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Weak interaction effects in low energy pion photoproduction¹

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Abstract

Weak interaction induced parity-violating asymmetries in low energy pion photoproduction are calculated to be of order 10^{-7} . The problem of isolating the weak neutral current dominated pion nucleon coupling is discussed.

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Introduction

The weak interaction can produce small but observable parity nonconserving effects in electromagnetic and hadronic reactions. Such effects have been detected in atomic (1,2) and nuclear (3) transitions, and in high energy electron scattering (4). In this paper weak interaction induced parity nonconservation in low energy pion photoproduction is discussed. It is suggested that this reaction could be particularly useful in determining the effective weak pion-nucleon coupling constant.

Parity nonconservation in nuclear transitions is usually described in terms of an effective weak nucleon-nucleon potential which mixes states of different parity. Transitions between mixed parity states lead to pseudoscalar asymmetries which are typically of order 10^{-6} . The half-dozen cases which have been measured are reviewed by McKellar (3) [see also Snover *et al.* (5)]. The microscopic description of the weak nucleon-nucleon potential involves pion and vector meson exchange. Parity violation arises because the weak interaction induces an irregular scalar (π) or axial vector (p, ω) nucleon coupling. The role of weak interaction theory is in calculating the strength of these irregular parity couplings. The weak vector meson-nucleon coupling f_v tends to be dominated by charged currents (6). On the other hand the irregular pion-nucleon coupling constant f_π is very small within the framework of the Cabibbo (charged current) theory but can be greatly enhanced in theories which have parity nonconserving neutral currents (7,8). A determination of f_π would provide, therefore, an additional constraint on weak interaction theories. Unfortunately vector

meson exchanges tend to be very important in determining the parity admixtures of nuclear states (3), and further nuclear complications (9) make it difficult to extract precise information on f_π from nuclear experiments.

It is well known that low energy pion photoproduction from nucleons is dominated by the Born approximation (10), that is, by terms of order $eg_{\pi NN}$ where e is the charge and $g_{\pi NN}$ is the renormalized strong π -nucleon coupling constant. If terms of order ef_π dominate the weak production amplitude, the measurement of parity-violating asymmetries in pion photoproduction would allow direct determination of the weak pion-nucleon coupling constant. We suggest that at low energy where the $\Delta(1232)$ contribution to photoproduction is not yet dominant this is in fact the case. Weak interaction effects in the ρNN coupling do not upset the simple interpretation.

The effective weak γNN coupling has been discussed recently by Paar *et al.* (11). An upper limit on the strength of coupling may be obtained from the measured circular polarization in the radiative neutron capture reaction on protons (12). An effective coupling of the strength estimated in (11) would lead to parity-violating asymmetries in $\gamma p \rightarrow \pi^+ n$ much smaller than those from the weak pion-nucleon vertex.

Using standard weak interaction meson-nucleon couplings (13) we calculate the expected magnitude for pseudoscalar asymmetries in $\gamma p \rightarrow \pi^+ n$. Although not given here similar results would be obtained for the radiative pion capture reaction. Three different asymmetries are considered. One involves circularly polarized photons on

unpolarized protons. The others are for unpolarized photons on protons polarized parallel (longitudinal configuration) or perpendicular (transverse configuration) to the incident beam. The different asymmetries can be used to isolate different aspects of the weak pion-nucleon vertex.

Pion Photoproduction

Strong Interaction Amplitude

The regular (parity-conserving) photoproduction amplitude is described using the chiral invariant effective Lagrangian model of Peccei (14). In lowest order the amplitude is given by nucleon, pion and Δ -pole terms and a contact term needed for gauge invariance. The explicit expressions for the amplitude in this model can be found in (14). Since we are interested in energies above the threshold region considered by Peccei a finite width is introduced in the Δ -propagator. All other unitarization effects are neglected.

A small additional contribution to the amplitude is included in the calculation. This is the t -channel ρ -exchange term, and it is calculated in the same way as the ω -exchange term for π^0 production in (15). Using a $\rho\pi\gamma$ coupling constant determined from the ρ -meson radiative width (16) and ρNN coupling constants from nucleon-nucleon potentials (17), it is found that ρ -exchange has about a 2% effect on the $\gamma p \rightarrow \pi^+ n$ cross section.

The general form of the amplitude (taken between Pauli spinors)

is

$$[1] \quad T = \chi_f^\dagger \left\{ F_1 \vec{\sigma} \cdot \vec{\epsilon} + F_2 \vec{\sigma} \cdot \vec{k} \vec{\epsilon} \cdot \vec{q} + F_3 \vec{\sigma} \cdot \vec{q} \vec{\epsilon} \cdot \vec{q} + i F_4 \vec{q} \cdot (\vec{k} \times \vec{\epsilon}) \right\} \chi_i,$$

where $\vec{q}$, $\vec{k}$ and $\vec{\epsilon}$ are the pion momentum, photon momentum and polarization vector, respectively. The transverse gauge condition has been imposed.

The calculated total $\gamma p \rightarrow \pi^+ n$ cross section is shown in Fig. 1 as a function of photon laboratory energy E_γ , with data points from the fit of Berends and Weaver (18). The model agrees very well with the empirical values up to $E_\gamma = 250$ MeV. Figure 2 shows the differential cross section (in the c.m. frame) for photon energies 185 and 240 MeV. Again agreement with experiment (19,20) is very good, and we conclude that the chiral Lagrangian Born terms provide a reasonable description of photoproduction in the low energy region.

Weak Interaction Effects

The irregular parity amplitude is obtained by replacing in the Born terms for the regular photoproduction amplitude one of the vertices by a weak interaction induced vertex of opposite parity.

Very little is known about the weak $\gamma N\Delta$ and $\pi N\Delta$ couplings.

There have been arguments that the weak $\pi N\Delta$ coupling should vanish (21), or at least should be very small compared to the πNN coupling. It is assumed here that the weak $\gamma N\Delta$ and $\pi N\Delta$ couplings can be neglected. This should be reasonable as long as the energy is low enough so that the Δ -pole terms do not dominate.

The irregular parity (weak interaction) pion-nucleon coupling is usually defined by the scalar coupling Lagrangian

$$[2] \quad \mathcal{L} = f_\pi \bar{N} (\vec{\phi} \times \vec{\tau})_3 N.$$

Within the framework of the Weinberg-Salam (WS) model (22,23)

extended to hadrons according to GIM (24), the coupling constant f_π has been estimated by Gari and Reid (7) to be 5.6×10^{-7} for $\sin^2 \theta_W = 0.25$. If only charged currents were present or if neutral currents were intrinsically parity conserving as in a left-right symmetric model (25), f_π would be much smaller. Estimates of f_π in Cabibbo theory range from 0.45×10^{-7} to 0.14×10^{-8} (26,27). It is not necessarily true, however, that neutral current effects dominate the irregular parity photoproduction amplitude.

It has been argued that in the exact SU(2) limit the $\Delta S = 0$ charged current contribution to the weak pion-nucleon vertex should vanish (26,27). An effective Lagrangian with this property (28) can be written as

$$[3] \quad \mathcal{L} = a_\pi \bar{N} \gamma^\mu \partial_\mu \vec{\phi} \cdot \vec{\tau} N.$$

For on-mass-shell nucleons this is equivalent to scalar coupling with

$$[4] \quad \tilde{f}_\pi = a_\pi |M_n - M_p|.$$

Off mass shell, for example, in the nucleon pole term of the photoproduction amplitude scalar and vector coupling need not give equivalent results. In fact the difference between using scalar and vector coupling is a term

$$[5] \quad i\sqrt{2} \frac{e \tilde{f}_\pi M_V}{M_p(M_p - M_n)} u(p') \sigma_{\mu\nu} \epsilon^{\mu\nu\lambda\rho} u(p).$$

Although $\tilde{f}_\pi$ (taken here to be 0.24×10^{-8}) is much smaller than the neutral current induced coupling constant f_π , the mass difference in the denominator makes [5] comparable in magnitude to the amplitude calculated with the usual scalar coupling Lagrangian [2].

The general form of the effective weak γNN vertex is discussed by Fischbach and Tadic (29). The only term that contributes for real photons is

$$[6] \quad e \frac{\lambda}{2M} i \sigma_{\mu\nu} \epsilon^{\mu\kappa\nu} \gamma_5.$$

In photoproduction where one of the nucleons coupling to the photon is off mass shell, [6] can give a non-zero contribution. Using the estimate of Paar *et al.* (11) for the coupling strength leads to parity-violating effects which are small compared to those from the weak pion vertex.

Finally consider the weak ρ -nucleon coupling given by

$$[7] \quad \mathcal{L} = \frac{1}{\sqrt{2}} f_\rho \bar{N} \gamma^\mu \gamma_5 \tau_\pm N \rho_\mu^\pm.$$

The coupling constant f_ρ is estimated (6) in both WS and Cabibbo theory to be 14×10^{-7} . This is larger than f_π , which makes the separation of π and ρ -exchange contributions to the weak nucleon-nucleon interaction difficult. Fortunately the small $\rho\pi\pi$ coupling makes the ρ -pole contribution to the weak photoproduction amplitude negligibly small.

The irregular parity photoproduction amplitude takes the form

$$[8] \quad \tilde{T} = x_f^\dagger \left\{ G_1 \vec{\epsilon} \cdot \vec{q} + iG_2 \vec{\sigma} \cdot (\vec{k} \times \vec{\epsilon}) + iG_3 \vec{\sigma} \cdot (\vec{q} \times \vec{\epsilon}) + iG_4 \vec{\sigma} \cdot \vec{k} \vec{q} \cdot (\vec{k} \times \vec{\epsilon}) + iG_5 \vec{\sigma} \cdot \vec{q} \vec{q} \cdot (\vec{k} \times \vec{\epsilon}) + iG_6 \vec{\sigma} \cdot \vec{q} \sigma \cdot (\vec{k} \times \vec{q}) \right\} \chi_i.$$

Pseudoscalar Asymmetries

Parity-violating asymmetries in the total and differential cross section for $\gamma p \rightarrow \pi^+ n$ arise from the interference of the regular parity T [1] and irregular parity $\tilde{T}$ [8] amplitudes. Three

different asymmetries are considered: one for circularly polarized photons on unpolarized protons, the others for protons polarized parallel or perpendicular to the beam direction.

The asymmetry in the differential cross section for production with polarized photons is

$$[9] \quad A_Y(\theta) = \frac{2 \operatorname{Re} T_+^\dagger \tilde{T}_+ - 2 \operatorname{Re} T_-^\dagger \tilde{T}_-}{|T_+|^2 + |\tilde{T}_-|^2},$$

where the subscripts ($\pm$) denote the photon helicity. The contribution of $\tilde{T}$ to the denominator has been neglected. The asymmetry in the total cross section is

$$[10] \quad A_Y = \frac{\sigma(\text{left}) - \sigma(\text{right})}{\sigma(\text{left}) + \sigma(\text{right})}.$$

For polarized protons (and unpolarized photons) the interference term between T and $\tilde{T}$ is

$$[11] \quad \begin{aligned} \vec{s} \cdot \vec{q} \operatorname{Re} \left\{ G_1^\dagger (F_1 + F_2 q^2 \sin^2 \theta) + k^2 G_2^\dagger F_4 + \vec{k} \cdot \vec{q} G_3^\dagger F_4 \right. \\ \left. + \vec{s} \cdot \vec{k} \operatorname{Re} \left\{ G_1^\dagger \left(-\frac{\vec{k} \cdot \vec{q}}{k^2} F_1 + q^2 \sin^2 \theta F_2 \right) \right. \right. \\ \left. \left. + F_4^\dagger (-\vec{q} \cdot \vec{k} G_2 - q^2 G_3 + q^2 k^2 \sin^2 \theta G_4) \right\} \right\}, \end{aligned}$$

where $\hat{s}$ is a unit vector in the direction of proton polarization.

The asymmetry for the transverse configuration ($\hat{s}$ parallel to $\vec{k}$) is defined by

$$[12] \quad A_T(\theta) = \frac{d\sigma(\hat{s} \cdot \hat{k} = +1, \hat{s} \cdot \hat{q} = \cos \theta) - d\sigma(\hat{s} \cdot \hat{k} = -1, \hat{s} \cdot \hat{q} = -\cos \theta)}{d\sigma(\hat{s} \cdot \hat{k} = +1, \hat{s} \cdot \hat{q} = \cos \theta) + d\sigma(\hat{s} \cdot \hat{k} = -1, \hat{s} \cdot \hat{q} = -\cos \theta)}$$

for the differential cross section and for the total cross section. In the longitudinal configuration ($\hat{s}$ perpendicular to $\vec{k}$) the

asymmetry in the differential cross section is calculated for $\hat{s}$, $\hat{k}$ and $\hat{q}$ coplanar and is

$$[14] \quad A_L(\theta) = \frac{d\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} = \sin\theta) - d\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} = -\sin\theta)}{d\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} = \sin\theta) + d\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} = -\sin\theta)}.$$

An asymmetry is also defined for the cross section integrated over the hemisphere of which $\hat{s}$ is the polar vector:

$$[15] \quad A_L = \frac{\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} > 0) - \sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} < 0)}{\sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} > 0) + \sigma(\hat{s} \cdot \hat{k} = 0, \hat{s} \cdot \hat{q} < 0)}.$$

Results

Results are presented for parity-violating asymmetries using both scalar [2] and vector [3] coupling in the irregular parity amplitude. The scalar coupling is dominated by neutral current effects, and the effective coupling constant using the WS model calculation of Gari and Reid (7) is $f_\pi = 5.6 \times 10^{-7}$. The vector coupling constant estimate ($f_{\pi NN} = 0.24 \times 10^{-8}$) of Körner (25) is used. Since vector coupling effectively increases off mass shell (28), it can lead to asymmetries comparable to scalar coupling even though $f_\pi \gg \tilde{f}_\pi$. The ρ -pole term in $\tilde{T}$ is negligible (less than 1%) compared to the weak pion contribution.

Figure 3 shows A_Y in the total $\gamma p \rightarrow \pi^+ n$ cross section with circularly polarized photons for scalar (solid line) and vector coupling. The asymmetry $A_Y(\theta)$ in the differential cross section (in the laboratory frame) at 190 and 250 MeV is given in Fig. 4 for scalar coupling. The qualitative shape for vector coupling is similar.

The asymmetries in the integrated cross section for the transverse configuration are shown in Fig. 5 by dashed (scalar) and

dash-dot (vector) lines. The longitudinal total cross section asymmetries A_L are given in the same figure for scalar and vector coupling (solid and dash-double-dot lines). Differential cross section asymmetries in the longitudinal configuration (scalar coupling) and the transverse configuration with scalar and vector coupling are plotted in Figs. 6, 7 and 8.

The maximum asymmetry occurs in production with polarized photons. The magnitude 4×10^{-7} based on the WS model is comparable to the asymmetry expected in low energy nucleon-nucleon scattering (30). The asymmetry for polarized protons in the longitudinal configuration is not quite as large as with polarized photons. It has the advantage, however, that the term [5] which normally dominates the charge current induced vector coupling is greatly suppressed. This allows the best separation of charged and neutral current effects.

Summary

Using the weak interaction induced meson-nucleon couplings that have been used in constructing weak nucleon-nucleon potentials, we calculate in this paper parity-violating asymmetries for $\gamma p \rightarrow \pi^+ n$. Unlike the NN interaction where vector meson exchange is important the weak ρ -nucleon coupling plays a negligible role in photoproduction. This allows a direct determination of the weak pion-nucleon coupling constant.

The calculation is restricted to low energy to keep the Δ -contribution under control. It is assumed here that the weak interaction induced $\gamma N\Delta$ and $\pi N\Delta$ couplings are negligible. This approximation is in need of further investigation.

Parity-violating asymmetries of order 10^{-7} are expected for $\gamma p \rightarrow \pi^+ n$. This is of the same order as the predicted parity-violating effects in low energy nucleon-nucleon scattering. The maximum asymmetry occurs for circularly polarized photons, but production with unpolarized photons on protons polarized in the beam direction gives the best separation of neutral and charged current effects.

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Figure Captions

1. Total cross section for $\gamma p \rightarrow \pi^+ n$ as a function of photon laboratory energy E_γ . Data points are from the fit of Berends and Weaver (18).
2. c.m. differential cross section for $\gamma p \rightarrow \pi^+ n$ compared with the 185 MeV data of Adamovich *et al.* (19) and the 240 MeV data of Fischer *et al.* (20).
3. Asymmetry in total cross section for pion production with circularly polarized photons.
4. Asymmetry in angular distribution for pion production with circularly polarized photons at 190 and 250 MeV laboratory energy.
5. Total cross section asymmetry for pion production on longitudinally polarized protons assuming scalar (—) and vector (— · —) coupling and integrated cross section asymmetry on transversely polarized protons assuming scalar (---) and vector (--- · ---) coupling.
6. Asymmetry of the differential cross section in the longitudinal configuration at 190 and 250 MeV using scalar coupling.
7. Asymmetry of the differential cross section in the transverse configuration at 190 and 250 MeV using scalar coupling.
8. Asymmetry of the differential cross section in the transverse configuration at 190 and 250 MeV using vector coupling.

Fig. 1

Fig. 2

Fig. 3

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 8