the nonrelativistic approximation of a circle for the allowed kinematical region. E. Fabri, Nuovo cimento 11, 479 (1954). Relativistic corrections are not too important for our arguments.

[12]The combined number of events of $\eta \to \pi^+ + \pi^- + \pi^0$ from Berkeley, Brookhaven, Yale, and Johns Hopkins is 165. The numbers for N_1, N_2, N_3 from this combined analysis are 40,45,80. A. Pevsner (private communication).

[13]The data from the Yale group alone [H. Foelsche et al., in Proceedings of the Eleventh International Conference on High-Energy Physics at CERN (to be published)], indicates such a "depopulation" of the middle sector. Their numbers for N_1, N_2, N_3 are 10, 4, and 12. However, these numbers are too small to be statistically significant.

[14]Taking into account angular momentum barriers, phase space, etc. See G. Feinberg, Phys. Rev. Letters 8, 151 (1962), G. Feldman, T. Fulton, and K. C. Wali, Nuovo cimento 24, 278 (1962).

[15]Brown and Singer propose enhancement of the charged mode of decay of η due to strong final-state interactions. Their mechanism, however, does not explain the Dalitz plot. L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

[16]Gell-Mann, Sharp, and Wagner, reference 2, and also Brown and Singer, reference 15, consider the problem relating to the $\eta \to 2\gamma$ to $\eta \to \pi^+ + \pi^- + \gamma$ ratio. They show assuming "ρ-dominance" model that $\eta \to 2\gamma$ predominates over $\eta \to \pi^+ + \pi^- + \gamma$. Our calculations based on invariance arguments give essentially the same results.

COSMIC-RAY COMPOSITION AT 10^{17}-10^{18} eV*

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Previous evidence on the primary composition has been limited to energies $\lesssim 10^{13}$ eV. One must find out the composition at higher energies in order to interpret more precisely the existing air-shower measurements on the primary energy spectrum and the isotropy. The measurements give energy per nucleus while the quantity of interest is magnetic rigidity, which relates to energy per nucleon. The evidence to follow indicates that the primary particles of total energy $\gtrsim 10^{17}$ eV are nearly all protons. Heavier nuclei are less abundant than at lower energies and may be completely absent.

There is clear experimental evidence that the proportion of muons $K = N_\mu/N$ in a proton-induced shower decreases with increasing proton energy ϵ. The data can be represented by writing $K = B\epsilon^{-q}$, where the value of q is approximately 0.25 and B is a constant.[1] For a shower produced by a heavy nucleus the muon ratio will be determined by the energy per nucleon E/A, where E is the total energy and A is the mass number. Therefore, for showers of the same total energy the muon ratio will vary with the primary mass

$$K = B(E/A)^{-q}. \quad (1)$$

Figure 1(a) shows the expected distribution in K for air showers measured at the same distance from the initial interaction, assuming the primary composition to be that which is present up to $\sim 10^{13}$ eV.[2] In practice, the distance between the initial interaction and the level of observation will fluctuate, from one shower to the next, by an amount which depends on the mean free path of the primaries. Thus, the variation of K with distance from the initial interaction must be taken into account. Until a shower has grown to maximum size and begun to decline, the muon ratio is expected to remain nearly constant. Beyond that point it is expected to increase rapidly until finally it levels off and approaches unity. Fluctuations in height of origin do not interfere with the application of Eq. (1) if one has the means to exclude showers that are past maximum development. Otherwise there may be large fluctuations in K which completely obscure the mass effect. On the other hand, if it can be established that fluctuations of K are due principally to fluctuations in height of origin, one can make use of the fluctuations to estimate the primary mean free path, and thus open another route for investigation of the composition.[3]

Using the MIT Volcano Ranch air shower array (elevation 820 g/cm^2, area 2 km^2 in 1959-60, the period to which the present results refer), detailed information was obtained on 2800 individual showers with $N > 10^7$. It was found that showers with $N > 4 \times 10^7$ and zenith angles such that $820 < X < 980$ g/cm^2 ($X = 820 \sec\theta$) are near maximum development. The same was found for larger showers ($N > 8 \times 10^7$) over the wider range $820 < X < 1140$ g/cm^2. During the time that

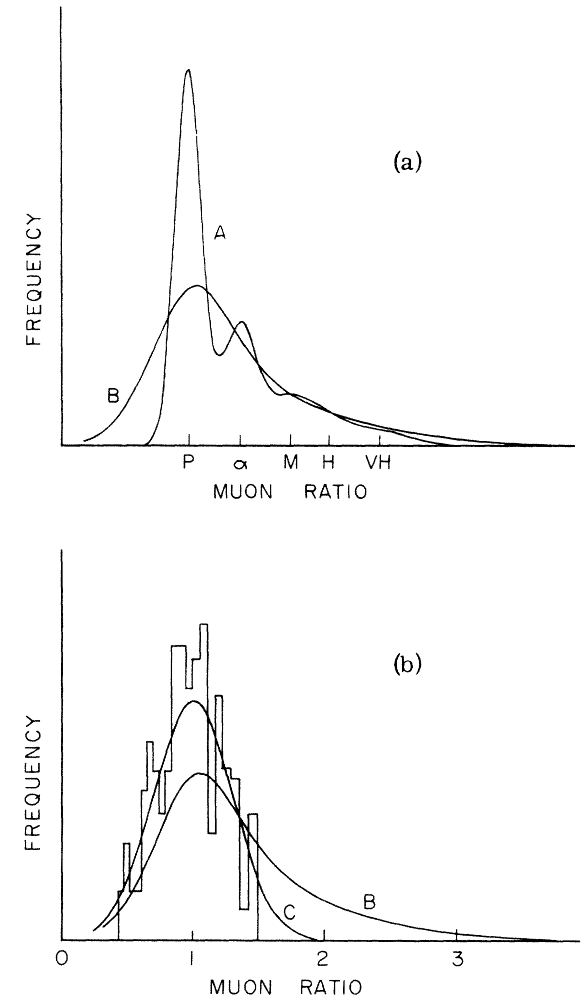

FIG. 1. Muon ratio distributions. (a) Expected distributions (K curves), assuming Gaussian errors of 10% (Curve A) and 30% (Curve B), for the primary composition observed at energies $\lesssim 10^{13}$ eV. Peaks for various groups of nuclei would fall where shown, if they could be resolved. (b) The histogram, explained more fully in the text, represents observed values of K. Instrumental errors are about the same (30% standard deviation) for all of the individual measurements. The two curves and the histogram are normalized to equal area. Curve B is the same as in (a), the horizontal scale being chosen so that the proton peak corresponds to the mean observed ratio. Curve C is the expected distribution for a pure composition, assuming 30% errors.

1200 of the 2800 events were recorded, a muon detector was in operation. The average lateral distribution of muons was measured, and also the dependence of $\langle K \rangle_{av}$ on N. Thus, for each event we could calculate the expected density of muons at the muon detector. We selected all showers that were sufficiently large and sufficiently vertical according to the criteria given above, in which the expected muon density was ten or more particles per muon detector area (3.3 m^2). The number of such events was 85. The distribution of ratios (observed muon density)/(expected muon density) is shown as a histogram in Fig. 1(b). The histogram is equivalent to a distribution in observed values of K, if we assume that the shape of the muon lateral distribution is invariant.[4] The data are incompatible with the K curve for a primary composition like that which is present at lower energies. However, at this point one can only say that the observed composition is more pure. The second K curve, which corresponds to a pure composition, could represent either pure protons or pure iron nuclei.[5] We note also that the entire width of the experimental distribution is accounted for by simple errors of measurement, which cannot have been greatly overestimated. Thus we can conclude not only that the primary particles have nearly the same mass, but also that fluctuations are small. Specifically, the muon ratio is not sensitive to intrinsic fluctuations in the elementary act.

Assured that the primary composition is relatively pure and that intrinsic fluctuations are negligible, we can safely attribute any differences we find between showers of the same size at a given level of observation to differences in their height of origin. It has been shown that if the mean free path of the primaries is 70-100 g/cm^2, then for an appropriate choice of observation level in relation to shower size, one must find showers of widely different ages in nearly equal abundance. On the other hand, if the primary particles are iron nuclei, which have a much shorter mean free path, showers that have the same size can never differ appreciably in age.[6] To apply this test we had to select showers with very large zenith angles and then examine their age. One measure of age is the ratio used above, $\rho_{\mu(\text{obs})}/\rho_{\mu(\text{exp})}$. Our data provide a second and independent measure, which we call the "shape parameter" and denote by P. $P = (\sum$ observed density)/($\sum$ expected density), where the summations are for all unshielded detectors which were further than 300 m from the shower axis, excluding the four to seven detectors that were used for finding the shower size and core location. For large vertical showers the value of P is always about 0.85. As a shower becomes older the lateral distribution measured with un-

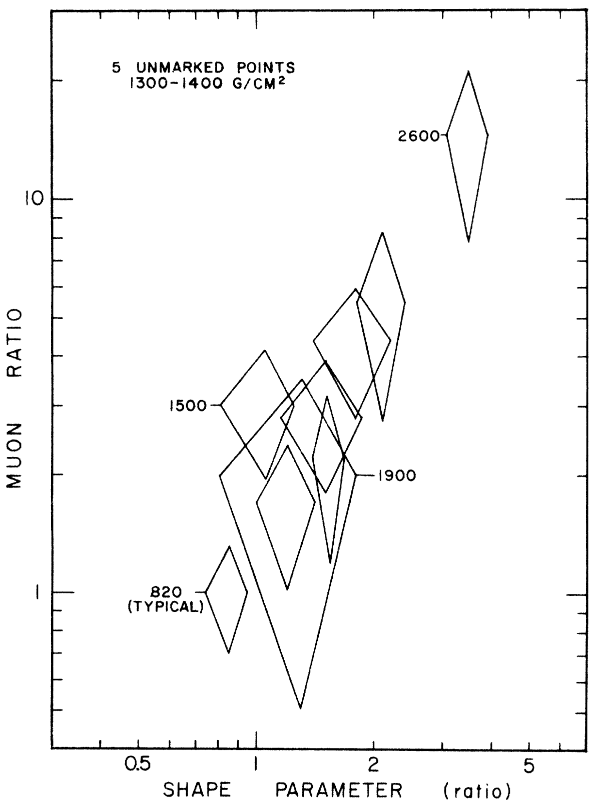

FIG. 2. Age measurements for extremely inclined air showers. The numbers near some of the points give the atmospheric depth (in g/cm^2) at which the shower was observed, derived from the zenith angle.

shielded detectors should become more and more flat, approaching the muon distribution, and the value of P should increase. In Fig. 2, measurements are shown for the eight most inclined showers of the 1200 referred to above. Also shown is a point typical of the 85 events of Fig. 1(b). It can be seen that the two measures of age are correlated with each other, as expected. The point marked 2600 is an example of extreme old age. If the shower primaries were iron nuclei, the five unmarked points would have to coincide, within experimental error. Also, there would be a regular progression from 2600 to 1900 to 1500 to the 1300-1400 group to the typical point for 820 g/cm^2. Instead, one sees what would be expected for proton primaries. Showers at the same depth have different ages, and a shower seen at a greater depth may be younger than another seen at a smaller depth. The same behavior has been reported by the Tokyo group for smaller showers at sea level.[7] It is incompatible with the assumption that nearly all of the primary particles are nuclei as heavy as iron.

For the events of Fig. 1(b) the average primary energy was about 2×10^{17} eV. In the case of Fig. 2 the showers were smaller (1 to 5×10^7 particles) but the average primary energy was at least as great.

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[1]J. Linsley, L. Scarsi, and B. Rossi, Suppl. J. Phys. Soc. Japan 17, 91 (1962). Other references are given in this paper, especially to S. Fukui, H. Hasegawa, T. Matano, I. Miura, M. Oda, K. Suga, G. Tanahashi, and Y. Tanaka, Suppl. Progr. Theoret. Phys. (Kyoto) 16, 1 (1960).

[2]C. J. Waddington, Suppl. J. Phys. Soc. Japan 17, 14 (1962). In this review, the most recent that we know of, the value 0.19 is given for $\Gamma_{Hp}(U,0)$, the intensity of H nuclei relative to protons for equal energy per nucleus. No breakdown is given for the H group ($Z \geq 10$). From a study of the most recent literature we conclude that a reasonable breakdown would be $\Gamma = 0.11$ for H_3 nuclei ($Z = 10$ to 15), $\Gamma = 0$ for H_2 nuclei ($Z = 16$ to 19), and $\Gamma = 0.09$ for H_1 nuclei ($Z = 20$ to 28).

[3]The ideas expressed in this paragraph seem to have developed concurrently in the United States, Russian, and Japanese groups. So far as one of us (J. L.) can recall, the development within the MIT group dates from remarks by W. Kraushaar in 1956 (unpublished). A formula equivalent to Eq. (1) appears in Fukui et al. (reference 1).

[4]We suppose that for individual cases $\rho_{\mu\,(\mathrm{obs})} = N_{\mu\,(\mathrm{obs})} f_\mu(r)$, where f_μ is the function we assume to be invariant. By $\rho_{\mu\,(\mathrm{exp})}$ we mean the product $N_{\mathrm{obs}} f_t(r) k(r)$, where N_{obs} is the observed size, f_t is the average lateral distribution of shower particles, and k is the average ratio of muon-to-shower particle density. Thus $\rho_{\mu\,(\mathrm{obs})}/\rho_{\mu\,(\mathrm{exp})}$ is proportional to $N_{\mu\,(\mathrm{obs})}/N_{\mathrm{obs}}$. By construction its average value is unity.

[5]Some theories of cosmic-ray origin predict pure iron as a limiting composition at high energies, iron being the heaviest element which has an appreciable cosmic abundance. Such could be the case if there were an upper limit for magnetic rigidity.

[6]We use the term "age," without tying it to any quantitative definition, as a convenience in describing the progressive changes that take place in an air shower as it grows to a maximum size and then dies out. The meaning we intend is qualitatively the same as the meaning of "age" in cascade theory. Age fluctuations will be large if the primary mean free path is about equal (not much less than) the characteristic length for changes in shower size, divided by the exponent of the integral energy spectrum.

[7]H. Hasegawa, T. Matano, I. Miura, M. Oda, S. Shibata, G. Tanahashi, and Y. Tanaka, Suppl. J. Phys. Soc. Japan 17, 86 (1962), and the earlier publication of the Tokyo group (reference 1).