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OF POLARIZATION OF HIGH ENERGY PROTONS

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ABSTRACT

We examine polarization phenomena in small momentum transfer high energy one-photon exchange processes in the reaction $p+A \rightarrow X+A$ where A is a complex nucleus and X is anything. We show that these polarizations can be related directly to photoproduction polarization effects in the reaction $\gamma+p \rightarrow X$ at low energies. We write explicit formulae for polarization effects in the case where $X \rightarrow \pi^0 + p$.

INTRODUCTION

It has been suggested⁽¹⁾ that the polarization of high energy proton beams may be measured utilizing photo-production data at low energies, for example in the region of energies where one produces the Δ resonance. This is possible since the process

$$p+A \rightarrow X+A \quad (1)$$

initiated by one photon exchange, the Primakoff effect,⁽²⁾ has a strong forward peak and actually can become dominant over strong interactions for a heavy target nucleus A at small momentum transfers. X is anything that can be made by one photon exchange. Given that X is the Δ resonance the dominance of one photon exchange at small angles has been established experimentally.⁽³⁾

We will show below that the process (1) carries identical polarization information to that obtained from the reaction

$$\gamma+p \rightarrow X. \quad (2)$$

For example, if the target proton is polarized the decay

$$X \rightarrow a+b \quad (3)$$

will show typical azimuthal asymmetry and this is identical to the asymmetry that will be found in the decay of X in reaction (1) viewed in the Jackson frame if the incident high energy proton is polarized.

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DERIVATION OF RESULTS

Figure 1 shows the Feynman graph for the one-photon exchange process

$$p + A \rightarrow X + A \rightarrow a + b \quad (4)$$

The amplitude for this process may be written in the form

$$A = (Q_1 + Q_2)^\mu M_\mu \frac{Ze}{k^2} F(k^2) \quad (5)$$

where M_μ is the current carried by the upper line $p \rightarrow X \rightarrow a+b$, and $F(k^2)$ is the form factor for the nucleus. It is advantageous for us to work in the rest frame of X in order to relate our results to photoproduction of X on polarized proton targets.

Fig.1. One photon exchange for process (4) with the kinematical variables indicated. The invariants are $Q_1^2 = Q_2^2 = M^2$, $p_2^2 = m^2$, $p^2 = s_1$, $q^2 = \mu^2$ and $k^2 = (Q_1 - Q_2)^2$.

It follows from gauge invariance that

$$k^\mu M_\mu = 0. \quad (6)$$

Choosing a coordinate system in the rest frame of X as in Figure 2 we then find that

$$A = 2Q_1^\mu M_\mu \frac{Ze}{k^2} F(k^2) \approx -\frac{Ze}{k^2} F(k^2) \frac{2Mp_L}{\sqrt{s_1}} \left\{ \frac{\sqrt{s_1}}{mv} \underline{p}_1 \cdot \underline{M}_1 - \left(\frac{s_1}{2} + \frac{s_1 p_1^2}{2v^2} \right) M_{||} \right\} \quad (7)$$

$$\approx -\frac{Ze}{k^2} F(k^2) \frac{2Mp_L}{mv} \vec{p}_\perp \cdot \vec{M}_\perp$$

under the condition

$$s_1/p_L^2 \ll \frac{\sqrt{s_1} p_L}{mv} . \quad (8)$$

The quantity ν is the photon energy in the frame in which X is at rest, $p_\perp$ is the transverse component of $\vec{p}$, the 3-momentum of X in the c.m. frame of the reaction (4), p_L is the proton laboratory momentum, m is the proton mass and s_1 the mass of X .

Fig.2. Coordinate system in the rest frame of X .

We can then write the differential cross section for the reaction (4) as

$$\begin{aligned} \frac{d\sigma}{ds_1 dk^2 dt} &= \frac{1}{2\lambda^{\frac{1}{2}}(s, m^2, M^2)} \frac{1}{(2\pi)^5} \int d^4q d^4p_2 d^4Q_2 \delta(q^2 - \mu^2) \delta(p_2^2 - m^2) \\ &\delta(Q_2^2 - M^2) \delta[s_1 - (p_2 + q)^2] \delta[t - (p_2 - p_1)^2] \delta[k^2 - (Q_1 - Q_2)^2] \quad (9) \\ &\delta^4(p_2 + Q_2 + q - p_1 - q_1) |A|^2 \end{aligned}$$

One finds then from (9)

$$\frac{d\sigma}{ds_1 dk^2 dt d\phi} = \frac{\pi}{16\lambda(s, m^2, M^2) \lambda^{\frac{1}{2}}(s_1, k^2, m^2)} \frac{1}{(2\pi)^5} |A|^2 , \quad (10)$$

Here ϕ is the azimuthal angle of particle a or b in the frame in which X is at rest measured say relative to the polarization

vector of the incident photon having momentum k as in Figure 3. As seen in (7), the photon is indeed polarized with polarization tensor $\hat{\epsilon}_T = \hat{p}_1$ given by the direction of $\underline{p}_1$. We can write (10) in terms of the cross section for the photoproduction of X ,

$$\gamma + p \rightarrow X \rightarrow a + b \quad (11)$$

since this is given by

$$\frac{d\sigma(\gamma p \rightarrow a + b)}{dtd\phi} = \frac{1}{32\pi^2} \cdot \frac{1}{\lambda(s_1, 0, m^2)} |\hat{\epsilon}_T \cdot M_T|^2 \quad (12)$$

The current M^μ being as in (5) with $\hat{\epsilon}_T$ the polarization of the incident photon. We have then

$$\frac{d\sigma}{ds_1 dk^2 dtd\phi} = \frac{Z^2 \alpha}{\pi} \frac{p_1^2}{\lambda^{\frac{1}{2}}(s_1, m^2, k^2)} \frac{|F(k^2)|^2}{k^4} \frac{d\sigma(\gamma p \rightarrow ab)}{dt d\phi} \quad (13)$$

For the case where X decays into a pion of four momentum q and a nucleon of four momentum p_2 , we can write the c.m. differential cross section for photoproduction by photons of momentum k , polarization $p_Y = \epsilon$ at an angle to the photoproduction plane ϕ , incident on

Fig.3. Coordinate system in rest frame of X showing definition of ϕ .

a nucleon of four momentum p_1 and polarization $\vec{s}$ (see Figure 3) as (4)

$$\begin{aligned} d\sigma(\gamma p_Y \rightarrow \pi^0 p) = d\sigma(\theta) \{ & 1 - \Sigma(\theta) p_Y \cos 2\phi + T(\theta) s_y - H(\theta) s_x p_Y \sin 2\phi \\ & - P(\theta) s_y p_Y \cos 2\phi + G(\theta) s_z p_Y \sin 2\phi \} . \end{aligned} \quad (14)$$

Here $d\sigma(\theta)$ is the unpolarized photoproduction cross section, the asymmetries $\Sigma(\theta)$ and $T(\theta)$ are the single polarization coefficients. The polarization of the recoil nucleon $P(\theta)$, $H(\theta)$ and $G(\theta)$ occur in (14) as double polarization coefficients. Expressions for the above quantities are as follows.⁽⁴⁾ Given H_1, H_2, H_3 and H_4 the complex s-channel helicity amplitudes in the notation of Walker⁽⁵⁾

$$d\sigma(\theta) = \frac{1}{2} \frac{q}{k} \left\{ |H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2 \right\} \quad (15)$$

$$P(\theta) = -\frac{q}{k} \frac{1}{d\sigma(\theta)} \operatorname{Im}(H_1 H_3^* + H_2 H_4^*) \quad (16)$$

$$\Sigma(\theta) = \frac{d\sigma_{\perp} - d\sigma_{\parallel}}{d\sigma_{\perp} + d\sigma_{\parallel}} = \frac{q}{k} \frac{1}{d\sigma(\theta)} \operatorname{Re}(H_1 H_4^* + H_2 H_3^*) \quad (17)$$

where $d\sigma_{\perp}$ and $d\sigma_{\parallel}$ are the cross sections for complete polarization perpendicular and parallel to the photoproduction plane, the target proton being unpolarized.

Given target nucleons polarized in the direction perpendicular to the plane of production and unpolarized photons

$$T(\theta) = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{q}{k} \frac{1}{d\sigma(\theta)} \operatorname{Im}(H_1 H_2^* + H_3 H_4^*) \quad (18)$$

where $d\sigma^{\uparrow}$ and $d\sigma^{\downarrow}$ are the cross sections for meson production from nucleons polarized up and down in the direction $\vec{k} \times \vec{q}$. Finally,

$$H(\theta) = -\frac{q}{k} \frac{1}{d\sigma(\theta)} \operatorname{Im}(H_1 H_3^* - H_2 H_4^*) \quad (19)$$

$$G(\theta) = -\frac{q}{k} \frac{1}{d\sigma(\theta)} \operatorname{Im}(H_1 H_4^* - H_2 H_3^*) \quad (20)$$

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