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A TEST OF TIME-REVERSAL INVARIANCE IN π^+ PHOTOPRODUCTION

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A B S T R A C T

It is proposed to measure polarizations of the recoil neutron in π^+ photoproduction in order to detect a possible T violation in the electromagnetic interaction of hadrons. Several possibilities of introducing T violating terms in the photoproduction current are discussed.

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1. INTRODUCTION

It has been pointed out by Bernstein, Feinberg and Lee ¹⁾ that there is at present no experimental evidence assuring time-reversal invariance in the electromagnetic interaction of hadrons. The authors propose several experimental tests on electromagnetic decays, e.g., η decay, $\Sigma^0 \rightarrow \Lambda^0 + e^+ + e^-$, etc..

In this note we consider T violating effects in electromagnetic production processes and their influence on measurable quantities. More specifically, we will show in some detail that polarization phenomena in the photoproduction of pions on nucleons are in general very sensitive to the presence of T violating terms in the production current.

However, to really provide a significant test of T invariance, one has to look for processes where the final state interactions are known or negligibly small. More precisely, the consequence of T invariance for photoproduction is Watson's theorem which, together with a dispersion-theoretical analysis, leads to the following conclusions.

In π^0 production

$$\gamma + p \rightarrow p + \pi^0 \quad (1.1)$$

a non-negligible, but poorly known imaginary part is present in the electric dipole amplitude. Therefore, π^0 production is not very useful for testing T invariance.

The situation is more promising in π^+ production

$$\gamma + p \rightarrow n + \pi^+ \quad (1.2)$$

where the imaginary part of the amplitude is up to the first resonance almost entirely determined by the rather well-known resonant scattering

phase shift. Furthermore, the work of Höhler and Schmidt ²⁾ and Müllensiefen ³⁾ shows that differential cross-sections and polarizations can, always assuming Watson's theorem, quite reliably be predicted from an amplitude consisting of the Born terms and the resonant magnetic dipole transition. As we will point out in Chapter 3, it is possible to exclude the main unknown in the π^+ amplitude, namely the electric quadrupole, by measuring the recoil neutron polarization at 90° in the centre of mass system using photons linearly polarized in the normal to the production plane.

Large deviations from these predictions should be regarded as indications of a T violation.

As long as we consider only one production process, nothing can be said about the isotopic structure of eventual T violating terms.

We would like to remark that T reversal violation in electromagnetic interactions, if it is responsible for the observed $K_2^0 \rightarrow 2\pi$ decay, must be quite strong. Thus, in the model of Ref. ¹⁾ one would expect large effects. Also in the model of Prentki and Veltman ⁴⁾ one would expect T violating effects, however they would be of the nature of a 10% or less perturbation on an electromagnetic process. In the latter case the I spin properties of the electromagnetic processes are unaffected, and one expects T violating effects in the $\Delta I = 0$ as well as in the $\Delta I = 1$ channels. In case that T is violated in electromagnetic interactions it is not a priori so that the I spin properties of the T violating part are identical with those of the T conserving part.

2. MODELS FOR A T VIOLATING PHOTOPRODUCTION CURRENT

We are going to discuss some simple models for the introduction of T violating (and, since we assume P and CPT invariance, C violating) terms in the photoproduction current.

The electromagnetic hadron current is split into two parts ¹⁾

$$J_\mu = j_\mu + k_\mu \quad (2.1)$$

where j_μ has the charge-conjugation property of the C conserving electromagnetic lepton current

$$C j_\mu C^{-1} = -j_\mu \quad (2.2)$$

whereas

$$C k_\mu C^{-1} = k_\mu \quad (2.3)$$

A non-vanishing k_μ , therefore, results in a C and T violation. As discussed by BFL, the current k_μ would manifest itself, e.g., in the transition matrix element $\langle \Lambda^0 | J_\mu | \Sigma^0 \rangle$ as complex form factors. Their relative phase determines the magnitude of T violating effects.

In photoproduction we are dealing, disregarding spin and isospin in this context, with a two-channel problem, the two channels being γN and πN .

For the n channel problem, T invariance implies that phases α_i of the channels can be chosen such that the $n \times n$ reduced S matrix ^{*)} $S_{J,P,\dots}$ becomes symmetric, i.e., there exists a diagonal matrix

^{*)} The S matrix is chosen to be diagonal with respect to the total angular momentum J, parity P, ... etc.

$$\varepsilon = \begin{pmatrix} e^{i\alpha_1} & & 0 \\ & e^{i\alpha_2} & \\ 0 & & e^{i\alpha_n} \end{pmatrix} \quad \alpha_i \text{ real} \quad (2.4)$$

such that for a general S matrix $S'_{J,P}$

$$S_{J,P} = \varepsilon^\dagger S'_{J,P} \varepsilon \quad (2.5)$$

is symmetric. Having achieved this symmetry for our 2-channel matrix, unitarity and the assumption that the Compton effect is given by the "diffraction" of photoproduction lead to Watson's theorem ⁵⁾

$$S_{J,P}^{\gamma N \rightarrow \pi N} = \pm i \left| S_{J,P}^{\gamma N \rightarrow \pi N} \right| e^{i \delta_{J,P}^{\pi N \rightarrow \pi N}} \quad (2.6)$$

Violation of T invariance, on the contrary, means that for all choices of phases α_i the matrix S in (2.5) is unsymmetric for at least some J,P,... and that therefore Watson's theorem is not valid for at least some partial waves.

A simple possibility of introducing T violation in photoproduction would be to discuss the measurable effects of an arbitrary phase of some of the multipoles $M_{E \pm}, E_{E \pm}$ ^{*)}. Estimates of their real parts could be obtained from dispersion theory ⁶⁾.

If Watson's theorem holds true, it is concluded from the experimentally determined πN phase shifts that the amplitude for $\gamma p \rightarrow n \pi^+$ is almost real below the first resonance if the resonant multipole is subtracted out. Therefore, a T violating ansatz is obtained by allowing for complex non-resonant CGLN amplitudes ⁷⁾ $A_1 \dots A_4$, conventionally defined by the following decomposition of the amplitude

*) We now include spin, the notation is that of CGLN ⁷⁾.

$$\begin{aligned}
M = & i\gamma_5 \gamma \cdot \varepsilon \gamma \cdot k_\gamma A_1 + 2i\gamma_5 (P \cdot \varepsilon q_\pi \cdot k_\gamma - P \cdot k_\gamma q_\pi \cdot \varepsilon) A_2 \\
& + \gamma_5 (\gamma \cdot \varepsilon q_\pi \cdot k_\gamma - \gamma \cdot k_\gamma q_\pi \cdot \varepsilon) A_3 \\
& + 2\gamma_5 (\gamma \cdot \varepsilon P \cdot k_\gamma - \gamma \cdot k_\gamma P \cdot \varepsilon - iM \gamma \cdot \varepsilon \gamma \cdot k_\gamma) A_4 \\
P = & \frac{1}{2} (p_{Ncl} + p'_{Ncl})
\end{aligned}
\tag{2.7}$$

More specifically, we use for the T conserving part of the A_i the ansatz

$$A_i^{cons} = A_i^{Born} + A_i^{Res} \tag{2.8}$$

The A_i^{Born} are calculated from the graphs

Fig. 1

and A_i^{Res} is the contribution of the $\frac{3}{2}, \frac{3}{2}$ resonance as derived by CGLN.

This ansatz predicts very well experimental differential cross-sections and the real parts of some multipoles determined from angular distributions as discussed by Höhler and Schmidt ²⁾ and Schmidt ⁶⁾.

6.

We now violate T invariance by adding purely imaginary (for physical values of s and t) functions $\tilde{A}_i(s,t)$ to the ansatz (2.8) such that the results of Ref. 2) are altered only within the experimental errors (the real parts of the multipoles are obviously not changed by this procedure). The point is, as we will see in the next Chapter, that predictions on polarization phenomena strongly depend on such an alteration and therefore are sensitive to T violating effects.

At present, there is nothing, except experiment, which could teach us the s and t dependence of these functions $\tilde{A}_i$. However, for low energies, it might not be too unreasonable to treat them in a pole approximation.

We write

$$\tilde{A}_i(s,t) = (g_i - g_i^*) \left\{ \frac{1}{s - m_{\text{pole}}^2} + \frac{1}{u - m_{\text{pole}}^2} \right\} + (g_i - g_i^*) \frac{1}{t - m_{\text{pole}}^2} \quad (2.9)$$

The sign in the brackets is dictated by crossing properties. For simplicity m_{pole}^2 and $m_{\text{pole}}'^2$ are chosen to be real and outside the physical region

$$\frac{-m_\pi^3}{m_N + m_\pi} + (m_N - m_\pi)^2 < m_{\text{pole}}^2 < m_N^2$$

or

$$m_N^2 < m_{\text{pole}}^2 < (m_N + m_\pi)^2 \quad (2.10)$$

and

$$m_{\text{pole}}'^2 > m_\pi^2$$

or

$$m_{\pi}^2 > m_{\text{pole}}^2 > -\frac{m_{\pi}^2 m_N}{m_N + m_{\pi}}$$

Certainly, the $\tilde{A}_i(s, t)$ do not have a pole at $s, u = m_N^2$ and $t = m_{\pi}^2$, because this would mean the introduction of complex charges and magnetic moments.

An even simpler ansatz would be to take constant T violating amplitudes instead of pole terms

$$\tilde{A}_i(s, t) = c_i = \text{const} \quad (2.11)$$

which can be visualized in terms of the following T violating gauge invariant contact Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & C_1' \bar{\psi}_N \gamma_5 \sigma_{\mu\nu} F_{\mu\nu} \psi_N \phi_{\pi} + C_2' \bar{\psi}_N \gamma_5 \gamma_{\mu} F_{\mu\nu} \psi_N (\partial_{\nu} \phi_{\pi}) \\ & + C_3' \bar{\psi}_N \gamma_5 F_{\mu\nu} (\partial_{\mu} \psi_N) (\partial_{\nu} \phi_{\pi}) + C_4' \bar{\psi}_N \gamma_5 \gamma_{\mu} F_{\mu\nu} (\partial_{\nu} \psi_N) \phi_{\pi} \end{aligned} \quad (2.12)$$

Terms of this kind, however, result in a dramatic energy dependence of differential cross-sections and therefore can only be used in a small energy interval.

By the very choice (2.7) of the amplitudes, all proposed procedures are automatically gauge invariant.

As emphasized by BFL, the concept of minimal coupling is not well defined since the hadron Lagrangian is not at all known. Even if it were defined in a certain model, T violation in the electromagnetic hadron current results in a non-minimal coupling of the photon if strong interactions conserve T . Therefore, the usually introduced amplitudes $A^{(\pm)}$ and $A^{(0)}$ may not be sufficient to describe the photoproduction of pions on nucleons. Non-minimality might be due to an isotensor coupling of the photon. The photoproduction amplitude is then written

8.

$$A = A^{(*)} \delta_{\alpha 3} + A^{(-)} \frac{1}{2} [\tau_{\alpha}, \tau_3] + A^{(0)} \tau_{\alpha} + A^{(2)} (3 \delta_{\alpha 3} \tau_3 - \tau_{\alpha}) \quad (2.13)$$

where $A^{(2)}$ describes the isotensor transition to an isospin $\frac{3}{2}$ final state. The relation

$$6\sqrt{2} A^{(2)} = \sqrt{2} (A_{\gamma p \rightarrow \pi^0 p} - A_{\gamma n \rightarrow \pi^0 n}) - (A_{\gamma p \rightarrow \pi^+ n} + A_{\gamma n \rightarrow \pi^- p}) \quad (2.14)$$

is, of course, not easy to check experimentally.

3. NUMERICAL CALCULATIONS

Two important questions remain to be discussed. First of all, we have to estimate possible errors in the theoretical prediction of polarizations under the assumption of Watson's theorem, i.e., T invariance. Then we have to investigate deviations from these predictions if "strong" T violating terms are present.

In the energy range $E_\gamma = 200 \dots 300$ MeV, the main unknown ^{2),3),6)} in the dispersion theory of π^+ production is the electric quadrupole transition $E_{1+}^{\pi+}$. The Born approximation estimate, which works very well ⁶⁾ for the real parts of the electric dipole $E_{0+}^{\pi+}$ and the magnetic dipole $M_{1-}^{\pi+}$, tells us that

$$|E_{1+}^{\pi+}| \leq \frac{1}{3} |M_{1+}^{\pi+}| \quad (3.1)$$

From Watson's theorem and experimental πN phase shifts the imaginary part of $E_{0+}^{\pi+}$ is found to be very small; $\text{Im } M_{1-}^{\pi+}$ also contributes very little to the error in polarizations ⁸⁾. Leaving $E_{1+}^{\pi+}$ completely unknown, the estimate (3.1) leads to an error of maximal 50% for the polarization of recoil neutrons produced by unpolarized photons on an unpolarized target at an energy $E_\gamma = 250$ MeV and $\theta_{\text{c.m.s.}} = 90^\circ$ ⁸⁾.

A much more favourable quantity to measure is the polarization P_{yy} (see the Appendix) of recoil neutrons produced by photons polarized perpendicularly to the reaction plane.

At $\theta_{\text{c.m.s.}} = 90^\circ$, this quantity is given by

$$P_{yy} = 2 \text{Im} [(2M_{1+}^{\pi+} + M_{1-}^{\pi+}) \mathcal{F}_1^*] \quad (3.2)$$

where $\mathcal{F}_1$ contains only $E_{0+}^{\pi+}$ and multipoles with $\ell \geq 2$ ^{*)}. Furthermore, errors in $M_{1-}^{\pi+}$ are suppressed due to the factor 2 in front of $M_{1+}^{\pi+}$.

*) It can be seen from the multipole decomposition ⁷⁾ of $\mathcal{F}_1$, defined in the Appendix, that at $\theta_{\text{c.m.s.}} = 90^\circ$ the multipoles M_{1+} and E_{1+} do not contribute to $\mathcal{F}_1$.

Assuming higher multipoles to be given by the Born approximation which is reasonable in our energy range and taking Schmidt's ⁶⁾ result for $E_{0+}^{\pi+}$, we conclude that the error in P_{yy} should be about that of the resonant phase shift α_{33} .

Next we are going to describe numerical estimates of T violation effects using the model of Chapter 2. We shall choose the residue in Eq. (2.10) as large as possible such that we change the angular distribution only within the experimental errors when adding the $\tilde{A}_i$ to the T conserving amplitude (2.8). It will then be seen that T violating effects can change polarizations much more than the expected theoretical errors so that their measurement seems to be a feasible way of detecting T violation.

We do not attempt to consider the question of defining a maximal T violation. It is, however, possible with a special choice of the constants in (2.10) to visualize its magnitude by comparing the residue of the $\tilde{A}_i$ with the residue of the Born terms

$$\begin{aligned}
 A_1^{\pi+} &= \frac{C}{s - m_N^2} \\
 A_2^{\pi+} &= - \frac{2}{t - m_\pi^2} \frac{C}{s - m_N^2} \\
 A_3^{\pi+} &= \frac{C' \mu_n}{u - m_N^2} - \frac{C' \mu_p}{s - m_N^2} \\
 A_4^{\pi+} &= - \frac{C' \mu_n}{u - m_N^2} - \frac{C' \mu_p}{s - m_N^2}
 \end{aligned} \tag{3.3}$$

where μ_p, μ_n are the anomalous proton and neutron magnetic momenta and

$$C = 2 m_N C' = 8\pi \sqrt{2} m_N e f \tag{3.4}$$

The residues in the $\tilde{A}_i$ are chosen such that the T violating terms have, except for poles in the t channel the same structure as the Born terms

$$\begin{aligned}
 \frac{1}{2} \tilde{A}_1^{\pi^+} &= \frac{a_1 C}{s - m_{Pole}^2} + \frac{b_1 C}{t - m_{Pole}^2} \\
 \frac{1}{2} \tilde{A}_2^{\pi^+} &= \frac{a_2 C}{s - m_{Pole}^2} + \frac{b_2 C}{t - m_{Pole}^2} \\
 \frac{1}{2} \tilde{A}_3^{\pi^+} &= \frac{c' a_3}{u - m_{Pole}^2} - \frac{c' a_4}{s - m_{Pole}^2} + \frac{c' b_3}{t - m_{Pole}^2} \\
 \frac{1}{2} \tilde{A}_4^{\pi^+} &= - \frac{c' a_3}{u - m_{Pole}^2} - \frac{c' a_4}{s - m_{Pole}^2} + \frac{c' b_4}{t - m_{Pole}^2}
 \end{aligned} \tag{3.5}$$

Results for several values of the a_i and b_i are displayed in Figs. 2-3 and Tables 1-2. They may serve as an illustration of the points mentioned above. It should be emphasized that the values of the a_i and b_i chosen for our curves and Tables correspond, according to the above-mentioned criterium, to a relatively "small" T violation. Nevertheless, the changes in the polarizations are outside the expected theoretical errors of the HS curves, if the energies and angles are appropriately chosen. A measurement of P_u, P_{xy}, P_{yy} for some centre of mass system angles in the energy range $E_\gamma = 200 \dots 250$ MeV would significantly test T invariance.

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A P P E N D I X

SOME FORMULAE

In this Appendix we collect some formulae concerning polarization phenomena in pion photoproduction. We write the centre of mass amplitude in the conventional form

$$\mathcal{F} = i \vec{\sigma} \cdot \vec{\varepsilon} \mathcal{F}_1 + \vec{\sigma} \cdot \vec{q} \vec{\sigma} \cdot \vec{k} \times \vec{\varepsilon} \mathcal{F}_2 + i \vec{\sigma} \cdot \vec{k} \vec{q} \cdot \vec{\varepsilon} \mathcal{F}_3 + i \vec{\sigma} \cdot \vec{q} \vec{q} \cdot \vec{\varepsilon} \mathcal{F}_4 \quad (\text{A.1})$$

where $\vec{\varepsilon}$ is the photon polarization vector, $\vec{q}$ and $\vec{k}$ are the centre of mass momenta in the final and initial states, $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ are the Pauli matrices; the $\mathcal{F}_i$ depend on the centre of mass energy $\sqrt{s}$ and the scattering angle θ . Inserting different polarization vectors, the amplitude $\mathcal{F}$ is written in the following way [the reaction plane is taken to be the x-z plane of a right-handed co-ordinate system (x,y,z)]:

photons linearly polarized in x direction: $\vec{\varepsilon}_x = (1, 0, 0)$

$$\mathcal{F}_{\varepsilon_x} = i \begin{pmatrix} H_1 & H_2 \\ H_2 & -H_1 \end{pmatrix} \quad (\text{A.2})$$

photons linearly polarized in y direction: $\vec{\varepsilon}_y = (0, 1, 0)$

$$\mathcal{F}_{\varepsilon_y} = \begin{pmatrix} -H_3 & H_4 \\ -H_4 & -H_3 \end{pmatrix} \quad (\text{A.3})$$

circularly polarized photons : $\vec{\varepsilon}_+ = \frac{1}{\sqrt{2}} (-1, -i, 0)$

$$\mathcal{F}_{\varepsilon_+} = \frac{i}{\sqrt{2}} \begin{pmatrix} H_3 - H_1 & -H_4 - H_2 \\ H_4 - H_2 & H_1 + H_3 \end{pmatrix} \quad (\text{A.4})$$

and

$$\vec{\varepsilon}_- = \frac{1}{\sqrt{2}} (1, -i, 0)$$

$$\mathcal{F}_{\varepsilon_-} = \frac{i}{\sqrt{2}} \begin{pmatrix} H_1 + H_3 & H_2 - H_4 \\ H_2 + H_4 & H_3 - H_1 \end{pmatrix} \quad (\text{A.5})$$

where

$$\begin{aligned} H_1 &= \mathcal{F}_2 \sin \theta + (\mathcal{F}_3 + \cos \theta \mathcal{F}_4) \sin \theta \\ H_2 &= \mathcal{F}_4 \sin^2 \theta + \mathcal{F}_1 - \cos \theta \mathcal{F}_2 \\ H_3 &= \mathcal{F}_2 \sin \theta \\ H_4 &= \mathcal{F}_1 - \mathcal{F}_2 \cos \theta \end{aligned} \quad (\text{A.6})$$

The density matrices for the final nucleons and unpolarized target nucleons are now calculated :

$$\mathcal{F}_{\varepsilon_x} \mathcal{F}_{\varepsilon_x}^+ = w_x + P_{yx} \sigma_y \quad (\text{A.7})$$

$$\mathcal{F}_{\varepsilon_y} \mathcal{F}_{\varepsilon_y}^+ = w_y + P_{yy} \sigma_y \quad (\text{A.8})$$

$$\mathcal{F}_{\varepsilon_+} \mathcal{F}_{\varepsilon_+}^+ = \frac{w_x + w_y}{2} + P_x \sigma_x + \frac{1}{2} (P_{xy} + P_{yx}) \sigma_y + P_z \sigma_z \quad (\text{A.9})$$

$$\mathcal{F}_{\varepsilon_-} \mathcal{F}_{\varepsilon_-}^+ = \frac{w_x + w_y}{2} - P_x \sigma_x + \frac{1}{2} (P_{xy} + P_{yx}) - P_z \sigma_z \quad (\text{A.10})$$

The quantities w_x and w_y are up to a factor q/k the cross-sections for pion production by in x and y direction linearly polarized photons ; polarizations of the recoil nucleons are usually defined by the P 's divided by the corresponding cross-section. Explicitly one finds

$$w_x = |\tilde{f}_1|^2 + |\tilde{f}_2|^2 + \sin^2 \theta |\tilde{f}_3|^2 + \sin^2 \theta |\tilde{f}_4|^2 \\ + 2 \sin^2 \theta \operatorname{Re} (\tilde{f}_1 \tilde{f}_4^* + \tilde{f}_2 \tilde{f}_3^* + \cos \theta \tilde{f}_3 \tilde{f}_4^*) \\ - 2 \cos \theta \operatorname{Re} (\tilde{f}_1 \tilde{f}_2^*) \quad (\text{A.11})$$

$$w_y = |\tilde{f}_1|^2 + |\tilde{f}_2|^2 - 2 \cos \theta \operatorname{Re} (\tilde{f}_1 \tilde{f}_2^*) \quad (\text{A.12})$$

$$P_{xy} = 2 \sin \theta \operatorname{Im} (\tilde{f}_1 \tilde{f}_2^* + \tilde{f}_1 \tilde{f}_3^* + \cos \theta (\tilde{f}_1 \tilde{f}_4^* - \tilde{f}_2 \tilde{f}_3^*) \\ - \tilde{f}_2 \tilde{f}_4^* + \sin \theta \tilde{f}_4 \tilde{f}_3^*) \quad (\text{A.13})$$

$$P_{yy} = 2 \sin \theta \operatorname{Im} (\tilde{f}_1 \tilde{f}_2^*) \quad (\text{A.14})$$

$$P_x = \sin \theta \operatorname{Re} (2 \cos \theta |\tilde{f}_2|^2 - 2 \tilde{f}_1 \tilde{f}_2^* - \tilde{f}_1 \tilde{f}_3^* \\ + (\cos^2 \theta - \sin^2 \theta) (\tilde{f}_2 \tilde{f}_4^*) + \cos \theta (\tilde{f}_2 \tilde{f}_3^* - \tilde{f}_1 \tilde{f}_4^*)) \quad (\text{A.15})$$

$$P_z = |\tilde{f}_1|^2 + (\cos^2 \theta - \sin^2 \theta) |\tilde{f}_2|^2 \\ - 2 \cos \theta \operatorname{Re} (\tilde{f}_1 \tilde{f}_2^* + \sin^2 \theta \tilde{f}_2 \tilde{f}_4^*) \\ + \sin^2 \theta \operatorname{Re} (\tilde{f}_1 \tilde{f}_4^* - \tilde{f}_2 \tilde{f}_3^*) \quad (\text{A.16})$$

In order to measure P_{xy} and P_{yy} one can either measure the final nucleon polarization (A.7), (A.8) or use polarized target nucleons : the density matrix for the target polarized in y direction is

$$\tilde{T}_{\varepsilon_x} G_y \tilde{T}_{\varepsilon_x}^+ = P_{xy} \quad (A.17)$$

$$\tilde{T}_{\varepsilon_y} G_y \tilde{T}_{\varepsilon_y}^+ = P_{yy} \quad (A.18)$$

In principle, a seventh independently measurable quantity exists ; its experimental determination would require the detection of polarization correlations with polarized target nucleons and circularly polarized photons.

T A B L E 1

		HS	T_1	T_2	T_4	S_1	S_2
$E_\gamma = 225 \text{ MeV}$	$\theta_{\text{c.m.s.}} = 0^\circ$	10.0	10.1	10.0	10.0	10.0	10.0
	45°	10.5	10.5	10.5	10.5	10.5	10.6
	90°	16.7	16.8	16.7	16.7	16.8	16.9
	135°	18.0	17.9	18.0	18.0	18.1	18.1
	180°	17.1	17.0	17.1	17.2	17.2	17.1
$E_\gamma = 320 \text{ MeV}$	0°	15.6	16.9	15.6	15.4	14.3	15.6
	45°	18.7	19.5	17.9	18.2	17.9	19.6
	90°	28.1	28.1	27.0	27.8	28.2	30.3
	135°	23.3	22.8	22.9	24.2	24.2	24.6
	180°	17.4	16.7	17.4	19.0	18.5	17.4

Differential cross-sections calculated from the amplitudes (2.8) and (3.5). A factor k/q is taken out.

HS : prediction from (2.8)

T_1 : t channel pole in A_1 only ;

T_2 : t channel pole in A_2 only ;

T_4 : t channel pole in A_4 only ;

S_1 : s and u channel pole in A_1 only ;

S_2 : s and u channel pole in A_2 only ;

$$b_1 = 0.1$$

$$b_2 = 0.1$$

$$b_4 = 0.6$$

$$a_1 = 0.1$$

$$a_2 = 0.1$$

$$m_{\text{pole}}^2 = 42m_\pi^2$$

$$m_{\text{pole}}^2 = 36m_\pi^2$$

T A B L E 2

		$\theta_{\text{c.m.s.}} = 0^\circ$	45°	90°	135°	180°
$E_\gamma = 225 \text{ MeV}$	HS	0.0	6.9%	6.8%	4.0%	0.0
	S_2	0.0	2.7%	-1.4%	-4.4%	0.0
	T_2	0.0	9.6%	12.5%	9.5%	0.0
250 MeV	HS	0.0	17.4%	14.2%	8.2%	0.0
	S_2	0.0	12.5%	4.9%	-1.9%	0.0
	T_2	0.0	21.2%	20.1%	15.5%	0.0

Polarization P_u of recoil neutrons produced by unpolarized photons. This polarization is particularly sensitive to changes in the amplitude A_2 which are therefore reproduced here. For definitions see Table 1.

R E F E R E N C E S

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FIGURE CAPTIONS ---

Figure 1 : Polarization of recoil neutrons produced by photons linearly polarized in x direction (for definitions see the Appendix) ; P_{xy} at 90° in the centre of mass system is plotted as a function of the photon lab. energy E_γ . The notation is given in Table 1.

Figure 2 : The same plot for P_{yy} , the polarization of recoil neutrons produced by photons polarized perpendicularly to the reaction plane. Since P_{yy} does not depend on the amplitude A_2 containing the photoelectric term, only the curves HS, T_1, T_4 and S_1 (same notation as in caption 1) are plotted.

Fig. 2

Fig. 3