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Parity violation in the two nucleon system*

John Missimer
Carnegie-Mellon University, Pittsburgh, Penna. 15213
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The parity violating polarization asymmetries of nucleon-nucleon scattering at energies below 20 MeV are subject to a model-independent analysis. I discuss the asymmetries necessary to determine completely the weak interaction parameters and relate them to the parity violating observables in the thermal capture of neutrons. One of the relations provides a check of the photon asymmetry, the observable most sensitive to models of nonleptonic weak interactions.

[NUCLEAR REACTIONS Deduce relations among nucleon-nucleon polarization asymmetries to determine parity violating amplitudes.]

The study of nonleptonic weak interactions through parity violation in nuclear processes has been inconclusive. The Cabibbo model has been used in successful estimates of the effects in the α decay of ^{16}O and in the 110 keV γ transition in ^{19}F, but in calculations of the circular polarization in the thermal capture of neutrons and of γ transitions in other complex nuclei, the same model has produced underestimates of at least an order of magnitude.[1]

Calculations of parity violating effects employ potential models of both the strong and weak interactions. A significant problem with current calculations is that different strong interaction potentials predict results which differ by an order of magnitude for the same weak potential, although not even the most favorable strong interaction can alleviate the disagreements between calculations and experiment.

The uncertainties inherent in potential model calculations suggest the desirability of determining the weak interaction parameters independently of a model. A model-independent analysis of already performed experiments is difficult because the experiments measure different effects in a variety of nuclear processes.

Recently, experimentalists have begun measuring polarization asymmetries in proton-proton and proton-neutron scattering.[2] Theoretical discussions[3] using potential models have estimated the magnitudes of the asymmetries and predicted the optimum energy for their detection.

I comment here that the polatization asymmetries of nucleon-nucleon scattering are subject to a model-independent analysis. I specify the asymmetries necessary to determine completely the weak interaction parameters and relate them to the parity violating observables in the thermal capture of neutrons. One of the relations provides a check of the photon asymmetry, the sharpest measurement for distinguishing among models of nonleptonic weak interactions.

The analysis is expressed in the formalism used by Danilov[4] to describe parity violation in thermal capture. In the approximation that only scattering in s waves is important, the scattering amplitude for proton-neutron scattering is:

$$\begin{aligned}A^{pn}(k) = {} & a_s^{pn}(k)P_s + a_t(k)P_t + p(k)(\vec{\sigma}_n + \vec{\sigma}_p)\cdot(\vec{k}+\vec{k}') \\ & + \tfrac{1}{2}t(k)[(\sigma_p - \sigma_n)\cdot(\vec{k}+\vec{k}') + (i\vec{\sigma}_p \times \vec{\sigma}_n)\cdot(\vec{k}-\vec{k}')] \\ & + \tfrac{1}{2}s^{pn}(k)[(\vec{\sigma}_p - \vec{\sigma}_n)\cdot(\vec{k}+\vec{k}') - (i\vec{\sigma}_p \times \vec{\sigma}_n)\cdot(\vec{k}-\vec{k}')]\,, \end{aligned} \tag{1}$$

where $\vec{k} = \frac{1}{2}(\vec{k}_n - \vec{k}_p)$, the definition chosen by Danilov. For proton-proton scattering or neutron-neutron scattering, the superscripts pn assume the labels pp or nn; the unlabeled amplitudes contribute only to pn scattering. The subscripts s and and t refer to singlet and triplet spin states of the s-wave scattering amplitudes.

Final state interaction theory[5] furnishes both the phase and the energy dependence of the parity violating amplitudes at low energies. The Fermi-Watson final state theorem requires that the phase of the amplitudes be determined by the dominant s-wave phase shifts, e.g., neglecting the small p-wave phase shift,

$$t(k) \simeq |t(k)|\, e^{i\delta_t(k)}\,. \tag{2}$$

Moreover, in the N/D formalism, the final state scattering phase shifts and the Born approximation to the amplitude determine the energy dependence. Since the weak amplitudes are determined for energies below 300 MeV by single pion or single vector meson exchange, their Born approximations vary little with energy at energies below 20 MeV. Therefore, the phase shifts produce most of the energy variation. Since the effective range approximation is also valid below 20 MeV, the weak scattering amplitude factors into a constant characteristic of the weak interactions and the strong amplitude describing scattering in the final state, e.g.

$$t(k) \simeq \tau^{(0)} |a_t(k)| e^{i\delta_t(k)} = \tau^{(0)} a_t(k) . \qquad (3)$$

Similarly,

$$p(k) \simeq \pi^{(1)} a_t(k) , \qquad (4a)$$

$$s^{NN}(k) \simeq \rho_s^{NN} a_s(k) . \qquad (4b)$$

This is the form of the amplitudes used by Danilov. His notation has been modified in order to indicate the isospin structure more explicitly; the numerical subscripts indicate the isospin transformation properties of the amplitude. The symbol ρ recalls that these amplitudes arise in potential models from one vector meson exchange, whereas the $\pi^{(1)}$ amplitude is produced by pion production as well.

Four polarization asymmetries are observable in nucleon-nucleon scattering. The polarization asymmetry is defined by:

$$\alpha_{NN} = \frac{\sigma_{NN}(+1) - \sigma_{NN}(-1)}{\sigma_{NN}(+1) + \sigma_{NN}(-1)} , \qquad (5)$$

where $\sigma_{NN}(h)$ is the helicity ($h = \pm 1$) cross section. The asymmetries are

$$\alpha_{pp}\sigma_{pp} = -4\pi k \rho_s^{pp} |a_s^{pp}(k)|^2 , \qquad (6a)$$

$$\alpha_{nn}\sigma_{nn} = -4\pi k \rho_s^{nn} |a_s^{nn}(k)|^2 , \qquad (6b)$$

$$\alpha_{pn}\sigma_{pn} = -4\pi k [2\pi^{(1)} |a_t(k)|^2 + \tau^{(0)} |a_t(k)|^2 + \rho_s^{pn} |a_s^{pn}(k)|^2] , \qquad (6c)$$

$$\alpha_{np}\sigma_{np} = -4\pi k [-2\pi^{(1)} |a_t(k)|^2 + \tau^{(0)} |a_t(k)|^2 + \rho_s^{pn} |a_s^{pn}(k)|^2] . \qquad (6d)$$

For n-p scattering asymmetries, the ordering of the subscripts np indicates polarized neutrons incident on protons, and the opposite ordering indicates polarized protons. McKellar[6] has remarked that measuring α_{np} would help determine the isovector amplitude $\pi^{(1)}$. If, in addition, α_{pn} can be measured, the amplitude can be determined unambiguously.

Two forward-backward asymmetry measurements provide additional information about the parity violating amplitudes. The forward-backward asymmetry is defined by:

$$\Delta_{NN}\sigma_{NN} = [\sigma_f(+1) - \sigma_f(-1)] - [\sigma_b(+1) - \sigma_b(-1)] , \qquad (7)$$

where the subscript f indicates that the differential cross section is integrated over the forward hemisphere, and b indicates integration over the backward hemishpere. For n-p scattering, the asymmetries are

$$\Delta_{np}\sigma_{np} = -2\pi k \{2\pi^{(1)} |a_t(k)|^2 + (\tau^{(0)} + \rho_s^{pn}) \mathrm{Re}[a_t^*(k) a_s^{pn}(k)]\} , \qquad (8a)$$

$$\Delta_{pn}\sigma_{pn} = -2\pi k \{-2\pi^{(1)} |a_t(k)|^2 + (\tau^{(0)} + \rho_s^{pn}) \mathrm{Re}[a_t^*(k) a_s^{pn}(k)]\} . \qquad (8b)$$

Thermal neutron capture[4,7] was the first process proposed for the study of parity violation in the nucleon-nucleon system. The circular polarization P_γ and asymmetry α are written in terms of parity violating amplitudes:

$$P_\gamma \sigma_\gamma = 8\eta [\rho_s^{pn} a_s(0) + \delta \tau^{(0)} a_t(0)] , \qquad (9a)$$

$$\alpha \sigma_\gamma = 16\eta \pi^{(1)} a_t(0) , \qquad (9b)$$

where σ_γ denotes the total cross section and

$$\eta = \frac{1}{6\pi M} (\mu_p - \mu_n) a_t(0) [a_t(0) - a_s^{pn}(0)] , \qquad (10a)$$

$$\delta = \left(3 - 2\frac{a_s^{pn}(0)}{a_t(0)}\right) . \qquad (10b)$$

In principle, the measurements described in Eqs. (6), (8), and (9) provide eight determinations of the five amplitudes describing parity violation in the nucleon-nucleon system. A single measurement determined the p-p or the n-n amplitude. Each of the n-p amplitudes is determined in at least two ways:

$$\pi^{(1)} = \frac{1}{16\eta a_t(0)} (\alpha\sigma_\gamma) \qquad (11a)$$

$$= \frac{1}{16\pi k |a_t(k)|^2} (\alpha_{np}\sigma_{np} - \alpha_{pn}\sigma_{pn}) \qquad (11b)$$

$$= \frac{1}{8\pi k |a_t(k)|^2} (\Delta_{np}\sigma_{np} - \Delta_{pn}\sigma_{pn}) , \qquad (11c)$$

$$\tau^{(0)} = -\left(\frac{|a_t(k)|^2}{|a_s(k)|^2} - \delta\frac{a_t(0)}{a_s(0)}\right)^{-1} \left(\frac{1}{8\pi k} (\alpha_{np}\sigma_{np} + \alpha_{pn}\sigma_{pn}) + \frac{1}{8\eta a_s(0)} P_\gamma\sigma_\gamma\right) \qquad (12a)$$

$$= -\frac{1}{8\pi k(|a_t(k)|^2 - |a_s(k)|^2)}\left((\alpha_{np}\sigma_{np} + \alpha_{pn}\sigma_{pn}) - \frac{2|a_s(k)|}{|a_t(k)|\cos(\delta_t - \delta_s)}(\Delta_{np}\sigma_{np} + \Delta_{pn}\sigma_{pn})\right), \tag{12b}$$

$$\rho_s^{pn} = -\left(\delta\frac{|a_s(k)|^2}{|a_t(k)|^2} - \frac{a_s(0)}{a_t(0)}\right)\left(\frac{\delta}{8\pi k|a_t(k)|^2}(\alpha_{np}\sigma_{np} + \alpha_{pn}\sigma_{pn}) + \frac{1}{8\eta a_t(0)}P_\gamma\sigma_\gamma\right) \tag{13a}$$

$$= -\frac{1}{8\pi k(|a_s(k)|^2 - |a_t(k)|^2)}\left((\alpha_{np}\sigma_{np} + \alpha_{pn}\sigma_{pn}) - \frac{2|a_t(k)|}{|a_s(k)|\cos(\delta_t - \delta_s)}(\Delta_{np}\sigma_{np} + \Delta_{pn}\sigma_{pn})\right), \tag{13b}$$

where $a_s(k) = a_s^{pn}(k)$ in this set of equations. A useful test for both experiments and calculations is provided by Eqs. (9a) and (9b):

$$(\alpha_{np}\sigma_{np} - \alpha_{pn}\sigma_{pn}) = \frac{\pi}{\eta a_t(0)} k|a_t(k)|^2(\alpha\sigma_\gamma). \tag{14}$$

Since both sets of observables measure the amplitude $\pi^{(1)}$, which may vary by an order of magnitude according to the model of weak interactions, the relationship is a low energy consistency check of the crucial parameter in the study of $\Delta S = 0$ nonleptonic amplitudes.

The other amplitudes do not vary as much as $\pi^{(1)}$ with weak interaction models, but their analysis is necessary for a complete understanding of parity violating processes. The isospin structure of the amplitudes ρ_s^{NN} is revealed in the decompositions:

$$\rho_s^{pp} = \rho^{(0)} + \frac{1}{\sqrt{10}}\rho^{(2)} - \frac{1}{\sqrt{2}}\rho^{(1)}, \tag{15a}$$

$$\rho_s^{nn} = \rho^{(0)} + \frac{1}{\sqrt{10}}\rho^{(2)} + \frac{1}{\sqrt{2}}\rho^{(1)}, \tag{15b}$$

$$\rho_s^{pn} = \rho^{(0)} - \sqrt{\tfrac{2}{5}}\,\rho^{(2)}. \tag{15c}$$

There are precisely three isospin amplitudes and they are uniquely determined by the three nucleon-nucleon amplitudes.

Theory does not suggest that any of the isospin amplitudes are negligible. Naively, octet dominance suggests that the isoscalar amplitudes are much larger than the isotensor. However, as a phenomenological description of pion decays of baryons, octet dominance may not apply to $NN\rho$ amplitudes.[8] Moreover, in calculations of the thermal neutron capture circular polarization [cf. Eq. (9a)] the two isoscalar amplitudes almost cancel.[9] The dominant contribution to P_γ is produced by the isotensor amplitude, which must be enhanced by two orders of magnitude to explain the experimental value. Isotensor dominance[6] has been proposed, but its theoretical justification has yet to be provided.

Whether isoscalar or isotensor amplitudes dominate cannot be resolved without analysis of the isovector amplitude $\rho^{(1)}$. Appearing as the isovector $(\tau_1^z\tau_2^0 + \tau_1^0\tau_2^z)$ in potential models, the amplitude arises in the factorization approximation from products of neutral currents such as $J_\mu^3 J_\mu^8$ or $J_\mu^3 J_\mu^0$, where the superscripts are SU(3) indices. The isovector amplitude does not occur in the Cabibbo model, which contains only charged currents. However, neutral currents occur in many models of the weak interactions. In the d'Espagnat model[10] and the Salam-Weinberg[11] gauge theory, the neutral currents which enhance $\pi^{(1)}$ also produce a significant $\rho^{(1)}$ amplitude. Hence, if neutral currents are as important in nonleptonic processes as they are in semileptonic processes, there is no justification for disregarding the isovector contributions to ρ_s^{nn} and ρ_s^{pp}. The isoscalar and isotensor amplitudes cannot be extracted from ρ_s^{pp} and ρ_s^{pn} alone.

The prognosis for performing the experiments capable of accurately determining the isospin amplitudes is not promising for several years. Of the measurements of P_γ [12] and α_{pp} [2] already made, only the measurement of P_γ has unambiguously observed an effect. Measurement of P_γ and α are currently being performed,[13] and α_{pp} is being measured more precisely. With the availability of monoenergetic, polarized neutron beams and polarized proton targets, experiments to measure α_{pn} and α_{np} are conceivable, if difficult. The polarization asymmetry α_{nn} is the most remote of the necessary experiments, since neutron-neutron scattering experiments have not been done at all. The alternative is a neutron-deuteron scattering experiment, but the extraction of the asymmetry parameters at the low energies required for a model-independent analysis appears to be a difficult theoretical problem. However, such an extraction is essential if theoretical arguments cannot be developed to discount the isovector component of ρ_s^{nn}.

Fortunately, determination of the isovector $\pi^{(1)}$ requires less difficult experiments and provides the most information about nonleptonic weak interactions.

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[1]M. A. Box *et al.*, J. Phys. G 1, 493 (1975); B. Desplanques, Ph.D. thesis, Universite de Paris-Sud. Centre d'Orsay, 1975 (unpublished).

[2]J. M. Potter *et al.*, Phys. Rev. Lett. 33, 1307 (1974); J. D. Bowman *et al.*, *ibid.* 34, 1184 (1975).

[3]M. Simonius, Phys. Lett. 41B, 415 (1972); Nucl. Phys. A220, 269 (1974); V. R. Brown, E. M. Henley, and F. R. Krejs, Phys. Rev. Lett. 30, 770 (1973); Phys. Rev. C 9, 935 (1974).

[4]G. S. Danilov, Phys. Lett. 18, 40 (1965); 35B, 579 (1971).

[5]J. Gillespie, *Final State Interactions* (Holden-Day, San Francisco, 1964).

[6]B. H. J. McKellar, Nucl. Phys. A254, 349 (1975).

[7]R. J. Blin-Stoyle and H. Feshbach, Nucl. Phys. 27, 395 (1961).

[8]E. Fischbach (private communication).

[9]H. J. Pirner and M. L. Rustgi, Phys. Rev. C 10, 2099 (1974); Nucl. Phys. A239, 427 (1975); K. R. Lassey and B. H. J.McKellar, Lett. Nuovo Cimento 11, 161 (1974); Aust. J. Phys. 27, 637 (1974); B. Desplanques, Nucl. Phys. A242, 423 (1975).

[10]B. d'Espagnat, Phys. Lett. 7, 209 (1963).

[11]G. Altarelli *et al.*, Nucl. Phys. B88, 215 (1975); H. Galic, B. Guberina, and D. Tadić, in Proceedings of the Symposium on Interaction Studies, Mainz, 1975 (North-Holland, to be published); J. Donoghue, Phys. Rev. D (to be published).

[12]V. M. Lobashov *et al.*, Nucl. Phys. A197, 241 (1972).

[13]R. Wilson (private communication).