EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-129

August 13th, 1985

Evidence for Pomeron Single-Quark Interactions in Proton Diffraction at the ISR

(R608 Collaboration)

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Abstract

Measurements are presented of two exclusive diffractive reactions, $pp \rightarrow (\Lambda^0 \phi^0 K^+)p$ and $pp \rightarrow (\Lambda^0 \bar{\Lambda}^0 p)p$, at $\sqrt{s} = 63$ GeV. Pronounced correlations with the beam direction are observed (in the rest frame of the forward-going bracketed system) for those outgoing particles which contain the beam valence quarks. In each case there is a forward- Λ^0 in correlation with a backward K^+ or p , respectively. No such behavior is seen for the particles which do not contain beam valence quarks (ϕ^0 and $\bar{\Lambda}^0$, respectively). Interpreted as examples of Pomeron-proton scattering, these results constitute evidence that, for these final states, the Pomeron interacts with a single valence quark and apparently back-scatters it. The subsequent hadronization leads to a longitudinal event structure.

Submitted to Physics Letters B

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^{*}) Supported in part by U.S. National Science Foundation grants PHY79-24766 and PHY85-09175

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Since the pioneering paper of Good and Walker^[1] on diffractive dissociation, the subject has received considerable experimental attention^[2]. Single diffraction, in which one of the incident beam particles is "excited" in a collision, has been studied with various combinations of incident particles from low energies up to the highest available SPS-Collider energies^[3] and shows a consistent behavior characterized by scaling of the invariant cross section at fixed excitation mass, M , and momentum transfer, t , to the system X in, e.g., $p_1 p_2 \rightarrow X p_2$. The system X is thought to result from an interaction between p_1 and an exchanged Pomeron, which has the quantum numbers of the vacuum.

At present, there is very little experimental information on the internal structure of X . Such information should shed light on possible partonic structure of the Pomeron^[4,5], and on its mechanisms of interaction. One possibility, suggested in ref. [6], is that the Pomeron couples in a pointlike way (similar to a photon) to quarks in the proton. The Pomeron may also couple to gluons in the proton, as suggested in ref. [7].

In the present Letter, we present results on two exclusive final states in pp interactions, measured in a forward multi-particle spectrometer experiment^[7,8,9] at the CERN Intersecting Storage Rings (ISR) with $\sqrt{s} = 63$ GeV:

$$\begin{aligned} pp &\rightarrow (\Lambda^0 \phi^0 K^+) p & (1) \\ pp &\rightarrow (\Lambda^0 \bar{\Lambda}^0 p) p. & (2) \end{aligned}$$

There are 1,144 and 2,186 examples of Reactions 1 and 2, respectively^[10].

In both Reactions 1 and 2, the bracketed systems (henceforth referred to as the "forward" systems) emerge along the beam direction with nearly the full beam momentum of 31.4 GeV/c. Fig. 1(a,d) show the total momenta of the forward systems in Reactions 1 and 2. The sharp peaks close to the beam momentum in both reactions indicate the quasi-two-body nature of the two processes. Figs. 1(b,e) show the signals of the ϕ^0 in Reaction 1 and of the Λ^0 - $\bar{\Lambda}^0$ crossing region in Reaction 2. There is no background in the signal for Reaction 2, whereas the ϕ^0 in Reaction 1, selected between 1.012–1.028 GeV, has 25% non- ϕ^0 background. This non- ϕ^0 background is accounted for in the analysis presented here by subtracting the distributions observed when the $K^+ K^-$ invariant mass is outside of the ϕ^0 region.

Figs. 1(c,f) are the invariant mass distributions of the forward systems in Reactions 1 and 2, respectively. There is no evidence of resonant structure either in these two mass spectra or in any of the 2-body sub-masses (not shown here). Thus, the final states in Reactions 1 and 2 are not the decay products of some higher mass excited nucleon states. It seems likely that we see continuum distributions which reflect the dynamical mechanism in the reaction.

To look for obvious dynamical effects in these reactions, we show in Fig. 2(a-f) the Gottfried-Jackson angular distributions (uncorrected for acceptance effects) of the individual particles in the centers-of-mass of the forward-going systems of Reaction 1(2). $\cos\theta = 1$ corresponds to the particle moving in the direction of the beam proton, as seen in the c.m. of the forward-going system. The solid curves in each case show the observed distributions expected if all particles were distributed according to isotropic phase space in their overall center-of-mass (determined by generating Monte Carlo events and passing them through a program which simulates the acceptance of the apparatus). There is remarkable forward and/or backward peaking observed for all particles except those (ϕ^0 and $\bar{\Lambda}^0$, respectively) that do not contain valence quarks of the beam proton. The ϕ^0 and $\bar{\Lambda}^0$ possess angular distributions which are more or less isotropic and are, in any case, completely different from those of their neighbor particles.

Further study of the distributions shown in Figs. 2 shows that striking correlations exist between those particles which display forward and/or backward peaking. Moreover, these correlations increase and sharpen with increasing invariant mass of their respective system. This is illustrated in Figs. 3(a,b), which are scatter plots of $\cos\theta_{\Lambda^0}$ vs. $\cos\theta_{K^+}$ and $\cos\theta_{\Lambda^0}$ vs. $\cos\theta_p$ at the upper end of the mass ranges

in Reactions 1 and 2, respectively. Figs. 3(c,d) are similar plots for corresponding high-mass isotropic Monte Carlo events passed through the acceptance program. We see pronounced and clear concentrations of events in one region for Reaction 1 (Λ^0 forward, K^+ backward) and in two regions of Reaction 2 (Λ^0 forward, p backward or p forward, Λ^0 backward).

The particles which display the correlations seen in Figs. 3 are special in that they contain the valence quarks of their beam proton. In both reactions, the forward- Λ^0 contains the valence ud -diquark, while the backward K^+ or p , respectively, contains the second valence u -quark. Referring to the quark diagrams in Figs. 4(a,b), we can conclude that, in the forward- Λ^0 peaks, the exchanged Pomeron interacted with a single valence u -quark in the beam proton.

Figs. 4(c) and 4(d) both contribute to the forward-proton peak seen in Fig. 3(b). Fig. 4(c) is the same mechanism discussed above, but with either a u - or d -quark in the backward hemisphere and with the $s\bar{s}$ pair contained in the diquark pair. Fig. 4(d) is an example of a mechanism we have discussed in an earlier publication^[7], in which a final-state proton retains the beam valence quarks while an iso-scalar state (in this case, a $\Lambda^0\bar{\Lambda}^0$ system) is produced in an interaction between the Pomeron and a gluon component of the other beam proton (perhaps also a Pomeron). In this Letter, we do not attempt to separate the contributions of Figs. 4(c) and 4(d) to the forward-proton peak in Reaction 2. Rather, we focus our attention only on the forward- Λ^0 peaks in both Reactions 1 and 2 and determine their absolute cross sections.

Corrections for the losses due to the imperfect acceptance of the spectrometer have been applied to the data. In order to calculate these corrections, we use the Feynman- x variables for each of the particles in the centers-of-mass of the forward systems of Reactions 1 and 2. x_F is defined such that unity corresponds to the maximum possible momentum of a particle in the 3-body final state. We make use of our observation that a distortion of isotropic phase space Monte-Carlo event distributions in the plane of $x_F(\Lambda^0)$ vs. $x_F(p)$ in Reaction 2 is sufficient to gain rather good agreement between the Monte-Carlo events and the data in all other distributions.

The absolute cross sections for the forward- Λ^0 signals in the single - diffractive Reactions 1 and 2 (counting both arms of the pp interaction) are (11.1 ± 1.1) and (4.6 ± 0.5) nbarn, respectively (we estimate an overall 50% systematic uncertainty due to the acceptance-correction procedure used). The cross sections correspond to the mass regions 3.2–4.0 GeV and 3.6–4.6 GeV in Figs. 1(c,f), respectively, and for the forward- Λ^0 spots in Figs. 3(a,b) selected using $|\cos \theta| > 0.5$. An additional limitation of the kinematic region to which these cross section values apply is illustrated in Fig. 5, which is the acceptance-corrected distribution of $x_F(\Lambda^0)$ in Reaction 2 for $4.2 < M(\Lambda^0\bar{\Lambda}^0 p) < 4.6$ GeV. Because of the limited acceptance at large x_F , the above cross sections are quoted only for $x_F(\Lambda^0) < 0.7$. The forward peaking of the Λ^0 's observed in Figs. 3(a,b) is kinematically associated with a similar peaking in the longitudinal momentum of the particle. The average x_F values for Λ^0 , $\bar{\Lambda}^0$ and p in Reaction 2, and for the selection made in Fig. 5, are $+0.6$, 0.0 and -0.6 , respectively. Similar values are found for Reaction 1.

We also note that the results presented here imply that these diffractive states deviate strongly from isotropic phase space ("fireball" model). They show, on the contrary, a longitudinal event shape which becomes more pronounced with increasing diffractive mass and has an axis strongly correlated with the Pomeron-proton collision axis, in agreement with an independent study we have made^[11] of the diffractive process: $pp \rightarrow (p\pi^+\pi^-\pi^+\pi^-)p$.

In conclusion, we have presented evidence that the exchanged particle in both Reactions 1 and 2, presumably the Pomeron, interacts with a single valence quark in the beam proton leading to a quark-diquark separation and hadronization as indicated in Figs. 4. This result is in qualitative agreement with the idea of a Pomeron-quark point-like coupling suggested in ref. [6]. This would lead to the back-scattering of a quark in the proton, leaving forward spectator-quarks. A partonic state is thereby formed, as in deep-inelastic scattering, which subsequently hadronizes into the observed final state. We note, however, that if the Pomeron had a significant partonic sub-structure with a $q\bar{q}$ com-

ponent similar to a meson, then a valence quark from the proton could be annihilated and the observed backward quark could then be viewed as a spectator from the Pomeron. Although these two possibilities are topologically very similar, some dynamical effects might distinguish them. Independently of these considerations, however, the conclusion of an underlying partonic process in the Pomeron-proton interaction seems unavoidable.

Finally, we note that the results discussed in this Letter seem to be incompatible with the notion expressed in refs. [1,12] that the diffractive state exists prior to the interaction as a virtual state which is then realized in the interaction. If this were the case, it would be difficult to understand the observed differences between those final state particles which contain beam proton valence quarks and those that do not. Further investigation of processes of this type with larger mass or with other forward baryons which contain only two of the valence quarks, such as Δ^{++} or Σ^+ , etc., would be illuminating.

We acknowledge the continuous aid and support of the ISR Experimental Support Group and Operations Group while these data were taken and also thank the CERN administration for their support. An interesting conversation with P. Landshoff is appreciated.

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Figure Captions

1. (a,d) Total laboratory momentum of forward systems in Reactions 1 and 2, respectively; (b) Invariant mass of K^+K^- in Reaction 1; (e) Scatter plot of invariant mass of $p\pi^-$ and $\bar{p}\pi^+$ for the two Vees in Reaction 2; (c,f) Invariant masses of the forward systems in Reactions 1 and 2.
2. Distributions in cosine of Gottfried-Jackson angles of individual particles in the forward systems; (a-c) Λ^0 , ϕ^0 , K^+ in Reaction 1; (d-f) Λ^0 , $\bar{\Lambda}^0$, p in Reaction 2. Solid lines are the results of Monte-Carlo calculations for isotropic phase-space events passed through our apparatus acceptance.
3. Scatter plot of cosines in Figs. 2; (a) Λ^0 vs. K^+ in Reaction 1 for invariant mass ($\Lambda^0\phi^0K^+$) 3.6–4.0 GeV; (b) Λ^0 vs. p in Reaction 2 for invariant mass ($\Lambda^0\bar{\Lambda}^0p$) 4.2–4.6 GeV; (c-d) same as (a-b) but for Monte Carlo events generated according to isotropic phase-space and passed through acceptance program.
4. Diagrams illustrating the quark flavors for: (a) forward- Λ^0 peak in Reaction 1; (b) Forward- Λ^0 peak in Reaction 2; (c-d) Two mechanisms which contribute to forward-proton peak in Reaction 2.
5. Acceptance-corrected distribution of $x_F(\Lambda^0)$ in Reaction 2 when $|\cos\theta| > 0.5$ for the "leading" particles and $4.2 < M(\Lambda^0\bar{\Lambda}^0p) < 4.6$ GeV.

Fig. 1

Fig. 2

$\Lambda^0 \phi K^+$

$\Lambda^0 \bar{\Lambda}^0 p$

Fig. 3

a)

b)

c)

d)

Fig. 4

Fig. 5