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The string percolation model and the interpretation of cosmic ray data above 10^{17} eV.

J. ALVAREZ-MUÑIZ[1], P. BROGUEIRA[2], R. CONCEIÇÃO[3], J. DIAS DE DEUS[2,4], M.C. ESPÍRITO SANTO[2,3], M. PIMENTA[2,3]
[1]*Dept. Física Partículas & IGFAE, Univ. Santiago de Compostela, 15782 Santiago, SPAIN*
[2]*Departamento de Física, IST, Av. Rovisco Pais, 1049-001 Lisboa, PORTUGAL*
[3]*LIP, Av. Elias Garcia, 14-1, 1000-149 Lisboa, PORTUGAL*
[4]*CENTRA, Av. Rovisco Pais, 1049-001 Lisboa, PORTUGAL*
jaime@fpaxp1.usc.es

Abstract: The study of the energy dependence of the depth of shower maximum and of the muon content in high energy cosmic ray showers are two widely used methods for the derivation of cosmic ray composition. An alternative interpretation of the energy dependence of these two observables is a change in the features of hadronic interactions at high energy. In this contribution we show that the string percolation hadronic model provides a consistent interpretation of cosmic ray data above 10^{17} eV. In particular we discuss the importance of the inelasticity and of the particle multiplicity in the most energetic shower interactions, as well as the crucial role played by the nature of the leading primary.

Introduction

The composition of cosmic rays (CRs) at high energies is still a matter of controversy. Two shower variables are used as experimental handles on composition, namely, the atmospheric depth of shower maximum $X_{\max}$, measured in fluorescence detectors, and the muon content of the shower on ground N_μ, measured in surface array detectors.

Fly's Eye/HiRes experimental data on the energy dependence of $X_{\max}$ show an increase in the slope around 10^{17} eV [1]. Concerning the muon component, at the AGASA array the lateral distribution function of muons was measured above 10^{17} eV and combined with the Akeno array data. It was observed that the slope of the density of muons at 600 m from the shower core $\rho_\mu(600)$ vs E is flatter in data than predicted by hadronic models. Assuming $\rho_\mu \propto E^\beta$, data gives $\beta = 0.84 \pm 0.02$ [2, 3], while from simulation $\beta \sim 0.9$ ($\beta = 0.92$ (0.89) for protons with QGSJET (SIBYLL), while for Fe $\beta = 0.88$ (0.87) [2]). Both features have been interpreted as a change in composition, going from more Fe-like to more proton-like showers. The HiRes-Mia muon data yield $\beta = 0.73$ [4], which seems to indicate a composition heavier than Fe at 10^{17} eV.

In this work we give an alternative interpretation of the energy dependence of $X_{\max}$ and N_μ as a change with energy of the features of hadronic interactions, and show that the string percolation model provides a consistent interpretation of cosmic ray data above 10^{17} eV.

The interpretation of cosmic ray data above 10^{17} eV

The features exhibited by CR data above 10^{17} eV have been attributed to a change in composition from heavier to lighter primaries as E increases. An alternative interpretation is a change in the features of hadronic interactions. In this interpretation a key role is given to the main variables characterising the first hadronic collisions.

The composition interpretation

Using Heitler's model of shower development [5], the average location of $X_{\max}$ in a shower initiated by a primary nucleus of energy E with A nucleons, is given by $\bar{X}_{\max} \simeq \bar{X}_1 + \bar{X}_0 \log(E/A)$, where $\bar{X}_1$ is the average depth of the first collision and $\bar{X}_0$ is the elongation rate. The muon content of the shower can be written as, $\bar{N}_\mu \simeq A(E/A)^\beta$. We then have,

$$\frac{d\bar{X}_{\max}}{d\log E} = \bar{X}_0 \left[1 - \frac{d\log A}{d\log E}\right], \qquad (1)$$

and for the $\log N_\mu$ dependence on E,

$$\frac{d\log N_\mu}{d\log E} = (1-\beta)\frac{d\log A}{d\log E} + \beta\,. \qquad (2)$$

As experimentally, above 10^{17} eV $d\bar{X}_{\max}/d\log E$ is larger and $d\log N_\mu/d\log E$ is slightly smaller, in comparison with lower energies, the conclusion is:

$$\frac{d\log A}{d\log E} < 0\,, \qquad (3)$$

i.e., for $E \gtrsim 10^{17}$ eV the average mass number should, in this interpretation, decrease with E.

The first collisions interpretation

Among the most important variables characterising the first hadronic collisions are the inelasticity K, defined as the fraction of energy distributed among the secondary particles except for the leading particle, the average (non-leading) multiplicity $\langle n \rangle$ at the collision energy and P_0, the probability of producing a leading π^0 in the collision.

Changing A has a similar effect on the behavior of $X_{\max}$ and N_μ with energy as changing K. The fastest particle in the collision, carrying an energy $(1-K)E$, will originate the shower branches that go deeper in the atmosphere. We can then write, $\bar{X}_{\max} \simeq \bar{X}_1 + \bar{X}_0 \log[(1-K)\frac{E}{E_0}]$, where E_0 is a low energy threshold. Regarding the muon content of the shower, a possible assumption is that while energy flows in the $(1-K)$ direction, the number of muons flows in the K direction and $N_\mu \sim N_\pi^\pm \propto KE$. We thus have,

$$\frac{d\bar{X}_{\max}}{d\log E} = \bar{X}_0 \left[\frac{d\log(1-K)}{d\log E} + 1\right], \qquad (4)$$

and

$$\frac{d\log N_\mu}{d\log E} = \frac{d\log K}{d\log E} + 1\,, \qquad (5)$$

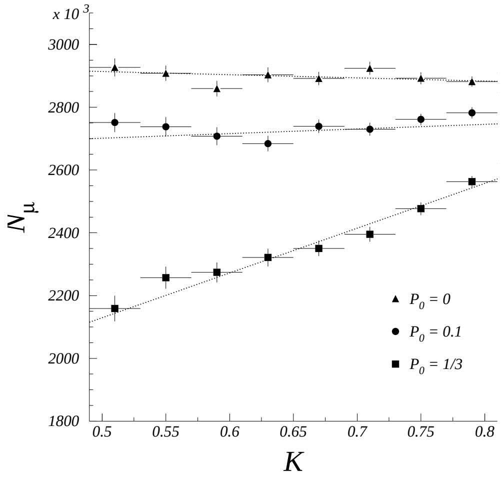

Figure 1: Hybrid Monte Carlo simulation prediction for the number of muons at ground as a function of inelasticity for different values of the probability P_0 of having a leading π^0 in a proton-induced shower of $E = 10^{18}$ eV.

Since above 10^{17} eV, $d\bar{X}_{\max}/d\log E$ is larger and $d\log N_\mu/d\log E$ smaller than at lower E, we infer that:

$$\frac{d\log K}{d\log E} < 0\,, \qquad (6)$$

i.e., the features in CR data can be alternatively explained by an inelasticity K decreasing with E.

A crucial point in this interpretation is the validity of the relation $N_\mu \propto K$ which depends strongly on P_0. In fact, when the leading particle is a proton carrying an energy $(1-K)E$, the number of muons decreases with K due to the combination of two effects: on one hand the production of secondary π^0s, which decay into γs, carrying an energy $\sim 1/3\ KE$ that is lost for muon production. On the other hand, the larger the K the smaller the energy carried by the leading particle, and hence the smaller the number of new charged pions and muons it will produce. However, if π^0's are themselves leading particles - $P_0 > 0$, (as it happens in percolation models), muons can only be produced in the K direction and N_μ is larger the larger the inelasticity. This can be seen in a very simplistic model in which the number of muons is proportional to the energy available for muon production in the first interaction $N_\mu \sim (1-P_0)\ (1-K)E +$

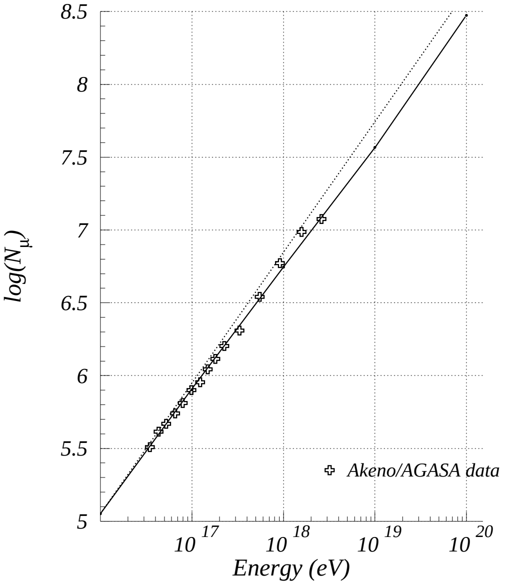

Figure 2: N_μ vs E. The results of the string percolation model (solid line) are compared to the Akeno/AGASA data (crosses). The dotted line corresponds to $N_\mu \propto E^{0.9}$ as predicted by most of the standard hadronic models.

$(2/3)\ KE$, where the factors $(1-P_0)$ and $2/3$ account for the energy lost into the electromagnetic branch. As a consequence,

$$\frac{dN_\mu}{dK} \sim (P_0 - \frac{1}{3})E, \qquad (7)$$

showing that the behavior of N_μ with K depends on P_0. The fact that it inflects at the particular value $P_0 = 1/3$ comes from the very simplistic treatment and cannot be taken seriously. This effect has been confirmed by a numerical implementation of P_0 in a full hybrid Monte Carlo simulation of shower development [6]. The result is shown in Fig 1, where the crucial role played by P_0 on the variation of N_μ with K is apparent.

Interpretation of CR data within the string percolation model

In string models of hadronic interactions, the production of secondaries in a collision is described in terms of color strings stretched between partons of the projectile and target. These strings fragment into new strings through $q-\bar{q}$ production and subsequently hadronize into particles. At low energy (or density) valence strings are formed, containing most of the collision energy. As the energy increases, additional sea strings, central in rapidity, are created taking away part of the energy carried by the valence strings. Softer secondaries are produced and K increases with energy. As energy (or density) increases, the number of strings increases. Strings, that look like small disks in transverse space to the collision axis, begin to overlap forming clusters and a cumulative effect occurs: the length in rapidity of fused strings is larger. At that stage fused (percolated) sea strings take over valence strings, and decay producing large rapidity secondaries. As a consequence K decreases above the percolation threshold at $E \simeq 10^{17}$ eV [7]. Percolation is in fact a mechanism for producing fast leading particles. It is worth mentioning that essentially all existing high energy strong interaction models based on QCD predict an increase with energy of K.

Percolation will also affect the multiplicity. Due to the fusion of strings less softer secondaries are produced and the multiplicity is reduced with respect to models in which strings decay independently. Besides, and since fused strings are sea strings of the $q-\bar{q}$ type, the fast leading secondaries that are produced can be π^0s with a probability P_0 that tends to $1/3$.

We have implemented the predictions of the string percolation model into the hybrid Monte Carlo simulation for all interactions above the percolation threshold, with a constant $P_0 = 1/3$; an inelasticity K decreasing with energy [8], and with a reduction of the multiplicity realized through a color summation factor [7]. In Fig. 2 we show the prediction of percolation on the behavior of N_μ with E. A fit to our results yields $\beta = 0.83$ compatible with the experimental value measured by the Akeno/AGASA array $\beta = 0.84 \pm 0.02$. In this study protons were used as primaries and the result in Fig. 2 corresponds to shifting the proton result to an intermediate and constant composition $A \sim 20$. It is interesting to note that when $E > 10^{19}$ eV, the Lorentz boost factor of π^0s is large enough so that they begin to interact instead of decaying, increasing the production of muons. A hint of this effect is seen in Fig. 2.

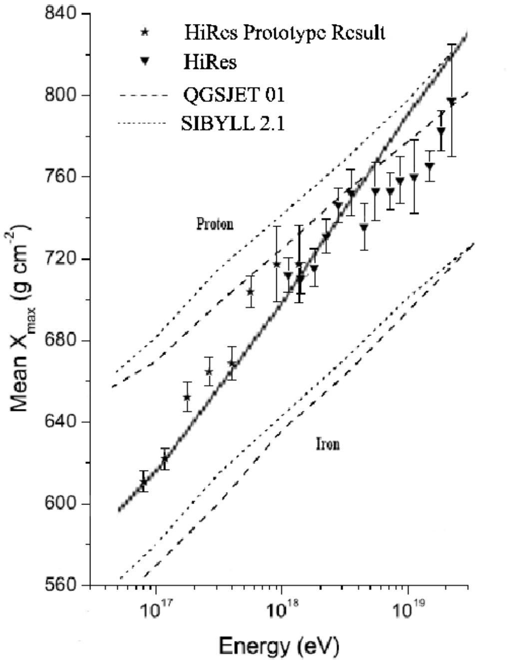

Figure 3: $X_{\max}$ vs E in the percolation model (solid line) along with data (symbols) and the predictions of SIBYLL and QGSJET.

Finally in Fig. 3 we show the prediction of the string percolation model on the behavior of $X_{\max}$ vs E. The prediction is reasonably consistent with data, following the tendency of the slope around 10^{17} eV. A slight overshoot of $X_{\max}$ can be seen at $E > 10^{18.5}$ eV. Clearly a full percolation Monte Carlo with evolution in E of all the relevant variables, including P_0, usable in air shower simulations, is needed. The solid line in Fig. 2 corresponds to the prediction for proton primaries scaled by a constant composition of $A \sim$ 15-20, the same average A with which the N_μ vs E prediction was scaled.

Conclusions

A string percolation hadronic model predicting a decrease of inelasticity K with energy above the percolation threshold ($E \simeq 10^{17}$ eV), a reduction of the average multiplicity $\langle n \rangle$, and a probability P_0 that the leading particle is a π^0 tending to $1/3$, can contribute to give a consistent explanation of the features of CR data in the energy range above 10^{17} eV, without the need for a composition changing with energy. More data above 10^{17} eV confirming the $X_{\max}$ and N_μ behavior with energy is also desirable.

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