ISSN 1330–0016
CODEN FIZBE7

ISOSPIN CORRELATIONS IN HIGH–ENERGY HEAVY–ION COLLISIONS

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Received 12 December 1994

UDC 539.12

PACS 25.75.+r, 12.38.Mh, 13.85.Tp, 24.60.Ky

We study the possibility of large isospin fluctuations in high-energy heavy-ion collisions by assuming that pions are produced semiclassically both directly and in pairs through the isovector channel. The leading-particle effect and the factorization property of the scattering amplitude in the impact parameter space are used to define the classical pion field. In terms of the joint probability function $P_{II_3}(n_0, n_-)$ for producing n_0 neutral and n_- negative pions from a definite isospin state II_3 of the incoming leading-particle system we calculate the two–pion correlation parameters f^0_{2,n_-} and the average number of neutral pions $(\langle n_0\rangle_{n_-})$ as a function of negative pions (n_-) produced. We show that only direct production of pions without isovector pairs leads to large isospin fluctuations.

1. *Introduction*

In recent years several cosmic-ray experiments [1] have reported evidence for the existence of Centauro events characterized by an anomalously large number of charged pions in comparison with the number of neutral pions, indicating that there should exist a strong long-range correlation between two types of the pions. The negative results of the accelerator searches for the Centauro events at CERN

[2,3,4] have suggested that threshold for their production must be larger then 900 GeV.

Such long-range correlations are possible if pions are produced semiclassicaly and constrained by global conservation of isospin [5–10].

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 interesting theoretical speculations [11–16] that localized regions of misaligned chiral vacuum might occur in ultrahigh-energy hadronic and heavy-ion collisions. These regions become coherent sources of a classical pion field. In early models [5,6], however, the coherent production of pions was taken for granted and considered as a dominant mechanism.

These models also predict strong negative correlations between the number of neutral and charged pions. In fact, the exact conservation of isospin in a pion uncorrelated jet model is known [7,8] to give the same pattern of neutral/charged fluctuations as observed in Centauro events. This strong negative neutral-charged correlation is believed to be a general property of the direct pion emission in which the cluster formation (or the short-range correlation between pions) is not taken into account [9,10,17–19].

In this paper, following the approach of our earlier paper [18], we consider the leading-particle effect as a source of a classical pion field in the impact parameter space. Pions are assumed to be produced from a definite isospin state of the incoming two-particle system both directly and in isovector pairs.

Coherently emitted isovector clusters decay subsequently into pions outside the region of $\pi\pi$ interaction. We discuss the behaviour of the joint probability distribution $P_{II_3}(n_0, n_-)$ of neutral and charged pions, the variation of the two-pion correlation functions f^0_{2,n_-} and the average number of neutral pions ($\langle n_0 \rangle_{n_-}$) as a function of the number of negative pions (n_-) produced.

We support the conclusion of Refs. 18 and 19 that the large isospin fluctuations are consequence of a direct production of pions.

2. *The eikonal S matrix with isospin*

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. We assume that the collision energy is large enough so that the central region is free of baryons.

The basic assumption of the independent pion-emission model, neglecting the isospin for a moment, is the factorization of the scattering amplitude $T_n(s, \vec{b}; 1 \dots n)$ in the b space:

$$T_n(s, \vec{b}; 1 \dots n) = 2sf(s, \vec{b}) \frac{\mathrm{i}^{n-1}}{\sqrt{n!}} \prod_{i=1}^{n} J(s, \vec{b}; q_i), \tag{1}$$

where, owing to unitarity,

$$|f(s,\vec{b})|^2 = e^{-\overline{n}(s,\vec{b})} \tag{2}$$

and

$$\overline{n}(s,\vec{b}) = \int \mathrm{d}q |J(s,\vec{b};q)|^2 \tag{3}$$

denotes the average number of emitted pions at a given impact parameter b. The function $|J(s,\vec{b};q)|^2$, after the integration over b, controls the shape of the single-particle inclusive distribution. A suitable choice of this function also guarantees that the energy and the momentum are conserved on the average during the collision.

The inclusion of isospin in this model is straightforward [6]. The factorization of T_n in the form (1) is a consequence of the pion field satisfying the equation of motion

$$(\Box + \mu^2)\vec{\pi}(s,\vec{b};x) = \vec{j}(s,\vec{b};x), \tag{4}$$

where $\vec{j}$ is a classical source related to $\vec{J}(s,\vec{b};q)$ via the Fourier transform

$$\vec{J}(s,\vec{b};q) = \int \mathrm{d}^4 x e^{\mathrm{i}qx} \vec{j}(s,\vec{b};x). \tag{5}$$

The standard solution of Eq. (4) is usually given in terms of in- and out-fields that are connected by the unitary S matrix $\hat{S}(\vec{b},s)$ as follows:

$$\vec{\pi}_{out} = \hat{S}^\dagger \vec{\pi}_{in} \hat{S} = \vec{\pi}_{in} + \vec{\pi}_{classical}, \tag{6}$$

where

$$\vec{\pi}_{classical} = \int \mathrm{d}^4 x' \Delta(x-x';\mu)\vec{j}(s,\vec{b};x'). \tag{7}$$

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

The coherent production of isovector clusters of pions is described by the following S matrix:

$$\hat{S}(s,\vec{b}) = \int \mathrm{d}^2\vec{e} |\vec{e}\,\rangle D(\vec{J};s,\vec{b}) \langle \vec{e}\,|, \tag{8}$$

where $|\vec{e}\rangle$ represents the isospin-state vector of the two-leading-particle system. The quantity $D(\vec{J};s,\vec{b})$ is the unitary coherent-state displacement operator defined as

$$D(\vec{J};s,\vec{b}) = \exp[\sum_c \int \mathrm{d}q \vec{J}_c(s,\vec{b};q)\vec{a}_c^\dagger(q) - H.c.], \tag{9}$$

where $\vec{a}_c^\dagger(q)$ is the creation operator of a cluster c and the summation $\sum_c$ is over all clusters. The clusters are assumed to decay independently into $c = 1, 2, \ldots$ pions and outside the region of strong interactions.

Clusters decaying into two or more pions simulate a short-range correlation between pions. They need not be well-defined resonances. The more pions in a cluster, the larger the correlation effect expected.

If the conservation of isospin is a global property of the colliding system, then $\vec{J}_c(s, \vec{b}; q)$ is of the form

$$\vec{J}_c(s, \vec{b}; q) = J_c(s, \vec{b}; q)\vec{e}, \tag{10}$$

where $\vec{e}$ is a fixed unit vector in isospace independent of q. The global conservation of isospin thus introduces the long-range correlation between the emitted pions.

3. Distribution of pions in isospace

If the isospin of two incoming particles is II_3 , then the initial-state vector of the pion field is $\hat{S}(s, \vec{b})|II_3\rangle$, where $|II_3\rangle$ is a vacuum state with no pions. The n-pion production amplitude is

$$\mathrm{i}T_n(s, \vec{b}; q_1 \ldots q_n) = 2s\langle I'I'_3; q_1 \ldots q_n|\hat{S}(s, \vec{b})|II_3\rangle, \tag{11}$$

where $I'I'_3$ denotes isostate of the outgoing leading particles. The unnormalized probability distribution of producing $n_+\pi^+$, $n_-\pi^-$, and $n_0\pi^0$ pions is defined as

$$W(n_+n_-n_0, I'I'_3, II_3) =$$

$$= \int \mathrm{d}^2b\mathrm{d}q_1\mathrm{d}q_2 \ldots \mathrm{d}q_n|\langle I'I_3n_+n_-n_0|\hat{S}(s, \vec{b})|II_3\rangle|^2, \tag{12}$$

where

$$n = n_+ + n_- + n_0.$$

Assuming further 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

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

as our basic relation for calculating various pion distributions, pion multiplicities, and pion correlations between definite charge combinations.

In order to obtain some more detailed results for multiplicity distributions and correlations, one should have an explicit form for the source function $J_c(s,\vec{b};q)$, $c = 1, 2, \ldots$.

We shall analyze the isospin structure of our model in the so–called grey–disk model in which

$$\overline{n}_c(s,\vec{b}) = \overline{n}_c(s)\theta(b_o(s) - b), \tag{14}$$

where $\overline{n}_c(s)$ denotes the mean number of clusters of the type c; $b_0(s)$ is related to the total inelastic cross section, and θ is a step function.

4. *Correlation between neutral pions*

We assume that pions are produced both directly and through isovector clusters of the ρ-type.

In order to calculate the first two moments of the joint probability distribution $P_{II_3}(n_0, n_{\_})$, we define the generating function $G_{II_3}(z, n_{\_})$

$$G_{II_3}(z,n_{\_}) = \sum_{n_0,n_+} P_{II_3}(n_+,n_{\_},n_0)z^{n_0}, \tag{15}$$

from which we calculate

$$\langle n_0\rangle_{n_{\_}} = \frac{\mathrm{d}}{\mathrm{d}z}\ln G_{II_3}(1,n_{\_}), \tag{16}$$

$$f^0_{2,n_{\_}} = \frac{\mathrm{d}^2}{\mathrm{d}z^2}\ln G_{II_3}(1,n_{\_}). \tag{17}$$

The form of the generating function $G_{II_3}(z, n_{\_})$ is the following

$$G_{II_3}(z,n_{\_}) = (I+\frac{1}{2})\frac{(I-I_3)!}{(I+I_3)!}\int_{-1}^{1}\mathrm{d}x|P_I^{I_3}(x)|^2\frac{A(z,x)^{n_0}}{n_0!}e^{-B(z,x)}, \tag{18}$$

where

$$2A(z,x) = (1-x^2)\overline{n}_\pi + z(1-x^2)\overline{n}_\rho + 2x^2\overline{n}_\rho \tag{19}$$

and

$$2B(z,x) = \overline{n}_\pi(1+x^2-2zx^2) + \overline{n}_\rho(2-z(1-x^2)). \tag{20}$$

Here $\overline{n}_\pi$ denotes the average number of directly produced pions, and $\overline{n}_\rho$ denotes the average number of ρ-type clusters which decay into two short-range correlated pions. The function $P_I^{I_3}(x)$ denotes the associate Legendre polinomial. Note that $A(1,x) = B(1,x)$.

The total number of emitted pions is

$$\langle n \rangle = \overline{n}_\pi + 2\overline{n}_\rho. \tag{21}$$

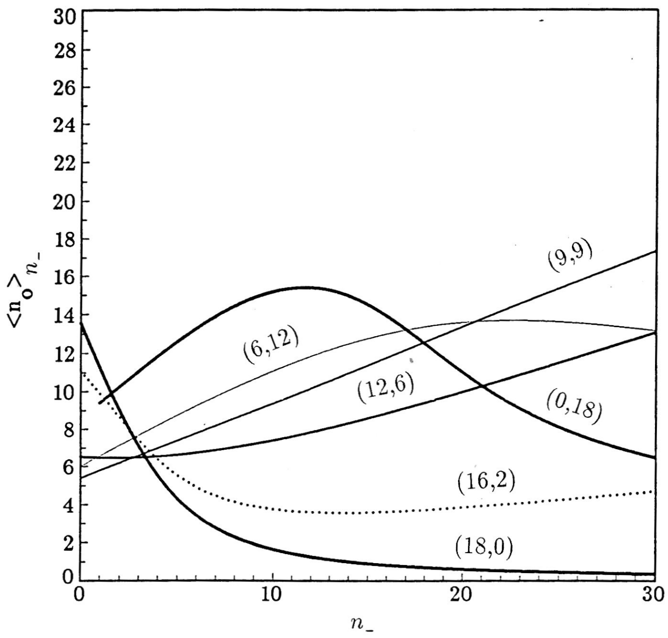

Fig. 1. The average number of neutral pions as a function of the number of negative pions for $I = I_3 = 1$ *and* $\overline{n}_\pi + \overline{n}_\rho = 18$. *The curves represent different combinations of* $(\overline{n}_\pi, \overline{n}_\rho)$, *the average number of directly produced pions and the average number of* ρ*-type clusters, respectively.*

In Figure 1 we show the behaviour of $\langle n_0 \rangle_{n_-}$ for different combination of $(\overline{n}_\pi, \overline{n}_\rho)$ when $I = I_3 = 1$. For Centauro-type behaviour to appear the slope of $\langle n_0 \rangle_{n_-}$ should be negative. However this is only possible if $\overline{n}_\rho = 0$. Recent estimate of the ratio of ρ– mesons to pions at accelerator energies is $\overline{n}_\rho = 0.10\overline{n}_\pi$.

In Figure 2 we show the behaviour of the dispersion $D(n_0)_{n_-}$ which is related to f^0_{2,n_-} as

$$f^0_{2,n_-} = D(n_0)^2_{n_-} - \langle n_0 \rangle_{n_-} \tag{22}$$

again for different pairs of $(\overline{n}_\pi, \overline{n}_\rho)$ and $I = I_3 = 1$. It should be interesting to measure f^0_{2,n_-} as it is a sensitive quantity of the pairing properties of the pions.

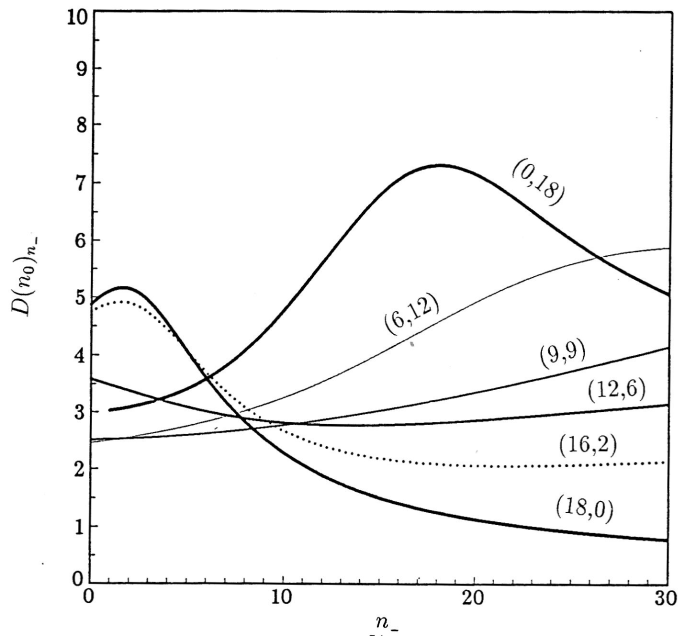

Fig. 2. The correlation function for two neutral pions as a function of the number of negative pions for $I = I_3 = 1$. The curves represent different combinations of $(\overline{n}_\pi, \overline{n}_\rho)$.

5. Conclusion

The results of the present analysis have shown that the emission of isovector clusters of pions in the framework of an unitary eikonal model with global conservation of isospin supresses the large isospin fluctuations of the Centauro-type for pions. This might suggest that Centauro-type effect, if it exists, will probably appear only in very limited regions of phase space where isovector clusters should be missing. How it is possible dynamically is not clear to the present authors. See, however, discussion in Refs. 13–16 and 20.

Acknowledgement

This work was supported by the Ministry of Science of Croatia under Contract No. 1 - 03 - 212.

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IZOSPINSKE KORELACIJE U VISOKO ENERGETSKIM SUDARIMA TEŠKIH IONA

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PACS 25.75.+r, 12.38.Mh, 13.85.Tp, 24.60.Ky

Uz pretpostavku da se pioni produciraju poluklasično, direktno i putem izovektorskih parova ispituje se mogućnost velikih izospinskih fluktuacija u sudarima teških iona kod visokih energija. Učinak vodećih čestica i faktorizacija amplitude raspršenja u prostoru parametra upada koristi se za definiciju klasičnoga pionskog polja. Pomoću raspodjelne funkcije $P_{II_3}(n_0, n_-)$ za produkciju n_0 neutralnih i n_- negativno nabijenih piona iz određenoga izospinskog stanja II_3 ulaznog sistema vodećih čestica izračunat je dvopionski korelacioni parametar f^0_{2,n_-} i srednji broj neutralnih piona $(< n_0 >_{n_-})$ kao funkcije broja produciranih negativno nabijenih piona (n_-). Pokazuje se da samo direktna produkcija piona bez izovektorskih parova vodi na velike izospinske fluktuacije.