Observation of Longitudinal Event Structure in Proton Diffractive Dissociation at the ISR

(R608 collaboration)

A.M. Smith
CERN, 1211 Geneva 23, Switzerland.

L. Meritet, M. Reyrolle¹, F. Vazeille
LPC-IN2P3, Université de Clermont-Ferrand, 63 Aubiere, France

R. Bonino, A. Castellina², S. Erhan, G. Ingelman³, M. Medinnis,
P.E. Schlein, P. Sherwood, S. Vernetto², J.G. Zweizig
University of California⁴), Los Angeles, California 90024, USA.

J. Alitti, B. Bloch-Devaux, J.B. Cheze, A. Montag⁴, J. Zsembery
Centre d'Etudes Nucleaires - Saclay, 91191 Gif-sur-Yvette, France.

Abstract

We study the internal structure of a forward-going $p\pi^+\pi^-\pi^+\pi^-$ system, with invariant mass in the range 2.5–4 GeV, produced through diffractive dissociation of a beam proton at the ISR. The shape of the system, as seen in its center-of-mass, deviates strongly from isotropic phase space and possesses, rather, a longitudinal structure with a major axis along the incoming proton direction. The final state proton momentum is aligned in the direction of the incoming proton, an effect which becomes more pronounced with increasing diffractive mass.

Submitted to Physics Letters B

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

¹) now at CERN, Geneva, Switzerland

²) now at Istituto di Cosmogeofisica del C.N.R., Torino, Italy

³) now at DESY, Hamburg, FRG

⁴) now at Weizmann Institute, Rehovoth, Israel

The cross-section for diffractive scattering has been well measured at different energies by detection of the quasi-elastically scattered particle and is described phenomenologically in terms of pomeron exchange [1,2]. It has been suggested [3] that the pomeron is a gluonic system, but the true nature of the pomeron and its coupling to hadrons is unknown. Furthermore, very little is known about the excited hadronic system in the hemisphere opposite the quasi-elastic particle. Depending on the nature of the pomeron-proton interaction [4] producing this system, it may have an isotropic shape in its center-of-mass [5] or, alternatively, a longitudinal structure along some preferred axis [6].

Differences between spherical and longitudinal event shapes should be visible in the rapidity and transverse momentum distributions of the final state particles. An isotropic decay ("fireball") of the diffractive system leads to a rapidity distribution which has a shape [2,7] similar to a Gaussian function and a width approximately independent of the excitation mass, M_X , of the system X in, e.g. $p_1 p_2 \rightarrow X p_2$. A longitudinal model, on the other hand, predicts a flat rapidity plateau stretching out to a limit which increases with $\ln(M_X)$. The transverse momenta are expected to increase with M_X in the isotropic case whereas they remain unchanged in longitudinal models.

The pseudorapidity distributions have been studied in two previous experiments at the Intersecting Storage Rings (ISR) at CERN. Results from the Pisa-Stony Brook experiment [8] are consistent with a Gaussian distribution and can therefore be interpreted in favour of a fireball behaviour (see also the discussion in [2]). The CHLM collaboration [9] claimed, on the contrary, that their data are well described by a longitudinal-phase-space model. The reason for this apparent disagreement could be due to the fact that the inclusive rapidity distribution from a longitudinal structure becomes similar to that obtained from isotropic phase space when M_X becomes small. In particular, the flat rapidity plateau is not developed for low mass systems. However, mesonic systems produced by diffractive dissociation of real photons have been shown to have a longitudinal structure [10].

In the present experiment, we have the advantage of diffractively produced states which are completely reconstructed with respect to particle momenta and identities, giving detailed information on the internal structure of the system. This increased information content of the data correspondingly increases the sensitivity of distinguishing different models. For the analysis presented here, we use 360,000 events of the exclusive reaction:

$$p p \rightarrow \{p \pi^+ \pi^- \pi^+ \pi^-\} p \quad (1)$$

with $\sqrt{s} = 62$ GeV and with the forward-going (bracketed) $p-4\pi$ system in the mass range $2.5 < M_X < 4.0$ GeV.

The apparatus of ISR experiment R608, used to obtain these data, is described in more detail elsewhere [11,12,13]. As in ref. [12], the diffractively produced system, $p-4\pi$ in Reaction (1), with total momentum approximately equal to the beam momentum of 31.4 GeV, entered a forward magnetic spectrometer with $\pm 8.6^\circ$ aperture and with a two-threshold Cerenkov counter system for particle identification. If the recoil proton momentum vector was outside the beam pipe, it was identified with a recoil-proton hodoscope as in ref. [13]. If it was inside the beam pipe a counter system, which covered most of the solid angle outside the spectrometer aperture, was required to have no hits. This technique was shown in ref. [14] to yield clean single-diffractive data.

The corrected distribution of the diffractive momentum transfer, t , shown in Fig. 1(a), is described by exponentials with slopes 20, 7.3, 4.1 GeV^{-2} in the three t -intervals 0.02-0.08, 0.08-0.2 and 0.2-2. GeV^2 respectively. The observed invariant mass of the $p-4\pi$ system, shown in Fig. 1(b), displays no resonance structure, although the $p\pi^+$ and $\pi^+\pi^-$ sub-mass distributions in Figs. 1(c,d) show clear evidence for Δ^{++} and ρ^0 production.

In order to make a detailed study of the event shape, we generate Monte Carlo events according to two different models; isotropic phase space (referred to hereafter as the "fireball" model) and a longitudinal model described below. The generated events are passed through a detector-simulation pro-

gram which produces the complete set of detector responses which are then analysed by the same reconstruction programs used for real data. For the fireball model, we generate the final states: $\Delta^{++}\rho^0\pi^-$, $\Delta^{++}\pi^+\pi^-\pi^-$ and $p\rho^0\pi^+\pi^-$ in the proportions 1:2:7, in good agreement with the observed mass spectra, as shown by the dashed curves in Figs. 1(c,d) (a small contribution, less than 5%, of $N^* \rightarrow p\pi^-$ is ignored).

The investigation of the longitudinal model was inspired by our study of the diffractively produced final states $\{\Lambda\phi K^+\}p$ and $\{\Lambda\bar{\Lambda}p\}p$ in pp interactions [15], which provides evidence for the interaction of a pomeron with a single quark of the incident beam particle. This result is in qualitative agreement with the suggestion in ref. [16] that the pomeron has a point-like coupling to quarks in the proton. Consequently, one would expect a proton quark to be back-scattered, leaving forward-going spectator-quarks. A parton system is thereby formed, as in deep-inelastic lepton scattering, which subsequently hadronizes into the observed final state.

Based on these ideas we have constructed a model [4] where the flavour of the quark (or anti-quark) struck by the pomeron is given by proton structure functions extrapolated to small x and Q^2 as in [16], ($Q^2 = -t$ and $x = Q^2/(M_X^2 + Q^2)$). The resulting parton system is hadronized according to the Lund string model [17], which has proven successful in describing the hadronization of similar partonic systems in deep-inelastic scattering [18,19]. Although the low mass of the hadronic system studied here makes it questionable whether a jet model is reliable, it has been shown [19] that, for hadronic masses above 3 GeV produced in neutrino scattering, a good description of the data can be obtained by some adjustment of parameters in the model. (Essentially, the normal hadronization procedure is followed further than usual before the last two particles are produced with momenta given by energy-momentum constraints.) We therefore only consider the region $3 < M_X < 4$ GeV in the following comparisons with this model and generate events with the kinematics of diffractive scattering according to the observed t -distribution and $dN/dM_X^2 \sim 1/M_X^2$.

The hadronization is carried out in an unbiased way and the $p-4\pi$ events, which occur randomly in the hadronization, are selected and passed through the acceptance simulation program. The solid curves in Figs. 1(b-d) are obtained in this way. The good agreement with the overall mass and the approximate agreement with the $p\pi^+$ and $\pi^+\pi^-$ submasses is not a trivial result since the hadronization is not explicitly forced into the observed final state. The mass distribution of the $p-4\pi$ system, as well as the production rates of Δ^{++} and ρ^0 result from the general principles of the model, which are in agreement with the observed properties of jet fragmentation at higher energies in other interactions. To understand the excess Δ^{++} production of the model in Fig. 1(c), we note that, when selecting the $p-4\pi$ state, there is a large probability ($\approx 40\%$) to back-scatter a d -quark leaving a forward uu -diquark which is likely to give a Δ^{++} . The smaller Δ^{++} signal in the data may indicate that the pomeron not only couples to quarks but also to a gluon component in the proton as discussed in ref. [12,20]. This latter mechanism leads to a mesonic system produced by gluonic interactions, with all three proton valence quarks going forward, and correspondingly less probability to result in a Δ^{++} .

As a first investigation of the overall event shape, we use sphericity [21], which is a measure of $p_{\perp}^2$ with respect to the reconstructed event axis which minimizes this $p_{\perp}$. We have found that the angle between the sphericity axis and the proton-pomeron axis is more sensitive than the sphericity itself for distinguishing spherical and longitudinal event shape at these small masses of the hadronic system. The distribution of this angle is shown in Fig. 2, where $\cos\theta = 1$ corresponds to the two axes being aligned. Since the distribution of uncorrected data is shown, Monte Carlo events generated according to the fireball model and the longitudinal model are passed through the detector-acceptance simulation program. The longitudinal model, which has an event axis aligned with the proton-pomeron axis, is clearly preferred by the data.

To get further information we also study the detailed internal properties of the diffractive state and first consider the angular distribution of the final-state proton (measured with respect to the incoming proton in the $p-4\pi$ center-of-mass). In Figs. 3(a-c) the uncorrected data for three mass-regions of the $p-4\pi$ state are compared to the two models, fireball and longitudinal (including detector acceptance).

Despite the diminishing acceptance for protons with larger cosine θ , the data show a strong forward and also a clear backward peaking which develops with increasing M_X , when compared with the fireball model. This feature of the data is rather well reproduced by the longitudinal model.

In Figs. 4, the longitudinal and transverse scaled momenta [22] of the proton, π^+ and π^- (measured with respect to the axis defined by the proton-pomeron collision in its cms) are shown for the uncorrected data and the two models. The data show clearly that the proton has more longitudinal momentum, forward in particular, and slightly less transverse momentum compared to the expectations from the fireball model. A similar tendency of larger longitudinal momenta, both forward and backward, is also observable in the pion x_F -spectra, although the effect is not as pronounced as for the proton (whereas the proton x_F data are plotted on a linear scale, the π^+ and π^- data are plotted logarithmically to display more clearly the behavior in the tails). The longitudinal model reproduces the data quite well, except for its somewhat too steep proton $x_\perp$ -spectrum.

Fig. 5 shows the acceptance-corrected x_F distribution of the proton. To obtain this corrected distribution, we use the longitudinal model event generator (and the detector simulation program), although almost the same corrected distribution results if the fireball event generator is used. The clear forward peaking which results agrees well with the longitudinal model but not at all with the fireball model. The large error bars on some of the points are due to limitations in the Monte Carlo statistics in the region of low acceptance.

It is noteworthy to point out that the clear forward-backward asymmetry observed for the proton in Fig. 5 does not arise from simple longitudinal phase space but requires some additional dynamics in the interaction, e.g. as generated in our longitudinal model. Since the most striking disagreement between the data and the fireball model is this forward peaking of the proton, there is a possibility that a good overall agreement could be achieved if only this effect is taken into account. To investigate this, we have used an "oriented fireball" model where isotropically-generated phase space events are rotated so that the angular distribution of the proton is in agreement with the data. However, no improved agreement over the fireball model is found with the data in Figs. 2, 4 or 5 [23].

We have verified that the results in this Letter do not depend significantly on the momentum transfer. A subsample with $|t| > 0.2 \text{ GeV}^2$ shows the same qualitative features as the total sample ($|t| > 0.02 \text{ GeV}^2$). Since there is symmetry around the proton-pomeron axis in the longitudinal as well as the isotropic model, no structure in the distribution of azimuthal angles (measured with respect to the diffractive scattering plane) is expected for the final state particles. From our comparison of models and data we indeed find this to hold within $\approx 25\%$.

From the studies presented here we conclude that diffractively produced hadronic states with a mass of only a few GeV have a longitudinal event shape. Although this study was for a particular diffractive state, the conclusion seems very general when considering our results for other final states in a similar mass region [12,15]. In the longitudinal model, which is in reasonable agreement with the data in Figs. 1-5, the diffractive state is formed by an underlying interaction at the parton level followed by a hadronization process similar to other inelastic hadronic processes. This is suggested by our evidence [15] for a pomeron single-quark interaction. An interaction of the pomeron with a gluon component of the proton may also occur, as is suggested for the production of $\{p + \text{isoscalar}\}$ states in ref. [12,20]. To gain more insight into the nature of the pomeron and its possible partonic structure, it will be of great interest to make further studies of the structure of diffractively produced states, both of low and higher masses, and compare them with the corresponding hadronic states produced in other interactions initiated by photons, leptons and hadrons.

The support of the ISR Experimental Support Group and Operations Group during the running of this experiment is gratefully acknowledged. We also thank the CERN administration for their continuing support.

References

- [1] U. Amaldi, M. Jacob, G. Matthiae, *Ann. Rev. Nucl. Sci.* 26 (1976) 385
G. Alberi, G. Goggi, *Phys. Reports* 74 (1981) 1
- [2] K. Goulianos, *Phys. Reports* 101 (1983) 169
- [3] F. E. Low, *Phys. Rev. D* 12 (1975) 163
S. Nussinov, *Phys. Rev. Lett.* 34 (1975) 1286; *Phys. Rev. D* 14 (1976) 246
- [4] G. Ingelman, CERN-EP/85-159, *Proceedings of the Workshop on Elastic and Diffractive Scattering at the Collider and Beyond*, Blois, France (June 1985)
- [5] R. Hwa, *Phys. Rev. Lett.* 26 (1971) 1143
M. Jacob, R. Slansky, *Phys. Rev. D* 5 (1972) 1847
- [6] D. Amati, A. Stanghellini, S. Fubini, *Nuovo Cimento* 26 (1962) 896
- [7] E.L. Berger, G.C. Fox, A. Krzywicki, *Phys. Lett.* 43B (1973) 132
- [8] G. Bellettini, *AIP Conf. Proc. No. 15, High Energy Collisions, 1973* (Stony Brook), ed. Chris Quigg (American Institute of Physics, New York, 1973) pp. 9-46.
- [9] M.G. Albrow et al., *Phys. Lett.* 51B (1974) 424; *Nucl. Phys.* B102 (1976) 275
- [10] D. Aston et al., *Nucl. Phys.* B166 (1980) 1; *Nucl. Phys.* B189 (1981) 15
M. Atkinson et al., *Nucl. Phys.* B229 (1983) 269
- [11] P. Chauvat et al., *The Performance of a 16,000 Wire Mini Drift MWPC System; CERN-EP/82-198; Proceedings of the 1983 DPF Workshop on Collider Detectors* (LBL-15973), p. 81; contribution to XXI International Conference on High Energy Physics, Paris, July, 1982
- [12] P. Chauvat et al., *Phys. Lett.* 148B (1984) 382
- [13] S. Erhan et al., *Phys. Lett.* 152B (1985) 131
- [14] L. Baksay et al., *Phys. Lett.* 55B (1975) 491
- [15] A.M. Smith et al. (R608 collaboration), *Phys. Lett.* 163B (1985) 267
- [16] A. Donnachie and P. V. Landshoff, *Nucl. Phys.* B244 (1984) 322
- [17] B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand, *Phys. Rep.* 97 (1983) 31
- [18] M. Arneodo et al. (EMC collaboration), *Phys. Lett.* 150B (1985) 458; *Phys. Lett.* 145B (1984) 156; *Phys. Lett.* 144B (1984) 302
- [19] H. Grassler et al., *Nucl. Phys.* B223 (1983) 269
D. Allasia et al., *Z. Phys.* C24 (1984) 119
- [20] P. Chauvat et al., *Proceedings of the XV International Symposium on Multiparticle Dynamics, Lund Sweden, 10-16 June 1984*, p. 53.
- [21] J.D. Bjorken, S.D. Brodsky, *Phys. Rev. D* 1 (1970) 1416
- [22] The scaled momenta are defined by $x_F = p_{\parallel}/p_{\max}$ and $x_{\perp} = p_{\perp}/p_{\max}$ where, in both cases, x is unity for the maximum possible momentum in the 5-body final state.
- [23] M. Medinnis [R608 Collaboration], *Proceedings of the Workshop on Elastic and Diffractive Scattering at the Collider and Beyond*, Blois, France (June 1985)

Figure Captions

1. (a) acceptance-corrected distribution of momentum transfer $|t|$ to the diffractive $p-4\pi$ system; invariant mass distributions (uncorrected for acceptance) of (b) the $p-4\pi$ system (M_X); (c) the $p\pi^+$ and (d) the $\pi^+\pi^-$ combinations. For (a,c,d) only events with $3 < M_X < 4$ GeV are used. The solid curve in (a) is the fit mentioned in the text, whereas those in (b-d) are results from the longitudinal model discussed in the text. The dashed curves in (c,d) correspond to the resonance parametrization of the "fireball" model discussed in the text.
2. Distribution of the angle between the sphericity axis and the proton-pomeron axis for uncorrected $p-4\pi$ events with $3 < M_X < 4$ GeV. The curves are from the models discussed in the text.
3. Observed (uncorrected) angular distributions of final state proton (measured with respect to incoming proton in the $p-4\pi$ cms) for the three indicated regions of the $p-4\pi$ invariant mass. Curves are from the fireball model (dashed) and longitudinal model (solid) discussed in the text (including detector acceptance).
4. Uncorrected distributions of scaled longitudinal and transverse momenta (with respect to the proton-pomeron axis) for the p , π^+ , π^- in the $p-4\pi$ center-of-mass with $3 < M_X < 4$ GeV. The curves are the results from the fireball model (dashed) and longitudinal model (solid) discussed in the text and include detector acceptance. Note the different linear and logarithmic vertical scales in (a) and (c,e).
5. Acceptance-corrected distribution of the proton scaled longitudinal momentum (with respect to the proton-pomeron axis) in the $p-4\pi$ center-of-mass with $3 < M_X < 4$ GeV. The curves are from the models discussed in the text. (Note that the distributions are normalized in the region covered by the data.)

Fig. 1

Fig. 2

Fig. 3

Fig- 4

Fig. 5