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ANALYSIS OF DOUBLE DIFFRACTION DISSOCIATION
IN NUCLEON-NUCLEON COLLISIONS AT THE CERN ISR

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ABSTRACT

Final results from combined measurements of single and double diffraction of protons and neutrons into $(N\pi)$ and $(N\pi\pi)$ final states are presented. The experiments were performed at the CERN Intersecting Storage Rings with the Split Field Magnet detector using proton and deuteron colliding beams.

The general properties of the dissociating vertex in single and double diffractive reactions are essentially identical. Mass spectra and decay angular distributions are compared with the predictions of a dual resonant Deck model. Decay angular correlations and a strong slope-mass correlation are observed also in double diffraction. Detailed tests of factorization indicate its validity over the full range of all kinematical variables and in their correlations.

A model-independent analysis gives strong support to the peripheral nature of diffraction dissociation, with double diffraction being concentrated in a narrow Gaussian ring at the edge of the proton. Both the exclusive and the inclusive double diffractive cross-sections display a marked increase over the ISR energy range. Both mechanisms yield comparable contributions to the peripheral increase of the total pp cross-section, with an approximate saturation of the Pomplin bound.

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1. INTRODUCTION

At very high energies, the study of diffractive phenomena in hadronic collisions becomes increasingly rich in new experimental information, owing to the kinematical possibility of investigating higher order excitations of the colliding hadrons [1]. The process of diffractive excitation can in fact be described by a series expansion in the number of vertices at which particle production takes place. For all orders of this expansion the final states are characterized by individual systems of limited invariant mass, separated by large rapidity intervals.

The study of single diffraction dissociation, in which excitation takes place at one vertex, has a natural extension at very high energies to the investigation of double diffraction dissociation, in which excitation at both vertices occurs simultaneously. This type of process has been the subject of a systematic experimental investigation throughout the entire energy range of the CERN Intersecting Storage Rings (ISR), where an unambiguous rapidity separation of the two diffracted multiparticle systems could easily be achieved. In fact, single and double diffraction are concentrated near the extremes of the available rapidity interval, whereas higher order terms, such as double Pomeron exchange, tend to populate with diffractive clusters also the central rapidity region.

Double diffraction bears a particular relationship to single diffraction, since both processes are mediated by the exchange of a single Pomeron, and should therefore display the simplest kind of factorization properties. In this respect, higher order terms in the diffractive expansion are complicated by multi-Pomeron exchanges, which contain a new type of vertex, at which Pomeron-Pomeron scattering takes place. In a t-channel picture the comparison of the experimental information on single and double diffractive processes may provide new information on the properties of the Pomeron and on its role in the production dynamics of multiparticle final states. From the s-channel viewpoint, on the other hand, double diffraction dissociation contributes new information on the spatial localization of a new class of processes, which appear to be extremely peripheral in impact parameter. This strengthens the arguments which advocate that diffractive

excitation is effectively confined to the surface of the interacting hadrons. The study of higher order diffraction excitation can therefore be considered as an important tool for the further understanding of the properties of inelastic diffraction and an essential instrument in establishing the physical nature of the Pomeron.

In this paper we report the final results of a systematic study of double diffraction dissociation in exclusive final states using the Split Field Magnet (SFM) detector at the CERN ISR. The storage ring configuration of the machine and the experimental set-up allowed an almost ideal detection scheme, in which the excitation at both vertices could be symmetrically detected under identical kinematical conditions. In addition to this, the very large interval of centre-of-mass energies covered by the ISR allowed the only systematic investigation to be carried out to date of the energy dependence of an exclusive diffractive process in this energy range. All three combinations of nucleon-nucleon collisions, leading to two- and three-body excited systems, were investigated, by making use of circulating proton and deuteron beams. The reactions studied were the following ones:

$$pp \rightarrow (p\pi^+\pi^-)(p\pi^+\pi^-), \quad 23 \leq \sqrt{s} \leq 63 \text{ GeV} \quad (1)$$

$$pn \rightarrow (p\pi^+\pi^-)(p\pi^-), \quad \sqrt{s} = 37 \text{ GeV} \quad (2)$$

$$nn \rightarrow (p\pi^-)(p\pi^-), \quad \sqrt{s} = 27 \text{ GeV} . \quad (3)$$

The extensive investigation program on high-energy diffractive processes [2-8] included also the study of the analogous single (as well as coherent) diffraction dissociation reactions on protons and neutrons [5-8]

$$pp \rightarrow (p\pi^+\pi^-)p, \quad \sqrt{s} = 53 \text{ GeV} \quad (4)$$

$$np \rightarrow (p\pi^-)p, \quad \sqrt{s} = 37 \text{ GeV} . \quad (5)$$

Results on reactions (4) and (5) have been analysed in detail in a previous publication [8]. They will be partially reported here for analysis in terms of new variables and for comparison purposes.

This paper is organized as follows: section 2 describes the experimental procedure and the analysis criteria for the selection of the event samples; in section 3 we discuss the invariant mass distributions together with the distributions of two-particle subsystems in three-body final states. Mass spectra of double diffraction are compared with the corresponding single diffraction spectra and with the predictions of a Deck model extended to double excitation. Differential cross-sections are presented in section 4, together with the analysis of the mass dependence of the slopes for diffraction dissociation at both vertices; section 5 deals with the decay angular correlations, for which specific predictions of the extended Deck model can be made. The factorization properties of single and double diffraction from the most general viewpoint of mass, four-momentum transfer and decay angular distributions are discussed in section 6. In section 7 we analyse the overlap functions of diffraction dissociation in terms of central and peripheral amplitudes, comparing the results with model-independent impact parameter bounds. In section 8 we discuss the energy dependence of the integrated cross-section for exclusive double diffraction and its connection, through factorization, with the behaviour of the inclusive single and double diffraction cross-sections. We then analyse the resulting contributions of diffractive processes to the rise of the proton-proton total cross-section. Our conclusions are given in section 9.

2. EXPERIMENTAL SET-UP AND PROCEDURE

In this section we describe the experimental apparatus used to detect diffraction dissociation events from reactions (1) to (5) and the trigger conditions defining the selection criteria. We then discuss the properties of the off-line event reconstruction chain and the characteristics of the final event sample.

2.1 Apparatus

The data on single and double nucleon diffraction were obtained at the CERN ISR using the SFM detector. The SFM, shown in fig. 1, provided momentum measurement of the charged particles produced in proton-proton, proton-deuteron and

deuteron-deuteron interactions over almost a 4π solid angle. It consists [9] of two symmetric magnetic spectrometers with a gap width of 1.1 m and a maximum field strength of 1 T. A detector equipped with multiwire proportional chambers, having a total of about 70,000 wires, surrounds the interaction region. A first set of chambers covers the central region with a box-like arrangement at large angles; a second set covers smaller angles in the two symmetric forward telescopes. Downstream of the main magnetic structure, two smaller compensator magnets analyse particles produced at small angles to the beams.

2.2 Triggers

In order to select events corresponding to the topology of reactions (1) to (5) a two-step trigger, at fast and slow level, was adopted. The fast trigger, common to all reactions, made use of the fast-OR of the chamber signals in order to require at least one charged particle in each telescope, as a signature of beam-beam interaction. A slower trigger [10], with a decision time of about 2 μ s, operated on the memory-OR signals of groups of 32 wires. The chamber complex in the forward telescopes was therefore equivalent to a two-dimensional hodoscope system with a resolution of 64 mm.

These hodoscope signals allowed the determination for each event of the pattern of multiplicity and distribution of hits in the various chamber planes. By applying majority logic to both the strip and the plane counts it was then possible to set upper and lower limits to the number of possible track candidates for each event of any reaction. These trigger conditions, complemented by the requirement that at least one leading particle be present in each produced system, were applied to forward acceptance regions in the detector, centred on the outgoing beam directions. In addition, in order to enrich the diffractive samples, a veto was imposed on charged particles emerging in the central region. As discussed in the following, these cuts were chosen so as to define acceptance limits for all reactions much wider than the actual limits in the kinematical variables reached by the sensitivity of the experiment.

Reactions (2), (3), and (5), which involve neutron diffraction, were measured with circulating deuteron beams and required efficient detectors for the spectator protons, peaked in the laboratory frame near one half of the incident deuteron momentum. A specific hardware processor was built for this purpose, which electronically defined suitable "roads" in the compensator spectrometers. This selection corresponded to approximately 98% probability for Fermi momenta up to 0.3 GeV/c in the deuteron rest frame and operated with essentially 100% acceptance.

2.3 Data reduction

A preliminary off-line filter was applied to the raw data, in order to reduce the number of events to be processed by the reconstruction chain. This filter refined the electronic trigger requirements to the ultimate available resolution and performed further topological selections using reconstructed space points. The surviving events were processed through the standard SFM program chain [11], performing pattern recognition and geometrical reconstruction of the charged particle tracks through the inhomogeneous magnetic field of the SFM. The resulting sample of events, with the required charged multiplicity and topology originating from an identified vertex, was then processed through a four-constraint kinematical fit. Events with a confidence level greater than 0.01 were kept in the final sample. Figure 2 shows, as an example, the χ^2 probability distribution for the double diffractive reaction (1) at $\sqrt{s} = 31$ GeV, together with the distributions of missing momenta in the transverse plane before the kinematical fit.

2.4 Normalization and acceptance

The absolute normalizations for our data samples were obtained by collecting monitor counts simultaneously with data taking for all runs. Two scintillation counter hodoscopes, placed in front of the compensator magnets, were used to record on tape the instantaneous value of the luminosity at the interaction region. During data taking, besides the beam-beam interaction rate, also the beam-gas background level and time-of-flight information between the two hodoscope systems were continuously monitored and recorded. The calibration of the monitor was

performed for each run using the Van der Meer method [12], by determining with a scanning procedure the effective height of the overlap of the vertical beam densities at the interaction point.

The acceptance of the apparatus, of the trigger, and of the selection and reconstruction programs was calculated by means of Monte Carlo methods. The observed distributions were then corrected, taking into account the geometrical acceptance of the detector, trigger and chamber inefficiencies, and backgrounds. In particular, the effects of absorption and scattering in the beam tubes and in the detector material, together with losses in the filtering, pattern recognition and reconstruction chain, were considered in detail.

In all double diffraction processes, the acceptance is smooth and almost uniform up to masses of the dissociated systems in excess of 3 GeV and up to t -values in excess of $2 (\text{GeV}/c)^2$, within the full range of decay angles in the rest frame of the diffracted systems. In particular, the dissociation at both vertices in the presence of an analysing magnetic field allows full acceptance down to t_{min} , the minimum value of t kinematically allowed for each set of produced masses. For reactions (4) and (5), however, elastic-like protons having $-t < 0.04 (\text{GeV}/c)^2$ could not be detected, owing to the presence of the beam vacuum tubes. This results in an experimental cut at $-t = 0.05 (\text{GeV}/c)^2$ for single diffraction reactions.

2.5 Event samples

Details on the event samples for reactions (1) to (3) are given in table 1. More information on reactions (4) and (5) can be found in ref. 8. An indication of the quality of the event samples and of the effectiveness of the selection criteria is displayed by several independent properties of the data.

The missing transverse momentum distributions, both in the plane of magnetic deflection and in the vertical plane (see fig. 2), indicate an almost negligible probability for extra undetected particles. This is supported by the investigation of other distributions, such as vertex plots or t -coplanarity correlation plots, which allow the estimation of the background contamination arising from

beam-gas interactions or from undetected π^0 production at the level of 1% to 2%, according to reaction and energy.

For processes involving neutron diffraction in the deuteron, the identification of the spectator protons is shown in fig. 3, where the reconstructed momentum distribution in the deuteron rest frame is in excellent agreement with the prediction of the deuteron wave function. Also the slight angular asymmetry induced by the Møller flux factor is reproduced by the experimental data. An essential element in assessing the diffractive nature of the observed reactions is given by the rapidity separation of the final clusters, which should approximately reproduce and track the available rapidity gap at each energy. This is neatly displayed by the data, as shown for example in fig. 4 for reaction (1). The two excited low-mass systems, characteristic of low multiplicity exclusive final states, are spread over a narrow range of rapidities. As shown in a previous experiment [13], the rapidity interval between the two final state systems is large enough, at ISR energies, to suppress any Regge exchange contributions other than the Pomeron. It has to be remarked that the extension in rapidity of the central veto, discussed in section 2.2, is considerably narrower than the separation between the two diffracted clusters.

The tracking capability and the analysing power of the SFM detector result in a typical mass resolution of 0.02 GeV and four-momentum transfer resolutions in the range 0.006 to 0.012 (GeV/c)² for different incident momenta. The invariant mass of a ($p\pi^+\pi^-$) system, computed with measured quantities before the fitting procedure, is shown in fig. 5a. The general features, resonance peaks and shape of the spectrum are almost identical to the final distributions (see section 3). Figure 5b shows a correlation plot of the four-momentum transfers independently measured at the two vertices of reaction (1), again before any fitting procedure. In both cases backgrounds and distortions appear almost unappreciable.

3. INVARIANT MASS DISTRIBUTIONS

In this section we analyse the general properties of the invariant mass distributions and compare the two- and three-body mass spectra of double diffraction with the corresponding spectra of single diffraction. We then consider the properties of the two-particle subsystems in three-body double diffraction [reaction (1)] and compare the over-all invariant mass distributions with the predictions of a Deck model calculation extended to double diffraction.

3.1 Invariant mass distributions

The excitation spectra of $(p\pi^-)$ systems produced in double and single diffraction of neutrons, reactions (3) and (5), are compared in fig. 6. The two distributions are strikingly indistinguishable, and both display signals at the position of the N(1680), superimposed on the same type of low-mass threshold enhancement. A very similar picture arises from the comparison of three-body single and double diffraction, in reactions (4) and (1) respectively, as shown in fig. 7. This property is strictly related to the diffractive nature of these processes, according to which nucleon dissociation factorizes at the two vertices and is dominated by isoscalar exchange at very high energies. A quantitative analysis of the mass spectra (see also section 4) may show a barely perceptible reduction in the threshold behaviour of single diffraction, which can be totally attributed to the four-momentum cut at $-t = 0.05 \text{ (GeV/c)}^2$ and to the slight effect of the slope-mass correlation. This cut is absent in the double diffractive sample.

The resonant structures at the position of the N(1470) and N(1688) are somewhat more evident in the $(p\pi^+\pi^-)$ systems, see fig. 7 and table 2, for which the non-resonant Deck-type background is more severely damped by the high-mass propagators. This is also clear in the mass distributions of the $(\Delta^{++}\pi^-)$ subsamples, shown in fig. 7, for which the signal is defined by $M_{p\pi^+} \leq 1.35 \text{ GeV}$ (see also fig. 9). The resonant signals appear more clearly in the backward hemisphere of the Gottfried-Jackson system, as shown by fig. 8, the forward hemisphere being in fact considerably more populated by non-resonant pion production. This property

can easily be understood in the framework of Deck models for exclusive low-multiplicity final states, as discussed in the following section. Owing to the strict similarity of the mass spectra at all energies, the data in the interval $23 \leq \sqrt{s} \leq 53$ GeV have been combined in fig. 8, for the purpose of higher statistics.

The distributions of fig. 7 display one of the most peculiar features of exclusive diffraction dissociation, namely the impressive stability of the mass spectrum as a function of energy. This feature is clearly also a property of double diffraction over the entire ISR energy range. A wider analysis shows [14] that the mass spectra of exclusive diffraction dissociation are indeed stable over the range of incident momenta between 10 GeV/c and 2000 GeV/c.

3.2 Two-particle subsystems

The invariant mass distributions of the $(p\pi^+)$ and $(p\pi^-)$ subsystems in the total samples of $(p\pi^+\pi^-)$ systems of single and double diffraction are shown in figs. 9 and 10. Also in this case, besides the energy independence of the spectra, the comparison does not show any appreciable difference between the final state substructures of the two processes, which appear to be dominated by the $\Delta^{++}(1236)$ isobar. A much weaker $\Delta^0(1236)$ structure appears in the $(p\pi^-)$ subsystems. The two Δ signals can be obtained by fitting the spectra with a p-wave Breit-Wigner distribution plus a background obtained from random combinations of tracks from different events. The ratio of the two integrated signals is consistent with the isospin ratio $\Delta^{++}:\Delta^0 = 9:1$, which gives direct experimental support to the isoscalar nature of the produced $(p\pi^+\pi^-)$ systems.

The observation of two-particle substructures which involve higher Q-values is usually prevented by the phase-space limitations associated with low-mass $(p\pi^+\pi^-)$ systems, which dominate the production dynamics. Given the observed stability of the mass distribution as a function of energy, we combined events from the four richest samples and applied a cut for events with masses below 1.9 GeV. Strong signals appear in both the $(\pi^+\pi^-)$ spectrum at the $\rho^0(770)$ mass and in the $(p\pi^-)$ distribution at the mass of the $N(1688)$ isobar (fig. 11). This

finding confirms that complex final state interactions take place in the three-body systems, and that for different invariant mass values of the parent system several quasi-two-body channels may simultaneously compete. This in turn may be relevant for the models, such as the Drell-Hiida-Deck one, which attempt to describe three-body diffraction as a superposition of quasi-two-body and direct channels.

3.3 Dual Deck model for double diffraction

All the theoretical approaches which describe higher order diffraction excitation can be considered as suitable generalizations of the multiperipheral model [15-17]. The Deck model, which appears to be particularly suitable [8] to describe angular correlations as well as mass and t -distributions for exclusive reactions, can easily be generalized to double diffraction [18]. In this model the diffractive dissociation at each vertex proceeds through elastic scattering on one component of a virtual configuration, which represents one of the possible eigenstates of the T -matrix for the incident hadron.

Consider the double diffraction diagram of fig. 12a, in which particles 1 and 4 represent outgoing baryons (protons or Δ^{++} in our case) and particles 2 and 3 represent pions. The relevant kinematical variables are the over-all momentum transfer t_2 [from a to the (34) system], the partial momentum transfer $t_1 = t_{a1}$, $t_4 = t_{b4}$, $u_1 = t_{a2}$, $u_2 = t_{b3}$ and the subenergies squared s_{ij} of the outgoing pairs of particles. In particular, we set $s_1 = s_{12}$ and $s_4 = s_{34}$.

The factorized double diffraction amplitude can be written in covariant form [18]

$$M_{DD} = \frac{1}{2} i A_a^\mu A_{b\mu} ,$$

where $A_{a,b}$ are the single diffraction amplitudes at the upper and low vertex, respectively.

If one takes into account pion exchange, baryon exchange, and direct pole contributions (fig. 12) one writes, in the Born approximation,

$$A_a^\mu = g_{a1\pi} \left[\frac{(p_a - p_1)^\mu + p_2^\mu}{t_1 - m_\pi^2} G_\pi(t_2) + \frac{(p_a - p_2)^\mu + p_1^\mu}{u_1 - m_1^2} G_1(t_2) + \frac{p_a^\mu + (p_1 + p_2)^\mu}{s_1 - m_a^2} G_a(t_2) \right] \quad (6)$$

and analogously for $A_{b\mu}$, with obvious replacements.

In the high-energy limit $p_a \simeq p_1 + p_2$, and one can write

$$A_a^\mu = 2g_{a1\pi} \frac{p_2^\mu Z_{st}'^a}{(t_1 - m_\pi^2)(s_1 - m_a^2)} + \frac{p_1^\mu Z_{su}'^a}{(u_1 - m_1^2)(s_1 - m_a^2)} \quad (7)$$

with

$$\begin{aligned} Z_{st}'^a &= G_\pi(t_2) (s_1 - m_a^2) + G_a(t_2) (t_1 - m_\pi^2) \\ Z_{su}'^a &= G_1(t_2) (s_1 - m_a^2) + G_a(t_2) (u_1 - m_1^2) \end{aligned} \quad (8)$$

and analogously for A_b^μ .

The form factors $G_i(t_2)$ define the t -dependence of the off-shell scattering amplitudes

$$G_i(t_2)G_j(t_2) = 2\sigma_{ij} e^{B_{ij}t_2}, \quad (9)$$

where σ_{ij} is the ij total cross-section and B_{ij} the slope of the ij elastic amplitude. We can assume

$$G_i(t_2) = \frac{2\sigma_{iN} e^{(B_{iN} - \frac{1}{2}B_{NN})t_2}}{\sqrt{2\sigma_{NN}}}. \quad (10)$$

Dualization is performed by replacing the propagators with the corresponding Veneziano functions, writing

$$A_a^\mu = 2g_{a1\pi} \left[p_2^\mu Z_{st}'^a V_{\pi a}(t_1, s_1) + p_1^\mu Z_{su}'^a V_{1a}(u_1, s_1) \right]$$

with

$$V_{\pi a} = \frac{\Gamma(-\alpha_s) \Gamma(-\alpha_t)}{\Gamma(1-\alpha_s-\alpha_t)}, \quad V_{1a} = \frac{\Gamma(-\alpha_s) \Gamma(-\alpha_u)}{\Gamma(1-\alpha_s-\alpha_t)} \quad (11)$$

and analogously at the lower vertex. The Regge trajectories are assumed to be

$$\begin{aligned}\alpha_t &= \alpha_\pi(t_1) = t_1 - m_\pi^2 \\ \alpha_u &= \alpha_N(u_1) = u_1 - m_1^2 \\ \alpha_s &= \alpha_N(s_1) = s_1 - m_a^2 + i\lambda \left[s_1 - (m_1 + m_\pi)^2 \right]^{\frac{1}{2}}.\end{aligned}\tag{12}$$

This model contains a rough parametrization for low-mass resonances in the s-channel, which is controlled by the parameter λ . This parametrization is rather rigid, so we do not expect to reproduce the mass spectra in detail.

Taking the product $A_{a b \mu}^\mu$ one finally gets, for two-body and quasi-two-body double diffraction processes

$$\begin{aligned}A_{a b \mu}^\mu &= 4g_{a1\pi} g_{b4\pi} \left\{ Z_{st}^{'a} \left[\left(p_2^\mu p_{3\mu} \right) Z_{st}^{'b} v_{\pi a} v_{\pi b} + \right. \right. \\ &\quad + \left. \left(p_2^\mu p_{4\mu} \right) Z_{su}^{'b} v_{\pi a} v_{4b} \right] + Z_{su}^{'a} \left[\left(p_1^\mu p_{3\mu} \right) Z_{st}^{'b} v_{1a} v_{\pi b} + \right. \\ &\quad \left. \left. + \left(p_1^\mu p_{4\mu} \right) Z_{su}^{'b} v_{1a} v_{4b} \right] \right\},\end{aligned}\tag{13}$$

where the scalar products $\left(p_i^\mu p_{j\mu} \right)$ reduce, in the high-energy limit, to the sub-energies squared s_{ij} , and the couplings $g_{a1\pi}$ and $g_{b4\pi}$ include a factor $\sqrt{-t_1}$ and $\sqrt{-t_4}$, respectively.

In specializing eq. (13) to the case of neutron double diffraction dissociation, reaction (3), also spin complications have been taken into account in the explicit evaluation of the amplitude. This however does not alter appreciably the features of the model with respect to the spinless case, as already observed [8] in the case of neutron single diffraction.

In comparing the model with the experimental data, we assumed for the off-shell cross-sections, which have the role of weight parameters,

$$\sigma_{1N} = 30 \text{ mb}, \quad \sigma_{\pi N} = 25 \text{ mb}, \quad \sigma_{aN} = 40 \text{ mb},$$

with slopes

$$B_{1N} = B_{aN} = 9 \text{ GeV}^{-2}, \quad B_{\pi N} = 10 \text{ GeV}^{-2}$$

as in ref. 8.

In the case of proton double diffraction, reaction (1), we assume a quasi-two-body mechanism proceeding via Δ^{++} production, as can be argued from the $(p\pi^+)$ mass spectra (fig. 9) which appear entirely dominated by Δ^{++} production. Spin effects have been neglected and the p-wave effect on the Δ^{++} Breit-Wigner behaviour has been taken into account. The weight parameters were in this case the same as for the neutron case, with the exception of σ_{1N} , set equal to 37.5 mb. This results in a better agreement between theory and experiment in the $(\Delta\pi)$ mass distributions. The model predictions are shown in figs. 13 and 14.

The agreement is quite impressive for neutron double diffraction, whereas for proton double diffraction the threshold behaviour and the low-mass peak position are not well reproduced by the model, which might be due to the perhaps too crude approximations made for this more complicated case. It has to be remarked that, particularly in the proton-proton case, the model appears rather sensitive to the choice of the parameters, and different sets of values produce better descriptions for different distributions. For example, the agreement with the decay angular distributions is greatly improved by increasing σ_{aN} to about 50 mb, which however sensibly worsens the description of the mass spectrum. The predictions of the model are compared with the experimental decay angular distributions in section 5. It is to be noted that only the relative ratio of the three off-shell cross-sections is relevant, since the theory is inadequate to predict absolute normalizations.

4. DIFFERENTIAL CROSS-SECTIONS

4.1 t-dependence

The differential cross-sections as a function of squared four-momentum transfer are shown in fig. 15 for single and double diffraction of neutrons, and in fig. 16 for single and double diffraction of protons. For reactions (1) and (3)

the data extend from $t_{\min}$ up to $-t = 2 \text{ GeV}^2$. For single diffraction, reactions (4) and (5), a cut at $-t = 0.05 \text{ GeV}^2$ corresponds to the experimental limitations due to the presence of the ISR vacuum chamber. The curves in figs. 15 to 17 represent phenomenological parametrizations of the data, which were fitted to the assumed form $d\sigma/dt = A_1 e^{b_1 t} + A_2 e^{b_2 t}$. This double exponential parametrization generally gives a good description of the differential cross-sections of inelastic diffraction [8]. The numerical results of the fits are given in table 3. Although both sets of data display very similar qualitative properties, the single diffractive reactions have considerably steeper slopes than the corresponding double diffractive reactions. This property can be interpreted in the framework of factorization, as being due to the presence of an elastic vertex in the former class of processes. In fact the t -dependence at this vertex is known to be steeper than the average t -dependence at the dissociation vertex, when averaged over the produced mass spectrum.

4.2 Slope-mass correlation

In single diffraction processes, the slope of the forward peak is known to be strongly dependent on the mass of the diffracted system. Factorization arguments, discussed in section 6, require that, by replacing an elastic vertex with an inelastic one, the slope-mass correlation in double diffraction be an even steeper function of mass, saturating at values of the order of 1 GeV^{-2} for very large masses. The mass dependence of the forward slope is usually known as a projection on a suitable mass axis of a much more complicated two-dimensional dependence of the slope on the production dynamics at both vertices of the reaction. One can write, from the most general two-dimensional case to specific projections:

$$b = f(M_1, M_2) \quad (14)$$

$$b_1 = f_1(M_1, m_p) \quad (14a)$$

$$b_2 = f_2(M_1, M_2 = M_1) \quad (14b)$$

$$b_3 = f_3(M_1, \langle M_2 \rangle) \quad (14c)$$

An example of a two-dimensional slope mass correlation is shown in fig. 18 for proton-proton double diffraction. The data cover a 5×5 matrix in the mass intervals; in fitting the slopes the symmetry of the initial state has been taken into account, and is reflected in the corresponding symmetry of the slope matrix. It can be seen that indeed the slope displays a complex behaviour in the plane of the masses of the two diffracted systems. The data of fig. 19 are the projections on the axis of equal masses [eq. (14b)] and the particular case of one elastic vertex in single diffraction [eq. (14a)]. A different one-dimensional reduction of the two-dimensional slope-mass correlation of double diffraction can be performed by averaging over the mass spectrum at one vertex, as in eq. (14c). These results will be discussed in section 6 in the framework of factorization tests. Figure 19 shows the slope dependence on mass, for identical mass intervals at both vertices. It is indeed a steeper function than in single diffraction, varying from about 20 GeV^{-2} at threshold to a saturation value for high masses at $b = 1.9 \text{ GeV}^{-2}$.

The energy dependence of the forward slopes, rather well known for elastic scattering where it displays a logarithmic shrinkage with increasing energy, is rather poorly known for single diffraction, where a mixed type of vertices contribute to build up the t -dependence of the differential cross-section. Double diffraction represents a new way of determining the energy dependence of the forward slopes for an inelastic vertex. This can be obtained at different mass values and independently of any subtraction procedure. The results are shown in fig. 20, where the forward slopes for three different mass intervals at both vertices of reaction (1) are plotted at five ISR energies. There is a strong indication that the slope at inelastic exclusive vertices is energy-independent, thus concentrating any possible shrinkage of single diffraction at the elastic vertex. With a Regge parametrization of the elastic slope of the type

$$b_{el}(s,t) = \frac{d}{dt} \ln \frac{d\sigma}{dt} = b_0(t) + 2\alpha'_P \ln \left(\frac{s}{s_0} \right), \quad (15)$$

the amount of shrinkage to be expected in single diffraction would be

$$\Delta b_{SD} = \alpha'_P \ln \left(\frac{s_2}{s_1} \right) \approx 1 \text{ GeV}^{-2} \quad (16)$$

in the range between PS and ISR energies, with a Pomeron slope $\alpha'_P \approx 0.3$, applicable to the small- t region ($-t < 0.1 \text{ GeV}^2$) of the elastic differential cross-section. For larger values of momentum transfer the amount of shrinkage would be substantially smaller. The value in (16) is consistent with experiment within the present uncertainties in the data [1] on exclusive processes of single diffraction at high energy.

To get a quantitative idea of the energy dependence of the forward slopes of double diffraction, we report in table 4 the slope of the effective Pomeron trajectory obtained by the three sets of data in fig. 20. They appear to be all consistent with zero or a very small value of α'_P .

The remarkable constancy of the forward slopes together with the observed stability of the mass spectra (see section 3 and ref. 14) point towards a description of exclusive diffraction dissociation with a mechanism essentially independent of incident energy, but for the value of the corresponding inelastic overlap function, which will be discussed in the following sections. These features may be in fact more easily reconciled with an s -channel picture of diffraction than with a notion of an inelastic Pomeron essentially different from the one appearing in high-energy elastic scattering.

5. DECAY ANGULAR DISTRIBUTIONS

In this section we discuss the decay angular distributions of two- and three-body diffracted systems, each vertex being independently considered. Single and double diffraction processes are compared with each other and with the predictions of the dual Deck model described in section 3.3. The angular correlations between different vertices in double diffraction will be discussed in section 6.

5.1 Decay moments

The decay angular distributions have been analysed in terms of normalized spherical harmonic moments, by evaluating the integrals

$$\langle Y_{\ell}^{m=0}(\cos \theta_J) \rangle = \frac{\int_{-1}^1 Y_{\ell}^{m=0}(\cos \theta_J) W(\cos \theta_J) d \cos \theta_J}{\int_{-1}^1 W(\cos \theta_J) d \cos \theta_J} \quad \ell=1\dots 6, \quad (17)$$

where $Y_{\ell}^{m=0}(\cos \theta_J)$ is the ℓ -th spherical harmonic function with $m = 0$, and $W(\cos \theta_J)$ is the measured differential cross-section in the polar angle of the proper analyser for each reaction in the t-channel helicity frame. The moments, averaged over four-momentum transfer, were evaluated separately in 17 mass bins for each of the six values of ℓ , and the results are shown in figs. 21 and 22 for the single and double diffractive reactions (4) and (1), respectively. The three-vector chosen as analyser is the Δ^{++} momentum. As for other features of the data, the two distributions appear almost identical.

In these plots the moments up to $\ell = 3$ are significantly different from zero for most of the mass range. The other moments show some fluctuations, although with limited significance, and their values are generally consistent with zero over the whole mass interval. The fact that the moments $\langle Y_{20} \rangle$ and $\langle Y_{30} \rangle$ are different from zero indicates that diffractive states with spin higher than $\frac{1}{2}$ are present in the final state.

The real and imaginary parts of the moments $\langle Y_{\ell}^m \rangle$ for $m = 0$ are consistent with zero throughout.

5.2 Decay angular correlations

It is well known that the Deck model for diffraction dissociation predicts specific correlations in the decay angular variables of the produced systems [19]. The azimuthal and polar decay angular distributions are expected to show accumulations in specific regions of the phase space, where different exchange mechanisms (see fig. 12) dominate. In particular, the pion exchange term populates the forward hemisphere of the Gottfried-Jackson frame, with the baryon exchange term being concentrated in the backward hemisphere at opposite azimuthal angles. The over-all angular distribution is the result of a complex interplay of all three terms that enter into eq. (6).

The azimuthal and polar asymmetries can be seen in fig. 23, which shows the correlation plots in the Jackson frame for reactions (1) and (4) with comparatively high statistics. These plots, besides indicating the uniformity of the acceptance over the full phase space, show that the angular correlations are essentially identical between single and double diffraction, and somewhat weaker than the ones observed in two-body final states [8]. The specific features of these distributions are best seen in the projections of the scatter plots, shown in fig. 24 for three-body single and double diffraction together with the prediction of the Deck model discussed in section 3.3. A similar comparison is shown in fig. 25 for two-body neutron diffraction. It can be seen that the observed angular correlations are well reproduced by the model, although, at variance with the two-body case, the three-body reactions cannot optimize simultaneously the description of the mass distributions and of the decay angular distributions with the same weights of the three contributing terms (see section 3.3).

A more sensitive test of the predictions of the model can be performed in the extreme forward and backward regions of the polar decay angle, in which the azimuthal distributions are more sensitive to the different production mechanisms. This can be seen in figs. 26 and 27, in which the azimuthal distributions for values of $|\cos \theta_J| > 0.8$ are compared with the predictions of the model.

6. FACTORIZATION PROPERTIES

The pole nature of the Pomeron leads directly to the property of factorization [20], according to which the amplitudes for elastic, single, and double diffraction can be written as

$$\begin{aligned} T_{P_1 P_2 \rightarrow P_1 P_2}(s, t) &= g_{P_1 P_1}(t) g_{P_2 P_2}(t) F(s) \\ T_{P_1 P_2 \rightarrow P_1 X_2}(s, t) &= g_{P_1 P_1}(t) g_{P_2 X_2}(t) F(s) \\ T_{P_1 P_2 \rightarrow X_1 X_2}(s, t) &= g_{P_1 X_1}(t) g_{P_2 X_2}(t) F(s) , \end{aligned} \quad (18)$$

where g_{ij} denote the vertex functions for the indicated coupling. Assuming the function $F(s)$ independent of the initial and final states, the ratios of amplitudes (18) are only dependent on the corresponding ratios of vertex functions.

This has considerable importance in placing stringent requirements on the relative strength of different reactions.

6.1 Forward slopes

As a consequence of (18) we can require, for example, by changing the initial states,

$$\frac{\frac{1}{2}(d\sigma/dt)(pp \rightarrow pX)}{(d\sigma/dt)(pp \rightarrow pp)} = \frac{(d\sigma/dt)(ap \rightarrow aX)}{(d\sigma/dt)(ap \rightarrow ap)} \quad (19)$$

and by changing final states

$$\frac{\frac{1}{2}(d\sigma/dt)(pp \rightarrow pX)}{(d\sigma/dt)(pp \rightarrow pp)} = \frac{(d\sigma/dt)(pp \rightarrow XY)}{\frac{1}{2}(d\sigma/dt)(pp \rightarrow pY)}, \quad (20)$$

where a denotes an incident hadron different from a proton and X, Y denote specific final states. With the differential cross-sections being almost exponential in restricted intervals of momentum transfer, eq. (19) leads to a simple relation among the forward slopes of double diffraction, single diffraction and elastic scattering

$$b_{DD}(M, M) = 2b_{SD}(M) - b_{el}. \quad (21)$$

This relation seems to be verified by the trend of the data in fig. 28, in which the two inelastic slopes become approximately equal to the elastic one in the same mass interval, in agreement with eq. (21). A more complete check of the slope factorization, relation (21), can be done by plotting the slopes as a linearized function of mass [21]. It is possible to test factorization both for the slope-mass correlation of the type (14b), as given by eq. (21), or for the correlation of the type (14c), for which eq. (21) becomes

$$b_{DD}(M_1, \langle M_2 \rangle) = b_{SD}(M_1) + \langle b_{SD}(M_2) \rangle - b_{el}, \quad (22)$$

where $\langle b_{SD} \rangle$ is the single diffraction slope averaged over the corresponding mass spectrum. The results of this test are shown in fig. 29. The slope values for proton single diffraction display a linear dependence on the variable $(M^2 - m_p^2)^{-1}$, and the dashed lines represent a linear fit to the data. From this fit and the

energy dependence (15) of the elastic slope it is possible to obtain quantitative predictions for the double diffraction slopes from (22) and (21), which are compared with the experimental values in figs. 29a and 29b, respectively. Indeed fig. 29a shows that the replacement of an elastic vertex by a diffractive dissociation vertex, averaged over mass, amounts to a simple decrease of the double diffractive slope by a fixed amount, around 3 GeV^{-2} . It is remarkable that the slopes of elastic scattering and inelastic diffraction, averaged over mass, differ by the same amount.

The situation is more complicated for the mass dependence of the double diffractive slope for equal masses at both vertices, fig. 29b, which does not display a linear dependence on the same mass variable. A quadratic parametrization was arbitrarily chosen, just to display the comparison between data and prediction in a more convenient way than on a linear mass scale. In both cases factorization between single and double diffraction is well verified by the small- t slopes over the entire mass interval.

6.2 Differential distributions

The next step in checking factorization is to consider the entire t -range of the differential cross-sections, according to eq. (20). This has been proved [22] to fail at large values of t when an elastic vertex comes into play, since the pronounced minimum in the elastic differential cross-section is absent in the inelastic diffraction channels. In the s -channel picture this violation arises from the completely different form of the elastic and inelastic amplitudes

$$T_{\text{el}} \sim \frac{J_1(b\sqrt{-t})}{b\sqrt{-t}}, \quad T_{\text{diff}} \sim J_0(b\sqrt{-t}) \quad (23)$$

or, in t -channel language, by the onset of absorptive cuts [23] at large values of four-momentum transfer. A t -dependent factorization test, not including elastic vertices, can be performed by using only the double diffractive processes (1) to (3) and with a generalization of eqs. (19) and (20) to the equality

$$\frac{d\sigma}{dt} \left[p n \rightarrow (p\pi^+\pi^-)(p\pi^-) \right] = \left\{ \frac{d\sigma}{dt} \left[p p \rightarrow (p\pi^+\pi^-)(p\pi^+\pi^-) \right] \frac{d\sigma}{dt} \left[n n \rightarrow (p\pi^-)(p\pi^-) \right] \right\}^{\frac{1}{2}}. \quad (24)$$

The prediction of the right-hand side of eq. (24), obtained through a parametrization [24] of the corresponding differential cross-section with peripheral amplitudes, is compared with data from reaction (2) in the left-hand side of (24) in fig. 30. Factorization among inelastic vertices is shown to hold to a very high degree of accuracy up to rather large values of momentum transfer.

A further factorization test, implied in eq. (19), shows that the production dynamics at one vertex, in terms of the mass distribution of a given final state, is completely independent of the type of reaction at the other vertex. The results are shown in fig. 31, in which factorization predicts unity for the ratios of normalized mass distributions:

$$R_{ij}(M) = \frac{d\sigma(i)}{dM} / \frac{d\sigma(j)}{dM} , \quad (25)$$

where the indices refer to different single or double diffractive reactions (1) to (5), and M is the invariant mass of the $(N\pi)$ or $(N\pi\pi)$ system, according to the case.

As a final test of factorization we have measured the correlation coefficients relative to the decay angles at the two vertices of reaction (1). In all cases values compatible with zero were obtained. These results indicate that the factorization hypothesis (18) is very well satisfied by exclusive inelastic diffraction, and in particular by double diffraction, when considering all the kinematical variable distributions independently as well as their mutual correlations.

7. IMPACT PARAMETER ANALYSIS

The impact parameter analysis of elastic scattering data at very high energy, combined with s-channel unitarity, has revealed interesting properties of elastic, inelastic, and diffractive processes [25-27] from the inclusive viewpoint. Very little is known, though, about the detailed structure of exclusive inelastic reactions, for which the full complex amplitude must be known, in order to perform a model-independent analysis [28-30]. Several methods have been proposed [31-36] to determine absolute lower bounds on $\langle b^2 \rangle$, the average of the impact parameter squared in exclusive reactions. The consequences of these bounds, applied to

reactions (1) to (5), will be discussed in this section, together with the implications on a peripheral model description of exclusive single and double diffraction.

7.1 Impact parameter bounds

The first bound, proposed by Webber [31], can be written as

$$\langle b^2 \rangle \geq \langle b_W^2 \rangle = \sum_{i=1}^{n-1} u_i \langle x_i \rangle, \quad (26)$$

where n is the number of final state particles in the exclusive process being considered and x_i their reduced longitudinal momenta. The arbitrary functions u_i are determined by the set of equations

$$\langle x_j \rangle = \sum_{i=1}^{n-1} \langle T_{ij} \rangle u_i, \quad T_{ij} = \vec{p}_{Ti} \cdot \vec{p}_{Tj} \quad (27)$$

in which T_{ij} is the transverse momentum correlation matrix.

Accounting for the presence of strong absorptive effects, the Henyey-Pumplin bound [35] is defined in terms of a variable τ

$$\tau = \sum_{i=1}^{n-1} \left(u_i \vec{p}_{Ti} \right)^2 / \left(\sum_{i=1}^{n-1} u_i x_i \right)^2, \quad (28)$$

from which the bound results as

$$\langle b^2 \rangle \geq \langle b_{HP}^2 \rangle = \left\langle \tau \left(\frac{d}{d\tau} \ln \frac{d\sigma}{d\tau} \right)^2 \right\rangle, \quad (29)$$

where $d\sigma/d\tau$ is the experimental τ -distribution.

A third possibility is given by the so-called central link bound [36], more apt to describe diffractive processes, which take place near the boundaries of the phase space,

$$\langle b^2 \rangle \geq \langle b_{CL}^2 \rangle = \frac{\langle \cos^2 \theta_k \rangle}{\langle p^2 \sin^2 \theta_k \rangle} \approx \frac{\langle x_k \rangle^2}{\langle x_k^2 \rangle}. \quad (30)$$

In eq. (30) link momenta in multiperipheral language are used, with the k -th line crossing $x = 0$; p is the c.m. momentum of the incoming protons, $\vec{r}_k$ is the transverse momentum transfer between the forward and backward hemispheres in the c.m. system, and $\vec{p}(1-\chi_k)$ is the corresponding longitudinal momentum transfer.

The methods just described, although different in principle, do not lead to significantly different bounds, as shown in table 5, with values at most of the order of 0.4 fm. The methods are essentially equivalent, and provide lower bounds which differ only in detail also when considering the single diffractive reactions. In particular, the possibility of strong absorptive effects does not appear to be supported by single or double diffractive data. As can be easily deduced from eq. (30), the bounds display a mass dependence of the same type as that of the forward slopes, which can be seen in linearized form in fig. 32. In this figure the double diffractive data are obtained from two different samples of reaction (1), at $\sqrt{s} = 31$ and 53 GeV, respectively, averaging over mass at one vertex. The single diffraction results are from the data [5,7,8] on reactions (4) and (5) of this experiment, and from two-body proton diffraction [37] measured at the ISR.

A primary purpose of this analysis is to compare the values of the bounds of exclusive diffractive reactions with the corresponding r.m.s. impact parameter values which can be deduced by describing the production mechanism with central or peripheral amplitudes. If a central production mechanism is assumed, in order to take into account the observed structure of the data in different mass intervals, one can parametrize the amplitudes in terms of two exponentials [8,38]

$$T(M,t) = i \left[a_1(M) e^{b_1(M)t} + e^{i\phi} a_2(M) e^{b_2 t} \right] \quad (31)$$

in which the second slope is essentially mass independent, or alternatively [39]

$$T(M,t) = a_1(M) \frac{J_1(b_0\sqrt{-t})}{b_0\sqrt{-t}} e^{At} + a_2(M) e^{bt} . \quad (32)$$

Expression (31) corresponds to a distorted Gaussian overlap function, whereas expression (32) describes the scattering on a black disk with smoothed edge and a

Gaussian-like tail. The transformations into impact parameter space of eqs. (31) and (32)

$$T(M,b) = \frac{1}{4\sqrt{\pi}} \int_0^\infty T(M,t) J_0(b\sqrt{-t}) dt \quad (33)$$

yield very similar results, and in the following only the worst (lowest b_{rms}) case, eq. (31), will be further considered.

It is now possible to evaluate the ratio between the lower bound and the r.m.s. impact parameter for central amplitudes in different mass intervals and for different reactions. The results are shown separately in fig. 33 for single and double diffraction, the latter for identical mass intervals at both vertices. It is clear that, apart possibly from the lowest mass bin, the hypothesis of a central mechanism is excluded by the data. A similar analysis for the integrated cross-sections, including also Fermilab data [40] on neutron two-body dissociation, is shown in fig. 34. Again the data lie definitely away from the band of values, between 0 and 1, which could accommodate a central production mechanism.

7.2 Peripheral approach

While the elastic amplitude is constrained to be central by unitarity, an impact parameter analysis shows [25] that inelastic diffraction must be essentially peripheral and concentrated around $b_0 \approx 1$ fm, since in the central region the open production channels are mainly non-diffractive.

The large difference between this result and the lower bounds discussed in the previous section suggests that the spin structure of the diffractive production amplitudes [29] must contribute considerably to the actual value of the r.m.s. impact parameter. Therefore a more appropriate form for the amplitudes comes from allowing the possibility of helicity flips and parametrizing the s-channel helicity amplitudes in terms of Bessel functions [41-43]

$$T_{\Delta\lambda}(M,t) = i C_{\Delta\lambda}(M) J_{\Delta\lambda}(b_0\sqrt{-t}) e^{At} \quad (34)$$

$$\frac{d\sigma}{dt} = \sum_{\Delta\lambda} |T_{\Delta\lambda}|^2,$$

in which the mass dependence of the coefficients $C_{\Delta\lambda}$ reflects the corresponding mass dependence of the average spin of the produced system.

In order for the differential cross-sections to reach a non-zero limiting value of the slopes at large masses, as indicated by the slope-mass correlation data (see section 4.2), the contributions of the amplitudes (34) to the integrated cross-section must be damped for increasing order of helicity flip $\Delta\lambda$.

This turns out to be actually the case when fitting eq. (34) to the data, without additional hypotheses. The integrated helicity flip contributions, normalized to the non-flip term

$$R_n = \frac{\int |T_n(M,t)|^2 dt dM}{\int |T_0(M,t)|^2 dt dM} \quad (35)$$

are shown separately in fig. 35 for single and double diffraction. Given the strong similarity of the data, the points in fig. 35 are the results of simultaneous fits to the seven double diffraction data samples of reactions (1) to (3) and to the two data samples of reactions (4) and (5), respectively. An almost Gaussian damping of the helicity flips terms seems to be favoured by the data, the values in fig. 35b being very similar to those in ref. 41. The main parameters of the fits are given in table 6. By performing independent fits to the different data samples, the results turn out to be very stable and substantially unchanged (see figs. 36 and 37).

Transforming the amplitudes (34) into impact parameter space we get the overlap functions for reactions (1) to (5)

$$T_{\Delta\lambda}(M,b) = \frac{1}{4\sqrt{\pi}} \int_0^\infty T_{\Delta\lambda}(M,t) J_{\Delta\lambda}(b\sqrt{-t}) dt \quad (36)$$

$$G(b) = \begin{pmatrix} 2 \\ 1 \end{pmatrix} \int_0^\infty \sum_{\Delta\lambda} |T_{\Delta\lambda}(M,b)|^2 dM .$$

An example of central and peripheral overlap functions for single and double diffraction is given in fig. 36. It can be seen that both reactions are centred

around $b_0 \approx 1$ fm, with double diffraction being strongly more peripheral than single diffraction. For double diffraction in fact the value of the parameter A in eq. (34) generates an almost Gaussian profile, with the process taking place only at the edge of the proton. Figure 37 shows that the parameters A and b_0 , which control the shape of the overlap function, are essentially constant throughout the entire ISR energy range, which reflects the absence of shrinkage of the differential cross-sections for double diffraction (section 4.2).

This impact parameter analysis, performed on the grounds of model-independent lower bounds and with general classes of models for exclusive production, yields a strong indication in favour of a peripheral mechanism for exclusive diffraction processes. This is in agreement with similar results on inclusive inelastic diffraction [44,45], and is strongly supported by an independent analysis of coherent diffraction of protons and neutrons on deuteron targets [8,46], in which peculiar interference effects can only be attributed to the complex structure of the peripheral amplitudes (34).

8. ENERGY DEPENDENCE OF THE INTEGRATED CROSS-SECTIONS FOR DOUBLE DIFFRACTION

8.1 Exclusive reactions

The energy dependence of exclusive inelastic diffraction at very high incident momenta is very poorly known, to the level of ignoring whether the cross-section of these processes has anything in common with the flattening and subsequent rising régime of the total and the elastic cross-sections. Only inclusive single diffraction is known to rise substantially in the ISR energy range [45,47]. In this respect the determination of the energy dependence of exclusive double diffraction gives information on a fundamentally new diffractive process, and represents the only systematic measurement of an exclusive diffractive process available to date in this energy region.

The cross-section for double diffraction of protons in three-body final states [reaction (1)] is shown in fig. 38 as a function of equivalent incident momentum. Numerical values are given in table 7. The data from reactions (2)

and (3) have also been included, after reduction [4] to the final state (1) through isospin coefficients and factorization. For this reduction a model-independent ratio for the total diffractive cross-sections in two- and three-body final states $\eta = \sigma(N \rightarrow N\pi)/\sigma(N \rightarrow N\pi\pi)$ is needed, owing to the large and different continuum contributions to the two mass spectra. The previous analysis and the data in fig. 30 imply a very good agreement among all three double diffractive cross-sections, but the cross-section values for reactions (2) and (3) are not linearly independent in the comparison with reaction (1) if one uses only data from our experiment. The values of η calculated from reactions (2) and (3) are 1.28 ± 0.06 at $\sqrt{s} = 26$ GeV and 1.27 ± 0.18 at $\sqrt{s} = 37$ GeV, which represents a further test of factorization at the integrated cross-section level. An independent value for η can be obtained from isospin analyses [48] of hadron-induced ($N\pi$) and ($N\pi\pi$) proton dissociation. These values are remarkably energy independent in the 30 GeV energy range; taking a weighted average and applying the proper isospin coefficients, one obtains

$$\frac{\sigma(n \rightarrow p\pi^-)}{\sigma(p \rightarrow p\pi^+\pi^-)} = 1.20 \pm 0.12$$

for $p_{\perp} < 30$ GeV/c. This value is in excellent agreement with the corresponding value 1.21 ± 0.50 at 1000 GeV/c [49,50].

Applying this factor to our data on reactions (2) and (3), we get the equivalent cross-sections for reaction (1) at $\sqrt{s} = 26.4$ and $\sqrt{s} = 37.2$ GeV given in table 7. The errors given are quadratic combinations of statistical and systematic uncertainties. Fitting the seven points to the function $\sigma = a + b \ln s$, we get a cross-section rising by $(51 \pm 5)\%$ in the s -range 544 GeV^2 to 3878 GeV^2 . If the last point at $\sqrt{s} = 63$ GeV is ignored, the cross-section rise becomes $(46 \pm 5)\%$ over the entire s -range. Introducing the exponent of a $(\ln s)^\alpha$ term as a free parameter, the fit over seven points yields α consistent with 1.

8.2 Inclusive reactions

Exclusive processes of the type (1) to (5) constitute a small but highly selected fraction of the total diffraction cross-section, single plus double, which represents, on the other hand, a substantial part of the total cross-section, $\sigma_D + \sigma_{DD} \approx \frac{1}{4}\sigma_{\text{tot}}$. The energy dependence of the inelastic diffractive processes is therefore extremely relevant to the understanding of the behaviour of the total proton-proton interaction probability.

Although inclusive measurements [47] can directly yield the value of the total cross-section of single diffraction σ_D , a corresponding value for the total cross-section of double diffraction σ_{DD} cannot be obtained directly by the experiment. This value, though, can be extracted through factorization relations among the amplitudes of different processes, as shown in fig. 39, of the type

$$\sigma_{DD} = \frac{\sigma_{X,p\pi\pi} \sigma_{X,p\pi\pi}}{4\sigma_{p\pi\pi,p\pi\pi}} \quad (37a)$$

$$\sigma_{DD} = \frac{\sigma_{X,p\pi\pi} \sigma_{X,p}}{2\sigma_{p\pi\pi,p}} \quad (37b)$$

$$\sigma_{DD} = \frac{\sigma_{X,p} \sigma_{X,p}}{4\sigma_{el}} \quad (37c)$$

in which the numerical factors take into account the symmetry of the initial state. Equations (37) link essentially all measurable types of diffractive processes, namely elastic scattering, exclusive and inclusive single diffraction, and exclusive and semi-inclusive double diffraction. In addition, data with different projectiles can be combined with proton data through eq. (19). This is shown in the compilation of fig. 40a, in which inclusive single diffractive data from direct measurements and factorization are combined [51] and display a rather good agreement with ISR inclusive measurements. A similar increase with energy is displayed by the compilation [51] of the inclusive cross-section for double diffraction, fig. 40b. The exclusive double diffraction data of this experiment and semi-inclusive results have been reduced to fully inclusive cross-sections by means of eqs. (37a), (37b) and eqs. (19), (20) for different initial particles and different final states.

A comparison between the two kinds of diffractive cross-sections in fig. 40 can be done through eq. (37c), which predicts, from the trend of σ_D in fig. 40a, a value of σ_{DD} indicated by the dashed curve in fig. 40b. This independent factorization prediction seems to be in good agreement with the data. Both diffractive processes have considerably large cross-sections, and at very high energies their magnitude and energy dependence become similar. This result is in agreement with the prediction of Regge theory [52]

$$\frac{\sigma_{DD}(s)}{\sigma_{SD}(s)} \sim \ln s, \quad (38)$$

according to which at large enough energy double diffraction must display a steeper rise and eventually dominate single diffraction. It is clear from the data in fig. 40 that in the ISR range single and double diffraction yield large and comparable contributions to the rise of the total proton-proton cross-section, with almost complete saturation of the Pomplun bound [53], $\sigma_D + \sigma_{DD} \lesssim \frac{1}{2} \sigma_{tot} - \sigma_{el}$, at the highest energies.

9. CONCLUSIONS

Making use of combined measurements with incident protons and neutrons, a systematic investigation of single and double diffraction dissociation processes into $(N\pi)$ and $(N\pi\pi)$ final states has been performed at the CERN ISR. These measurements allow a direct comparison of the basic nucleon dissociation mechanisms under identical experimental conditions. From the analysis of both types of processes a homogeneous picture emerges, which strongly suggests a universal behaviour of diffraction dissociation mechanisms at high energies. This is further supported by the analysis [8] of the corresponding coherent diffraction processes in the same energy range.

The general features of the production and decay of low-mass systems are reproduced by a Deck calculation; in particular the expected decay angular correlations are indeed observed in the data. The forward slope of double diffraction is found to be a much steeper function of mass than in single diffraction, as predicted by factorization arguments.

Factorization itself is checked in detail in the comparison between single and double diffraction, and is found to be satisfied to a very high degree in all the relevant kinematical variables and in their mutual dependence.

Based on a model-independent analysis in terms of lower bounds on the r.m.s. impact parameter, the overlap functions of inelastic diffraction are found to be strongly peripheral. This is indicated by the direct transformation in b-space of inclusive and exclusive differential distributions, and is further supported by the analysis of interference effects in coherent diffraction [8]. In particular, the impact parameter profile of double diffraction indicates that this process takes place essentially at the edge of the proton structure.

The integrated cross-section for exclusive double diffraction, measured at seven different energies over the ISR range, displays a marked energy dependence with a sizeable logarithmic rise. The same applies for both single and double inclusive diffraction. The rise with energy of these cross-sections can be described by an increase of opacity of the overlap function around 1 fm, in a region of space in which elastic scattering and unitarity confine both the growth of the total cross-section and the inclusive diffraction processes. In this context it is interesting to remark that the increase of the total diffractive cross-section almost saturates the Pomplin bound and represents a major contribution to the corresponding increase of the total proton-proton interaction probability in the ISR energy range.

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Table 1

Parameters of the seven data samples of double diffraction of nucleons

	$pp \rightarrow (p\pi^+\pi^-) (p\pi^+\pi^-)$						$nn \rightarrow (p\pi^-) (p\pi^-)$	$np \rightarrow (p\pi^-) (p\pi^+\pi^-)$
	23	31	45	53	63			
$\sqrt{s}$ (Gev)	23	31	45	53	63		27	37
Event sample	2265	3497	2032	3944	1535		1543	785
Background subtraction (%)	0.7	0.6	0.8	0.4	4.1		1.7	0.4
Integrated luminosity (μb^{-1})	10798	18791	17831	51555	23075		13277	8223
Systematic accuracy of the monitor (%)	7	5	10	10	5		7	7
Total systematic + statistic uncertainty (%)	11.7	10.7	14.9	15.6	13.8		11.6	11.8

Table 2

Resonance parameters from the Breit-Wigner fits to the $(p\pi^+\pi^-)$ mass spectra of double diffraction of protons

Reaction	$\sqrt{s}$ (GeV)	M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)
$pp \rightarrow (p\pi^+\pi^-) (p\pi^+\pi^-)$	23	1449 ± 11	137 ± 43	1670 ± 10	120 ± 10
	31	1440 ± 20	152 ± 29	1705 ± 15	120 ± 9
	45	1440 ± 11	175 ± 45	1714 ± 12	128 ± 5
	53	1450 ± 13	130 ± 49	1710 ± 9	126 ± 22
	63	1468 ± 27	130 ± 43	1702 ± 11	131 ± 24

Table 3

Numerical results of the fits to the differential cross-sections of double diffraction to the assumed form $d\sigma/dt = A_1 e^{b_1 t} + A_2 e^{b_2 t}$

Reaction	$\sqrt{s}$ (GeV)	A_1 ($\mu\text{b GeV}^{-2}$)	b_1 (GeV^{-2})	A_2 ($\mu\text{b GeV}^{-2}$)	b_2 (GeV^{-2})
$pp \rightarrow (p\pi^+\pi^-) (p\pi^+\pi^-)$	23	16.84 ± 2.09	15.2 ± 2.52	11.51 ± 0.88	2.87 ± 0.11
	31	23.41 ± 2.30	15.93 ± 2.21	12.02 ± 0.78	2.75 ± 0.08
	45	41.24 ± 6.77	21.00 ± 3.66	16.65 ± 1.16	3.12 ± 0.09
	53	24.60 ± 3.08	13.89 ± 2.37	13.07 ± 1.01	2.92 ± 0.09
	63	30.37 ± 6.29	23.36 ± 4.29	23.10 ± 7.03	3.20 ± 0.05
$nn \rightarrow (p\pi^-) (p\pi^-)$	27	31.36 ± 3.10	19.97 ± 1.80	14.66 ± 0.42	2.63 ± 0.04

Table 4

Effective slopes of the Pomeron trajectory deduced from the data of double diffraction of protons at five ISR energies. The values correspond to the indicated mass intervals at both vertices of the reaction.

$M_{1,2} < 1.5 \text{ GeV}$	$1.5 < M_{1,2} < 1.7 \text{ GeV}$	$M_{1,2} > 2.1 \text{ GeV}$
$\alpha'_{\mathbb{P}} = 0.03 \pm 0.1$	$\alpha'_{\mathbb{P}} = 0.02 \pm 0.04$	$\alpha'_{\mathbb{P}} = 0.01 \pm 0.01$

Table 5

Comparison of three different lower bounds (Webber, central link and Henyey-Pumplin) on the r.m.s. impact parameter for double diffraction of protons

$\sqrt{s}$ (GeV)	$\langle b_W^2 \rangle^{1/2}$ (fm)	$\langle b_{CL}^2 \rangle^{1/2}$ (fm)	$\langle b_{HP}^2 \rangle^{1/2}$ (fm)
23	0.369 ± 0.006	0.376 ± 0.006	0.384 ± 0.012
31	0.366 ± 0.004	0.367 ± 0.004	0.391 ± 0.008
45	0.378 ± 0.004	0.370 ± 0.004	0.415 ± 0.009
53	0.390 ± 0.004	0.378 ± 0.004	0.403 ± 0.008
63	0.385 ± 0.008	0.371 ± 0.007	0.376 ± 0.015

Table 6

Parameters of the simultaneous fits with peripheral amplitudes to double and single diffractive reactions.

Reactions	χ^2/df	A (GeV ⁻²)	b_0 (GeV ⁻¹)	b_{rms} (fm)
(1) + (2) + (3)	0.91	1.12 ± 0.03	5.30 ± 0.1	1.028
(4) + (5)	1.36	2.58 ± 0.02	5.27 ± 0.05	0.99

Table 7

Integrated cross-sections of exclusive double dif-
fraction in all three isospin combinations. The
values with an asterisk have been obtained through
independent factorization factors (see text).

Reaction	$\sqrt{s}$ (GeV)	p_{ℓ} equiv. (GeV/c)	σ (μb)
$pp \rightarrow (p\pi^+\pi^-) (p\pi^+\pi^-)$	23	287	4.82 ± 0.56
	26*	371	5.80 ± 0.87
	31	490	5.53 ± 0.59
	37*	738	6.42 ± 1.0
	45	1057	6.99 ± 1.04
	53	1470	5.96 ± 0.93
	63	2060	8.41 ± 1.16
$nn \rightarrow (p\pi^-) (p\pi^-)$	26.4	371	8.39 ± 0.96
$pn \rightarrow (p\pi^+\pi^-) (p\pi^-)$	37.2	738	7.72 ± 0.90

Figure captions

- Fig. 1 : Artist's view of the Split Field Magnet detector.
- Fig. 2 : a) Probability distribution for the four-constraint fit to reaction (1) at $\sqrt{s} = 31$ GeV.
b) and c) Missing momentum distributions for the same sample of events in the bending plane and in the vertical plane, respectively; r.m.s. values are indicated.
- Fig. 3 : Momentum distribution of spectator protons in the deuteron rest frame for reactions with neutron diffraction. The line is the prediction of the Hulthén wave function. The inset shows the spectator angular distribution and the isotropic prediction corrected by the Möller flux factor.
- Fig. 4 : Rapidity distributions of the $(p\pi^+\pi^-)$ systems of reactions (1) at the five ISR energies. The arrows indicate the beam rapidities.
- Fig. 5 : a) Raw invariant mass distribution of $(p\pi^+\pi^-)$ systems from reaction (1), prior to the kinematical fit.
b) Correlation plot of the four-momentum transfers t_1 and t_2 at the two vertices of reaction (1), prior to the kinematical fit.
- Fig. 6 : Invariant mass distributions of $(p\pi^-)$ systems in single and double diffraction of neutrons.
- Fig. 7 : Invariant mass distributions of $(p\pi^+\pi^-)$ systems in double diffraction of protons at the five ISR energies, (a) to (e). The inner curves (crosses) show the mass distribution of the $(\Delta^{++}\pi^-)$ final states. The last frame shows the same quantities for single diffraction of protons at $\sqrt{s} = 53$ GeV.

- Fig. 8 : Invariant mass distributions of $(p\pi^+\pi^-)$ systems for double diffraction of protons in the forward and backward hemispheres of the Gottfried-Jackson frame. The data from the samples in the range $23 \leq \sqrt{s} \leq 53$ GeV have been combined.
- Fig. 9 : Invariant mass distributions of the $(p\pi^+)$ subsystems in double diffraction of protons at five ISR energies, (a) to (e). The last frame shows the same quantity for single diffraction of protons at $\sqrt{s} = 53$ GeV.
- Fig. 10 : Invariant mass distributions of the $(p\pi^-)$ subsystems in double diffraction of protons at five ISR energies, (a) to (e). The last frame shows the same quantity for single diffraction of protons at $\sqrt{s} = 53$ GeV.
- Fig. 11 : a) Invariant mass distribution of the $(\pi^+\pi^-)$ subsystem in double diffraction of protons for $M_{p\pi^+\pi^-} > 1.9$ GeV. The data from the samples in the range $23 \leq \sqrt{s} \leq 53$ GeV have been combined.
b) Same as in (a) for the $(p\pi^-)$ subsystem.
- Fig. 12 : Schematic diagram of the Deck model amplitudes for two-body double diffraction.
- Fig. 13 : Invariant mass distribution of double diffraction of neutrons at $\sqrt{s} = 27$ GeV. The curve is the prediction of the resonant dual Deck model described in the text.
- Fig. 14 : Invariant mass distribution of double diffraction of protons at $\sqrt{s} = 53$ GeV for selected $(\Delta^{++}\pi^-)$ final states. The curve is the prediction of the resonant dual Deck model described in the text.
- Fig. 15 : Differential cross-section integrated over mass for single and double diffraction of neutrons. The curves are double exponential fits described in the text.

- Fig. 16 : Differential cross-section for double diffraction of protons integrated over mass at the five ISR energies, (a) to (e). The last frame shows the same quantity for single diffraction of protons at $\sqrt{s} = 53$ GeV. The curves are double exponential parametrizations.
- Fig. 17 : Differential cross-sections for double diffraction of protons for mass selections at only one vertex, showing a strongly different behaviour in the forward direction. Data from the samples in the range $23 \leq \sqrt{s} \leq 53$ GeV have been combined. The curves are double exponential parametrizations of the data.
- Fig. 18 : Two-dimensional plot of the slope-mass correlation for double diffraction of protons at $\sqrt{s} = 23$ GeV. The mass values at the two vertices of the reaction are plotted along the horizontal axes.
- Fig. 19 : Mass dependence of the forward slopes of double diffraction of protons at the five ISR energies for identical mass selections at both vertices. The last frame shows the same quantity for single diffraction of protons at $\sqrt{s} = 53$ GeV.
- Fig. 20 : Energy dependence of the forward slopes for diffraction of protons in three different mass intervals simultaneously selected at both vertices.
- Fig. 21 : Normalized spherical harmonic moments $\langle Y_1^0 \rangle$ of the Δ^{++} direction of motion for double diffraction of protons at $\sqrt{s} = 31$ GeV. The data are computed in the t-channel helicity frame as a function of mass for $\ell = 1$ to 6.
- Fig. 22 : Normalized spherical harmonic moments $\langle Y_1^0 \rangle$ of the Δ^{++} direction of motion for single diffraction of protons at $\sqrt{s} = 31$ GeV. The data are computed in the t-channel helicity frame as a function of mass for $\ell = 1$ to 6.

- Fig. 23 : Correlation plots of the decay angles in the Gottfried-Jackson frame for (a) single and (b) double diffraction of protons.
- Fig. 24 : Polar angle projections of the scatter plots of fig. 23 for single and double diffraction of protons. The curves are the predictions of the dual Deck model.
- Fig. 25 : Polar angle distributions for single and double diffraction of neutrons in the Gottfried-Jackson frame. The curves are a dual Deck model calculation.
- Fig. 26 : Azimuthal decay distributions for forward and backward polar angles for double diffraction of protons. The curves are the predictions of the dual Deck model.
- Fig. 27 : Azimuthal decay distributions for forward and backward polar angles for double diffraction of neutrons. The curves are the predictions of the dual Deck model.
- Fig. 28 : Slope-mass correlation for double diffraction of protons for identical mass cuts at both vertices. The solid curve is a power-law parametrization of the data. Also shown is a similar parametrization for single diffraction of protons (dashed curve) and the value of the slope of pp elastic scattering.
- Fig. 29 : a) Linearized plot of the slope-mass correlation of single diffraction of protons (dashed line). The data from double diffraction of protons, averaged over the mass of one vertex, are compared with the absolute factorization prediction [solid line, from eq. (22)].
b) Plot of the slope-mass correlation for single diffraction of protons (dashed curve) with data from double diffraction of protons. The data have been obtained with identical mass cuts at both vertices. The solid curve is the absolute factorization prediction of eq. (21).

Fig. 30 : a) Differential cross-section for double diffraction of neutrons. The solid line is a fit to the data in the form of eq. (34). Also shown (displaced by a factor of 2) the same type of fit for the differential cross-section of double diffraction of protons.
b) Differential cross-section for double diffraction of protons on neutrons, reaction (2). The solid line is the absolute factorization prediction from the data in (a) and eq. (24).

Fig. 31 : a) Invariant mass distribution at the neutron vertex of double diffraction of protons on neutrons, reaction (2).
b) Invariant mass distribution at the proton vertex of reaction (2).
c), d) Ratio of the mass distributions in (a) and (b) to the corresponding normalized distributions of symmetric double diffraction of protons and neutrons, reactions (1) and (3).
e), f) Ratio of the mass distributions in (a) and (b) to the corresponding normalized distributions of single diffraction of protons and neutrons, reactions (4) and (5). In this case the experimental t -cut ($-t > 0.05 \text{ GeV}^2$) in the single diffraction data has been applied also to the double diffraction data.

Fig. 32 : Linearized mass dependence of the impact parameter lower bounds [eq. (30)] for single and double diffraction of nucleons. Data on single diffraction from this experiment ($n \rightarrow p\pi^-$, $p \rightarrow p\pi^+\pi^-$) and from ref. 7 ($p \rightarrow n\pi^+$). Data on double diffraction from $pp \rightarrow (p\pi^+\pi^-) (p\pi^+\pi^-)$ at $\sqrt{s} = 31 \text{ GeV}$ and $\sqrt{s} = 53 \text{ GeV}$ (this experiment).

Fig. 33 : Ratio of the r.m.s. impact parameter lower bound to the value of b_{rms} obtained by a fit to the differential cross-sections with central amplitudes (31) as a function of mass.
a) Single diffraction of protons and neutrons (data from this experiment and ref. 37).

b) Double diffraction of protons at two different energies. The regions to be populated by a central dissociation mechanism would be below one.

Fig. 34 : Energy dependence of the ratio between impact parameter bound and the value of b_{rms} obtained by a fit to the differential cross-section with the central amplitudes (31). Data for double diffraction (this experiment) in the upper band, data for single diffraction (this experiment and refs. 37, 40) in the lower band. The shaded areas indicate the average values with one standard-deviation errors. The region to be populated by a central dissociation mechanism would be below 1.

Fig. 35 : Relative ratio of the integrated helicity contributions to the total cross-section, normalized to the integrated non-flip term R_0 , as a function of $n = \Delta\lambda$, a) for double diffraction of protons and neutrons, b) for single diffraction of protons and neutrons. The results are obtained through simultaneous fits to all independent reaction channels, as discussed in the text. The vertical bars represent the spread of values of independent fits to each channel.

Fig. 36 : Impact parameter profiles for central [eq. (31), dotted lines] and peripheral [eq. (34), solid lines] amplitudes for a) single diffraction of neutrons and b) double diffraction of protons. The essential parameters are given in table 6.

Fig. 37 : Dependence of the parameters A and b_0 , which control the shape of the overlap function (36) for double diffraction, on equivalent incident momentum. The results are from independent peripheral fits to the three channels (1) to (3) at seven different energies. The lines are drawn to guide the eye.

Fig. 38 : Energy dependence of the integrated cross-section for double diffraction of protons, reaction (1). The results of reactions (2) and (3) have been reduced to the final state (1) through independent factorization factors, as discussed in the text (hollow points). The line is a $\ln(s)$ fit to the data.

Fig. 39 : Schematic diagrams of single and double diffractive processes leading to exclusive, semi-inclusive and totally inclusive final states. The corresponding cross-sections are related through factorization equations of the type (37).

Fig. 40 : a) Compilation of inclusive single diffraction cross-sections in high-energy pp collisions. Data for different incident particles [51] have been reduced to pp interactions assuming factorization [see eq. (19)].

b) Compilation of inclusive double diffraction cross-sections in high-energy pp collisions. Data for different incident particles [51] have been reduced to pp interactions assuming factorization. The points have been obtained from semi-inclusive and exclusive (this experiment) double diffraction data. The dashed curve is an estimate of the energy dependence of σ_{DD} from the inclusive data in (a) and eq. (37c).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

$$pp \rightarrow (\rho \pi^+ \pi^-) (\rho \pi^+ \pi^-)$$

Fig. 7

$$pp \rightarrow (\rho \pi^+ \pi^-)(\rho \pi^+ \pi^-)$$

Fig. 8

$$pp \rightarrow (p \pi^+ \pi^-) (p \pi^+ \pi^-)$$

Fig. 9

$$pp \rightarrow (\rho \pi^+ \pi^-) (\rho \pi^+ \pi^-)$$

Fig. 10

$p p \rightarrow (p \pi^+ \pi^-) (p \pi^+ \pi^-)$

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

$$pp \rightarrow (p \pi^+ \pi^-) (p \pi^+ \pi^-)$$

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

$$pp \rightarrow (p\pi^+\pi^-)p$$

Fig. 22

Fig. 23

Fig. 24

Fig. 25

$$pp \rightarrow (p\pi^+\pi^-)(p\pi^+\pi^-)$$

$$\sqrt{s} = 53 \text{ GeV}$$

Fig. 26

$$nn \rightarrow (p \pi^-)(p \pi^-)$$

$$\sqrt{s} = 27 \text{ GeV}$$

Fig. 27

Fig. 28

Fig. 29

Fig. 30

Fig. 31

Fig. 32

Fig. 33

Fig. 34

Fig. 35

Fig. 36

Fig. 37

Fig. 38

Fig. 39

Fig. 40