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PHOTOPRODUCTION OF VECTOR MESONS

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ABSTRACT

From recent high-energy photoproduction experiments we have gained new insights into photon interactions both in the area of spectroscopy of vector mesons and in the area of the interaction dynamics on the nucleon structure level. The interplay between photon structure and nucleon/nuclear structure is analysed by the measurement of inelastic vector meson photoproduction.

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1. INTRODUCTION

In this talk I will try to review what has been learnt during the recent past about the photoabsorption process:

$$\gamma + \left\{ \begin{array}{l} \text{proton} \\ \text{nucleus} \end{array} \right\} \rightarrow \text{vector meson} + \text{hadron(s)} .$$

The data I shall consider have been obtained mainly with real photons, on proton targets and at high energies in the range from 20 to 200 GeV. The physics I am going to discuss can be classified with respect to the nature of the photon when interacting with matter. The initial photon behaves in three ways¹:

a) As a hadron-like photon carrying the quantum numbers of a neutral vector meson state. Here we will consider processes of diffractive or elastic vector meson production (Fig. 1a) as well as inelastic processes where a quark from the vector meson state interacts with an antiquark from the proton (or vice versa) as shown by the example in Fig. 1b.

b) As a point-like photon corresponding to a quantum of the electromagnetic field (QED) which interacts with quarks from the target resulting in hadronic jets as indicated by the example in Fig. 1c.

c) As a so-called anomalous component being a source of asymptotically-free quarks and gluons (beyond the quark/gluon content of the vector meson states) as described by the theory of strong interaction quantum chromodynamics (QCD).

I shall concentrate on the first two classes; the anomalous component so far studied in $\gamma\gamma$ collisions will not be considered here.

The hadron-like component is responsible for almost 99% of the total cross-sections for $\gamma p \rightarrow \text{hadrons}$ whereas the point-like component counts for < 1%. So we have first

to discuss the question of how to distinguish experimentally these components from each other.

FIGURE 1
Photon proton interactions with
production of a vector meson

FIGURE 2
Kinematical ranges for studying soft and
hard processes

The separation can be achieved on the basis of kinematics. For real photons a useful quantity is the transverse momentum of the produced particle or jet which is defined perpendicular to the photon beam direction (p_T). It corresponds to a spatial resolution of $\lambda = \pi/p_T$ (uncertainty principle). Hadron-like photon interactions are a soft phenomenon, i.e. they cover low p_T values and die out at larger p_T . Point-like photon interactions reach larger p_T values and dominate the total hadronic cross-section above some p_T value. The kinematical ranges being available for separate studies are illustrated by comparing them to the radial dependence of a nuclear potential in Fig. 2 (One-Boson-Exchange approximation²). The soft processes (hadron-like γ) allow studies over a wide range down to a distance of at least 0.1 fm (p_T of a jet of several GeV). The study of the point-like γ requires smaller distances and high p_T values, respectively, i.e. they are automatically sensitive to interactions on a subnuclear level ($p_T > 2$ GeV).

In the following presentation I shall spend most of my time discussing soft processes where a broad spectrum of results on vector meson production exists. Here will be included diffractive vector meson production, the related subject of vector meson spectroscopy and then a section on studies of dynamics in soft inclusive processes $\gamma + p \rightarrow V + X$. A subsequent smaller part will be devoted to the field of point-like photon interactions where first results exist from virtual photon scattering, and which is the subject of current and future experimental activities at high-energy accelerators and colliders.

2. DIFFRACTIVE PRODUCTION OF VECTOR MESONS

2.1 The hadron-like photon

The photon, interacting with a nucleus, is in a hadronic state due to its coupling to $q\bar{q}$ pairs with a coupling strength proportional to the electric charge of the quarks. The lifetime of such a $q\bar{q}$ state as given by the uncertainty principle grows with E_γ and drops with increasing $q\bar{q}$ mass (Fig. 3). The Vector Dominance Model (VMD) assumes that (due to strong interactions between q and $\bar{q}$) the intermediate hadronic $q\bar{q}$ states are dominated entirely by the existing neutral vector meson states. So the photon is represented by a superposition of such vector meson states³:

$$|\gamma\rangle = \sum_V \frac{4\pi}{\gamma_V^2} |V\rangle$$

where the vector meson-photon coupling strength depends on the electric charge of the quarks:

$$\frac{4\pi}{\gamma_V^2} \propto \left(\sum_{q \in V} e_q \right)^2 .$$

$$E_\gamma \gg m_{q\bar{q}}: \\ C \cdot \Delta\tau \approx \frac{2 \cdot E_\gamma \hbar c}{(m_{q\bar{q}} \cdot c^2)^2}$$

FIGURE 3
Photon dissociation into $q\bar{q}$

FIGURE 4
VMD picture of the photoabsorption process

FIGURE 5
Energy dependence of A_{eff}/A for carbon, copper and lead⁴

The neutral vector meson states contributing are first of all the well-known lowest mass states ρ^0 , ω and ϕ , and ρ^0 is the strongest component ($\rho:\omega:\phi = 9:1:2$) due to its favoured quark content.

In the GeV photon energy range considered here the length of flight of a photon in, for example, a virtual ρ^0 state is of the order of several fm (uncertainty relation, see Fig. 3), whereas the mean free path of the ρ^0 is only ~ 1 fm ($\sigma_{\text{tot}}(\rho N) \approx 40$ mb). As a consequence the γ absorption in matter is essentially reduced to vector meson-nucleus scatterings (Fig. 4).

This picture implies the well-known shadowing effect which relates the photoproduction of hadrons on nuclei to that on nucleons. A compilation of recent total cross-section measurements⁴ is shown in Fig. 5. The results are expressed by the effective number of nucleons participating in the interaction (A_{eff}) for a target of nucleon number A . The data are inconsistent with simple surface effects since $A_{\text{eff}} \neq A^{2/3}$. More sophisticated models test VMD by extending the set of vector mesons contributing to the interaction. The effect that A_{eff}/A drops with energy has been interpreted as being an indication that mesons more massive than ρ , ω and ϕ participate in shadowing. They can become important when $E\gamma$ increases since their lifetime grows with $E\gamma$. Candidates for such states are radial excitations of ρ , ω and ϕ which will be discussed later in this talk.

2.2 $\gamma + p \rightarrow V + p$

For the simple process $\gamma + p \rightarrow V + p$ the VMD model suggests that the virtual vector meson stemming from the photon becomes real by an appropriate four-momentum transfer (Fig. 1a). Typical properties are those of diffractive scattering processes being well-known as a phenomenon in optics. A simple model assuming scattering of two particles with Gaussian density distributions predicts a cross-section depending exponentially on the four-momentum transfer squared from γ to vector meson due to

$$\frac{d\sigma}{dt} \propto e^{-b|t|}.$$

(For massless particles $|t|$ is equal to p_T^2 .) The slope parameter b is connected to the radius of the interaction by $b = 1/2 (R_p^2 + R_\rho^2)$ and has for $\gamma p \rightarrow \rho^0 p$ typically a value of 7 GeV^{-2} .

Photoproduction processes and "elastic" vector meson scattering are related to each other via VMD (assuming the optical theorem):

$$\frac{d\sigma}{dt}(\gamma N \rightarrow VN) = \frac{\alpha\pi}{\gamma_V^2} \frac{d\sigma}{dt}(VN \rightarrow VN).$$

Coupling constants and hadronic cross-sections have been determined simultaneously by measuring $\gamma A \rightarrow VA$ for various A ; however corresponding experiments have been

carried out a long time ago and are not very accurate⁵. More recently the elastic process $VN \rightarrow VN$ has been derived from measurements of $\pi p \rightarrow \pi p$ and $Kp \rightarrow Kp$ assuming naive quark model relations. As an example we consider here the ϕ photoproduction process $\gamma p \rightarrow \phi p$ where the prediction (indicated in Fig. 6) has been calculated from πp and Kp data^{6,11}. We note that the prediction describes well the energy dependence of the cross-section while the normalization provides a measure of the coupling strength $\alpha\pi/\gamma_\phi^2$.

The picture of photon vector meson transitions introduced to describe the diffractive process of vector meson photoproduction is also valid for describing the vector meson production by e^+e^- annihilation (Fig. 7) where the γ is virtual. Quantitative relations have been deduced; in particular the cross-sections are related via the optical theorem:

$$\sigma_{\text{peak}}(e^+e^- \rightarrow V) = \frac{64\pi^2 \alpha b}{m_V \Gamma_V \alpha_{\text{tot}}^2(Vp)} \sigma(\gamma p \rightarrow Vp)$$

where b is the slope parameter in $d\sigma/dt \propto e^{-b|t|}$ mentioned above. This relation has been found to be well satisfied in the case of ρ^0 , ω and ϕ mesons at the level of accuracy reached in measurements on complex nuclei (see above). As a consequence vector mesons seen in photoproduction should also be seen in e^+e^- annihilations and vice versa.

FIGURE 6
 $\sigma(\gamma p \rightarrow \phi p)$ vs. E_γ

FIGURE 7
 $e^+e^- \rightarrow V$

FIGURE 8
The vector mesons as $q\bar{q}$ systems

FIGURE 9
Production processes for radial excitations V'

Which states are expected? Both processes are sensitive to the production of vector mesons coupling directly to the photon. These are in general all vector meson states which have quantum numbers identical to those of the photon, i.e. $J^{PC} = 1^{--}$. Considering the vector mesons as $q\bar{q}$ systems due to the quark model this implies (Fig. 8) 3S_1 states occurring, of course, as ground states V ($1 {}^3S_1$) and also as radial excitations V' ($2 {}^3S_1, 3 {}^3S_1, \dots$). For sufficient binding energy $q\bar{q}$ can also be in a 3D_1 state which could cause overlap with the 3S_1 states. The ground states with small masses are probably free of 3D_1 admixtures whereas this is not clear for V' states⁷.

The production process for radial excitations is assumed to be the same as for the ground states; however their photoproduction is also possible via so-called off-diagonal terms (Fig. 9). This extra term can spoil the comparison between γp and e^+e^- data.

2.3 Spectroscopy of radial excitations of ρ , ω and ϕ

The motivation for this field of study has at least three distinct aspects:

a) There is (in nuclear physics) a continuous interest in analysing the nuclear potential in terms of meson exchange processes. No detailed knowledge exists about the rôle of higher mass vector meson states.

b) Any analyses of soft photon interactions rely on the knowledge of the vector meson states representing the hadron-like photon state. The contributions from radial excitations can in general not be neglected³. I have mentioned already their effect in shadowing.

c) There is interest concerning the potential of the $q\bar{q}$ system built up by the light quarks u, d, s :

$$|\rho^0\rangle = \frac{1}{\sqrt{2}} (|u\bar{u}\rangle - |d\bar{d}\rangle)$$

$$|\omega\rangle = \frac{1}{\sqrt{2}} (|u\bar{u}\rangle + |d\bar{d}\rangle)$$

$$\phi = |s\bar{s}\rangle.$$

The potential cannot be easily calculated^{7,8} and has so far not been determined by measurements. Assuming that one can make for the light (u,d,s) quark states the same ansatz as for the heavy (c,b) quarks, i.e.

$$V = -\frac{K_1}{r} + K_2 r$$

one expects an effect from the quark masses: the first (Coulomb-like) term gives a binding energy and hence a separation $m_{V'} - m_V$ proportional to m_q whereas the second (confinement) term gives separation proportional to $m_q^{-1/3}$. So it is predicted that the second term becomes more important when going from heavy to light quarks. The effective m_q dependence of $m_{V'} - m_V$ should change approximately by a factor $(m_{u/d}/m_c)^\alpha$ where α has a negative value.

Candidates for radial excitations of ρ , ω and ϕ in photoproduction and e^+e^- annihilations have been discussed for a long time. The best known candidate called $\rho'(1600)$ has been seen at a mass of ~ 1600 MeV and with a broad width in the range 200-400 MeV in both photoproduction and e^+e^- annihilation. Figure 10a shows as an example some mass spectra obtained in photoproduction. At least three decay modes have been observed:

FIGURE 10a
Mass spectra for studying $\rho'(1600)$

FIGURE 10b
Search for ω' and ϕ'

- $\rho'(1600) \rightarrow 2\pi^+2\pi^-$ ⁹. The curve corresponds to $e^+e^- \rightarrow 2\pi^+2\pi^-$ ¹¹ (with arbitrary normalization).
- $\rho'(1600) \rightarrow 2\pi^0\pi^+\pi^-$ ¹². The first peak at ~ 1250 MeV corresponds to the B meson ($J^{PC} = 1^{+-}$); the two peaks can be separated from each other by requesting for the subsystem of $\pi^+\pi^-\pi^0$ a mass inside or outside the ω mass region.
- $\rho'(1600) \rightarrow \pi^+\pi^-$ ¹³.

A fourth mode $\rho'(1600) \rightarrow \eta\pi^+\pi^-$ has been studied. The $\eta\pi^+\pi^-$ mass spectrum is consistent with very little $\rho'(1600)$ production ¹⁴.

Results on radial excitations of ω and ϕ stem from e^+e^- annihilations measured mainly at the Orsay DCI ring ^{10,15} and from diffractive photoproduction mainly at the CERN Omega facility ¹⁶⁻¹⁹. Both experimental programs have searched for candidates in the possible common decay modes $\omega\pi^+\pi^-$, $K\bar{K}$, $K\bar{K}\pi$ and $\pi^+\pi^-\pi^0$. Figure 10b shows a compilation of recent measurements. The curves in the e^+e^- data correspond to an overall fit (not including $\pi^+\pi^-\pi^0$ which has been measured more recently ¹⁵). The dotted or dashed lines in the photoproduction data are predictions from e^+e^- fit results. One sees that for the candidates being observed a consistent interpretation has so far not been obtained since there is no simple correspondance in the two important decay channels $\omega\pi^+\pi^-$ and $K_S^0 K^\pm \pi^\mp$. The details of this comparison have been discussed elsewhere ^{11,20,21}.

The status of the search for ρ' , ω' and ϕ' states is summarized as follows:

a) Data from γp and e^+e^- are consistent with $\rho'(1600)$ being the first radial excitation of the ρ^0 . Possible 3D_1 admixtures have not been resolved so far. This problem might spoil the measurements of mass, width and γp production cross-section.

b) Candidates for ω' or ϕ' are also observed and lie in the mass range 1.6 to 1.8 GeV. However, there is at present no consistent interpretation of the data. As main result can be considered that there is no substantial candidate below 1.6 GeV (neither in γp nor in e^+e^-).

c) The mass values quoted above imply:

$$1.4 = \left(\frac{m_{u/d}}{m_c} \right)^\alpha = \left(\frac{300 \text{ MeV}}{1500 \text{ MeV}} \right)^\alpha \rightarrow \alpha = -0.2 ,$$

i.e. the effective dependence on m_q in

$$V = -\frac{K}{r} + K_2 \cdot r$$

changes towards the confinement term when going from $c\bar{c}$ to $u\bar{u}$, $d\bar{d}$ so supports

principally the naive expectation.

For further details more and better data are needed, in particular in e^+e^- annihilations. Good possibilities might exist at the e^+e^- colliders VEPP-3 (Novosibirsk) and BEPC (Beijing, China). For photoproduction there are running high-energy projects at CERN (Experiment WA69) and at FNAL. In the near future lower energy activities will be possible at the Stretcher Ring in Bonn and probably at IEL (KEK, Japan) and at CEBAF (Charlottesville, USA).

3. SOFT INCLUSIVE PROCESSES

My next subject to be discussed concerns low p_T inelastic processes of the type

$$\gamma + p \rightarrow V + X$$

where X is a system of at least two hadrons including the recoiling nucleon.

FIGURE 11
Distribution of $\sigma(\rho^0)/\sigma(\omega)$ as a function of x_F of the vector mesons

The VMD picture introduced to describe the "elastic" vector meson production is also very useful for discussing such soft inelastic processes. In this case there is some probability that the initial V and p interact by their quark and gluon content with each other to form new vector meson states (Fig. 1b). Recent data^{22,23} exist on ρ^0 , ω , $\rho^\pm$, ϕ and K^* all coming from one CERN experiment with photons in the range $20 < E_\gamma < 70$ GeV. This cross-section has been measured inclusively, i.e. integrating over all kinematical variables describing the system X. The kinematics of the vector mesons has been studied in terms of the so-called Feynman variable x_F which is a measure of the momentum fraction (in the overall c.m.s.) taken away by the vector meson into the direction of the initial photon

$$x_F = \frac{P_{||}^*}{P_{\max}^*} = \frac{2P_{||}^*}{\sqrt{S}}$$

I will first discuss the cross-section ratio for ρ^0 and ω production (Fig. 11). For the elastic production $\gamma p \rightarrow \rho/\omega p$ this ratio has a value of 9 consistent with the VMD

prediction given by the relative coupling strengths due to the quark contents. The elastic x_F range corresponds to the dashed area close to $x_F = 1$ in Fig. 11.

The inelastic data cover a wide range including $x_F = 0$. They indicate a value of ~ 1 in the central region, i.e. at $x_F = 0$ and a smooth rise with increasing x_F . This observation can be interpreted as follows: at small x_F the vector meson and the proton state provide valence quarks and sea quarks from gluons for forming new ρ^0 and ω with essentially the same probability like in πN or $K N$ scattering. This class of interaction is in addition to another class which conserves the relative strengths of ρ and ω in the initial state like in a simple diffraction process.

Guided by these ideas the (Lorentz-invariant) differential cross-sections

$$\tilde{\sigma}(x_F) = \frac{1}{\pi} \frac{E^*}{p_{\max}^*} \frac{d\sigma(\gamma p \rightarrow Vx)}{dx_F}$$

(where E^* and $p_{\max}^*$ are the energy and maximal possible momentum of the inclusive vector mesons in the overall c.m.s.) has been decomposed into a non-diffractive (N) and a diffractive part (D) on the basis of the following assumed relation:

$$\tilde{\sigma}(\rho^0) = N + D$$

$$\tilde{\sigma}(\omega) = N + 1/9 D.$$

The factor 1/9 takes into account the difference of initial photon coupling strengths of ρ^0 and ω .

FIGURE 12
The component D as a function of x_F

FIGURE 13
The component N as a function of x_F
(open circles) and $\rho^\pm$ data (squares)

The diffraction part (Fig. 12) rises with x_F and is quantitatively described by a Triple Regge Model calculation²². All variable parameters have been determined in other processes and are imposed here. One can see that this model provides an adequate description of the data.

The non-diffractive part (Fig. 13) falls in the forward direction. It is compared to the measurement of $1/2[\tilde{\sigma}(\rho^+) + \tilde{\sigma}(\rho^-)]$ coming from the same experiment²². The observed agreement is expected if there is a common production mechanism responsible for the non-diffractive production of ρ^0 , ω , ρ^+ and ρ^- so that the following third relation would hold

$$1/2 [\tilde{\sigma}(\rho^+) + \tilde{\sigma}(\rho^-)] = N .$$

A phenomenological description of the production mechanism has been obtained on the basis of a quark fusion model (full curve drawn in Fig. 13). In this model²⁴ a quark from the hadron-like photon state recombines with a target quark to form the outgoing vector meson. With quark distributions related to the structure functions F_2 on a naive parton model level by

$$F_2(x) = x \cdot f(x) \cdot \sum_q e_q^2$$

the invariant cross-section is written

$$\frac{d\tilde{\sigma}}{dx_F} = \frac{4\pi^2}{3m_V^2} \sum_{q_1, \bar{q}_2} \frac{g_{q_1 \bar{q}_2}^2}{4\pi} \left\{ f_Y^{q_1}(x_1) f_{\rho^0}^{\bar{q}_2}(x_2) + f_Y^{\bar{q}_2}(x_1) f_{\rho^0}^{q_1}(x_2) \right\}$$

$$x_1 - x_2 = x_F ; \quad x_1 x_2 = \frac{m_V^2}{s} .$$

The sum runs over all possible valence and sea quarks $q_1, \bar{q}_2$ which couple to the outgoing vector meson with the coupling strength $g_{q_1 \bar{q}_2}$. Assuming for the vector meson structure functions that they are the same as for the pion both sets, i.e. that for the meson and that for the proton are parametrized in the literature and have been taken from there²⁵ in the kinematical range closest to that of the data. One sees good agreement in the shape (having an arbitrary normalization) from large x_F when the distribution is dominated by the valence quarks of the beam (interacting with sea quarks of the target proton) down to $0 < x_F < 0.5$ where valence quarks of the proton have also been taken into account.

At this point it may be asked if one would learn anything about the quark structure in nuclei (in the soft regime) by measuring the inelastic vector meson production on nuclear targets. In such an experiment it would be certainly difficult to reach a high accuracy. Such studies have to impose Glauber theory and require knowledge of nuclear density distributions since multiple scattering effects are expected to be strong²⁶.

FIGURE 14
 $d\sigma(\gamma p \rightarrow \phi p)/dx_F$ vs. x_F ¹³

FIGURE 15
Contributions to the cross-section formula in the text. Full quark lines denote valence quarks, dashed quark lines sea quarks

Another detailed study has been carried out recently for inclusive ϕ production²³ in the process

$$\gamma + p \rightarrow \phi + X.$$

Figure 14 shows the data together with a quantitative prediction for the diffractive part (again obtained in the framework of the Triple-Regge Model) and a qualitative prediction from the quark-fusion model. In this case two types of diagram have been taken into account (Fig. 15): normal planar ones and unconnected non-planar ones which are in general suppressed with respect to the planar diagrams (OZI rule²⁷). The prediction is the incoherent sum of the four types of contributions illustrated in Fig. 15 with two effective coupling strengths for planar and non-planar case, respectively, as unknown parameters. The latter have been determined in a fit to the data leading to the relative contributions indicated in Fig. 14. The non-planar diagrams account for up to 50% and are thus non-negligible. In particular, $V_Y V_p$ which can contribute only via the non-planar case is substantial.

4. HARD SCATTERING PROCESSES

4.1 The point-like photon

Acting as an elementary field quantum the photon couples point-like to the electric charge of quarks in matter (Fig. 16). This type of interaction is accessible in the kinematical range of hard scattering processes (large p_T) where VMD as a typical soft phenomenon has died out. There are very elementary processes (Fig. 17): the QCD-Compton process and the photon-gluon fusion process which are calculable in QCD. They provide interesting possibilities for testing QCD and -- assuming the validity of

QCD -- for measuring structure functions of quarks and gluons in the target. They are sensitive to details of the initial state like the polarization of the photon or the nucleus for which it is predicted that they induce spin alignment of final state vector mesons²⁸. No such data exist to date from such hard processes with real photons. (They are expected in the next few years.) However there are first results on hard ρ^0 production which have been obtained under different kinematical conditions, namely with virtual space-like photons. They will be reported here after a brief discussion on virtual photon scattering.

FIGURE 17
Lowest-order processes

FIGURE 16
Point-like photoabsorption

4.2 Results from virtual space-like photons

A virtual photon being produced by e or μ scattering is specified by a four-momentum transfer q where q^2 corresponds to the squared invariant mass of the photon (Fig. 18). The lifetime for the photon being in a ρ^0 state is then dependent on q^2 in the sense that it can be reduced by increasing $|q^2|$: $\tau_\rho \propto E_Y/(|q^2| + m_\rho^2)$ or $\hbar = c = 1$). At which q^2 the vector meson interactions can be neglected so that the photon is approximately point-like has to be answered by experiments. I will discuss here what conclusions can be drawn from the measurement of shadowing with virtual space-like photons where recent data exist²⁹ (Fig. 18). The data are parametrized by A_{eff}/A (see above) as a function of $|q^2|$ over a range up to 30 GeV^2 . The curves are predictions from a theoretical VMD model assuming realistic nuclear densities. Shadowing is observed for low q^2 ($|q^2| < 1 \text{ GeV}^2$) and is there consistent with results at $q^2 = 0$ (indicated in Fig. 18). It seems to decrease for $|q^2| > 1 \text{ GeV}^2$, and $A_{\text{eff}}/A = 1$ (no shadowing) is reached for $|q^2| \approx 10 \text{ GeV}^2$. This estimate is in fair agreement with other methods.

The new results on hard ρ^0 production come from the EMC experiment at CERN³⁰. High-energy muons have been scattered on hydrogen providing photons in the $|q^2|$ range from 1 to 60 GeV^2 . I will restrict myself to the exclusive process

$\gamma p \rightarrow \rho^0 p$ which we have discussed for $q^2 = 0$ earlier, but consider here for $\langle |q^2| \rangle = 11.2 \text{ GeV}^2$. The t' distribution where t' is the four-momentum transfer squared for $\gamma \rightarrow \rho^0$ ($t' = t - t_{\min}$) is shown in Fig. 19a. It is relatively flat, i.e. significantly flatter than the distribution for $q^2 = 0$. The exclusive ρ^0 production changes from a diffraction process at $q^2 = 0$ with objects of finite size to a typical point-like scattering process at large $|q^2|$.

Another striking change concerns the polarization of the ρ^0 : it is measured in the ρ^0 decay angular distribution ($\rho^0 \rightarrow \pi^+ \pi^-$) defined by the angle of π^+ with respect to the outgoing proton in the ρ^0 rest frame (Fig. 19b). Whereas at $q^2 = 0$ the transverse polarization of the photon (helicity = ± 1) is transferred to the ρ^0 state ($\sin^2 \theta$ distribution), there is a transfer from a transverse to a longitudinal polarization at large $|q^2|$ ($\cos^2 \theta$ distribution). This latter ρ^0 polarization is not consistent with VMD. Theoretical descriptions have to be found. Simple pictures like the special photon-gluon graph³¹ (Fig. 20) are not sufficient for describing this data.

FIGURE 18
 A_{eff}/A as a function of Q^2 for targets of C, Cu and Pb 4,29

FIGURE 19a
 t' distribution for $\gamma p \rightarrow \rho^0 p$ 30

FIGURE 20
Photon gluon fusion model for $\gamma p \rightarrow V p$

FIGURE 19b
 $\cos \theta$ distribution of the data in Fig. 19a 30

5. SUMMARY

a) Experiments on photoproduction of vector mesons have been carried out mainly at high energies and on protons.

b) Soft processes are well approximated by the Vector Dominance Model for both "elastic" and inelastic vector meson production.

c) The spectroscopy of vector meson states of ρ , ω , and ϕ families are still not on a satisfactory level. More data (e^+e^- and γp) are needed.

d) An interesting area for studying interaction dynamics on the nucleon/nuclear structure level has been opened up by experiments measuring inclusive vector meson production in soft and hard photon scatterings.

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