Parity violation in few-nucleon systems

J. Carlson and M. Paris

1 Theoretical Division, Los Alamos National Laboratory
2 Theory Division, Jefferson Lab

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Abstract. We summarize recent results on parity-violation in few-nucleon systems, including $pp$ elastic scattering and $np$ radiative capture. These results are relevant to recent or present experimental measurements at TRIUMF and LANSCE, respectively. We also present results for other potential or planned experiments, summarizing the contributions they will make to understanding the weak parity-violating $NN$ interaction. Dependencies upon the $NN$ strong interaction are also addressed.

PACS. 21.30.+v Few-body systems – 24.80.+y Nuclear tests of fundamental interactions and symmetries

1 Introduction

New experiments to explore parity-violation in the $NN$ interaction have recently been completed or are presently underway or in planning stages at various institutions around the world. These include measurements of parity-violating (PV) interactions in $pp$ elastic scattering [1] at TRIUMF, $np$ radiative capture [2] and deuteron electrodisintegration [3] at JLAB. These measurements are designed to probe various aspects of the weak PV $NN$ interaction, including the weak PV $\pi$NN coupling, typically denoted $f_\pi$. We review a recent analyses of these and other potential experiments within a consistent framework, using two- and few-nucleon systems as a tool for forming a reliable understanding of the weak PV $NN$ interaction.

2 Framework

Here we adopt the nucleon-nucleon PV potential developed by Desplanques et al. [4] in terms of meson exchanges. This model parameterizes the PV $NN$ interaction in terms of $\pi$, $\rho$, and $\omega$-meson exchanges, where the strengths of the interaction are obtained from the product of a weak PV coupling on one vertex and a strong coupling at the other. It is now clear that meson couplings other than the pion in the DDH model should not be taken too literally, but rather as a simple representation of the PV mixings in low-energy NN scattering.

The aim of these calculations is to develop a systematic framework for studying PV observables in the few-nucleon systems, where accurate microscopic calculations are feasible, and to use available and forthcoming experimental data on these observables to constrain the strengths of the short- and long-range parts of the two-nucleon weak interaction. We have performed calculations with various $NN$ strong-interaction models of the parity-conserving (PC) $NN$ interaction, including the Argonne $v_{18}$ (AV18) [5], Nijmegen I (NIJM-I) [6], and CD-Bonn (BONN) [7] models. These all provide high-quality fits to the available $NN$ scattering data, though there are some differences in their structures. One does not expect the weak PV couplings extracted from experimental results to be precisely the same for different strong-interaction models. The various experiments, though, when analyzed with any consistent strong- and weak-interaction model, should consistently be reproduced by the same $NN$ mixing angles.

The PV mixing angles are obtained [8] from the asymptotic behavior of the 2 solutions for $J=0$, and the 4 solutions for $J>0$. The PV couplings introduce, for example, $p$-wave components in the deuteron, as illustrated in Fig. 1.

3 Results

Here we adapt the notation of the vector $PV_{3P1}$, proportional to

$$
\begin{align*}
U_{13} & = J \frac{1}{\sqrt{2}} \left( \frac{1}{2} \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix} \right) \\
U_{23} & = J \frac{1}{\sqrt{2}} \left( \frac{1}{2} \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & -1 \end{pmatrix} \right) 
\end{align*}
$$

for the two solutions for $J=0$. The combination $\mu U_{13} + \nu U_{23}$ gives the total wavefunction of the system. The $P$-wave mixing is given by

$$
\begin{align*}
\mu & = \left( \frac{1}{2} \right)^{1/2} \left( \frac{1}{2} \right)^{1/2} \\
\nu & = \left( \frac{1}{2} \right)^{1/2} \left( \frac{1}{2} \right)^{1/2}
\end{align*}
$$

The relative amplitude $\alpha$ of the nonrotating parity-conserving $PV_{3P1}$ wavefunction to its magnitude is

$$
\alpha = \left( \frac{\sqrt{2}}{2} \right)^{1/2} \left( \frac{1}{2} \right)^{1/2} 
$$

This is the same amplitude as the $1P_1$ of the $NN$ strong-interaction parity-conserving wavefunction. $PV_{3P1}$ wavefunctions are proportional to the basis of $1P_1$, $3P_1$, $3P_3$, and $3P_1$ states, such that the deviation from the parity-conserving states is 0. The $2P_1$ components are negligible for the $\pi$NN system.

Fig. 1: $PV_{3P1}$ components of the deuteron, with and w/o pion coupling in DDH models of the strong-interaction parity-conserving (PC) $NN$ interaction, including the Argonne $v_{18}$ (AV18), Ni- jmegen I (NIJM-I), and CD-Bonn (BONN) models. These all provide high-quality fits to the available $NN$ scattering data, though there are some differences in their structures. One does not expect the weak PV couplings extracted from experimental results to be precisely the same for different strong-interaction models. The various experiments, though, when analyzed with any consistent strong- and weak-interaction model, should consistently be reproduced by the same $NN$ mixing angles.

3.1 Experimental Results

The experimental results for $pp$ elastic scattering at TRIUMF [1] and $np$ radiative capture at JLAB [2] are consistent with the predictions of the DDH model. The $np$ radiative capture results are in good agreement with the predictions of the DDH model, with a small deviation from the parity-conserving states.

3.2 Potential Experiments

The potential experiments for the $np$ radiative capture at JLAB, the deuteron electrodisintegration at JLAB, and the $pp$ elastic scattering at TRIUMF provide additional constraints on the weak PV $NN$ interaction. These experiments are designed to probe various aspects of the weak PV $NN$ interaction, including the weak PV $\pi$NN coupling, typically denoted $f_\pi$. We review a recent analyses of these and other potential experiments within a consistent framework, using two- and few-nucleon systems as a tool for forming a reliable understanding of the weak PV $NN$ interaction.

3.3 Dependencies upon the $NN$ strong interaction

The weak PV couplings are sensitive to the $NN$ strong interaction, and the dependencies upon the $NN$ strong interaction are also addressed. We have performed calculations with various $NN$ strong-interaction models of the parity-conserving (PC) $NN$ interaction, including the Argonne $v_{18}$ (AV18), Nijmegen I (NIJM-I), and CD-Bonn (BONN) models. These all provide high-quality fits to the available $NN$ scattering data, though there are some differences in their structures. One does not expect the weak PV couplings extracted from experimental results to be precisely the same for different strong-interaction models. The various experiments, though, when analyzed with any consistent strong- and weak-interaction model, should consistently be reproduced by the same $NN$ mixing angles.

3.4 Summary

In summary, we have reviewed recent results on parity-violation in few-nucleon systems, including $pp$ elastic scattering and $np$ radiative capture. These results are relevant to recent or present experimental measurements at TRIUMF and LANSCE, respectively. We also present results for other potential or planned experiments, summarizing the contributions they will make to understanding the weak parity-violating $NN$ interaction. Dependencies upon the $NN$ strong interaction are also addressed.
Fig. 2. Comparison of original and adjusted DDH models with TRIUMF measurements. Note that, for the same coupling constants, the 3P wave is nearly independent of the strong-interaction potential, while the 1P wave does show some dependence.

3 Results

An analysis of the pp longitudinal asymmetry places some constraints on the short-range part of the T=1 PV interaction.\[9\] Somewhat surprisingly, the original DDH model of the PV interaction, obtained from fairly simple estimates of the hadronic physics, did a reasonable job of predicting the longitudinal asymmetries measured at around 40 and 220 MeV. Small adjustments in the couplings, as illustrated in Fig. 2, can be used to reproduce the experimental results.

In principle a similar longitudinal asymmetry experiment could be performed for np scattering. We have also computed this result for various PV interactions. Figure 3 shows the expected asymmetry for various strong interaction models (AV18, BONN, and NIJM-I). The strong-interaction model dependence is quite weak. The figure also presents results for the DDH model adjusted to reproduce the pp longitudinal asymmetry (DDH-adj), and for a model with only a non-zero pion weak coupling (DDH-π).

The np longitudinal asymmetry depends upon a mixture of short-range and long-range (pion) components of the PV NN interaction, while the pp longitudinal asymmetry does not depend upon the pion coupling at all.

In the DDH model, the short-range parts of the interaction are parameterized as heavy meson (ρ and ω) exchange. The longest-range part of the interaction should be directly accessible to experiment, and in principle could be calculated from QCD. The experimental situation regarding this part of the interaction is still under debate, however.

Analysis of circular polarization of the photons in 18F decay indicates a small value of the weak πNN coupling. While calculations of the strong-interaction eigenstates in these nuclei are more difficult than in few-nucleon systems, in this particular measurement a known β-decay can be used to infer the strength of the relevant two-body matrix element. Analyses of other recent experiments, in particular 133Cs, yield a potentially different answer, however. This measurement would seem to indicate a larger value of the pion coupling. A recent analysis of the situation is given in the paper of Haxton, Liu, and Ramsey-Musolf.\[10\]

The np → dγ experiment underway at the LANSCE facility is designed to study the weak πNN coupling. The correlation between the photon asymmetry and the initial neutron spin is a parity-violating observable, and depends almost solely on the pion coupling. In Table 1, we report results for the photon asymmetry using various strong interaction models, with both the full DDH model and the pion coupling alone.

The two-nucleon currents required for current conservation play a significant role in the total thermal cross section (see Table 1), and can also affect the PV asymmetry. However, the Siegert theorem can be used to essentially eliminate the model dependence in these currents, as shown by the excellent agreement between various strong interaction models.

It is, of course, also possible to use explicit exchange current models to perform these calculations. The low-energy photon asymmetry, though, involves delicate calculations which are beyond the scope of this paper.