Parity-Nonconserving Asymmetry in *n-d* Scattering

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The weak parity-nonconserving asymmetry in the total cross section for the scattering of longitudinally polarized neutrons from deuterons at 14.4 MeV is estimated using strong *n-d* scattering amplitudes from an *s*-wave, separable-potential Faddeev calculation. The weak force is parametrized in terms of ρ, ω, and π exchange and treated perturbatively. We find that $A_{nd}=0.8\times10^{-7}$ when $A_{pp}=2.6\times10^{-7}$.

Parity nonconservation in hadron scattering has been of considerable interest to physicists as evidence for the interaction of these particles through weak forces which occur in addition to the strong and electromagnetic ones.[1,2] The study of the parity-nonconserving (PNC) weak force directly through *N-N* scattering is imperative, so that ambiguities arising from experiments involving complex nuclei can be eliminated.[2,3] At the present time only *p-p* scattering can be carried out to sufficient precision.[4] The expected magnitude for the asymmetry of that total cross section relative to the helicity of the projectile is approximately 10^{-7} at low energies.[3,5-7] However, some models, such as the factorization approximation of the Cabibbo model, predict no asymmetry in *p-p* scattering. A recent analysis of nuclear parity-nonconserving experiments in terms of a phenomenological weak *N-N* potential predicts larger asymmetries for *n-p* scattering than for *p-p* scattering.[3] It is therefore natural to consider *p-d* or *n-d* scattering. Because the low-energy three-body problem is now amenable to "exact" solution, one might hope to be able to interpret such an experiment unambiguously. Furthermore, parity-nonconserving *p-d* scattering experiments should help to determine a unique set of parameters for a phenomenological $V_{\rm PNC}$.[3] The subject of this Letter is a report of the first attempt to estimate the asymmetry for the scattering of longitudinally polarized neutrons from deuterons utilizing strong *n-d* off-shell amplitudes obtained by solving the Faddeev equations and by treating the weak parity-nonconserving force within the framework of three-body perturbation theory.[8]

To estimate the order of magnitude of the asymmetry and to study some features of the *n-d* parity-nonconserving experiment, we report here the results using the weak-interaction model studied in Ref. 5 for *p-p* and *n-p* scattering and a separable *s*-wave strong interaction. Thus, we assume a weak PNC force resulting from ρ and ω exchange of the form

$$\begin{pmatrix} V_{\rm PNC}{}^{\rho} \\ V_{\rm PNC}{}^{\omega}\end{pmatrix} = \frac{-1}{M}\begin{pmatrix} f_\rho g_\rho \vec{\tau}_1\cdot\vec{\tau}_2 \\ f_\omega g_\omega\end{pmatrix}\left[\begin{pmatrix}1+\mu_v \\ 1\end{pmatrix} i(\vec{\sigma}_i\times\vec{\sigma}_j)\cdot[\vec{p}, v(r_{ij})] + (\vec{\sigma}_i-\vec{\sigma}_j)\cdot\{\vec{p}, v(r_{ij})\}_+\right], \tag{1a}$$

$$v(r_{ij}) = (4\pi r_{ij})^{-1}\exp(-m r_{ij}), \tag{1b}$$

where $M=939$ MeV is the nucleon mass, $\mu_v=3.70$ is the isovector magnetic moment, $\vec{\sigma}_i$ and $\vec{\tau}_i$ are the nucleon spin and isospin operators, respectively, $\vec{r}_{ij}=\vec{r}_i-\vec{r}_j$ and $\vec{p}_{ij}=\frac{1}{2}(\vec{p}_i-\vec{p}_j)$ are the relative spatial and momentum coordinates of the nucleons, and $m=775$ MeV is the average mass of the ρ and ω. The small isoscalar anomalous magnetic moment coupling of the ω to the nucleon is neglected. We have chosen the coupling constants to be[5] $g_\omega=\sqrt{2}\,g_\rho$, $g_\rho{}^2/4\pi=0.62$, $f_\omega=f_\rho$, and $f_\rho=1.4\times10^{-6}$. Similarly, we assume for the one-pion exchange

$$V_{\rm PNC}{}^{\pi} = i\frac{g_\pi f_\pi}{2^{3/2}M}(\vec{\sigma}_i+\vec{\sigma}_j)\cdot[\vec{p}, v_\pi(r_{ij})](\vec{\tau}_i\times\tau_j)_{(3)}, \tag{2a}$$

$$v_\pi(r_{ij}) = (4\pi r_{ij})^{-1}\exp(-m_\pi r_{ij}), \tag{2b}$$

where $m_\pi = 139$ MeV is the mass of the charged pion, and the coupling constants were chosen[5] in the absence of neutral currents to be the Cabibbo values $g_\pi^2/4\pi = 14.4$ and $|f_\pi^{\mathrm{Cab}}| = 4.3\times10^{-8}$; we take f_π^{Cab} to be positive. If neutral currents are postulated, f_π^{nc} is expected[9] to be positive and 8–12 times $|f_\pi^{\mathrm{Cab}}|$. For simplicity we assume it to be a factor of 10 larger.

For the strong interaction we have used rank-one, separable potentials with parameters fitted to the N-N singlet and triplet low-energy scattering data. The potentials have the form

$$V_i(p,p') = -(\lambda_i/M)g_i(p)g_i(p'), \tag{3a}$$

$$g_i(p) = (\beta_i^2 + p^2)^{-1}, \tag{3b}$$

where $\lambda_s = 0.1533$ fm^{-3}, $\beta_s = 1.183$ fm^{-1}, $\lambda_t = 0.3819$ fm^{-3}, and $\beta_t = 1.406$ fm^{-1}. The choice of such a simple interaction is open to criticism, especially the neglect of the N-N p-wave interaction. However, the complexity of the three-body calculation is enormous. In addition, the predictions for the singlet phase shifts are very good up to 100 MeV laboratory energy, the triplet phases are well represented up to 55 MeV, and the deuteron pole is correctly reproduced.

We have evaluated the asymmetry in the total cross section for the scattering of longitudinally polarized nucleons by protons, neutrons, and deuterons (omitting Coulomb forces):

$$A = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-). \tag{4}$$

The asymmetries for p-p and n-p scattering are given in order to compare with the previous predictions using the same weak potential model but more realistic (Hamada-Johnston and Bryan-Gersten) two-body potentials.

In each case, we relate the total cross section to the imaginary part of the forward elastic-scattering amplitude by means of the optical theorem. In particular,

$$\sigma_\pm \sim \mathrm{Im}\textstyle\sum_m \{\langle\vec{\mathrm{p}}, \pm, m\,|\,M^s + M^w\,|\,\vec{\mathrm{p}}, \pm, m\rangle\}, \tag{5}$$

where m is the spin projection of the target and M^s and M^w are the strong and weak scattering amplitudes, respectively. In the n-d calculation, one has

$$\mathrm{Im}\,\langle M^w\rangle = \mathrm{Im}\,\langle nd\,|\,W^w\,|\,nd\rangle + \mathrm{Im}\,\{\langle nd'\,|\,W^s\,|\,nd\rangle + \langle nd\,|\,W^s\,|\,nd'\rangle\}, \tag{6}$$

where the weak interaction is included perturbatively and one can write, symbolically,[8]

$$W^w = (\hat{1} + W^s G)T^w(\hat{1} + GW^s). \tag{7}$$

In these equations, W^s is the off-shell three-body scattering wave function, d represents the normal-parity deuteron ground state, and d' represents the additional odd-parity part of the deuteron ground state which results from the presence of the PNC weak interaction.

We present here results for the only 14.4 MeV, where our N-N elastic total cross sections are $\sigma_{pp} \simeq 450$ mb and $\sigma_{np} \simeq 630$ mb, in reasonable agreement with experiment ($\sigma_{pp}^{\mathrm{expt}} \simeq 460$ mb, $\sigma_{np}^{\mathrm{expt}} \simeq 640$ mb). The corresponding N-N asymmetries are given in Table I along with those of Ref. 5. These values are about twice the realistic-potential predictions of Ref. 5 for the Bryan-Gersten interaction. For the Hamada-Johnston potential, which has a hard core, the prediction for $A_{np}^{\rho\omega}$ is lower than that obtained for the Bryan-Gersten potential and our comparison with that is correspondingly worse. That this discrepancy is due to the lack of repulsion in our separable interaction may be seen from the last column, which gives our results for the Malfliet-Tjon I-III potentials.[10] The neutral-current A^π result is of course 10 times that of the Cabibbo model.

The asymmetry calculation for the n-d scattering is composed of several terms; see Eqs. (6) and (7). Strong amplitudes W^s were obtained with the code of Larson and Hetherington.[11] Our $\sigma_{nd} \simeq 700$ mb compared with the experimental value of about 770 mb. Because of the N-N central-potential assumption, the amplitudes for the various three-body amplitudes separate into doublet and quartet spin contributions for each total orbital angular momentum, L. Such would not be the case if we have included a tensor inter-

TABLE I. Nucleon-nucleon asymmetries calculated at 14.4 MeV incident energy using the strong-interaction model of this Letter and the Bryan-Gersten and Hamada-Johnston models of Ref. 5. The Malfliet-Tjon I–III potentials are from Ref. 10.

Model	$10^7 A_{pp}^{\rho\omega}$	$10^7 A_{np}^{\rho\omega}$	$10^7 (A_{np}^{\pi})^{\mathrm{Cab}}$	$10^7 (A_{np}^{\pi})^{\mathrm{nc}}$
Present	2.6	1.0	−0.11	−1.1
BG	1.1	0.4	−0.06	⋯
HJ	1.0	0.22	−0.06	⋯
MT I–III	1.2	0.55	−0.10	⋯

TABLE II. Neutron-deuteron asymmetries calculated at 14.4 MeV incident nucleon energy utilizing the three-body techniques described in the text. (All numbers have been multiplied by 10^7.)

$A_{nd}{}^{\rho}$	$A_{nd}{}^{\omega}$	$(A_{nd}{}^{\pi})^{\text{Cab}}$	$(A_{nd}{}^{\pi})^{\text{nc}}$
0.59	0.23	-0.053	-0.53

action for the triplet force. It was found that convergence with respect to total L was quite rapid, and we quote here results from summing only $L=0, 1$. [In the terms linear in W^s in Eq. (6), terms involving $L=2$ were found to be of the order of 10% of the total linear contribution to W^w.]

Results for the separate contributions to the asymmetry by the ρ-, ω-, and π-exchange parity-nonconserving weak interactions are presented in Table II. It is clear that ρ exchange provides the largest contribution to the asymmetry in the Cabibbo model; however, if a neutral-current model is assumed, the π-exchange contribution can have a magnitude similar to that found for the ρ exchange. Contributions from the odd-parity part of the deuteron ground state were found to be small; in the cases of ρ and ω exchange, strong cancellations occurred in the doublet amplitudes making them essentially negligible. We find a total asymmetry prediction for the scattering of longitudinally polarized neutrons from deuterons within the Cabibbo model of

$$A_{nd}{}^{\text{Cab}} = 0.77 \times 10^{-7}.$$

In the neutral-current model, the prediction is somewhat smaller,

$$A_{nd}{}^{\text{nc}} = 0.28 \times 10^{-7}.$$

Comparison of our predictions for n-n and n-d scattering with the experimental data for p-p and p-d scattering is interesting. Preliminary results from Los Alamos were reported earlier.[4] The asymmetry measurements have been pushed down to

$$A_{pp} = (0.1 \pm 1.4) \times 10^{-7},$$

$$A_{pd} = (-0.4 \pm 0.9) \times 10^{-7}.$$

From the discussion of Table I, it is clear that our discrepancy for A_{pp} arises largely from the lack of repulsion in the strong potential. Because of complexity of the three-body problem, especially with regard to the strong phases, it is difficult to assess the error expected for A_{nd}. Consequently a three-body calculation including short-range repulsion and even tensor forces will be required before one can hope to use this reaction to extract quantitative information about the weak Hamiltonian. However, the magnitude of the predicted asymmetry may serve as a guide to experimental physicists. Furthermore, we expect the asymmetry to be energy dependent because of the large spin dependence of the strong n-d scattering amplitude. Calculation of the energy dependence will be reported in a more complete paper.

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