

Centauro- and anti-Centauro-type events

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Assuming that leading particles in high-energy hadronic and nuclear collisions become sources of a classical pion field, we show that the direct production of pions favors Centauro (mainly charged) events and that the production of pions through the ρ -type channel favors anti-Centauro (mainly neutral) events. We also observe a strong negative neutral-charged correlation in both cases.

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I. INTRODUCTION

Recently, there have been several interesting theoretical speculations [1–6] that localized regions of misaligned vacuum might occur in ultrahigh-energy hadronic and heavy-ion collisions. These regions become coherent sources of a classical pion field. The models in [1–6] predict large isospin fluctuations on the event-to-event basis, in particular, the fluctuation in the neutral-to-charged ratio, thus offering a possible explanation of Centauro cosmic-ray experiments [7]. Although the actual dynamical mechanism of the production of a classical pion field in the course of a high-energy collision is not known, there exist a number of calculations in which the coherent production of pions is considered to be a dominant mechanism [8,9]. These early models also predict strong negative correlations between the numbers of neutral and charged pions. In fact, the exact conservation of isospin in a pion uncorrelated jet model is known [10,11] to give the same pattern of charged and/or neutral fluctuations as observed in Centauro events. This strong negative neutral-charged correlation is believed to be a general property of direct pion emission in which cluster formation is not taken into account [12–14]. The same conclusion is drawn when a proper multipion symmetrization combined with isospin is considered [15].

In this paper we consider the leading-particle effect as a possible source of a classical pion field. Pions are produced from a definite isospin state of the incoming leading-particle system either directly or through the cluster emission mechanism.

Coherent emitted clusters decay subsequently into pions outside the region of interaction. We discuss the behavior of the probability distribution of the neutral-to-charged ratio and the corresponding two-pion correlation functions C_{ab} when the total number of pions produced is finite but large.

II. COHERENT PRODUCTION

Many results on hadronic and nuclear collisions can be understood in terms of a simple picture that the outgoing particles have three origins: beam fragmentation, target fragmentation, and central production. At high energies most of the pions are produced in the central region. To isolate the central production, we adopt high-energy longitudinally dominated kinematics, with two leading particles retaining a large fraction of their incident momenta.

With a set of independent variables s , $\{\mathbf{q}_{iT}, y_i\} \equiv q_i$, $i = 1, 2, \dots, n$, the n -pion contribution to the s -channel unitarity becomes an integral over the relative impact parameter b of the two incident leading particles:

$$F_n(s) = \frac{1}{4s} \int d^2b \prod_{i=1}^n dq_i |T_n(s, \mathbf{b}; 1 \dots n)|^2, \quad (1)$$

where $dq = d^2q_T dy / 2(2\pi)^3$. The normalization is such that

$$F_n(s) = s\sigma_n(s), \quad \sigma_{\text{inel}}(s) = \sum_{n=1}^{\infty} \sigma_n(s). \quad (2)$$

The leading-particle effect is crucial for an approximate treatment of the multiparticle s -channel unitarity integral, Eq. (1), which enables us to consider the colliding particles as a classical source of pions in the following way. At high energies the matter distributions of the two-leading-particle system are Lorentz-contracted disks in the center-of-mass system. A highly excited localized system occurs just after the collision and then relaxes through the coherent emission of pions [16]. According to [17], this type of coherent emission of pions should saturate close to the threshold since, once it starts, the resulting pion emission, in the absence of a “resonance cavity,” prevents further buildup of pion fields. The basic equation for the pion field is

$$(\square + \mu^2)\pi(s, \mathbf{b}; x) = \mathbf{j}(s, \mathbf{b}; x), \quad (3)$$

where \mathbf{j} is a classical source. If the source $\mathbf{j}(s, \mathbf{b}, x)$ is

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static, i.e., independent of time, no pion can be radiated. However, in the dynamical case of hadronic or nuclear collisions, \mathbf{j} acquires time dependence and radiates pions. The reference to the initial leading-particle system is contained in the variables \mathbf{b} and s . The standard solution of Eq. (3) is given in terms of in and out fields that are connected by the unitary S matrix $\hat{S}(\mathbf{b}, s)$ as follows:

$$\pi_{\text{out}} = \hat{S}^\dagger \pi_{\text{in}} \hat{S} = \pi_{\text{in}} + \pi_{\text{classical}} . \quad (4)$$

The S matrix following from such a classical source is still an operator in the space of pions. On the other hand, inclusion of isospin requires $\hat{S}(s, \mathbf{b})$ to be also a matrix in the isospace of the leading particles.

If the isospin of the system of two incoming (outgoing) leading particles is II_3 and $(I'I'_3)$, respectively, then the initial-state vector for the pion field is $\hat{S}(s, \mathbf{b})|II_3\rangle$, where $|II_3\rangle$ is a vacuum state with no pions but with two leading particles in the isostate characterized by II_3 . Then the n -pion production amplitude is

$$iT_n(s, \mathbf{b}; q_1 \cdots q_n) = 2s \langle I'I'_3; q_1 \cdots q_n | \hat{S}(s, \mathbf{b}) | II_3 \rangle . \quad (5)$$

The unnormalized probability distribution of producing $n_+ \pi^+$, $n_- \pi^-$, and $n_0 \pi^0$ pions is defined as

$$W(n_+ n_- n_0, I'I'_3; II_3) = \int d^2 b dq_1 dq_2 \cdots dq_n \times |\langle I'I'_3 n_+ n_- n_0 | \hat{S}(s, \mathbf{b}) | II_3 \rangle|^2 , \quad (6)$$

where $n = n_+ + n_- + n_0$. The coherent production of pions from a classical source [Eq. (3)] is described by the S matrix

$$\hat{S}(s, \mathbf{b}) = \int d^2 \mathbf{e} |\mathbf{e}\rangle D(\mathbf{J}; s, \mathbf{b}) \langle \mathbf{e} | , \quad (7)$$

where $|\mathbf{e}\rangle$ represents the isospin-state vector of the two-leading-particle system. It has the property that

$$\langle \mathbf{e} | \mathbf{e}' \rangle = \delta^{(2)}(\mathbf{e} - \mathbf{e}') , \quad (8)$$

$$\langle \mathbf{e} | II_3 \rangle = Y_{II_3}(\mathbf{e}) , \quad (9)$$

where $Y_{II_3}(\mathbf{e})$ is the usual spherical harmonic. The quantity $D(\mathbf{J}; s, \mathbf{b})$ is the unitary coherent-state displacement operator defined as

$$D(\mathbf{J}; s, \mathbf{b}) = \exp \left[\int d^4 q \mathbf{J}(s, \mathbf{b}; q) \mathbf{a}^\dagger(q) - \text{H.c.} \right] , \quad (10)$$

where $\mathbf{a}^\dagger(q)$ is the creation operator of a physical pion and

$$\mathbf{J}(s, \mathbf{b}; q) = \int d^4 x e^{iqx} \mathbf{j}(s, \mathbf{b}; x) \quad (11)$$

is the Fourier transform of a classical pion source. Note that each charged state of the pion field has a source that varies arbitrarily in space and time. However, if we assume pions to be identical, then the isospin of all pions, regardless of their momenta, is coupled to form the total isospin. This is obtained by considering a coherent production with $\mathbf{J}(s, \mathbf{b}; q)$ of the form

$$\mathbf{J}(s, \mathbf{b}; q) = J(s, \mathbf{b}; q) \mathbf{e} , \quad (12)$$

where \mathbf{e} is a fixed unit vector in isospace. At this point the conservation of isospin becomes a global property of the system, restricted only by the relation

$$\mathbf{I} = \mathbf{I}' + \mathbf{I}_\pi ,$$

where \mathbf{I}_π denotes the isospin of the emitted pion cloud. In this model, the pions in the cloud are uncorrelated and described by the same wave function in momentum space for each pion.

Assuming further that the total number of emitted pions is finite but large, and that all (I', I'_3) are produced with equal probability, we can sum over all possible isospin states of the outgoing leading particles to obtain

$$P_{II_3}(n_+ n_- n_0 | n) = \frac{\sum_{I'I'_3} W(n_+ n_- n_0, I'I'_3; II_3)}{\sum_{n_+ + n_- + n_0 = n} \sum_{I'I'_3} W(n_+ n_- n_0, I'I'_3; II_3)} . \quad (13)$$

This is our basic relation for calculating various pion multiplicity distributions, pion multiplicities, and pion correlations between definite charge combinations. In general, the probability $W(n_+ n_- n_0, I'I'_3; II_3)$ depends on $(I'I'_3)$ dynamically. The final-leading-particle production mechanism usually tends to favor the $(I', I'_3) \approx (I, I_3)$ case, for example, if the final leading particles are nucleons or isobars. However, if the leading particles are colliding nuclei, it is reasonable to assume almost equal probability for various (I', I'_3) owing to the large number of various leading isobars in the final state.

Note that, in general, the n -pion cloud contains components of all isospins: $I_\pi = 0, 1, \dots, n$. The case when both the isospin state of the incoming- and that of the outgoing-leading-particle systems are fixed has been treated in [12].

III. GRAY-DISK DYNAMICS

In order to obtain some detailed results for multiplicity distributions and correlations, we have to choose an explicit form for the source function $J(s, \mathbf{b}; q)$.

The results on the isospin structure are most easily analyzed in the gray-disk model in which

$$\int d^4 q |J(s, \mathbf{b}; q)|^2 = \Delta \theta(b_0 - b) . \quad (14)$$

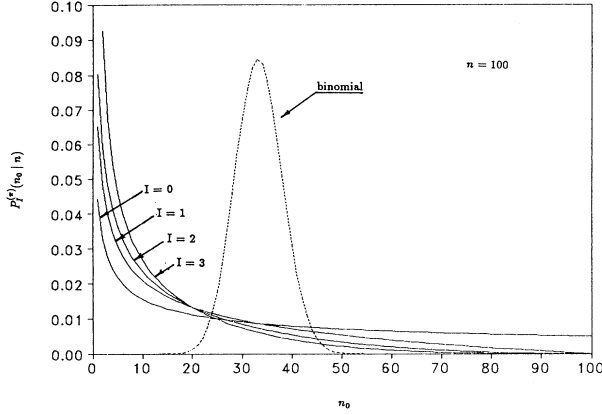


FIG. 1. Multiplicity distributions $P_I^{(\pi)}(n_0|n)$ of neutral pions for $n = 100$ when the total isospin of the incoming-leading-particle system is $I = 0, 1, 2, 3$. The dashed line represents the corresponding binomial distribution with the isospin invariance neglected.

Here Δ and b_0 are in general energy-dependent parameters and θ is a step function. The parameter Δ is expected to grow linearly with $\ln s$ in the central region. Such behavior is also expected from a multiphipheral model.

For $I_3 = I$, it is straightforward algebra to calculate the probability of creating n pions of which n_0 are neutral pions:

$$P_I^{(\pi)}(n_0|n) = \sum_{n_+ + n_- = n - n_0} P_{II}(n_+, n_-, n_0|n) \quad (15)$$

$$= \binom{n}{n_0} \frac{B(n_0 + \frac{1}{2}, n - n_0 + I + 1)}{B(\frac{1}{2}, I + 1)}. \quad (16)$$

Here $B(x, y) = \Gamma(x)\Gamma(y)/\Gamma(x+y)$ is the Euler beta function. Note that $P_I^{(\pi)}(n_0|n)$ differs considerably from the binomial distribution given here by

$$3^{-n} 2^{n-n_0} \binom{n}{n_0}.$$

In Fig. 1 we show the behavior of $P_I^{(\pi)}$ for $n = 100$ and for different isospin ($I = 0, 1, \dots$) of the initial-leading-particle system. Figure 1 also shows a comparison with the corresponding binomial distribution. It is clear that our direct-pion-emission model predicts many more events with a small number of neutral pions (Centrauro events), in particular, if the isospin of the initial-leading-particle system is large.

IV. NEUTRAL-TO-CHARGED RATIO

A. Centauro events

Let us define $R = n_0/n$, the fraction of neutral pions in an event with n pions. Then it is easy to see that in the limit $n \rightarrow \infty$, with R fixed, the probability distribution

$nP_I^{(\pi)}(n_0|n)$ scales to the limiting behavior

$$nP_I^{(\pi)}(n_0|n) \rightarrow P_I^{(\pi)}(R) = \frac{(1-R)^I}{B(\frac{1}{2}, I+1)\sqrt{R}}. \quad (17)$$

This limiting probability distribution is different from the usual Gaussian random distribution for which one expects $P_I^{(\pi)}(R)$ to be peaked at $R = \frac{1}{3}$ as $n \rightarrow \infty$.

Instead, we find peaking at $R = 0$ although

$$\langle n_0 \rangle = n - \langle n_{ch} \rangle = \frac{1}{2I+3}n \quad (18)$$

and

$$\langle n \rangle = \frac{1}{2}\langle n_{ch} \rangle = \frac{1}{3}n \text{ for } I = 0.$$

The distribution (17) for $I = 0$ is similar to the distribution that has been derived and advocated in the disoriented chiral condensate model [2]. Although the final distributions of pions look the same, the underlying mechanism is different. In the disoriented chiral model, the classical pion field satisfies a nonlinear equation of motion that can be reduced to the equation with a time-dependent effective mass

$$[\square + \mu_{\text{eff}}^2(t)]\pi(x) = 0,$$

in contrast to our Eq. (3).

In addition, there is also a strong isospin correlation between various pion-pair channels:

$$\begin{aligned} C_{00}^{(I)} &= 4 \frac{I+1}{2I+5}, \\ C_{cc}^{(I)} &= \frac{1}{(I+1)(2I+5)}, \\ C_{0c}^{(I)} &= -\frac{2}{2I+5}, \end{aligned} \quad (19)$$

where

$$C_{ab}^{(I)} = \frac{\langle n_a n_b \rangle}{\langle n_a \rangle \langle n_b \rangle} - 1.$$

Note the strong negative neutral-charged correlation, which is a general property of direct pion production. Experimentally, this correlation is positive at least at high energies.

B. Anti-Centauro events

Let us now assume that pions are produced through the coherent production of clusters that decay into two or more pions. The more pions in a cluster, the larger the correlation effect expected. Here we restrict our discussion to isovector clusters of the ρ type. The pion distribution and correlations follow from (15) by observing that

$$\begin{aligned}
n_{\rho+} &= \frac{1}{2}n - n_- , \\
n_{\rho-} &= \frac{1}{2}n - n_+ , \\
n_{\rho 0} &= \frac{1}{2}n - n_0 .
\end{aligned} \tag{20}$$

We find that

$$P_I^{(\rho)}(n_0|n) = P_I^{(\pi)}(\frac{1}{2}n - n_0|\frac{1}{2}n) , \tag{21}$$

where $n = 2, 4, \dots$ is even.

In the limit $n \rightarrow \infty$, with $R = n_0/n$ fixed, we find the following behavior:

$$nP_I^{(\rho)}(n_0|n) \rightarrow P_I^{(\rho)}(R) = \frac{2(2R)^I}{B(\frac{1}{2}, I+1)\sqrt{1-2R}} . \tag{22}$$

This distribution is sharply peaked at $R = \frac{1}{2}$, i.e., when $n_0 = \frac{1}{2}n$. According to (22), there is a substantial probability of events only with neutral pions (anti-Centauro events). The neutral-charged correlations are found to be less negative than in the case of direct pion production:

$$C_{0c}^{(I)} = -\frac{1}{(I+2)(2I+5)} . \tag{23}$$

In Fig. 2 we show the behavior of (21) for $n = 100$, and $I = 0, 1, 2, 3$.

V. CONCLUSION

Assuming that leading particles in high-energy hadronic and nuclear collisions become a source of a classical pion field, we have shown that the coherent production of pions favors Centauro-type events, whereas the coherent production of ρ -type clusters will favor anti-Centauro-type events. In the anti-Centauro case, n/n_0 peaks near 1. The pions in the events of $n \sim n_0$ contain very large total isospins of $I_\pi \sim n$. Therefore the final leading particle must also include isospins of $I' \approx I_\pi$, to

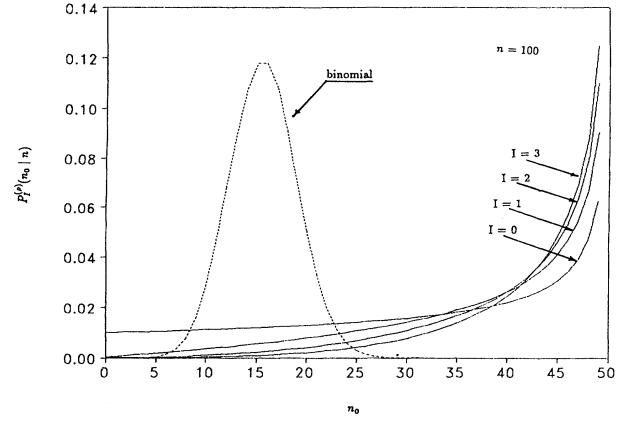


FIG. 2. Same as Fig. 1, except that pions are assumed to be emitted through the isovector ρ -type channels.

match the initial isospin I if it is small. That is, the existence of the peak near $n_0/n = 1$ in $P(n_0|n)$ requires an abundance of very high I' states, which is possible in heavy-ion collisions. The same argument can be made for the Centauro case. We also predict a strong negative neutral-charged correlation. It is clear that one should consider π , ρ , and other multipion cluster production to obtain a realistic picture of the classical pion production.

In addition, the chosen form of the source function of the classical pion field, Eq. (14), is too simple. One should probably try to find a more adequate space-time structure leading to the pion condensate, for example [17]. Another possibility is to relate the pion-source function to the single-particle inclusive distribution. We hope to address this question in the near future.

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