INCLUSIVE PHOTOPRODUCTION OF ϕ MESONS AT PHOTON ENERGIES OF 25-70 GeV

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ABSTRACT

Results are presented on inclusive ϕ photoproduction for incident energies between 25 and 70 GeV. Distributions in Feynman x , p_T and decay angles are presented and interpreted in terms of quark fusion models. We demonstrate a similarity with the corresponding pion-induced reaction and obtain information on the hadronic nature of the photon.

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1. INTRODUCTION

Studies of inclusive ϕ production using hadron beams [1] have indicated that the process is dominated by ϕ mesons produced centrally, i.e. at small values of Feynman x ($x_F \equiv 2p_L^*/\sqrt{s}$). These data have been interpreted in terms of quark fusion models. In the present investigation, inclusive ϕ photoproduction has been studied. The photon can interact either as a hadron or by a more direct point-like process. We find that, in the present reaction, the photon behaves much like a hadron for production both in the central region and for $x_F \approx 1$ where a diffractive mechanism dominates. Our photon energy range of 25-70 GeV overlaps the mean energies used in previous hadron beam studies.

2. EXPERIMENTAL PROCEDURES

The data were obtained at the CERN Super Proton Synchrotron (SPS) as part of a photoproduction experiment using a tagged photon beam and the Omega spectrometer. Full details of the apparatus are given elsewhere [2]. The data considered here were primarily derived from a trigger which required a charged particle multiplicity of between 4 and 9 in a forward detector together with at least one of the charged particles being flagged as a kaon by a threshold Čerenkov counter. This Čerenkov counter, filled with carbon dioxide at atmospheric pressure, was divided into 32 cells and enabled kaons and pions of momenta between 5.7 and 17.0 GeV/c to be distinguished. To reject a background of purely electromagnetic events, the trigger also required that at least one particle was detected outside the median plane.

Pattern recognition and geometrical reconstruction of the events in Omega were carried out using the program ROMEO. Events were selected by requiring that at least one positively and one negatively charged particle were in the momentum range 5.7 to 17.0 GeV/c and gave no signal in the Čerenkov counter. Such particles were classified as kaons, although there was at this stage a small background of protons and antiprotons. The event vertex was required to be within the hydrogen target, and at least four charged particles were required to be fitted to this vertex. Cuts on the dip angle of tracks were also applied to eliminate a small residual electromagnetic background.

The resulting K^+K^- invariant mass distribution is shown in fig. 1. There are ~ 4000 ϕ mesons giving a FWHM of 8 MeV which is consistent with the experimental resolution. All results in this paper were obtained by taking events in the ϕ -peak region ($1.010 < m_{K^+K^-} < 1.030$ GeV) and subtracting backgrounds deduced from sideband regions ($0.995 < m_{K^+K^-} < 1.005$ GeV, and $1.035 < m_{K^+K^-} < 1.045$ GeV). The mean observed charged multiplicity of events containing a ϕ meson is 6, which is the same as the mean multiplicity for the general sample of events observed with this trigger. Tests show that no significant number of ϕ mesons has been rejected by the elimination of electromagnetic events.

3. ACCEPTANCE

Since we are studying ϕ production inclusively, events do not have to be reconstructed completely, but have merely to satisfy the trigger requirements and have two reconstructed kaons. Most events in the data sample have six or seven charged particles in the final state, and many have at least one π^0 reconstructed in the photon detector. Owing to undetected particles, the majority of events also have a substantial amount of missing energy. For these reasons we take the two reactions

$$\gamma p \rightarrow K^+K^- \pi^+ \pi^- \pi^0 p$$

and

$$\gamma p \rightarrow K^+K^- \pi^+ \pi^- \pi^+ \pi^- \pi^0 \pi^0 p ,$$

as models to estimate the acceptance. Events were generated by a Monte Carlo method with p_T -limited phase space, as seen in our data for other channels [2,3]. The beam energy spectrum was given a $1/E_\gamma$ dependence and the ϕ decay distribution was taken to be isotropic. The resulting distributions of x_F and p_T for the ϕ meson from both simulated reactions are not significantly different from each other or from the experimental data.

Figure 2 shows the acceptance as a function of x_F and beam energy E_γ . Only a small range of x_F has good acceptance for a given value of E_γ , and this range varies with E_γ . The large areas of zero acceptance are due to one or both kaons not being in the momentum range required for identification in the Čerenkov

counter. Further effects on the acceptance are due to the trigger requirement of four to nine charged particles in a forward detector and to overlap between pions and kaons, causing failure of the kaon identification. The former effect cuts the acceptance severely for $x_F \geq 0.8$, while the latter has more effect for higher photon energies or for low- p_T tracks.

4. THE x_F AND p_T DISTRIBUTIONS

The cross-section for inclusive ϕ photoproduction, corrected for the decay branching ratio, is shown in fig. 3. As well as the statistical errors shown, there is an over-all normalization uncertainty of $\sim 30\%$. The data are divided into three ranges of E_γ , using in each case only that range of x_F throughout which the acceptance was greater than 20%. The values of $d\sigma/dx_F$ for different E_γ ranges match up well in the overlap regions: there is no significant variation of $d\sigma/dx_F$ with E_γ .

Also shown in fig. 3 are some ϕ photoproduction data obtained from a separate, parallel trigger in our experiment, which required two and only two charged particles in the forward direction giving no observed signal in the Čerenkov counter. The ϕ mesons from these events (which have a low reconstructed charge multiplicity but may have further undetected particles) are restricted to $E_\gamma < 34$ GeV because of the limitations of the Čerenkov counter. These events are for $x_F > 0.8$ but exclude elastic production for which $x_F > 0.95$. These results illustrate production at large x_F , which would be expected to be mainly in the two-prong trigger. However, they must be treated with caution because of a possible loss due to events which do not satisfy the trigger. The peaking at large x_F indicates production of ϕ mesons by a diffractive mechanism involving target break-up.

Figure 4 shows the p_T^2 distribution for ϕ mesons with $x_F < 0.7$. The data are well represented by an exponential in p_T^2 with a slope of -2.2 ± 0.1 (GeV/c) $^{-2}$. For $x_F > 0.7$, the p_T^2 slope appears to be significantly steeper with a value of -3.0 ± 0.3 (GeV/c) $^{-2}$.

5. DECAY ANGULAR DISTRIBUTION

The decay angular distribution has been studied in both the helicity and the Gottfried-Jackson frames. The polar angle θ is defined as the angle between the K^+ direction in the ϕ -meson rest frame and the z-axis appropriate to the frame. To ensure that there are no regions of zero acceptance in the decay angular distribution, events were selected such that the ϕ -meson momentum was between 17 and 26 GeV/c. The acceptance is then effectively constant as a function of the decay angles. Since the shape of the angular distribution is not affected by the biases in acceptance at large x_F , we include all results from the four- to nine-prong trigger and do not place any restriction on x_F .

The azimuthal angular distributions are consistent with being flat. Figures 5 and 6 show the $\cos \theta$ distributions in the helicity and Gottfried-Jackson frames for two ranges of x_F . The $\cos \theta$ distributions have been fitted to the form $A(1 + \alpha \cos^2 \theta)$, and the results for the parameter α are given in table 1.

There is a clear difference in the decay angular distribution for the data above and below a value of $x_F \sim 0.7$. For $x_F < 0.7$, the ϕ -meson decay is reasonably consistent with being isotropic in the helicity frame, whilst for $x_F > 0.7$, $\alpha_H \sim -1$, indicating an s-channel helicity conserving production mechanism. This clearly points to there being at least two production mechanisms, one for the central region and one for the region of large x_F . In the Gottfried-Jackson frame we find $\alpha_{GJ} = -0.4 \pm 0.1$ for $x_F < 0.7$ and $\alpha_{GJ} = 0.1 \pm 0.2$ for $x_F > 0.7$.

An alternative analysis in terms of spin-density matrix elements shows that the off-diagonal elements are consistent with zero (see table 2).

6. INTERPRETATION AND THE PHOTON STRUCTURE FUNCTION

We have shown that the data on ϕ photoproduction are consistent with there being two production mechanisms. For one of these, for $x_F > 0.7$, the peaking in $d\sigma/dx_F$ indicates diffractive production. This is supported by the evidence for s-channel helicity conservation as is observed in other double diffractive dissociation processes [4].

The second mechanism, for $x_F < 0.7$, produces ϕ mesons which are essentially unaligned and which are strongly peaked centrally. This behaviour is similar to that observed in ϕ production in πp collisions [1]. Figure 7 shows our highest energy data together with results obtained with a π^- beam of 63 GeV/c. The pion cross-sections have been divided by a factor of 200 so that they are suitably normalized for the comparison. [This normalization factor is consistent with Vector Dominance Model (VDM) expectations.] Both the shape of $d\sigma/dx_F$ and the decay angular distribution of the ϕ meson are similar for production by pions and by photons. The only observed difference is that the p_T^2 slope is somewhat steeper in pion production, having a value of -3.4 ± 0.3 [1].

The data on ϕ production in pion-proton collisions have been successfully described by the quark fusion model [1]. Hence it is natural to invoke the same mechanism for the central part of the photoproduction data, with the photon behaving like a hadron through the Vector Dominance Model:

$$|\gamma\rangle = \frac{e}{F_\rho} |\rho\rangle + \frac{e}{F_\omega} |\omega\rangle + \frac{e}{F_\phi} |\phi\rangle .$$

A general expression for the quark fusion [5] cross-section for the reaction $A + B \rightarrow \phi + X$ is

$$\frac{d\sigma}{dy} = \frac{2E}{\sqrt{s}} \frac{d\sigma}{dx_F} = \frac{4\pi^2}{3m_\phi^2} \sum_a \frac{g_a^2}{4\pi} \left[F_A^a(x_1) F_B^{\bar{a}}(x_2) + F_A^{\bar{a}}(x_1) F_B^a(x_2) \right] . \quad (1)$$

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

$$x_1 - x_2 = x_F ; \quad x_1 x_2 = m_\phi^2/s . \quad (2)$$

We have allowed for separate contributions from u and d quarks, with Zweig-violating coupling g , and s quarks with a normal hadronic coupling g_s . It is suggested that both contributions occur for J/ψ and T production in hadron-hadron collisions [5]. The Zweig-violating coupling of the ϕ is expected to be appreciably larger than for either of those particles, and it has been proposed [6] that $g^2/g_s^2 \approx 0.06$ for the ϕ .

Because of the small value of m_ϕ^2/s in the present experiment, and the range of x_F covered, the kinematical relations (2) constrain the fractional momentum x_2 of the quark coming from the proton to lie in the range $0.02 \lesssim x_2 \lesssim 0.04$. Thus it is reasonable to assume that the proton contribution is dominated by sea quarks. Equivalently, the fractional momentum x_1 of the quark coming from the photon is comparatively large, so it is reasonable to assume that the photon contribution is dominated by valence quarks. With these assumptions, and in addition taking the quark distributions of the ρ , ω and ϕ to be the same, the cross-section for photoproduction in the central region is given by

$$\begin{aligned} \frac{d\sigma}{dy} &= \frac{2E}{\sqrt{s}} \frac{d\sigma}{dx_F} = \frac{4\pi^2\alpha}{3m_\phi^2} \left[\frac{g^2}{4\pi} \left(\frac{4\pi}{f_\rho^2} + \frac{4\pi}{f_\omega^2} \right) + \frac{r_s g_s^2}{4\pi} \frac{4\pi}{f_\phi^2} \right] 2F_V(x_1) S_P(x_2) \\ &= \text{const } F_V(x_1) S_P(x_2) . \end{aligned} \quad (3)$$

Here r_s is the relative fraction of strange quarks found in the proton sea, $F_V(x_1)$ is the valence-quark distribution of the vector mesons, and $S_P(x)$ is the sea-quark distribution of the proton.

The quark distributions of the proton are reasonably well known; we have specifically used those of Moore [7]. Nothing is known about the quark distributions of the vector mesons, so as a first guess we take them to be the same as those of the pion [7]. The results of the calculation are shown as the solid line in fig. 7, where the normalization has been adjusted to fit the data. Taking $g^2/g_s^2 = 0.06$, $r_s = 0.5$, it corresponds to $g_s^2/4\pi = 1.5$ which is perfectly acceptable.

In terms of the quark fusion model, with unpolarized quarks, the angular distribution of the K^+ in the Gottfried-Jackson frame is given by $(1 + \alpha \cos^2 \theta)$ with

$$\alpha = -(1 - 4m_q^2/m_\phi^2) , \quad (4)$$

where m_q is the mass of the quark involved. If the ϕ is produced predominantly by s quarks ($m_q \approx 0.5$) then we expect $\alpha \approx 0$. Alternatively, if the ϕ is produced predominantly by u, d quarks ($m_q \approx 0.3$) then $\alpha \approx -0.65$. The observation that the off-diagonal spin matrix elements are consistent with zero can be interpreted in this model as an absence of quark polarization.

In the simple model presented above, the ratio of s quark to u,d quark production is

$$R_s = \frac{r_s g_s^2}{g^2} \frac{f_\rho^2 f_\omega^2}{f_\phi^2 (f_\rho^2 + f_\omega^2)}, \quad (5)$$

which has the value ~ 1.4 for $r_s \sim 0.5$. In other words, we expect s quarks to contribute about equally with u,d quarks. This expectation is consistent with the value of $\alpha = -0.36 \pm 0.09$ found in this experiment.

An alternative development from eq. (3) is to use it to obtain the shape of F_V directly from the data. The absolute magnitude cannot be obtained because of the normalization uncertainty in the data and because of the intrinsic uncertainty in the magnitude of g^2 and g_s^2 (though not in their ratio). The results are shown in fig. 8, and the solid line comes from a fit to the pion structure function [7]. Not unexpectedly, the agreement is good.

As an alternative to the hadronic structure function which we have used here for the photon, we could have considered the QCD structure function arising from the point interaction of the real photon [8]. In this case, eq. (3) is replaced by

$$\begin{aligned} \frac{d\sigma}{d\gamma} &= \frac{2E}{\sqrt{s}} \frac{d\sigma}{dx_F} = \frac{4\pi\alpha^2}{3m_\phi^2} \ln(m_\phi^2/\Lambda^2) \left(\frac{5}{9} \frac{g^2}{4\pi} + \frac{1}{9} \frac{r_s g_s^2}{4\pi} \right) 2F_\gamma(x_1) S_p(x_2) \\ &= \text{const } F_\gamma(x_1) S_p(x_2), \end{aligned}$$

where Λ is the scale parameter for QCD, and $F_\gamma(x_1)$ is the (suitably normalized) standard QCD structure function. This, with arbitrary normalization, is shown as the broken line in fig. 8 and clearly cannot provide a good description of the data. This is not surprising, since with Λ in the usually accepted range 0.5-1.0, the contribution of this point-like process for our conditions is expected to be small compared with the VDM contribution.

We conclude that the data on ϕ photoproduction in the central region are consistent with the quark fusion model, with the photon interacting as a hadron through vector-meson dominance. There is no evidence in this experiment for a contribution from the point-like interaction of the real photon.

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REFERENCES

- [1] ACCMOR Collaboration and others reported by D.R.O. Morrison, preprint CERN-EP/79-102 (1979).
- [2] D. Aston et al., Nucl. Phys. B166 (1980) 1.
- [3] D. Aston et al., preprint CERN-EP/80-31 (1980), to be published in Nuclear Physics.
- [4] E. Kogan, Nucl. Phys. B122 (1977) 383.
- [5] R. Moore and A. Donnachie, J. Phys. G 4 (1978) 1835.
A. Donnachie and P.V. Landshoff, Z. Phys. C 4 (1980) 231.
- [6] A. Donnachie and P.V. Landshoff, Nucl. Phys. B112 (1976) 233.
- [7] R. Moore, J. Phys. G 5 (1979) 1509.
- [8] C. Llewellyn Smith, Phys. Lett. 79B (1978) 83.

Table 1

Values of α from a fit of the ϕ decay distributions to $A(1 + \alpha \cos^2 \theta)$

Range	Helicity	Gottfried-Jackson
$0.2 < x_F < 0.7$	-0.31 ± 0.09	-0.36 ± 0.09
$0.7 < x_F < 1$	-0.89 ± 0.08	$+0.06 \pm 0.23$
$0.4 < x_F < 0.6$	-0.36 ± 0.13	-0.44 ± 0.12
$0.2 < x_F < 0.4$	-0.09 ± 0.17	-0.25 ± 0.15
$p_T^2 < 0.6$	-0.30 ± 0.11	-0.40 ± 0.10
$p_T^2 > 0.6$	-0.29 ± 0.16	-0.19 ± 0.18

Table 2

Spin-density matrix elements for $x_F < 0.7$

	Helicity	Gottfried-Jackson
ρ_{00}	0.32 ± 0.04	0.28 ± 0.04
ρ_{11}	0.34 ± 0.04	0.36 ± 0.04
ρ_{1-1}	0.05 ± 0.03	0.05 ± 0.03
$\text{Re}(\rho_{10})$	-0.02 ± 0.02	0.02 ± 0.02

Figure captions

- Fig. 1 : K^+K^- effective mass.
- Fig. 2 : Acceptance contours for ϕ mesons as a function of x_F and E_γ . The numbers on the contours indicate the fractional acceptance and the acceptance is zero for all points outside the 0 contour.
- Fig. 3 : x_F distributions both for the main multiplicity data (in three different energy ranges) and for data taken with a two-prong trigger. The data clearly indicate the absence of a dependence of the cross-section on E_γ .
- Fig. 4 : p_T^2 distributions for $x_F < 0.7$. The line is a fit to the data.
- Fig. 5 : Distribution of $\cos \theta$ in the helicity and Gottfried-Jackson frames for $x_F < 0.7$.
- Fig. 6 : Distribution of $\cos \theta$ in the helicity and Gottfried-Jackson frames for $x_F > 0.7$.
- Fig. 7 : Comparison of x_F distributions for ϕ photoproduction from this experiment with previous hadron work; the shape expected on a theoretical model is shown, and is normalized approximately to the photon results. For comparison purposes, the cross-section for hadron-induced reactions has been divided by 200.
- Fig. 8 : Photon structure function. The solid curve shows the approximate shape of the pion structure function, while the dashed curve is for a QCD structure function. The relative normalizations are arbitrary.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8