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WHAT IS CENTAURO?*

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IS THE PRIMARY OF HIGH Z?

The celebrated Centauro event[1] found in the Mt. Chacaltaya emulsion exposures by the Brazil-Japan collaboration continues to resist rational interpretation. The event is described in terms of production of a leading "fireball", with the parameters listed in Table I. The main properties of this event have been inferred from the data, and are not here called into question.

TABLE I

Primary Energy	~	1000 TeV
Production Height	~	50 m above apparatus
	~	500 gm/cm^2 from the top of the atmosphere
"Fireball" Mass	~	200 GeV
"Fireball" Multiplicity	~	100
Multiplicity of π^o and e in the "Fireball"	~	0
$\langle p_\perp \rangle$ of Secondaries from the "Fireball"	~	1.7 ± .7 GeV

The absence of π^o's in the event would suggest a high-Z primary nucleus as the source. This interpretation, however, appears to be untenable since there is a negligible probability that a nucleus would penetrate so deeply into the atmosphere. Furthermore, the mean transverse momentum of the secondaries is much larger than the value typical of a nuclear fragmentation.

These objections, however, offer no obstacle to another interpretation: that the primary object initiating the collision is a glob of nuclear matter of very high density.[2,3] Since the $\langle p_\perp \rangle \sim$ 3-5 times the normal value typical of a nucleus, we might expect a density ~ 30-100 times that of ordinary nuclear matter. This highly compressed glob would have a radius 3-5 times smaller than that of an ordinary nucleus. If the larger transverse momentum is associated with the binding energies possessed by the constituents of the dense nuclear matter, these binding energies are much greater than those of conventional nuclear matter. Thus, were such globs of primordial

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superdense nuclear matter to exist, the reduced geometrical cross section and increased binding energy might allow these globs to penetrate 500 gm/cm^2 of atmosphere and initiate events of the Centauro type.

Nevertheless, there are still many major difficulties confronting such a hypothesis. One difficulty is the nature of the primary spectrum. If high energy, high-Z primaries exist with flux sufficient to account for Centauro events ($\sim 10^{-2} m^{-2} yr^{-1}$ for $E \sim 10^6$ GeV at 500 gm/cm^{-2}), one would expect a much larger number at lower energies. However, the flux of relativistic high-Z ($Z \gtrsim 30$) primaries at the top of the atmosphere is known[4] to be $\sim 10^3 m^{-2} yr^{-1}$. Assuming a power law integral spectrum, $N(E) \alpha E^{-1.5}$, we need to cut-off the flux of superdense globs at an energy $E \gtrsim 1$ TeV. A possible explanation for such a cut-off is that the superdense globs are metastable and have some finite lifetime. The less energetic globs would have a smaller time dilation factor and hence would have been removed from the primary spectrum. Another possible explanation would be that the process by which these globs are formed is very energetic, and that the spectrum of produced globs is not close to the $1/E^{1.5}$ behavior typical of cosmic rays.

A second problem concerns the mechanism of fragmentation of the primary in the actual Centauro event. It is a priori unlikely that superdense nuclear matter exists in a free state. We might expect, however, that globs of superdense matter could be metastable. If the density of the glob is 30-100 times ordinary nuclear matter density, we would almost certainly expect that the matter would be in the quark phase. In a central collision of an air nucleus with the metastable glob of quark matter, the glob might become sufficiently excited for it to "boil" or explode.

WHAT HOLDS THE GLOB TOGETHER?

The primary obstacle to a straightforward description of the glob in terms of quark matter is the determination of a mechanism which would hold the glob together. Such a mechanism might be provided if the glob were in an exotic configuration involving strange or charmed quarks. Although the energy of the exotic quark glob could be higher than that of ordinary nuclear matter, the glob might have to decay through an intermediate state of yet higher energy. For example, if there were a mismatch in the exotic quantum numbers of the quark glob and nuclear matter, then the intermediate configuration might be a glob of quark matter with different quantum numbers than those of the metastable quark glob. Such a configuration could be reached by the weak interaction Hamiltonian and the glob would have a long lifetime.

Another mechanism is suggested by deRujula, Giles and Jaffe (DGJ),[5] who have discussed the properties of quantum chromodynamics when the color symmetry is slightly broken, so that the color field is of large but finite range. Under these circumstances, the conventional conjecture of perfect confinement of quarks and other color-bearing particles (e.g., diquarks and gluons) no longer holds.

The quark in such a model is expected to be a complex object of relatively large mass (indeed, as the range of the color force tends to infinity, so also does the quark mass) and large size (of order of the range of the color field). The long-range color field of such a highly massive quark should attract nucleons via an induced color dipole-moment. If such a quark is produced in a dense environment of nuclear matter, it might pick up an amount of nucleons comparable in mass to that of the original quark. Indeed, DGJ estimate that in the most stable configuration the nuclear matter has a mass ~ 80% of the quark mass. The presence of a quark excess in the conjectured superdense glob of nuclear matter may therefore provide an attractive force, and aid in compressing the glob to such high density, and in maintaining it in a stable state.

In the DGJ picture of a glob of quark matter bound by an extra quark, the nucleus would have the quantum numbers of a quark. In collisions with air nuclei, the glob will be stripped of its loosely bound matter, and in a central collision a Centauro might be produced. The additional quark necessarily penetrates to sea level. In the more conventional quark matter description, the glob need not penetrate to sea level, and might explode in a central collision with an air nucleus. In the DGJ model, the glob would be stable, and a low energy cut-off in the primary spectrum might be due to the production process for the globs.

EXPERIMENTAL IMPLICATIONS

The hypothesis we have made is so qualitative and so speculative that a detailed theoretical treatment is not likely to be fruitful. There are, however, fairly definite implications for observations. The flux of extremely relativistic high-Z ($Z \gtrsim 30$, $A \gtrsim 50$-100) primaries must be large enough to generate Centauro events. If these high-Z primaries have large penetrating power, as we have conjectured, then there could be a rate for Centauro events at sea level which is within an order of magnitude of the rate at Mount Chacaltaya. These events might be observable in terms of an unexpected amount of energy deposition. A detector with dimensions $\gtrsim$ 30m × 30m, exposed for at least a year, would be necessary to see such events.

In the absence of a catastrophic "Centauro" collision, we would expect that the globs lose per collision at most only a few percent of their energy. The reason for supposing this is best seen in the rest frame of the glob. The slowest particles produced in that frame (the isotropic component) become the fastest in the experimental frame of reference, and should dominate the energy loss. If the mass of this isotropic component or produced "fireball" is m and the mass of the glob is M, then the energy ΔE of the produced fireball in the laboratory frame is

$$\Delta E/E \simeq m/M \equiv k \quad . \tag{1}$$

A reasonable range of values for m is ~ 3-30 GeV leading to $\Delta E/E \lesssim 1\%$ for $M \sim 100$-300 GeV. The differential energy loss of the glob is

$$\frac{d\langle E\rangle}{dx} \sim \frac{k}{\lambda}\langle E\rangle \qquad (2)$$

giving a range

$$R \sim \frac{\lambda}{k} \ln \frac{E}{M} \qquad (3)$$

Using $E \sim 10^6$ GeV and $\lambda \sim 500$ gm/cm^{-2}, we see that $R \sim 10^5$ gm/cm^{-2}. That is, in the absence of the catastrophic "Centauro" collisions, these globs could penetrate 100-1000 m of rock before being stopped. Thus underground experiments might also be relevant. However, again because of the low rate, it is not clear to us that existing underground data offer evidence refuting our hypothesis.

Data from measurements of horizontal air showers, however, appear to provide a stronger constraint.[6] The rate for showers of size $> 10^4$ and with zenith angle $> 70°$ (corresponding to a depth $\gtrsim 3000$ gm/cm^{-2}) is comparable to the rate for Centauro events at Mount Chacaltaya. The penetration length for catastrophic collisions, therefore, should be $\lambda \lesssim 500$ gm/cm^2. We conclude that most globs do not survive catastrophic collisions to arrive at sea level.

Assuming the glob contains a quark, we can estimate the concentration of quarks in the earth from this source. Taking 10^8 years as a characteristic time for quarks to be "stirred" by geological processes within a layer of depth ~ 100 m, we find a mean density of quarks

$$\mathcal{N} \lesssim 10^{-2}\ \mathrm{cm}^{-3} \quad , \qquad (4)$$

safely within experimental limits.[7]

We conclude that the hypothesis we have made, while rather contrived and qualitative, is not obviously in contradiction with what is known. If the practical difficulties are not unreasonable, it might be worthwhile to test this hypothesis experimentally. This testing might be done by improving searches for penetrating relativistic high-Z primaries at high altitudes, and by searching at sea level or underground for unusual energy deposition which might be initiated by such a particle.

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