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A Two-Step Dynamical Picture of Diffraction Dissociation
and the High Energy Behaviour of Transverse Momenta.

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A B S T R A C T

It is known that single diffraction dissociation in few-body hadron collisions is sharply separated from non-diffractive processes even when the latter occupy neighbouring regions of phase space. A possible general explanation is that diffraction dissociation of a particle into successive channels of increasing multiplicity is characterized by a competition between these channels, a lower one being abruptly closed by the opening up of the next higher one. We show that this explanation works quite well for proton diffraction dissociation in π^-p collisions at 16 GeV/c. The reaction is considered as a two-step process, production of a fireball X ($\pi^-p \rightarrow \pi^-X$) and decay of X . By analysing the distributions in the mass of X , we find that the competition operates sharply between the decay channels $X \rightarrow \pi N, 2\pi N, 3\pi N$, and that it can be explained by pure phase space effects in the fireball decay. These results imply that the phase space effects just mentioned combined with the small momentum transfer property of the dissociation $\pi^-p \rightarrow \pi^-X$ are sufficient to account for the smallness of the transverse momenta p_T of all secondaries in the reactions considered. We note that the situation would be different at much larger energies, where fireballs of very high mass could be occasionally produced. Irrespective of whether such heavy fireballs would be produced diffractively or not, phase space arguments now imply that their decay will tend to give both higher multiplicities and higher p_T of the secondaries. We indicate the possible interest of these considerations for recent observations of large p_T secondaries at the CERN Intersecting Storage Rings.

1. Introduction

The first and main aim of this paper is to investigate the sharp separation found experimentally in few-body hadron collisions at high energy between diffraction dissociation of one of the incident particles and non-diffractive processes, even when the latter occupy neighbouring regions of phase space. This separation, which can be seen in various ways for 3-body processes like $\pi^\pm p \rightarrow \pi^\pm \pi^0 p$ [1-3], becomes also very striking for 4-body processes like $\pi^\pm p \rightarrow 2\pi^\pm \pi^\mp p$ when the method of longitudinal phase space (LPS) analysis is used [4,5]. As suggested recently by one of us [6], a possible general explanation could be that diffraction dissociation of a given incident particle into successive channels of increasing multiplicity gives rise to a sort of competition between these dissociation channels, a lower one being closed by the abrupt opening up of the next higher one above its own threshold.

Taking the case of proton diffraction dissociation in 16 GeV/c $\pi^- p$ collisions and using missing mass data kindly made available to us by the ABBCCHW Collaboration [7], we show in sections 2 and 3 that this qualitative explanation works quite well. It consists in considering proton diffraction dissociation as a two-step process, the first step being the formation of a fireball by diffractive excitation of the proton $\pi^- p \rightarrow \pi^- X$, and the second one the decay of X into ν particles (a nucleon and $\nu-1$ pions). The competition mentioned above is clearly seen in the data by comparing the distributions in the mass M_X for $X = \pi N, 2\pi N, 3\pi N$; each of the two first distributions ($X = \pi N$ and $2\pi N$) is found to drop sharply in the M_X range where the next one ($X = 2\pi N$ and $3\pi N$ respectively) has its threshold rise. For each channel the mass distribution concerned is the part of the missing mass distribution which corresponds to single diffraction dissociation of the proton; how these distributions are extracted from the data is explained in section 2.

To study somewhat more quantitatively the competition between successive decay channels of the excited proton or "fireball" X , we consider in section 3 two phase space models for this decay, one with restricted longitudinal momenta ("longitudinal" phase space) and the other without any other restriction than momentum-energy conservation ("full" phase space). Starting from the overall distribution of M_X as given by the data, we find that both phase space prescriptions reproduce very well the M_X distributions of low multiplicity channels.

In other words, the competition between successive decay channels is mainly a phase space effect in the fireball decay, and it automatically limits the transverse momenta of the decay products (assuming the fireball formation process to have small momentum transfer). These properties should hold for the region of low fireball masses where the decay multiplicity is low, say up to $M_x \lesssim 2.5$ or 3 GeV.

The last two sections of the paper turn to the more speculative extension of these ideas to collisions of much higher energy where formation of quite heavy fireballs might become possible, be it presumably with a very small cross section. For large fireball mass, the decay multiplicity becomes correspondingly large and the relative separation between thresholds in M_x becomes too small for the competition described above to take place. If the matrix element for fireball decay does not contain a low cut-off in momentum or transverse momentum, so that full phase space still controls this decay in an important way, one finds that both the multiplicity ν and the transverse momentum p_T of the decay particles grow with M_x , a rough estimate for their averages being $\bar{\nu} \propto M_x^{2/3}$ and $\bar{p}_T \propto M_x^{1/3}$. We remark in section 5 that this qualitative trend is not necessarily limited to diffraction dissociation but could hold for more general mechanisms of particle production proceeding through the intermediate step of fireball formation. Irrespective of whether they apply only to diffraction dissociation or also to other types of collisions, we note that these considerations may be of relevance in connection with the recent observation of unexpectedly large transverse momenta at the CERN Intersecting Storage Rings [8].

We end this introduction by quoting a recent investigation of Johns et al. [9] which, like ours, is based on a two-step mechanism of particle production and is concerned with missing mass spectra. This work differs from the present one in an essential way, however. The fireball decay is assumed to follow the statistical bootstrap theory of Hagedorn and Frautschi which predicts dominance of a cascade of two-body decays and limits the decay momenta on dynamical rather than phase space grounds.

2. Missing mass distribution for $\pi^- p \rightarrow \pi^- X$ at 16 GeV/c and its analysis in terms of exclusive channels

For our discussion, the relevant part of the distribution in the missing mass M_X for the reaction $\pi^- p \rightarrow \pi^- X$ is the region of low M_X . There, the dominant contribution is expected to be due to the single diffraction dissociation of the proton. The results of the LPS analysis of specific exclusive channels permit a more precise determination of the missing mass region dominated by diffraction dissociation of the proton.

At 16 GeV/c, the distribution in the (πN) mass for the 3-body channels $\pi^- p \rightarrow \pi^- (\pi N)$ is almost entirely dominated by diffraction dissociation of the proton [2,3]. In the 4-body channel $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$, on the other hand, the LPS analysis shows that two dissociation processes are important, of the proton and pion respectively, and that they are joined continuously to each other in phase space [4]. Obviously then, the overall distribution in the $(\pi^+ \pi_s^- p)$ mass, given for 16 GeV/c by the solid line in Fig. 1, contains both contributions. Here π_s^- and π_f^- refer to slow and fast π^- respectively, the corresponding cms longitudinal momenta p_L verifying $p_{Ls} < p_{Lf}$ (the incident π^- is given positive p_L). Separation of the contribution from the proton dissociation is possible by taking the $(\pi^+ \pi_s^- p)$ mass distribution in the appropriate sector of LPS, characterized by the fact that the π^+ , π_s^- and p have negative p_L ; this distribution is shown in Fig. 1 as a dashed line. To estimate the effect of possible tails of proton diffraction dissociation in the neighbouring LPS sectors, we also show the dotted-dashed distribution corresponding to $x^+ < 0.05$, $x_s^- < 0.05$, where the x_i are the reduced longitudinal momenta of ref. 4, $x_i \approx p_{Li}/p_{cms}$ (p_{cms} incident cms momentum). We notice that all three distributions of Fig. 1 are essentially the same up to $M(\pi^+ \pi_s^- p) \approx 1.7 - 1.8$ GeV, and that the two distributions based on LPS cuts are similar throughout. It is only for $M(\pi^+ \pi_s^- p) \geq 1.75$ GeV that the non-diffractive contribution becomes important. It seems reasonable to assume the same feature to be also true for the two non-fitted 4-body channels $\pi^- p \rightarrow \pi^- (\pi^0 \pi^0 p)$ and $\pi^- p \rightarrow \pi^- (\pi^+ \pi^0 n)$, and more generally for the overall missing mass distribution. We expect therefore that, up to $M_X \approx 1.75$ GeV, the missing mass distribution is entirely due to the single diffraction dissociation of the proton whereas the higher missing mass region must necessarily contain other contributions.

Further support for the above conclusion comes from the factorization property of diffraction dissociation. Factorization has been shown to hold to a good approximation for diffractive parts of several channel cross sections [10]. For the missing mass distribution, factorization can be tested using the data for $\pi^- p \rightarrow \pi^- X$ at 16 GeV/c (solid line of Fig. 2) and the data for $pp \rightarrow pX$ at 24 GeV/c [11]. Up to $M_x \approx 1.75$ GeV, the ratio $\frac{d\sigma}{dM_x}(pp \rightarrow pX) / \frac{d\sigma}{dM_x}(\pi^- p \rightarrow \pi^- X)$ is found to be almost constant and equal to the ratio of elastic cross sections $\sigma_{el}(pp \rightarrow pp) / \sigma_{el}(\pi^- p \rightarrow \pi^- p)$ (with an accuracy of about 20%). As expected from the previous discussion of the non-diffractive contribution in the channel $\pi^- p \rightarrow \pi_f^-(\pi^+ \pi_s^- p)$, factorization indeed breaks down for $M_x \gtrsim 1.75$ GeV *).

We start now with our analysis of the missing mass distribution of $\pi^- p \rightarrow \pi^- X$ at 16 GeV/c in terms of the contributions of specific exclusive channels. First of all, we separate the channels $\pi^- p \rightarrow \pi^- [(p\pi^0) + (n\pi^+)]$ and the "rest", i.e. the channels $\pi^- p \rightarrow \pi^- (\nu \geq 3 \text{ particles})$. Here ν denotes the decay multiplicity of the dissociated proton, $(\nu+1)$ is the multiplicity of the collision. The respective histograms are shown in Fig. 2. In the region $M_x \approx 1.4 - 1.7$ GeV, both cross sections exhibit a strong M_x dependence. Decrease of the first and increase of the second occur with almost equal and opposite slopes, thus adding up to the weak M_x dependence of the overall missing mass distribution **). In other words, we observe a clear compensation between the competing channels of proton dissociation $p \rightarrow \pi N$ and $p \rightarrow \nu \geq 3$ particles. Actually, the competing channels are $p \rightarrow \pi N$ and $p \rightarrow \pi\pi N$ because the missing mass threshold for the

*) It is of some interest to notice that for $M_x \gtrsim 1.75$ GeV the cross section $\frac{d\sigma}{dM_x}(\pi^- p \rightarrow \pi^- X)$ becomes larger than the cross section $\frac{d\sigma}{dM_x}(pp \rightarrow pX)$ renormalized by the ratio of elastic cross sections. This may well be due to the effect of the diffraction dissociation of the second incoming particle because it is known that the dissociation of a pion is stronger than of a proton.

**) In the region $M_x \approx 1.4 - 1.8$ GeV, the missing mass distribution shows some structure, presumably due to resonances ($N^*(1400)$, $N^*(1700)$). This structure is less visible in the two separate M_x distributions as it occurs on the steep slopes.

channels $\pi^- p \rightarrow \pi^- (4 \text{ particles})$ seems to be located at $M_x \approx 1.7 \text{ GeV}$. Such a threshold value of M_x for $\pi^- (4 \text{ particles})$ is indeed indicated by the distributions of the fitted channels $\pi^- p \rightarrow \pi^- (\pi^+ \pi_s^- \pi^0 p)$ and $\pi^- p \rightarrow \pi_f^- (\pi^+ \pi_s^- \pi^+ n)$.

We now turn to the question whether a similar property of compensation between competing channels of proton diffraction dissociation is also true for higher multiplicities. To study this problem one must take into account the fact, recognized earlier, that the missing mass distribution for $M_x \gtrsim 1.75 \text{ GeV}$ is not entirely due to single diffraction dissociation of the proton. As we shall now show, it is nevertheless possible to treat the case of proton dissociation into three and four particles.

First of all, one can decompose the missing mass distribution for reactions $\pi^- p \rightarrow \pi^- (v \geq 3 \text{ particles})$ into the distribution for $\pi^- p \rightarrow \pi_f^- [(\pi^+ \pi_s^- p) + (Z^0 p) + (\pi^+ Z^0)]$ where Z^0 denotes two or more neutrals, and the "rest" distribution (see Fig. 3). Below the threshold for $\pi^- p \rightarrow \pi^- (5 \text{ particles})$ which is found to be at about $M_x \approx 2.1 \text{ GeV}$ ^{*}, the "rest" is obviously given by those channels $\pi^- p \rightarrow \pi^- (4 \text{ particles})$ which contain one neutral only.

Secondly, we return to the separation of the single dissociation of the proton in the channel $\pi^- p \rightarrow \pi_f^- (\pi^+ \pi_s^- p)$ which was already discussed (Fig. 1). For our further considerations, it is important to notice in Fig. 1 that its contribution to the $(\pi^+ \pi_s^- p)$ mass spectrum exhibits, starting at $M(\pi\pi p) \approx 1.75 \text{ GeV}$, an almost linear drop to approximately zero at $M(\pi\pi p) \approx 2.6 \text{ MeV}$. If we assume the same behaviour to hold for the other two dissociations of the proton into 3 particles $(\pi^0 \pi^0 p \text{ and } \pi^+ \pi^0 n)$, we are able to construct for these channels the $M(\pi\pi N)$ mass distributions corresponding to single dissociation of the proton by deducing them from the overall missing mass distributions for channels $\pi^- (Z^0 p)$ and $\pi^- (\pi^+ Z^0)$. Indeed, according to our previous analysis, it is reasonable to assume that diffraction dissociation of p into $(\pi^0 \pi^0 p)$ and $(\pi^+ \pi^0 n)$ dominates

^{*}) From the values of M_x for the thresholds of the $\pi(\pi N)$ channels ($\approx 1.1 \text{ GeV}$), $\pi(2\pi N)$ channels ($\approx 1.4 \text{ GeV}$) and $\pi(3\pi N)$ channels ($\approx 1.7 \text{ GeV}$), we would expect the threshold for the $\pi(4\pi N)$ channels to be around $M_x \approx 2.0 \text{ GeV}$. The data for the channels $\pi^- (p \pi^+ \pi^+ \pi^- \pi^-)$, $\pi^- (p \pi^+ \pi^- Z^0)$ and $\pi^- (\pi^+ \pi^+ \pi^- Z^0)$ indicate the value $M_x \approx 2.1 - 2.2 \text{ GeV}$.

the latter distributions up to $M_x \approx 1.7$ GeV (i.e. up to the $\pi(4 \text{ particles})$ threshold), and that a linear drop then takes place reaching the value zero around 2.6 MeV. Obtained in this way, the $(\pi\pi N)$ mass distribution of the contribution from single proton dissociation to all $\pi^-(\pi\pi N)$ channels is shown in Fig. 3, where the shaded strip gives the linear drop and illustrates the uncertainty suggested by the two LPS cuts used in Fig. 1.

Fig. 3 also shows as dotted-dashed line the difference between the full and dashed distributions. It concerns the channels $\pi^-(4 \text{ particles})$, at least below the threshold for the next higher channels, i.e. in the interval $M_x \approx 1.7 - 2.1$ GeV. It does not contain, however, contributions of type $\pi^-(pZ_0)$ and $\pi^-(\pi^+ Z_0)$, i.e. the contributions of the channels $\pi^- p \rightarrow \pi^-(3\pi^0 p)$ and $\pi^- p \rightarrow \pi^-(\pi^+ 2\pi^0 n)$. On the other hand, it must undoubtedly contain some contributions which are not due to single diffraction dissociation of the proton, and the two effects may compensate each other to some extent. Therefore the dotted-dashed distribution in Fig. 3 should be, up to ~ 2.1 GeV, a reasonable approximation to the true distribution in $M(3\pi N)$ for single dissociation of the proton into four particles.

We are now able to conclude from Fig. 3 that the channels $\pi^-(\pi\pi N)$ and $\pi^-(3\pi N)$ appear as competing channels of proton diffraction dissociation, with a clear compensation between the drop of one and the rise of the other in the interval $M_x \approx 1.7 - 2.1$ GeV. These features of competition and compensation are similar to those found in Fig. 2 for the dissociations into two and three particles. We notice, however, that in the present case the compensation effect concerns smaller slopes and is less complete because the two channels add up to a total distribution which itself decreases for $M_x > 1.7$ GeV.

The phenomenon discussed here is very likely to be of general nature. In the next section we discuss its interpretation in terms of strong phase space effects in the framework of a simple dynamical picture for diffraction dissociation.

3. Two-step dynamical picture of diffraction dissociation

The competition between different dissociation channels discussed in the previous section can be explained in a natural way by assuming a two-step dynamical picture of diffraction dissociation. These two steps are the formation of an excited system or "fireball" and its subsequent decay. The competition then takes place between successive decay channels of the fireball, the rapid opening up of one channel above its threshold being compensated by the closing down of the lower multiplicity channels. These rapid changes are essentially due to phase space effects.

Consider the differential cross section $d\sigma_v/dM$ for diffraction dissociation of the proton into a final state of given multiplicity; M is the effective mass of the fireball and is identical to the missing mass M_x defined earlier, v is the decay multiplicity of the fireball, $(v+1)$ the multiplicity of the overall collision. In the two-step picture, $d\sigma_v/dM$ is written as the product of the fireball mass spectrum $\rho(s,M)$ and the branching ratio $P_v(M)$ for fireball decay into v particles:

$$\frac{d\sigma_v}{dM} = \rho(s,M) \cdot P_v(M) \quad (1)$$

the $P_v(M)$ being subject to the normalization condition

$$\sum_v P_v(M) = 1 \quad (2)$$

In principle the factorization (1) should be written for the double differential cross section $d^2\sigma_v/dMdt$ and ρ should contain t in addition to s , the cm energy squared. We deal here with the cross section integrated over the t -peak. The condition (2) is equivalent to

$$\frac{d\sigma}{dM} = \sum_v \frac{d\sigma_v}{dM} = \rho(s,M) \quad (3)$$

We do not attempt to construct any theoretical model for the fireball mass spectrum $\rho(s,M)$ but rather take it directly from the data. This is an obvious attitude in view of the aim of our discussion. According to the analysis

in the previous section, the overall missing mass distribution (shown as the solid line in Fig. 2 and repeated as the solid lines marked (1) in Figs. 4 and 5) can be interpreted as the fireball mass spectrum up to $M_x \approx 1.75$ GeV. For higher values of M_x one has to estimate the non-diffractive contribution and subtract it from the experimental distribution. As discussed in section 2 in connection with Fig. 3, this can be done with reasonable reliability up to about $M_x \approx 2.1$ GeV just by subtracting the non-diffractive contribution to the channels $\pi^- p \rightarrow \pi^-$ (3 particles). This subtraction replaces the line (1) by the line marked (2) in Figs. 4 and 5. The line (2) gives the fireball mass spectrum used in our further discussion.

Our aim in the following is to show that the main features of the competition between successive dissociation channels can be understood in the two-step picture as due to phase space properties, in particular to the fast rise of the phase space for fireball decay above channel thresholds. If this is so, the same qualitative behaviour will hold for any dynamical model based on the two-step picture in which the matrix elements are reasonably smooth functions of the momenta. To illustrate the insensitivity of our results, we shall consider two distinct versions of phase space for the fireball decay, namely decay according to "longitudinal" phase space with restricted transverse momenta and isotropic decay according to full phase space. We have also examined a third version in the case of the channel $\pi^- p \rightarrow \pi^- (2\pi N)$; it notes that $2\pi N$ is dominantly $\pi\Delta$ and uses longitudinal or full phase space for the decay $X \rightarrow \pi\Delta$. The results were again the same.

The reason for the insensitivity is simple. In the fireball mass region studied here, the mean energies of nucleon and pions from the fireball decays $X \rightarrow \pi N$ and $2\pi N$ are small in the fireball rest frame. From the histograms shown in Figs. 2 and 3 one can estimate

$$\bar{E}_N + \bar{E}_\pi \approx 1500 \text{ MeV}, \quad \bar{E}_N + 2\bar{E}_\pi \approx 1830 \text{ MeV} \quad (4)$$

Both longitudinal and transverse momenta must then be small. This is why one cannot discriminate between the descriptions of fireball decay just mentioned on the basis of the M_x spectra alone. Other distributions of course allow a discrimination, but they reflect specific properties of the decay matrix element rather than phase space effects, and our aim here is to concentrate on the latter which turn out to be very strong.

Both for the longitudinal and full phase space versions of fireball decay, the probability of decay into ν particles has the form

$$P_\nu(M) = c(M)h_\nu \int \delta^4(Q - \sum_1^\nu k_i) \prod_1^\nu g_i(\vec{k}_i) d_3 \vec{k}_i / 2E_i \quad (5)$$

where $Q = (M, \vec{0})$ and $k_i = (E_i, \vec{k}_i)$ are energy-momentum four-vectors. The coefficient h_ν is to be determined from the data. The particular form

$$h_\nu = \lambda^\nu / (\nu-1)! \quad (6)$$

corresponds to independent emission of pions. The normalization function $c(M)$ is determined by the condition (2).

For fireball decay according to the longitudinal phase space with restricted transverse momenta we choose the functions $g_i(\vec{k}_i)$ in the form

$$g_i(\vec{k}_i) = A \exp(-\alpha_i k_{Ti}^2)$$

k_{Ti} being the length of the transverse component of $\vec{k}_i$ and the constant A being taken to satisfy the normalization

$$2\pi \int g_i k_{Ti} dk_{Ti} = 1$$

The values of α_i were taken to be 8 GeV^{-2} for pions and 4 GeV^{-2} for nucleons (for M large, this corresponds to an average transverse momentum of 300 MeV for pions and 440 MeV for nucleons). It was found that such a simple parametrization (with h_ν given by (6) for $\lambda = 2$) explains to a good accuracy the observed competition between different dissociation channels. This is shown in Figs. 4 and 5, where the results for $d\sigma_\nu/dM$ obtained from the model calculation are compared with the data for 2-, 3- and 4-body decays of the fireball. It will be noted that the results are computed as histograms. This is convenient since our computed $P_\nu(M)$ must be multiplied by the fireball mass spectrum $\rho(s, M)$, i.e. by the solid line (2) of Figs. 4 and 5, to give our prediction for $d\sigma_\nu/dM$.

We emphasize that the correct shapes of the mass spectra for 2-, 3- and 4-body decays were obtained in our calculation as a consequence of the properties of the longitudinal phase space. The relevant point is the difference in behaviour

of the longitudinal phase spaces for $(\nu-1)$ and ν particle decays near the threshold for the ν particle decay. As seen in Fig. 6, the ν particle longitudinal phase space volume has for small ν an abrupt increase above the kinematical threshold. For $\nu \leq 5$ this increase occurs in a region where the $(\nu-1)$ particle phase space volume is already beyond its own region of fastest increase. To be more specific, consider the logarithmic derivatives

$$R_{\nu-1} = d \ln V_{\nu-1}(M) / dM \quad \text{and} \quad R_{\nu} = d \ln V_{\nu}(M) / dM$$

where V_{ν} is the longitudinal phase space volume for ν particles. For small ν , R_{ν} is much larger than $R_{\nu-1}$ in the region of abrupt increase of the ν particle phase space. It is this property which is responsible for the observed increase of the probability $P_{\nu}(M)$ and the simultaneous decrease of $P_{\nu-1}(M)$. Note that the quantities R are independent of the normalization of the phase space volumes V .

The property of longitudinal phase space just discussed turns out to hold for full phase space as well. In this case we take the functions g_i in the expression (5) to be $g_i(\vec{k}_i) = 1$. We then again obtain the correct mass spectra, as shown in Figs. 4 and 5 (with h_{ν} of form (6) the parameter λ is now 8 GeV^{-2}). This is now due to the behaviour of full phase space for which R_{ν} is again considerably larger than $R_{\nu-1}$ when ν is small. We therefore conclude that the observed competition between different dissociation channels appears in the framework of the two-step dynamical picture as a consequence of phase space properties.

4. The limitation of transverse momenta

The results of the previous section, especially the good fits obtained with full phase space for fireball decay, throw a somewhat unexpected light on the problem of explaining in dynamical terms the empirically observed law of small transverse momenta. We return to the remark made above in connection with eq. (4). It means that for the two lowest dissociation reactions $\pi^- p \rightarrow \pi^- X$, $X = \pi N$ and $2\pi N$, the missing mass spectra alone imply that the decay particles have small momenta in the rest frame of the fireball. Consequently, the transverse momenta of the decay particles are necessarily small if the fireball formation reaction has small momentum transfer. For these low multiplicity channels, the property of the missing mass spectra which is relevant here is their narrowness, i.e. their fast drop occurring soon after their abrupt threshold rise. As we saw, in the framework of the two-step picture, these features are explainable as pure phase space effects, the fast drop for one dissociation channel being due to the fast threshold rise for the next.

We pursue this line of reasoning somewhat further. Single diffraction dissociation of the proton, $p \rightarrow X$, is only expected to occur if t , the squared momentum transfer, is small enough. This condition, when applied to the transverse part of t , restricts the transverse momentum of X . When applied to the longitudinal part, it restricts the range of the overall spectrum of mass M_X , i.e. of the function $\rho(s, M)$ considered in the previous section. If the restriction on M_X is such that only low multiplicity decays are allowed by full phase space, which will be the case for $M_X \lesssim 2.5$ or 3 GeV, our above considerations apply and the transverse momenta of the secondaries will automatically be limited irrespective of the details of the matrix element for fireball decay. This will be true when the collision energy is not too high (perhaps $p_{lab} \lesssim 50$ or 100 GeV).

Let us now speculate on what might happen at much larger energies. Although dissociation into fireballs of rather low mass M_X may well remain dominant, the overall range of M_X produced diffractively should increase because larger M_X can be produced at small momentum transfer. We are thus led to consider in our two-step picture the production of heavier fireballs giving higher decay multiplicities. We do this in the full phase space version, i.e. without a priori limitation of transverse momenta. Examination of phase space curves for $\nu \gtrsim 5$ shows that the competition phenomenon by which one decay channel is closed due to

the threshold rise of the next is no longer so pronounced. In fact, it disappears altogether for large M_x and v , because the relative displacement between successive threshold rises then becomes insignificant. In the full phase space version of the two-step picture, this has the interesting consequence that diffraction dissociation producing massive fireballs will give decay products with larger transverse momenta even when the transverse momentum of the fireball itself is small (this transverse momentum p_T is anyway unimportant for heavy fireballs because the large mass M_x makes the transverse velocity p_T/M_x small).

A simple estimate of what can be qualitatively expected is obtained by noting that our full phase space model with eq. (6) is equivalent to the Fermi statistical model for particle production in the form using relativistic phase space [12]. It is here applied to the decay of a fireball with mass $M_x \gg m_p$. As shown by Satz [13], the mean decay multiplicity $\bar{v}$ and the mean energy $\bar{E}$ per decay particle in the fireball rest frame then grow with M_x like

$$\bar{v} \propto M_x^{2/3}, \quad \bar{E} \propto M_x^{1/3}.$$

For isotropic decay and small transverse velocity of the fireball, the mean transverse momentum of the decay particles will also grow like

$$\bar{p}_T \propto M_x^{1/3}$$

This trend must in fact be more general than the assumptions under which we just derived it. Any decay matrix element which has no cut off on momenta or transverse momenta will lead to essentially the same qualitative conclusions which can be summarized as follows:

- i) In a two-step dynamical picture of single diffraction dissociation and for low mass M_x of the produced fireball, phase space effects impose a competition between successive decay channels. This automatically restricts the energies E of the decay particles in the fireball rest frame, and hence their transverse momenta p_T in the overall collision.
- ii) For high fireball mass M_x , the quantities E and p_T as well as the decay multiplicity v increase slowly with M_x .

- iii) The fact that single diffraction dissociation occurs only at small momentum transfer implies that case i) is the only one possible at moderate energies (perhaps $p_{\text{lab}} \lesssim 50$ or 100 GeV).
- iv) As the energy increases, a small but increasing fraction of single diffraction dissociation events can produce fireballs of high mass. Their decay will have higher multiplicities and involve particles of higher transverse momenta.

A word of caution is needed, of course, with regard to further conclusions which one might be tempted to draw from our reference to the statistical model. Just to take an example among many, it would be wrong to accept the statistical model predictions for the K/π or $\bar{p}/\pi$ ratio and to apply them to the fireball decay. These ratios are controlled by the relative strength of the various decay matrix elements, not by their momentum dependence.

5. Possible generalizations and concluding remarks

Although it is our study of single diffraction dissociation which led us to develop them, the considerations of the previous section are actually of a more general nature. They can be extended to a variety of particle production mechanisms involving two steps, the formation of fireballs and their subsequent decay (numerous models of this type have been proposed over the last three decades and there is little point in reviewing them here). As long as the fireballs are of limited mass (say $M_X \lesssim 3 \text{ GeV}$) and are produced with such transverse momenta p_T that the ratio p_T/M_X is reasonably small, the phase space effects discussed above will again operate and guarantee small p_T for the decay products. When the energy increases, production of heavier fireballs may occur, be it perhaps in a very small fraction of all collisions. As shown in the previous section, this will lead to collisions which have both higher multiplicities and larger transverse momenta than the bulk of inelastic processes.

It is interesting to note in this connection that secondaries with unexpectedly large p_T have been observed at the CERN Intersecting Storage Rings, their (very small) number increasing markedly with the collision energy [8]. Our considerations suggest that this phenomenon may have a rather general origin and may occur in single diffraction dissociation as well as in other production mechanisms involving the formation of fireballs as intermediate step.

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REFERENCES

- [1] A. Białas et al., Nucl.Phys. B11 (1969) 479.
- [2] J. Bartsch et al., Nucl.Phys. B19 (1970) 381.
- [3] K. Boesebeck et al., Nucl.Phys. B40 (1972) 39.
- [4] W. Kittel et al., Nucl.Phys. B30 (1971) 333.
- [5] J.V. Beaupré et al., Nucl.Phys. B46 (1972) 1.
- [6] L. Van Hove, Perspectives in the systematic study of multiparticle reactions, in Proceedings of the III. International Colloquium on Multiparticle Reactions (Zakopane, Poland, June 1972), Report P Nr 1421/VI/PM, Institute Badań Jądrowych, Warsaw (1972).
See also L. Van Hove, Lectures on high energy hadron physics, CERN Preprint TH.1539 (1972), to be published in Proceedings of the International School of Subnuclear Physics (Erice, July 1972).
- [7] Aachen - Berlin - Bonn - CERN - Cracow - Heidelberg - Warsaw Collaboration, paper contributed to the IVth International Conference on High Energy Collisions, Oxford (April 1972), and private communication.
- [8] Saclay - Strasbourg Collaboration and CERN - Columbia - Rockefeller Collaboration, papers contributed to the XVIth International Conference on High Energy Physics, Chicago - Batavia (September 1972). See Plenary Session Report by M. Jacob, Proceedings of the XVIth International Conference on High Energy Physics (September 1972), ed. by J.D. Jackson and A. Roberts (NAL, Batavia, Illinois, 1972), vol. 3, p. 373.
- [9] F. Johns et al., Phys.Rev.Letters 29 (1972) 756.
- [10] P.G.O. Freund, Phys.Rev.Letters 21 (1968) 1375;
N.K. Yamdagni and S. Ljung, Phys.Letters 37B (1971) 117;
E. De Wolf et al., Nucl.Phys. B46 (1972) 333.

- [11] U. Amaldi et al., Phys.Letters 34B (1971) 435;
J.V. Allaby et al., paper contributed to the IVth International Conference
on High Energy Collisions, Oxford (April 1972);
P. Pirilä and P.V. Ruuskanen, The amount of diffraction dissociation in
proton-proton scattering at 24 GeV/c, CERN Preprint TH.1551 (1972), to be
published in Nuovo Cimento.
- [12] P.P. Srivastava and G. Sudershan, Phys.Rev. 110 (1958) 765.
- [13] H. Satz, Nuovo Cimento 37 (1965) 1407.

FIGURE CAPTIONS

Figure 1 : Distribution in the $(\pi^+\pi_s^-\bar{p})$ mass for the channel $\pi^-\bar{p} \rightarrow \pi^-\pi^-\pi^+\bar{p}$ at 16 GeV/c. See the text for details.

Figure 2 : Solid line: Missing mass distribution for $\pi^-\bar{p} \rightarrow \pi^-\bar{X}$ at 16 GeV/c.
Dashed line: Distribution in the (πN) mass for the three particle channels $\pi^-\bar{p} \rightarrow \pi^-\bar{[(p\pi^0) + (n\pi^+)]}$.
Dotted-dashed line: Missing mass distribution for the channels $\pi^-\bar{p} \rightarrow \pi^-\bar{(\nu \geq 3 \text{ particles})}$.

Figure 3 : Solid line: Missing mass distribution for reactions $\pi^-\bar{p} \rightarrow \pi^-\bar{(\nu \geq 3 \text{ particles})}$.
Dashed line: Missing mass distribution for $\pi^-\bar{p} \rightarrow \pi_f^-\bar{[(\pi^+\pi_s^-\bar{p}) + (Z^0\bar{p}) + (\pi^+Z^0)]}$ where Z^0 denotes two or more neutrals.
Dotted-dashed line: Missing mass distribution for $\pi^-\bar{p} \rightarrow \pi^-\bar{(\nu \geq 4 \text{ particles})}$ with exception of the channels $\pi^-\bar{p} \rightarrow \pi^-\bar{[(Z^0\bar{p}) + (\pi^+Z^0)]}$.
Shaded strip: The $(\pi\pi N)$ mass distribution of the contribution from single proton dissociation to all $\pi^-(\pi\pi N)$ channels with the uncertainty suggested by the two LPS cuts used in Fig. 1.

Figure 4 : Experimental (πN) mass distribution for $\pi^-\bar{p} \rightarrow \pi^-\bar{[(p\pi^0) + (n\pi^+)]}$ together with the predictions of the model for fireball decay based on the longitudinal phase space (dashed line) and full phase space (dotted-dashed line). Solid lines represent the overall missing mass distribution for the $\pi^-\bar{p} \rightarrow \pi^-\bar{X}$ at 16 GeV/c (1) and the estimated contribution from the single dissociation of proton (2).

Figure 5 : Experimental estimate of the missing mass distributions of the contribution from single proton dissociation to $\pi^- p \rightarrow \pi^- (2\pi N)$ and $\pi^- p \rightarrow \pi^- (3\pi N)$ together with the predictions of the model for fireball decay based on the longitudinal phase space (dashed lines) and full phase space (dotted-dashed lines). Solid lines represent the overall missing mass distribution for the $\pi^- p \rightarrow \pi^- X$ at 16 GeV/c (1) and the estimated contribution from the single dissociation of proton (2).

Figure 6 : Longitudinal phase space for $v \leq 6$ calculated according to the formula (5) without factor $c(M)h_v$ and with functions $g_i(\vec{k}_i)$ taken as explained in the text. The vertical scale is logarithmic.

Figure 7 : Full phase space for $v \leq 6$ calculated according to the formula (5) without factor $c(M)h_v$ and with $g_i(\vec{k}_i) = 1$. The vertical scale is logarithmic.

FIG. 1

FIG.2

FIG.5

FIG. 6

FIG. 7