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Photon-Nucleus Collisions and the Relative Phase Between the $\gamma + p \to \pi^0 + p$ and $\rho_0 + p \to \pi^0 + p$ Amplitudes

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Abstract

The photoproduction of neutral pions with nuclear targets at photon energies in which experimental data are available ($E_{\gamma_{Lab}} \leq 8.7$ GeV, $.1 \leq -t \leq .25$ $(\text{GeV}/c)^2$) is analyzed within the framework of Glauber theory. In our approach the quantity $A_{eff} \equiv \dfrac{\sigma(\gamma A \to \pi^0 A)}{\sigma(\gamma N \to \pi^0 N)}$ depends essentially on the ratio $\dfrac{A_{\rho_0 N \to \pi^0 N}}{A_{\gamma N \to \pi^0 N}} \equiv \left|\dfrac{A_{\rho_0 N \to \pi^0 N}}{A_{\gamma N \to \pi^0 N}}\right| e^{i\phi}$. As the moduli of these amplitudes are known experimentally, from the nuclear data one may extract the value of ϕ. It is found a value $\phi \approx -(20^\circ - 35^\circ)$ in variance with VMD predictions $(\phi = 0)$.

I. Introduction

Due to the spatial proximity between production and rescattering in nuclear matter, it is possible to extract information on the scattering amplitudes of unstable, very short lived systems. That was the case for the ρN , ωN and ϕN cross-sections [1].

The nuclear "microlaboratory" may also be used as interferometer in order to measure the relative phase between different scattering amplitudes. From the interference between processes which take place in the nucleus via different number of states, information on the relative phase between different elementary amplitudes may be obtained. In that sense we may quote the extraction of the ratio between the real and the imaginary part of the elastic ρN [1,2] and ϕN [1,3] scattering amplitudes. As an additional example we may mention the study of Cocho et al. [4] on the disappearance of the shadowing (and the possible appearance of antishadowing) in the collision of virtual, space-like photons with heavy nuclei as the square invariant momentum transfer Q^2 of the virtual photon increases. In this analysis the virtual photon + nucleon $\rightarrow$ rho + nucleon production amplitude ($``\gamma" + N \rightarrow \rho + N$) plays an essential role. The energy dependence of this cross-section changes very fast, as Q^2 increases (from zero (real photons) to $2\left(\frac{\text{Gev}}{c}\right)^2$). Reggeology suggests that this change in the energy behaviour of the modulus of the amplitude be correlated with a change in the phase. It was shown that a parametrization of the $``\gamma" + N \rightarrow \rho + N$ forward scattering amplitude including the phase suggested by Reggeology allowed to fit rather well the shadowing data. One may consider such analysis of the shadowing in heavy nuclei as a "measure" of the $Q^2$ dependence of the phase of the $``\gamma" + N \rightarrow \rho^0 + N$ scattering amplitude.

In this paper we present a similar analysis of the photoproduction of neutral pions in medium and heavy nuclei. We consider the data of the Cornell group [5]; the photon energy E_γ used is $3.2 \lesssim E_\gamma \lesssim 8.6$ (GeV) and the momentum transfer t, $.1 \lesssim -t \lesssim .25$ $(\mathrm{GeV/c})^2$.

The experimental data are given in table I. The quantity presented is A_{eff} , that is the ratio between the measured cross-section and A times the cross section for the photoproduction of neutral pions off single nucleons, with A the atomic number of the nuclear target.
One significant feature of the data is that although A_{eff} decreases when the photon energy increases this decrease is smaller than the one predicted by Glauber theory [6] if the $\gamma + N \to \pi^0 + N$ and $\rho_0 + N \to \pi^0 + N$ amplitudes are related by vector meson dominance (VMD). In their analysis the authors of the Cornell experiment [5] need $A_{\rho_0 N \to \pi^0 N} / A_{\gamma N \to \pi^0 N}$ to be four times smaller than the VMD prediction in order to fit the data. In this Glauber approach, in the "optical model" language of Gottfried and Yennie [6], the photoproduction of pions off nuclei occurs via the interference between the, so called, one and two steps processes. In the one step process the photon interacts with a nucleon of the target and produces a pion which is rescattered or absorbed by other nucleons before leaving the target. In the two-step process the γ produces a vector meson which propagates and interacts with other nucleons before being converted into a pion which may interact or being absorbed before leaving the nucleus. As it was emphasized by Gottfried and Yennie [6], given a photon energy E_γ , the contribution of a vector meson V will be small if the quantity $m_V^2 / \rho E_\gamma \sigma^T_{VN}$ is much smaller than one. (m_V is the mass of the vector meson, σ^T_{VN} is the vector meson-nucleon total cross-section and ρ is the nuclear density).

In the energy range of the Cornell experiment one expects the contribution from vector mesons with masses larger than 1 GeV to be small and the main contribution to the two step process to come from the ρ_0, ω and ϕ. However, only isospin T = 1 exchange contributes to the $\omega N \to \pi^0 N$ and $\phi N \to \pi^0 N$ amplitudes, they have opposite sign on protons and neutrons and almost cancel on nuclear targets. (This comment also holds for the T = 1 exchange part of the $\gamma N \to \pi^0 N$ amplitude). These observations allow us to take in the analysis only the contribution of the ρ_0 meson. Therefore, the relevant elementary amplitudes will be $A_{\gamma N \to \pi^0 N}$ and $A_{\pi^0 N \to \pi^0 N}$ for the one step process, and $A_{\gamma N \to \pi^0 N}$, $A_{\rho_0 N \to \rho_0 N}$, $A_{\rho_0 N \to \pi^0 N}$ and $A_{\pi^0 N \to \pi^0 N}$ for the two step process.

Experimentally, the nonflip amplitudes dominate $\gamma N \to \rho_0 N$, $\pi^0 N \to \pi^0 N$, $\rho_0 N \to \rho_0 N$. The single flip, natural parity exchange amplitude dominates $\gamma N \to \pi^0 N$ and $\rho_0 N \to \pi^0 N$. These imply that only one independent amplitude controls each reaction.

As it is discussed later, one of the main parameters of the analysis is the ratio

$$B \equiv \frac{e}{2\gamma_\rho} \frac{A_{\rho^0 N \to \pi^0 N}}{A_{\gamma N \to \pi^0 N}} \quad \text{where } \frac{e}{2\gamma_\rho} \text{ is the photon-rho coupling constant} \qquad (1)$$

VMD suggests that B is real and $\simeq 1$. Meyer et al. [5] have shown that instead of B = 1, a value of B = 0.25 is needed to fit the data [5] if B is assumed to be real.

However, the experiments [17,18] show $|B| \sim .7$ in conflict with the experimental value of A_{eff} if B is real. On the other hand, if VMD is not obeyed, it is not clear why B might be real. As a matter of fact, the $\gamma N \to \pi^0 N$ and $\rho_0 N \to \pi^0 N$ cross-sections show different energy behaviour and in the spirit of Reggeology one would expect phases different for each process. Indeed, the recent analysis of Barker et al. [7] suggests for the $\gamma N \to \pi^0 N$ amplitudes a different phase from the one due to the exchange of the ω-trajectory which seems to dominate the $\rho_0 N \to \pi^0 N$ amplitudes [8].

In this paper we will define $B = |B| e^{i\phi}$, take $|B|$ from the experimental data [17,18] and compute A_{eff} as a function of ϕ. We will find that the analysis implies $\phi \neq 0$. We find a value $\phi \simeq -(20^o - 35^o)$ (in $-t \approx .15$ $(GeV/c)^2$) in agreement with the analysis of Barker et al. [7] for $\gamma N \to \pi^0 N$ (assuming the existence of such a phase à la Regge).

In section II, we present the optical approach to Glauber theory and stress the main feature of the elementary particle amplitudes which enter in the analysis.

In section III, we discuss the parametrization of these elementary amplitudes and compute the value of ϕ.

A few remarks on these numerical results are presented in section IV.

II. Nuclear formalism and elementary amplitudes

In this section we present the features of the nuclear Glauber formalism that we need in the computation and discuss the relevant features of the elementary particle amplitudes which enter into the analysis.

As it was discussed in the introduction we are concerned with the effective nucleon number A_{eff} , which is defined as the ratio between the cross-section of photoproduction in a nuclear target containing A nucleons and photoproduction from a single nucleon.

To describe the interaction of high energy photons with nuclei to produce π^{o}, we add the one-step and the two-step contributions. We follow Gottfried and Yennie (6) to write the amplitude for creation of a pion at a point (b, z) (b is the impact parameter) inside a nucleus:

$$F = F(\text{one-step}) + F(\text{two-step})$$

$$\simeq \eta^{-1} e^{-\frac{\sigma_{\pi N}}{2} T(b,z)} A_{\gamma N \to \pi N} \left\{ 1 + i\xi + B\left[e^{-\frac{\sigma_{\rho N}}{2}(1-i\alpha_{\rho N})\eta T(b,-z)} - 1 \right] \right\} \quad (2)$$

In this expression $\sigma_{\pi N}$ and $\sigma_{\rho N}$ are the total π^{o}-nucleon and ρ_{o}-nucleon cross-sections. B is defined in (1); this parameter would be real and equal to one if the amplitudes $A_{\rho_o N \to \pi^{o} N}$ and $A_{\gamma N \to \pi^{o} N}$ were related by VMD.

$$\xi = \frac{m_{\rho}^{2}}{k \rho\, \sigma_{\rho N}(1 - i\alpha_{\rho N})} \quad , \qquad (3)$$

where $\alpha_{\rho N}$ is the ratio of real to imaginary parts of the forward ρ_c-nucleon scattering amplitude, m_ρ is the rho mass, K is the photon energy and $\rho = \rho(b,z)$ is the nuclear density. $\eta = 1 + i\xi$ and $T(b,z)$ is the profile function associated to the nuclear density, i.e.,

$$T(b,z) = \int_{-\infty}^{z} \rho\,(b,z')\,dz' \quad . \tag{4}$$

We can write the effective nucleon number for π^0 -photoproduction as follows,

$$A_{eff} = \int d^2b\,dz \left| 1 - B + i\xi + B\, e^{-\frac{\sigma_{\rho N}}{2}(1 - i\alpha_{\rho N})\eta T(b,-z)} \right|^2 \frac{\rho(b,z)}{|\eta|^2}\, e^{-\sigma_{\pi N} T(b,z)} \tag{5}$$

The main features of the elementary amplitudes which are relevant to us are:

i) $\rho_o N \to \rho_o N$. The analysis of experiments on nuclear targets (1,9) suggests $\sigma_{\rho_o N} \simeq \sigma_{\pi^o N}$, $\alpha_{\rho_o N} \simeq \alpha_{\pi^o N}$.

ii) $\gamma N \to \rho_o N$. This process is dominated by the diffractive non-flip amplitude (10), and the data are consistent with $\gamma N \to \rho_c N$ and $\rho_o N \to \rho_o N$ been related by VMD.

iii) $\gamma N \to \pi^o N$. Different authors have analysed these reactions (7,11,12). For $E_\gamma > 4$ GeV and in the momentum transfer range we are interested, one has that:

a) natural parity exchange dominates

$$H_1 \approx H_{-1} \; , \; H_o \simeq -H_2 \; ,$$

where H_o and H_2 are non-flip and double-flip helicity amplitudes and $H_{\pm 1}$ are single-flip helicity amplitudes. (Notation of Barbour and Moorhouse [11]).

b) the non-flip (H_o) and double-flip (H_2) helicity amplitudes are small with respect to the single flip amplitudes $(H_{\pm 1})$.

a) and b) imply that we may write

$$H_{\pm 1} = |H_{\pm 1}| e^{i\phi_\gamma} , \text{ with } |H_{\pm 1}| \sim \sqrt{\frac{d\sigma}{dt}(\gamma N \to \pi^\circ N)}$$

c) the t behaviour of the $H_{\pm 1}$ helicity amplitude is consistent with the "dual absorption model" [13], i.e. $H_{\pm 1} \sim J_1(r\sqrt{-t})$ with J_1 a Bessel function and $r \simeq 1$ fermi.

d) the energy dependence of $\frac{d\sigma}{dt}(\gamma N \to \pi^\circ N)$ is different from the prediction of pure ω -trajectory exchange (in variance with the behaviour of the $\rho_o N \to \pi^\circ N$ amplitudes).

iv) $\rho_o N \to \pi^\circ N$. Although this reaction has not been measured directly, from isospin conservation one may extract the relevant information from the reactions: $\pi^+ p \to \rho^+ p$, $\pi^- p \to \rho^- p$ and $\pi^- p \to \rho^\circ n$, i.e.

$$\frac{d\sigma}{dt}(\rho_o p \to \pi^\circ p) = \frac{1}{2}\left\{\frac{d\sigma}{dt}(\pi^+ p \to \rho^+ p) + \frac{d\sigma}{dt}(\pi^- p \to \rho^- p) - \frac{d\sigma}{dt}(\pi^- p \to \rho^\circ n)\right\} \tag{6}$$

The energy dependence is consistent with pure ω-exchange.
(If $\frac{d\sigma}{dt} \sim s^{2\alpha-2}$, $\alpha(t) \simeq 0.46 + t$ [8]) .

Although the errors are large, the data are consistent with single-flip and natural parity exchange dominance and with a t-behaviour given by the dual absorption model, i.e. $\left[J_1\left(r\sqrt{-t}\right)\right]^2$ with $r \simeq 1\, f_m$ [13].

Taking into account that in nuclei the ratio between the number of protons and the number of neutrons is $\approx$ 1 we may write [14]

$$|B|^2 = \frac{I}{\left.\frac{d\sigma}{dt}\right|_{\pi^0 \to \rho_0}} \tag{7}$$

$$I = \frac{8}{\alpha}\left(\frac{\gamma_\rho^2}{4\pi}\right)\frac{1+R}{2} \left.\frac{d\sigma}{dt}\right|_{\gamma \to \pi^0} \tag{8}$$

$$R = \frac{\frac{d\sigma}{dt}(\gamma n \to \pi^0 n)}{\frac{d\sigma}{dt}(\gamma p \to \pi^0 p)} \tag{9}$$

Experimentally [15] $R \gtrsim 0.9$ at 8.2 GeV and $\approx .8$ at 4.7 GeV for $-t < 0.5$.

III. Numerical Results

In this section we analyze the neutral pion photoproduction data in medium and heavy nuclear targets (Al, Cu, Ag and Pb) of the Cornell experiment [5].

The basic formula is Eq. (6), and as we mentioned before, we will take $B = |B| e^{i\phi}$, fix $|B|$ from experiments and leave ϕ as a free parameter to be determined by the nuclear photoproduction data.

We first proceed to parametrize the different functions that enter in Eq. 6.

$\rho_0 N \to \rho_0 N$. In the energy range we are considering we parametrize the data [16] by

$$\sigma_{\rho N} = 22 \left(1 + \frac{1.15}{K}\right) mb \tag{10}$$

$$\alpha_{\rho N} = -0.41 K - .4 \qquad \text{with } k \text{ in GeV.}$$

$\pi^0 N \to \pi^0 N$. Same parametrization as for $\pi^0 N \to \pi^0 N$ [1,9], i.e., $\sigma_{\rho_0 N} \simeq \sigma_{\pi^0 N}$ and $\alpha_{\rho_0 N} \simeq \alpha_{\pi^0 N}$

$\gamma N \to \rho_0 N$. It is well approximated by VMD [10] and we write

$$A_{\gamma N \to \rho_0 N} = \sqrt{\frac{\alpha \pi}{\gamma_\rho^2}} \; A_{\rho_0 N \to \rho_0 N} \; . \tag{11}$$

$\gamma N \to \pi^0 N$. $\alpha_{eff} = 0.19 + 0.26\, t$ [7] (to be compared with $\alpha_\omega = 0.46 + t$) From the DESY [17] and SLAC [18] experiment and in an average momentum transfer $-t = .15\ (\mathrm{GeV/c})^2$ we have for the differential cross-section the data of the second row of table II.

$\rho_0 N \to \pi^0 N$. Although the errors are large the data are consistent with single flip and natural parity exchange dominance and with an energy dependence due to pure ω -trajectory exchange. From the experimental data [8] for $\rho_0 p \to \pi^0 N$ we have written the third row of table II.

In the fourth row of table II we have written the quantity I (Eq. 9) and in the last row the ratio

$$|B| = \left(\frac{I}{\frac{d\sigma}{dt}\Big|_{\rho_0 \to \pi^0}} \right)^{1/2}$$

(Only the central values are given without estimating the errors). The ratio increases with the energy between values 0.6 and 0.75. We may fit the data by

$$|B| \simeq 0.54 \quad K^{0.13} \tag{12}$$

<u>Nuclear density.</u> We take the Wood-Saxon shape [19]

$$\rho(b,z) = \rho_0 \left(1 + e^{\frac{r-c}{a}}\right)^{-1} \quad , \; r = \sqrt{b^2 + z^2} \tag{13}$$

where a = 0.545 f_m ; c = 1.12 $A^{1/3} f_m$; ρ_0 = 0.169 f_m^{-3}

<u>Numerical results.</u> With all these parameters fixed, the effective nucleon number A_{eff} depends only on the phase ϕ . The numerical results are given in table III. The lower and higher values of $-\phi_{rad}$ correspond to the lower and higher values of the error bars in table I.

From table III we can note

i) $\phi \neq 0$

ii) there is no clear energy dependence although $-\phi$ seems to increase with energy.

iii) Although a value $-\phi = 0.5$ rad gives an overall resonable fit, a better fit is obtained if we allow $-\phi$ to increase with the nucleon number A (this is not allowed in Glauber theory).

Final Remarks

In the last section we have found that, in variance with VMD, our analysis implies for the relative phase ϕ between the $\rho_0 p \to \pi^0 p$ and $\gamma p \to \pi^0 p$ a value different from zero. Let us compare our results with other phenomeno-logical analysis of these amplitudes.

First of all the $\rho_0 p \to \pi^0 p$ reaction seems to be dominated by pure ω-trajectory exchange and we expect for this reaction

$$H_{\pm 1} = |H_{\pm 1}| (-i) e^{i\alpha_\omega(t)\frac{\pi}{2}} \tag{14}$$

This is not the case for $\gamma p \to \pi^0 p$. The energy dependence is not given by pure ω-trajectory exchange and in analysis based in finite energy sum rules and fixed-t dispersion relations the phases are not given by Eq. (15). Consider in the recent work of Barker, Donnachie and Storrow [7], the real and imaginary parts of $H_{\pm 1}$ in $E_\gamma = 4$ GeV(see Fig. 1). If we write

$$H_1 + H_{-1} = |H_1 + H_{-1}|\, i\, e^{i\alpha_1(t)\frac{\pi}{2}} , \tag{15}$$

from fig. 1 we find that

$$\alpha_1(-t=0.1) \simeq 0.20 ; \ \alpha_1(-t=.2) \simeq .05 ; \ \alpha_1(-t=.3) \simeq .20$$

If $\alpha_\omega(t) = 0.46 + t$, then we have for $\phi = \frac{\pi}{2}\left[\alpha_1(t) - \alpha_\omega(t)\right]$
$-\phi(-t=.1) \simeq .25$ rad; $-\phi(-t=.2) \simeq .33$ rad; $-\phi(-t=.3) \simeq .57$ rad.
These numbers are in reasonable agreement with the results of table III,

especially in the case of heavy nuclei. Therefore, we may conclude that the slowness of the fall of A_{eff} when the energy E_γ increases is due to the presence of the relative phase between the $\rho_0 N \to \pi^0 N$ and $\gamma N \to \pi^0 N$ amplitudes.

Finally we must stress that the analysis seems to show that $-\phi$ decreases when the nucleon number A increases, which is not allowed in Glauber theory. Although, better experimental data are needed to settle this question, this feature deserves a separate attention.

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Figure Caption

Fig. 1 Single-flip amplitudes of the reaction $\gamma p \to \pi^0 p$ at $E_\gamma = 4$ GeV[7]. Black points correspond to the Im. part of the amplitude and the white points to the real part.

Target	3.2 GeV	4.6 GeV	6.4 GeV	8.6 GeV
Al	11.4 ± 0.6	11.0 ± 0.6	10.8 ± 0.6	
Cu	21.3 ± 1.1	19 ± 1.0	22.4 ± 1.4	19.9 ± 1.2
Ag	27.0 ± 1.6	31.5 ± 1.7	30.3 ± 1.8	27.7 ± 1.7
Pb	42.7 ± 2.5	41.6 ± 2.4	44.7 ± 2.6	39.6 ± 2.5

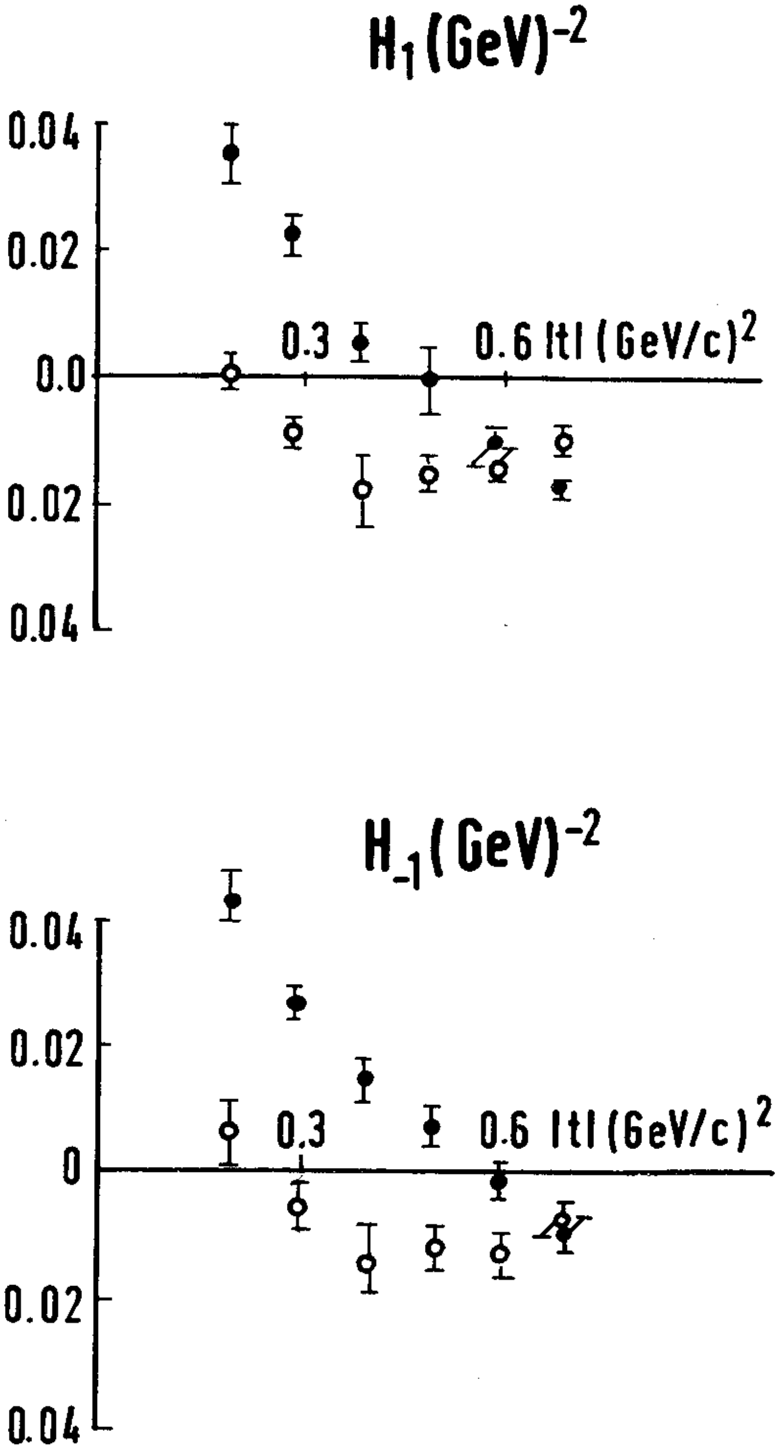
Table I. Energy

E_γ (Gev)	3	4	5	6	9	12
$\frac{d\sigma}{dt}(\gamma p \to \pi^\circ p)\Big\vert_{-t=.15}$ $\frac{\mu b}{Gev^2}$	2.4±.24	1.7±.19	1.06±.14	.86±.06	0.47±.05	.3±.04
$I_{-t=.15}$ $\mu b/(Gev)^2$	1.5±.15	1.08±.13	.67±.09	.55±.04	.3 ±.03	.19±.03
$\frac{d\sigma}{dt}(\rho_o p \to \pi^\circ p)$ $mb/(Gev)^2$	.73±.18	.44±.11	.33±.08	.26±.06	.15±.04	.105±.03
$B=\left[\frac{\frac{d\sigma}{dt}(\rho_o p \to \pi^\circ p)}{I}\right]^{1/2}$	.70	.64	.70	.69	.71	.74

Table II. $\gamma p \to \pi^\circ p$ and $\rho_o p \to \pi^\circ p$ differential cross-sections (we use $\frac{\gamma_\rho^2}{4\pi} = 0.61$ (9))

E_γ (Gev)	Al	Cu	Ag	Pb
3.2	.62-.88	.60-.83	.20-.45	.21-.45
4.6	.60-.85	.36-.56	.55-.72	.20-.40
6.4	.67-.88	.77-.95	.60-.77	.41-.50
8.7	- - - -	.62-.82	.51-.71	.38-.53

Table III. Values of ϕ which fit the A_{eff} values of Table I.


$H_1 (GeV)^{-2}$
0.04
0.02
0.3
0.6 |t| $(GeV/c)^2$
0.0
0.02
0.04
$H_{-1} (GeV)^{-2}$
0.04
0.02
0.3
0.6 |t| $(GeV/c)^2$
0
0.02
0.04

Fig·1