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**Baryons in cosmic ray showers
and the interaction depth**

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ABSTRACT

Guided by a topological model of baryon production in high-energy collisions, we consider the qualitative effect of secondary baryon production in cosmic ray showers. We argue that the smaller range of baryons, relative to mesons, will tend to reduce the depth of the shower maximum X_{max} without reducing the variation in this observable. This effect could reduce significantly the discrepancy between Fly's Eye data and existing cosmic ray shower Monte Carlo models for incoming protons, and we argue that this effect is unlikely to be washed out by the baryon energy spectrum being soft. We also comment on the likelihood of baryon-rich events mimicking the Centauro data.

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High-energy cosmic ray showers exhibit^(1,2) several features that are not adequately modelled by the Monte-Carlo simulation programs⁽³⁾ currently used, assuming proton primaries. One of these features is the depth of the shower maximum X_{max} observed by the Fly's Eye experiment.⁽¹⁾ This is significantly smaller ($X_{max} \simeq 690 \pm 3 \pm 20 \text{ g cm}^{-2}$) than expected on the basis of existing simulations of showers initiated by primary protons ($X_{max} \simeq 803 \pm 2 \text{ g cm}^{-2}$). The measured value of X_{max} agrees better with simulations of showers initiated by nuclei such as Iron ($X_{max} \simeq 705 \pm 3 \text{ g cm}^{-2}$). On the other hand, the observed variation in X_{max} , ($\sigma \simeq 85 \pm 2 \text{ g cm}^{-2}$), is in good agreement with simulations of proton-induced showers ($\sigma \simeq 80 \pm 1 \text{ g cm}^{-2}$), whereas a smaller variation is expected for nucleus-induced showers ($\sigma \simeq 66 \pm 2 \text{ g cm}^{-2}$), essentially because they contain a larger number of secondaries.* Another potentially interesting feature of high-energy cosmic rays is the existence of "Centauroids"⁽⁴⁾ and "mini-Centauroids" events that appear to contain relatively few photons compared to the number of charged particles.

In this paper we consider the possibility that secondary baryon production might help explain either or both of these features. The possible rôle of baryons in the Fly's Eye experiment might be to speed up shower development and yield a smaller value of X_{max} , because baryonic secondaries have a shorter range than the pions, without affecting significantly the total number of secondaries and hence not altering predictions for the variation in X_{max} . The possible rôle of baryons in modelling Centauroid events is a potential source of charged particles that need not be accompanied by as many photons as could be expected if all the secondaries were pions.

A detailed study of these possible rôles of secondary baryons would eventually require their incorporation in Monte-Carlo programs for simulating cosmic ray shower development in the upper atmosphere. We will not attempt that here.

* A dominant heavy-element composition for ultrahigh energy cosmic rays would be inconsistent with a cutoff and hump at $\sim 10^{19}$ eV due to cosmic ray interactions with the 3° K background⁽⁵⁾.

However, the potential significance of the effect could perhaps be gauged in advance by considering baryon production in a model for proton-nucleus collisions. In fact, we shall use a crude topological model⁽⁶⁻⁷⁾ for particle production in high-energy e^+e^- annihilation. The possibility of its relevance to high-energy hadron-hadron collisions rests on the similarities between multiparticle production in e^+e^- annihilation and hadron-hadron collisions at lower energies, and on the model's successes in explaining baryon production in low-energy e^+e^- annihilation, including the total multiplicity and the energy-fraction distribution,⁽⁸⁾ and in predicting⁽⁹⁾ the total charged multiplicity subsequently observed at LEP.⁽¹⁰⁾

Using the topological model's prediction for the number of secondary baryons produced in collisions with the centre-of-mass energy of 1 TeV, we find it possible to explain a significant fraction of the discrepancy between the Fly's Eye data⁽¹⁾ and Monte-Carlo models⁽³⁾ that neglect such secondary baryon production. Moreover, the energy-fraction distribution predicted by the model is sufficiently hard that the effect of the shortness of the baryonic mean free path is not compensated by a soft spectrum. The topological model predicts more baryons than might have been expected naïvely, and baryon and photon multiplicity distributions that are not Poisson. These effects do not give a large number of "Centauroid-like" events, although occasionally "mini-Centauroid-like" events may occur.

We start by discussing the possible rôle of secondary baryons in cosmic ray shower development. It is well-known that X_{max} depends on the total cross-section σ_{tot} and the inelasticity K . We will assume that all the cosmic ray primaries are protons, and leave σ_{tot} and K the same as in conventional simulations of proton-induced showers. We will neglect the probable admixture of alpha particles. We expect that

$$X_{max} \simeq R_p + c(R_s) \quad (1)$$

where R_p is the range of protons in air, and (R_s) is the average range of secondaries. We parametrize the secondaries as having probability p of being pions and $1 - p$

of being baryons, so that

$$\langle R_s \rangle = pR_\pi + (1-p)R_p \quad (2)$$

where R_π is the range of pions in the air. We therefore expect that

$$\Delta X_{max} = X_{max}(p) - X_{max}(1) \simeq c(1-p)(R_p - R_\pi) \quad (3)$$

Is is known that at low energies $\sigma_{tot}(\pi N) \simeq \frac{2}{3}\sigma_{tot}(pN)$, in agreement with naïve quark-model counting.* We assume that this is also the case at higher energies,

$$R_\pi \simeq \frac{3}{2}R_p \quad (4)$$

Substituting into equation (3), we therefore find

$$\Delta X_{max} \simeq -\frac{c}{2}(1-p)R_p \quad (5)$$

where

$$X_{max}(1) \simeq \left(1 + \frac{3c}{2}\right) R_p \quad (6)$$

in the naïve model without secondary production.

The calculation of X_{max} requires knowledge of R_p , c and p . Once $\sigma_{tot}(pN)$ is fixed, so is R_p . We assume that in the energy range (1 to 10 TeV) of interest to the Fly's Eye experiment $\sigma_{tot}(pp) \approx \sigma_{tot}(p\bar{p}) \simeq 72 \text{ mb}$,⁽¹⁰⁾ corresponding to $\sigma_{tot}(pN) \simeq 580 \text{ mb}$ in air and hence

$$R_p \simeq 50 \text{ g cm}^{-2} \quad (7)$$

Equation (6) then tells us that within the simplified parametrization (1), with

* For example, at $E_{cm} \simeq 25 \text{ GeV}$ $\sigma_{tot}(\pi^+p) \sim 25 \text{ mb}$, while $\sigma_{tot}(pp) \sim 40 \text{ mb}$.⁽⁹⁾

$X_{max}(1) \simeq 803 \text{ g cm}^{-2}$, the constant of proportionality is given by

$$c \simeq 10 \quad (8)$$

Equation (5) then suggests that the effect on the calculated value of X_{max} of a non-zero baryon production probability p would be

$$\Delta X_{max} \simeq -250(1-p) \text{ g cm}^{-2} \quad (9)$$

which might well be a significant effect.

Data⁽¹¹⁻¹³⁾ on the e^+e^- annihilation into jets at centre-of-mass energies $\simeq 40 \text{ GeV}$ indicate that

$$\frac{\#(p + \bar{p})}{\#(\text{charged particles})} \simeq 0.1 \quad (10)$$

for energy fractions $z = E/E_{jet} \sim 0.2$. Assuming for simplicity equal numbers of π^0, π^+, π^- and equal numbers of $n, \bar{n}, p$ and $\bar{p}$, the result (10) would correspond to $p \simeq 0.87$. In fact, the discussion in the next paragraph indicates that the probability p might be even lower.

In a topological model^(4,6) for baryon production in e^+e^- collisions we find that the baryon-to-meson multiplicity ratio tends to increase at higher energies. Fig. 1 shows our predicted baryon multiplicity distributions for centre-of-mass energies $E_{cm} = 100, 10^3 \text{ GeV}$ and we note quite a rapid increase. Calculating the absolute value of the mean of the meson multiplicity and its distribution is not possible without extra assumptions, but we do expect⁽¹⁴⁾ the mean baryon multiplicity to grow more rapidly than the mean meson multiplicity in the present range of E_{cm} , as seen in Fig. 2. On the basis of the topological model results in this figure we estimate $p \simeq 0.75$ at a centre-of-mass energy $E_{cm} \sim 1 \text{ TeV}$, typical of the Fly's Eye experiment. This would correspond, via equation (9), to a reduction of X_{max} of about 60 g cm^{-2} , which would remove about half of the discrepancy between the Fly's Eye value of X_{max} and existing baryon-less Monte-Carlo simulations⁽¹⁾ of proton-induced showers.[†]

† Moreover, one expects some alpha particles as well as protons from any cosmic ray source.

This effect could in principle be partially or totally compensated if the secondary baryon spectrum was very soft, in which case baryonic secondaries would be inefficient at dissipating the shower energy. We implicitly neglected any difference between meson and baryon energy distributions in deriving equation (9). In point of fact, both the low-energy e^+e^- data and our topological model^[6,8] for jet fragmentation indicate a substantial hard component in the baryonic energy fraction distribution, as illustrated in Fig. 3. Indeed, we expect a constant or even slightly rising meson-to-baryon ratio at large $z = E/E_{jet}$. Therefore we think that the possible effect of baryonic secondaries is unlikely to be substantially compensated by a softer energy distribution.

It should be recalled that although baryon-less Monte-Carlo models of proton-induced showers fail to estimate X_{max} correctly, they do find the correct variation σ for X_{max} . However, Monte-Carlo simulations of showers induced by heavy nuclei, although they give X_{max} correctly, give too small a value for σ .^[11] This is essentially because nucleus-induced showers contain more secondary particles, and therefore the shower fluctuations from event to event are reduced. Since the inclusion of baryons in showers does not significantly alter the total number of particles in the shower, we do not expect the predictions for σ of the baryon-less Monte-Carlo simulations of proton-induced showers to be significantly altered.

It therefore seems that the inclusion of secondary baryons in Monte-Carlo simulations of proton-induced showers could go some way towards explaining the values of X_{max} and σ found by the Fly's Eye experiment,^[11] without postulating a significant nuclear component in high-energy cosmic rays. However, this suggestion needs to be investigated more deeply by including a realistic model for secondary production into Monte-Carlo simulations of cosmic ray showers.

We end this paper by commenting on another surprising feature of high-energy cosmic rays, namely the appearance of "Centauroids" and "mini-Centauroids" events in which there are relatively few photons.^[12] Events with large numbers of baryons and relatively few pions would have this property, so the question is how often they

would occur. Our topological model^[6-7] for hadron production in jets suggests, as mentioned above, that the baryon-to-pion ratio should increase at higher energies. Moreover, the baryon multiplicity distribution is not expected to be Poisson, as seen in Fig. 1. There is an enhanced probability for events with a high number of baryons, although these are still quite rare. The underlying reason for this is the enhanced combinatorial probability of producing a topologically non-trivial defect in the chiral condensate field if there are large numbers of partons in the final state. In other words, the topological model predicts that the number of baryons produced grows faster than the number of partons. The combination of large numbers of baryons and large fluctuations suggest that Centauroid events might be possible, but to answer this question one needs a more detailed model for the meson multiplicity distribution. Conservatively, we hypothesize that each link in a triangulation of space using partons as vertices has a fixed probability $m(1-m)$ for (not) producing a meson, with the value of m chosen as to obtain the correct total mean charged multiplicity at some low energy. This predicts uniquely the meson multiplicity distribution at all energies. Figure 4 is the resulting "LEGO" plot of the proton plus antiproton multiplicity versus the photon multiplicity (including only $\pi^0 \rightarrow 2\gamma$). We see that a few "mini-Centauroid-like" events appear with $\#(p + \bar{p}) \simeq \#(\gamma)$, whereas traditional models would not have such events.

A more detailed Monte-Carlo simulation would again be needed to substantiate this suggestion, but we do feel that the possibility of explaining mini-Centauroid-like events by fluctuations in conventional physics is worthy of this further study.

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FIGURE CAPTIONS

- 1) The topological model prediction ^[5,6] of baryon multiplicity distributions at $E_{cm} = 100$ GeV (dot-dash line) and 10^3 GeV (continuous line). The continuous line is the Poisson distribution with the same mean ($\langle n_B \rangle = 4.55$) as the predicted distribution at 10^3 GeV.
- 2) The topological model prediction ^[5,6,7] for the ratio n_B/n_{ch} of mean charged baryon (proton plus antiproton) multiplicity and the mean total charged multiplicity, as a function of E_{cm} .
- 3) The topological model prediction ^[5,6] of the baryonic energy-fraction distribution at $E_{cm} = 1$ TeV.
- 4) "LEGO" plot of the predicted proton plus antiproton multiplicity versus the photon multiplicity (including only $\pi^0 \rightarrow 2\gamma$) at $E_{cm} = 1$ TeV.