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INCLUSIVE PHOTOPRODUCTION OF ρ AND ω IN THE PHOTON ENERGY RANGE 20 TO 70 GeV

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ABSTRACT

Inclusive production of ρ^0 , ω , and $\rho^\pm$ at low transverse momentum has been measured in γp collisions with photons of energy 20 to 70 GeV. The vector mesons have been studied as functions of the Feynman variable x_F , varying between -0.2 and 0.95 , i.e. excluding the "elastic" peaks of ρ^0 and ω photoproduction. For $x_F \lesssim 0.6$ the vector meson cross-sections are approximately equal; that is, $\sigma(\rho^0) \approx \sigma(\omega) \approx \frac{1}{2}[\sigma(\rho^+) + \sigma(\rho^-)]$. For $x_F > 0.6$, it is observed that $\sigma(\rho^0) > \sigma(\omega) > \frac{1}{2}[\sigma(\rho^+) + \sigma(\rho^-)]$ and the differences increase with increasing x_F . Over the x_F range $-0.2 < x_F < 0.95$ the vector mesons are produced similarly to non-diffractive leading particles in hadron-hadron collisions with an extra diffractive component in ρ^0 and ω production.

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1. INTRODUCTION

We report here on the measurement of the inclusive scattering processes

$$\gamma p \rightarrow \rho^0 X, \quad (1)$$

$$\gamma p \rightarrow \omega X, \quad (2)$$

and

$$\gamma p \rightarrow \rho^\pm X, \quad (3)$$

where X is a system of at least two particles with a mass m_X greater than the sum of the proton and the pion mass. The “elastic” processes, where the proton alone recoils against ρ^0 or ω , were distinguished by multiplicity or kinematics and have been presented elsewhere [1,2].

The experiment was carried out with bremsstrahlung photons in the energy range 20 to 70 GeV. The vector meson production was studied mainly over the forward hemisphere in the over-all centre-of-mass system (c.m.s.), in terms of the kinematical variable $x_F \cong 2p_L^*/\sqrt{s}$ (where p_L^* is the momentum of the vector meson parallel to the photon beam direction in the c.m.s.) in the range from -0.2 to 0.95 . The transverse momentum p_T of the vector mesons perpendicular to the photon beam direction ranged from zero to about 1.2 GeV; this range is usually considered to be the low- p_T regime.

The study of photoproduction of low- p_T vector mesons is of intrinsic interest in the analysis of photon interactions and also for comparison with hadron-hadron and lepton-hadron interactions in terms of quark-parton models [3].

In hadron-hadron interactions at low p_T the valence quark content of the initial beam particle can completely or partially persist in final-state hadrons. These hadrons, the so-called leading particles, carry a sizeable fraction of the total energy, and they have characteristic x_F distributions. In the first class, where the incident particle does not change its nature, the Lorentz-invariant differential cross-section rises significantly with increasing x_F , resulting in a fragmentation peak; in the second class, where the initial hadron hands over only a part of its valence quark content (i.e. for a meson, a quark or an antiquark), the invariant cross-section is spread widely in x_F , but has, at the energies considered here, a monotonic rise with increasing x_F up to a value of about 0.3 and falls slightly for large x_F [4].

In the photoproduction of hadrons, leading-particle effects are expected in so far as the photon interacts as a vector meson. This assumption, usually expressed in terms of the vector-meson dominance (VMD) hypothesis, is valid to a good approximation at low p_T . Then the leading particles of the first class are dominantly the usual vector mesons ρ^0 , ω , and ϕ [5]. In previous studies such leading particles were seen in photoproduction at lower energy [6,7]. The second class is represented by photoproduction of $\rho^\pm$, when one quark or antiquark is common to the incident ρ^0 or ω , respectively. This class should contribute also to inelastic ρ^0 or ω photoproduction with a similar cross-section.

In this experiment we are sensitive to the relative production of ρ^0 , ω , and $\rho^\pm$. VMD predicts that the ρ^0 -induced hadron production is nine times stronger than that induced by ω . Simple diffractive ρ^0 and ω production via the “elastic processes” $\gamma p \rightarrow \rho^0/\omega p$ reflect directly these

photon–vector meson coupling strengths. Here we discuss whether inelastic ρ^0 and ω photoproduction “remembers” the relative strength of ρ^0 and ω as hadronic states in the photon beam, or if such a “memory” gets lost, since parton effects are responsible for the inelastic ρ^0 and ω production.

2. EXPERIMENTS AND DATA

The data were obtained at the CERN Super Proton Synchrotron (SPS) as part of a photoproduction experiment using the Omega Spectrometer with a tagged photon beam. The experimental details have been described elsewhere [8]. The primary photons tagged in the momentum range from 20 to 70 GeV were incident on a 60 cm liquid hydrogen target. The experiment was able to measure multiparticle final states. The π^0 s were measured via their decay into two photons. Charged kaons and protons/antiprotons were identified within the momentum range $5 < p_K < 18$ GeV and $19 < p_p < 35$ GeV, respectively, by means of a threshold Cherenkov counter; moreover, recoil protons were identified in the range $\sim 0.2 < p_p < 1$ GeV by measuring their energy loss dE/dx in a scintillation counter [9]. Particles with mass assignments different from those of the pions were excluded when forming 2π or 3π mass combinations (see below).

The inclusive data were derived from two different triggers in the experiment. One trigger required a charged particle multiplicity between 3 and 8 in the forward detector. From the interaction of 9.9×10^8 photons within the tagging range, incident on 2.54×10^{24} protons/cm² of hydrogen, a total of 1.3×10^5 events were recorded with this trigger (main data set). In the data reduction we removed all events consistent with elastic vector-meson production, i.e. $\gamma p \rightarrow \rho^0 p (\rho^0 \rightarrow \pi^+ \pi^-)$ and $\gamma p \rightarrow \omega p (\omega \rightarrow \pi^+ \pi^- \pi^0)$, by excluding the corresponding topologies (which also rejected a few inelastic events).

Another trigger required a charged forward multiplicity of two (“2-prong trigger”) and rejected electron–positron pairs. This data set contained essentially [besides the elastic ρ^0 and ω production, due to $\gamma p \rightarrow \rho^0 p (\rho^0 \rightarrow \pi^+ \pi^-)$ and $\gamma p \rightarrow \omega p (\omega \rightarrow \pi^+ \pi^- \pi^0)$, respectively] the inelastic reaction

$$\gamma p \rightarrow \pi^+ \pi^- (m\pi^0) p, \quad m \geq 1.$$

Figure 1 shows, for both data sets, the distribution of m_X^2 , the mass-squared recoiling against any $\pi^+ \pi^-$ system of an event. The “elastic process” $\gamma p \rightarrow \rho^0 p$, contributes clearly to the distribution of the second data set (peak at $m_X^2 = m_p^2$ in fig. 1b) and was excluded from the further analysis of the inelastic data by requiring $x_F < 0.95$ for any $\pi^- \pi^+$ system in the ρ^0 mass band of $m_{\pi^+ \pi^-}$ between 0.475 and 1.075 GeV. We also excluded elastic ω -production in $\gamma p \rightarrow \pi^+ \pi^- \pi^0 p$. These cuts were applied to both data sets.

3. EXPERIMENTAL RESULTS

3.1 Total cross-section for inelastic photoproduction of ρ^0 , ω , and $\rho^\pm$

Figures 2, 3, and 4 show the inclusive mass spectra of the particle systems $\pi^+ \pi^-$, $\pi^+ \pi^- \pi^0$ and $\pi^\pm \pi^0$ of the main data set (charged multiplicity 3 to 8). The distributions each include two-pion/three-pion combination with $x_F > -0.2$, i.e, the signals of the vector mesons are restricted

to this x_F range. So events with double ρ^0 , ω , or $\rho^\pm$ production are counted twice; those contributions were measured to be small [10]. The $\rho^0/\rho^\pm$ meson production was determined by fitting the mass spectrum with a Breit-Wigner resonance term (BW) and a mass-dependent background term (BG)*):

$$d\sigma/dm = BG(c \cdot BW + b). \quad (4)$$

The Breit-Wigner function was taken to be of the form,

$$BW(m) = mm_R \Gamma(m) / [(m^2 - m_R^2)^2 + m_R^2 \Gamma^2(m)],$$

where m_R is the resonance mass. The Breit-Wigner width Γ was given the mass-dependent form

$$\Gamma(m) = \Gamma_R (q/q_R)^{2\ell+1} \rho(m)/\rho(m_R),$$

where

$$\rho(m) = (q_R^2 + q^2)^{-1},$$

q being the three-momentum of each of the decay products in the ρ rest frame, q_R the value of q at the resonance mass, and ℓ the relative angular momentum of the decay particles. For the ρ^0 (fig. 2), a Breit-Wigner formula modified by a skewing factor $(m_R/m)^4$ was used. This factor was suggested by Ross and Stodolsky (the RS factor) in order to account for the skewness of the ρ^0 signal in elastic ρ^0 photoproduction [1,11]. For the background distribution in $\pi^+\pi^-$ and $\pi^\pm\pi^0$ mass spectra we have chosen

$$BG(m) = a(m - m_{th})^\beta \cdot e^{-(\gamma m + \delta m^2)},$$

where a, β, γ , and δ are determined by the fit, and m_{th} is the threshold mass for $\pi\pi$ combinations.

This form for parameterizing the background describes the mass distributions obtained by combining a π from one event in the data sample with the corresponding π found in the next event of the same type (“uncorrelated” background) with consistent values of β, γ , and δ . For the ρ^0 fits we took into account, in addition to Eq. (4), a term which described a K^0 peak occurring from $K_S^0 \rightarrow \pi^+\pi^-$ decays close to the event vertex.

The ω production was determined by fitting to a Breit-Wigner function with $\Gamma(m) = \Gamma_R$ and the background was taken to be a third-order polynomial.

The results of the fits to the mass distributions in figs. 2, 3, and 4 are shown by the curves and are specified quantitatively in table 1. The ρ/ω mass values and the ρ^0 width were fixed to the nominal values. We note that the ρ fits were obtained with the Breit-Wigner function modified by the RS factor, as was suggested from fits with the ρ^0 mass as free parameter (see subsection 3.3). The ω width determined in the fit reflects the experimental resolution ($\sigma \sim 15$ MeV).

*) Alternatively, $d\sigma/dm = c \cdot BW + b \cdot BG$ was used, providing resulting values of c , which were consistent with the corresponding ones from Eq. (4).

We calculated the inelastic ρ^0 cross-section^{*}, averaged over the photon energy range ($20 < E_\gamma < 70$ GeV) for $-0.2 < x_F(\rho^0) < 0.95$, to be

$$\sigma(\gamma p \rightarrow \rho^0 X) = 21.6 \pm 1.0 \pm 2.2 \mu\text{b},$$

where the first error came from the fitting procedure and the second from estimated systematic uncertainties.

These values are corrected for acceptance losses by the apparatus and the analysis procedure. In particular, the geometrical acceptance given by the experimental apparatus was determined by a method of rotating a single event around the beam direction (see ref. 12 for details), resulting in the dashed curves in figs. 2, 3, and 4.

The ρ^0 cross-section was also determined for two consecutive intervals of the photon energy ($20 \leq E_\gamma < 40$ GeV and $40 \leq E_\gamma < 70$ GeV), yielding results which are consistent with no energy dependence. The ω and $\rho^\pm$ cross-sections were determined relative to the ρ^0 by including an individual correction factor for the π^0 loss due to the geometrical restrictions of the photon detector (see ref. 13 for details of this method). The following cross-sections and statistical errors were calculated integrating x_F from -0.2 to 0.95 and averaging over the photon energy range $20 < E_\gamma < 70$ GeV:

$$\begin{aligned}\sigma(\gamma p \rightarrow \omega X) &= 15.8 \pm 2.4 \mu\text{b}, \\ \sigma(\gamma p \rightarrow \rho^+ X) + \sigma(\gamma p \rightarrow \rho^- X) &= 27.9 \pm 6.4 \mu\text{b}.\end{aligned}$$

The systematic errors on these values are approximately the same as for ρ^0 production. A separate study of $\pi^+\pi^0$ and $\pi^-\pi^0$ mass distributions has confirmed that the data are consistent with equality of the ρ^+ and ρ^- cross-sections. In the following it is always the sum of $\pi^+\pi^0$ - and $\pi^-\pi^0$ -distributions that is considered. The signal from the added spectra is denoted by " $\rho^\pm$ ". We note that the inelastic cross-sections of ρ^0 - and ω -production are of the same order of magnitude, whereas the corresponding elastic cross-sections (not included here) differ by about a factor of 10: $\sigma(\gamma p \rightarrow \rho^0 p) = 9.4 \pm 0.1 \mu\text{b}$, $\sigma(\gamma p \rightarrow \omega p) = 1.2 \pm 0.1 \mu\text{b}$ [1].

3.2 Dependence on charged hadronic multiplicity and mass recoiling against the vector meson

The production of ρ^0 and ω was studied as a function of the charged hadronic multiplicity and of m_X^2 , the mass-squared recoiling against the vector meson ($\rho^\pm$ was not analysed because of low statistics). The rates were determined by fitting ρ^0 and ω to $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ mass spectra (raw data sets) for multiplicities from 3 to 12 and slices of m_X^2 , and are shown in figs. 5 and 6^{**}). The dependence on m_X^2 (full points) follows the trend of the general m_X^2 distribution (see fig. 1).

3.3 Dependence on x_F

Figures 7, 8, and 9 show $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, and $\pi^\pm\pi^0$ mass spectra for various x_F intervals of the two- and three-pion mass combinations, respectively. The curves correspond to the fit results following the procedure outlined in Section 2. The ρ^0 signals were fitted using the Breit-Wigner

^{*}) The number of ρ^0 with statistical error was taken from fits to the $\pi^+\pi^-$ mass distributions split into intervals of $x_F(\rho^0)$, as explained below. The result agrees with the over-all fit but yields a smaller error (see table 1).

^{**}) The trigger acceptance of $N_\omega(m_X^2)$ follows the curve given for $N_\rho(m_X^2)$ in fig. 6a.

formula modified by the skewing factor throughout the x_F range. However, acceptable fits for the ρ^0 signal were obtained with and without the skewing factor; these fits yielded consistent numbers of ρ^0 , with values for the ρ^0 mass being systematically 20 MeV lower in the fits without the skewing factor. In the higher x_F intervals it was found that the ρ^0 mass values obtained from fits with the skewing factor were closer to the nominal value than those without this factor, whereas for lower x_F intervals no conclusion could be drawn (see table 1).

The cross-section $d\sigma/dx_F$ for inclusive ρ^0 , ω , and $\rho^\pm$ production resulting from the fits to the multiplicity trigger data only are shown in fig. 10 (open squares), with appropriate corrections for the acceptance of the apparatus. The errors shown here include the errors from the acceptance calculations, which were typically of the order of 10%. They do not include the over-all systematic error coming from the normalization to the ρ^0 cross-sections.

The complementary contributions from the “two-prong trigger” which complete the inelastic data were determined correspondingly. The results from adding both contributions bin-by-bin is also shown in fig. 10 (full points). They constitute the total inelastic cross-section over the x_F range considered (the elastic ρ^0 and ω meson production would have contributed only outside this x_F range, namely for $x_F > 0.95$).

3.4 Dependence on p_T^2

Figure 11 shows $d\sigma/dp_T^2$ for inclusive ρ^0 and ω production (obtained by dividing the p_T^2 distributions in slices Δp_T^2 and fitting mass distributions for these slices of p_T^2), for the data integrated over the whole x_F range ($-0.2 < x_F < 0.95$). The full lines correspond to fits assuming a p_T^2 dependence $d\sigma/dp_T^2 \propto \exp(-ap_T^2)$. Fits allowing for $d\sigma/dp_T^2 \propto \exp(-ap_T^2 - bp_T^4)$ were also carried out. The slope parameters are given in table 2; they are all consistent with one another and with typical values for inclusive particle production in this kinematical range (see, for instance, ref. 5).

4. DISCUSSION

The differential cross-sections $d\sigma/dx_F$ of inclusive ρ^0 , ω , $\rho^\pm$ production (open circles in fig. 10) were converted, on an event-by-event basis, to Lorentz-invariant differential cross-sections according to

$$F(x_F) = (1/\pi)(E^*/p_{\max}^*)(d\sigma/dx_F),$$

where E^* and $p_{\max}^*$ are energy and maximal possible momentum of the inclusive vector meson in the overall c.m.s. The results are shown in fig. 12 (full points).

For the ρ^0 (fig. 12a), comparisons are made with corresponding photoproduction data at 9.6 GeV photon energy [6] (open circles) and with $\pi^\pm p \rightarrow \rho^0 X$ at 16 GeV pion momentum. In the latter case, π^+ and π^- data [14] were averaged, and the resulting cross-sections were scaled by a factor of 1/200, which accounts for the reduction in cross-section when describing the photoproduction in terms of simple vector dominance [15]. The comparison with the 9.3 GeV data implies that photoproduction data are approximately energy independent over the x_F range considered here. We note that ρ^0 photoproduction has a forward peak ($x_F > 0.75$) well below the x_F range of the “elastic” channel $\gamma p \rightarrow \rho^0 p$ ($x_F > 0.95$).

The pion-induced ρ^0 production (scaled by $1/200$) reproduces the photoproduction data in the central region, but does not have a prominent forward peak. The difference is, in fact, already plausible from simple leading-particle considerations (assuming VMD): the ρ^0 can be produced by the incoming photon directly, whereas the pion has to exchange quantum numbers in order to produce a ρ^0 .

According to VMD, a diffractive leading-particle effect of the first class in ρ^0 photoproduction (see section 1) implies that there is a similar leading-particle effect in ω photoproduction with a relative cross-section smaller by a factor of $\sim 1/9$, and no such effect in $\rho^\pm$ photoproduction. The data are in agreement with an extra contribution to ω production at the highest x_F relative to $\rho^\pm$ production. However, the $\rho^\pm$ photoproduction decreases with increasing x_F (for $x_F > 0.65$) and is thus not compatible with the flattening of the pion-induced ρ^0 production.

An intercomparison of the photoproduced vector mesons ρ^0 , ω , and $\rho^\pm$ was made more quantitative by considering the ratios $\sigma(\rho^0)/\sigma(\omega)$, $\sigma(\rho^0)/\sigma(\rho^\pm)$, and $\sigma(\omega)/\sigma(\rho^\pm)$ as a function of x_F of the vector mesons (fig. 13). For $x_F \lesssim 0.5$ the ratios are consistent with 1, 0.5, and 0.5, respectively. Such ratios can be understood as arising from various models [3] particularly also from the quark-parton fusion picture discussed below. At higher x_F values, where diffractive leading-particle effects can be expected to show up ($x_F \gtrsim 0.5$), the ratios rise steeply with x_F . In particular, the rise of $\sigma(\rho^0)/\sigma(\omega)$ is consistent with a smooth continuation to a value of ~ 9 predicted by VMD for “elastic” production of ρ^0 and ω in the range of $x_F > 0.95$. Both $\sigma(\rho^0)/\sigma(\rho^\pm)$ and $\sigma(\omega)/\sigma(\rho^\pm)$ quantify first-class leading-particle effects in ρ^0 and ω production which are not present for $\rho^\pm$.

Guided by the data, the invariant cross-sections were decomposed into a diffractive (D) and a non-diffractive part (N) on the basis of the following assumed relations:

$$F(\rho^0) = N + D,$$

$$F(\omega) = N + 1/9 D.$$

Figure 14 shows the component D as a function of x_F as derived from the ρ^0 and ω data. A simple estimate of this diffractive part can be obtained if we assume Pomeron dominance, Pomeron factorization, and the validity of the triple-Regge formalism (see fig. 14). With these assumptions, the inclusive cross-section for $\gamma p \rightarrow \rho^0 X$ is given by

$$d^2\sigma/dtdx_F = \beta_{\gamma\rho P}(0)\beta_{\gamma\rho P}^2(t)G_{PPP}/16\pi(1-x_F),$$

and the differential cross-section for $\gamma p \rightarrow \rho^0 p$ is given by

$$d\sigma/dt = (1/16\pi)\beta_{\gamma\rho P}^2(t)\beta_{ppP}^2(t).$$

Here $\beta_{\gamma\rho P}(t)$ is the γ - ρ -Pomeron vertex form-factor, $\beta_{ppP}(t)$ is the proton-proton-Pomeron vertex form factor, and G_{PPP} is the triple-Pomeron coupling. For the latter we use the result of a triple-Regge fit [16] to the pp-data of Albrow et al. [17], yielding $G_{PPP} \simeq 0.25 \text{ mb}^{1/2} \simeq 0.40 (\text{mb} \cdot \text{GeV}^{-2})^{1/4}$ with rather small errors.

Away from the very small t region, the mean slope of pp elastic scattering at 40 GeV is $\simeq 10 \text{ GeV}^{-2}$. Using the parametrization of the pp total cross-section of Donnachie and Landshoff [18] to obtain the Pomeron component at 40 GeV, we find

$$\beta_{pp}^2(t) = 51.3 \exp(-5|t|)(\text{mb} \cdot \text{GeV}^{-2})^{1/2}.$$

The average value of the forward differential cross-section for $\gamma p \rightarrow \rho^0 p$ over the energy range $20 < E_\gamma < 70 \text{ GeV}$ is $76 \pm 14 \mu\text{b GeV}^{-2}$ [1], and fitting the differential cross-section with a single exponential gives a slope of $\simeq 8 \text{ GeV}^{-2}$. Hence we find

$$\beta_{\gamma p}^2(t)/16\pi \simeq 1.48 \times 10^{-3} \exp(-3|t|)(\text{mb} \cdot \text{GeV}^{-2})^{1/2}.$$

Our final result for the diffractive component of $\gamma p \rightarrow \rho^0 X$ is thus

$$d^2\sigma/dt dx_F \simeq [(4.2 \pm 0.5)/(1 - x_F)] \exp(-3|t|)(\mu\text{b} \cdot \text{GeV}^{-2})$$

or equivalently,

$$D(x_F) = (E^*/p_{\text{max}}^*)(0.43 \pm 0.05)/(1 - x_F) (\mu\text{b}).$$

This result is shown as the band in fig. 15. It provides a satisfactory description and supports the separation of the data into diffractive and non-diffractive components.

The diffractive effect in inelastic ρ^0 photoproduction is probably accompanied by a mass skewing effect (see Section 3.3), suggesting that there is the same “distortion” involved as in the “elastic” process $\gamma p \rightarrow \rho^0 p$. Further insight would require an extension of the kinematic range (in x_F and p_T^2) and various details such as, for instance, a study of vector-meson spin alignments. This will be one of the subjects of a forthcoming experiment [19].

The component N is shown in fig. 16 and compared with $1/2[F(\rho^+) + F(\rho^-)]$. The observed agreement over the whole x_F range 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:

$$1/2[F(\rho^+) + F(\rho^-)] = N.$$

The general picture which has emerged of non-diffractive particle production at high x_F (see ref. 3) is that in which a high- x quark from the beam particle combines with a low- x quark from the target to produce the observed hadron. The inclusive distribution is then given by the structure function of a fast forward moving valence quark which recombines with a slow sea quark to produce the outgoing hadron. This is the extreme limit of the quark fusion model, in which the general expression for the reaction $A + B \rightarrow C + X$ is

$$(2E/\sqrt{s})(d\sigma/dx_F) = (4\pi^3/3m_c^2) \sum_q (g_q^2/4\pi) \times [F_A^q(x_1) F_B^{\bar{q}}(x_2) + F_B^{\bar{q}}(x_1) F_A^q(x_2)].$$

Here $F^q(x)$ are the quark distributions with the sum running over all types of quark q , and g_q is the effective coupling of C to $q\bar{q}$. The fractional momenta of beam and target (x_1 and x_2 , respectively) carried by the quarks are given by

$$x_1 - x_2 = x_F, \quad x_1 x_2 = m_C^2/s.$$

Obviously, as $x_F \rightarrow 1$, $x_1 \rightarrow 1$, $x_2 \rightarrow m_C^2/s \simeq 0$, so that the cross-section is dominated by the valence quarks of the beam and the sea quarks of the target particle, i.e. it goes over to the recombination model.

In the recombination model the inclusive data at large x_F simply reflect directly the valence quark distribution of the beam particle, in this case primarily the ρ^0 , through vector dominance. An earlier analysis of central ϕ photoproduction [5] demonstrated that the vector-meson valence-quark distributions are consistent with those of the pion, i.e. $\sim (1 - x)$ as $x \rightarrow 1$. A more precise form of the pion valence-quark distribution is given by $x(1 - x)$ [20]. Both of these are consistent with the data of fig. 16 for $x_F \gtrsim 0.5$.

To extend this description of the data to smaller x_F we generalize to the fusion model. Although the theoretical justification for this approach to the production of light-mass states such as the ρ is not well founded, we do note that it appears to be valid for ϕ production, both in photon interactions and in pion interactions [5,21].

Including the contribution from the valence quarks of the proton, as well as that from the sea, we have

$$(2E/\sqrt{s})(d\sigma/dx_F) \sim V_\rho(x_1) [\alpha V_p(x_2) + \beta S_p(x_2)].$$

Here $V_\rho(x)$ is the valence-quark distribution of the ρ , which we take as $\sim x(1 - x)$, and $V_p(x)$ and $S_p(x)$ are, respectively, the valence- and sea-quark distributions of the proton for which we use those of Moore [20]. For ρ^- and ρ^0 production $\alpha = 1, \beta = 2$, and for ρ^+ production $\alpha = 2, \beta = 2$, i.e. there is in principle a difference between ρ^+ and ρ^- . However, as we have stressed, the proton sea-quark distribution dominates so there is no detectable difference in the data. The result of this calculation is shown as the solid line in fig. 16, with arbitrary normalization. It clearly — and perhaps surprisingly — provides a good description of the data for $x_F \gtrsim 0$.

5. SUMMARY AND CONCLUSIONS

The inclusive photoproduction of the vector mesons ρ^0 , ω , and $\rho^\pm$ on hydrogen has been observed, averaged over the photon energy range from 20 to 70 GeV and over the x_F range of the vector meson from -0.2 to 0.95 , with total cross-sections of $\sigma(\gamma p \rightarrow \rho^0 X) = 21.6 \pm 1.0 \mu\text{b}$, $\sigma(\gamma p \rightarrow \omega X) = 15.8 \pm 2.4 \mu\text{b}$, and $[\sigma(\gamma p \rightarrow \rho^+ X) + \sigma(\gamma p \rightarrow \rho^- X)] = 27.9 \pm 6.4 \mu\text{b}$. These results have an additional estimated systematic uncertainty of $\pm 2.2 \mu\text{b}$.

The Lorentz-invariant differential cross-sections for ρ^0 , ω , and $\rho^\pm$ are approximately equal in the central region [$\sigma(\rho^0) \simeq \sigma(\omega) \simeq 1/2 [\sigma(\rho^+) + \sigma(\rho^-)]$], but show significant differences with increasing x_F : $d\sigma(\rho^0)/dx_F$ builds up a strong forward peak; $d\sigma(\omega)/dx_F$ flattens; and $d\sigma(\rho^\pm)/dx_F$ decreases rapidly for $x_F \gtrsim 0.6$. The excess of ρ^0 and ω photoproduction relative to $\rho^\pm$ in the forward direction can most simply be interpreted in the picture of vector-meson dominance where the ρ^0 and

ω , as beam particles, give rise to a diffraction peak, whereas the $\rho^\pm$ has to be produced in the collisions. This picture of forward diffractive production is confirmed by explicit calculation, assuming Pomeron factorization. The ρ^+ , ρ^- and non-diffractive ρ^0 , ω production is consistent with a simple quark recombination (quark fusion picture), and indicates that the valence-quark distribution of the vector meson is the same as that of the pion.

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REFERENCES

- [1] D. Aston et al., Nucl. Phys. **B209** (1982) 56.
- [2] M. Atkinson et al., preprint CERN-EP/83-45 (1983), to be published in Nucl. Phys. B.
- [3] See, for example, P.D.B. Collins and A.D. Martin, Rep. Prog. Phys. **45** (1982) 335.
W. Kittel and V. Fialkowski, Rep. Prog. Phys., to be published.
- [4] See, for example, M. Barth et al., Nucl. Phys. **B223** (1983) 296.
- [5] D. Aston et al., Nucl. Phys. **B179** (1981) 215.
- [6] E. Kogan et al., Nucl. Phys. **B122** (1977) 383.
- [7] C.A. Nelson et al., Phys. Rev. D **17** (1978) 647.
- [8] Experiments at CERN in 1980 (CERN, Geneva, 1980); experiment WA57.
- [9] A. Schlösser, Univ. Bonn report IR-80-11 (1980).
- [10] M. Atkinson et al., preprint CERN EP/83-106 (1983), submitted to Nucl. Phys. B.
- [11] M. Ross and L. Stodolsky, Phys. Rev. **149** (1966) 1172.
- [12] J. Bröring, Univ. Bonn report IR-82-7 (1982).
- [13] V. Liebenau, Univ. Bonn report IR-83-14 (1983).
- [14] M. Deutschmann et al., Nucl. Phys. **B103** (1976) 426.
- [15] T.H. Bauer et al., Rev. Mod. Phys. **50**, No. 2 (1978).
- [16] A. Donnachie and P.V. Landshoff, private communication.
- [17] M.G. Albrow et al., Nucl. Phys. **B108** (1976) 1.
- [18] A. Donnachie and P.V. Landshoff, preprint Manchester-TH83-13 (1983), to be published in Nucl. Phys. B.
- [19] Experiments at CERN in 1983 (CERN, Geneva, 1983); experiment WA69.
- [20] R. Moore, J. Phys. **G5** (1979) 1509.
- [21] C. Daum et al., Nucl. Phys. **B186** (1981) 205 and Z. Phys. **C1** (1983) 1.
Yu.M. Antipov et al., Phys. Lett. **110B** (1982) 326.
P. Sixel et al., Nucl. Phys. **B199** (1982) 381.

Table 1
Results of fits to the $\pi^+\pi^-\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\pi^0$ mass distributions as explained in the text

Particle combination	Data set	Resonance	Mass (MeV)	Width (MeV)	Resonance signal (No. of events)	χ^2/DOF	Comment
$\pi^+\pi^-$	Fig. 2	ρ^0	775 fixed	145 fixed	11540 ± 1957	1.46	With RS factor
	Fig. 7a-f	ρ^0	775 fixed	145 fixed	10292 ± 423	-	Sum of single fits with RS factor
$\pi^+\pi^-\pi^0$	Fig. 3	ω	783 fixed	34.2 ± 4.8	1942 ± 231	1.30	Sum of single fits
	Fig. 8a-f	ω			1886 ± 180	-	
$\pi^+\pi^0$	Fig. 4	$\rho^\pm$	775 fixed	145 fixed	2981 ± 348	1.20	Sum of single fits
	Fig. 9a-f				3122 ± 346	-	
$\pi^+\pi^-$	$0.3 < x_F < 0.6$	ρ^0	753 ± 4	145 fixed	4116 ± 247	1.20	Without RS factor
			774 ± 4	145 fixed	3598 ± 216	1.34	With RS factor
$\pi^+\pi^-$	$0.6 < x_F < 0.8$	ρ^0	761 ± 5	145 fixed	1326 ± 86	1.40	Without RS factor
			786 ± 4	145 fixed	1333 ± 89	1.39	With RS factor
$\pi^+\pi^-$	$0.8 < x_F < 0.95$	ρ^0	743 ± 5	145 fixed	828 ± 50	1.37	Without RS factor
			770 ± 4	145 fixed	775 ± 54	1.30	With RS factor

Table 2
Fit results to p_T^2 distributions

Fit	$d\sigma/dp_T^2 = A \cdot \exp(-a \cdot p_T^2)$		$d\sigma/dp_T^2 = A \cdot \exp(-a \cdot p_T^2 - b \cdot p_T^4)$			Fit range		
	$A [\mu\text{b} \cdot \text{GeV}^{-2}]$	$a [\text{GeV}^{-2}]$	χ^2/DOF	$A [\mu\text{b} \cdot \text{GeV}^{-2}]$	$a [\text{GeV}^{-2}]$	$b [\text{GeV}^{-4}]$	χ^2/DOF	(GeV^2)
ρ^0	64.86 ± 7.53	3.03 ± 0.35	1.96/7	69.16 ± 10.34	3.59 ± 0.89	-0.70 ± 0.94	1.55/6	$0 < p_T^2 < 1.4$
	64.16 ± 9.20	2.88 ± 0.64	0.4/3					$0 < p_T^2 < 0.5$
ω	61.57 ± 8.73	4.20 ± 0.54	5.19/7	72.29 ± 12.10	5.62 ± 1.09	-1.98 ± 1.15	3.17/6	$0 < p_T^2 < 1.4$
	64.20 ± 10.36	4.39 ± 0.80	3.75/3					$0 < p_T^2 < 0.5$

Figure captions

- Fig. 1 Distribution of $m_{\mathbf{x}}^2$, the mass-squared recoiling against any $\pi^+\pi^-$ system of an event, a) for the main data set (charged-particle multiplicity between 3 to 8) and b) for the second data set (charged forward multiplicity 2).
- Fig. 2 Distribution of $m_{\pi^+\pi^-}$ for the main data set (charged-particle multiplicity 3 to 8).
- Fig. 3 Distribution of $m_{\pi^+\pi^-\pi^0}$ for the main data set (charged-particle multiplicity 3 to 8).
- Fig. 4 Distribution of $m_{\pi^\pm\pi^0}$ for the main data set (charged-particle multiplicity 3 to 8).
- Fig. 5 The number of a) ρ^0 and b) ω as a function of the charged-particle multiplicity NCT (main data set) corrected for the geometrical trigger acceptance indicated by the curve.
- Fig. 6 The number of a) ρ^0 and b) ω as a function of $m_{\mathbf{x}}^2$, the mass-squared recoiling against the vector meson (combined data sets) corrected for the geometrical trigger acceptance indicated by the curve.
- Fig. 7 Distributions of $m_{\pi^+\pi^-}$ for various intervals of $x_F(m_{\pi^+\pi^-})$: a) $-0.2 < x_F < 0$; b) $0 < x_F < 0.2$; c) $0.2 < x_F < 0.4$; d) $0.4 < x_F < 0.6$; e) $0.6 < x_F < 0.8$; f) $0.8 < x_F < 0.95$.
- Fig. 8 Distribution of $m_{\pi^+\pi^-\pi^0}$ for the corresponding x_F intervals as in fig. 7.
- Fig. 9 Distribution of $m_{\pi^\pm\pi^0}$ for the corresponding x_F intervals as in fig. 7.
- Fig. 10 Distribution of $d\sigma/dx_F$ for inclusive a) ρ^0 , b) ω , and c) $\rho^\pm$ production for the main data set (open circles) and for the combined data sets (full points). The data points have been corrected for geometrical acceptance which varies with x_F as shown.
- Fig. 11 Distribution of $d\sigma/dp_T^2$ for inclusive a) ρ^0 and b) ω production. The data are corrected for acceptance losses. The line corresponds to a fit of $d\sigma/dp_T^2 = A \cdot \exp(-ap_T^2 - bp_T^4)$ given in table 2.
- Fig. 12 Distribution of the invariant cross-section $F(x_F) = (1/\pi)(E^*/p_{\max}^*)(d\sigma/dx_F)$ for inclusive a) ρ^0 , b) ω , and c) $\rho^\pm$ production. The full points are this experiment. The data points drawn in for comparison are from ref. 6: $\gamma p \rightarrow \rho^0 X$ at 9.3 GeV (open circles in fig. 12a), and from ref. 14: $\pi^\pm p \rightarrow \rho^0 X$ at 16 GeV (∇ in fig. 12a).
- Fig. 13 Distribution of a) $\sigma(\rho^0)/\sigma(\omega)$, b) $\sigma(\rho^0)/\sigma(\rho^\pm)$, and c) $\sigma(\omega)/\sigma(\rho^\pm)$ as a function of x_F of the vector mesons (V). P indicates pomerons.
- Fig. 14 Triple-Regge diagram for diffractive photoproduction of vector mesons.
- Fig. 15 The component D as a function of x_F as derived from the ρ^0 and ω data. The curve is explained in the text.
- Fig. 16 The component N as a function of x_F as derived from the ρ^0 and ω data (full points) and from the $\rho^\pm$ data (squares). The straight line and the curve are explained in the text.

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