in the $^1S_0 - ^3P_0$ and $^3S_1 - ^1P_1$ channels. In contrast, sensitivity to the $\Delta I = 1$ component of the effective weak Hamiltonian is provided by a measurement of the asymmetry in the capture of polarized thermal neutrons. This observable is sensitive to $\Delta I = 1$ mixing effects in the $^3S_1 - ^3P_1$ channel and thereby to $f_\pi$. Much evidence points to a value of $f_\pi$ significantly smaller than the expected weak current enhancement predicted by DDH. On the other hand the
measurements on $P_\gamma$ in the decay of $^{21}\text{Ne}$, to be discussed below, provide contradictory evidence. Except for negligible contributions from $h^{(1)}_\rho$ etc., $A_\gamma$ in thermal np capture is directly proportional to $f_\pi$: $A_\gamma = -0.11 \times f_\pi$. For the DDH “best guess” value of $f_\pi$, $A_\gamma = -0.5 \times 10^{-7}$. (cf. Table 2).

In view of the small expected effect, the demands on a measurement of $A_\gamma$ are high, but on the other hand the neutron polarization can be made large so that one gains a large factor compared to the small analyzing power in the $P_\gamma$ experiment. The $A_\gamma$ experiment became feasible with the development of intense beams of cold polarized neutrons ($5 \times 10^9$ neutrons/s over $3 \times 5cm^2$) from the high flux reactor at the Institut Laue-Langevin (ILL). In the experiment described by Alberi et al. [53, 54], capture of the neutrons takes place in a 23 liter liquid hydrogen target, in which the hydrogen was converted to pure parahydrogen by a catalyst in order to avoid depolarization of the neutrons by scattering. Two large tanks of liquid scintillator (400 liter volume each) detected the 2.2 MeV photons. The neutron polarization ($P = 0.70 \pm 0.07$) was reversed about once a second by passing the neutrons through a thin current strip. By comparing the ratio of count rates in the two detectors for the two opposite neutron spin directions the differences in detector efficiency and in neutron flux cancels. Systematic errors considered in the experiment included: (i) variation in the neutron flux with time (fluctuation about 0.1%) so that a small residual error remains after averaging over all 1s measurements; (ii) effect of spin flipper magnetic fields on the detectors, compensating coils and shielding reduced these effects to negligible proportions; (iii) displacement of the neutron beam arising from the interaction of the magnetic moment with inhomogeneous magnetic fields; and (iv) spurious electrical effects on the electronic circuits, such as a shift in discriminator level when the power to the spin flipper is turned on. It is understood that the troubling effects are those for which a reversal of the neutron spin has a spurious effect on the count rates without being associated with the true parity-violation signal. In this, as well as other experiments at the same level of accuracy, spurious electronic effects are avoided by making an overall change of the phase of the polarization reversal relative to the measurement cycle. In the present case a second spin flipper which was reversed every 27s was used for this purpose.

The final result, $A_\gamma = (-0.15 \pm 0.47) \times 10^{-7}$, is consistent with, but four times more accurate, than an earlier result obtained by the same method [54] $A_\gamma = (-0.6 \pm 2.1) \times 10^{-7}$. The new result is limited by statistical uncertainties. It is thought that, given more running time on a suitable high flux reactor, another order of magnitude improvement in accuracy could be achieved (AL88). This would at last settle the question of neutral current enhancement of the isovector pion exchange coupling constant. For now the above result is still consistent with the DDH best guess for $f_\pi$ (see Table 2).

d) Neutron Spin Rotation: When transversely polarized slow neutrons pass through matter, parity-violating forces rotate the neutron polarization direction about the momentum direction. Coherent rotation was proposed as a method to detect par-
Figure 7: Arrangement to measure PNC neutron spin rotation.

Parity violation by F.C. Michel[13] already in 1964. Parity-nonconserving neutron spin rotation was first demonstrated experimentally in 1980 by Forte et al.[21] when transmission of cold neutrons (polarization $P_n = 0.91$) through $^{117}$Sn was shown to exhibit an unexpectedly large rotation angle per cm of tin of $\phi = (36.7 \pm 2.7) \times 10^{-7}$ rad/cm. The experiment demonstrated that neutron spin rotation is a viable tool to study parity nonconservation in nuclei.

A measurement of neutron spin rotation in hydrogen would serve much the same purpose as the above measurement of $A_\gamma$, in that both quantities depend almost exclusively on the pion weak coupling constant. A calculation based on the DDH “best guess” weak coupling constants by Avishai and Grange[55] predicts $\phi = -8.84 \times 10^{-9}$ rad/cm, when the Paris potential was used to describe the strong NN interaction (see Table 2). The Seattle group[56] has proposed an arrangement similar to Fig. 7, using a 25 cm thick sample of parahydrogen that is pumped back and forth between two containers in positions 1 and 2.

6 Few Nucleon Systems

There exist several parity experiments on few body systems which are, strictly speaking not NN measurements, but which are of note because they are amenable to reasonably precise analysis.

a) Polarized Thermal Neutron Capture on Deuterium. One example is a polarized thermal neutron capture measurement on deuterium—$\bar{n}d \rightarrow t\gamma$ for which the most recent determination[58] has yielded $A_L = (42 \pm 38) \times 10^{-7}$ more on ref.[53, 57].

b) $A_\gamma$ in $p-d$ and $p-\alpha$ Scattering. The techniques used to measure the longitudinal analyzing power in pp scattering have been applied to scattering of protons by helium (46 MeV[58]) and by deuterium (15 MeV[58], 45 MeV[59], 800 MeV[60]). It
should be emphasized at the outset, that experiments in which the scattered particles are detected over a certain angular range should not be interpreted as a measurement of the helicity dependence in the total cross section. Rather, there is every reason to believe that $A_z$ has a strong dependence on angle which needs to be taken into account. This requires the experimenters to determine not only the angular acceptance function of the apparatus, but also the relative contribution from inelastic channels. The apparatus accepts only elasticity scattered particles or breakup products as well.

In principle, the wave functions of the target nuclei are sufficiently well known that the measured $A_z$ can be interpreted in terms of contributions from weak NN coupling constants, but considerable theoretical work is required to determine the expansion coefficients. The task is made more difficult if the experiments include breakup channels.

$p - \alpha$ scattering: Elastic $p - \alpha$ scattering at low energies has attractive theoretical and experimental features, such as simple nuclear structure and high breakup threshold. On the other hand, experiments on $p - \alpha$ scattering are even more difficult than for pp, because in this energy range the regular, parity-allowed transverse analyzing power for $p - \alpha$ scattering is much larger than for pp scattering, so that the corrections for first moments of transverse polarization (see pp scattering above) require special attention. In fact, the large sensitivity to transverse polarization in $p - \alpha$ scattering was exploited in the 15 MeV pp experiment by substituting He for the H target to deduce the magnitude of the unwanted first moments of transverse polarization in the proton beam[61]. At somewhat higher energies the situation is more favorable but still difficult. An unpleasantly large sensitivity to transverse polarization in a first experiment[62] at 46 MeV was later reduced by an order of magnitude by redesigning the angular acceptance function of the apparatus[58]. The angular acceptance was chosen to take advantage of the sign reversal of the transverse $p - \alpha$ analyzing power to reduce the unwanted effects, while at the same time accepting a range of scattering angles (primarily $\theta = 30^\circ - 60^\circ$) where the sign of $A_z(\theta)$ does not change. In addition, to simplify the theoretical interpretation, the wall thickness of the target vessel was chosen such that only elastically scattered protons have sufficient energy to penetrate the wall. The result of the improved experiment[58] is

$$< A_p^{p-\alpha}(\theta), 46 \text{ MeV } > = -(3.34 \pm 0.93) \times 10^{-7},$$

where the error includes statistical and systematic errors.
channels as intermediate states in the matrix elements. The reliability and parameter dependence of the calculations was studied in detail. The result for $A_z$ in terms of the meson exchange coupling constants are shown in Table 2. The short range correlations are based on hard repulsion. The vector meson ($\rho$ and $\omega$) contributions are more sensitive to short range correlations than are the corresponding pion terms. With a “soft” short-range correction factor (Jastrow factor), $A_z$ is roughly a factor two larger in magnitude ($-6 \times 10^{-7}$). The same is seen for pp scattering (compare Tourreil-Sprung supersoft core with Reid soft core\[64\]). The constraints on meson exchange weak coupling constants provided by this experiment are very similar to that given by the $^{19}\text{F}$ measurement discussed below.

**p-d scattering:** Of the three results reported for $p-d$ scattering, only one is a measurement of the total cross section. The longitudinal analyzing power in the p-d total cross section at 800 MeV proton energy was measured at Los Alamos\[60\] by measuring the helicity dependence of the absorption in a 1m long liquid deuterium target, using the same equipment and methods as used for the 800 MeV pp experiment. The largest correction $[(3.74 \pm 0.37) \times 10^{-7}]$ comes from the intensity modulation associated with helicity reversal. However, the sensitivity to these effects could be measured accurately by inserting a grid into the $H^{-}$ particle beam. In this way about 10% of the beam particles lose their electrons so that the resulting $H^{+}$ ions can be removed from the beam to change the beam intensity without changing other beam parameters. The result of the experiment, is $A_z = (1.7 \pm 0.8 \pm 1.0) \times 10^{-7}$.

The two results at lower energies (15 MeV and 43 MeV) used essentially the same equipment and the same methods as the corresponding pp experiments. Both experiments are based on detection of scattered particles over a limited angular range and thus do not measure $A_z$ in the total cross section. To complicate matters further, the experiments do not separate elastic scattering from breakup, because the small binding energy of the deuteron makes it impossible to distinguish elastic and breakup events in the integral-counting method (current integration). Thus a theoretical analysis would have to integrate not only over the appropriate range of scattering angles but also over the part of the breakup phase space that is detected in the experiment, taking into account the corresponding weight and acceptance function of the apparatus. So far, calculations of $A_z$ have been reported only for the total elastic p-d cross section. Thus they cannot be compared to the experimental results and consequently no entry for p-d scattering is shown in Table 2. The Faddeev calculations of Kloet et al.\[65, 66\] predict for the total cross section $A_z^{\text{tot}}$ values of $-1.87 \times 10^{-7}$ at 14.4 MeV and $+1.39 \times 10^{-7}$ at 40 MeV.

The 43 MeV experiment at SIN\[59\] chose the wall thickness of the target vessel such that only one proton in a given breakup event reaches the detection system. This considerably simplifies the calculation which, however, is still very difficult. At 43 MeV, the experimental result for pd elastic scattering and breakup protons in the laboratory angular range 24° to 61° is $(+0.4 \pm 0.7) \times 10^{-7}$. The largest correction by far $[(-3.25 \pm 0.30) \times 10^{-7}]$ is for modulation of the transverse polarization moments. The
angular acceptance function for different Q-values of the breakup spectrum for this experiment is known, so that a calculation for a realistic comparison to the experiment is possible in principle. On the other hand, for the earlier 15 MeV measurement\[28\] \((A_{z} = -(0.35 \pm 0.85) \times 10^{-7})\) the acceptance function has not been specified.

c) \(^{6}\text{Li}(n, \alpha)^{3}\text{H}\) reaction with polarized cold neutrons. Studies of PNC asymmetries in the reactions \(^{6}\text{Li}(n, \alpha)^{3}\text{H}\) and \(^{10}\text{B}(n, \alpha)^{7}\text{Li}\) in which polarized thermal neutrons are captured with large cross sections have been suggested by Vesna et al.\[67\]. The development of high flux beams of cold neutrons at the VVR-M reactor at the Leningrad Institute of Nuclear Physics has made possible a much improved determination of the helicity dependence in the \(^{6}\text{Li}(n, \alpha)^{3}\text{H}\) reaction\[68\]. A multisection proportional chamber was irradiated with cold neutrons (average wave length 4\(\text{Å}\)) of intensity \(2 \times 10^{10}n/s\) and polarization 80\%. The chamber consisted of 24 double chambers arranged along the path of the neutron beam, with half of each double chamber detecting tritons emitted along the direction of the neutron momentum, the other half detecting tritons in the opposite direction. Each chamber has its own target of \(^{6}\text{LiF}\) deposited on thin Al foils. About 90\% of the neutron beam was absorbed in the chambers. Possible left-right asymmetries in the chambers were reduced to the point where their contribution to the final result is expected to be less than \(10^{-8}\). The neutron polarization was changed by means of an adiabatic flipper. The measured asymmetry coefficient \((-0.64 \pm 0.55) \times 10^{-7}\) is much smaller than the theoretical estimate\[69, 70\] based on a cluster model of \(^{6}\text{Li}\) (see Table 2). The disagreement between the experimental value and the theoretical number calculated with the DDH best guess values is yet another indication that \(f_{\pi}\) is considerably smaller than the “best guess” value.

7 Isolated Parity-Mixed Doublets (Two-Level Systems)

7.1 Experiments

Little benefit is gained from observations of PNC in hadronic interactions unless the results can be interpreted to yield information about either the weak or the strong part of the NN interaction, depending on whether one considers the hadronic weak interaction (weak coupling constants) or the short range behaviour of the strong interaction to be the most interesting part of the problem. Except for the cases discussed above, in which experiments on the nucleon-nucleon system and few-body systems have given interpretable results, the most important source of information derives from experiments on light nuclei, in which PNC effects result from the interference of two relatively isolated levels of the same total angular momentum but opposite parity. As discussed in a previous review\[8\] the observed effects are much magnified compare to the small effects in the NN system provided the interfering levels are closely spaced.
Table 2: Expansion coefficients for the contributions to the PNC observables from the individual meson-exchanges and calculated observables for three sets of coupling coefficients. All numbers should be multiplied by the factor $10^{-7}$. 

| Coupling Coefficients | Observable | Value |
|------------------------|------------|-------|
| Set 1                  | A          | 0.123 |
|                        | B          | 0.456 |
|                        | C          | 0.789 |
| Set 2                  | A          | 0.123 |
|                        | B          | 0.456 |
|                        | C          | 0.789 |
| Set 3                  | A          | 0.123 |
|                        | B          | 0.456 |
|                        | C          | 0.789 |
and the members of the parity doublet have very different decay amplitudes. Overall, the larger magnitude of the effects to be measured (typically $10^{-4}$ to $10^{-5}$ compared to $10^{-7}$ in the NN system itself) simplifies the experiments. Regrettably, the larger effects are at the expense of a difficult burden in determining the nuclear structure of the states involved with sufficient accuracy. For the experiments, the observations on parity-mixed doublets require different experimental techniques: the expected effects are large enough that sufficient statistical accuracy can be obtained by detecting individual events (as opposed to the integral counting techniques used for NN and few-body experiments). This then permits sufficient energy resolution in the detection system to isolate the levels of interest.

Until a decade ago, studies of parity-mixed doublets in light nuclei ($^{18}$F, $^{19}$F, $^{21}$Ne) concerned primarily gamma-decay measurements, in particular the gamma asymmetry $A_\gamma$ in the decay of polarized $^{19}$F, and the circular polarization $P_\gamma$ of decay gamma rays from unpolarized nuclei ($^{18}$F, $^{21}$Ne). The results of these experiments, which have been discussed extensively in the previous review by Adelberger and Haxton\cite{8}, are summarized in Table 3. Since the transitions in these three nuclei essentially exhaust the available pool of favorable particle-bound parity-doublets, the search for additional parity doublets turned to particle-unbound states in light nuclei, even though the higher excitation energy of these states tends to complicate the nuclear structure issues. The only new experiments on narrow, parity-mixed doublets are measurements of the longitudinal analyzing power $A_z$ in ($p,\alpha$)-reactions, specifically $^{19}$F($p,\alpha$)$^{16}$O and $^{13}$C($p,\alpha$)$^{10}$B. Besides $A_z$, another signal of parity nonconservation is the transverse analyzing power $A_x$, i.e., a measurement with polarization transverse to the beam momentum but in the scattering plane. A measurement of $A_x$ has been reported for $^{19}$F($p,\alpha$)$^{16}$O (see Table 3). The general theory of parity mixing of elastic scattering resonances (and in particular the application to $^{14}$N) has been discussed by Adelberger, Hooobhoy and Brown\cite{72}. Study of a J=2 doublet in $^{16}$O near 13 MeV excitation energy has been been proposed by Bizetti and Maurezen\cite{73}. Extensive calculations of the longitudinal and transverse analyzing powers for different models of the weak and strong interactions have been reported by Dumitrescu\cite{74} and by Kniest et al.\cite{75}.

To illustrate the experimental methods and problems in measurements of $A_z$ in resonance reactions, as opposed to the corresponding measurements e.g. in pp scattering, we discuss the recent measurement\cite{76,77} of the analyzing power $A_z$ in the $^{13}$C($p,\alpha$)$^{10}$B reaction. The experiment uses longitudinally polarized protons near 1.16 MeV to excite a narrow ($\Gamma=4$ keV) J=0$^+$ (T=1) state in $^{14}$N at $E_x = 8.624$ MeV. This state interferes with a second, much wider state ($\Gamma=440$ keV) of opposite parity located 178 keV above the first. Therefore a small admixture of the short-lived $0^-$ level into the long-lived $0^+$ level will amplify PNC observables involving the decay of the $0^+$ level. The experimental arrangement (Fig. 7) consists of a scattering chamber with scintillation counters to detect $\alpha$-particles emitted near 35$^\circ$ and 155$^\circ$. The detector geometry and the target thickness were carefully optimized to obtain the best
Table 3: Experimental and DDH “best” theoretical values for parity violating experiments in p- and s,d-shell nuclei.

| Reaction   | Excited State | Measured Quantity | Experiment $\times 10^{-5}$ | Theory $\times 10^{-5}$ |
|------------|---------------|-------------------|-----------------------------|-------------------------|
| $^{15}$C(p, $\alpha$)$^{14}$N | J=0$^+$, T=1 8.264 MeV  
J=0$^-$, T=1 8.802 MeV | $[A_z(35^\circ) - A_x(155^\circ)]$ | 0.9 ± 0.6 \cite{71} | -2.8 \cite{72} |
| $^{19}$F(p, $\alpha$)$^{20}$Ne | J=1$^+$, T=1 13.482 MeV  
J=1$^-$, T=0 13.462 MeV | $A_z(90^\circ)$  
$A_x$ | 150 ± 76 \cite{73}  
660 ± 240 \cite{79}  
100 ± 100 \cite{80} | |
| $^{18}$F | J=0$^-$, T=0 1.081 MeV | $P_\gamma$  
mean | $-70 \pm 200$ \cite{81}  
$-40 \pm 300$ \cite{82}  
$-100 \pm 180$ \cite{83}  
17 ± 58 \cite{84}  
27 ± 57 \cite{85}  
12 ± 38 | 208 ± 49 \cite{8} |
| $^{19}$F | J=$\frac{1}{2}^-$, T + $\frac{1}{2}$ 0.110 MeV | $A_\gamma$  
mean | $-8.5 \pm 2.6$ \cite{86}  
$-6.8 \pm 2.1$ \cite{87}  
$-7.4 \pm 1.9$ | $-8.9 \pm 1.6$ \cite{8} |
| $^{21}$Ne | J=$\frac{1}{2}^-$, T = $\frac{1}{2}$ 2.789 MeV | $P_\gamma$ | 80 ± 140 \cite{88} | 46 \cite{8} |
statistical error in the measurement, while at the same time minimizing systematic errors. Calculations based on the known resonance parameters predict a sharp energy dependence of $A_z$ across the $0^+$ resonance, and an angular dependence which changes sign between forward and back angles. It was found that the difference in analyzing power between back-angle and forward-angle detectors, $A(B) - A(F)$, yields the largest PNC signals. However, the most important advantage is that in the difference certain systematic errors are reduced, because they have similar effects on $A(F)$ and $A(B)$. For a weak matrix element of $-1.04$ eV$^2$ the expected signal, taking into account the finite spread in energy and angle, was $A(B) - A(F) = -2.8 \times 10^{-5}$. While this effect is considerably larger than for pp scattering, the very narrow (4 keV) low energy resonance has a cross section with a strong dependence on energy and angle, and a large transverse analyzing power. Therefore special methods had to be developed to measure and control the beam energy, the beam position and the residual transverse polarization. The targets were sputtered, 4 keV thick C enriched in $^{13}$C. Effects from target non-uniformity and $^{12}$C build-up were reduced by translating the target in a raster pattern during the experiment. The beam polarization (typically $P = 0.84 \pm 0.01$) was reversed every 20 ms at the ion source. A separate measurement was made to place an upper limit ($\Delta E < 0.45$ eV) on the magnitude of a possible variation in beam energy when the proton spin is reversed since the rapid variation of cross section across the resonance might give a significant spurious signal. To measure the distribution of intensity and (unwanted) transverse polarization of the beam, 0.6 mm wide target strips were moved stepwise through the beam in the vertical and horizontal direction. Beam position and beam direction were controlled with a feedback system which processed information from beam currents on slits located before and after the target. Modulation of beam position associated with polarization reversal was found to be $<0.4$ mm. Many spurious effects, including effects of energy modulation, spin misalignment, correlations between spin and beam position and correlation between spin and beam angle etc., were found to vary strongly over the resonance. Fortunately, it was possible to find an energy where most of the systematic errors nearly vanished, while the parity-violation signal was near the maximum value. By making measurements primarily at this particular energy, the sum of systematic errors was reduced to $< 1.5 \times 10^{-6}$. The final result, $A(B) - A(F) = (0.9 \pm 0.6) \times 10^{-5}$, corresponds to a weak matrix element of $0.38 \pm 0.28$ eV, i.e., opposite in sign and smaller in magnitude than the theoretical expectation.

7.2 Analysis

That high quality wavefunctions are needed for interpreting these experiments is clear from the following argument. Suppose one evaluates the nuclear wavefunction in the usual $0\hbar \omega, 1\hbar \omega$ shell model basis. Of course, a realistic wavefunction presumably includes also an additional $2\hbar \omega$ component,

$$|\psi^+ > = |0\hbar \omega > + \epsilon |2\hbar \omega >$$

(41)
Figure 8: Experimental setup for parity mixing in $^{14}\text{N}$ by measurement of $A_z$ in $p+^{13}\text{C}$ elastic scattering. Scintillation detectors detect scattered protons at four azimuthal angles for forward (A) and backward (B) angles. A NaI scintillator detects capture $\gamma$-rays. The 4 keV thick self-supporting $^{13}\text{C}$ target (D) is surrounded by a cold shroud (E) to reduce buildup of contaminants. Four-jaw adjustable slits (F and additional sets of slits upstream and downstream of the chamber) and steering magnets (such as G) are used to stabilize beam position and beam direction by means of a feedback system.
which is small—$\epsilon \ll 1$—if the simple shell model picture is valid. Then if one calculates a typical parity conserving observable such as the Gamow-Teller matrix element or magnetic moment, which do not connect $|0h\omega>$ and $|2h\omega>$ levels, a reasonably accurate result should obtain, since any corrections are $O(\epsilon^2)$

$$<\psi^+|\mathcal{O}|\psi^+> = <0h\omega|\mathcal{O}|0h\omega> + O(\epsilon^2).$$

However, in evaluating a parity mixing term, we are dealing with a $1h\omega$ level which can connect to either of its $0h\omega$ or $2h\omega$ counterparts, whereby corrections to simple shell model estimates are $O(\epsilon)$ and are much more sensitive to omission of possible $|2h\omega>$ states—

$$<\psi^-|\mathcal{H}_{wk}|\psi^+> = <1h\omega|\mathcal{H}_{wk}|0h\omega> + O(\epsilon).$$

In fact, these expectations are borne out, both theoretically and experimentally. On the theoretical side, Haxton compared a simple $0h\omega$, $1h\omega$ evaluation with a large basis $0h\omega$, $1h\omega$, $2h\omega$ calculation of parity mixing between the $0^-$; $1081keV$ and $0^+$; $1042keV$ states of $^{18}$F, and determined $^{[\text{89}]}$

$$<0^-|\mathcal{H}_{wk}|0^+ >_{0.1,2h\omega} \simeq \frac{1}{3}.\quad (44)$$

This calculation clearly reveals that such $O(\epsilon)$ core polarization effects are substantial, although clearly any such estimates are very model dependent and would seem to offer little hope for calculational rigor. Nevertheless, in some cases there is an opportunity to “measure” this effect. It was pointed out by Bennett, Lowry and Krien $^{[\text{90}]}$ and independently by Haxton $^{[\text{89}]}$ that the form of the parity violating nucleon-nucleon potential arising from pion exchange

$$V_{NN}^{PV}(\pi - \text{exch}) = \frac{i}{2\sqrt{2}}g_{\pi NN}f_\pi(\tau_1 \times \tau_2)_3(\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2m_N}, \frac{e^{-m_Nr}}{r} \right]\quad (45)$$

is an isotopic partner of the two-body pion exchange contribution to the timelike component of the weak axial vector current, which is probed in nuclear beta decay

$$A_0 = A_0 (\text{one - body}) + \frac{i}{2}g_{\pi NN}g_A(\tau_1 \times \tau_2)_+ (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2m_N}, \frac{e^{-m_Nr}}{r} \right].\quad (46)$$

Then by measuring this two body matrix element of $A_0$ in a beta transition between levels which are isotopically related to those involved in the weak parity mixing process, this weak pion exchange contribution to nuclear parity violation can be calibrated experimentally. Of course, the difficulty with this procedure is that there is no model-independent means by which to separate the one- and two-body contributions to $A_0$. Nevertheless, Haxton has pointed out that the ratio of such terms

$$\frac{|A_0 (\text{two - body})|}{|A_0 (\text{one - body})|} \simeq 0.5\quad (47)$$
Figure 9: Energy levels for light nuclear parity violation experiments.

is relatively *model-independent*, and by measurement of the $^{18}$Ne beta decay rate, one determines experimentally

$$\frac{<0^-|H_{wk}|0^+>^{\exp}}{<0^-|H_{wk}|0^+>_{0,1\hbar\omega}} \approx 0.35$$

(48)

in good agreement with the full $2\hbar\omega$ theoretical estimate. Unfortunately, such a large basis calculation is only made possible by the feature that $^{18}$F is only two nucleons away from $^{16}$O—heavier s,d shell nuclei involve bases which are too large for current computing capacity.

Because of the difficulties outlined above associated with extraction of theoretical information from experimental signals arising from nuclear experiments, physicists have tended to emphasize only p-shell and light s,d shell nuclei for believable experiments—in particular $^{18}$F, $^{19}$F, $^{21}$Ne and $^{14}$N—and we shall discuss each in turn.

$^{18}$F: We begin our discussion with the simplest case to analyze—measurement of the circular polarization in the decay of the $0^-$ 1081 keV excited state of $^{18}$F to the ground state—cf. Fig. 9.

Because of the existence of the $0^+$ state only 39 keV away at 1042 keV, assuming that the weak parity mixing occurs only between these two levels should be a good approximation. However, the pseudoscalar 1081 keV state is an isoscalar while its scalar 1042 keV analog is an isovector. Thus any such mixing is sensitive only to the $\Delta I = 1$ piece of the effective parity violating weak Hamiltonian and thereby effectively only to $f_\pi$.

Another helpful feature of this case is the existence of a substantial nuclear enhancement factor. Because the E1 transition is between isoscalar states this transition is isospin forbidden, leading to the comparatively long lifetime $\tau_{1081} = 27.5 \pm 1.9$ ps. On the other hand the analogous M1 transition is very fast—$\tau_{1042} = 2.5 \pm 0.3$ fs—corresponding to 10.3 ± 1.5 Weisskopf units. The resulting circular polarization then
can be written as

\[ P_\gamma(1081) = 2\Re \left[ \frac{\epsilon \text{Amp}(M1)}{\text{Amp}(E1)} \right]. \] (49)

Since for dipole emission

\[ \Gamma_\gamma \sim | < f | \mathcal{O} | i > |^2 \times E_\gamma^3 \] (50)

we find

\[ \left| \frac{\text{Amp}(M1)}{\text{Amp}(E1)} \right| = \left( \frac{\tau_+}{\tau_0} \right)^\frac{1}{2} \left( \frac{1081}{1042} \right)^\frac{3}{2} = 111 \pm 8. \] (51)

The expected circular polarization is then

\[ |P_\gamma(1081)| \approx 222 \left\langle \left| \mathcal{H}_{wk} \right| - \right\rangle_{39keV} \] (52)

and we observe that there exist two separate enhancement factors, one kinematic and associated with the near degeneracy of the mixed states and the second dynamic and associated with the suppression of the E1 matrix element. Note that because of this suppression, we quote above only the absolute magnitude of the circular polarization since a reliable calculation of the sign of the electric dipole amplitude is probably out of the question. Finally, the isospin related

\[ ^{18}\text{Ne} \rightarrow ^{18}\text{F}(0^-; 1081keV) + e^+ + \nu_e \] (53)

transition can be used in order to normalize the pion exchange matrix contribution to the weak matrix element, in the fashion described above leading to

\[ |P_\gamma(1081)| = 4320 f_\pi. \] (54)

In addition to the theoretical clarity of this transition it has also been examined experimentally by five different experimental groups, all of whose results are in agreement as shown in Table 3. We see then that there is as yet no evidence for the existence of a non-zero circular polarization and that this result implies an upper bound on the value of the weak NN\pi coupling which is considerably smaller than the “best value.” While the resulting number is certainly within the DDH bounds, it requires considerably cancellation among the factorization, sum rule and quark model contributions in order to achieve a result this small.

\[ ^{19}\text{F}: \text{Another important result has been obtained in the } ^{19}\text{F system, where the asymmetry has been measured in the radiative decay from the polarized } \left| \frac{1}{2}^-; 110keV \right> \text{ first excited state down to the } \left| \frac{1}{2}^+; \text{g.s.} \right> \text{ ground state. The experiment has been performed twice, and has yielded a non-zero signal at the } 10^{-4} \text{ level as indicated in Table 3. Here the asymmetry is defined via} \] (55)

\[ \frac{d\Gamma}{d\Omega} \sim 1 + A_\gamma \mathbf{P}_F \cdot \mathbf{q}_\gamma \]
and, under the assumption that only the ground and first excited state are involved in the mixing, has the form

\[ A_\gamma = 2 \frac{< + |H_{wk}|>}{110 \text{keV}} \times \text{Re} \frac{\text{Amp}(M1)}{\text{Amp}(E1)}. \]  

(56)

Here the magnetic dipole amplitude can be written in terms of the measured (2.6289 µN) and calculated (-0.2 µN) magnetic moments of the \( \frac{3}{2}^+ \) and \( \frac{1}{2}^- \) states respectively, while the E1 amplitude is given in terms of the known lifetime of the \( \frac{1}{2}^- \) level, yielding

\[ A_\gamma = \frac{< + |H_{wk}|>}{5.2 \pm 0.4 \text{eV}}. \]  

(57)

As in the case of \(^{18}\text{F}\) the pion exchange contribution to the weak matrix element can be calibrated in terms of the measured \(^{19}\text{Ne} \rightarrow ^{19}\text{F}(0^-; 110 \text{keV}) + e^+ + \nu_e\) amplitude, while the vector exchange pieces can be calculated in the shell model, yielding

\[ A_\gamma = -96 f_\pi + 35(h_\rho^0 + 0.56h_\omega^0). \]  

(59)

Note that since both mixed states are isodoublets the asymmetry is sensitive to both \( \Delta I = 0 \) and \( \Delta I = 1 \) components of the effective weak Hamiltonian, and we see in Tables 2,3 that the use of “best value” numbers yields a value for this asymmetry which is in excellent agreement both in sign and in magnitude with the measured number.

**\(^{21}\text{Ne}:** The nucleus \(^{21}\text{Ne}\) possesses states \( |\frac{1}{2}^+; 2795 \text{keV}> \) and \( |\frac{1}{2}^-; 2789 \text{keV}> \) which are separated by only 5.74±0.15 keV. In addition the E1 transition of the 1089 keV level down to the \( \frac{3}{2}^+ \) ground state is extraordinarily retarded, having a lifetime \( \tau = 696 \pm 51 \text{ps} \) and corresponding to \( \sim 10^{-6} \) Weisskopf units. One predicts then a circular polarization to be

\[ P_\gamma(2789) = -2 \frac{< + |H_{wk}|>}{5.74 \text{keV}} \text{Re} \left( \frac{\text{Amp}(M1)}{\text{Amp}(E1)} \right) \times \left( \frac{1 + \delta_- \delta_+}{1 + |\delta_-|^2} \right) \]  

(60)

where here \( \delta_- \) is the M2/E1 mixing ratio for the \( \frac{1}{2}^- \) transition and \( \delta_+ \) is the E2/M1 mixing ratio for the \( \frac{1}{2}^+ \) transition. Taking \( |\delta_-| < 0.6 \) from experiment and \( \delta_+ \approx 0 \) from theoretical estimates, we have

\[ |P_\gamma| = \frac{1 < + |H_{wk}|>}{9.5^{+3.4}_{-0.6} \text{eV}} \]  

(61)

which indicates, as in the case of \(^{18}\text{F}\) the strong effects of both dynamical and kinematic amplification and the fact that theory cannot really predict the absolute sign
of the highly suppressed E1 amplitude. Since both \( \frac{1}{2}^+ \) and \( \frac{1}{2}^- \) states are isodoublets the weak parity mixing involves both \( \Delta I = 0 \) and \( \Delta I = 1 \) components of the weak Hamiltonian and a shell model calculation gives

\[
P_\gamma = 29500 f_\pi + 11800(h^{0^+}_\rho + 0.56h^{0^+}_\omega). \tag{62}
\]

Comparing with the analogous calculation for the case of \(^{19}\text{F}\) we see that the vector- and pion-exchange amplitudes come in with opposite signs, indicating the difference the “odd-proton” \((^{19}\text{F})\) and “odd-neutron” \((^{21}\text{Ne})\) nuclei and that the nuclear enhancement factors are nearly a factor of 300 larger in the case of \(^{21}\text{Ne}\) due to the near degeneracy and strong suppression of the E1 decay amplitude discussed above. Using the “best value” numbers one finds that sizable cancellation between the pion- and vector-exchange components takes place so that the predicted and experimental size for the circular polarization are in agreement, but this requires a significant value for \(f_\pi\) which is inconsistent with the upper bound determined from \(^{18}\text{F}\). We shall have more to say on this problem in a later section.

\(^{14}\text{N}\): The only p-shell nucleus to make our list is \(^{14}\text{N}\) for which there exist states \(|0^-, 8776 \text{ keV}\rangle\) and \(|0^+, 8624 \text{ keV}\rangle\), which are separated by only 152 keV. Both states are isotopic triplets but calculation indicates that mixing is due predominantly to the \(\Delta I = 0\) component of the effective weak interaction. In this case one observes \(A_z\) for the delayed proton emission from the \(0^+\) state and there exists a dynamical enhancement factor of \([\Gamma_p(0^-)/\Gamma_p(0^+)]=[\frac{1}{2}]\approx 11\). While at first glance, one might believe that the shell model analysis might be relatively reliable, inasmuch as a p-shell nucleus is involved, the problem is that the natural parity state in \(^{14}\text{N}\) is predominantly \(2^\omega\) in character unlike previously studied parity doublets wherein the natural parity state is primarily \(0^\omega\). Thus a very large shell model basis is required and various approaches lead to predictions

\[-1.39\text{eV} \leq -|H_{\text{wk}}| + \leq -0.29\text{eV} \tag{63}\]

if the DDH value of \(h^{(0)}_\rho\) is employed. The discrepancy with the positive sign of the measured number is disturbing and remains to be explained.

Notice that we have not attempted to analyze the \(^{16}\text{O}(2^-)\) alpha decay problem. That is because mixing occurs with any of the many \(2^+\) levels of \(^{16}\text{O}\) and there is no reason to favor any particular level. Thus the calculation, while it has been performed, is thought to be rather uncertain, even though achieving a result in agreement with the experimental number.[91]

8 Nuclear Parity Violation and Statistical Methods

Above we spoke despairingly about the use of heavy nuclei in experiments involving nuclear parity violation because of the lack of believable nuclear wavefunctions. Recently, however, it has become clear that in some cases one can actually employ heavy
nuclei by exploiting their statistical properties. The case in point involves a set of high precision longitudinally polarized epithermal neutron scattering measurements performed on a series of heavy nuclei at LANSCE by Frankle et al. The first round of such experiments involved $^{239}$U and $^{232}$Th targets, and a set of transmission experiments revealed parity-violating asymmetries, with a statistical significance of greater than 2.5 standard deviations, in three U states and seven Th states. Now when such an epithermal neutron is captured, the resulting compound nuclear state is made up of linear combinations of $10^5$ to $10^6$ single-particle configurations so that one would expect that a statistical model of the nucleus, with observables treated as random variables should be quite sufficient. In such a picture one expects to find occasional p-states in a large background of s-wave resonances, and the roughly one third of these which are $p_{\frac{1}{2}}$ character can mix with both nearby and distant $s_{\frac{1}{2}}$ levels, leading to the observed parity violating asymmetries. The mixing matrix elements of the weak interaction should be of single particle character. The experimenters interpret the measured longitudinal asymmetries for compound nuclear states in the region $10 eV < \Delta E < 300 eV$ in terms of a mean squared matrix element $M^2 = \langle | \mu | H_{wk} | \nu > |^2 > \Delta E$. Then, using the ergodic theorem, this number can be identified with the ensemble average, yielding the result

$$M = [\text{Av}( \langle | \mu | H_{wk} | \nu > |^2 > \Delta E)]^{\frac{1}{2}} = 0.58^{+0.50}_{-0.25} meV. \quad (64)$$

The size of the mixing is about what one might expect, as the density of states in this region is about a thousand times larger than found in light nuclei, changing the typical 1 eV value found for typical isolated weak levels to the 1 meV determined above. However, it is possible to be somewhat more quantitative by using the microscopic framework developed by French, who relates experimental and theoretical mean square matrix elements in terms of a strength $\alpha$ of a schematic symmetry violating interaction $\alpha U_2$ where $U_2$ is the residual shell-model interaction acting in a model space. With the value $\langle | \mu | U_2 | \nu > |^2 > \Delta E = 2.6 keV^2$ for $^{239}$U from ref. one finds then $\alpha^2_{p}$. Using the G-matrix formalism and the closure approximation Johnson et al. have attempted to make contact between the statistical formalism of French and the underlying weak Hamiltonian developed in ref. Their results are summarized in Table 4 for three different sets of weak interaction couplings, as given by the DDH best values, improved best values as later calculated by Feldman et al., and empirical numbers generated by Adelberger and Haxton. As can be seen, all are in agreement with the experimental number, indicating that the overall scale of the parity-violating interaction is basically correct.

In the first data taken by this group it was found that out of seven levels in $^{232}$Th exhibiting parity violation all seven had the same sign for the asymmetry! This result appeared to be in strong contradiction with the presumed statistical nature of the mixing process, which would seem to require roughly equal positive and negative values. However, with the taking of additional data on other nuclei the number of data points on either side of zero has evened out somewhat, and at the present time
Table 4: Experimental and theoretical values for weak mixing parameters as determined in epithermal neutron scattering.

| Interaction | $\alpha/G_Fm_N^2$ | M(meV) |
|-------------|-------------------|--------|
| DDH         | 2.67              | 0.98   |
| ref. 8      | 1.54              | 0.52   |
| ref. 19b    | 1.07              | 0.39   |

the thorium result is thought to be due to some quirk of nuclear structure.

9 A New Probe of Nuclear Parity Violation: the Anapole Moment

A somewhat different approach to the problem of measuring NNM matrix elements was recently proposed in the realm of electron scattering. The idea here is somewhat subtle and so requires a bit of explanation. Suppose that one is considering the most general matrix element of the electromagnetic current between a pair of nucleons. The most general form allowed by spin and gauge invariance considerations is

$$< N(p') | V_{\text{em}}(0) | N(p) >= \bar{u}(p') [ f_1(q^2) \gamma_\mu - i \frac{f_2(q^2)}{2m_N} \sigma_{\mu\nu} q^\nu$$

$$+ \frac{f_A(q^2)}{m_N^2} (q^2 \gamma_\mu - q_\mu q_\nu \gamma_5) \gamma_5 - i \frac{f_E(q^2)}{2m_N} \sigma_{\mu\nu} q^\nu \gamma_5] u(p)$$

(65)

where $q = p - p'$ is the four-momentum transfer. Here $f_1(q^2), f_2(q^2)$ are the familiar charge, magnetic couplings respectively. The remaining two terms involving $f_A(q^2), f_E(q^2)$ may look unfamiliar as they are usually omitted on the grounds of parity conservation. However, if one allows for the possibility that parity is violated, then such terms must be included. The term involving $f_E(q^2)$ is found to be time reversal violating as well as parity violating and corresponds to a nucleon electric dipole moment. On this basis, we can safely omit it. However, the term $f_A(q^2)$ is time-reversal allowed and must be retained in a general analysis. It is generally called the “anapole moment” and would appear to be a fundamental property of the nucleon. However, this is not the case. In fact the anapole moment is not strictly speaking an observable since estimates of its size depend upon the weak gauge in which one chooses perform the calculation. How can this be? The resolution of the paradox lies in the way such a quantity could be measured—i.e. via parity violation in electron scattering. In such an experiment the total parity violating signal arises due to the coherent sum of photon exchange diagrams involving the anapole moment.
plus diagrams involving both photon and $Z^0$ boson exchange, as shown in Fig. 9. Of course, the sum of these effects must be an observable and independent of gauge. However, it is not required that each diagram individually be gauge independent. (In this way the anapole moment is like the neutrino charge radius, which is similarly gauge-dependent.)

It would seem then that attempts to measure the anapole moment cannot possibly be meaningful. However, this is fortunately not the case. In order to see how this comes about we divide the anapole moment into its one-body and many-body components. For the one-body (impulse-approximation) term we find

$$V = -\frac{1}{m_N^2} \sum f_A^i \left[ \sigma_i \nabla^2 - \sigma_i \cdot \nabla \nabla \right] r^2 \quad (66)$$

where $f_A^i$ is the anapole moment of the $i$th nucleon. The magnitude of this term then is determined by the properties of the nucleon and not the nucleus and, of course, its size is gauge dependent. On the other hand, many body contributions such as those generated by single meson exchange within the nucleus, as shown in Fig. 11, are gauge independent and grow as the square of the nuclear radius—$f_{\text{many-body}}^A \sim <R^2> \sim A^{3/2}$. In the limit $A \rightarrow \infty$ then this many body and gauge independent quantity must dominate over its gauge dependent single body counterpart and the anapole moment will be an observable. In fact, calculations have shown that in the real world many cases exist for even moderately heavy nuclei where the many body component should be the dominant effect. This occurs both in the case of heavy nuclei such as $^{133}$Cs where the pion exchange contribution has been estimated to be a factor of three larger than the tree-level $Z^0$-exchange piece and even in $^{19}$F, where the existence of nearby $\frac{1}{2}^+, \frac{1}{2}^-$ levels enhances the many body component by a factor of two and makes it comparable to the tree-level piece. In these cases or others then, to the extent that the many body term could be measured and that its size is dominated by the
diagrams shown in Fig. 11, this would provide in principle an independent way of measuring the weak parity violating NNM couplings.

At the present time, there is some indication that an anapole moment has been seen via a study of parity nonconserving signals from different hyperfine levels in atomic Cs (ref. [96]). The measured signal is of the same order but somewhat larger than theoretical expectations. [97] However, this is only preliminary and it will be some time before it will be known if this technique represents a viable approach to the study of nuclear parity violation.

10 How Large are the Weak Couplings

In our analysis above we have consistently compared the experimental results with theoretical predictions based on the “best value” guesses of DDH for the weak NNM vertex functions. However, it is also possible and desirable to determine such couplings purely empirically. If the couplings obtained in this fashion are found to be mutually consistent they then form a benchmark against which past and future particle physics calculations can be calibrated. Of course, there are many parameters involved and many parity violating experiments so a simple statistical fit is probably not appropriate. However, a little thought reveals that the process can in principle be made meaningful, as pointed out by Haxton and Adelberger. On the experimental side, the data set to be fit was restricted to those cases wherein one has both good statistical precision as well as a reasonable expectation for a reliable theoretical calculation. This limits things to the $\vec{p}\vec{p}$, $\vec{p}\vec{\alpha}$, $^{18}\text{F}$, $^{19}\text{F}$, and $^{21}\text{Ne}$ systems. On the theoretical side, a few prejudices from the DDH analysis were employed in order to characterize all results in terms of just two free parameters—$f_{\pi}$ and $\eta$, which characterizes the
Figure 12: Experimental constraints on weak couplings.

Table 5: Fitted values for weak NNM couplings. All numbers are to be multiplied by the factor $3.8 \times 10^{-8}$.

|          | Range     | Fitted value |
|----------|-----------|--------------|
| $f_\pi$  | $0 \rightarrow 30$ | 6            |
| $h_0^\rho$ | $30 \rightarrow -81$ | -15         |
| $h_1^\rho$ | $-1 \rightarrow 0$ | -0.5        |
| $h_2^\rho$ | $-20 \rightarrow -29$ | -20         |
| $h_0^\omega$ | $15 \rightarrow -27$ | -13         |
| $h_1^\omega$ | $-5 \rightarrow -2$ | -1.5        |

SU(6) breaking in the calculation and interpolates between factorization ($\eta = 0$) and pure SU(6)$_W$ ($\eta = 1$) results. The result of this fit is shown in Table 5 and in a different form in Fig. 12.

As can be seen therein, there exists a fundamental problem in that while the $^{18}$F data require a very small value for $f_\pi$, a much larger value is needed in order to cancel against $h_0^\rho$ to produce the very small circular polarization seen in the decay of $^{21}$Ne. In fact, were $^{21}$Ne to be omitted as a constraint a very satisfactory fit of the remaining experiments would result as shown in Table ???.

So what is the problem? Of course, one possibility is that the simple and appealing single meson exchange picture developed above is not appropriate. However, in view of the success obtained with the corresponding meson-exchange approach to the ordinary nucleon-nucleon potential this seems unlikely. Rather it would seem that the most likely explanation lies in our inability to perform an adequate large basis calculation for nuclear systems. Indeed the inclusion of core polarization effects for the lighter $^{19}$F and $^{19}$F systems has already been shown to lead to very substantial changes.
Likewise recent calculations by Horoi and Brown have indicated the importance of inclusion of $3\hbar\omega$ and $4\hbar\omega$ states in the shell model basis for calculations involving parity violation in p- and s,d-shell nuclei.\[98\]

11 The Future of Nuclear Parity Violation

Above we have examined the many attempts to understand the phenomenon of nuclear parity violation from the first measurements during the 1950’s until the present day. We have seen that despite the many and elegant experiments which have been completed and the extensive theoretical effort which has gone into this problem, many difficulties still remain and it is not yet clear that the simple meson exchange picture is able to explain all the varied results. Were this to be verified it would be very surprising since a similar single meson exchange picture is remarkably successful in explaining all aspects of the ordinary nucleon-nucleon potential. Nevertheless it remains to be seen. In the mean time, it is interesting to ask whether say by the end of the decade experiments will be available to aid in this process and/or whether new theoretical work will be able to add new illumination on the mechanism of nuclear parity violation.

In the case of theoretical work, we are somewhat pessimistic. Barring some clear breakthrough it is unlikely that things will change much during this period. One might think that lattice methods might be of help here, but when one is dealing with three-hadron matrix elements of a four-quark operator, we are still far from being able to make reliable calculations. In the case of non-lattice procedures, the only semi-rigorous technique which has yet to be applied consistently to this problem is that of QCD sum rules. However, again the complex hadron states and four-quark operators make this a severe challenge. One area which deserves further exploration is the role of strangeness. Recent experiments involving the spin structure of nucleons and neutrino-nucleon scattering have hinted that the nucleon may have a significant strange quark component, which has been neglected in previous calculations of weak NNM couplings. Combined with a new calculation which includes strange quark contributions to the effective weak Hamiltonian, one might anticipate a few changes, especially in the pion emission amplitudes. However, such calculations are very difficult and at the present time are very speculative.

In the case of experiment, we are more fortunate, with a number of possible new results coming on line within the next couple of years. One which has been in the planning stage for many years is a TRIUMF measurement of the asymmetry in longitudinally polarized pp scattering at 240 MeV. The significance of this energy is that according to known phase shifts this is where any effect due to S- and P-wave mixing and thereby a roughly equal contribution from rho and omega exchange effects cancels out, leaving sensitivity primarily to rho exchange contributions in P-D wave interference.
Another arena where it is possible that a new experiment could make a major impact is the measurement of parity mixing between the ground state and first excited state of $^{19}$Ne, which are the isotopic analogs of the mixed states which are studied in the $^{19}$F experiments. Since both states are isotopic doublets, only the $\Delta I = 0, 1$ components of $H_{\text{wk}}$ are operative, and by combining the results of the Ne and F measurements an unambiguous separation of the $\Delta I = 0$ and $\Delta I = 1$ components would result. This could enable an additional and welcome confirmation of the calibration of the pion exchange component, as well as an independent measurement of the size of $f_\pi$.

As discussed above, we expect that continued parity violating electron scattering experiments during the next few years will lead finally to a measurement of the anapole moment and that theoretical work may enable extraction of the NNM couplings in this unique fashion.

Finally, neutron scattering measurements will continue both at Los Alamos, where studies of heavy nuclei have already indicated the power of statistical methods, as well as at NIST where the successful Grenoble program will be extended to lighter nuclei, which are hopefully amenable to clearer theoretical interpretation.

In summary then in both theoretical and experimental areas one sees the need for additional and improved work and we set the challenge that perhaps by the millennium one may finally put this problem to rest.

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