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ABNORMAL PHOTONIC ENERGY - A SIGNAL OF QUARK MATTER
POSSIBLY SEEN IN EXOTIC COSMIC RAY EVENTS

Apostolos D. Panagiotou

CERN- EP Division, CH-1211 Geneva 23, Switzerland

and

University of Athens, Physics Department

Nuclear & Particle Physics Division

Panepistimiopolis, GR-157 71 Athens, Hellas

and

A. Karabarounis and A. Petridis

University of Athens, Physics Department

Nuclear & Particle Physics Division

Panepistimiopolis, GR-157 71 Athens, Hellas

Abstract

We develop a phenomenological method to select possible Quark matter forming events in ultra- relativistic nucleus-nucleus interactions. We compare the released photonic and hadronic energies from a Quark matter forming event and from a normal Hadronic event and derive a relation, which may be used in an event-by-event analysis to differentiate the two phases. We determine thus two regions of QCD deconfinement.

We also discuss the hadronic, photonic energy and multiplicity contents and the $\langle P \rangle$ of several exotic cosmic ray events at ultra high energies. On the basis of the phenomenological model, we suggest that the "Centauro" type are Quark matter events near the projectile fragmentation region with very large baryochemical potential. The "Anti-Centauro" type events are created by vacuum excitation in the central region with near zero μ_b .

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1. Introduction

Over the past few years there have been numerous proposals of signatures for the identification of QCD deconfinement and the phase transition from the ordinary nuclear matter to Quark matter. Some of these signals are relevant to the production of direct gammas or gamma-pairs [1] and lepton-pairs [2].

Experimentally, in order to use these probes to identify the formation of Quark matter, it is necessary to search at specific regions of invariant mass. It is often the case that one has to consider very large invariant masses, $M \geq 4-5$ GeV, where the cross section is very small or in the presence of intense background, to reveal differences which may be due to the sought for phase transition. An additional difficulty is the "global" nature of these signals, i.e., the effect is searched for in an average measurement (event). It may not be noticed, therefore, in interactions where only a small fraction of central collisions lead to the formation of Quark matter. They are, hence, difficult to implement in such limiting experiments.

In this paper we propose a new and different procedure for the selection of possible Quark matter forming events. Our approach has two aims:

- 1) To search for signals of deconfinement on an event-by-event basis and not in an average measurement. This procedure has the advantage of picking out and examining the events, which are more likely to have formed Quark matter, from the abundant hadronic interactions.
- 2) To avoid the restriction of the probe to specific mass regions,

where the low yield and high background make mass reconstruction very difficult, obscuring the signal.

The phenomenological model we present uses certain plausible assumptions and arguments, which do not conflict with any known theoretical model nor contradict any existing experimental data. On the contrary, cosmic ray data support its predictions in the corresponding energy domains. We show this agreement in a detailed analysis and discussion of some exotic cosmic ray events and we form systematics which will help understand the peculiarities of the mechanism of the interaction. We assume a priori that the events we consider go through the process of a phase transition to Quark matter and subsequent hadronization. Our aim is: (a) to understand the unusual features in terms of a phase transition to a QCD deconfined state, (b) explain the peculiarities in terms of the phenomenological model and known principles and (c) classify the events in regions and mechanisms of QCD deconfinement.

In section 2 we present the phenomenological theoretical framework; in section 3 we discuss the regions of deconfinement; in section 4 we analyze and discuss some characteristic features of several cosmic ray events; in section 5 we classify these exotic cosmic ray events in two regions (modes) of deconfinement; in section 6 we draw a "picture" of the development of the nuclear interaction with increasing energy and we discuss the cosmic ray events, as well as recent data from $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV. Finally, we summarize and propose experiments in specific energy regions with corresponding characteristic features.

2. Theoretical Considerations

In our approach we deal with the entire photonic and hadronic energies released in a central nucleus - nucleus collision. We do not differentiate the possible sources of these energies and, therefore, we do not require invariant mass reconstruction or particle identification. To formulate our phenomenological model, we consider two central ($A_p = A_t$) events, with the same center of mass energy. We assume that one event produces Quark matter, while the other remains in the hadronic phase. In the case of $A_p \neq A_t$, the effect we shall discuss would be somewhat weaker, due to the contributions of the spectator matter to the normal hadronic processes. It should, however, still hold true in the region of phase space where we detect the hadronization of the "Quark matter fireball", i.e. at mid-rapidity.

The hadronization of the Quark-Gluon plasma, formed in an event in the central region, will produce in the final state hadrons, leptons and gammas, with:

$$E_{cm}^Q = E_h^Q + E_l^Q + E_\gamma^Q \quad (1)$$

where, E_h^Q , E_l^Q and E_γ^Q are the detected hadronic, leptonic and photonic energies, respectively. The net photonic energy is the sum of the contributions:

$$E_\gamma^Q = E_\gamma^Q(qq \rightarrow \gamma\gamma) + E_\gamma^Q(\pi^0 \rightarrow \gamma\gamma) + E_\gamma^Q(\pi^+ \pi^- \rightarrow \gamma\gamma) + E_\gamma^Q(\eta \rightarrow \gamma's) + \dots \quad (1a)$$

The event remaining in the hadronic phase will give, similarly:

$$E_{cm}^H = E_h^H + E_l^H + E_\gamma^H \quad (2)$$

where the net detected photonic energy is the sum of:

$$E_{\gamma}^H = E_{\gamma}^H(\pi^0 \rightarrow \gamma\gamma) + E_{\gamma}^H(\pi^+ \pi^- \rightarrow \gamma\gamma) + E_{\gamma}^H(\eta \rightarrow \gamma's) + \dots \quad (2a)$$

Equating relations (1) and (2) we have:

$$E_h^Q + E_{\ell}^Q + E_{\gamma}^Q = E_h^H + E_{\ell}^H + E_{\gamma}^H \quad (3)$$

Dividing (3) by the product $[E_{\gamma}^Q \times E_{\gamma}^H]$ we obtain after some rearrangement:

$$(E_h^Q/E_{\gamma}^Q) + (E_{\ell}^Q/E_{\gamma}^Q) + 1 = (E_h^H/E_{\gamma}^H) [(E_h^Q/E_{\gamma}^Q) + (E_{\ell}^Q/E_{\gamma}^Q) + 1] \quad (4)$$

In ref.'s 3,4 which consider an expanding Quark-Gluon plasma, it can be shown that, for integrated lepton and gamma pair invariant masses between 0.3 and 2 GeV and for temperatures $T = 284$ MeV, $T = 227$ MeV and $T = 154$ MeV, the ratio of their production rate is:

$$[(dN/dy)_{\pi^0} + (dN/dy)_{\mu^+\mu^-}] / [(dN/dy)_{\gamma\gamma}] \simeq 10^{-8} \quad (5)$$

This result does not depend critically on the temperatures or mass range chosen.

Experimentally [5], the comparison between the invariant cross section for π^0 and $\mu^+\mu^-$ production in p+A interactions at 200 GeV, in the same transverse momentum range and for invariant masses $1 \leq M_{\mu^+\mu^-} \leq 5$ GeV, shows that:

$$[\frac{1}{3} \frac{d\sigma}{dp_T}]_{\mu^+\mu^-} / [\frac{1}{3} \frac{d\sigma}{dp_T}]_{\pi^0} \simeq 10^{-8} \quad (6)$$

In the hadronic phase the energy distribution of leptons is higher in energy than that of π^0 -produced gammas by a factor of

about 5. Assuming that these distributions are roughly similar in the two phases and taking into account in addition the e^+e^- contribution [5], as well as all gamma-producing processes (1a,2a), it is obvious that the terms (E_h/E_γ) on both sides of equation (4) are negligibly small. This conclusion is not altered appreciably if one takes into account the small possible decay of hadrons into leptons. With these considerations relation (4) finally becomes:

$$(E_h/E_\gamma)^Q = (E_h/E_\gamma)^H [(E_h/E_\gamma)^H + 1] - 1 \quad (7)$$

Equation (7) is derived by considering the total energy content of central ($A_p = A_t$) events. It holds also true in a more limited phase space, the central region, in the decay of the Quark matter and hadronic "fireball", in a more general nucleus-nucleus collision. It indicates that, if there is a variation between the net photonic energy released in a Quark matter event compared to a hadronic event, then there will be a variation in the ratio $(E_h/E_\gamma)^Q$ between the two phases. In the extreme case of $E_h \rightarrow 0$, the ratio $(E_h/E_\gamma)^Q$ becomes very large, as in the case of certain cosmic ray events we shall discuss below.

We plot rel. (7) in fig. 1, taking the ratio of the hadronic (mesonic plus baryonic) to the photonic energy to be $(E_h/E_\gamma)^H \approx 3$, on the average, in the decay of a hadronic "fireball". A point to note in rel. (7) is the basic difference in the range of values of the ratio $(E_h/E_\gamma)^Q$ in the two regions ">1" and "<1" of fig. 1. In the upper region there are no a priori limits. In the lower region the minimum value for the ratio is about 0.25, corresponding

to zero hadronic energy emitted from the Quark matter event by virtue of relation (7). This is not a physical case, however, since it prohibits the production of hadrons in the process of hadronization.

In determining the regions of deconfinement, we note that Quark matter can be formed either by vacuum excitation with baryochemical potential $\mu_b \simeq 0$, or by nucleon "melting" in a compressed (and heated) nuclear matter with large μ_b . In the former case, the relative abundance of (anti)baryons is rather negligible due to their large mass and, hence, their contribution to the hadronic energy. Since the energy sharing between π^0 , π^+ and π^- is on the average equal, we have:

$$E(\pi^0 \rightarrow \gamma\gamma) \simeq (E_{\pi^-} + E_{\pi^+})/2$$

Therefore, the upper limiting value of the ratio (E_h/E_Q) in the region of fig. 1 with $\mu_b \simeq 0$ should be less than $\simeq 2$, if we include the additional contributions of photonic energy, viz. eq. (1a). This value of the ratio is about two standard deviations away from the hadronic phase value of $\simeq 3$, [6]. Since in an event-by-event analysis fluctuations are more likely to show up, we consider as possible Quark matter forming events those having ratio less than two standard deviations (2σ) from the hadronic value, bearing also in mind the limiting value of $E_h/E_Q > 0.25$.

In the latter case of deconfinement, in an environment of large μ_b , there is no obvious theoretical argument for establishing approximate limits for (E_h/E_Q) . Therefore, in order to avoid misinterpreting uncorrelated fluctuations in the photonic and hadronic energies of normal events, we consider as

possible Quark matter forming events those with values of the ratio $(E_h/E_\gamma)^Q$ at more than four standard deviations (4σ) from the hadronic value. A careful statistical analysis must be made, however, to determine whether central events, with hadronic and photonic energy ratios outside these limits, are not likely to be hadronic matter events.

With these qualitative limits for "phase differentiation", we determine two approximate regions of possible Quark matter forming events, shown in fig. 1:

- 1) $(E_h/E_\gamma)^Q > 4\sigma$ of the hadronic value, with large μ_b .
- 2) $(E_h/E_\gamma)^Q < 2\sigma$ of the hadronic value, with $\mu_b \simeq 0$.

A question is raised immediately: How could the net photonic energy from the hadronization of Quark matter be smaller or larger than the corresponding energy in the hadronic phase? We try to answer this question for each region separately.

Before we discuss these regions, we wish to point out the effect of the baryochemical potential, μ_b , on particle production and in particular on the relative pion/nucleon and hadron/gamma multiplicities. To make a quantitative assessment, we consider the amount of saturation of statistical phase space for u,d- quarks and the suppression of u,d- antiquarks as a function of μ_b , as well as the dependence of particle production on their mass. We calculate the ratio of the so-called Boltzmann approximation for the particle densities:

$$N(\text{pion})/N(\text{nucleon}) \simeq 3/2 \exp\{[-4\mu_b/3 - (M_\pi - M_n)]/T\} \quad (8)$$

$$N(\text{hadron})/N(\text{gamma}) \simeq 1 + 2/3 \exp\{[4\mu_b/3 + (M_\pi - M_n)]/T\} \quad (9)$$

where the factor 3/2 comes from the number of particle species and assuming on the average $N(\text{gamma}) = N(\text{pion})$. We have assumed that $B^{1/4} = 200 \text{ MeV}$, $T(\mu_b = 0) = 160 \text{ MeV}$ and $\mu_b(T = 0) = 960 \text{ MeV}$ for the construction of the critical boundary between the Hadronic and Quark matter phases [7]. Fig. 2 is a plot of relations (8,9). We observe a strong suppression of pions relative to nucleons as a function of increasing baryochemical potential, approaching about three orders of magnitude for large μ_b . The same is true for the relative hadron-gamma production. We see a suppression of gammas with increasing μ_b , approaching about two orders of magnitude for large μ_b . The size of these effects depends, of course, on the choice of the boundary values; it has, however, the same trend and it is rather insensitive to small variations of these values at large μ_b . Entropy considerations for the pion/baryon density give roughly similar results [8,9].

Another important effect of the baryochemical potential may be the reduction of the particle multiplicity in Quark matter forming events with large μ_b . Since pions constitute the bulk of the event multiplicity, a strong suppression of their production by the large baryochemical potential will cause a reduction of the event multiplicity. Thus, we may observe - contrary to common expectations - a Quark matter event (produced in large μ_b environment) with smaller multiplicity than a normal hadronic event at the same center of mass energy. We shall show that in certain cosmic ray events this may indeed be what is happening.

3. Regions of Deconfinement

We discuss now the two regions of deconfinement of fig. 1, in terms of the mechanism, the hadronic/photonic energy content and the charged/gamma particle multiplicity of the interaction.

I. Large Baryochemical Potential Region.

(a) Large Nuclear Stopping — Mid-Rapidity : In ultra-relativistic nuclear interactions with large stopping power, the Quark matter, possibly formed in the central rapidity region, will be rich in u,d- quarks, through the "melting" of a large number of participant nucleons. Hence, the u,d- quark phase space will be substantially filled, resulting in considerable Pauli blocking for the creation of additional light quarks through gluon (mainly) and quark fragmentation. In addition, the large baryochemical potential will also suppress equally the light antiquark creation. Therefore, before the onset of hadronization, the Quark-Gluon plasma will have high u,d- quark and low u,d- antiquark content. This peculiar quark content of the plasma will have important consequences on the type and multiplicity of the hadronization products.

Upon hadronization, emitted baryons will conserve the large baryonic number and will bring a substantial portion of the plasma entropy (which decreases with increasing μ_b) to the hadronic phase, since they carry about twice the entropy of pions at $\mu_b \simeq T$ [8]. We do not consider here the production of strange particles, since their relative abundance compared to non-strange hadrons and hence their corresponding contribution to the hadronic energy is rather small [7]. Since strange quarks are created in $s\bar{s}$ -

pairs, strange hadron production will draw from the light $q\bar{q}$ -quarks produced in the plasma.

As a result, the premordial excess of constituent u,d- quarks in the Quark-Gluon plasma should hadronize predominantly into nucleons, while pions and strange hadrons will deplete the (suppressed) $q\bar{q}$ - pairs. The final state should have the following characteristics:

- 1) An enhancement of baryons (mostly nucleons) at mid-rapidity, which will be more pronounced the higher the plasma temperature.
- 2) A suppressed pion emission and, therefore, photons, compared to the hadronic case where phase space and baryochemical potential effects do not constrain light $q\bar{q}$ - quark production.

$$3) \left(\frac{E_H}{E_\gamma} \right) > 1 \quad \text{and} \quad \left(\frac{E_Q}{E_h} \right) > \left(\frac{E_H}{E_h} \right), \quad \text{in accordance with rel. (7), a consequence of the previous two results.}$$

(b) Small Nuclear Stopping — Projectile Rapidity: As the nuclear stopping decreases at higher energies, but is still sufficient to produce deconfinement in the strongly Lorentz-contracted projectile [10], Quark matter could be formed near the projectile rapidity with baryochemical potential much larger than at mid - rapidity [11] and, correspondingly, with more profound implications. Using the same arguments as before, we may foresee the predominant emission of non-strange baryons and the strong inhibition of pions and hence photons. The consequence of this would be $E_Q \rightarrow 0$, leading to peculiar events with $\left(\frac{E_Q}{E_h} \right) \gg \left(\frac{E_H}{E_h} \right)$ and $N_h \gg N_\gamma$. Such exotic events with $\left(\frac{E_Q}{E_h} \right)$ very

large have been observed in cosmic ray nuclear collisions, the so-called "Centauro" and "Mini-Centauro" events [12].

A thought to entertain at this point is the possibility that the curves for deconfinement and chiral symmetry restoration - in a T versus μ_b plane - are not identical at very large μ_b values [13]. In contrast to the $\mu_b = 0$ case where the two phase transitions coincide, as shown by statistical QCD calculations [14], at very large μ_b and rather small T , chiral symmetry may continue to remain spontaneously broken (until higher values of μ_b), even though the transition to the deconfined-quark phase was accomplished. This may have as a consequence the deconfined quarks to retain their dynamical mass (acquired through their interaction) and, hence, instead of a "Quark-Gluon plasma" to have a "constituent (valence) Quark matter" [15]. This state will hadronize back roughly to its premordial nucleons satisfying the conservation principles ⁽⁺⁾. This, we suggest, may be the mechanism for the production of "Centauro" events.

II. "Zero" Baryochemical Potential Region.

Nuclear Transparency — Mid-Rapidity: At ultra-high energies where nuclear stopping has practically disappeared, we expect to form Quark matter profusely at mid-rapidity through vacuum excitation [16]. In the central region the Quark-Gluon plasma has

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In this extreme case (anti)strange hadrons may also be strongly suppressed, since their creation requires in addition light anti-quarks (which are not produced), raising an interesting question on strangeness production and hadronization.

almost zero baryochemical potential [17], hence the production of light $q\bar{q}$ - quarks is not impeded by the afore-mentioned effects. Pions are strongly favored over heavier particles (baryons) and the charged and gamma multiplicities should increase appreciably compared to the Hadronic phase. This is a consequence of the very large entropy, which the Quark-Gluon plasma now possesses at $\mu_b \simeq 0$.

Since the multiplicity of the pion species is equal on the average and each π^0 decays into two gammas, there is approximately one gamma ray for each charged pion. Hence, we may expect at mid-events with $N_h < N_\gamma$, if we take into account the additional sources of gammas, viz. rel. (1a). For the energy content, we expect the total photonic energy $E_Q > (E_\pi + E_\gamma)/2$, leading to $(E_Q/E_h) < 2$, since the (anti)baryon multiplicity and corresponding contribution to the hadronic energy may be considered relatively negligible in the central region (lower region of fig. 1). Such exotic events, with relative predominance of photonic energy, have been observed in ultra-high energy cosmic ray nuclear interactions [18-20], the so-called "Anti-Centauro" events [21].

4. Cosmic Ray Events

In the last twenty years, cosmic ray experiments have reported numerous most unusual - and still not well understood - events [12,18-20,22-25]. Some of these events, the so-called "Centauro" and "Mini-Centauro" [12], show complete absence or very much reduced photonic energy, hence absence or strong suppression of all pion species, respectively. They may be considered, therefore,

as predominantly baryon emitting events. Other exotic events, the so-called "Anti-Centauro" [21] exhibit relative predominance of photonic energy and gamma multiplicity. Both types of events possess exceedingly large transverse momenta, three to six times the value of hadronic reactions.

New types of hadronic interactions or the creation of a new kind of matter were suggested to be responsible for the peculiarities of these events. It was shown through Monte Carlo simulations [18,19] that these events could not originate from any kind of rare statistical fluctuations in the hadronic and photonic content of normal hadronic interactions. Therefore, a new type of matter, Quark matter, was conjectured to be created, which gave rise to these unusual phenomena [12,18,19].

We shall examine now the multiplicity and energy contents, as well as the average transverse momentum of hadrons and gammas for several exotic cosmic ray events from ref's [12,18-20,22-25].

4.1 Multiplicity and Energy Contents

The multiplicity and energy content of the events was obtained by using an energy threshold, $E_{\min} = 1 - 4 \text{ TeV}$. From the many very high energy events available in the literature, we have selected a number of them on the basis of being: (a) fully analyzed in terms of the hadronic and photonic contents and (b) a nucleus-nucleus interaction with hadron multiplicity $N_h > 15$. The later criterion may help ensure the mass of the projectile nucleus to be larger than 15, as we shall discuss below. The cosmic ray events analyzed do not all have the same experimental conditions and

collision parameters. They are expected, therefore, to show differences when compared individually in detail. Average features, however, should form systematics for events of similar processes.

In fig. 3 we plot the hadron/gamma multiplicity as a function of the event energy. We assume a $\pm 20\%$ average uncertainty in the event multiplicity, an upper limit of the uncertainties reported. We observe that events with energy below about 3000 TeV are located in the $N_h > N_\gamma$ region, while those with higher energy in the $N_h < N_\gamma$ region. The former region contains the Centauro type events and the later the Anti-Centauro type ones. Two Mini-Centauro events at energy 485 and 1620 TeV lie close to the $N_h = N_\gamma$ line and may be mistakably considered to be normal hadronic interactions. The hadron multiplicity assignment, however, is considerably underestimated and the gamma overestimated for all Mini - Centauro events [12]. The important feature of fig.3 is the very peculiar behavior of the variation of the multiplicity ratio with event energy. As the energy increases, the ratio N_h/N_γ increases and reaches very large values at event energies of the order of 1500 TeV. At higher energies it starts to drop sharply and above about 5000 TeV it remains roughly constant, with a mean value $\langle N_h/N_\gamma \rangle = 0.4 \pm 0.04$ [26].

A similar astounding behavior is observed in the plot of the ratio of the energy content (E_h/E_γ) as a function of the event energy, fig. 4. Again we have assumed a 20% average uncertainty in the energies and the inelasticity coefficient ($K=0.3$), consistent with the accepted range of K values. Fig. 4 is divided into three regions by the two approximate "phase differentiation" lines:

$E_h / E_\gamma = 5$ and $E_h / E_\gamma = 2$, corresponding to $+4\sigma$ and -2σ from the approximate hadronic value of 3. We observe here that the hadronic to the photonic energy ratio increases to very large values with increasing event energy, up to approximately 1500 TeV. At higher energies the ratio drops sharply to values below "2" and stays roughly constant in the event energy range of 5000 to 50000 TeV, with mean value $\langle E_h / E_\gamma \rangle = 1.63 \pm 0.22$. We note that had we chosen the gamma inelasticity coefficient to be $K = 0.25$, the mean value would be 1.96 ± 0.26 .

For some events, the uncertainty in the multiplicities and corresponding energies of the primary reaction products may be larger than 20 %. This could be due to the variable height of the parent interaction [27], effectively ranging between 100 and 1200 meters for the events considered, causing air showers of different intensity for each event. The air cascading has as a result the apparent increase of the gamma content of the interaction. On the other hand, one also expects a continuous increase of gamma production of non-pionic origin at progressively higher energies [28]. They are produced in collisions of quarks and gluons and from annihilation of $q\bar{q}$ quarks in interacting hadrons and more so in a Quark-Gluon plasma [29].

To detect changes in the systematics of gammas and hadrons, possibly suggesting changes of origin, we plot in fig. 5 the average energy per gamma or hadron. We have included all available events regardless of the value of N_h . The data are from the high energy showers of electromagnetic and hadronic origin. We notice that the average energy per hadron fluctuates with no apparent

tendency in the entire event energy range, with a mean value $\langle E_h / N_h \rangle = 50 \pm 5$ TeV/particle. The large variations between some events may be the result of the differences in both the (uncontrolled) collision parameters and experimental conditions between events.

For the gammas the situation is somewhat different. Here we observe a variation by a factor of "2" between the mean energy per gamma in the two approximate energy regions, $E_{\text{total}} > 2500$ TeV and < 2500 TeV, with mean values $\langle E_{\gamma} / N_{\gamma} \rangle = 8.0 \pm 0.8$ TeV and 3.7 ± 0.3 TeV, respectively. We also notice that, for the events in the energy range between 2500 to 50000 TeV, the fluctuations of the average energy per gamma are small and within the error of their mean, in contrast to the lower energy region. Whether the difference of a factor of "2" is alone sufficient to suggest change of the systematics and, hence, change of the origin of the gammas in the events between the two regions is not conclusive.

4.2 Average Transverse Momentum

We examine next the exotic cosmic ray events in terms of their transverse momenta of both hadron and gamma components, where available. In the cases where the $\langle P_T \rangle$ is not given in the literature, we calculate it from their $\langle ER \rangle$ values, where E , R are the energy and lateral extend of the shower from the event's center of gravity, assuming an effective height of 1.2 Km, corresponding to about 1 cascade unit [27]. For several events we have used their $\langle ER \rangle$ values after clusterization [24].

We present the variation of the $\langle P_T \rangle$ with event multiplicity

in two figures, grouping the events in two approximate energy regimes: event energy less than 3000 TeV and greater than 3000 TeV. The reason for this separation is the apparent change of the event features, as seen in fig.s' 3,4 and the passage of the events from the "Centauro" type to the "Anti-Centauro" type, as we discussed in the previous section.

In figure 6 we plot the $\langle P \rangle_T$ versus the total charged multiplicity of events in ref.'s [12,19,23,25]. We also show the mean values for the $^{16}\text{O} + \text{Au}$ reaction at 200 GeV/A, obtained in the interval $D\eta = \pm 2$ about mid-rapidity, for both the experimental data [30] and the corresponding Monte Carlo simulation for central collisions. The JACEE events, with $\langle P \rangle_T > 0.5$ GeV/c for the neutral pions, come mostly from "medium mass projectile plus lead" interactions, with roughly 20 - 110 TeV total energy. The $\langle P \rangle_T$ is obtained in a pseudorapidity interval of 1 - 3 units above mid-rapidity for N-N interaction [21]. The events with $\langle P \rangle_T < 0.5$ GeV/c are (Si - Fe) + Pb collisions at approximately 0.9 - 2.1 TeV total energy. Only two of the five similar events are plotted. Where unknown, the uncertainty in $\langle P \rangle_T$ was taken to be $\pm 25\%$, roughly equal to the mean of the known uncertainties.

We note in fig. 6 that the $^{16}\text{O} + \text{Au}$ average event exhibits a low $\langle P \rangle_T$ of about 0.38 GeV/c, similar to the Monte Carlo simulation of hadronic interactions. This $\langle P \rangle_T$ value is of the same magnitude as that measured in pp interactions at 200 GeV [31]. The JACEE events at an energy range of 0.9 to 2.1 TeV have $\langle P \rangle_T \leq 0.45$ GeV/c and fit well in the systematics of the $^{16}\text{O} + \text{Au}$ interactions at 0.96 and 3.2 TeV [30].

Since the JACEE and Centauro type events have unknown collision impact parameters and different incident energies, it is difficult to follow a systematic development of the $\langle P \rangle_T$ dependence on multiplicity. In order to offer a possible interpretation of the data, we invoke the following (generally accepted) assumptions:

(a) The mass of the interacting nuclei ($A = \text{Si} - \text{V}$, $A = \text{Pb}$, Ag/Br) and the estimated event energy range between 20_p and 110_t TeV are sufficient, in principle, to form Quark matter in a central collision.

(b) The hadronization of Quark-Gluon plasma creates particles with large average P_T .

The JACEE events with $\langle P \rangle_T > 0.5$ GeV/c all have masses of the colliding nuclei and incident energies within these ranges. For these events we observe an apparent increase of the average P_T with decreasing event multiplicity. This trend continues to the Centauro type events, at event energies above 300 TeV, with charged multiplicities below 100 and $\langle P \rangle_T \approx 1.5$ GeV/c, which have the additional feature of "zero" or very small pion content. A linear fit to the events with $\langle P \rangle_T > 0.5$ GeV/c gives: $\langle P \rangle_T = -4.4 \times 10^{-4} N_{ch} + 1.4$ GeV/c. We might, therefore, witness in these events the formation of Quark matter in progressively richer μ_b environment, resulting in progressively smaller particle multiplicity of the Quark matter-forming interactions, due to the suppression of pions, culminating in the Centauro events, as we suggested and discussed earlier. The available interaction energy is carried now by the baryons and appears as very large $\langle P \rangle_T$.

Fig. 7 contains the exotic cosmic ray events with event energy

greater than 3000 TeV, as well as several points from the $p\bar{p}$ measurements at $\sqrt{s} = 1.8$ TeV, [32]. It exhibits the dependence of the average P_T of this class of events on their total multiplicity. For the $p\bar{p}$ data we assume that $N(\gamma) = N(\pi^- + \pi^+)$ on the average. We observe a smooth continuation of the $\langle P_T \rangle$ with multiplicity for the $p\bar{p}$ and cosmic ray data points (except for two events). After a steep rise at very low multiplicities, as indicated by $p\bar{p}$ data at $\sqrt{s} = 546$ GeV [33], a roughly constant $\langle P_T \rangle \simeq 0.55$ GeV/c is seen in the multiplicity range between approximately 40 and 120. At larger multiplicities the $\langle P_T \rangle$ increases again fast to values well over 3 GeV/c. The over all behaviour of the average P_T resembles the dependence predicted by Van Hove for a phase transition [34].

It is important to note here the two main and basic differences between fig's 6 and 7:

— The average P_T possibly increases with decreasing event multiplicity in fig. 6 (for events with $\langle P_T \rangle > 0.5$ GeV/c), while in fig. 7, after the plateau, it increases strongly with increasing multiplicity.

— The maximum $\langle P_T \rangle$ in fig. 7 is more than twice that in fig. 6.

To investigate further the average P_T feature of these events, we plot in fig. 8 the $\langle P_T \rangle$ as a function of the ratio N_h/N_γ , whose systematics we discussed in the previous section. We show both hadron and gamma component of the $\langle P_T \rangle$ where available. For $N_h/N_\gamma > 1$, a gradual increase of the average P_T with increasing ratio towards the Centauro events may be inferred. For $N_h/N_\gamma < 1$, the Anti-Centauro type events scatter vertically in a narrow range of

the ratio. In fig. 9 we show the variation of $\langle P \rangle_T$ with E_h/E_γ for these events and we have also included the average event from the 16 O + Au central collision [30]. A similar trend as in fig. 8 is suggested by the data, that is the $\langle P \rangle_T$ increases with increasing E_h/E_γ towards the Centauro events, and also increases steeply to very large values in the narrow range of the ratio between 1 and 2 (\$).

The point to be noted is that the cosmic ray events, which exhibit a large departure of their E_h/E_γ and N_h/N_γ values from the corresponding values in hadronic interactions, possess also exceedingly large average P_T , far beyond that of the hadronic phase. These events, therefore, possess all three quantities, which distinguish them from normal hadronic interactions. If we conjecture that these events are Quark matter forming events, we may conclude that the data suggest the existence of two energy regions and correspondingly two modes of QCD deconfinement (fig. 1).

5. Classification of Cosmic Ray Events

Examining the energy regimes and corresponding characteristic features of the cosmic ray events shown in fig's 3-7 and based on our description of the two regions of deconfinement in fig. 1, we may draw the following "picture" for the development of nucleus-nucleus interactions, leading to Quark matter events.

Starting at lower event energies of a few TeV, the large nuclear stopping (about 50-60 % [35]) may induce the formation of Quark matter in some events at mid-rapidity, in an environment with

(\$)

The events appearing in both figures are not all the same, due to unavailable corresponding measurements.

substantial baryochemical potential. For these events the ratio E_h/E_γ becomes larger than the hadronic phase value. As the interaction energy increases, the value of this ratio for Quark matter events also increases. At event energies above about 300 TeV, "Mini-Centauro" type events begin to appear, with Quark matter being formed progressively also near the projectile fragmentation rapidity. In this region the baryochemical potential assumes large values, affecting strongly the multiplicity and energy contents of each type of hadronized particle. We expect progressively a relative increase of baryons over pions, large E_h/E_γ , an overall reduction in the event multiplicity and an increase of the average P_T (see fig's 3,4,6).

The culmination of this tendency is the appearance of "Centauro" events, at an observed event energy of the order of 1500 TeV. Here, in the presence of very small (but sufficient) nuclear stopping, Quark matter is formed near the projectile rapidity in a very high μ_b environment and at rather low temperatures, in the highly Lorentz-contracted and excited projectile, through "cold compression". Low temperature and high density result in a small entropy for the Quark matter phase. The hadronization of the "constituent Quark matter" reproduces closely the original nuclear (baryonic) configuration, resulting in the absence of pions, N_h/N_γ and E_h/E_γ very large and in a relatively small particle multiplicity. The available interaction energy is carried by the baryons and appears as large P_T .

As the energy further increases and the nuclear stopping tends to near zero, there are no more "pure" Centauro events.

Quark-Gluon plasma is now formed profusely in the central region through vacuum excitation in an environment with $\mu_b \simeq 0$. The "constituent Quark matter" near the projectile rapidity tends to diminish in importance. The hadronization of these two regions of deconfinement has opposite effects on the particle composition and multiplicity. We expect, hence, both energy (E_h/E_γ) and multiplicity (N_h/N_γ) ratios to start dropping from the very high values attained at the typical Centauro events.

With further increase of the event energy, more energy is available for vacuum excitation in the central region and quickly the mid-rapidity created Quark-Gluon plasma will give the dominant character and features of the event: large multiplicity, $N_h/N_\gamma < 1$ and $E_h/E_\gamma < 2$. We have now the "Anti-Centauro" type event, observed at event energies above about 5000 TeV. This type of events possess the peculiar feature of a center core, a "halo" and shower spots. In our picture, the halo may contain the very penetrating "nucleons" from the hadronized "constituent Quark matter" of the projectile nucleus, as well as soft gammas from air cascades and from the central region (plasma-created gammas), Lorentz-boosted to near the projectile rapidity. The peripheral showers are produced by the harder component of the hadronized Quark-Gluon plasma at mid-rapidity, which also possesses larger $\langle P_T \rangle$. We note that, in events where the hadron multiplicity is measured in the halo, it is smaller than that found in the peripheral showers.

The approximate constancy of both ratios (fig's 3,4) in the large event energy range (5000 to 50000 TeV) may suggest that the Quark-Gluon plasma, formed in the central region by vacuum

excitation and giving the dominant features of the event, has reached some state of equilibrium, as far as the relative content of the hadronization products is concerned. Thus, the increase of the event energy from 5000 TeV to 50000 TeV does not seem to vary appreciably the relative abundance and corresponding relative energy of hadrons and photons, despite the variable experimental conditions. The influence of the variable contribution of air cascades is compounded in the fluctuations of these quantities (see also fig. 5).

6. Discussion of Cosmic Ray Events

It would be very interesting to determine the energy regime for the occurrence of both types of cosmic ray events. An accurate estimation is difficult, however, because here we use the "total" event, without distinction between central and projectile rapidity regimes and without good knowledge of the projectile and target nuclei. Despite that, we may make some rough estimations. For the typical Centauro events with average event energy of the order of 1500 TeV, if we assume, for example, a projectile mass of about $A \simeq 75$, equal to their average hadron multiplicity, we estimate $E_{\text{lab}}/A \simeq 20$ TeV, corresponding to $\sqrt{s} \simeq 190$ GeV for the nucleon - nucleon ("N-N") system. Since the occurrence of Centauro type events necessitates small nuclear stopping, we may suggest that near complete nuclear transparency in nucleus-nucleus collisions begins at energies $E_{\text{lab}}/A > 20$ TeV.

For the Anti-Centauro events, the minimum known event energy is approximately 6000 TeV. If we assume, for example, that the primary

particle has mass $A \simeq 60(30)$, we may infer that dominant vacuum excitation in nucleus - nucleus interactions sets in at E_{lab}/A of the order of 100(200) TeV, corresponding to $\sqrt{s} \simeq 430(610)$ GeV for the N-N interaction. Our conjecture is that possible Quark-Gluon plasma formation through vacuum excitation, in an extended volume in the central region, begins at energies $\sqrt{s} > 500$ GeV for the N-N system.

This suggestion is in agreement with the interpretation of the (beginning) plateau in the $\langle P \rangle$ versus dN/dy distribution, observed by UA1 at $\sqrt{s} = 546$ GeV in pp collisions [33]. According to Van Hove [34], the plateau in this distribution corresponds to a mixed phase of Quark-Gluon plasma and hadronic matter, before the system goes entirely into the deconfined phase where the $\langle P \rangle_T$ increases again. This behavior of the $\langle P \rangle_T$ distribution is a typical feature of a phase transition in which the entropy and, hence, the particle multiplicity, continuously increase with energy. This trend is expected in the case of Quark-Gluon plasma formation through vacuum excitation in an $\mu_b \simeq 0$ environment, as it may possibly be the case with the events in fig. 7. To our understanding, this feature is observable in interactions characterized by near complete nuclear transparency and, therefore, it may not be seen in nucleus-nucleus collisions with nuclear stopping or in Centauro type events. In the latter cases, we may expect in Quark matter forming events the particle multiplicity to decrease with increasing ub , as we discussed earlier in fig. 6.

If indeed Quark-Gluon plasma begins to be formed in $p\bar{p}$ collisions by vacuum excitation at $\sqrt{s} > 500$ GeV, the events should

exhibit characteristics such as $N_h / N_\gamma < 1$ and $E_h / E_\gamma < 2$, among other. We note that the ratio $\langle N_h / N_\gamma \rangle$ decreases from about unity at lower energies to 0.72 ± 0.07 at $\sqrt{s} = 546$ GeV in $p\bar{p}$ collisions [36]. A similar tentative indication might be extracted from the JACEE "4L-II-27" event of $p + \text{Ag/Br}$ interaction at 80 TeV [23], corresponding to $\sqrt{s} \simeq 670$ GeV for a "p+3N" interaction. A ratio $N_h / N_\gamma = 0.4 \pm 0.16$ is reported in a pseudorapidity interval of 2 units close to the central region.

The scatter plot of the ratio N_h / N_γ versus $\sqrt{s}$ for the cosmic ray events we consider, including the two cases mentioned above and denoted by a circle, is shown in fig. 10. Where unknown, the projectile mass is approximately estimated to be in the range 20 to 70. A similar trend with that of fig. 3 is seen, despite the uncertainties in the mass of the projectile. The ratio increases to very large values with increasing $\sqrt{s}$, up to about $\sqrt{s} \simeq 200$ GeV and then decreases at higher energies. Events with $\sqrt{s} > 500$ GeV possess values $N_h / N_\gamma < 1$, with a mean value of 0.4 ± 0.04 .

7. Summary - Proposals

In summary, we considered the photonic and hadronic energies from all possible sources emitted in central nucleus-nucleus collisions. We have derived an equation relating the ratio of these energies in the Quark matter and hadronic phases. Our analysis leads to the following conclusions:

- 1) The selection of possible Quark matter forming events could be made in an event-by-event mode, on the basis of their value of (E_h / E_γ) .

2) Two regions of deconfinement are determined: One with $(E/E_h) \gamma$ larger than "4σ" of the hadronic value, characterized by large u_b and enhanced baryon (nucleon) content at mid-rapidity, or near the projectile rapidity at very high energies. The other region has $(E/E_h) \gamma < 2σ$ of the hadronic value, characterized by $\mu_b \simeq 0$. The Quark-Gluon plasma is now formed in the central region by vacuum excitation at ultra high energies.

The selection of possible Quark matter forming events out of the many more hadronic interactions is very important, because it offers the possibility for further study of these events with respect to different particle multiplicity ratios, rapidity and P_T distributions, HBT correlations, e.t.c., which may provide additional evidence for the phase transition.

We have also examined the energy, multiplicity and average P_T characteristics of several exotic very high energy nuclear interactions in cosmic rays. We suggest that the Centauro and Anti-Centauro type events are created by two different mechanisms of QCD deconfinement: "cold compression" near the projectile fragmentation region, with very large baryochemical potential, and vacuum excitation in the central rapidity region, with near zero baryochemical potential, respectively. A rough estimation of the starting energy for near complete nuclear transparency gives E_{lab}/A larger than about 20 TeV. For the onset of dominant Quark-Gluon plasma formation through vacuum excitation, we estimate $E_{lab}/A > 100$ TeV in intermediate mass nucleus - nucleus interactions.

On account of the above discussion, we propose the following

search for Quark matter creating events in accelerator based experiments:

- (i) 200 GeV/nucleon heavy ion beams: Mid-rapidity, for events with $E_h/E_\gamma > 4\sigma$ of the hadronic value, and $N_h/N_\gamma \gg 1$, in central collisions (large nuclear stopping). Heavy mass systems will give a more pronounced signal.
- (ii) $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collider: Central region, for Anti-Centauro type events with $E_h/E_\gamma < 2$ and $N_h/N_\gamma < 1$.
- (iii) $\sqrt{s}$ /nucleon = 100 - 200 GeV and $A_p = A_t \simeq 200 - 100$ heavy ion collider: Fragmentation regions, for Centauro and Mini-Centauro type events with E_h/E_γ and N_h/N_γ very large; at energies $\sqrt{s}/A \geq 250$ GeV and $A_p = A_t \simeq 200$, in the central region for Anti-Centauro type events.

Several attempts have been made to form Centauro type events in diffractive fireball production in $p\bar{p}$ collisions at $\sqrt{s} = 546$ and 900 GeV [37]. The results have been negative, in agreement with our discussion and "picture" of the process. We are inclined to believe that such events cannot be produced in $p\bar{p}$ interactions.

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TABLE I. CENTAURO EVENTS

<u>Event</u>	<u>Name</u>	<u>E_{γ}(TeV)</u>	<u>$E_h(\gamma)$(TeV)</u>	<u>E_h(TeV)</u>	<u>E_{tot}(TeV)</u>	<u>E_h/E_{γ}</u>	<u>Ref.</u>
CENTAURO	I	0	330	1100	1100	-	12
CENTAURO	II	0	370	1233	1233	-	12
CENTAURO	V	0	350	1167	1167	-	12
M.CENTAURO	I	32	446	1487	1519	46.5	12
M.CENTAURO	IV	52	130	433	485	13.6	12
P3-C2-223		25	302	1007	1032	40	19
"PAMIR"		70	759	2530	2600	36.1	12
P3-C2-B178		95	845	2817	2855	30.1	22

TABLE II. ANTI-CENTAURO EVENTS (#)

<u>Event</u>	<u>Name</u>	<u>E_{γ}(TeV)</u>	<u>$E_h(\gamma)$(TeV)</u>	<u>E_h(TeV)</u>	<u>E_{tot}(TeV)</u>	<u>E_h/E_{γ}</u>	<u>Ref.</u>
ANDROMEDA		20418	9490	31633	52051	1.55	18
M.ANDROM.	III	6748	2589	8627	15375	1.3	18
P3-C1-90		14813	5229	17430	32243	1.2	19
P3-C5-505		6914	3493	11643	18557	1.7	19
HALINA		2468	1071	3570	6038	1.45	19
P3-C2-201		1740	1068	3560	5300	2.05	19
TATYANA		5970	4060	13533	19503	2.27	20

(#)

Anti-Centauro type events with measured hadronic and photonic energies in both halo and showers are used.

FIGURE CAPTIONS

- Fig. 1. A plot of rel. (7) for $(E_h/E_\gamma)^H = 3$. For a discussion see the text.
- Fig. 2. A plot of rel.'s (8,9) as a function of the baryochemical potential of the Quark-Gluon plasma.
- Fig. 3. Scatter plot of (N_h/N_γ) versus total event energy. Data from ref.'s [12,18-20,23]. Only three of the five similar Centauro events are shown.
- Fig. 4. Scatter plot of E_h/E_γ versus total event energy. For the Anti-Centauro events the energies come from the showers and halo. Data from ref.'s [12,18-20,23]. Only three of the five similar Centauro events are shown.
- Fig. 5. Scatter plot of the average energy per "particle" versus total event energy. $O (E_h/N_h)$; $+ (E_\gamma/N_\gamma)$. Typical error is shown for the event at 15400 TeV.
- Fig. 6. Average P_T versus total charged multiplicity for events with $E_{tot} < 3000$ TeV. Data from ref.'s [12,18-20,22,23]. The Centauro point at multiplicity 75 is the average of five very similar events.
- Fig. 7. Average P_T versus total multiplicity for cosmic ray events with $E_{tot} > 3000$ TeV. Data from ref.'s [12,18-20,22,23].
- Fig. 8. Average P_T versus the ratio N_h/N_γ for some cosmic ray events. Data from Ref.'s [12,18-20,22,23]. The Centauro point is the average of five very similar events.

Fig. 9. Average P_T versus the ratio E_h/E_γ for some cosmic ray events. Data from Ref.'s [12,18-20,22,23]. The Centauro point is the average of five very similar events.

Fig. 10. Scatter plot of N_h/N_{N-N} versus V_s for the cosmic ray events. Only three of the five similar Centauro events at $\sqrt{s} \approx 180$ GeV are shown. Open circles denote p- induced events.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8.

Fig. 9.

Fig. 10.