Interpretation of "exotic" events of multiple production at very high energies

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It has been demonstrated by using the model of independent particle production that allowance for the isotopic properties of pions sharply changes the numerical distribution of neutral and charged pions and makes it possible to explain the presence of events with a very small (or very large) fraction of neutral hadrons without invoking new physical concepts

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The processes of multiple generation of particles due to hadronic collisions produce primarily π^+, π^-, and π^0 mesons in equal numbers, on the average. At the same time, cosmic rays have shown the presence of events at higher energies than 100 GeV, in which the final state had many hadrons $n \sim 10^2$, and π^0 mesons, the so-called Centaur-type events, were missing.[1] Since the absence of π^0 mesons seems to be highly unlikely when about 10^2 pions are produced, such events were interpreted in many studies as events associated with new, unusual processes such as liberation of quarks or production of many baryons in the absence of pions.[2]

On the other hand, the "inverse" events, in which only γ-ray quanta (i.e., most likely only π^0 mesons, $\pi^0 \to 2\gamma$) are produced and charged particles are missing, have been known for some time.[3] Special mechanisms were proposed to explain such events. We should like to point out that if the isotopic properties of pions (which were ignored earlier) are taken into account, then such events may lose their exotic nature—the probability for production of a large number of pions without π^0 mesons (or vice versa without $\pi^\pm$ mesons) is rather high and consistent with observation.

The role of the isotopic-spin effects will be analyzed within the framework of the model for production of the coherent state of pions (see Ref 4). If the π^+, π^-, and π^0 mesons were not coupled to each other, then we would have the following expression for the final state:

$$|f> = e^{-c/2} \exp\{ \int d^3k \sum_i f_i(k) a_i^+(k) \} |0>,$$
$$c = \sum c_i = \sum_i \int d^3k |f_i(k)|^2, \quad i = +, -, 0 \tag{1}$$

where $a_i^\dagger$ are the creation operators for i-type pions, $|0\rangle$ is the pion vacuum, and $|f(k)|^2$ determines the momentum distribution of pions [$f_i(k)$ is the effective density of the pion current source]. The probability for production of $\pi^\pm$ and π^0 mesons in this case would have the same form as in the model of uncorrelated jets and a Poisson distribution with respect to the number n_i of pions of each type with the average value $\langle n_i \rangle = c_i$ would exist.

We shall assume that f_i are components of the $\mathbf{f}$ vector in the isotopic space and that a_i and $a_i^\dagger$ are components of $\mathbf{a}$ and $\mathbf{a}^+$. The $|f\rangle$ state in Eq. (1) does not have a specific isospin I (or electric charge), but has states with large values of I which increase with increasing number of particles. This is consistent with the conservation of total isospin in the collision process. For example, the isospin of a pion system cannot be higher than 2 in the collision of two nucleons and in the production of only pions. For simplicity, we shall analyze a case in which the total pion isospin is equal to 0 and 1. Other small values $I \sim 1$ should give similar results for a large number of pions $n \gg 1$.

The state with isospin I and projection I_z appears as a result of averaging $|f\rangle$ in the directions of the $\mathbf{f}$ vector in the isospace with and appropriate spherical function $Y_{I,I_z}(\theta,\phi)$ (Ref. 4)

$$|f; I, I_z> = e^{-\frac{c}{2}} \int d\Omega_e Y^*_{I,I_z}(\theta,\phi) \exp\{ \int d^3k \mathbf{f}(k) \mathbf{a}^+(\mathbf{k}) \} |0>, \mathbf{f} = f\mathbf{e}, \tag{2}$$

where $\mathbf{e}$ is a unit vector. The net distributions with respect to the number of produced π^+, π^-, and π^0 mesons, which are normalized to unity, in the states with $I = 0,1$ have the form

$$W(n_i; I, I_z) \cong \frac{c}{2} \frac{2I+1}{1+\beta} e^{-c} \frac{c^{n_0} (c/2)^{n_+ + n_-}}{n_0! n_+! n_-!} B^2\left(\frac{n_0+1+a}{2}, \frac{n_+ + n_- + 2 + \beta}{2}\right), \tag{3}$$

where **B** is the Euler beta function and $n_+ = n_- + I_z$, $n_0 + \alpha$ is an even number and has nonvanishing values of $\alpha = 1$ for $I = 1$ and $I_z = 0$, $\beta = 1$ for $I = 1$ and $I_z = \pm 1$. The total average number of pions is assumed to be large, $\langle n \rangle = c \gg 1$.

The important point is that the distributions with respect to the number of neutral pions $w_0(n_0)$ and charged pions $w_{ch}(n_{ch})$ for $I = 0$ and 1 are much broader than those obtained by ignoring the constraints imposed on the isospin of the pion system.

First, we shall examine the case $I = 0$. After summing (3) over the charged pions $n_{ch} = n_+ - n_-$, we can see that in the main region of variation of n_0

$$w_0(n_0, I = 0) \cong \frac{1}{\sqrt{2c}} \frac{\Gamma\left(\frac{n_0 + 1}{2}\right)}{\Gamma\left(\frac{n_0}{2} + 1\right)}, \quad \langle n_0 \rangle \cong \frac{c}{3}, \quad c - n_0 \gg \sqrt{c}, \tag{4}$$

i.e., for example, the probability for occurrence of events without π^0 mesons is high, amounting here to more than 10% for $\langle n \rangle \cong c = 100$. The probability $w_0(n_0, I = 0) \sim (n_0 c)^{-1/2}$ decreases slowly to $n_0 \sim c$ with increasing n_0, where $w_0(c, I = 0) \cong 1/2\, c$ and then decreases to zero in the region $|n_0 - c| \sim \sqrt{c}$. Such behavior of w_0 can be explained by a large fraction of Centaur-type events in which the π^0 mesons are missing at $\langle n \rangle \gg 1$. The probability for the occurrence of such events for w_0 would be $e^{-c/3} \sim e^{-33} < 10^{-14}$ for the original Poisson distribution, i.e., they would not be observed.

Analogously, after summing (3) over n_0 we can see that for $c - n_{ch} \gg \sqrt{c}$

$$w_{ch}(n_{ch}, I = 0) \cong \frac{1}{c} \left(1 - \frac{n_{ch}}{c}\right)^{-1/2}, \quad \langle n_{ch} \rangle \cong 2c/3, \tag{5}$$

i.e., we again obtain a slowly varying function of n_{ch}. The probability $w_{ch}(n_{ch}, I = 0)$

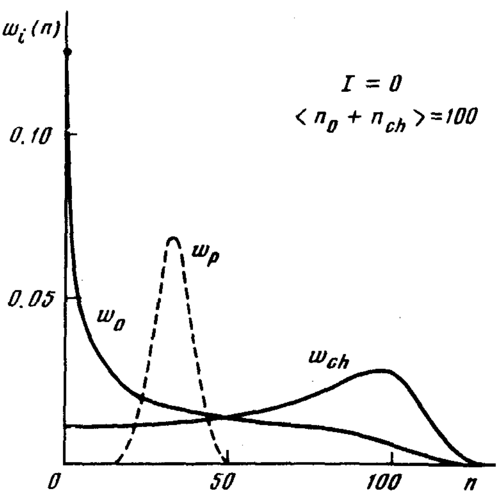

FIG. 1. Numerical distribution of charged pions $[w_{ch}(n)]$ and neutral pions $[w_0(n)]$ in the state with a total isospin zero (n are even numbers). For comparison, the dashed line represents the $w_p(n)$ distribution for π^+, π^-, and π^0 obtained in the same model in which the isotopic invariance is ignored.

increases slowly with increasing n_{ch}, reaching a maximum at $n_{ch} \approx c$

$$w_{ch}(c, I = 0) \cong \frac{\Gamma(1/4)}{\sqrt{2\pi}\,(2c)^{3/4}} \tag{6}$$

and then decreases in the interval $|n_{ch} - c| \sim \sqrt{c}$. The events without charged pions $[w_{ch}(0, I=0) \cong c^{-1} = 0.01]$, which also have been observed in cosmic rays, comprise a sizable fraction. The probabilities of w_0 and w_{ch}, which were calculated using approximate formulas ($c \gg 1$), are also illustrated in Fig. 1.

The same qualitative results were obtained when the states with $I = 1$ were selected. We shall give them only for the main region $c - n \gg \sqrt{c}$. The asymptotic distributions of neutral particles are given by

$$w_0(n, I=1) \cong \begin{cases} 3\sqrt{2}\,\Gamma\left(\frac{n}{2}+1\right) \Big/ c^{3/2}\,\Gamma\left(\frac{n}{2}+\frac{1}{2}\right) \sim \frac{3}{c}\left(\frac{n}{c}\right)^{1/2}, & I_z = 0, \\ 3(c-n)\,\Gamma\left(\frac{n}{2}+\frac{1}{2}\right) \Big/ (2c)^{3/2}\,\Gamma\left(\frac{n}{2}+1\right) \sim \frac{3}{2c}\,\frac{c-n}{(cn)^{1/2}} & I_z = 1 \end{cases} \tag{7}$$

and those of the charged particles are

$$w_{ch}(n, I = 1) \cong \begin{cases} \frac{3}{2}\left(1 - \frac{n}{c}\right)^{1/2}, & I_z = 0, \\ \frac{3}{2}\,(n+1)\,/\,c^{3/2}\,(c-n)^{1/2}, & I_z = 1. \end{cases} \tag{8}$$

These very broad distributions satisfy the *KNO* scaling conditions in the main region of their variation. Not that the conditions $\langle n_0 \rangle = c/3$, $\langle n_{ch} \rangle = 2c/3$ for $I = 1$ are satisfied only after averaging with equal weights over all the projections I_z. We also note that the distributions of the total number of pions for the analyzed isospins retain their original form (Poisson form in our model), i.e., they are not broadened,

$$w(n) \cong 2e^{-c}\,\frac{c^{n+1}}{(n+1)!}, \quad (n = 2m \text{ for } I = 0, \; n = 2m+1 \text{ for } I = 1). \tag{9}$$

The distributions for the neutral and charged particles broaden sharply because averaging over the relative projections f_i when selecting the states with a definite isospin in (2). This leads to averaging of the original distributions which have sharp peaks for the values $c_i \sim |f_i|^2$ and which are not directly connected with the small, isolated isospins.

We have examined only one of the simplest models of multiple generation of pions and made a number of simplifying assumptions: we have ignored the production of other particles, disregarded momentum conservation and did not consider the effects of the leading particles (these effects would lead to a broadening of the original multiplicity distributions). It is unlikely, however, that such refinements can change the main qualitative result for a large number of produced pions.

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