Parity-Violating Effects in Two-Nucleon Systems

R. Schiavilla^{1,2}, J. Carlson³, M. Paris³

¹ Jefferson Laboratory, Newport News, Virginia 23606

² Physics Department, Old Dominion University, Norfolk, VA 23529

³ Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract.

We report recent results obtained for the parity-violating (PV) asymmetries in pp elastic scattering, np radiative capture at thermal neutron energies, and deuteron electro-disintegration in quasi-elastic kinematics. The available data on the pp longitudinal asymmetry are used to put constraints on some of the PV vector-meson couplings occurring in the DDH model for the PV nucleon-nucleon interaction. In the np capture, we show that a measurement of the associated asymmetry will lead to an essentially model-independent determination of the PV pion coupling to the nucleon. Finally, in quasi-elastic electron scattering we demonstrate that the asymmetry induced by hadronic weak interactions (and associated currents) is two orders of magnitude smaller than that originating from interference of the γ - and Z -exchange amplitudes.

1 Introduction

Two-nucleon experiments are the clearest probes of hadronic parity violation. A recent experiment has measured the longitudinal asymmetry in pp elastic scattering [1], while another one is underway to measure the photon asymmetry in low-energy np radiative capture [2]. This experiment has been designed to provide a definitive measurement of the weak πNN coupling constant, which determines the longest-range part of the parity-violating (PV) nucleon-nucleon interaction.

This interaction—and associated electromagnetic currents—also induce an asymmetry in deuteron disintegration at quasi-elastic kinematics with polarized electrons, in addition to the asymmetry originating from the interference of the γ - and Z -exchange amplitudes. Indeed, it has been speculated that these hadronic weak interaction effects could cloud the interpretation, in terms of

single-nucleon properties, of the experimental asymmetries, recently measured in the $d(e, e')pn$ SAMPLE experiments at the MIT-Bates facility [3, 4].

In the present contribution, we review results of recent calculations of the above processes [5, 6, 7], carried out by using the Desplanques, Donoghue, and Holstein (DDH) meson-exchange model of the PV NN interaction [8].

2 Asymmetry in pp elastic scattering

The longitudinal asymmetry in pp elastic scattering is given by [5]

$$A(E) = \frac{\text{Im} [M_{10,00}(E, 0) + M_{00,10}(E, 0)]}{\text{Im} [\sum_{SM_S} M_{SM_S, SM_S}(E, 0)]}, \quad (1)$$

where $M_{S'M'_S, SM_S}(E, \theta)$ denotes the amplitude for scattering $SM_S \rightarrow S'M'_S$, SM_S being the pair spin and its z -projection. One should note that, in the absence of PV interactions, the amplitude $M_{00,10}$ would vanish. The expression above for $A(E)$ ignores the contribution of the Coulomb amplitude (a divergent quantity in the limit $\theta=0$), and for this reason $A(E)$ will be referred to as the “nuclear” asymmetry. The effect of including explicitly the amplitude induced by the Coulomb potential is discussed in Ref. [5].

Figure 1. Total nuclear asymmetries obtained with various combinations of strong- and weak-interaction potentials are compared to data, see text.

The calculated nuclear asymmetries are compared with the available data (see [1] and references therein) in Fig. 1. The curves labeled AV18, BONN, and NIJ-I correspond to the strong-interaction potentials of Refs. [9, 10, 11], respectively, in combination with the DDH potential, with the coupling constants h_{ρ}^{pp} and h_{ω}^{pp} determined by a rough fit to data [5]. There is very little sensitivity to the input strong-interaction potential, the larger differences displayed in the earlier study of Ref. [12] may be attributable to larger differences in the p -wave phase shifts. The reduced difference is undoubtedly a consequence of the more extended pp and pn scattering data-base to which present potentials are fitted, as well as of the much higher accuracy achieved in these fits.

We also show in Fig. 1 the AV18 results which correspond to a DDH potential using the “best” estimates for the h_{ρ}^{pp} and h_{ω}^{pp} coupling constants [8]. A number of comments are now in order. The data point at 221 MeV essentially determines the value of h_{ρ}^{pp} . As pointed out by Simonius [13], the dominant contributions to the total asymmetry in the energy range under consideration here are those associated with the 1S_0 - 3P_0 and 3P_2 - 1D_2 partial waves. At energies close to 225 MeV the 1S_0 - 3P_0 contribution vanishes. As a result, the total asymmetry in this energy region is almost entirely due to the 3P_2 - 1D_2 contribution, which is known [13] to be approximately proportional to the following combination of coupling constants, $h_{\rho}^{pp}g_{\rho}\kappa_{\rho} + h_{\omega}^{pp}g_{\omega}\kappa_{\omega}$, where g_{ρ} , κ_{ρ} , ... are the vector and tensor coupling constants of the ρ and ω mesons to the nucleon. The ω tensor coupling is much smaller than the ρ tensor coupling, as suggested by vector-meson-dominance arguments. Indeed, in the BONN model, κ_{ω} is taken to be zero, and hence the data point at 221 MeV fixes h_{ρ}^{pp} (for given g_{ρ} , κ_{ρ} , and Λ_{ρ}). This is the reason for the $\simeq 44\%$ increase (in magnitude) of h_{ρ}^{pp} with respect to the DDH “best” estimate.

Below 50 MeV, however, the calculated total asymmetry is dominated by the 1S_0 - 3P_0 contribution, approximately proportional to [13] $h_{\rho}^{pp}g_{\rho}(2 + \kappa_{\rho}) + h_{\omega}^{pp}g_{\omega}(2 + \kappa_{\omega})$. The increase in magnitude of h_{ρ}^{pp} required to fit the point at 221 MeV, now leads to a total asymmetry $|A(E)|$ below 50 MeV, which is too large when compared to experiment. Thus, in order to reproduce the 13.6 MeV and 45 MeV data points, the overall strength of the coupling constant combination above needs to be reduced significantly. Since $g_{\rho}(2 + \kappa_{\rho})$ and $g_{\omega}(2 + \kappa_{\omega}) = 2g_{\omega}$ have the same sign, this requires making the sign of h_{ω}^{pp} opposite to that of h_{ρ}^{pp} .

Figure 2. Curves of constant total χ^2 obtained by analyzing the experimental pp data with the AV18 model, and ρ - and ω -meson strong-interaction couplings in the DDH potential from the Bonn-2000 model. The curves indicate surfaces of total $\chi^2 = 1, 2, 3, 4$, and 5 for various values of h_{ρ}^{pp} and h_{ω}^{pp} .

We also present an analysis of the extracted coupling constants and their

experimental errors [5]. Figure 2 shows contours of constant total χ^2 at levels of 1 through 5 versus the coupling constants h_{ρ}^{pp} and h_{ω}^{pp} . As is apparent in the figure, there is a rather narrow band of acceptable values for h_{ρ}^{pp} and h_{ω}^{pp} at total $\chi^2 = 1$ for the 3 experimental data points. At this level, h_{ρ}^{pp} can range from approximately -14 to -28, with a simultaneous (and strongly-correlated) variation in h_{ω}^{pp} from roughly -2 to +10, all in units of 10^{-7} .

3 Asymmetry in np radiative capture

The parity-violating (PV) observable in the np radiative capture—the asymmetry in the angular distribution of the outgoing photon with respect to the direction of the initial neutron polarization—is very sensitive to the weak parity-violating πNN coupling [14, 15]. Since this coupling contributes to the longest-range part of the interaction, it provides a window into the hadronic weak interaction in a manner similar to the role the standard πNN coupling provides in strong-interaction physics. Its experimental determination, however, has proven to be very difficult. Measurements of the circular polarization of *gamma-ray* decays in ^{18}F [16] have been interpreted to indicate a very small πNN coupling as compared to theoretical expectations based upon hadronic models [8], while measurements in atomic ^{133}Cs seem to favor a much larger value [17]. The analysis of both these experiments is complicated by the difficulty of handling reliably, from a theoretical stand-point, the many-body aspects of the problem in these complex systems. These issues have been addressed in Refs. [18] and [19]. More recently, PV asymmetry measurements of neutron resonances in compound nuclei seem to require even larger values of the weak πNN coupling constant [20].

For these reasons, an experiment measuring the photon asymmetry in np capture has been undertaken at the LANSCE facility [2]. As mentioned above, previous studies of this process [14, 15] showed that this asymmetry is very sensitive to the weak πNN coupling constant, while essentially unaffected by short-range contributions. In Ref. [6] we investigated the model dependence of this result by considering several different high-quality interactions fit to the strong-interaction data.

We employed the standard DDH meson-exchange model of the (PV) NN interaction, solving the full Schrödinger equation for the scattering state as well as the deuteron bound state. The equations and relevant mixing parameters in the S -matrix were discussed in considerable detail in Ref. [5] for the case of pp elastic scattering. While the short-range contributions to the PV interaction should not be viewed as resulting only from the exchange of single mesons, the seven parameters of the DDH model can still be employed to characterize all the low-energy PV mixings. For example, two-pion exchange could play a role [21], however we assumed that its effects could be included, at least at low energy, through the combination of pion- and short-range terms present in the DDH model.

We calculated the asymmetry for the AV18 [9], Bonn-CD [10] and Nijmegen-

I (NIJM-I) [11] interactions. Each strong interaction model has associated exchange currents. For the AV18 we included currents from the momentum-independent terms (π - and ρ -currents) as well as terms from the momentum-dependent terms in the interaction, for a review see Ref. [22]. For the Bonn-CD and NIJM-I interactions, we only included π - and ρ -currents with the cutoffs from the Bonn-CD model ($\Lambda_\pi=1.72$ GeV and $\Lambda_\rho=1.31$ GeV). Contributions from other meson exchanges in the Bonn and Nijmegen models were neglected. In all calculations, the currents associated with Δ excitation and $\omega\pi\gamma$ transition were also considered [22].

The total cross section at thermal neutron energies is due to the well-known M_1 transition connecting the parity-conserving (PC) 1S_0 np state to the PC deuteron state. The calculated values for each model are given in Table I, both for one-body (impulse) currents alone and for the one- and two-body currents. In each case the largest two-body contribution, approximately two-thirds of the total, comes from the currents associated with pion exchange. The total cross section is in good agreement with experimental results, which are variously quoted as 334.2(0.5) mb [23] or 332.6(0.7) mb [24]. It would be possible to adjust, for example, the transition magnetic moment $\mu_{\gamma N\Delta}$ of the Δ -excitation current to precisely fit one of these values, here we simply choose a $\mu_{\gamma N\Delta}$ of 3 n.m., which is consistent with an analysis of γ - N data at resonance.

The PV asymmetry arises from an interference between the M_1 term above and the E_1 transition, connecting the 3P_1 PV np state to the PC deuteron state and the 3S_1 PC np state to the 3P_1 PV deuteron state. The PV components of the wave functions are generated by the DDH potential, including π -, ρ -, and ω -exchange mechanisms. In Ref. [6] we took the linear combination of ρ - and ω -weak coupling constants corresponding to pp scattering from an earlier analysis [5] of these experiments. The remaining couplings were taken from the DDH "best guess" estimates. Finally, as in the earlier analysis of pp scattering, the cutoff values in the meson-exchange interaction were taken from the Bonn-CD potential ($\Lambda_\pi=1.72$ GeV, $\Lambda_\rho=1.31$ GeV, and $\Lambda_\omega=1.50$ GeV).

Table 1. Total np capture cross-sections (in mb) and np radiative capture asymmetries (in units of 10^{-8}) in various models. Asymmetries are reported for pion-exchange only and full DDH interactions.

Interaction	Cross Section		Asymmetry	
	Impulse Current	Full Current	pion-only	full DDH
AV18	304.6	334.2	-4.98	-4.85
NIJM-I	305.4	332.5	-5.11	-4.95
Bonn-CD	306.5	331.6	-4.97	-4.83

With these couplings, we obtain the asymmetries also listed in Table I. The results are consistent with earlier [14] and more recent [25] estimates, and all agree within a few per cent, which is also the magnitude of the contributions from the short-range terms. The E_1 transition has been calculated in the long-

wavelength approximation (LWA) with the Siegert form of the E_1 operator, thus eliminating many of the model dependencies and leaving only simple (long-range) matrix elements. In Ref. [6] we explicitly calculated corrections beyond the LWA E_1 terms, and found them to be quite small.

4 Asymmetry in $d(e, e')pn$ electro-disintegration

The SAMPLE experiment[3, 4] has measured the parity-violating asymmetry in polarized electron quasi-elastic scattering on the deuteron. This asymmetry has two distinct contributions: one associated with interference of the γ - and Z -exchange amplitudes, and the other induced by PV NN interactions. The first contribution was recently studied in Ref. [26], where it was shown that two-body terms in the nuclear electromagnetic and weak neutral currents only produce 1–2% corrections to the asymmetry due to the corresponding single-nucleon currents.

In Ref. [6] we investigated the asymmetry originating from hadronic weak interactions, updating and sharpening earlier predictions obtained in Refs. [27, 28]—these studies did not include the effects of PV currents.

The expression for the asymmetry from γ - Z interference was given in Ref. [26], while that due to the hadronic weak interaction reads [7]

$$A(q, \omega, \theta_e) = \frac{v'_T R'_T(q, \omega)}{v_L R_L(q, \omega) + v_T R_T(q, \omega)}, \quad (2)$$

where v_L , v_T , and v'_T denote electron kinematical factors, R_L and R_T are the standard longitudinal and transverse response functions, and R'_T is the PV response function, defined as

$$R'_T(q, \omega) = \sum_i \sum_f \delta(\omega + m_i - E_f) \text{Im} [\mathbf{j}_{fi}(\mathbf{q}) \times \mathbf{j}_{fi}^*(\mathbf{q})]_z. \quad (3)$$

Here the three-momentum transfer $\mathbf{q}$ has been taken to define the spin-quantization axis (the z -axis), and $\mathbf{j}_{fi}(\mathbf{q}) \equiv \langle f | \mathbf{j}(\mathbf{q}) | i \rangle$ are the matrix elements of the electromagnetic current. In terms of electric and magnetic multipole operators, the cross product above is expressed as

$$\text{Im} [\mathbf{j}_{fi}(\mathbf{q}) \times \mathbf{j}_{fi}^*(\mathbf{q})]_z \propto \sum_{l \geq 1} \text{Re} \left[\langle J_f || M_l(q) || J_i \rangle \langle J_f || E_l(q) || J_i \rangle^* \right], \quad (4)$$

and therefore vanishes unless (i) the initial and/or final states do not have definite parity (as is the case here because of the presence of PV NN interactions) and/or (ii) the electric and magnetic multipole operators have unnatural parities $(-)^{l+1}$ and $(-)^l$, respectively, because of PV electromagnetic currents, such as the one-body anapole current [29] and the two-body currents due to PV NN interactions [7].

In the initial study of Ref. [6], the one-body anapole current was taken as [29]

$$\mathbf{j}_{PV}^{(1)}(\mathbf{q}) = \frac{Q^2}{2m^2} \sum_i [a_S(Q^2) + a_V(Q^2)\tau_{i,z}] \sigma_i e^{i\mathbf{q}\cdot\mathbf{r}_i}, \quad (5)$$

where Q^2 is the squared four-momentum transfer ($Q^2 = q^2 - \omega^2$), and the isoscalar and isovector anapole form factors are normalized as

$$a_{S,V}(0) = \frac{h_\pi g_\pi}{4\sqrt{2}\pi^2} \alpha_{S,V}, \quad (6)$$

with $\alpha_S = 1.6$ and $\alpha_V = 0.4$ from a calculation of pion-loop contributions [29]. Here h_π and g_π are weak and strong πNN coupling constants, respectively. More recent estimates of the nucleon anapole form factors give somewhat smaller values for $\alpha_{S,V}$ [30, 31, 32]. A complete treatment would require estimates of short-distance contributions [33] and electroweak radiative corrections [7].

Only the PV two-body current associated with the π -exchange term in the DDH interaction were included in the calculations of Ref. [6] (in addition, of course, to the PC two-body currents discussed in the previous section). The PV currents from ρ and ω exchanges have not yet been considered [7, 19], but are not expected to play a significant role. One should note that at the higher momentum transfers of interest here, 100–300 MeV/c, relevant for the SAMPLE experiments, it is not possible to include the currents through the Siegert theorem, they must be calculated explicitly.

Figure 3. Contributions (in magnitude) to the longitudinal asymmetry in the electrodisintegration of the deuteron as function of the final electron energy. The kinematical setting corresponds to one of those relevant for the SAMPLE experiments: the initial electron energy is 120 MeV and the electron scattering angle is 145.9° . The $(-)$ and $(+)$ symbols denote the signs of the various contributions. See text for further explanations.

In Fig. 3 we show the asymmetry for one of the SAMPLE kinematics for the AV18 plus full DDH interaction. The total asymmetry is given by the sum of the three contributions shown. The contribution labeled “DDH interaction” is

that originating directly from the DDH interaction, while that labeled “PV γ -couplings” is from the (one-body) anapole term and the two-body pion current. Results at higher Q^2 are similar. The Bonn-CD model leads to predictions, for both the asymmetry and inclusive cross section, which are very close to those obtained with the AV18 [7].

In Fig. 4 we plot the asymmetry at the top of the quasi-elastic peak as a function of the four-momentum transfer. SAMPLE kinematics have Q^2 equal to 0.1 (GeV/c)^2 and 0.043 (GeV/c)^2 , respectively. The leading γ - Z term decreases in magnitude with Q^2 , as expected. This term does not contribute, of course, for the real photons produced in the np radiative capture. Also shown in the plot is the asymmetry obtained by retaining only the pion term in the DDH interaction, with a coupling given by the “best guess”.

Figure 4. Contributions (in magnitude) to the longitudinal asymmetry in the deuteron electro-disintegration at the top of the quasi-elastic peak, plotted as function of the four-momentum transfer Q^2 . The $(-)$ and $(+)$ symbols denote the signs of the various contributions. See text for further explanations.

These results demonstrate that, in the kinematics of the SAMPLE experiments, the asymmetry from the γ - Z coupling is two-orders of magnitude larger than that associated with the PV hadronic weak interaction. Hence even the largest estimates of the weak πNN coupling constant will not affect extractions of nucleon matrix elements.

5 Conclusions

In the present contribution, we have reported recent results obtained for the parity-violating asymmetries in pp elastic scattering, np radiative capture, and deuteron electro-disintegration within the framework of the DDH model of the parity-violating hadronic weak interaction.

An analysis of the pp PV longitudinal asymmetry, carried out by using combinations of modern-day strong interaction potentials and the DDH PV potential, shows that the available data provide a strong constraint on allowable linear combinations of ρ and ω PV coupling constants. Combining the statistical

and systematic errors in quadrature, h_{ρ}^{pp} is constrained by present data to approximately 35%, at the level of one standard deviation.

We find that the model-dependence of the np -capture asymmetry is quite small, at a level similar to the expected contributions of the short-range parts of the interaction. This process is in fact dominated by the longer-range pieces of the interaction associated with pion-exchange, and hence this experiment is a clean probe of that physics.

Similarly, we find that the SAMPLE experiment measuring the asymmetry in electron scattering on the deuteron is a very clean probe of nucleon properties. The processes associated with two-nucleons, including parity violation in the deuteron and scattering wave functions, and the currents associated with these interactions, play a very small role at reasonable values of the momentum transfer. These experiments, then, probe distinct aspects of weak-interaction physics.

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