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PROTON SPECTRA ACCORDING TO THE DIFFRACTION EXCITATION MODEL

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A B S T R A C T

Inclusive proton spectra arising from pp collisions are calculated from the diffraction excitation model. Comparison with the data shows that diffraction dissociation cannot account for a major part of σ_{inel} at low energies ($s \lesssim 50 \text{ GeV}^2$), but that it could be the dominant mechanism at ISR energies.

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Hopefully forthcoming experiments at higher energies ($s \gtrsim 400 \text{ GeV}^2$) will decide whether any of the presently popular models provides an adequate description of inelastic collisions. Many of the experiments proposed for distinguishing between the various models are not easy to carry out. There is, however, one readily observable quantity, the spectrum of leading protons in $pp \rightarrow pX$, which has quite striking features if the diffraction excitation model¹⁾⁻⁶⁾ is correct. Should these features be confirmed by the data, they will not find a natural explanation within the multiperipheral model.

We report here on calculations of proton spectra implied by the diffraction excitation model (DEM). We emphasize that we have been totally unimaginative: we have simply taken the model at face value and determined its consequences. Nevertheless, we come to conclusions that often differ significantly from those reported previously. Some of these disagreements are rather technical and will be mentioned presently, but others are of a more fundamental nature. The latter stem from our having taken a very orthodox - if one prefers, naïve - view of diffraction scattering. In particular, we only equate the diffraction excitation cross-section σ_{diff} to σ_{inel} as $s \rightarrow \infty$. The s dependence of σ_{diff} is then largely determined by kinematical constraints, and a reasonable decrease with increasing longitudinal momentum transfer $\sqrt{t_{\parallel}}$. With the exception of Adair^{1),4)} most previous work tends to dismiss the $t_{\parallel}$ effect, but to our mind a model that does not impose a requirement for longitudinal coherence is not a model of diffraction dissociation. We have also refrained from adding any triple Regge terms to our broth^{6),7)}; in our view the DEM, among other things, already contains a description of the triple Regge region.

From our assumptions we conclude that diffraction dissociation provides a minor part of σ_{inel} at accelerator energies, but that it could well be the dominant mechanism at ISR energies. The remainder of σ_{inel} would then have to be ascribed to exchange processes falling as a power of s . If this picture is borne out it would mean that there is a profound change in the character of hadronic collisions as s rises from moderate to high values, a change that is completely hidden in σ_{tot} and in those inclusive distributions that scale at low s .

We briefly recall the assumptions of the model. A pp collision is viewed as a sequence of two steps: 1) one or both protons are excited into "fireballs" F_1 and F_2 having masses M_1 and M_2 ; and 2) these F_i decay. The diffraction excitation cross-section $d\sigma_{\text{ex}}/d\Omega^* dM_1 dM_2$

becomes s independent when $s/M_1 \rightarrow \infty$, and the F_i have the proton's quantum numbers. In F_i 's rest frame all decay products have strongly confined momenta⁸⁾; hence, the mean number of pions radiated from F_i is proportional to M_i , and the Feynman x of the nucleon emerging from F_i is $\sim m/M_i$, where m is the nucleon mass. The logarithmic growth of the multiplicity $\langle n \rangle$, and the fact that the proton's $d\sigma/d^2p dx$ is rather flat over much of the x range is taken to imply⁹⁾ that $d\sigma_{ex}$ has the asymptotic form $(M_1 M_2)^{-2} dM_1 dM_2$.

Therefore the inclusive proton cross-section has three separate contributions: those cases where the observed proton was never excited, those where the observed proton was excited but the other not, and those where both were excited. We call these processes I, II and III, respectively. These three processes occur explicitly in the excitation cross-section:

$$\frac{d\sigma_{ex}}{d\Omega^* dM_1 dM_2} = \delta(M_1 - m) \frac{d\sigma_1}{d\Omega^* dM_2} + (M_1 \leftrightarrow M_2) + \frac{d\sigma_2}{d\Omega^* dM_1 dM_2}, \quad (1)$$

where Ω^* is the c.o.m. angle in $F_1 F_2$ production, and the terms correspond, respectively, to processes I, II and III. The one and two-fireball cross-sections are taken to have the simple forms¹⁰⁾

$$\frac{d\sigma_1}{dt_1 dM} = c_1 \sigma_{tot} b f(M) e^{-bt_1} e^{-b't''}, \quad (2)$$

$$\frac{d\sigma_2}{dt_1 dM_1 dM_2} = c_2 \sigma_{tot} b f(M_1) f(M_2) e^{-bt_1} e^{-b't''}, \quad (3)$$

where $\sqrt{t_1}$ is the transverse momentum transfer. If f is normalized to one, $\sigma_i \rightarrow c_i \sigma_{tot}$ when $s \rightarrow \infty$, and $(2c_1 + c_2) \sigma_{tot} = \sigma_{inel}$ if one assumes that as $s \rightarrow \infty$ only diffraction dissociation survives. For f we adopt the convenient form^{5), 11)}

$$f(M) = 2\Delta_0 \Delta^{-2} e^{-2\Delta_0/\Delta}, \quad (4)$$

where $\Delta \equiv M - M_0$, $M_0 \equiv m + m_\pi$, and Δ_0 is the value of Δ where f has its maximum.

The s dependence of $\sigma_1(s)$ and $\sigma_2(s)$ is shown in Fig. 1 for various values of b' and Δ_0 . For all "reasonable" b' ($\gtrsim 5 \text{ GeV}^{-2}$), σ_2 is insignificant at $s \lesssim 50$, and only becomes comparable to $\sigma_2(\infty)$ at the highest ISR energies. $\sigma_1(s)$ is fully developed at all ISR energies, and is roughly $\frac{1}{2}$ to $\frac{2}{3}$ of $\sigma_1(\infty)$ at $s \lesssim 50$. Hence diffraction excitation can only provide a goodly share of σ_{inel} at $s \lesssim 50$ if double excitation is negligible as $s \rightarrow \infty$, but as we shall see, this is ruled out by the low energy data.

The contribution of process I to the inclusive cross-section is

$$E \frac{d\sigma_I}{d^3p} = \frac{2\sqrt{s}}{p} \frac{d\sigma_I}{d\Omega dM_2^2} \simeq \frac{1}{\pi} \frac{s}{x} \frac{d\sigma_I}{dt_1 dM_2^2}, \quad (5)$$

where $1-x \simeq (M_2^2 - m^2)/s$. This is a distribution which is sharply peaked about $x = 1 - \Delta_0(\Delta_0 + 2m)/s$. For values of x well below the peak it has the behaviour, Ref. 12), $s^{-\frac{1}{2}}(1-x)^{-\frac{3}{2}}$, while the peak rises like s .

We now turn to process III, - II being a special case thereof. Let $(Q_{10}, \vec{Q})$ and $(E, \vec{p})$ be the four-momenta of F_1 and the observed proton in the c.o.m. frame, $(E_0, \vec{p}_0)$ that of the proton in F_1 's rest frame. For fixed $\vec{p}$, E_0 , M_1 and M_2 , one must integrate $\vec{Q}$ over a cone with axis $\vec{p}$ and opening angle $\theta' = 2 \cos^{-1} [(EQ_{10} - M_1 E_0)/pQ]$. If $\theta'^2 \ll 1$, one finds

$$E \frac{d\sigma_{III}}{d^3p} = \frac{2}{x} \int dM_1 dM_2 dE_0 M_1 e^{-bPQ\theta'^2} I_0(2bPQ\theta\theta') E_0 \frac{dD(M_1; p_0)}{d^3p_0} \frac{d\sigma_2}{dt_1 dM_1 dM_2}, \quad (6)$$

where P is the incident momentum, I_0 a modified Bessel function, and $D(M_1; p_0)$ the decay distribution for F_1 into a proton. In Eq. (6) $d\sigma_2$ is to be evaluated at θ , which is the observed proton's scattering angle¹³⁾. A further integration over $p_\perp$ yields

$$\frac{d\sigma_{III}}{dx} = 2\pi \int dM_1 dM_2 dE_0 M_1 \left(\frac{\sqrt{s}}{2Q} \right) E_0 \frac{dD}{d^3p_0} \frac{d\sigma_2}{dM_1 dM_2}. \quad (7)$$

D is taken to have the thermodynamic form ¹⁴⁾

$$E_0 \frac{dD}{d^3p_0} = N e^{-E_0/T}, \quad (8)$$

and is normalized to $\frac{1}{2}$ within the kinematically allowed region for all M_1 .

A comparison of the model's consequences with the preliminary ISR data ¹⁵⁾ at $s=440$ is shown in Fig. 2. It should be noted that the normalization of these data is not known, nor is there discrimination between elastic and inelastic collisions when $x \rightarrow 1$. One should, therefore, confine one's attention to the relative magnitude of the data points for $x \lesssim 0.95$. Some of the parameters used in producing the theoretical curve are, so to say, predetermined: T is taken as the Hagedorn temperature ⁸⁾ 160 MeV; $b = 7 \text{ GeV}^{-2}$ so as to produce agreement with the $p_{\perp}^2$ distribution at $x \simeq 0.2$ of Ratner et al. ¹⁶⁾, and $2c_1 + c_2 = 0.84$ from the known value of $\sigma_{\text{el}}/\sigma_{\text{tot}}$ ¹⁷⁾. The model will always produce a minimum at large x provided $p_{\perp}$ and s are large enough; where and when it occurs is primarily determined by Δ_0 , to a lesser degree by b , and to a small extent by c_1/c_2 and T . For simplicity's sake we set $c_1 = c_2$; however, we must point out that if double-excitation is negligible, Refs. 3), 5), ($c_2 \simeq 0$), our proton spectra would disagree with the data at low energies ¹⁸⁾, whereas this is not the case if c_1 and c_2 are comparable. The fit shown in Fig. 2 is obtained with $M_0 + \Delta_0 = 1.6 \text{ GeV}$. By consulting Fig. 1 one finds that 29% of σ_{inel} must then be ascribed to non-diffractive channels at $s = 440$.

The behaviour of the spectra in the region where process I is comparable to II + III is fairly complicated ¹⁹⁾ as can be seen in Figs. 3 and 4. There are two reasons for this complexity: i) process I is squeezed into an ever smaller x interval as s increases, whereas II and III show approximate early scaling; and ii) the angular fall-off of II and III is considerably weaker than that of I because the latter is not smeared out by the decay distribution. In this connection we should point out that a measurement of the neutron spectrum would serve as a useful check, because neutrons can only come from processes II and III. Figures 3 and 4 also show features that have been observed previously ^{5), 6)}: a correlation between the x and $p_{\perp}$ behaviour ²⁰⁾ such that the $p_{\perp}$ fall-off becomes steeper with increasing x , and a growth towards $x = 1$ of the scaling regime as s increases.

When considering the scaling aspects of the model, one must remember that at finite s there is a portion of σ_{inel} that is not diffractive, and that the model does not say how this portion of the cross-section is distributed in x and $p_{\perp}$. By requiring a constant σ_{inel} we find that this non-diffractive part is approximately $70 s^{-1/3}$ mb, if s is in GeV^2 .

We close the description of our results with a cautionary remark: although the qualitative aspects of our predictions, as shown in Figs. 3 and 4, are not very sensitive to changes in the model's parameters, the quantitative features are, and would change considerably if the preliminary ISR data were to be modified appreciably. Needless to say, if the data were drastically wrong, - i.e., if there is no rise as $x \rightarrow 1$, and no minimum anywhere, the model would have to be discarded.

If the forthcoming data confirm our calculations, further tests of the model will have to be devised. To this end we put forward two suggestions that have not, to our knowledge, been proposed already. The first of these would test the model's assumption that a proton in the $x \rightarrow 1$ spike is correctly described by process I, i.e., that a measurement of x near 1 essentially determines the multi-body state in the opposite hemisphere. According to the model, if an extremely leading proton is observed at $x = 1 - [(M_2^2 - m^2)/s]$, there is also a nucleon at $x \simeq -m/M_2$, and a number $\sim (M_2 - m - m_{\pi})/(T + m_{\pi})$ of pions whose c.o.m. can be roughly identified with that nucleon. It will be rather difficult to identify the nucleon in this cluster and measure its x , but it should be possible to determine the correlation between the x of the very leading proton and the charge multiplicity in the opposite hemisphere. If the model fails this test, it would mean that the missing mass does not belong to a single closely grouped cluster. This would be the case if diffraction excitation were frequently accompanied by pionization, in which case the missing mass would be divided between two clusters (see below).

Our second proposal goes more to the heart of the matter, for it would clearly reveal the diffractive nature of process II (and thereby of I). Consider the scattering of high energy protons from complex nuclei. Then only the amplitude for II, but not for I or III, can be coherent over the whole nucleus, because it is only in this case that the nucleus can remain intact in its ground state. Put another way, in process II the leading particle is a nuclear constituent. Proton spectra from nuclear collisions should then be quite different from those in pp collisions: II would be enhanced with respect to I and III by a factor that grows rapidly with A , and for

x below the spike the $p_{\perp}$ distribution should narrow appreciably as nuclear coherence requires $t_{\perp} \approx 0$ in the fireball production step. But of far greater importance is the fact that the range of M_1 values accessible to coherent production via process II can be varied by changing the nuclear radius R and incident momentum p_L : $(M_1^2 - m^2) \lesssim 2p_L/R$. If one bears in mind that $x \approx m/M_1$ in process II, one sees that the proton spectrum should undergo rather predictable and highly visible contortions as one varies R and p_L .

We close with some observations concerning the scope of the diffraction excitation model. If one envisages a hadron as an assembly of constituents bound by some force field, one is led quite naturally to classify collisions into categories where one or both complexes are excited - i.e., into processes I, II and III. It is therefore not surprising that theories of composite structures usually provide predictions of single and double excitation probabilities ²¹⁾. But one must except that other kinds of processes may also be important in highly relativistic encounters, in particular interactions between the binding fields of the collision partners. Such field-field interactions would resemble the two-photon processes of electrodynamics, and would yield slow particles in the c.o.m. - primarily pions. It is therefore quite likely that the diffraction excitation model, in its present form, does not provide a complete description of multiple production as $s \rightarrow \infty$ ²²⁾, and that it may have to be augmented with concepts taken from the multiperipheral model.

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R E F E R E N C E S

- 1) R.K. Adair, Phys.Rev. 172, 1370 (1968).
- 2) R.C. Hwa and C.S. Lam, Phys.Rev.Letters 27, 1098 (1971), and references cited therein.
- 3) M. Jacob and R. Slansky, Phys.Letters 37B, 408 (1971).
- 4) R.K. Adair, Phys.Rev. D5, 1105 (1972).
- 5) M. Jacob and R. Slansky, Yale preprint (Phys.Rev., in press).
- 6) R.C. Hwa, Phys.Letters 37B, 405 (1971); 39B, 251 (1972).
- 7) E.M. Gordon and C.S. Lam, Cambridge University preprint DAMTP 72/13.
- 8) The DEM can therefore be viewed as a very special case of the thermodynamic model [cf., R. Hagedorn and J. Ranft, CERN preprint, TH.1440 (1972)], in that it specifies the initial distribution of fireball velocities, and postulates the existence of at most two fireballs.
- 9) R.K. Adair ^{1),4)} takes a somewhat different viewpoint, in that he assumes an asymptotic logarithmic decrease with s of the cross-section for producing fireballs of fixed mass. This leads him to

$$d\sigma_x \sim (M_1 M_2)^{-1} [\ln M_1 \ln M_2]^{-1/2},$$

and a $d\sigma/dx$ which falls rapidly as $x \rightarrow 0$ [see Fig. 3 of Ref. 4].

- 10) We have assumed the factorized form (3) purely for the sake of simplicity but this may not be justified. The slope parameter's b and b' are taken as M independent.
- 11) We have verified that our results are insensitive to the threshold behaviour of $f(M)$.
- 12) We therefore disagree with the statement in Ref. 6) that process I is important in the medium x region; for details see Fig. 2.
- 13) The evaluation of Eq. (6) presented in the figures was carried out numerically to a precision of $\sim 2\%$. Threefold integration is involved, but that over E_0 can be expressed analytically through a power series expansion of I_0 . With the exception of the small angle approximation we use exact kinematics throughout. The spectra are not shown near $x=0$ because the small angle approximation is not valid there.

- 14) The assumption of isotropic decay is questionable for moderate values of M_1 . Such F 's cannot decay into many pions, yet they may have appreciable angular momenta. By hypothesis, all F 's have helicity $\pm \frac{1}{2}$ for small $t_\perp$, so anisotropic decay cannot be ruled out. (Adair⁴⁾ has studied multibody decays with Monte Carlo techniques and finds rather isotropic distributions.) We ignore the possibility of anisotropic decay, but it could be of importance in the x regime where processes II and III compete with I, for there rather small values of M_1 are involved. If the model is successful, a detailed study of this x regime may provide information concerning the angular momenta present in the excitation spectrum. The assumption that protons emerge from 50% of all F decays is also ad hoc; diffraction merely implies that F is in the same isospin state as the proton, but sets no limits on the branching ratio once two-pion emission is possible.
- 15) M.G. Albrow et al. (CERN-Holland-Lancaster-Manchester Collaboration); reported by J.C.H. Sens at the 4th International Conference on High Energy Collisions, Oxford, April 1972 and CERN preprint (revised).
- 16) L.G. Ratner et al., Phys.Rev.Letters 27, 68 (1971); also paper presented to the Rochester meeting of the APS Division of Particles and Fields, August 1971.
- 17) A. Bohem et al., to be published; reported by P. Strolin at the 4th International Conference on High Energy Collisions, Oxford, April 1972.
- 18) J.V. Allaby et al., CERN Report 70-12 (1970); and contribution to the 4th International Conference on High Energy Collisions, Oxford, April 1972. If we set $c_2=0$ (no double excitation), and require $\sigma_{\text{diff}} = \sigma_{\text{inel}}$ as $s \rightarrow \infty$, we find a proton spectrum that is considerably higher than these data for $x \gtrsim 0.9$ for any reasonable choice of Δ_0 and b' .
- 19) On this point we appear to disagree with Ref. 5), where it is stated that the $p_\perp$ distribution can be inferred directly from $d\sigma/dx$.
- 20) Adair finds no such correlation, however; cf., Ref. 4), p. 1110.
- 21) Cf., e.g.,
N. Byers and S.C. Frautschi, in Quanta, ed., Y. Nambu, University of Chicago Press (1970);
W. Czyz, Proceedings Xth Cracow School of Theoretical Physics (1970).

- 22) Our preliminary calculation of pion production indicates that the model, with the parameters as given above, predicts multiplicities that are rather too low. In this connection we point out that σ_{inel} is correctly given by the DEM even if pionization is a separate process, provided that this type of pion production is always accompanied by excitation of the projectiles.

NOTE ADDED

Conclusions similar to ours for the amount of diffractive processes at $s = 50 \text{ GeV}^2$ have been reached by P. Pirilä and V. Ruuskanen from normalization to the leading particle peak in the missing mass spectrum.

FIGURE CAPTIONS

Figure 1 :

The single and double fireball production cross-sections, σ_1 and σ_2 ; the solid curves show σ_1 , the dashed ones σ_2 . In Fig. 1a the curves are labelled by the mass at the maximum of $f(M)$, $M_0 + \Delta_0$, and $b' = 10 \text{ GeV}^{-2}$ throughout. The arrows below the abscissa indicate s for an incident laboratory momentum $p_L = 25 \text{ GeV}$, corresponding to the CERN PS, and for three c.o.m. momenta P that cover the energies available at the CERN ISR. Figure 1b shows the b' variation of $\sigma_i(s)$ at fixed $M + \Delta_0 \equiv 1.6 \text{ GeV}$. The curves are labelled by P ; they correspond to the PS energy ($P = 3.5$), and to the bottom and top of the ISR range.

Figure 2 :

The invariant inclusive cross-section $Ed\sigma/d^3p$ plotted as a function of $x \equiv p_{||}/P$ for $\theta = 55 \text{ mrad}$ at $s = 440(\text{GeV})^2$, and compared to the preliminary ISR data ¹⁵⁾. The model parameters are $M_0 + \Delta_0 = 1.6 \text{ GeV}$, $b' = 10 \text{ GeV}^{-2}$, $b = 7 \text{ GeV}^{-2}$, $c_1 = c_2$, $T = 0.16 \text{ GeV}$. The dashed curves show the separate contributions of processes I, II and III, and the solid curve is their sum. At this value of s , and with the parameters given above, the model ascribes $\sim 29\%$ of σ_{inel} to non-diffractive processes. Hence, the theoretical curve should fall somewhat below the data, but not nearly as much as seen on the Figure. However, it must be remembered that the normalization of these data is not well known.

Figure 3 :

Invariant cross-sections at $s = 440 \text{ GeV}^2$. The parameters are the same as in Fig. 2; the x distributions are labelled by $p_{\perp}^2$ in GeV^2 , and the $p_{\perp}^2$ distributions by x .

Figure 4 :

Invariant cross-sections for various values of s . The x distributions are for $p_{\perp}^2 = 0.25 \text{ GeV}^2$. All parameters are as in Fig. 2.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.