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T/E

BAKED ALASKA

J. D. BJORKEN[★]

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

and

K. L. KOWALSKI AND C. C. TAYLOR[†]

Department of Physics
Case Western Reserve University
Cleveland, Ohio 44106

ABSTRACT

We speculate that, in the interiors of large "fireballs" produced in very high-energy collisions, vacuum states of the strong interactions are produced with anomalous chiral order parameters. If true this can lead to anomalously large fluctuations in the charged-to-neutral ratio of produced hadrons (Centauro and anti-Centauro behavior). We also discuss strategies for an experimental search.

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1. Introduction

Most people know Baked Alaska as a dessert. Ice cream is covered with meringue, and quickly baked in a hot oven such that the ice cream does not melt. We shall be discussing a system hot on the outside and cold on the inside; hence the name. The appellation is borrowed from a similar phenomenon occurring in condensed matter physics. This, and yet another reason for the title, will be mentioned at the end of the talk.

This work[1,2] has benefitted from an early assist from M. Weinstein. Other related work is by Anselm and Ryskin[3], by Blaizot and Krzywicki[4], and by Rajagopal and Wilczek[5]. It has been stimulated by data, in particular cosmic-ray emulsion events[6,7] .

2. Baked Alaska in Hadron-Hadron Collisions

We consider those hadron-hadron collisions at collider cms energies for which there is an especially large (non-jetty) transverse-energy release. In this high-multiplicity, high-E_T situation, the collision debris will expand outward from the collision region at the speed of light for a considerable distance (a few fermi) before decoupling into distinguishable hadrons (Fig. 1).

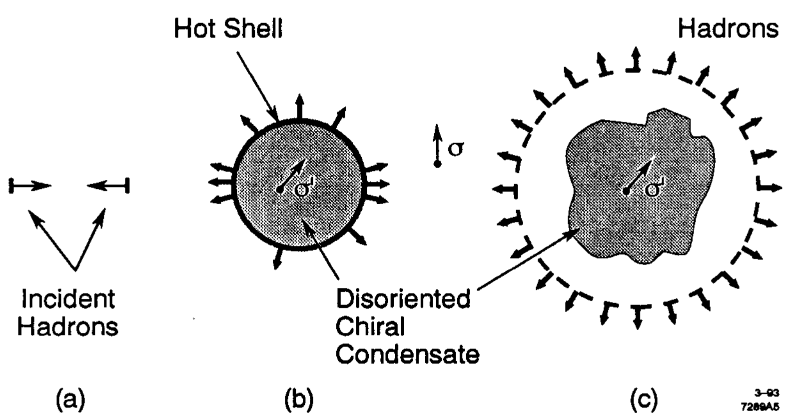

Figure 1. Evolution of a high multiplicity, high energy collision: (a) before, (b) during, and (c) after.

We presume that the energy is carried outward from the original collision region at the speed of light, so that the geometry at intermediate times is that of a hot, thin shell with a relatively cold interior. We do not presume local thermodynamic equilibrium in this dynamics. Indeed the opposite extreme of free-streaming produces a hotter, thinner shell and a colder interior, although our picture is not so bad even for ideal hydrodynamic expansion[8].

What is of interest to us here is not the outer hot shell, but the interior cold region, which relaxes back to something akin to vacuum. And what will be central to what follows is *which* vacuum. The strong-interaction vacuum is almost degenerate owing to the approximate $SU(2)_L \times SU(2)_R$ chiral symmetry. This symmetry is spontaneously broken in a way analogous to what is supposed to occur in the Higgs sector. This phenomenon is described by the chiral fields

$$\Phi = \sigma + i\vec{\tau} \cdot \vec{\pi} \quad \Leftrightarrow \quad q_L \bar{q}_R \tag{1}$$

where

$$q = \binom{u}{d} \tag{2}$$

and

$$\langle \Phi \rangle = \langle \sigma \rangle = f_\pi \neq 0 \ . \tag{3}$$

The fields $(\sigma, \vec{\pi})$ form an $O(4)$ 4-vector. Now suppose that in the interior of the hot shell the vacuum orientation differs, and is tilted into one of the pion directions

$$\langle \sigma \rangle = f_\pi \cos\theta \qquad \left\langle \vec{\pi} \right\rangle = f_\pi \widehat{u} \sin\theta \ . \tag{4}$$

Here $\widehat{u}$ is a unit vector, and f_π is the pion decay constant. The extra energy cost comes from the pion mass term in the effective Hamiltonian,

$$\Delta E = \frac{1}{2}\mu_\pi^2 \left\langle \vec{\pi}^2 \right\rangle = \frac{1}{2}\mu_\pi^2 f_\pi^2 \sin^2\theta = (10\ MeV/fm^3)\sin^2\theta \ , \tag{5}$$

and is not very large. Thus there is little reason to *expect* the interior vacuum chiral orientation to be identical to the exterior orientation.

A bubble of disoriented vacuum in isolation would collapse, owing to the energy residing on the bubble surface. In this situation, however, that surface energy is overwhelmed by the energy contained in the hot shell, allowing the interior disoriented chiral condensate to survive until the shell decouples and hadronizes. Then the interior vacuum has to straighten out, and radiate away its pionic orientation. This radiation is the observable of interest. It will be coherent, semiclassical, and event-by-event of a given (cartesian) isospin. In other words, in some events the deflection of the vacuum orientation may be in the π^0 direction, in which case all of the condensate radiation will be π^0's. In other events the deflection will be orthogonal to the π^0 direction, in which case all the emitted pions will be charged. The latter case is Centauro behavior, while the former can be called anti-Centauro. In addition, these coherent pions are emitted from a large volume, implying low-p_T. This behavior is called Chiron by the cosmic-ray community[6].

3. Space-Time Geometry

Let us now build up a more detailed space-time description. Away from the light cone sources are absent, and the equations will be those governing the behavior of the σ and $\vec{\pi}$ fields, usually given by the σ-model. (This in turn looks just like the standard-model Higgs Lagrangian.)

At large distance (low momentum) scales the dynamics of the massive σ field is frozen out, while the low energy interactions of the pions are not strong. Let us for the moment neglect them. We then have free propagation except where the hot source exists—on (or very near) the light cone. Neglecting the pion mass and isospin , we have

$$\Box\pi \cong S(t)\,\delta(t^2 - \vec{x}^{\,2}) \ . \qquad (6)$$

A one-dimensional slice is shown in Fig. 2.

Radiation emitted from the sources fills the two far-zone regions R. The near-zone C is where the purported condensate will reside, due to a constant average source $S(t) = \overline{S}$. Note that once the information that the source is turned off arrives in the center of the light cone, the region V relaxes back to normal vacuum.

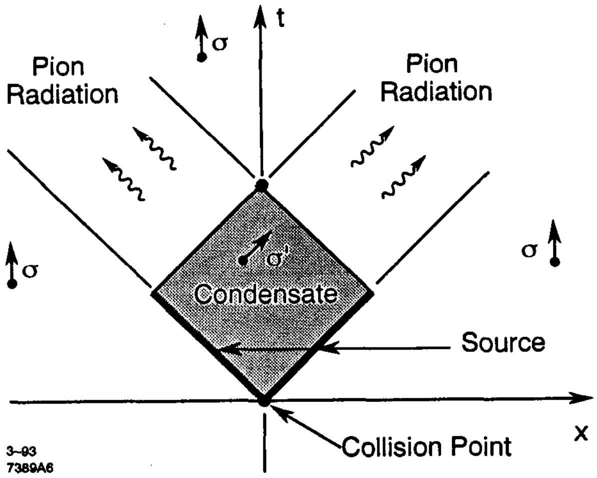

Figure 2. Space-time evolution of (massless) pion radiation from a source on the light cone in 1+1 dimensions.

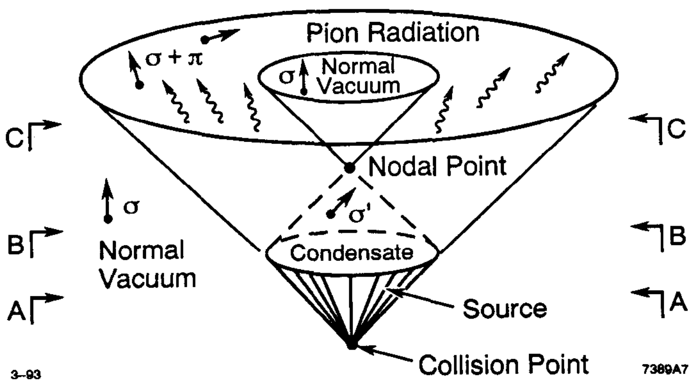

Figure 3. Figure 2, now in 3+1 dimensions.

The 3-dimensional picture is similar and is shown in Fig. 3, assuming spherical symmetry. The field at any point P in the interior of the light cone is determined by placing a past light cone with vertex at P and summing the source contributions along the intersection of the light cones. A special point is the nodal point, whose past light cone intercept the source just as it is turned off. The region within that light cone and the light cone from the collision point contains the disoriented condensate.

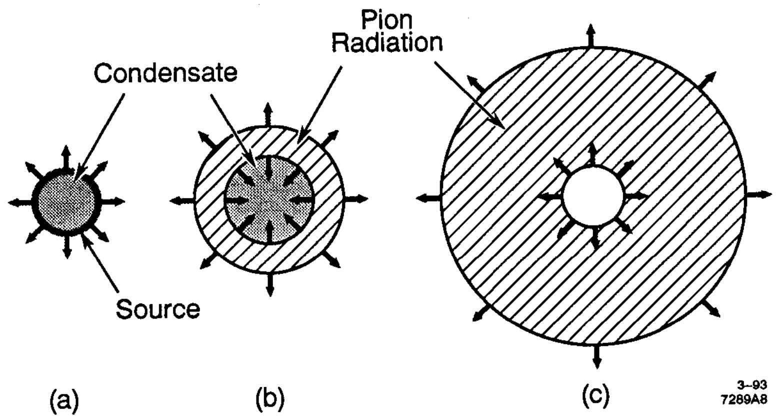

Figure-4. Three time slices A, B, and C of Fig. 3.

Three time slices of this picture are shown in Fig. 4. At early times one sees the condensate contained within the source, expanding out at the speed of light. Later the condensate is surrounded by radiation. At the boundary between them, an imploding information wave heralds the fact that the source is turned off. Still later, after the "nodal time," the ordinary vacuum is found within the outgoing shell of coherent pion field.

While the detailed dynamics is most certainly more complicated than this sketch, much of the overall global geometry we have described may survive the complications. Some of the features which may be generic are the following:

1. Excitations of the chiral condensate are naturally just the Goldstone modes—namely pions.

2. The process is semiclassical.

3. This means the emitted pions are *coherent* (there will therefore be *no* Bose-Einstein enhancement for this component)[9].

4. Event-by-event we may view the condensate as having a definite (Cartesian) isospin; this leads to large charged-to-neutral fluctuations (Centauro and anti-Centauro behavior).
5. The emission volume is very large.
6. Consequently the mean p_T of emitted pions will be low—probably *nonrelativistic* in the condensate rest frame.
7. The signal (number of coherent pions) grows as R^3, where R is the decoupling radius; the background from the hot shell grows as R^2.
8. Consequently signal/noise $\sim R \sim (dN/d\eta)^{1/2}$.
9. There can be expected to be anomalous charge fluctuations if the cartesian isospin of the condensate has a component orthogonal to the π^0 direction. This may lead to extra sources of inner bremsstrahlung and low-mass dileptons.

However all of these suppositions invite a much more critical examination.

4. Open Questions

There are a lots of issues to be addressed, and we have not done much more than identify a number of them. It seems clear that even if the idea is right, there are so many uncertainties that progress will have to be data-driven. Much of our attention thus far has been to examine the strategies for serious experimental study of these ideas, and indeed to try to stimulate the experiments themselves. Consequently, advancing the status of the underlying theory has suffered.

We now survey some of the complications and what can be said about them:

i) The real equations are nonlinear; what happens when that is taken into account?

Thus far, not much has been done in the 1+3-dimensional case of experimental interest. However, Blaizot and Krzywicki[4] have made a very interesting investigation of a 1+1 dimensional case. They assume a heavy-ion, central-plateau, boost-invariant geometry with boost-invariant boundary conditions[10], and neglect pion mass. They use the nonlinear σ-model to calculate the classical pion-field in the region between the colliding ions. They find that the chiral orientation *precesses* with increasing proper time (Fig. 5). This precession is driven by the nonlinear coupling of the central condensate to the receding neighboring condensates which are in an earlier state of evolution, owing to relativistic time dilation.

Formally the precession comes about as follows. Using a nonlinear realization for the chiral field

$$\Phi = \sigma\, e^{i \vec{\tau} \cdot \vec{\pi}} \tag{7}$$

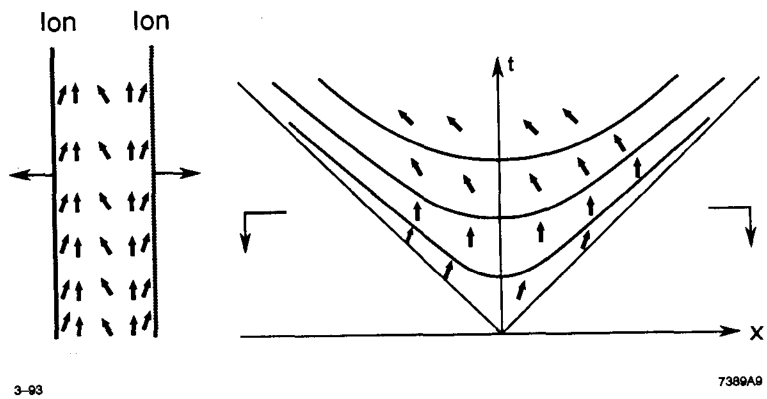

Figure 5. A cartoon of the precession of the chiral vector in a 1+1 dimensional solution of the σ-model found by Blaizot and Krzywicki.

one finds a constant $|\sigma| = f_\pi$ everywhere, so that the pion field freely propagates

$$\Box \vec{\pi} = 0 \ . \tag{8}$$

This means that $\vec{\pi}(t,x)$ is a sum of left-moving and right-moving pieces:

$$\vec{\pi} = \vec{\pi}_R(t-x) + \vec{\pi}_L(t+x) \ . \tag{9}$$

But because of the assumed boost-invariant boundary condition it is also only a function of proper time $\tau = \sqrt{t^2 - x^2}$. The only function with this property is the logarithm, so

$$\vec{\pi}(t,x) = \vec{\pi}_0 \, \ell n \left(\frac{t^2 - x^2}{\tau_0^2} \right) \tag{10}$$

and

$$\underset{\sim}{\Phi} = \underset{\sim}{f_\pi} \left(\frac{t^2 - x^2}{\tau_0^2} \right)^{i \vec{\tau} \cdot \vec{\pi}_0} \quad . \tag{11}$$

ii) How does the effect depend on a source which is not spherically symmetric?

In almost all collinear reference frames there is a lot more energy propagating in the beam directions than at 90°. How does this affect the situation?

It seems reasonable to assume that the source strength scales with $dE_T/d\eta$ or $dN/d\eta$. However it is a *scalar*, not vector source. Imagine at $\eta = 0$ it is a sum of δ-function pulses of standard strength separated by a certain time interval Δt:

$$\Box \pi = \sum_n S \, \delta^4(x - x_n) \qquad t_n = n \Delta t \cong |\vec{x}_n| \ . \tag{12}$$

Then sources at large rapidity will be weakened by relativistic time dilation; the time interval between pulses is $e^{|\eta|} \Delta t$ and the contribution to the pion field in the center of the light cone goes like $e^{-|\eta|}$ relative to the contribution at $\eta = 0$.

iii) How does the effect depend upon an angular asymmetry in the source strength?

In general we cannot expect the source on the light cone which creates the disoriented condensate to be the same in all directions. For example, suppose at $\eta = 0$, $\phi = \pi$ the decoupling time is earlier than at $\eta = 0$, $\phi = 0$. Then a transverse boost can be applied to equalize the decoupling times (Fig. 6). It is in this frame that we can expect the emitted coherent pions to be (on average) at rest, and the nodal point, where the imploding information-waves converge, to lie on the time-axis. In the laboratory frame the condensate moves *toward* the strong source (cf. Fig. 7), and its mean four-velocity is measured by the four-vector describing the nodal point.

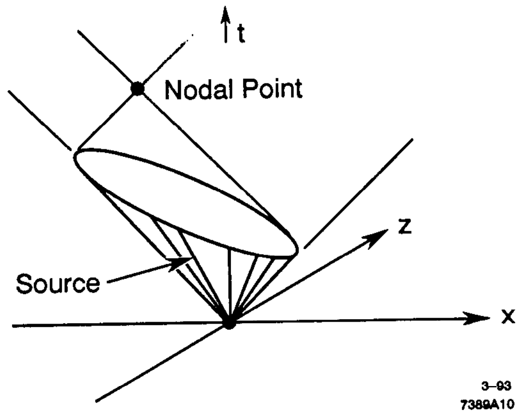

Figure 6. Effect of an azimuthally asymmetric source? The space-time picture in the laboratory frame.

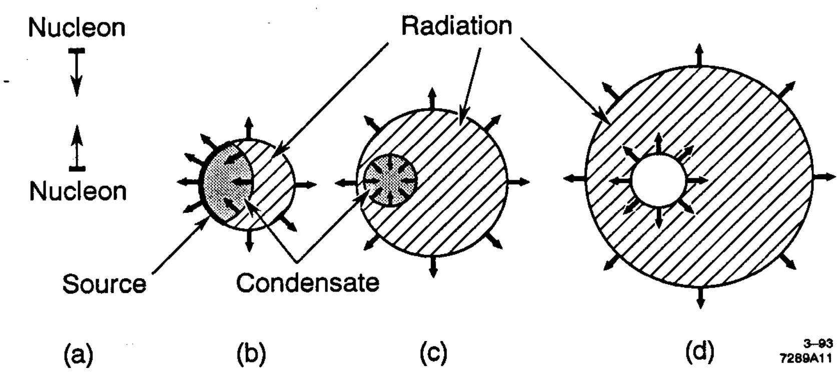

Figure 7. Time slices of the collision (a) before, (b) during, (c) later, and (d) after.

This nodal point can be constructed in each collinear reference frame, and serves as a useful marker for the expected condensate four-velocity as function of η and ϕ (cf. Fig. 8).

If significant transverse flow occurs, say $v_\perp \gtrsim 0.5$ (why not?), there is an interesting consequence for the phenomenology, provided the emitted pions are indeed non-relativistic in the condensate rest frame. They will be focussed into a "coreless jet" in the laboratory frame of reference (Fig. 9), with half the pions found within a cone angle

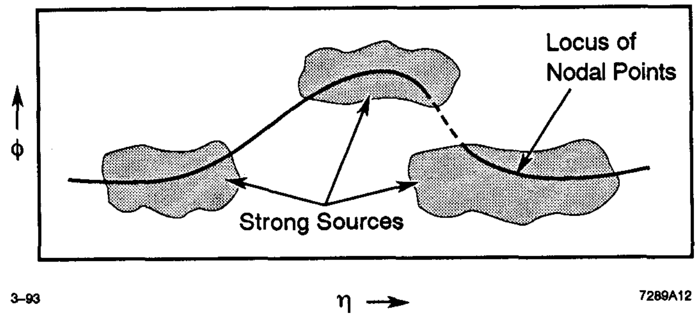

Figure 8. Schematic of the locus of the nodal-point velocity directions in the lego plot. Chiral condensate can be expected to be found near that path.

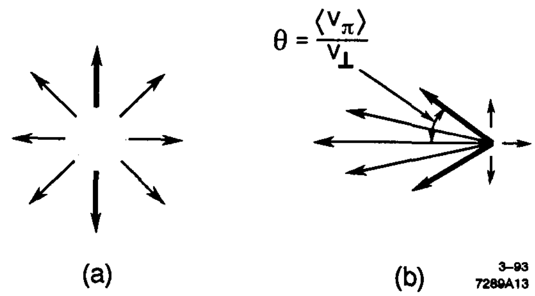

Figure 9. Effect of a transverse drift velocity $v_\perp$ on the laboratory velocities of the chiral-condensate pions: (a) condensate rest frame, (b) laboratory frame. Non-relativistic pions are here assumed.

$$\theta = \frac{\langle v_\pi \rangle}{v_\perp} \tag{13}$$

which could be less than unity in favorable cases. This is the Chiron behavior claimed to be seen in cosmic-ray events[6].

iv) What happens in the leading-particle regions?

The leading-particle regions are where the cosmic-ray evidence exists. It is possible that the signal/noise is most favorable in that case, because the "hot shell" has a hole in it in the beam-fragment direction (Fig. 10). The multiplicity of leading particles is limited by energy-momentum conservation. On the other hand, the coherent pions are soft, and carry relatively little energy but quite a lot of entropy. They may therefore leak out the forward-direction hole in the hot container and be seen relatively background-free.

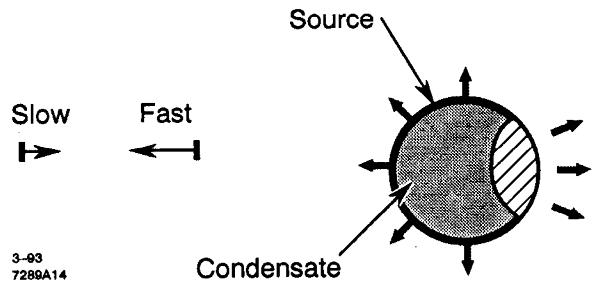

Figure 10. A possible geometry in the beam direction. We are in a reference frame (a) when the right-mover has low momentum (10-30 GeV) and the left mover has very high momentum. The multiplicity in the right-moving beam direction is limited by momentum conservation, so that the condensate signal may be more easily seen.

v) Is there "texture" in the lego plot?

If the source of disorientation is linked to perturbative branching processes, it may have a self-similar structure leading to patchiness and "texture" in the condensate itself. In addition there could be domains and domain walls in the interior region.

We have not done more than worry about this problem. However, recently Rajagopal and Wilczek[5], motivated by arguments that the deconfining phase transition is second-order, have considered the effect of long-range correlations near the phase transition on fluctuations in the charged-to-neutral ratio. They have in particular looked into the question of textures and argue that the σ-model dynamics implies a rapid smoothing of small-scale textures into large-scale ones. This most dramatically occurs in an out-of-equilibrium "quench" from a hot initial state to a "cold" vacuum-like final state similar to the picture we use here. The theoretical technology for investigating this is similar to what is used in studies of large-scale structures in the universe[11], and more work is in progress.

vi) What about chiral symmetry breaking?

It will have been noticed that we have been quite schizoid in our description of the condensate, half the time assuming it to be extreme relativistic and the other half of the time to be nonrelativistic. Does this make sense?

Some numerical work has already been done which indicates that the effect of pion mass on the dynamics at early times (i.e. before the nodal time; in region C of Fig. 3) is not large. Only at large times, in the radiation zone, does the effect of the mass become dominant.

Note that the energy and entropy radiated away vanishes in the chiral-symmetry limit

$$E_{\text{coh}} \sim \left(\frac{1}{2}\, m_\pi^2 f_\pi^2 \sin^2\phi\right)\cdot\left(\frac{4}{3}\,\pi R^3\right) \approx m_\pi N_{\text{coh}} \tag{14}$$

so that these questions really matter. More work does remain to be carried out.

It is not clear at what pion mass scale the trouble begins. Were the pion mass 1.4 MeV instead of 140 MeV, it might be hard to raise objections. So the question becomes one of determining the mass scale at which the phenomenology breaks down. Some candidates are f_π, $4\pi f_\pi$, r_π^{-1}, $m_q = 350$ MeV, $m_\rho \sim m_\sigma \sim 700$ MeV.

vii) What about other degrees of freedom beside pions?

Constituent quarks have a large Yukawa coupling to the pion field and are known to have an important effect on the σ-model description of the chiral limit of QCD. They may be an important "impurity" in the chiral condensate. However, we must keep in mind that the interior volume need not be pure QCD vacuum, but only "cold" enough to possess the order parameter $\langle\Phi\rangle$ of the spontaneously broken chiral phase of QCD.

viii) What is the nature of the source?

This question is still mysterious. Single-particle transition currents will not do, and some collective coordinates probably need to be found. In particular one needs an idea as to what source parameter determines the strength and direction of the chiral disorientation.

ix) What about charge conservation?

The semiclassical state which we describe is a very peculiar one: if the cartesian isospin points in any direction other than the π^0 direction, it is not an eigenstate of electric charge; only the average charge is zero. There is a troublesome question of principle involved here.

However it is possible to construct a coherent (semiclassical) quantum state which is electrically neutral, and which in fact has a (sharp) isospin of zero. This is accomplished by[2] first constructing a coherent state which points in a given cartesian isospin direction $\hat{\eta}(k)$

$$\left|\vec{\eta}\right\rangle = \exp \int d^3k\, \vec{a}^{\dagger}(k) \cdot \vec{\eta}(k)\,|0\rangle \ , \tag{15}$$

where as usual $\vec{a}^{\dagger}(k)$ is the piece of pion field containing creation operators. Then one averages over isospin orientations of $\vec{\eta}$

$$|\eta\rangle = \int d\Omega_{\hat{\eta}} \left|\vec{\eta}\right\rangle \ . \tag{16}$$

As will be discussed later, this state, when restricted to a single space-time mode

$$\vec{\eta}(k) = \hat{\eta} f(k) \ , \tag{17}$$

and then projected onto a configuration with definite particle number, expresses the same pattern of charged/neutral fluctuations as what we conjecture for the classical limit.

Still unknown is the mechanism, if any, which can dynamically produce such a state in the course of a high energy collision.

5. General Inferences and a Cosmic Ray Example

Despite all the uncertainties, we are tempted to draw some tentative inferences on what is necessary to mount an experiment search[12]:

i) First one should search for concentrations of pions in a patch in the lego plot which are unusually rich (or poor) in π^0's.

ii) The optimal size of the patch in the lego plot for seeing the effect is not obvious; a variety of choices must be made.

iii) A cut from above on the p_t (e.g. $p_t < 100$ MeV) of the $\pi^\pm$ and the γ's from π^0 comprising the sample is desirable to enhance the signal in the presence of a lot of noise (the debris produced by the hot shell).

iv) Large $dN/d\eta$ is needed. In fireball language, fireball masses in excess of 50 GeV are desirable. This would mean $dN/d\eta > 40$. We return to this issue later.

v) The forward-direction, large rapidity regime may be the best place to look. This means η of at least 3 at the TeVatron collider and at least 6 at the SSC.

vi) The experiment is not easy and requires good instrumentation, sophistication in pattern analysis, and careful statistical tests.

One may gain some inspiration from cosmic-ray-emulsion-chamber events. In addition to evidence from the Chacaltaya-Pamir collaboration[6], the JACEE collaboration[7,12] has observed interesting candidate events in balloon-borne emulsion-calorimeter exposures. One is illustrated in Fig. 11. It is initiated by a single charged primary, and the collision occurs within the detector. Almost all the leading particles are photons. The γ's appear to cluster into two groups. The leading cluster, indicated by the circle, consists of about 32 γ's with $\langle p_t \rangle \approx 200$ MeV and only one accompanying charged particle. A possibly distinct cluster has three times as many γ's as charged hadrons (about 54 γ's versus about 17 charged). This event is one out of a sample of 70 or so. The γ/charged ratio for the generic sample is unity; normal events are seen! However the events are found in the emulsion by

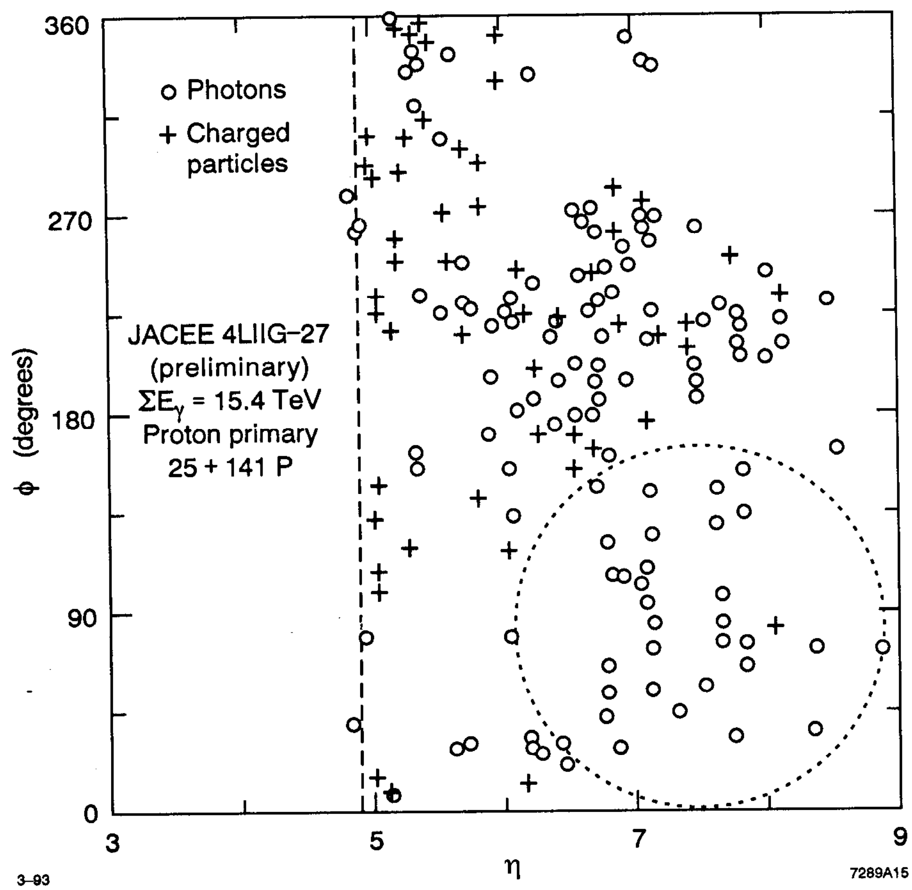

Figure 11. JACEE event showing the leading particle region $\eta > 5$). At lower rapidities the photon detection efficiency becomes small.

scanning for the leading photon showers. So there is a "trigger bias" in favor of a large neutral fraction.

6. Prospects for Experiments

As we have indicated, the method for searching for the disoriented chiral condensate consists of choosing a patch of the lego plot, and counting the charged particles and photons event-by-event within that acceptance. If possible a p_t cut from above should be applied.

For a given event one then defines the neutral fraction f:

$$f = \frac{N_\gamma/2}{N_\gamma/2 + N_{ch}} \cong \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+} + N_{\pi_-}} \ . \tag{18}$$

The expected statistical distribution will be binomial. For the chiral condensate, if the direction of disorientation is random, it is easy to show that the distribution of f is inverse square-root

$$\frac{1}{N}\frac{dN}{df} = \frac{1}{2\sqrt{f}} \ . \tag{19}$$

This was first derived by Anselm and Ryskin[3]. The $I = 0$ coherent-state construction discussed in Section 4, subsection ix), closely approximates this distribution (cf. Fig. 12).

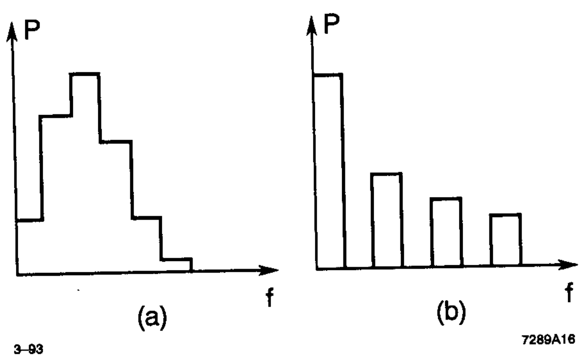

Figure 12. Histograms for $N = 6$ of (a) the binomial distribution and (b) the Kowalski-Taylor chiral condensate distribution which follows from Eqs. (15), (16), and (17).

For the anti-Centauro search (which seems the easiest to do), one can cut on large f ($f > 0.8$ or $f > 0.9$, say) and plot the frequency of occurrence of events above the cut versus total estimated pion multiplicity $N = N_{ch} + \frac{1}{2} N_\gamma$ in the sample. The conventional, binomial-distribution part will fall off exponentially with increasing N, while the disoriented-condensate part will give a constant contribution. So one would search for a break in the falling exponential (Fig. 13).

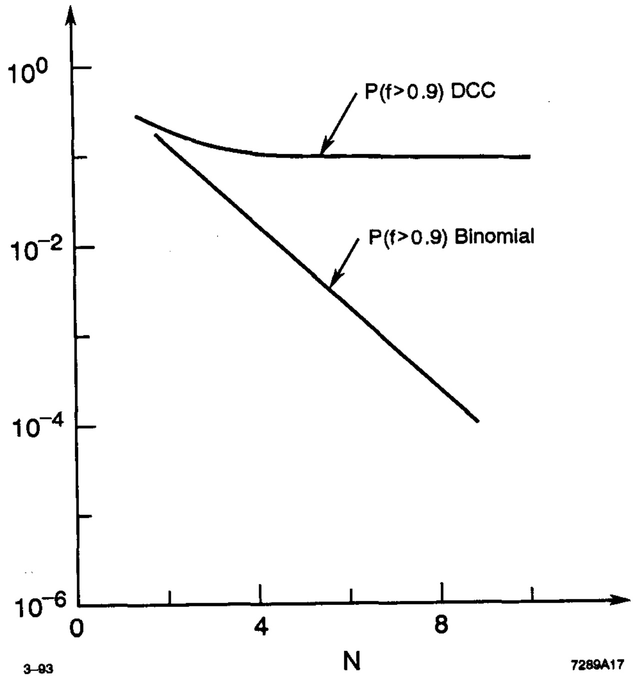

Figure 13. Behavior of the fraction of events with neutral-fraction $f > 0.9$ as function of estimated number of pions in the sample.

Some simulation work has been done, which indicates that for reasonable sample sizes ($N \gtrsim 10$) the chiral-condensate contribution is observable above the statistical noise if it is present at the 0.1 percent level or more.

The experimental possibilities are quite limited. Hadron-hadron collider energies are essential. At the Fermilab TeVatron it appears very difficult for CDF or DO to efficiently count both low-p_t charged particles and low-p_t photons. A new proposal ("MAX"; P864, Bjorken and Longo co-spokesmen[13]) to attempt this experiment was recently submitted, but was rejected. A new attempt for a small test program to initiate study of this physics ("MiniMax," J. Bjorken and C. Taylor co-spokesmen) is in preparation.

The RHIC heavy-ion collider is an attractive possibility. We have not carefully examined the Baked Alaska phenomenon for ion-ion collisions. While the volume of the container for the condensate may be larger, so also will be the thickness of the hot shell. What this does to the signal/noise optimization requires more study.

However, proton-ion collisions are especially attractive. It may in fact happen that in order to create a violent enough early stage of the collision to make the condensate, the incident nucleon must traverse a lot of nuclear matter. After all it is in p-emulsion events that the phenomenon is claimed to be seen. So even were a Fermilab experiment to find a negative result, the existence of the phenomenon could not logically be ruled out.

At the SSC/LHC there are of course excellent opportunities in principle for pursuing this physics—although again it is probably difficult to do it with the generic detectors. The FAD (full-acceptance detector) initiative at the SSC[1,14] has provided the stimulus for almost all of this work we have discussed. A sketch of the present thinking of what FAD might look like is in Fig. 14. The physics of the JACEE event would land on a calorimeter wall located 100 m downstream of the collision point at radii ranging from a few centimeters to a meter.

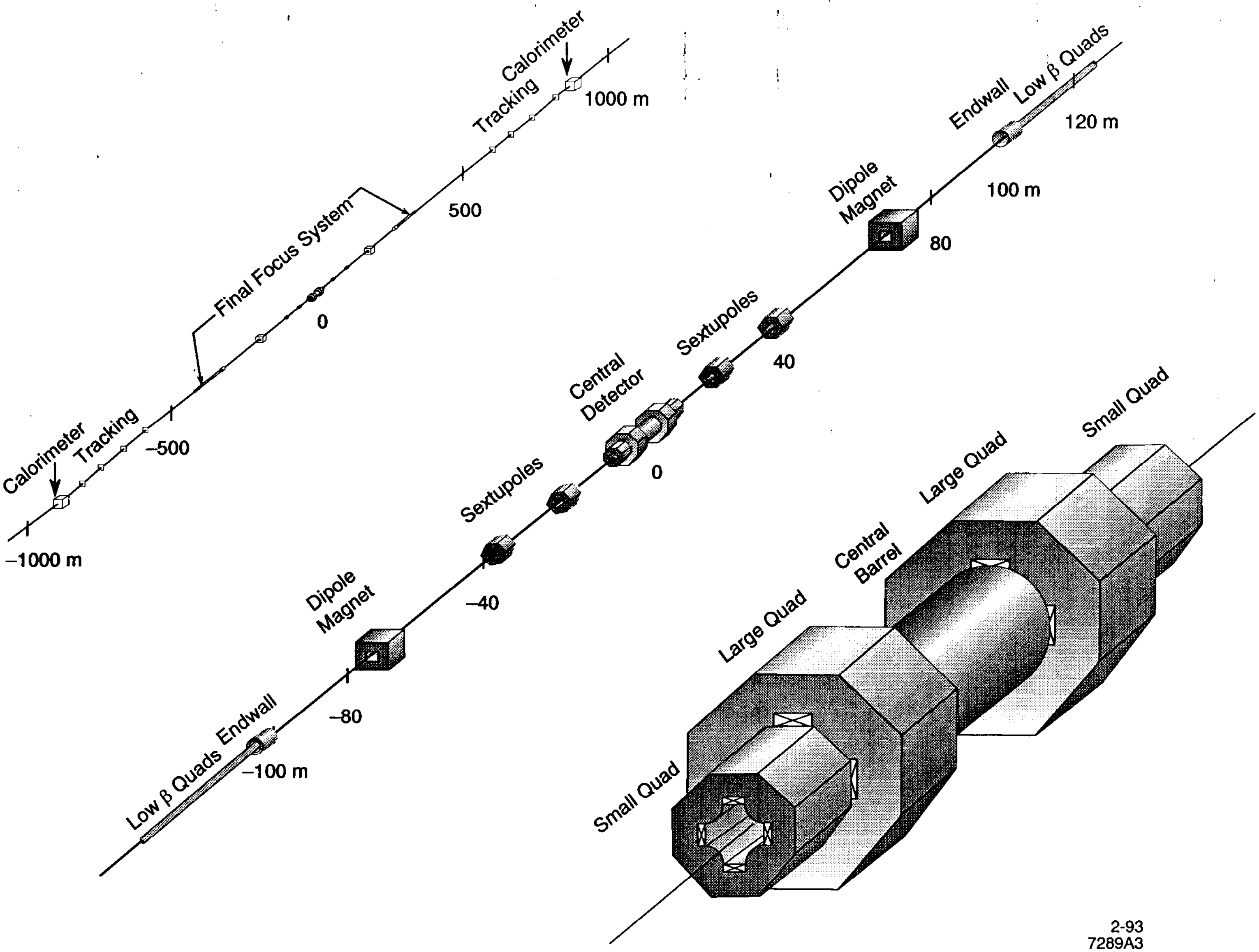

Figure 14. A layout of the extant choice for conceptual design of a Stage-N full-acceptance detector (FAD) for the SSC. The Stage-I detector to be proposed to the SSC will be more modest.

7. Final Comments: Why Baked Alaska?

As we mentioned, the nickname "Baked Alaska" originates elsewhere, in condensed-matter physics. It turns out that in superfluid He^3, a phase transition from the metastable A phase to B phase is believed by some[15] to be induced by a similar mechanism, where a local hot source such as ionization creates in the superfluid A phase an outwardly moving hot shell within which is the B phase. Unlike our application, in this case the bubble continues to expand and converts the entire sample to the opposite phase[16]. But there is another phenomenon, not quite analogous, but similar enough, which we would like to mention in conclusion. It is sonoluminescence, which one of us (J.D.B.) vividly encountered thanks to a recent talk at SLAC by Seth Putterman, who has recently led some beautiful experimental studies[17,18] . For a long time it has been known that micron-size bubbles in water emit light when exposed to intense sound waves. Only recently, however, have single bubbles been examined under controlled conditions. Putterman and his colleagues study single bubbles centered in a spherical flask of water exposed to a resonant s-wave acoustic field. They find a synchronous emission of light pulses with pulse width less than 50 picoseconds and pulse-to-pulse jitter also less than 50 picoseconds[17]. The frequency spectrum is consistent with black body, with a temperature of 25 thousand degrees. They recently have accurately measured[18] the time evolution of the bubble radius via laser-light scattering, and have provided an accurate theoretical interpretation. What happens is that the compressional phase of the acoustic cycle induces an unstable, highly nonlinear implosion of the bubble. As the bubble surface reaches Mach I, an imploding shock front is created, and the light is emitted when the shock front converges to the nodal point. The mechanism of light emission is not yet well understood, but some calculations[19] estimate the temperature at the nodal point to be higher than half a million degrees. Sonoluminescence is a remarkable, efficient transducer of a diffuse low energy source to a concentrated high energy one.

Where does the Baked Alaska come in? Well, it seems that all this has a medical application. If one introduces a bit of egg albumin (egg-white) in the neighborhood of the bubble surface, it turns out that the sonoluminescence cooks it. One is left with a micron-sized hollow sphere, made of this cooked egg-white[20]. Such spheres (in practice made from human serum albumin) comprise a very useful tracer when introduced into the blood circulatory system, because they are safe, and easily detected and located via ultrasound scattering. And, unlike many tracers, they are biodegradeable and nontoxic.

All this should remind us that some of the best science really is hard to anticipate beforehand. Unlike gluons, W's, Z's, and the top quark, some discoveries just don't lend themselves to being created by Monte-Carlo simulations in advance; they just have to be found by direct experimentation. The odds that the particle-physics Baked Alaska or something like it is really there may not be very high. We are speculating rather wildly. But the only way to find out is to do the experiments. We think someone should do them!

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