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Extrapolation of Hadronic Physics to Air Shower Energies

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EXTRAPOLATION OF HADRONIC PHYSICS TO AIR SHOWER ENERGIES

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ABSTRACT

In this talk I review the role of hadronic interactions in interpretation of data from air shower experiments with energies $\gg 100$ TeV.

1 Introduction

The flux of cosmic rays above 10^{14} eV is so low that it has been necessary to use ground-based air shower detectors with large exposure factors to study a large sample of events. Interpretation of air shower data to obtain information of astrophysical interest requires extrapolation of the physics of hadronic interactions beyond the kinematic region covered by accelerator experiments. At the same time, it is possible in principle to learn something about hadronic interactions from the cosmic ray data.

Fixed target accelerator experiments, in which the full kinematic range can be studied for charged hadrons interacting on a variety of nuclear targets, are available for $E_{\rm lab} < 1$ TeV. Collider experiments presently extend to $\sqrt{s} \sim 1$ TeV, equivalent to $E_{\rm lab} \sim 1000$ TeV, but only the central region is accessible.[b] Atmospheric cascades depend strongly on the forward fragmentation region, however, because that is where the energy content is. Of particular importance is the inelasticity, i.e. the fraction of energy not carried off by the fragment of the incident hadron in a collision of an energetic hadron with a target nucleus. This energy is available for production of secondary particles and is therefore important in determining how fast cascades develop. Voyvodic presented at this conference [3] a nice analysis of inelasticity and energy flow as derived from present accelerator experiments.

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[b] An exception is the UA7 experiment at the CERN $\bar{p}p$ collider,[1, 2] which gives limited information about π^0 production at large Feynman x.

The uncertainty of how to extrapolate beyond the existing data implies a corresponding uncertainty in the interpretation of the air shower experiments. In this talk, I discuss two examples: coincident multiple muons deep underground and longitudinal development of air showers. In both cases, a principal astrophysical goal of the measurements is to determine the elemental composition of the incident cosmic radiation. An important constraint comes from direct measurements of the primary spectrum and composition with experiments flown on balloons and sattelites. At present, direct measurements extend to just above 100 TeV, which is the very low energy end of the air shower range. An initiative to extend direct measurements to 10^{15} eV, and thus to obtain a full decade of overlap with air shower experiments, is discussed in a separate paper submitted to this conference.[4]

2 Multiple muons

There are several deep underground experiments [5, 6, 7, 8, 9, 10] which use the overlying rock as a filter to observe muons which had $E_\mu > E_\mu(\min) \sim 1$ TeV when they were produced by cosmic ray interactions in the atmosphere. Some of these [11, 10] have also reported results of coincidences between underground muons and the shower size measured at the surface, which gives an indication of the primary energy of the event. Relative rates of coincident muons as a function of multiplicity are sensitive to primary composition in the energy range from roughly 10^{14} to 10^{17} eV, depending on the depth and the size of the underground detector. This includes the "knee" of the spectrum around 5×10^{15} eV where the spectrum becomes steeper. There is great interest in understanding the composition in this energy region because of its potential significance for the origin and acceleration mechanism of high energy cosmic rays.[12, 4, 13, 14, 15]

The sensitivity of multiple muons to primary composition arises because heavy primaries of high energy produce more $\sim$ TeV muons than protons of the same total energy.[16] The interpretation is obscured, however, because, in the energy region beyond the reach of direct experiments, it is possible to adjust the intensity and the composition of a trial spectrum simultaneously. Thus there may be more than one solution consistent with a given set of observations. The ambiguity can in principle be reduced by studying surface-underground coincidences. Another check is to use the same models to simulate different kinds of air shower experiments, such as the size spectrum measured at the surface.

A principle source of uncertainty in interpretation of coincident multiple muons is the finite area of the underground detector. One must either rely on simulations to calculate the lateral distribution and hence the probability matrix for observing n muons when $m \geq n$ are present at the depth of the detector or one must reconstruct the true multiplicity distribution from the observed one with the help of measured separations. In the case of simulations, one of the most

uncertain aspects of the calculations is unfortunately the transverse momentum distributions of the parent pions and kaons that determine the separation of the observed muons. The reconstruction option is also problematic because it depends in part on knowledge of the separation distribution at distances from the shower core larger than the dimension of the detector.

I have discussed the uncertainties in models of hadronic interactions relevant to the underground multiple muon data and their effects on its interpretation in detail elsewhere.[15] Here I show in Fig. 1 a result obtained previously,[17] which illustrates the sensitivity of underground coincident muons to composition. The data points are from the Frejus experimen showing the reconstructed multiplicity distribution at the depth of the detector.[7] The calculations [17] are made for three different primary compositions using the parametrizations of Forti *et al.*[18] The solid line is for a primary spectrum that contains 80% protons above 10^{15} eV. The dashed line is for the opposite case, 80% primary iron above 10^{15} eV, with an identical "all-particle" spectrum (i.e. the same intensity of nuclei as a function of total energy per nucleus). The dotted line is for a spectrum with a rigidity-dependent steepening at 3×10^6 GV and a slightly lower total intensity than the other two spectra above 100 TeV. A similar result favoring "light" composition been obtained by the MACRO group from their data.[6]

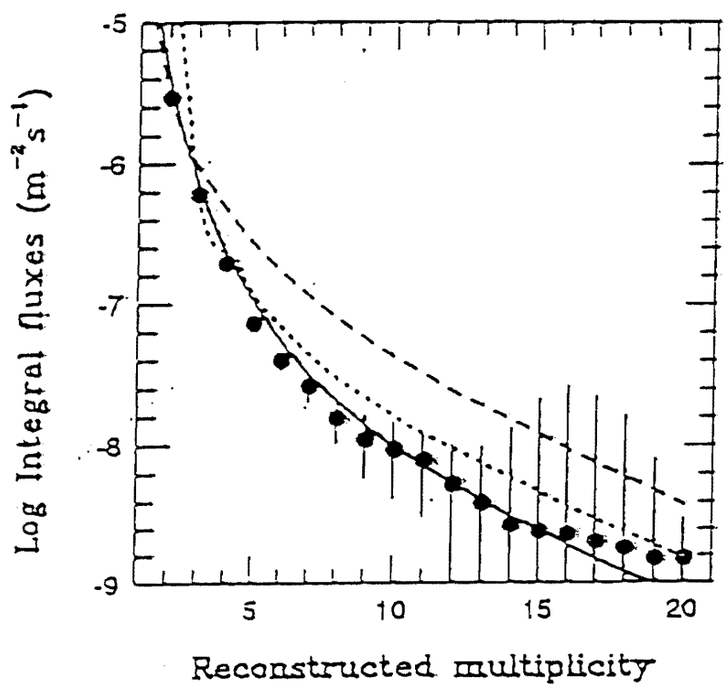

Fig. 1. Calculated rates of multiple muons for three different assumed primary spectra (see text) compared with the reconstructed multiplicity of the Frejus experiment.[7] There is no renormalization of the calculations relative to the data.

Other kinds of experiment, however, seem to indicate the opposite conclusion, namely, a heavy composition in the region of the knee.[19, 20, 21] This discrepancy is an outstanding problem in high energy cosmic ray physics, and it indicates the need for a systematic approach to a broad range of data with a consistent set of models. An important ingredient of this analysis will be a realistic treatment of fragmentation and interactions of incident nuclei. A recent effort in this direction is contained in Ref. [22]

3 Longitudinal shower profiles

Another aspect of showers that is sensitive to composition is the longitudinal development of the showers. The number of particles in a cascade multiplies as the shower develops through the atmosphere until the total number of charged particles in the cascade reaches a maximum. After shower maximum the number of particles decreases as the rate at which particles are created falls below the rate at which they are absorbed (or fall below threshold). The atmospheric depth of shower maximum (X_{max}, g/cm^2) is approximately proportional to logarithm of the energy per nucleon. On the other hand, the area under the shower profile is proportional to the total energy deposited in the cascade, i.e. the energy of the primary nucleus minus the energy carried away by neutrinos and muons which penetrate the Earth. Thus, for the same total energy, a shower generated by a heavy nucleus has on average a depth of maximum higher in the atmosphere (smaller X_{max}) than a proton shower.

The Fly's Eye detector comes closest to providing a direct measure of longitudinal development of air showers from which both energy and depth of maximum can be estimated on a shower by shower basis. Its effective threshold at present is somewhat above 10^{17} eV. Simulations of showers in this energy regime require a significant extrapolation of hadronic interaction models beyond the reach of current colliders (from $\sqrt{s} \leq 1.8$ TeV to $\sqrt{s} \sim 50$ TeV). The model dependence of this extrapolation, and its effect on interpretation of the data, is discussed in detail elsewhere.[23, 24, 25] Figure 2 from Ref. [24] compares the measured energy dependence of the mean depth of maximum with simulations for two models of hadronic interactions. The upper band is for protons and the lower band for iron nuclei as the primary particles. In each case, the upper edge of the calculated band is for the minijet model [26] and the lower edge for the KNP model.[27] There is a suggestion of an increasing fraction of heavy nuclei as energy increases above 10^{18} eV, consistent with a transition to an extragalactic component.[28]

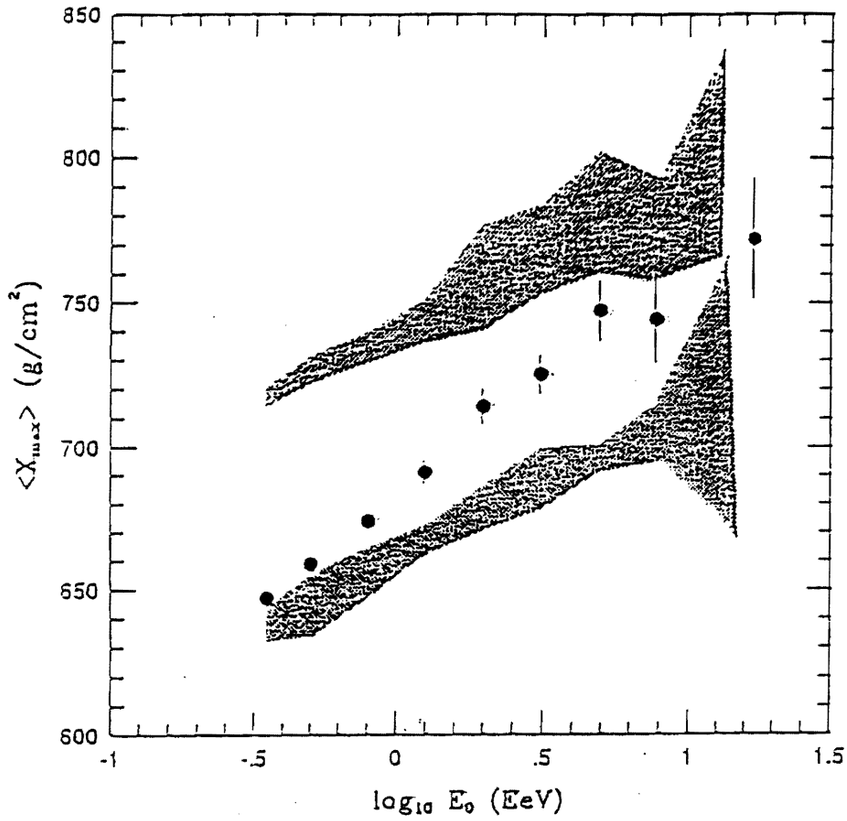

Fig. 2. Average depth of maximum as a function of primary energy (EeV) from the Fly's Eye experiment compared to calculations [24] for proton-induced showers (upper band) and for iron-induced showers (lower) band. The bands reflect statistical errors in the Monte Carlo as well as the difference between two models of high energy interactions (see text).

4 Conclusion

In addition to the experiments discussed briefly here, there are many other new and improved air shower detectors, several of which were discussed at this conference. Many of these experiments were motivated by the search for point sources of ultra-high energy photons, but they have the potential to provide improved data for the cosmic ray question as well. The possibility [4] of extending direct measurements of the primary spectrum and composition to 10^{15} eV together with this intensified experimental effort holds out the prospect of resolving the longstanding puzzle of the origin of the highest energy cosmic radiation.

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