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LETTER TO THE EDITOR

Relevance of cosmic ray data above 10^{12} eV to models of high energy interactions

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Abstract. Recent experiments on proton–proton collisions with the intersecting storage ring facility have shown a number of features which may be explained by the high energy 'scaling' model of Feynman. We have examined cosmic ray data in some detail to 10^{18} eV and find that they do not support the model being valid, at least without serious modification, to these much higher energies.

In a previous paper (Wdowczyk and Wolfendale 1972) an examination was made of the implications for high energy cosmic rays of the 'scaling' model of Feynman (1969) being valid at all energies. It was pointed out that although at first sight cosmic ray data could be brought into agreement by assuming an increase of the mass of the primary cosmic rays with increasing energy, it was very necessary that a variety of cosmic ray data, particularly concerning extensive air showers, should be examined in detail before a firm conclusion could be made. In the present letter we give a summary of such a detailed examination.

It is first necessary to study the extent to which a model for high energy nucleon–nucleon collisions can be used in the cosmic ray situation which comprises nucleon–air nucleus collisions. A number of experimental results have been examined (particularly the precise data from CERN at 24 GeV/c by Eichten *et al* 1972) and it is found that the effect of intranuclear cascading, which in principle will cause a difference between the two classes of collisions, is rather small. In what follows the effect of cascading is disregarded.

A prominent feature of the scaling hypothesis is the logarithmic rise with increasing primary energy of the mean multiplicity of secondaries produced in collisions (figure 1, curves S1 and S2). Other facts of importance are the expected constancy of multiplicity of secondaries carrying a significant fraction of the primary energy (say, those with more than 10%) and the rapid saturation of the mean transverse momentum of the secondaries. In many previous studies of high energy cosmic rays (eg by Adcock *et al* 1969 and Hillas *et al* 1971) it was shown that a multiplicity law of the form E_p^{α} with α near $\frac{1}{4}$, was applicable. Clearly the biggest difference between $E_p^{1/4}$ and $\ln E_p$ is at the highest energy and it is in this region that we shall commence this study.

As pointed out in our earlier work there is immediately the question of primary mass. In general, the problem of the identification of the mass of the primary cosmic rays has not been solved but we now believe that there is reasonable evidence for at least a significant fraction of the primaries being protons right up to the highest energies. The reason for this statement is the observation in a number of experiments

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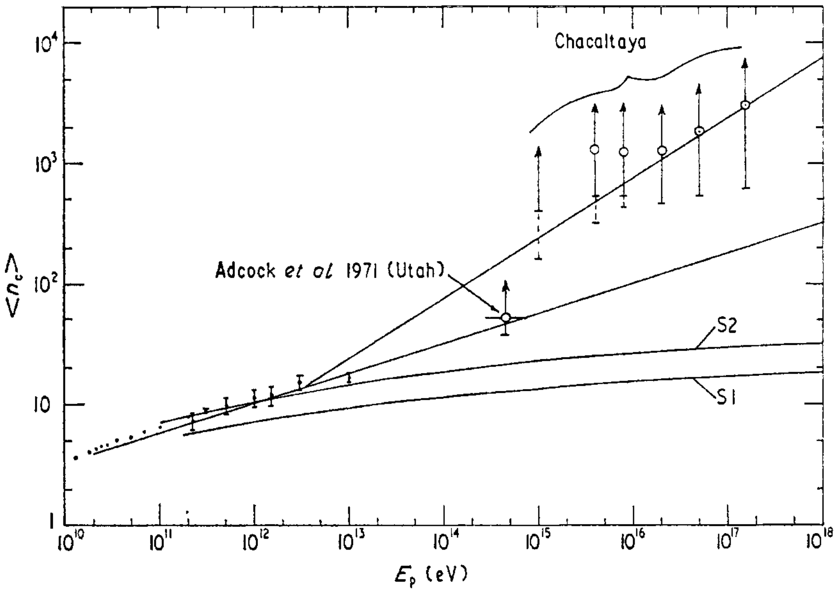

Figure 1. Mean multiplicity of charged secondaries, $\langle n_c \rangle$, in high energy collisions. Below 2×10^{12} eV the data refer to accelerator experiments on p–p collisions and are derived from the summary of Jacob (1972). Between 2×10^{12} eV and 2×10^{13} eV they refer to hadron–emulsion nucleus interactions; the point at 3×10^{12} eV is from the summary by Lohrmann and Teucher (1962) and refers to events with no black tracks, and the point at 10^{13} eV comes from the summary by Gonguli and Malhotra (1972) and relates to interactions with fewer than three black tracks.

At higher energies the multiplicities are weighted means for cosmic rays primary–air nucleus collisions. Details are given in the text.

The straight lines refer to the $E^{1/4}$ and $E^{1/2}$ multiplicity 'laws' used in previous work (eg Adcock *et al* 1971) and the scaling 'laws' S1 and S2 refer, respectively, to fits by Boggild *et al* (1971) to accelerator data at 19 GeV/c, and by Morrison (1972) to accelerator data at ISR energies.

of phenomena which indicate fluctuations in longitudinal development of the showers, such as would arise from protons with their long interaction mean free path. The evidence prior to 1968 was considered by Adcock *et al* (1968) and it was concluded there that a distinction could not be made between the 'normal' composition (ie mainly protons) and one in which the fraction of heavy nuclei slowly increased above 10^{15} eV due to an assumed galactic modulation mechanism. However, with the latter composition the energy dependence of the mean primary mass would be much less than that required in the analysis of Wdowczyk and Wolfendale (1972); with the mean mass required in the latter treatment the predicted fluctuations would be less than those observed. Confirmation for the view that protons predominate in the energy region at least up to 10^{17} eV comes from recent studies by Khristansen *et al* (1971) and Catz *et al* (1972, private communication) of the fluctuations of shower age.

If it is assumed that the fraction of protons in the primary radiation is considerable then the data on the longitudinal development of showers can be used to give information about the form of the multiplicity law. The sensitivity arises because the position of the shower maximum is determined by the length of the electromagnetic cascades resulting from the generated neutral pions. For the scaling model a few very energetic neutral pions are produced, the cascades are long and the shower maximum will be low in the atmosphere, whereas with high multiplicities the cascades are much shorter and the shower maximum correspondingly higher. The best experimental measurements appear to be those of Bradt *et al* (1966) and Antonov *et al* (1971) on extensive air showers recorded at mountain altitude (Chacaltaya) and aeroplane altitudes respectively. In the work of Bradt *et al* the intensity of showers was studied as a function of zenith angle and information about longitudinal development was thereby derived; the work of Antonov *et al* gave information for near vertical showers. The result is an estimate of at least a lower limit to the height above sea level at which the maximum number of particles in the shower occurs. These maxima are found to be systematically higher than those predicted by the scaling law and, indeed, somewhat higher than would occur for an $E_p^{1/4}$ law. An estimate of the multiplicity of those secondary particles carrying the majority of the energy has been made and this is given in figure 1. (It is assumed in the analysis that the number of charged pions is twice the number of neutral pions.) The dotted lines arise if the Chacaltaya data alone are considered.

In the same energy region measurements on the attenuation length of showers, muon lateral distributions and height of origin of Čerenkov radiation all indicate a more rapid degradation of primary energy than would follow from the scaling hypothesis.

Continuing to lower energies there is a useful set of data from the work of the Utah group (Coats *et al* 1970, Cannon and Stenerson 1971) in which a large muon detector was operated underground. At the primary energies in question (10^{14}–10^{15} eV) the primary composition is known with greater confidence and is indeed thought to be mainly protonic. This is because such direct measurements as have been made of the composition show that at least up to 5×10^{12} eV protons dominate and an unreasonable spectrum would need to be adopted in order to reverse this situation by 10^{14} eV. Furthermore, the fluctuation considerations referred to earlier extend down to 10^{15} eV and these give the same result. In an earlier work (Adcock *et al* 1971) the data of Coats *et al* and Cannon and Stenerson were analysed and, again, agreement was found with an $E_p^{1/4}$ law. More recent calculations have been made and these show clear inconsistency with the predictions for scaling. The multiplicities derived from the analysis of the Utah data are indicated in figure 1. It should also be pointed out that the analysis by Adcock *et al* (1970) of the experiments of Coats *et al* (1970) indicated a mean transverse momentum ($0{\cdot}6\pm0{\cdot}05$ GeV/c) which is somewhat higher than the asymptotic limit from scaling.

A comparison of the derived multiplicities and the scaling predictions of figure 1 shows clear inconsistency, at least above 10^{14} eV. In fact, the comparison of the cosmic ray data with the scaling predictions is not strictly valid because of the different energy spectra in the respective analyses—the separation of the effective multiplicities will indeed be greater than shown and this is the reason for the upper limits to the errors being as shown. It should also be remarked that the two sets of cosmic ray data are affected differently by fluctuations in multiplicity and this is probably the main reason for the apparent difference in best estimates near 10^{15} eV.

Continuing downwards still further in primary energy there is the region between 10^{12} and 10^{14} eV which is still accessible only in the cosmic radiation. There is some evidence here in favour of scaling from the near constancy of the charge ratio of cosmic ray muons, the data in question relating to primary energies below about 2×10^{13} eV. A similar situation exists for the shape of the muon spectrum, which corresponds to a pion production spectrum having a differential exponent of $2{\cdot}75 \pm 0{\cdot}1$ in the region where it has been measured: $E_\pi \lesssim 10^{14}$ eV (the exponent is the quantity γ in the relation $N(E)\mathrm{d}E = \mathrm{A}E^{-\gamma}\mathrm{d}E$). However, it has been realized recently that the primary spectrum which had been thought of as having a constant slope from about 10^{11} to 10^{15} eV may suffer a change of slope in this region. The evidence is the fact that the most recent direct measurements, by Ryan *et al* (1972), give a differential exponent of $2{\cdot}75 \pm 0{\cdot}03$ up to a few times 10^{12} eV but on extrapolating this spectrum to 10^{15} eV the intensity is nearly a decade too low to fit the value derived from EAS data. Now this intensity is known rather well in so far as it comes from measurements made near shower maximum where nuclear interaction model details are not too important; if the 10^{15} eV point is required to be fitted then the primary spectral index must diminish above 10^{12} eV to about 2·47. This exponent is now significantly lower than the pion production spectrum exponent and if the hypothesis about the reduced slope of the primary spectrum is correct this means that although the scaling hypothesis is in general agreement with the cosmic ray data below a few times 10^{12} eV it ceases to be valid at higher energies.

The conclusion from the cosmic ray data is thus that scaling in its simple form becomes less and less applicable as the energy exceeds 10^{12} eV. A possible explanation is that there are two types of collisions, one following a scaling mechanism and the other following a statistical mechanism and that the rôle of the latter process becomes more important at higher energies.

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