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Multiplicity Distribution and Production Mechanisms
in High Energy Hadron Collisions

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ABSTRACT

Wroblewski has noted that, in inelastic hadron collisions at high energy, the average charged multiplicity $\langle n \rangle$ and the dispersion $D = (\langle n^2 \rangle - \langle n \rangle^2)^{1/2}$ obey a linear law $D = A\langle n \rangle - B$ with A, B constant. We show that such a linear relation is easily understood if there are two distinct classes of inelastic collisions, each having approximately constant cross section and reasonably small dispersion, but one having markedly larger multiplicities than the other. The low multiplicity class, naturally identified with diffraction dissociation, is found to have a cross section about equal to the elastic cross section, both for pp and πp collisions.

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1. As was first recognized by Czyżewski and Rybicki [1], the multiplicity distribution of charged particles produced in inelastic collisions of hadrons at high energy has simple empirical properties. Wroblewski [2] noted recently that a linear equation describes surprisingly well the relation between the average $\langle n \rangle$ of the charged multiplicity n and its dispersion D defined by

$$D = (\langle n^2 \rangle - \langle n \rangle^2)^{\frac{1}{2}}$$

He finds

$$D = A \langle n \rangle - B \quad (1)$$

with $A = B = 0.585$ for pp collisions in the p_{lab} range 4 - 205 GeV/c^{*)}. For πp collisions, data are only available in the range 4 - 25 GeV/c. The linear law is again satisfied, the constants being $A = 0.44$ for both π^+ , $B = 0.22$ for π^+ and $B = 0.09$ for π^- .

Our purpose is to show that the linear law (1) can be simply understood if there are two distinct classes of inelastic collisions, each having a constant cross section and a reasonably small dispersion, but one having markedly larger multiplicities than the other. Indeed, let p_1 and $p_2 = 1 - p_1$ be the probabilities for an inelastic collision to belong to the classes 1 and 2, and let $\bar{n}_i$, D_i be the values of $\langle n \rangle$ and D for class i . As is well known, the values of $\langle n \rangle$ and D for the full set of inelastic collisions are then given by

$$\langle n \rangle = p_1 \bar{n}_1 + p_2 \bar{n}_2, \quad D^2 = p_1 D_1^2 + p_2 D_2^2 + p_1 p_2 (\bar{n}_1 - \bar{n}_2)^2 \quad (2)$$

For $\bar{n}_1 \gg \bar{n}_2$ and to leading order in $\bar{n}_1$ or $\langle n \rangle$ these relations give

$$D \approx (p_1 p_2)^{\frac{1}{2}} \bar{n}_1 \approx a \langle n \rangle \quad \text{with} \quad a = (p_2/p_1)^{\frac{1}{2}} \quad (3)$$

*) The more recent 300 GeV/c point of NAL [3] also obeys this relation within the large experimental errors.

To the next order one obtains

$$D \approx (p_1 p_2)^{\frac{1}{2}} (\bar{n}_1 - \bar{n}_2) + \frac{1}{2} (p_1 p_2)^{-\frac{1}{2}} (p_1 D_1^2 + p_2 D_2^2) / \bar{n}_1$$

$$= a \langle n \rangle - b \quad \text{with} \quad b = a \bar{n}_2 - (p_1 D_1^2 + p_2 D_2^2) / (2a \langle n \rangle) \quad (4)$$

If in each class $D_i^2 \approx \bar{n}_i$, the quantity b reduces to

$$b \approx a \bar{n}_2 - (2a)^{-1}$$

Constancy of the parameter a over a given energy interval means that the p_i are constant; the cross sections $\sigma_i = p_i \sigma_{inel}$ for the two classes of collisions are then also constant since the total inelastic cross section σ_{inel} has this property. Constancy of the parameter b can occur under various conditions; constant values for $\sum p_i D_i^2 / \langle n \rangle$ and $\bar{n}_2$ would give it, but also compensating increases of these two quantities with energy.

2. The idea that two separate classes of inelastic hadron collisions may exist at high energy is a natural one and it has been considered by many authors. The most concrete discussion of its applicability, also using the multiplicity distribution, is due to Fiałkowski [4]. Diffraction dissociation, which has been shown to dominate 3- and 4-body collisions for $p_{lab} \gtrsim 10$ GeV/c with approximately constant cross sections [5], is the natural candidate for the low multiplicity class (our class 2); the average $\bar{n}_2$ could be constant as assumed by Fiałkowski, but it could also grow slowly with energy due to the opening up of new diffraction dissociation channels. Plenty of models exist for the collisions of the high multiplicity class 1 (Bremstrahlung, thermodynamical, uncorrelated jet, various forms of multiperipheral model); one could have the Poisson distribution property $D_i^2 = \bar{n}_i$ assumed by many authors, but there are of course many other possibilities, in particular a slow increase of $D_i^2 / \bar{n}_i$ which could compensate an increase of the average class 2 multiplicity $\bar{n}_2$ and thereby make the parameter b in eq.(4) approximately energy independent.

3. To obtain a rough estimate of the p_i and $\bar{n}_i$ from the data we shall simply identify the empirical values of A and B obtained by Wroblewski for eq.(1) with the quantities a and b of eqs.(3) and (4). A more precise use of eq.(2) is hardly justified without knowing more than we do on the expected sizes of the D_i^2 (especially D_1^2). Using eq.(3) one finds $p_2 = 0.255$ for pp (in good agreement with Fiałkowski) and $p_2 = 0.163$ for $\pi^\pm p$ collisions. It is interesting to remark that the resulting diffraction dissociation cross sections $\sigma_2^{pp} \approx 7.7$ mb and $\sigma_2^p \approx 3.4$ mb are very close to the elastic cross sections $\sigma_{el}^{pp} \approx 9$ mb and $\sigma_{el}^{\pi p} \approx 4$ mb respectively. If factorization is applied to elastic and inelastic diffraction, one is led to write

$$\sigma_{el}^{pp} + \sigma_2^{pp} = (1 + \xi_p)^2 \sigma_{el}^{pp}, \quad \sigma_{el}^{\pi p} + \sigma_2^{\pi p} = (1 + \xi_\pi)(1 + \xi_p) \sigma_{el}^{\pi p}$$

and one finds $\xi_p \approx \xi_\pi \approx 0.4$. The cross sections for simple and double dissociation would then be $2\xi \sigma_{el} \approx 0.8 \sigma_{el}$ and $\xi^2 \sigma_{el} \approx 0.16 \sigma_{el}$ respectively.

We discuss next the average multiplicity $\bar{n}_2$. We use eq.(4) in which we put

$$D_1^2 = (1 + \Delta_1) \bar{n}_1, \quad D_2^2 = \bar{n}_2$$

The ansatz for D_2^2 is unimportant because of the small values of $p_2, \bar{n}_2$. The result is

$$b = a \bar{n}_2 - (2a)^{-1} (1 + \Delta_1)$$

where the term in Δ_1 has been simplified by the approximation $p_1 \bar{n}_1 \approx \langle n \rangle$. The value of $\bar{n}_2$ is then

$$\bar{n}_2 = b/a + (1 + \Delta_1)/(2a^2)$$

We can now replace a, b by Wroblewski's empirical parameters A, B.

Putting $\Delta_1 = 0$ (positive Δ_1 and consequently larger $\bar{n}_2$ may be more probable) we find

$$\bar{n}_2 \approx 2.5 \text{ for } pp, \quad 3.1 \text{ for } \pi^+p, \quad 2.8 \text{ for } \pi^-p$$

Although the approximation (4) and the present status of the data may be insufficient for this purpose, we comment briefly on the differences between the values of $\bar{n}_2$. That $\bar{n}_2^{\pi p} - \bar{n}_2^{pp}$ is about 0.5 looks reasonable since diffraction dissociation of the pion is restricted to 3, 5, ... pions by G-parity, whereas the proton can dissociate into any number of particles. The difference between $\bar{n}_2$ for π^+p and π^-p is more difficult to understand in diffractive terms but may be attributable to our neglecting Δ_1 . If we take $\bar{n}_2$ the same for $\pi^\pm p$, we conclude that Δ_1 , i.e. $D_1^2/\bar{n}_1$, is somewhat larger for π^-p than for π^+p . This effect could be due to a larger amount of charge exchange processes in class 1 collisions for π^-p . One can indeed imagine that the processes of the high multiplicity class 1 are in majority of vacuum exchange type (these would be the same for $\pi^\pm p$), but that class 1 contains in addition processes of charge exchange type; these should be more abundant in π^-p than in π^+p collisions and could increase $D_1^2/\bar{n}_1$ more for the former than for the latter.

4. We end by noting that other assumptions on the simultaneous presence of various collision types are not as likely to explain Wroblewski's linear relation than the simple two-class assumption here used. For the case of $N > 2$ distinct classes of collisions, the eqs.(2) are replaced by

$$\langle n \rangle = \sum p_i \bar{n}_i, \quad D^2 = \sum p_i D_i^2 + \sum_{i < j} p_i p_j (\bar{n}_i - \bar{n}_j)^2$$

The presence of several terms in $(\bar{n}_i - \bar{n}_j)^2$ makes it more difficult to achieve linearity of D in $\langle n \rangle$. Rather than to assume two distinct classes of collisions it is also common to consider two types of secondaries in each collision, e.g. fragments and central particles. The charged

multiplicity is then in each collision a sum $n_1 + n_2$, the n_i being the numbers of charged particles of each type. This assumption gives

$$\langle n \rangle = \langle n_1 \rangle + \langle n_2 \rangle, \quad D^2 = D_1^2 + D_2^2 + 2(\langle n_1 n_2 \rangle - \langle n_1 \rangle \langle n_2 \rangle) \quad (5)$$

Linearity of D in $\langle n \rangle$ is again more difficult to achieve than in the case of two distinct classes of collisions because it requires a special assumption on the correlation term in eq.(5).

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