Method for studying the chemical composition of the primary cosmic radiation at and above 10^{17}eV

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A new method is proposed for studying the chemical composition of the primary cosmic radiation. In this method the flux of high-energy muons and the intensity of the Cerenkov radiation of extensive air showers would be measured simultaneously, and the shape of the Cerenkov pulse would be used to fix the shower maximum.

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The chemical composition of the primary cosmic radiation at energies above 10^{15} eV is one of the most important questions in cosmic-ray physics today, but it can be studied only indirectly, through a study of extensive air showers (EAS). The exponent a in the expression $N_\mu \sim E_0^a$, which gives the number of muons in the EAS (N_μ) as a function of the primary energy (E_0), is known to be strictly less than unity. The particular value of a for a given muon energy threshold ranges from 0.7 to 0.9, depending on the model used for the EAS evolution.

In a first approximation (the superposition model), a primary nucleus with mass number A will cause A showers, each with a primary energy E_0/A. In the superposition model, therefore, the number of muons $N_{\mu A}$ in an EAS caused by nucleus A is $\overline{N}_{\mu A} \sim A\,(E_0/A\,)^a \sim A^{\,1-a} = A^{\,0.2}$ (if we assume $a = 0.8$.). Calculations show that this behavior remains the same even when the nucleus–nucleus interaction is examined in more detail. A characteristic more sensitive to the nucleus–nucleus interaction is the A dependence of the relative fluctuations in the number N_μ for a fixed primary energy.[1)] According to the superposition model, for example, the fluctuations vary in proportion to $A^{\,-0.5}$, while the fragmentation model[1] predicts $A^{\,-0.3}$.

We would like to keep the fluctuations in N_μ as small as possible so that we can resolve the peaks in the N_μ distribution corresponding to different groups of nuclei. One possibility might be to study the N_μ distribution for a fixed number of electrons,

N_e, in showers at sea level, since the fluctuations in N_μ for a fixed N_e are extremely large, although the fluctuations in N_μ at a fixed E_0 are only 10–12%, even for protons. A rather broad E_0 distribution corresponds to a given value of N_e (for primary protons), so that the fluctuations in N_μ at a fixed N_e reach a level of about 50%. It would be much better to study the N_μ distribution of showers at a fixed primary energy E_0 (Ref. 2; E_0 can be fixed by measuring the Cerenkov radiation, whose intensity Q is proportional to E_0 at sea level).

In this letter we wish to propose another method for studying the chemical composition of the primary rays, based on measurement of not only E_0 and N_μ (the primary energy for the EAS and the number of muons in it) but also the position of the EAS maximum. An effective method for determining the position of this maximum from the shape of the Cerenkov-radiation pulse has been proposed by Fomin and Khristiansen[3] and has now been adopted widely.[4] As it turns out, fixing E_0 and $x_{\max}$ (the position of the maximum) reduces the relative fluctuations in N_μ, while having essentially no effect on a (in the expression $N_\mu \sim E_0^a$). It therefore becomes easier to resolve different groups of nuclei.

Figures 1 and 2 show the results calculated for the predicted N_μ distributions (> 10 GeV) for $E_0 = 10^{17}$ eV and for two $x_{\max}$ intervals: from 600 to 700 g/cm^2 and from 650 to 750 g/cm^2. In these calculations we assumed the primary-radiation chemical composition given by Simon[5]: 38% p, 17% α, 16% CNO, 17% $Z = 10$–16, 3% $Z = 17$–24, and 9% $Z \geqslant 25$; the exponent is $a = 0.8$, and the error in the determination of N_μ is 5%, as is that in the determination of E_0. We see that the peaks corresponding to protons, α particles, and heavier nuclei are resolved. The relative heights of the peaks are determined by the fixed $x_{\max}$ interval. In using this method in practice we might determine the muon flux density and the Cerenkov intensity. Calculations show that the fluctuations in the muon number density decrease with distance from the shower axis, reaching $\sim 3\%$ at a distance ~ 100 m; the fluctuations in the Cerenkov intensity at a distance ~ 300 m are on the order of 5%. Interestingly, the exponent a also decreases (to 0.75). Since the fluctuations drop to an even lower level if we also fix

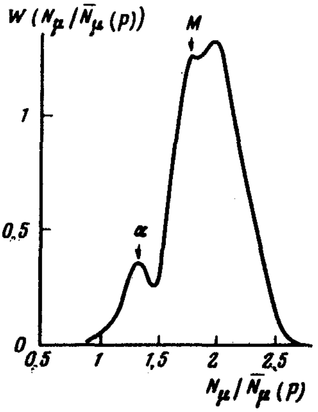

FIG. 1. N_μ distribution in extensive air showers with a fixed primary energy, $E_0 = 10^{17}$ eV, and with a shower maximum in the interval $x_{\max} = 600$–700 g/cm^2.

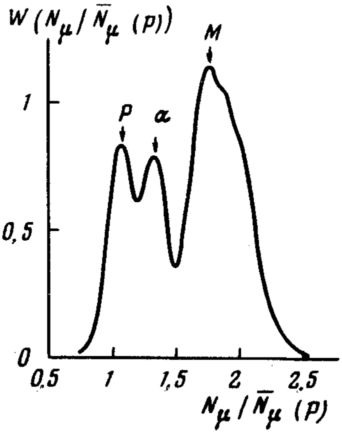

FIG. 2. The same as in Fig. 1, for $x_{\max} = 650–750$ g/cm^2.

the position of the shower maximum, we conclude that in practice the accuracy with which N_μ and Q are determined depends on the accuracy with which the position of the shower axis and the detector area are determined. Recent refinements in EAS apparatus[6] (the sensitive areas have been increased, and the accuracy has been improved) give us a solid practical basis for arguing that the accuracy which we have assumed here for the N_μ and Q measurements can actually be achieved.[2)] With accurate measurements, we can thus take the value of N_μ in a study of showers with a fixed primary energy and a fixed position of the maximum as a good measure of the atomic number of the primary particle causing the EAS. By gradually varying $x_{\max}$ we should be able to find consistent data for the chemical composition of the primary radiation causing showers with maxima at different positions. By integrating over $x_{\max}$ we would obtain data for the chemical composition of the primary radiation at a fixed E_0.

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[1)] The square root of the dispersion of a quantity, divided by its mean value, is taken as a measure of the relative fluctuations.

[2)] In principle, the values of E_0 and $x_{\max}$ could be found by measuring the electric field E at various distances r from the EAS axis.[7] The modulus of the field vector is proportional to the primary energy, $|\bar{E}| \sim E_0$, and the profile $E(r)$ is determined by the position of the maximum. This method has the advantage that measurements can be carried out around the clock, whereas Cerenkov radiation can be measured only on clear, moonless nights.

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[1] N. N. Kalmykov and G. G. Kulikov, Izv. Akad. Nauk SSSR, Ser. Fiz. **38**, 1024 (1974).
[2] G. B. Khristiansen, V. B. Atrashkevich, N. N. Kalmykov, and Yu. A. Fomin, Proceedings of the International Cosmic Ray Conference, London, Vol. 9, 1965, p. 774.
[3] Yu. A. Fomin and G. B. Khristiansen, Yad. Fiz. **14**, 642 (1971) [Sov. J. Nucl. Phys. **14**, 360 (1972)].
[4] H. R. Allan, Proceedings of the International Cosmic-Ray Conference, Plovdiv, Vol. 10, 1977, p. 414.
[5] M. Simon *et al.*, Proceedings of the International Cosmic-Ray Conference, Kyoto, Vol. 1, 1979, p. 352.
[6] J. Linsley, Proceedings of the EAS Workshop, University of Utah, 1979, p. 81.
[7] B. V. Atrashkevich, O. V. Vvedeneev, and G. B. Khristiansen, Proceedings of the International Cosmic-Ray Conference, München, Vol. 8, 1975, p. 3086.

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