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A STUDY OF A_2 - AND g -RESONANCE PRODUCTION IN $\pi^- p \rightarrow K^- K^0 p$

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ABSTRACT

We present the results and the analysis of a high-statistics experiment to study A_2 and g production in the reaction $\pi^- p \rightarrow K^- K_S^0 p$ at 10 GeV/c. In each resonance region we perform a moment analysis of the data; and from the moments we determine the production amplitudes as a function of t . We find A_2 production proceeds dominantly by natural-parity (pomeron and f) exchange. We compare A_2 and diffractive $K^*(1420)$ production. We find g production proceeds by π and ω exchange; we determine the $g \rightarrow K\bar{K}$ branching ratio.

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1. INTRODUCTION

We study the reaction $\pi^- p \rightarrow K^- K_S^0 p$ at 10 GeV/c using the University of Geneva two-arm spectrometer¹⁾. We collected 40,000 such events. We determine the moments of the K^- angular distribution, and from these the production amplitudes, as a function of t , in the A_2 - and in the g -resonance regions. The information we obtain for $\pi^- p \rightarrow A_2^- p$ is complementary to that obtained for the reactions $K^+ p \rightarrow K^*(1420)^+ p$ by the same apparatus at the same energy^{2,3)}. A study of this set of diffractive processes is invaluable in determining properties of pomeron exchange and in attempts to unravel the pomeron- and f -exchange contributions. Recent studies can be found elsewhere^{4,5)}. On the other hand, g production is non-diffractive and proceeds via π and ω exchange. We shall see that the difference between A_2 and g production is strikingly evident in the data, and in the structure of the underlying amplitudes. The prominence of π exchange in g production allows the determination of the product of the $\pi\pi$ and $K\bar{K}$ branching ratios of the g resonance.

The organization of the paper is as follows. In Section 2 we present the moments as a function of t , firstly, in the A_2 -mass region, and, secondly, in the g -mass region. The allowed exchanges for A_2 and g production are given in Section 3, together with the definition of the amplitudes we use to describe $\pi^- p \rightarrow K^- K_S^0 p$ production. Section 4 describes the determination of the amplitudes in the A_2 -mass region; and in Section 5 we compare A_2 and $K^*(1420)$ production and discuss the implications for pomeron and f exchange. In Section 6 we perform the amplitude analysis in the g -resonance region; this is complicated by the presence of non-negligible $L = 4$ $K^- K^0$ production^{6,7)}. In Section 7 we study the interference between the resonant $L = 3$ and $L = 2, 4$ natural-parity-exchange (NPE) amplitudes in the g -mass region. We find that g production by NPE is consistent with ω -exchange expectations, and we estimate the $g \rightarrow K\bar{K}$ branching ratio by relating the ω -exchange contributions for g and ρ production. In Section 8 we study the π -exchange contribution to g production. We extrapolate to the π exchange pole and calculate the $g \rightarrow K\bar{K}$ branching ratio. We summarize our results in Section 9.

2. DATA SELECTION AND MOMENT ANALYSIS IN THE A_2 AND g REGIONS

We have measured the reaction $\pi^- p \rightarrow K_S^0 K^- p$ with a seen $K_S^0 \rightarrow \pi^+ \pi^-$ decay using the University of Geneva two-arm spectrometer. The apparatus consisted of:

- i) a beam spectrometer to measure direction, momentum, and mass of the incident particle,
- ii) a proton arm at large angle (38° to 70° in the laboratory), to measure direction and momentum of slow recoil protons in the range of momentum transfer $0.07 < -t < 1.0 \text{ (GeV/c)}^2$, using multiwire proportional chambers (MWPCs) (6 planes) and a high-precision time-of-flight system;
- iii) a forward arm, consisting of MWPCs (8 planes), to record the directions of forward emitted charged particles within a large solid angle (0.3 sr). There is no magnetic momentum analysis.

A detailed description of the spectrometer can be found in Ref. 1.

Channel identification is done first by requiring a second vertex at least 30 mm downstream from the πp vertex to select the $K_S^0 \rightarrow \pi^+ \pi^-$ candidates. Events of the correct topology are then processed by a kinematical 2C-fit, and accepted if $P(\chi^2) > 5\%$. Finally we require $M_{K^- p} > 1.9 \text{ GeV}$ to eliminate Y^* contributions and their kinematical reflections at high $K_S^0 K^-$ mass.

The quality of the data sample can be checked by estimating the background under the unfitted K^0 -mass peak, or independently, by inspecting the shape of the $P(\chi^2)$ distribution. In both cases, we find a background of 4%.

Figure 1 shows the $K_S^0 K^-$ -mass spectrum of the final sample of 40,000 events, and illustrates the dominance of A_2 and g production in this mass region. The sensitivity of the data, corrected for unseen K^0 decays, is

$$N/\sigma(\pi^- p \rightarrow K^0 K^- p) = 7670 \pm 600 \text{ weighted events}/\mu\text{b}.$$

Our cross-section normalization is in very good agreement with other $A_2^- \rightarrow K^0 K^-$ production data⁸⁾.

We have calculated the moments of the angular distribution of the K^- in the t -channel helicity frame of the $K^0 K^-$ system. We have corrected for geometrical acceptance of the spectrometer, efficiencies, and absorption and decay of incident and outgoing particles, using the linear method described in Ref. 1. Figure 2 shows the unnormalized moments $N\langle Y_J^M \rangle$ in the A_2 -mass region ($1.2 < M < 1.4$ GeV) as a function of t , as obtained by fitting the terms $J \leq 4$ and $M \leq 4$. The normalization of the spherical harmonics is such that $\langle Y_0^0 \rangle = 1$.

Figure 3 shows the moments in the g -mass region ($1.55 < M < 1.85$ GeV), resulting from a fit of the terms $J \leq 8$ and $M \leq 2$.

3. AMPLITUDES AND ALLOWED EXCHANGES IN $\pi^- p \rightarrow K^- K_S^0 p$

To extract the $\pi^- p \rightarrow K^- K_S^0 p$ amplitudes from the experimental moments it is convenient to use combinations of helicity amplitudes with definite asymptotic exchange naturality. The moments can be expressed⁹⁾ as the sum of bilinear products of these amplitudes $L_{\lambda\pm}$, where $L_{\lambda\pm}$ describe, to leading order in the energy, the production of a $K^- K_S^0$ system of spin L , helicity λ by natural- and unnatural-parity exchange, respectively. In terms of the helicity amplitudes, $H_{L\lambda}$, we have

$$L_{\lambda\pm} \equiv \left[H_{L\lambda} \pm (-1)^{\lambda+1} H_{L,-\lambda} \right] / \sqrt{2}, \quad \lambda \neq 0 \quad (1)$$

$$L_0 \equiv H_{L0},$$

that is only UPE occurs for $\lambda = 0$. We will use the abbreviated notation $L_{\pm} \equiv L_{1\pm}$. The amplitudes are normalized so that their moduli squared give the contribution to $d\sigma/dt$, that is

$$\frac{d\sigma}{dt} = |S_0|^2 + |P_0|^2 + |P_+|^2 + \dots \quad (2)$$

A summation over helicity flip and non-flip at the nucleon vertex is implicit in each bilinear product, that is

$$|L|^2 = |L_f|^2 + |L_{nf}|^2.$$

The interference terms can be rewritten in the form

$$\text{Re} (L'L^*) = |L'| \cdot |L| \cdot (\xi \cos \phi)_{L'L} , \quad (3)$$

where ξ is the degree of nucleon spin coherence ($0 \leq \xi \leq 1$) and ϕ is the relative phase between amplitudes L and L' . We note that the expressions for the observed moments do not contain interference terms between NPE and UPE amplitudes.

The observed moments, $\langle Y_J^M \rangle$ of Figs. 2 and 3, show immediately that the production mechanisms are different in the A_2 - and g-mass regions. In the spin-2 A_2 -mass region we observe strong negative $\langle Y_4^0 \rangle$ and $\langle Y_4^2 \rangle$ moments, whereas in the spin-3 g-mass region we have a positive signal in $\langle Y_6^0 \rangle$ and a weaker negative signal in $\langle Y_6^2 \rangle$. Retaining only the $\lambda \leq 1$, spin-L resonant amplitudes, these moments are

$$\begin{aligned} \langle Y_{2L}^0 \rangle &= C_1 |L_0|^2 - C_2 (|L_-|^2 + |L_+|^2) \\ \langle Y_{2L}^2 \rangle &= C_3 (|L_-|^2 - |L_+|^2) , \end{aligned}$$

where C_i are positive known coefficients. This implies that A_2 production is dominated by NPE (D_+), whereas g production proceeds mainly via UPE (F_0), and to a lesser extent via NPE (F_+). We also notice from the $J = 8$ moments that the $L = 4$ NPE amplitude (G_+) cannot be neglected in the g-resonance region.

The difference between g and A_2 production is due to the restrictions of G-parity at the meson vertex. For the production of a K^-K^0 system of spin L the allowed exchanges are given in Table 1.

From a study of the SU(3)-related reactions $K^+p \rightarrow K^{*+}p$ we expect isoscalar NPE and isovector UPE to be dominant. The pomeron (P), ω , and f exchanges contribute dominantly to over-all single helicity-flip amplitudes, which vanish as $\sqrt{-t}$ in the forward direction. For UPE, π and B couple to over-all helicity-flip amplitudes, whereas A_1 and Z quantum-number-exchange couple to over-all non-flip amplitudes. Z is used to denote the possible 2^{--} exchange-degenerate partner of the A_1 . The π -exchange pole is extremely close to the physical region so π dominates A_1 exchange in the forward scattering region. The relative strength of the amplitudes

with the quantum numbers of B and Z exchange are not so well known. There is evidence¹⁰⁻¹¹⁾ from related reactions to suggest that non-flip Z exchange is larger for $-t \lesssim 0.2 \text{ GeV}^2$, while B exchange dominates for $-t \gtrsim 0.2 \text{ GeV}^2$.

The effects manifest in the data indicate that A_2 production proceeds dominantly by pomeron and f exchange, and that g production is due to π , and to a lesser extent ω , exchange.

4. AMPLITUDE ANALYSIS IN THE A_2 -MASS REGION

The t-structure of the observed $K^- K^0$ t-channel moments in the A_2 mass region, $1.2 < M < 1.4 \text{ GeV}$, is shown in Fig. 2. The explicit relations between the moments and the production amplitudes L_+ , L_0 , and L_- are given in Table 2. The five largest moments $\langle Y_{4,2,0}^0 \rangle$, $\langle Y_{4,2}^2 \rangle$ show the dominance of the NPE amplitude D_+ , and indicate that all other amplitudes will be much less reliably determined. The non-zero $\langle Y_4^3 \rangle$ moment is attributable to interference of D_+ with the helicity-two NPE amplitude D_{2+} . The structure of $\langle Y_3^{0,2} \rangle$ can be accounted for by $P_+ D_+$ interference and shows no evidence for a $P_0 D_0$ effect. The UPE amplitudes are much harder to isolate. The moments $\langle Y_4^1 \rangle$ and $\langle Y_2^1 \rangle$, taken together with $\langle Y_4^3 \rangle$, imply small $D_0 D_-$ interference, but a larger $S_0 D_-$ contribution. There is no evidence of either a P_0 or P_- effect, except possibly $S_0 P_0$ interference in the first t bin of $\langle Y_1^0 \rangle$.

As a result of these observations, we performed an amplitude analysis of the $J \leq 4$, $M \leq 4$ moments in the A_2 -mass region in terms of the magnitudes and coherences of the NPE amplitudes, D_+ , D_{2+} , P_+ , and of the UPE amplitudes, D_0 , D_- , S_0 . Neglect of P_0 and P_- means the moments $\langle Y_{3,1}^1 \rangle$ are not included in the analysis, and as $\langle Y_3^3 \rangle$ is also compatible with zero we do not determine the $P_+ D_{2+}$ coherence. Moreover, the data cannot determine reliably the individual coherences in the weak UPE sector. We therefore assume nucleon spin-coherence and, motivated by π -B exchange degeneracy, $(\cos \phi)_{D_0 D_-} = -1$.

The results are shown in Fig. 4. We see the expected dominance of the NPE amplitude, D_+ . The clear $\langle Y_4^3 \rangle$ signal is described by a D_{2+} contribution of approximately 10% the magnitude of D_+ . The suppression of the UPE D-wave amplitudes

(associated with B and Z exchange) is to be compared with their relatively stronger π -exchange structure in $K^\pm p \rightarrow K^*(1420)^\pm p$ (see Fig. 4 of Ref. 2).

We may compare the values of $|D_0|$ of Fig. 4 with those obtained from charge-exchange (CEX) A_2^0 production. Data are available for $\pi^+ n \rightarrow A_2^0 p$ at 4 GeV/c¹²⁾, and for $\pi^- p \rightarrow A_2^0 n$ at 12 and 15 GeV/c¹³⁾. We interpolated the measured t-channel partial cross-sections $\rho_{00}^D d\sigma/dt$ using the form $p_L^{2-2\alpha}$ with $\alpha(t) = -0.2 + 0.8t$. To convert to $|D_0|^2$ we included a 4.7% $A_2 \rightarrow K\bar{K}$ branching ratio¹⁴⁾, we multiplied by $\frac{1}{2}$ due to isospin, and corrected to a $1.2 < M < 1.4$ GeV mass interval. The values obtained for $|D_0|$ at $p_L = 10$ GeV/c are indicated by the dashed line in Fig. 4. The agreement between $|D_0|$ obtained from CEX and non-CEX reactions means that there is no evidence for isoscalar UPE in $\pi^- p \rightarrow A_2^0 p$.

An interesting feature of our analysis is the importance of S-wave $K^- K^0$ production in the A_2 -mass region (see Fig. 4). In general, it is difficult to extract lower partial waves, and to study the reliability of this determination of S_0 we repeated the analysis with P_0 included, together with $P_- \equiv -0.5 P_0$, but with S_0 omitted. The description of the moments was again reasonable, though not quite as good as that with S_0 included and P_0 omitted. Essentially the only change in the amplitude components shown in Fig. 4 is that $|S_0| \rightarrow |P_0|$ and, of course, no SD interference. The same ambiguity was present in the analysis of the moments as a function of the $K^- K^0$ mass⁷⁾. There we argued, from the expected dominance of S_0 (rather than P_0) just above threshold and from the continuity of the solution as a function of mass, that the solution with the large S_0 in the A_2 region was favoured. There are other indicators that this is the physical solution. Firstly, by comparing π to ω exchange for $Kp \rightarrow K^*(890)p$, and by comparing the P-wave background in the g region (see below), there are indications that $|P_0| \lesssim |P_+|$. Secondly, by comparing $K^+ K^-$ and $K_S^0 K_S^0$ production data¹⁵⁾ (in particular the equality of the $\langle Y_2^0 \rangle$ moments) it has been noted that the P-wave π -exchange amplitude is small in our mass range. Quantitatively we find this P_0 cannot account for the required UPE contribution needed in $K^- K^0$ production. For these reasons we favour the $K^- K^0$ -amplitude solution with the relatively large S_0 and a small P_0 contribution. Even

if the two most forward points shown for $|S_0|$ are overestimated, owing to the omission of a possible P_0 contribution which peaks at small t (π exchange) and to large acceptance corrections, the t structure still implies a strong non-flip component (Z exchange) in S_0 at small t . The analysis of the data as a function of the produced K^-K^0 mass showed an S-wave enhancement in this mass range⁷⁾. This coincided with the bump previously seen in K^+K^- and $K_S^0K_S^0$ production¹⁵⁾ and suggests that it should be attributed partly to $I = 1$, and not solely to $I = 0$, S-wave $K\bar{K}$ production. The importance of the non-flip exchange component for $I = 1$ S-wave production considerably complicates the extraction of $\pi\pi \rightarrow K\bar{K}$ partial waves from $K\bar{K}$ -production data, particularly the determination of the $I = 0$ S-wave.

5. THE RELATION BETWEEN A_2 AND $K^*(1420)$ DIFFRACTIVE PRODUCTION

A_2 production by NPE in the process $\pi^-p \rightarrow A_2^-p$ proceeds via pomeron and f exchange. We may write the dominant amplitude

$$D_+(A_2) = P + f. \quad (4)$$

This contribution to the differential cross-section for A_2 production, $|D_+(A_2)|^2$, is shown in Fig. 5. It is obtained from $D_+(K^-K^0)$ of Fig. 4 after correcting for (i) the unseen A_2 decay modes (using an $A_2 \rightarrow K\bar{K}$ branching ratio of 4.7%), and (ii) for the finite mass interval (1.2-1.4 GeV) using an A_2 Breit-Wigner form.

This may be compared with $K^*(1420)$ production isolated from the related $K^\pm p \rightarrow K^0 \pi^\pm p$ reactions. High-statistics data for these latter processes have been taken, with the same spectrometer, at the same beam energy. These data were analysed²⁾ to determine the $K^0 \pi^\pm$ production amplitudes in the mass region $1.34 < M < 1.5$ GeV and $K^*(1420)$ production was also found to proceed dominantly via the NPE amplitudes $D_+(K^{*\pm})$. The differential cross-sections for $K^*(1420)$ production, or more precisely $|D_+|^2$, are also plotted in Fig. 5, after correction for the unseen^{†)} $K^*(1420)$ decay modes and for the finite mass bin. The cross-over at $-t = 0.3$ (GeV/c)² has been interpreted in terms of the pomeron-, f - and ω -exchange contributions³⁾,

$$D_+(K^{*\pm}) = \gamma P + \beta(f \mp \omega),$$

†) We include a factor of 3/2 to allow for $K^* \rightarrow K^\pm \pi^0$ and use a $K^* \rightarrow K\pi$ branching ratio of 56.1%.

where the coefficients γ and β are introduced since we have used P and f to denote the exchange contributions for A_2 production, see Eq. (4).

Here we wish to compare pomeron and f exchange in A_2 and $K^*(1420)$ production. Before confronting the data, it is informative to anticipate values of the coefficients γ and β . From $SU(3)$ -invariance and magic f, f' mixing we expect $\beta = \frac{1}{2}$. To estimate the relative coupling γ of the pomeron, we may use the f, f' -dominated pomeron hypothesis¹⁶⁾. According to this scheme^{4,5)}

$$\gamma = \frac{1}{2}(1 + r) \quad \text{with} \quad r(t) = \frac{\alpha_P - \alpha_f}{\alpha_P - \alpha_{f'}}, \quad (6)$$

where $\alpha_i(t)$ are the usual trajectory functions. In the symmetry limit $r = 1$ and the pomeron is an $SU(3)$ singlet. The departure of r from 1 represents the effect of $SU(3)$ mass breaking.

To facilitate the comparison of A_2 and $K^*(1420)$ production we plot, in Fig. 5, the ratio

$$R = \left[\frac{\sigma(K^{*+}) + \sigma(K^{*-})}{\frac{1}{2}\sigma(A_2)} \right]^{\frac{1}{2}} \quad (7)$$

versus t , where we have used the differential cross-sections, $\sigma \equiv d\sigma/dt |D_+|^2$, shown in the upper part of the figure. We have used the sum of K^{*+} and K^{*-} cross-sections to remove the interference contributions between the even (P, f) and odd (ω) G -parity exchanges. If we assume $|\omega|^2$ is small compared to $|P + f|^2$, then R is an indicator of the relative strength of the pomeron and f contributions. If the processes are dominated by pomeron exchange then we expect $R \approx 1 + r$, whereas if f exchange is dominant we expect $R \approx 1$.

From Fig. 5 we see that $R = 1.25 \pm 0.03$ for $-t < 0.4$ $(\text{GeV}/c)^2$. Assuming that $r(t) \approx 0.5$ at $-t = 0.2$ $(\text{GeV}/c)^2$, and that the relative pomeron- f phase is 60° , this value of R implies that the pomeron relative to f -exchange contribution is 1:1 in $\pi^- p \rightarrow A_2 p$, and is 1.5:1 in $Kp \rightarrow K^*(1420)p$ at 10 GeV/c .

Before closing this section it is appropriate to comment on the observed $P_+ D_+$ coherence in the A_2 region (cf. Fig. 4). This gives information on the behaviour

of the relative phase $\phi_{PD} = \delta_D + \theta_D - \delta_P - \theta_P$, where θ and δ are, respectively, the appropriate K^-K^0 production and decay phases. If we assume that the production phases θ_P and θ_D are in accordance with Regge expectations this would give information on δ_P in the A_2 region. However, the P_+D_+ coherence observed for the related $K^*(1420)$ reactions indicated anomalous behaviour for θ_P in the $K^*(1420)^\pm$ region; see, in particular, Fig. 12 of Ref. 3 [†]). We therefore cannot obtain a reliable estimate of δ_P .

6. AMPLITUDE ANALYSIS IN THE g-RESONANCE REGION

The t structure of the moments of the K^-K^0 angular distribution in the g -mass region, $1.55 < M < 1.85$ GeV, is shown in Fig. 3. Clearly the data do not allow a full amplitude determination (cf. Table 2). We use the t -channel moments $\langle Y_J^M \rangle$ with $J \leq 8$, $M = 0, 2$ to determine the magnitudes and coherences of the NPE amplitudes L_+ , and of the UPE amplitudes L_0 , with $L \leq 4$. We are led to this simplification by the results in the A_2 -mass region. From the A_2 analysis we expect that $L_+L'_{2+}$ interference terms will contribute to the $M = 1$ moments at least as strongly as $L_0L'_-$ interference terms. The data are unable to determine both L_- and L_{2+} . However, these small amplitudes only contribute quadratically to the $M = 0, 2$ moments and so it should be reliable to use these moments to determine the more dominant L_0 and L_+ amplitudes.

As mentioned before, the $J = 6, M = 0$ and 2 moments show that g -resonance production proceeds mainly by UPE (F_0), and to a much lesser extent by NPE (F_+). The dominance of the $\langle Y_4^2 \rangle$ and $\langle Y_2^2 \rangle$ moments, as compared with the other $M = 2$ moments, indicates a very strong D_+ component in the g region. Moreover, the $J = 8$ moments suggest that $L = 4$ K^-K^0 production by NPE exchange (G_+) must be included in this mass interval. The presence of sizeable D_+ and G_+ amplitudes make the determination of $|F_+|$ very difficult. The difficulty is apparent from the expression for the $J = 6, M = 2$ moment :

$$\langle Y_6^2 \rangle = -0.431 |F_+|^2 - 0.258 |G_+|^2 - 0.844 \operatorname{Re} (D_+ G_+^*) .$$

[†]) Here θ_P denotes the P-wave K^-K^0 production phase; it corresponds to the phase of the odd-signatured K^* production amplitude of Fig. 12(c) of Ref. 3.

The "background" waves, D_+ and G_+ , are associated with pomeron exchange and are therefore enhanced relative to the (ω -exchange) resonant amplitude F_+ . On the other hand, since P_+ , D_+ , and G_+ are expected to be nucleon spin coherent, the data give valuable information on the relative phases of these amplitudes.

There is no evidence for the $L = 4$ UPE amplitude G_0 , either from Fig. 3 or from the moments as a function of the produced K^-K^0 mass⁷⁾. This is in agreement with the exchange expectations of Table 1. We therefore set $G_0 = 0$, and for $J \geq 7$ include only moments with $M = 2$ in the analysis^{†)}.

In each t interval we use the $J \leq 8$, $M = 0, 2$ moments to determine the magnitudes and relative phases of the amplitudes within the NPE sector (P_+ , D_+ , F_+ , G_+) and within the UPE sector (S_0 , P_0 , D_0 , F_0). For each t interval all the solutions are enumerated using the Barrelet zero technique¹⁷⁾ and the solution selected to correspond with that obtained as a function of mass in the g region⁷⁾. The ambiguity is essentially only in the lower partial waves; in particular for the S , P , and D_0 amplitudes. We note also that the analysis assumes, within each sector, that the amplitudes have a common coherence factor ξ . Within the UPE sector there is no reason why this should be correct and so only the dominant UPE coherence, $\xi \cos \phi$, may be meaningful. F_0 is the dominant UPE amplitude and the other UPE quantities are much less reliably determined. To sum up, we note that the analysis should be reliable and unambiguous for (D_+ , F_+ , G_+) and F_0 .

The results for the g -production amplitudes and the background D - and G -waves, together with their respective coherences, are shown in Fig. 6. The lower partial waves are, in general, not so well determined and depend on the Barrelet solution that is selected⁷⁾. For our solution the magnitudes of S_0 , P_0 , P_+ are approximately 1.0, 0.6, 0.7 $\sqrt{\mu\text{b}}/\text{GeV}$, respectively, at $-t = 0.15$ $(\text{GeV}/c)^2$, and 0.3, 0.1, 0.2 $\sqrt{\mu\text{b}}/\text{GeV}$ at $-t = 0.5$ $(\text{GeV}/c)^2$. The coherence of S_0F_0 is positive for all t , that of P_0F_0 is ≈ -0.4 for $-t < 0.3$ $(\text{GeV}/c)^2$ and that of P_+D_+ is negative for all t .

†) The data for the $\langle Y_0^2 \rangle$ moment were smoothed at $-t = 0.13, 0.38$, and 0.45 $(\text{GeV}/c)^2$.

The difference of odd-L and even-L K^-K^0 production mechanisms is strikingly evident in Fig. 6. For UPE, the g-production amplitude F_0 (π exchange) dominates the background D_0 amplitude (B, Z exchange). On the other hand, for NPE, g production proceeds via F_+ (ω exchange) which is smaller than, and of different t structure from the even-L background D_+ and G_+ amplitudes (pomeron, f exchange). The expected single-helicity-flip character of the NPE amplitudes is clearly apparent for D_+ and G_+ .

7. g-PRODUCTION BY NPE -- ω EXCHANGE

Although the presence of the relatively large D_+ and G_+ background waves complicate the determination of $|F_+|$ they do yield valuable phase information. To interpret the observed behaviour of the NPE coherences (D_+F_+ , F_+G_+ , D_+G_+), shown in Fig. 6, we write the relative phase of each amplitude pair in the form

$$\phi_{LL'} \equiv \theta_L + \delta_L - \theta_{L'} - \delta_{L'},$$

where θ are production phases and δ decay phases of the K^-K^0 system. Both D_+ and G_+ arise from pomeron and f exchange. We therefore expect their production phases, $\theta_D \approx \theta_G$, to be increasing relatively slowly from just above 90° as $-t$ increases from $t = 0$. Now in the g-resonance region we are above the $A_2(1310)$, 2^+ resonance (δ_D approximately $120-160^\circ$) and below the $A_2^*(1900)$, 4^+ resonance^{6,7}) (δ_G approximately 20°). Moreover, for the resonant F^+ amplitude we have $\delta_F \approx 90^\circ$ and, assuming it is produced by ω exchange, we expect θ_F to change from about $50-60^\circ$ at $t = 0$, to 0° at $-t \sim 0.4$ $(\text{GeV}/c)^2$ where $\text{Im } \omega$ changes sign[†]). This latter cross-over is generally associated with the ω nonsense-wrong-signature-zero at $\alpha_\omega = 0$ arising in the exchange-degenerate picture. This qualitative picture of the production and decay phases is shown in Fig. 7 and is seen to account for the observed features of the NPE coherences (cf. Fig. 6). In particular the rapid phase change associated with ω exchange is manifest in the behaviour of $\xi \cos \phi$ for D_+F_+ .

†) This expectation is based on an analysis of K^* production³); there we found an ω contribution somewhat modified from the exchange-degenerate form, $1 - \exp(-i\pi\alpha)$.

The structure of $|F_+|$ for g production may be compared with the ω -exchange contribution isolated from the ρ -production reactions

$$\frac{d\sigma_{\omega}(\rho)}{dt} \equiv \frac{1}{2} (\rho_{11} + \rho_{1-1}) \left[\frac{d\sigma}{dt} (\pi^+ p \rightarrow \rho^+ p) + \frac{d\sigma}{dt} (\pi^- p \rightarrow \rho^- p) - \frac{d\sigma}{dt} (\pi^- p \rightarrow \rho^0 n) \right]. \quad (8)$$

Following Hoyer et al.¹⁸⁾ we apply finite-mass sum rules and two-component duality to relate the ω -exchange contributions to these resonance-production reactions at a given energy

$$\frac{d\sigma_{\omega}(\rho)/dt}{d\sigma_{\omega}(g)/dt} \approx \left(\frac{m_{\rho}^2}{m_g^2} \right)^{-2\alpha_{\omega}(t)}. \quad (9)$$

From our results for $|F_+|$ (see Fig. 6) we can estimate g production by ω exchange at 10 GeV/c, provided we are given the $g \rightarrow K\bar{K}$ branching ratio,

$$\frac{d\sigma_{\omega}(g)}{dt} = |F_+|^2 / [\text{B.R.}(g \rightarrow K\bar{K})]. \quad (10)$$

Taking $\alpha_{\omega} = 0.4 + 0.9t$ in Eq. (9), we then calculate $d\sigma_{\omega}(\rho)/dt$. In Fig. 8 we compare our prediction with 6 GeV/c ρ production data¹⁹⁾, after allowing for the different beam momenta using the usual $p_L^{2-2\alpha_{\omega}}$ dependence. The curves, shown for two different $g \rightarrow K\bar{K}$ branching ratios, result from the curve through $|F_+|$ on Fig. 6. The comparison, which is most relevant^{†)} for $0.1 < -t < 0.2$ (GeV/c)², favours a branching ratio

$$\frac{\gamma(g \rightarrow K\bar{K})}{\gamma(g \rightarrow \text{all})} \approx 0.015. \quad (11)$$

The 16 GeV/c data for isospin-zero NPE ρ production²⁰⁾ has larger errors, but a similar comparison yields compatible results.

8. g PRODUCTION BY UPE -- π EXCHANGE

The structure of $|F_0|$ of Fig. 6 is indicative of π exchange, and the values may be extrapolated to the π pole ($t = \mu^2$) to give a more direct determination of

†) Recall that the amplitude analysis for $0.2 < -t < 0.5$ (GeV/c)² revealed a relatively large G_+ contribution, which made the extraction of F_+ particularly difficult. It is therefore not surprising that the anticipated dip in $d\sigma_{\omega}(g)/dt$ is very shallow.

the $g \rightarrow K\bar{K}$ branching ratio than that we obtain from $|F_+|$. To do this we use the Chew-Low form

$$\frac{d\sigma}{dt} = \frac{1}{m_N^2 p_L^2} \frac{g^2}{4\pi} \left(\frac{-te^{b(t-\mu^2)}}{(t-\mu^2)^2} \right) (2L+1) \int \frac{M^2}{q_\pi} |f_L|^2 dM, \quad (12)$$

with $L = 3$, where M is the produced K^-K^0 mass, $q_\pi^2 = 1/4 M^2 - \mu^2$, and

$$f_L = \frac{M_R \sqrt{\Gamma_\pi \Gamma_K}}{M_R^2 - M^2 - iM_R \Gamma}$$

We integrate over the experimental mass bin, 1.55-1.85 GeV. The total width of the g resonance is $\Gamma = \Gamma_\pi + \Gamma_K + \Gamma_0$, where

$$\Gamma_i(M) = \gamma_i \left(\frac{q_i}{q_i^R} \right)^7 \frac{D(q_i^R)}{D(q_i)}$$

with a barrier factor $D(z) = 225 + 45z^2 + 6z^4 + z^6$ and interaction radius $R = 3.5 \text{ GeV}^{-1}$. We take the mass and width of the g resonance to be $M_R = 1.69 \text{ GeV}$, $\gamma = 0.18 \text{ GeV}$; and the momentum of the other decay channels, in addition to the $\pi\pi$ and $K\bar{K}$ channels, to be represented by $q_0 = q_K$. We fit $|F_0|^2$ to Eq. (12) with $(\gamma_\pi \gamma_K)$ and the slope b as free parameters. The fit^{†)} is shown by the curve through $|F_0|$ on Fig. 6 and corresponds to

$$\sqrt{\gamma_K \gamma_\pi} / \gamma = 0.056 \pm 0.017$$

$$b = 4.5 \pm 1.1 \text{ GeV}^{-2}.$$

If we take the particle table¹⁴⁾ value of the $\pi\pi$ branching ratio, $\gamma_\pi/\gamma = 24 \pm 1\%$, then we find the $g \rightarrow K\bar{K}$ branching ratio is

$$\gamma_K/\gamma = 1.3 \pm 0.4\%.$$

This determination is in agreement with the independent estimation, $\gamma_K/\gamma \sim 1.5\%$, which we obtained in the previous section from the NPE amplitude, F_+ .

†) We omit the first point owing to the large acceptance corrections in the near forward direction.

The above numbers yield a ratio of the $K\bar{K}$ and $\pi\pi$ decay modes of the g resonance of

$$\gamma_K/\gamma_\pi = 0.056 \pm 0.017 .$$

This is to be compared with the SU(3) value

$$\frac{\gamma_K}{\gamma_\pi} = \frac{1}{2} \left(\frac{q_K^R}{q_\pi^R} \right)^7 = 0.13 .$$

Note that SU(3) comparisons are better satisfied without including barrier factors²¹⁾.

To agree with SU(3) we would have had to input $\gamma_\pi/\gamma = 16\%$, which would have led to $\gamma_K/\gamma = 2\%$.

9. CONCLUSIONS

Here we summarize the main results of our study of A_2 and g production by the reaction $\pi^- p \rightarrow K^- K^0 p$ at 10 GeV/c.

9.1 The A_2 -mass region

- i) We find A_2 production proceeds dominantly by NPE. The t -channel D_+ amplitude is dominant, but a non-zero $\langle Y_4^3 \rangle$ signal leads to a D_{2+} contribution which is, on the average, 10% of $|D_+|$.
- ii) The UPE amplitude D_0 is consistent in magnitude and t structure with that found in CEX A_2^0 production, and lends support to the assumption that UPE is dominantly isovector in $\pi^- p \rightarrow A_2 p$.
- iii) S-wave $K^- K^0$ production is important in the A_2 region, the t structure implying a strong non-flip component at small t (Z exchange). Combined with the $K^- K^0$ analysis as a function of mass⁷⁾, and with $K^+ K^-$ and $K_S^0 K_S^0$ -production data¹⁵⁾, this suggests the existence of an $I = 1, 0^+$ state under the A_2 .
- iv) There is relatively little P-wave $K^- K^0$ production, although the $P_+ D_+$ coherence is well determined.

- v) A_2 and $K^*(1420)^\pm$ production are related using the f, f' dominated scheme for the pomeron. We estimate the pomeron relative to f exchange and find, for example, at $-t \approx 0.2 \text{ (GeV/c)}^2$ a ratio 1:1 in $\pi^- p \rightarrow A_2 p$ at 10 GeV/c.

9.2 The g-mass region

- i) We find g production proceeds dominantly by UPE (π exchange).
- ii) We extrapolate to the π -exchange pole and find $\sqrt{\gamma_\pi \gamma_K}/\gamma = 5.6 \pm 1.7\%$, where γ_π/γ and γ_K/γ are the $\pi\pi$ and $K\bar{K}$ branching ratios of the g , respectively. Taking $\gamma_\pi/\gamma = 24\%$ this gives $\gamma_K/\gamma = 1.3 \pm 0.4\%$.
- iii) The resonant NPE amplitude, F_+ , is reasonably consistent with ω exchange, both in structure and in its interference behaviour with the $L = 2$ and 4 NPE amplitudes (D_+ and G_+). It is, however, poorly determined, because g production by NPE (ω exchange) is masked by the production of $L = 2$ and $L = 4$ $K^- K^0$ systems, which can proceed by pomeron and f exchange.
- iv) Finite-mass sum rules and duality allow a comparison of the NPE amplitude, F_+ , with ρ -production data. This hypothesis leads to an estimate of the $g \rightarrow K\bar{K}$ branching ratio of $\gamma_K/\gamma \approx 1.5\%$.

Finally, we note that at higher energies $\pi^- p \rightarrow K^- K^0 p$ will be dominated by even- L $K^- K^0$ production by NPE. Information about the odd- L states will be obtained mainly through interference with the even- L production amplitudes. The study of the reactions $\pi^\pm p \rightarrow K^\pm K_S^0 p$ and $K^\pm p \rightarrow K_S^0 \pi^\pm p$ at SPS energies will, when combined with πN and KN elastic-scattering data, provide a powerful probe of the properties of the pomeron.

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Table 1

Allowed exchanges in $\pi^- p \rightarrow K^- K^0 p$
for the production of a spin-L $K^- K^0$ system

	L even (e.g. A_2)	L odd (e.g. g)
NPE	P, f, ρ	ω, A_2
UPE	$B(Z)$	$\pi(A_1)$

Table 2

The unnormalized moments $\sqrt{4\pi} N \langle Y_J^M \rangle$ in terms of the amplitudes L_0 , L_- , and L_+ , defined in the text^{*)}. We use the abbreviated notation $LL' \equiv \text{Re}(L^*L')$. A summation over helicity flip and non-flip at the nucleon vertex is implicit in each bilinear product, that is $\text{Re}(L^*L') = \text{Re}(L_f^*L'_f + L_{nf}^*L'_{nf})$.

$\sqrt{4\pi} N \langle Y_0^0 \rangle$	$= S_0^2 + P_0^2 + P_-^2 + P_+^2 + D_0^2 + D_-^2 + D_+^2 + F_0^2 + F_-^2 + F_+^2 + G_0^2 + G_-^2 + G_+^2$
$\sqrt{4\pi} N \langle Y_1^0 \rangle$	$= 2S_0P_0 + 1.789P_0D_0 + 1.549(P_-D_- + P_+D_+) + 1.757D_0F_0 + 1.656(D_-F_- + D_+F_+) + 1.746F_0G_0 + 1.690(F_-G_- + F_+G_+)$
$\sqrt{4\pi} N \langle Y_1^1 \rangle$	$= 1.414S_0P_- + 1.096P_0D_- - 0.633P_-D_0 + 1.014D_0F_- - 0.717D_-F_0 + 0.976F_0G_- - 0.756F_-G_0$
$\sqrt{4\pi} N \langle Y_2^0 \rangle$	$= 0.894P_0^2 - 0.447(P_-^2 + P_+^2) + 0.639D_0^2 + 0.319(D_-^2 + D_+^2) + 0.596F_0^2 + 0.447(F_-^2 + F_+^2) + 0.581G_0^2$ $+ 0.494(G_-^2 + G_+^2) + 2S_0D_0 + 1.757P_0F_0 + 1.714D_0G_0 + 1.434(P_-F_- + P_+F_+) + 1.565(D_-G_- + D_+G_+)$
$\sqrt{4\pi} N \langle Y_2^1 \rangle$	$= 1.414S_0D_- + 1.096P_0P_- + 1.171P_0F_- - 0.717P_-F_0 + 0.452D_0D_- + 1.107D_0G_- - 0.808D_-G_0 + 0.298F_0F_- + 0.225G_0G_-$
$\sqrt{4\pi} N \langle Y_2^2 \rangle$	$= 0.548(P_-^2 - P_+^2) + 0.391(D_-^2 - D_+^2) + 0.365(F_-^2 - F_+^2) + 0.356(G_-^2 - G_+^2) - 0.293(P_-F_- - P_+F_+) - 0.319(D_-G_- - D_+G_+)$
$\sqrt{4\pi} N \langle Y_3^0 \rangle$	$= 2S_0F_0 + 1.757P_0D_0 + 1.746P_0G_0 - 1.014(P_-D_- + P_+D_+) + 1.380(P_-G_- + P_+G_+) + 1.193D_0F_0 + 0.422(D_-F_- + D_+F_+)$ $+ 1.091F_0G_0 + 0.704(F_-G_- + F_+G_+)$
$\sqrt{4\pi} N \langle Y_3^1 \rangle$	$= 1.414S_0F_- + 1.171P_0D_- + 1.014P_-D_0 + 1.195P_0G_- - 0.756P_-G_0 + 0.633D_0F_- + 0.298D_-F_0 + 0.498F_0G_- + 0.129F_-G_0$
$\sqrt{4\pi} N \langle Y_3^2 \rangle$	$= 0.926(P_-D_- - P_+D_+) - 0.378(P_-G_- - P_+G_+) + 0.578(D_-F_- - D_+F_+) + 0.514(F_-G_- - F_+G_+)$
$\sqrt{4\pi} N \langle Y_4^0 \rangle$	$= 0.857D_0^2 - 0.571(D_-^2 + D_+^2) + 0.546F_0^2 + 0.091(F_-^2 + F_+^2) + 0.486G_0^2 + 0.245(G_-^2 + G_+^2) + 2S_0G_0 + 1.746P_0F_0$ $- 1.069(P_-F_- + P_+F_+) + 1.162D_0G_0 + 0.318(D_-G_- + D_+G_+)$
$\sqrt{4\pi} N \langle Y_4^1 \rangle$	$= 1.414S_0G_- + 1.196P_0F_- + 0.976P_-F_0 + 1.107D_0D_- + 0.698D_0G_- + 0.225D_-G_0 + 0.498F_0F_- + 0.343G_0G_-$
$\sqrt{4\pi} N \langle Y_4^2 \rangle$	$= 0.845(P_-F_- - P_+F_+) + 0.452(D_-^2 - D_+^2) + 0.453(D_-G_- - D_+G_+) + 0.288(F_-^2 - F_+^2) + 0.256(G_-^2 - G_+^2)$
$\sqrt{4\pi} N \langle Y_5^0 \rangle$	$= 1.741P_0G_0 - 1.101(P_-G_- + P_+G_+) + 1.699D_0F_0 - 1.201(D_-F_- + D_+F_+) + 1.052F_0G_0 + 0.068(F_-G_- + F_+G_+)$
$\sqrt{4\pi} N \langle Y_5^1 \rangle$	$= 1.206P_0G_- + 0.953P_-G_0 + 1.140D_0F_- + 1.075D_-F_0 + 0.577F_0G_- + 0.431F_-G_0$
$\sqrt{4\pi} N \langle Y_5^2 \rangle$	$= 0.798(P_-G_- - P_+G_+) + 0.871(D_-F_- - D_+F_+) + 0.525(F_-G_- - F_+G_+)$
$\sqrt{4\pi} N \langle Y_6^0 \rangle$	$= 1.691D_0G_0 - 1.235(D_-G_- + D_+G_+) + 0.841F_0^2 - 0.630(F_-^2 + F_+^2) + 0.504G_0^2 - 0.025(G_-^2 + G_+^2)$
$\sqrt{4\pi} N \langle Y_6^1 \rangle$	$= 1.155D_0G_- + 1.055D_-G_0 + 1.112F_0F_- + 0.517G_0G_-$
$\sqrt{4\pi} N \langle Y_6^2 \rangle$	$= 0.844(D_-G_- - D_+G_+) + 0.431(F_-^2 - F_+^2) + 0.258(G_-^2 - G_+^2)$
$\sqrt{4\pi} N \langle Y_7^0 \rangle$	$= 1.672F_0G_0 - 1.295(F_-G_- + F_+G_+)$
$\sqrt{4\pi} N \langle Y_7^1 \rangle$	$= 1.131F_0G_- + 1.095F_-G_0$
$\sqrt{4\pi} N \langle Y_7^2 \rangle$	$= 0.848(F_-G_- - F_+G_+)$
$\sqrt{4\pi} N \langle Y_8^0 \rangle$	$= 0.831G_0^2 - 0.665(G_-^2 + G_+^2)$
$\sqrt{4\pi} N \langle Y_8^1 \rangle$	$= 1.115G_0G_-$
$\sqrt{4\pi} N \langle Y_8^2 \rangle$	$= 0.421(G_-^2 - G_+^2)$

*) These coefficients have been checked with those calculated by W. Männer. We thank him for providing a table for comparison.

Figure captions

- Fig. 1 : $K_S^0 K^-$ effective mass spectrum, for $0.07 \leq |t| \leq 1.0$ (GeV/c)². The spectrum is shown before (histogram) and after (points with error bars) acceptance correction. A constant factor of 5.8 due to the azimuthal aperture of the proton detector is not included in the correction.
- Fig. 2 : Corrected spherical harmonic moments of the angular distribution of the K^- , in the t-channel helicity rest frame of the produced $K^- K^0$ system, as a function of t in the A_2 -mass region, $1.2 < M(K^- K^0) < 1.4$ GeV. The data are for $\pi^- p \rightarrow K^- K^0 p$ at 10 GeV/c.
- Fig. 3 : As for Fig. 2, but in the g-mass region $1.55 < M(K^- K^0) < 1.85$ GeV.
- Fig. 4 : The 10 GeV/c $\pi^- p \rightarrow K^- K^0 p$ amplitudes in the A_2 -mass region, $1.2 < M(K^- K^0) < 1.4$ GeV. The curve for $|D_0|$ shows the prediction obtained from CEX A_2^0 production. The coherences of SD_0 and $-SD_-$ are assumed equal, and are denoted by SD. The SD and $D_+ D_{2+}$ coherences are not well determined and the curves only indicate the trend of the results.
- Fig. 5 : The NPE cross-sections, $|D_+|^2$, for $\pi^- p \rightarrow A_2 p$ and $K^+ p \rightarrow K^*(1420)^+ p$ at 10 GeV/c. The cross-sections are corrected for the unseen decay modes and for the tails of the Breit-Wigner distributions outside the fitted mass intervals. This latter correction is a factor 1.23 and 1.27 for the A_2 and $K^*(1420)$ mass intervals, respectively. The ratio R is discussed in Section 5.
- Fig. 6 : The 10 GeV/c $\pi^- p \rightarrow K^- K^0 p$ amplitudes in the g-mass region, $1.55 < M(K^- K^0) < 1.85$ GeV, obtained from the data of Fig. 3. The extreme fluctuations seen in the $3 \leq J \leq 5$ moments at $-t = 0.29$ (GeV/c)² were removed before amplitude analysis. Only representative errors are shown for $|D_0|$ and the $D_0 F_0$ coherence.

Fig. 7 : An Argand plot of the phases of the NPE amplitudes, D_+ , F_+ , G_+ , in the g -resonance region. θ and δ are the $K\bar{K}^0$ production and decay phases, respectively. The sketch is for $-t \approx 0.1 \text{ (GeV/c)}^2$; for $-t \approx 0.5 \text{ (GeV/c)}^2$, F_+ is rotated anticlockwise by about 90° . The observed coherences (cf. Fig. 6) favour $\delta_D \approx 110^\circ$.

Fig. 8 : Data for ρ production by ω exchange at 6 GeV/c, taken from Ref. 19. The curves are the finite-mass sum-rule predictions, obtained from the g -production amplitude F_+ of Fig. 6, for two different values of the $g \rightarrow K\bar{K}$ branching ratio.

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b

Fig. 4

Fig. 5

$\pi^-p \rightarrow K^-K^0p$ AMPLITUDES IN THE g REGION

Fig. 6

Fig. 7

Fig. 8