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ABSTRACT

Recent theoretical developments relevant to the search for production of “mis-aligned” vacuum in high energy collisions are reviewed.

1. Introduction

At present Cyrus Taylor and I are co-spokesmen of a small test/experiment¹ which is now being commissioned in the Fermilab collider. The purpose of this program is to search for something called disoriented chiral condensate (dcc). The participants and institutions are listed at the end of this report.

What we mean by dcc is nothing more than a piece of vacuum, chirally rotated from its usual orientation in internal-symmetry space. While the ideas discussed here are speculative, we believe that there is a chance that reasonably large pieces of dcc may be produced in high energy collisions of hadrons, be they pions and nucleons or heavy-ions. In this report I will not describe the experiment, details of which can be found elsewhere,² but rather what has been going on in theory that is relevant to our experimental search. The history of the subject is old, but sparse.³⁻¹² There is at present growing interest in the subject, and a lot has happened quite recently.¹³⁻³³

2. Basic Idea

We consider generic high energy $p-\bar{p}$ collisions which lead to a sizeable multiplicity of produced particles, but not necessarily with high- p_T jets in the final state. The time evolution of such a system is quasi-macroscopic, because the formation or hadronization time for outgoing hadrons can be rather large, 3-5f. Before the hadronization occurs, the initial-state partons, produced in a volume considerably less than a cubic fermi, stream outward at essentially the speed of light in all directions. Most of the outgoing energy/momentum can be expected to be concentrated near the light-cone; i.e. on the fireball surface.

But it is the interior region inside this fireball that is of interest to us. Provided the interior contains not too much residual energy density, it should be something like vacuum, and therefore must carry with it a chiral order parameter $\langle 0 | q_L \bar{q}_R | 0 \rangle \neq 0$ associated with the near-degeneracy of the strong vacuum with re-

spect to $SU(2)_L \times SU(2)_R$ chiral rotations. However, there is little if any reason why the chiral order parameter inside the hot expanding shell of collision debris should be the same as that found in the ordinary vacuum on the outside. The extra energy density from the intrinsic symmetry breaking is small,³⁴ although—as we shall see—the nonvanishing pion mass, a direct measure of the strength of intrinsic chiral-symmetry breaking, does affect potential observables in a very significant way. But in any case it is possible to entertain the notion that well inside the light-cone the chiral vacuum (using the well-known $O(4)$ σ -model language) does not point in the σ direction, but rather in one deflected toward one of the π directions. Then at late times this disoriented vacuum (the dcc) will relax back to ordinary vacuum, radiating away the difference via its collective modes (pions).

The most important feature of this radiation is its semiclassical, coherent nature. This leads to the expectation of anomalously large fluctuations event-by-event in the ratio of the number of charged-pions to neutral-pions produced. If the event-by-event deviation of the chiral orientation from the σ direction is random, it follows that the distribution of neutral fraction

$$f = \frac{N_{\pi^0}}{N_{\pi^+} + N_{\pi^-} + N_{\pi^0}} = \frac{N_{\pi^0}}{N} \quad (1)$$

is inverse-square-root, as N becomes large:

$$\frac{dP}{df} = \frac{1}{2\sqrt{f}}. \quad (2)$$

This result was found⁷ already in 1983 and has been independently rediscovered many times in the interim.^{9,10,11,12,27} If f is very small for a given event, then one has Centauro behavior. For f near 1, there is “anti-Centauro” behavior: many photons, very few charged hadrons. Both extremes are claimed to be seen in cosmic-ray data.^{35,36} Equation (2) forms the basis for our experimental search. For larger and larger sample multiplicities N , the probability of finding extreme values of f via normal (binomial-distribution) fluctuations falls exponentially, while the dcc mechanism predicts a nonvanishing limiting value.³⁷

3. Geometry and Dynamics

The description of the space-time evolution of the dcc produced in a high-energy collision is most naturally attacked via classical or semiclassical methods. The main tool which has been used is the nonlinear and/or linear σ -model: the strong-interaction analog of the standard-model description of the Higgs sector in electroweak theory. At the classical level, the description naturally begins at some small proper time near the light cone, where the evolution of the system has proceeded enough to allow the meaningful introduction of σ and π collective coordinates.³⁸ If the viewpoint of Manohar and Georgi³⁹ is accepted; namely, that the mass-scale for which the chiral effective action (σ -model) can be used extends

to 1 GeV or so, then this initial proper time might be quite small, of order 0.2–0.3*f*. On this proper-time surface the initial condition of the chiral field

$$\Phi = \sigma + i \vec{\tau} \cdot \vec{\pi} \quad (3)$$

can be expected to be noisy, but with an average $\langle \Phi \rangle \sim 0$, i.e. “on the top of the Mexican-hat potential”

$$V = \lambda(\Phi^\dagger \Phi - f_\pi^2)^2 . \quad (4)$$

As proper time increases, one may expect—and detailed calculations show^{19,21,27,29}—that the field Φ promptly “rolls” into its minimum with

$$\langle \Phi^\dagger \Phi \rangle \sim f_\pi^2 . \quad (5)$$

In addition Rajagopal and Wilczek show²⁷ via numerical simulation that much of the original initial-state energy finds its way into long-wavelength modes. This has been interpreted by Huang and Wang²¹ in terms of linear σ -model mean-field theory. During the rolling phase the pion mass is imaginary, leading to unstable growth of the Goldstone modes, and especially of the low-momentum modes.

All this is suggestive that the interior of the double-cone region of space-time shown in Fig. 1 may, in the limit of exact chiral symmetry, relax into a disoriented vacuum. At late times, the inside of the interior forward light-cone has relaxed back to ordinary vacuum, while the region between the two light cones contains the Goldstone-boson (pion) radiation field, all of which in a given event has the same (Cartesian) isospin.

This entire picture is concretely implemented in the nonlinear σ -model, where a set of classical solutions found by Anselm⁹ and others^{10,12} has the form

$$\Phi(x) = U_L f_\pi e^{i\tau_3 \pi(x)} U_R^\dagger \quad (6)$$

with (in the chiral limit)

$$\square \pi(x) = 0 \quad (7)$$

except on the light-cone at those early times $t \leq T$ which are prior to hadronization. This “Abelian” version of the theory is rather easily visualized, and for simple enough geometries exact solutions can be found. Generalizations to the linear σ -model lead to similar results.^{19,20,29,32}

Pion mass effects are readily included in the description. In the nonlinear σ -model one reverts from the free massless wave equation to essentially a sine-Gordon equation instead. A major effect is to introduce a phase-oscillation $e^{+im_\pi \tau}$ into the field Φ . So at proper times large compared to m_π^{-1} , the condensate is washed out; essentially it has evolved into the radiation field of massive pions.^{19,29} At proper times small compared to m_π^{-1} , the pion-mass effects can be neglected. What all this implies is that at a proper time somewhere around (1-2) m_π^{-1} , one should simply decompose the dcc field into physical-pion normal modes and let them propagate out to infinity as free non-interacting states. But at earlier proper times the σ -model description (with exact chiral symmetry) should be adequate.

As shown in Fig. 2, this leads to two cases which have distinct space-time evolution, corresponding to whether the time the source is “on” is short or long in comparison to m_π^{-1} . Probably the latter choice is the most appropriate. But more study of each case is needed.

Several interesting geometries have been by now investigated in some detail. However these have a lot of symmetry, while for experimental reasons there is, as we shall see, reason to look at the less symmetric solutions. The description most relevant to our experiment expresses the pion field in terms of the lego variables, η , ϕ , the (transverse) distance ρ from the collision axis, and of course the time t . The source distribution can likewise be characterized in terms of these variables as well. We assume here that it has support only on the light cone, while the pion field is nonvanishing everywhere within the light cone. Upon using these variables, one may without loss of generality only consider the (massless) pion field emitted at 90° from the collision axis at $\phi = 0$. All other values can be obtained via longitudinal boosts and azimuthal rotations. It then follows that the field π appearing in Eq. (6) is obtained from solving

$$\square\pi(x) = S(x) . \quad (8)$$

We visualize the source function as a sum of contributions (with uniform measure) from different regions of the lego plot and, for a given η and ϕ , from a sequence of values of transverse radii ρ (again with uniform measure). So we write

$$\begin{aligned} S(x) &= \sum_i S_i \delta^4(x - x_i) \\ &\Rightarrow \int d\rho' d\eta' d\phi' S(\rho', \eta', \phi') \delta^4(x - x') \end{aligned} \quad (9)$$

with

$$x' = (\rho' \cosh \eta', \rho' \sinh \eta', \rho' \cos \phi, \rho' \sin \phi) \quad (10)$$

and of course

$$x = (t, 0, \rho, 0) . \quad (11)$$

It follows that

$$\pi(x) = \int d\rho' d\eta' d\phi' S(\rho', \eta', \phi') D_{\text{ret}}(x - x') . \quad (12)$$

After a short calculation (and then dropping primes), one finds

$$\pi(t, \rho, 0, 0) = \frac{1}{4\pi} \int \frac{d\eta d\phi}{(t \cosh \eta - \rho \cos \phi)} S\left(\frac{(t^2 - \rho^2)}{2(t \cosh \eta - \rho \cos \phi)}, \eta, \phi\right) . \quad (13)$$

At large times, near the light-cone, when

$$(t - \rho) \ll (t + \rho) \quad (14)$$

this reduces to a more transparent form:

$$\pi(t, \rho, 0, 0) = \frac{1}{4\pi\rho} \int \frac{d\eta d\phi}{(\cosh \eta - \cos \phi)} S\left(\frac{(t - \rho)}{(\cosh \eta - \cos \phi)}, \eta, \phi\right) \quad (15)$$

Assuming that S is a reasonably smooth function, the important feature of this expression is that there is a strong short-range rapidity correlation between pion field and source. This is to be expected, since all degrees of freedom are spinless, and only elementary vector exchanges (or Regge singularities with $J \geq 1$) can generate long-range rapidity correlations. Thus the spacetime region over which the chiral orientation can be expected to remain coherent may be limited to $(\Delta\eta, \Delta\phi) \lesssim 1-2$; and $\delta\tau \lesssim (1-2)m_\pi^{-1}$, unless somehow the physics of the “soft” Pomeron is closely related to chiral dynamics.⁴⁰ This would have to be expressed by way of a singular behavior of the source at early times. Putting that speculation aside, the visibility of the dcc which can be produced will depend in an important way on the residual factors 2 uncertainty in the above guesstimates for correlation lengths.

What we do conclude from this line of argument is that the radiated dcc is a kind of “wake-field” following behind the collision fireball-shell, as shown in Fig. 3. Shown there is the structure of the wake-field and the nature of the underlying dynamics as best as I can see it at present.

One feature of experimental importance is that the groups of coherently emitted dcc pions may have a net transverse drift velocity v_\perp .¹⁶ That is, the rest-frame of the group of observed pions may be in transverse motion relative to the beam axis. If this v_\perp is comparable to the mean internal velocity $\langle v \rangle$ of the pions (evaluated in the rest-frame of the group) then a majority of the laboratory-frame pions will be collimated into a “coreless jet.” Because the area from which the pion group is emitted may be several square fermis, the mean internal velocity $\langle v \rangle$ may be semi-relativistic or even non-relativistic. This implies the relative p_T of the pions in the ‘coreless jet’ may be under 100 MeV. It is interesting that this phenomenon of coreless jets is claimed to be seen in the cosmic-ray data.³⁵ The Chacaltaya group has, by chance, even dubbed this phenomenon “Chiron.”⁴¹ Perhaps this choice of name is a felicitous one.

There is clearly still a lot to do at the classical level. I have only taken a cursory look (Fig. 3) at solutions such as Eq. (15), appropriate for the Anselm class of solutions to the nonlinear σ -model. It would be interesting to have a thorough look, including a repeat using, at the least, the mean-field linear σ -model. It would then be interesting to study, at first perturbatively, correlations in the evolution of two pieces of dcc in different regions of the lego plot. Do they “attract” or “repel?” Does the presence of dcc in one region of the lego plot stimulate production in neighboring regions? If so, a Regge-like dependence of dcc production on cms energy might conceivably emerge.

4. Quantum Effects

The expression of these classical ideas in quantum terms is most naturally done in terms of coherent states^{6,7,12,26} or squeezed states.²⁴ One may formally construct these by exponentiating the field (or its square) and then by averaging over isospin orientations (with or without a weight function; it makes not much

difference).³¹

Taking matrix elements of such an operator between vacuum and an N -pion state yields the inverse-square root distribution, Eq. (2), as N becomes large. This is essentially the original way the inverse square root formula was derived.⁷

Less clear is whether such a coherent state is really *created* as a consequence of the dynamics. I am not aware of much work which addresses this. Perhaps a tractable starting point would be investigation of the Blaizot-Krzywicki boost-invariant 1+1 dimensional geometry,¹⁰ using the linear σ -model treated at the quantum level in the mean-field approximation, instead of the classical non-linear sigma model. The recent work of Blaizot and Krzywicki²⁹ on the linear σ -model treated classically appears to be an excellent starting point. If that program were to work, it might then be not too large a step to generalize the calculation to the wake-field geometry leading to Eq. (15).

In any case, it is clear that much progress has been made, and that there is much left to be done. I feel that the theoretical understanding of dcc has progressed to a point where in the not-too-distant future it may be possible to create simulations of the production process realistic enough to be used in the interpretation of our experiment.

5. Participants in Fermilab Test/Experiment T864

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7. Figures and Captions

Fig. 1: Space-time evolution of disoriented chiral condensate.

Fig. 2: Pion mass effects: (a) short hadronization time and (b) long hadronization time.

Fig. 3: Structure of the dcc “wake-field.”

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41. In Greek mythology Chiron is an important centaur; it is also a constellation found near Centaurus. I thank Professor S. Hasagawa for this explanation.