Explaining Centauro Events by Formation of Pions in the Isospin Singlet Channel

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(Received 13 October 1993)

Peculiar cosmic ray events (Centauros) with anomalously large fluctuations in their isospin composition have been observed during the past twenty years. Multiparticle symmetrization has been put forward as an explanation of the effect. In this Letter we show how the formation of pions through the sigma channel when combined with symmetrization can lead to a scenario where the isospin distribution is not only broadened but inverted. For reasonable choices of parameters we find that events can actually prefer consisting of either nearly all neutral or all charged pions.

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

Peculiar isospin fluctuations have been observed in cosmic ray events for over three decades and are known as Centauro events [1]. Emulsion measurements have detected tracks from extremely energetic, 10^{14} eV, high-multiplicity, $N \approx 75$, cosmic ray events and determined whether the various particles are charged. If the interaction were hadronic, $\frac{1}{2}$ of the tracks should be neutral. Neutral tracks would originate from the $\frac{1}{3}$ of the hadrons which should be π_0's and then decay into two photons. Charged tracks should correspond to the $\frac{2}{3}$ of the hadrons which were positive or negative pions. A large deviation from the fraction of $\frac{1}{2}$ would be inconsistent with random uncorrelated emission from a source that respects isospin symmetry. Such behavior has indeed been observed and has motivated exotic explanations, from quark droplets to disordered chiral condensates [2].

In 1984 Lam and Lo [3–6] suggested that the large isospin fluctuations were due to the Bose nature of the emitted pions. They considered both the case of emission from a large number of deltas and that of thermal emission, though under the constraint that the source size approached zero. Using diagrammatic techniques [7], the same conclusion was obtained for a thermal Gaussian source of finite size emitting according to symmetrization weights of outgoing particles. Reference [7] demonstrated that such symmetrization enhancements do not require an assumption that a source has somehow equilibrated which would require a long reaction time, but merely that multiparticle trajectories are weighted by outgoing multiparticle wave functions. In this Letter we consider the case where pions are created not singly but in pairs. In particular, we consider the case where pions are created in pairs through the isospin singlet channel. We refer to this channel as the sigma channel, in reference to the sigma meson in nuclear physics. We are only concerned with the fact that the pions are created in isosinglet pairs and not concerned with whether the emission is from the decay of a meson with a specific mass or angular momentum.

We present arguments that in the absence of symmetrization, the isoscalar channel is strong due to isospin constraints, particularly for emission from gluon-induced collisions, and perhaps from coupling to the sigma field which might have rapid fluctuations due to the chiral phase transition. We then show that emission through the sigma channel is enormously enhanced by runaway-symmetrization effects. Using a model where all pions arise from isoscalar emission, we show that Centauro and anti-Centauro events occur readily.

If pions are created singly from a large number of independent sources, the chance that an event with N pions has n_0, n_+, and n_- neutral, positive, and negative pions would be given by a binomial distribution,

$$P(n_0, n_+, n_-) = \frac{1}{Z} \frac{N!}{n_0! n_+! n_-!} \omega(n_0)\omega(n_+)\omega(n_-). \quad (1)$$

Here Z is a normalization and $\omega(n)$ is the average enhancement due to the symmetrization of the outgoing particles. This can be thought of as the averaged multiparticle wave function squared, where the wave function is averaged over all source points as well as all outgoing momenta. The symmetrization enhancement $\omega(n)$ is unity when source sizes are large, but grows as the probability of populating specific momentum states exceeds unity. As the source size goes to zero $\omega(n)$ approaches $n!$. In this limit all isospin configurations are equally probable.

In Ref. [7] it was shown how to calculate such enhancement factors with a diagrammatic technique where independent emission was assumed. The case of Gaussian emission for both momenta and spatial coordinates was shown to be calculable analytically. In this model $\omega(n)$ depends on n, the characteristic momenta Δ, and the spatial extent R of single-particle emission where symmetrization was ignored. The method exactly calculates symmetrization corrections for all $n!$ interference terms. In order for symmetrization effects to be strong many particles must be emitted with momenta less than $1/R$. This is analogous to a local equilibrium picture, where symmetrization effects are strong when many particles have condensed into the ground state. Neglecting symmetrization, single-particle emission has the form

$$S(x, \mathbf{p}) = \delta(t) \exp\left(-\frac{r^2}{2\,R^2} - \frac{p^2}{2\,\Delta^2}\right). \quad (2)$$

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The weights $\omega(n)$ for this case are given by the integrals

$$\omega(n) = \frac{\int d^3p_1 d^3p_2 \cdots d^3p_n d^3r_1 d^3r_2 \cdots d^3r_n \exp\left(-\frac{\sum_i^n r_i^2}{2\,R^2} - \frac{\sum_i^n p_i^2}{2\,\Delta^2}\right) |\phi(\mathbf{r}_1, \mathbf{r}_2 \cdots \mathbf{r}_n; \mathbf{p}_1, \mathbf{p}_2 \cdots \mathbf{p}_n)|^2}{\int d^3p_1 d^3p_2 \cdots d^3p_n d^3r_1 d^3r_2 \cdots d^3r_n \exp\left(-\frac{\sum_i^n r_i^2}{2\,R^2} - \frac{\sum_i^n p_i^2}{2\,\Delta^2}\right)}\,, \tag{3}$$

where ϕ is the n-particle plane wave function with all $n!$ terms. The expression for $\omega(n)$ in Ref. [7] is analytic and exact, but it relies on an iterative procedure which is too lengthy to include here.

For this paper we assume a value of 250 MeV/c for Δ which corresponds to a mean transverse momentum characteristic of high energy collisions. For exploratory purposes this simplified model is sufficient. Figure 1 shows the probability of seeing n_0 neutral pions for four cases, the base distribution, $R = 3$ fm, 1.5 fm, and 0 fm. The $R = 0$ limit is unphysical as it violates the uncertainty principle, but it is interesting as a mathematical limit. The total number of pions created is 78. For each distribution the average number of neutral pions is 26.

Although the enhancements in Fig. 1 represent many orders of magnitude, it is still unlikely that an event with 78 pions will be nearly all charged pions if the source size is chosen reasonably. The smallest reasonable size for such a large number of pions would be about 1.5 fm. For this size, the chance that an event has 0 to 6 neutral pions is still less than 1 in 10^3. By pushing the source size down to 1 fm, the probability of $n_0 \leq 6$ is about 4%, but at 1 fm the pion density at the origin would be $5/\mathrm{fm}^3$.

When pion pairs come from an isoscalar, one-third of the pairs are neutral pions and two-thirds of the pairs consist of one positive and one negative pion. Thus the symmetrizations of charged and neutral pions are on different footings. This makes calculations such as those shown in Fig. 1 difficult. However, if we are interested

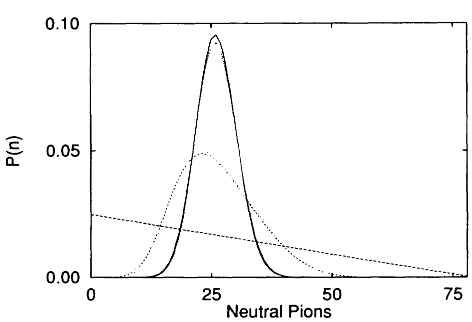

FIG. 1. The probability of seeing a given number of neutral pions assuming 78 pions were emitted independently. The solid line represents the isospin distribution neglecting symmetrization. Symmetrization leads to increasingly broadened distributions for smaller radii, $R = 3$ fm, dotted line, $R = 1.5$ fm, short dashes, $R = 0$ fm, long dashes. Unlike the case of isoscalar emission, the distribution is only broadened and extreme isospin imbalances are improbable unless the source size is extremely small.

in calculating only the probability of seeing a given number of neutral pions, we can rotate the measurement in isospin space such that instead of neutral, positive, and negative pions one measures neutral, x, and y states. We express the creation operators for such states below:

$$x^\dagger(p) = \frac{1}{\sqrt{2}}[a^\dagger(p) + b^\dagger(p)]. \tag{4}$$

$$y^\dagger(p) = \frac{1}{\sqrt{2}i}[a^\dagger(p) - b^\dagger(p)].$$

In this basis an isoscalar decay will lead to two neutral pions, two x pions, or two y pions, all with equal probability. From completeness, one can see that the probability $P(N, n_0)$ of seeing N pions with n_0 neutral pions does not depend on whether the charged pions are measured in eigenstates of charge or in the $x - y$ eigenstates:

$$P(N, n_0) = \sum_{\substack{n_+, n_- \\ n_+ + n_- = N - n_0, \{\mathbf{p}\}}} |\langle\psi|n_0, n_+, n_-, \{\mathbf{p}\}\rangle|^2, \tag{5}$$

where $|\psi\rangle$ is the outgoing many-pion state which in this case is an isoscalar. Conservation of charge does not need to be written into the sum as it will come about from the matrix element.

Since $P(N, n_0)$ includes a sum over all states with a given number of charged particles and since the number of quanta is not affected by the transformation in Eq. (4) we can replace the sum in Eq. (5) over charged states with a sum over x and y states. This is analogous to transforming the basis for polarized light. Charged states correspond to right- and left-handed circular polarizations and x and y states correspond to linear polarizations.

We are now in a position to write down an expression for $P(N, n_0)$ as a sum over all different combinations of n_x and n_y subject to the constraint that n_x, n_y, and n_0 are all even numbers:

$$P(N, n_0) = \sum_{\substack{n_x, n_y = \text{even} \\ n_x + n_y = N - n_0}} \frac{1}{Z} \frac{\frac{N}{2}!}{\frac{n_x}{2}!\frac{n_y}{2}!\frac{n_x}{2}!} \omega(n_x)\omega(n_y)\omega(n_0). \tag{6}$$

This expression relies on a strong assumption. It assumes that correlations between pions from the same resonance are lost. For example, they need not be emitted back to back due to momentum conservation. This assumption of independent emission is necessary only in that it makes the calculation tractable. Including the fact that pions originate from the same point would only increase interference effects. If pions do indeed scatter several times beyond their origin, the assumption of independent emission becomes more reasonable.

As the source size approaches zero, the weights go to $n!$

which means that the weights can overwhelm the $(n/2)!$ terms in the denominator. This leads to distributions favoring extreme isospin fluctuations. This behavior is illustrated in the plot of $P(N, n_0)$ in Fig. 2. Probability distributions are shown for four cases, the base distribution where symmetrization is ignored, $R = 3$ fm, $R = 1.5$ fm, and $R = 0$ fm. The base distribution has twice the variance as the distribution in Fig. 1 which should be the case whenever particles are produced in pairs, as has been discussed in the context of charged particle multiplicity distributions [8]. For the case of $R = 1.5$ fm, emission of 78 pions with only zero to six neutral pions has a 57% probability. The $R = 0$ limit is exactly the same as what one would obtain assuming isoscalar emission with all the pions in one state [9,10].

There is also a large enhancement for the case where a large fraction of the pions are neutral. These are referred to as anti-Centauro events. Since the average number of neutral pions is one-third of the total, in the limit of an extremely bimodal distribution, anti-Centauro events must be half as likely as Centauro events if isospin symmetries are conserved. This type of behavior has been observed experimentally [1,11].

The most pressing question to answer is whether the emission of 78 pions into what must be only a few units of rapidity, and mostly due to isoscalar emission, has more than a vanishing probability. But symmetrization enormously enhances the chance for such an event. The enhancement is the average of $\omega(n_0)\omega(n_x)\omega(n_y)$ for the various combinations that sum to N. For a 1.5 fm source this enhancement is 13 orders of magnitude, and for a 1.0 fm source, 36 orders of magnitude. If the emission of neutral pions at a given multiplicity is determined by a binomial distribution

$$P_0(n_0) = \frac{\frac{N_{\max}}{2}!}{(\frac{N_{\max}}{2} - \frac{n_0}{2})!\frac{n_0}{2}!} p^{\frac{n_0}{2}} (1-p)^{\frac{N_{\max}-n_0}{2}}, \qquad (7)$$

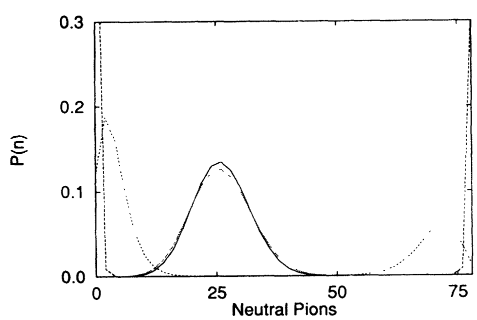

FIG. 2. The same as Fig. 1, except assuming the pions were emitted via isoscalar channels. The solid line represents the isospin distribution neglecting symmetrization. Symmetrization leads to increasingly broadened distributions for smaller radii, $R = 3$ fm, dotted line, $R = 1.5$ fm, short dashes, $R = 0$ fm, long dashes. Compared to the case where pions were emitted singly as in Fig. 1, the initial distribution is broadened and for sufficiently small sources there is a preference for extreme isospin imbalances.

the symmetrization-corrected distribution is

$$P(n_0) = \frac{1}{Z} P_0(n_0)\omega(n_0). \qquad (8)$$

For sufficiently large $N_{\max}$ the symmetrization enhancement ω overwhelms the $(n_0/2)!$ in the denominator. The distribution is then weighted near $N_{\max}$ which is set roughly by energy conservation. This is illustrated in Fig. 3, where both P_0 and P are plotted for the case where $pN_{\max} = 4$ in Fig. 3(a) and for $pN_{\max} = 10$ in Fig. 3(b). For both cases $N_{\max}$ is set to 100 and $R = 1.5$ fm. Of course multiplicity distributions are much more complicated than weighted binomials, but this example demonstrates that the very existence of such high multiplicity events could be the result of symmetrization.

By viewing the $pN_{\max}$ dependence in Fig. 3, one can also get a feeling for how strong the emission from the isoscalar channel must be in order for symmetrization to play a large role in the multiplicity distribution. Unless isoscalar emission would contribute at least a half dozen pions in one or two units of rapidity on average, this mechanism is probably not responsible for Centauro behavior. Given that a high energy hadronic reaction could occur inside a nucleus which is highly Lorentz contracted in the collision's center of mass, it would not be unreasonable to expect roughly a dozen pions per unit rapidity. Isoscalar channels could be responsible for a a good frac-

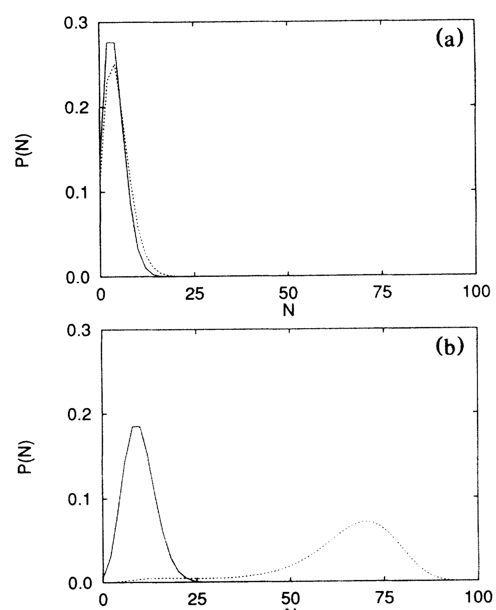

FIG. 3. Multiplicity distributions for binomial distributions, solid lines, and for symmetrization corrected distributions, dashed lines. (a) is for the case where $N_{\max} = 100$, $pN_{\max} = 4$, and $R = 1.5$ fm. (b) is the same except $pN_{\max} = 10$. This demonstrates that symmetrization can strongly affect the multiplicity distribution if isoscalar emission would account for at least a half dozen pions when symmetrization is neglected.

tion of such pions. Pions couple strongly to the sigma meson in many intermediate-energy nuclear physics models. The sigma field, which is also associated with the spontaneous breaking of chiral symmetry, should be rapidly changing due to the chiral transition and therefore radiating pion pairs [2]. Also, the hadronization of gluons should prefer isoscalar channels as gluons carry no isospin.

One question that comes to mind is whether emission through other multipion modes would lead to the same effect. Mesons such as the omega or rho do not decay into two pions of the same isospin, hence symmetrization will not readily enhance emission through those channels. Any structure created from gluons such as a glueball, however, which would have zero isospin and positive g parity, would therefore decay into an even number of pions. One matrix element, M, that describes the decay of an isoscalar into n pions has the structure

$$|M| \propto (\pi_0^2 + \pi_x^2 + \pi_y^2)^{\frac{n}{2}}. \tag{9}$$

This is exactly the same form one would use assuming $n/2$ isoscalar pairs were emitted, however, it is not the only isoscalar matrix element, except in the limit that all the pions have the same momenta. Other matrix elements do not allow all the pions to be in one eigenstate, and since they vanish when the pions have small relative momenta, they will not be greatly enhanced by symmetrization. Thus if we consider the emission of any large number of pions, constraining pions such that they are in an overall isosinglet can lead to smaller symmetrization enhancements and weaker isospin imbalances than enhancements found by constraining them pairwise.

Other behavior should accompany isospin fluctuations as a signal of runaway symmetrization effects. The transverse momenta spectra should have a large component within 100 to 200 MeV/c and the rapidities of the outgoing particles should be bunched into a few units of rapidity. These distortions to the spectra should be especially strong for events with large isospin asymmetries, and they should exist only for pions of the overpopulated flavor.

It is possible that this behavior could not be reproduced at a current accelerator. Colliders can produce proton beams with energies of 10^{12} eV, while Centauro events have energies in the neighborhood of 10^{14} eV. A collider can produce much more center of mass energy than a cosmic ray event, but a cosmic ray might be able to produce more particles in a given amount of phase space because the target for a cosmic ray is often a nucleus. Either the relativistic heavy ion collider under construction at Brookhaven or the Large Hadron Collider at CERN would easily be able to attain equivalent energy densities for nuclear targets. We should point out that a cosmic ray colliding with an atmospheric nucleus near the detector at Chacaltaya excludes a heavy ion as a projectile as the heavy ion would have to travel through many mean free paths of atmosphere before arriving near the detector.

The effects of pair creation for bosons with respect to quantum mechanical coherence is not a new subject. Applications of squeezed light, or two-photon lasers [12], share many of the same principles as the behavior described here. Superfluids are another example where effective Hamiltonians feature terms which create bosonic quanta in pairs. Hawking radiation of boson pairs has been investigated as well [13]. Squeezed pion states have also been studied in the context of relativistic heavy ion collisions [14].

It is difficult to obtain the sort of detailed information from an emulsion measurement that one would get from sophisticated detectors at large accelerator laboratories. This has always been true. Cosmic rays offered the first evidence for pions, jets, and charmed quarks. But, in each case definitive conclusions were not reached until after the phenomena were observed by purely terrestrial means. This may again be the case with Centauro events. By considering isoscalar radiation of pion pairs, we have demonstrated that symmetrization can create laserlike behavior where a large number of pions crowd not only into a small region of phase space in momentum, but also into a single isospin state. Whether this is indeed the explanation for Centauro behavior should be borne out by either further investigation of data from cosmic rays or future generations of accelerator-based experiments.

This work was supported by W. Bauer's Presidential Faculty Fellow Award, NSF Grant No. PHY-925355, and from NSF Grant No. PHY-9017077.

[1] C.M.G. Lattes, Y. Fujimoto, and S. Hasegawa, Phys. Rep. **65**, 151 (1980).
[2] K. Rajagopal and F. Wilczek, Nucl. Phys. **B399**, 395 (1993).
[3] C.S. Lam and S.Y. Lo, Phys. Rev. Lett. **52**, 1184 (1984).
[4] C.S. Lam and S.Y. Lo, Phys. Rev. D **33**, 1336 (1986).
[5] C.S. Lam and S.Y. Lo, Int. J. Mod. Phys. A **1**, 451 (1986).
[6] B. Lacroix and C.S. Lam, Can. J. Phys. **66**, 34 (1988).
[7] S. Pratt, Phys. Lett. B **301**, 159 (1993).
[8] T.T. Chou and C.N. Yang, Phys. Lett. B **135**, 175 (1984).
[9] C. Greiner, C. Gong, and B. Müller, Phys. Lett. B **316**, 226 (1993).
[10] D. Horn and R. Silver, Ann. Phys. (N.Y.) **66**, 509 (1971).
[11] J.D. Bjorken, K.L. Kowalski, and C.C. Taylor, "Observing Disoriented Chiral Condensates," SLAC report, 1993 (to be published).
[12] H.P. Yuen, Phys. Rev. A **13**, 2226 (1974).
[13] R.F. Bishop and A. Vourdas, J. Phys. A **19**, 2525 (1986).
[14] A. Vourdas and R.M. Weiner, Phys. Rev. D **38**, 2209 (1988).