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A NEW METHOD TO DETERMINE COMPOSITION USING HIGH ENERGY MUONS

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Abstract

We propose a method of determining the primary cosmic ray chemical composition as a function of shower energy or size near the knee of the spectrum. The technique calls for an array of atmospheric Cherenkov detectors (or electron detectors) to be operated in conjunction with a highenergy muon detector underground. For showers of fixed energy (or size) measured by the surface array, the muon detector can determine the mean number of muons, the mean number of muon pairs, and the mean number of muon triplets per shower. These three average values can be measured by muon detectors of modest size, and no model of the muon lateral distribution is required. The three quantities are simply related to three moments of the mass distribution, so direct information about the chemical composition is obtained and results from different experiments can be compared unambiguously.

Experiments which detect high energy muons produced in cosmic ray air showers of measured energy or size can provide valuable information about the chemical composition of the primary cosmic rays and how that composition changes with energy (if it does) near 10^{15} eV. Numerous studies /1/ have attempted to measure the mean atomic mass <A>. Even if there were no discrepancies between results of the different studies, that one mean value would only weakly constrain composition models unless <A> were very close to an extreme value of 1 or 56. For intermediate values of <A>, additional information about the mass distribution is required. The following three measurable quantities provide useful constraints: (1) the mean number of muons K_1, (2) the mean number of muon pairs K_2, and (3) the mean number of muon triplets K_3, per shower of fixed energy or size. (A . shower with n muons has $n!/[m!(n-m)!]$ m-fold muon combinations. For example, a shower with 6 muons has 15 pairs and 20 triplets.)

Because each of the measured quantities is a mean value, it is not necessary to make a complete measurement in individual showers, and it is therefore possible to measure these quantities with finite-size muon detectors. Suppose some type of air shower detector at the surface is used in conjunction with a deep underground muon detector so that muons in the detector with zenith angle $\theta<\theta_o$ can be counted if and only if they are produced by showers of a specified class (e.g. showers in a narrow energy or size range). Now suppose the muon detector operates with area A and solid angle $\Omega=2\pi(1-\cos\theta_o)$ for time t, and it records M muons from showers selected by the surface detector. The muon intensity is $M/(A\Omega t)$, and the surface detector can determine the intensity of showers of the specified class. The mean number of muons K_1 in that shower class is simply the ratio of muon intensity to shower intensity.

To evaluate K_2 with a finite-size detector, one counts the number of muon pairs as a function of separation r. (Ideally one would want to count pairs at all separations r. In practice it suffices if some dimension of the muon detector is large compared to the mean separation of muons. The

Homestake and Gran Sasso . detectors easily satisfy this condition, For a small detector, a mobile "outrigger" detector could be used to gain exposure for large separations.) After correcting for the detector's exposure as a function of r, one has the mean number of muon pairs per shower as a function of r, and K_2 is obtained by integrating over r. This is equivalent to expressing K_2 as an area integral of a type of decoherence curve (for showers selected from a small range in energy or size).

Evaluation of K_3 is analogous to that of K_2, except muon triplets must be counted in all triangular configurations. After correcting for the detector's uneven exposure, one gets a mean number of triplets per shower for each triangular configuration, and K_3 is then obtained by integrating over all configurations. (A more complete description of the measurement procedure for K_m has been presented /2/.)

No model of the lateral distribution of muons in air showers is required for the experimental measurement of the quantities K_m. These mean values depend on the muon energy threshold and the class of air showers selected, but are otherwise independent of the experimental configuration.

The quantities K_m can be used for composition studies in various ways. For example, any composition hypothesis can be tested by comparing its expected values for K_m (based on shower simulations) with experimentally measured K_m 's. Another way is to use these quantities to determine three different moments of the primary cosmic ray mass distribution, thereby expressing the information without reference to particular composition hypotheses. Variations of this latter method are emphasized in this paper.

To exhibit the power of K_2 and K_3 in determining composition, the following approximation is useful: If the mean number of high energy muons in a shower of some particular type is N, then the probability P_n of such a shower producing n muons is given by the Poisson distribution

$$P_n = \frac{N^n e^{-N}}{n!} . \qquad (1)$$

The expected number of m-fold muon combinations (singles, pairs, triplets, etc.) is then

$$K_m = \sum_{n=m}^{\infty} \frac{n!}{m!(n-m)!} P_n = \frac{N^m}{m!} . \qquad (2)$$

If iron showers produce x times as many muons as proton showers, then K_3 is x^3 times as large for a pure proton composition as for a pure proton position. (For a surface detector which selects showers of fixed size, x 6 and K_3 is more than 200 times greater for a pure iron composition than a pure proton composition.)

For a proton shower (A=1) of total energy E (much greater than the muon threshold energy, which is assumed to be about 1 TeV or greater) the expected number of muons is given by a power law /3,4/,

$$N_1 = á E^b . \qquad (3)$$

(This form is not dependent on a particular choice of interaction model, although the actual value of b 0.77. may be uncertain by 5% due to uncertainties in the interaction model.) Using a superposition model for nuclei, the expected number of muons resulting from a -primary of mass A and energy E is then

$$N_A - N_1 A^{1-b}. \tag{4}$$

We now consider two experimental operating modes:
<u>Mode 1 (fixed total energy).</u> The surface detector in this mode may be an array of atmospheric Cherenkov detectors which can determine the total energy of each air shower. Only muons recorded in coincidence with air showers from a specified energy range would then be counted. If f_A is the fraction of cosmic rays of fixed total energy E which have atomic mass A, then the expected number of m-fold combinations from the mixed composition is

$$K_m = (N_1^m/m!) \sum_A f_A A^{(1-b)m} . \tag{5}$$

For m=1,2,3, the quantities

$$\Gamma_m = (m!/N_1^m) K_m - \sum_A f_A A^{(1-b)m} \tag{6}$$

are moments of the mass distribution with powers 0.23, 0.46, 0.69, respectively, since (1-b) 0.23.
<u>Mode 2 (fixed shower size S).</u> The surface detector in this mode may be an array of electron detectors capable of selecting showers of size S. The shower energy E_A then depends on the primary's atomic mass A. For analytic calculations in this mode we assume heavy nuclei break into a superposition of proton showers and that a proton shower of size S corresponds to an energy $E_1=äS^{â}$, where â=0.75 and ä is also constant. One can then derive an expression for K_m:

$$K_m = (N_1^m/m!) \frac{\sum_A f_A A^{(1-\beta)(1-\gamma) + m(1-\beta b)}}{\sum_A f_A A^{(1-\beta)(1-\gamma)}} . \tag{7}$$

Here γ is the differential cosmic ray spectral index. It is assumed that the fractions f_A are constant over the range of energies contributing to showers of a fixers size ($E_{56}=2.6E_1$), so the same spectral index γ is assumed to apply to all nuclear masses in that small energy range. The exponent in the numerator of the expression for K_1 happens to be close to 0, so that sum is approximately 1. One can therefore define the following approximate mass distribution moments:

$$\begin{aligned}
\Gamma_1 &= N_1/K_1 \approx \sum_A f_A A^{(1-\beta)(1-\gamma)} = \sum_A f_A A^{-0.42} \\
\Gamma_2 &= (2/N_1) K_2/K_1 \approx \sum_A f_A A^{(1-\beta)(1-\gamma)+2(1-\beta b)} \approx \sum_A f_A A^{0.42} \\
\Gamma_3 &= (6/N_1^2) K_3/K_1 = \sum_A f_A A^{(1-\beta)(1-\gamma)+3(1-\beta b)} \approx \sum_A f_A A^{0.84}
\end{aligned} \tag{8}$$

In either of these two operating modes, the three experimentally determined moments of the mass distribution provide constraints on the mass distribution. Any hypothetical composition model could be rejected if its three moments were at variance with experimentally determined values. Alternatively, if the composition were assumed to be dominated by four particular values of A, the three moments could be used to solve for the fractions f_A (since their sum must be 1).

For these moments to be useful in this way, the uncertainties in the experimentally determined values must be small compared with the range expected from plausible composition models. Because the exponents of the various $\tilde{A}_m$ moments differ by small numbers, each must be accurately determine if it is to provide information which is independent of the other moments. Uncertainty in the experimental values can arise from the following:

(1) Limited statistics for determining the mean values K_m . The number of showers required to achieve a specified accuracy in the quantities K_m depends on m and N_1 (and hence on the primary energy and the muon threshold energy). Simple simulations can be used to estimate the needed number of showers for any specific experimental situation.

(2) Inexactness of the model approximations. This analysis idealizes the muon number distribution as an exact Poisson distribution, showers of primary mass A as super-positions of proton showers, and the mean number of muons in a proton shower as a simple power law in energy. These are good approximations for models with only moderate scaling violation /4/, so their inexactness should cause only minor errors in $\tilde{A}_m$. For mode 2, there is the additional assumption that proton shover energy and size are related by $E=äS^{â}$. This relationship is required to hold for an energy range given by factor $56^{â}=20$. The exact value of â (and hence the powers of the $\tilde{A}_m$ cents) will depend on shower size and detector altitude.

(3) Random experimental errors in energy (or size) measurements and shower fluctuations in Cherenkov light (or number of electrons). Numerical simulations indicate that these effects induce only small errors in $\tilde{A}_m$. The value of N_1 which relates the $\tilde{A}_m$'s to the K_m 's should be a spectrally weighted average over the range of shower m energies (or sizes) which the experiment attempts to accept:

(4) Uncertainty in the mean muon number N_1 for proton showers. To infer a mass distribution moment $\tilde{A}_m$ from the measured K_m values, a value for N_1 must used. Small changes in the nuclear interaction model can affect the values of N_1 at primary energies much greater than the muon energy threshold, as needed here. A measurement of N_1, even for just one proton energy and one muon threshold, would be a very valuable check on the interaction model. Operating in conjunction with a surface electron array, nuon detector (large enough to accept with confidence only muon bundles which are fully contained in the detector) could measure N_1 by finding the irst) peak of the muon multiplicity distribution. The measurement must be done at high enough proton energy or low enough muon threshold so that N_1 1, d the method assumes that protons are present in the composition and not strongly dominated by helium nuclei.

In conclusion, it may be possible to determine experimentally three moments of the mass distribution. For mode 2 (fixed size), the moments are more independent of each other than for mode 1 (fixed energy), and there is less sensitivity to uncertainty in the precise value of N1. In mode 2, however, it is necessary to assume that the composition is not changing very rapidly with energy, and the power-law relationship between energy and shower size must be known. In either mode, the moments are derived from the directly-measurable mean values Km which can themselves be used as tests of composition models.

References

1. Recent reviews are C.E. Fichtel and J. Linsley, Ap. J, 300, 474 (1986); T. Stanev, Proc. 19th ICRC (La Jolla), 9_, 383 (1985).
2. J.W. Elbert and P. Sommers, "Muon Physics in 'Deep' Detectors", UUHEP preprint 83/20, presented at Int. Symp. on pp Colliders, Tokyo (1983).
3. J.W. Elbert, Proc. DUMAND Summer Workshop (ad. A. Roberts), Scripps-La Jolla, 2,, 101 (1979).
4. T.K. Gaisser and T. Stanev, NIM,A235, 183 (1985).

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