Composition of primary cosmic rays at energies $\sim 10^{15}$ eV from data on high-energy muons in extensive air showers

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A critical analysis of experimental data on high-energy muons in air showers is carried out to derive information about the composition of primary cosmic rays near the bend in the energy spectrum at $\sim 10^{15}$ eV. A set of Monte Carlo simulated air showers from different elemental species have been used to study expectations for three different experiments: the Tien Shan study of muons with energy above 5 GeV at an altitude of 690 g/cm^2, the Moscow State University experiment for muons with energy above 10 GeV at sea level, and the Kolar-gold-field experiment for muons with energy above 220 GeV at 930 g/cm^2. The results show that when showers are grouped according to shower size the sensitivity of the total number of high-energy muons to primary composition is greatly reduced. In fact, it is found that the data cannot discriminate between models which assume energy-independent low-energy composition and those which assume energy spectra which steepen above some value of rigidity cutoff around 10^{14} eV/nucleon. In order to make a composition-sensitive measurement of the high-energy muon component it is necessary to make these measurements at fixed energy rather than at fixed shower size.

I. INTRODUCTION

A successful interpretation of various observations on air showers requires a detailed knowledge of the energy spectra of various nuclear groups in the primary cosmic-ray flux at air-shower energies $> 10^{13}$ eV. This knowledge is also required for a better understanding of the nature of cosmic-ray sources and the processes dominating the acceleration and propagation of cosmic rays in the galactic space. Direct measurements[1–4] of the composition of the primary cosmic-ray flux have been possible up to energies of only about a few hundred GeV per nucleon due to experimental constraints on the size and weight of the balloon- or satellite-borne detectors and exposure times. Attempts[5] are being made to extend these measurements to higher energies ($\sim 10^{13}$ eV per nucleus) using emulsion chambers. Indirect measurements of the primary composition at energies $\sim 10^{13}$–10^{15} eV from studies of the energy spectra[6] of hadrons and γ rays and delayed hadrons[7] in air showers have suggested a change in the relative composition of various nuclear groups with increasing energy above $\sim 10^{13}$ eV, leading to the dominance of heavier nuclei in the primary flux at energies $\sim 10^{15}$ eV. The variation of the percentage of medium-heavy (silicon-group) and heavy (iron-group) nuclei with energy from 10^{13} to 10^{16} eV that is suggested is shown in Fig. 1.

Experimental results[8–16] on the characteristics of the high-energy muon component in air showers have been used by many workers to study the primary composition at air-shower energies since various calculations have shown that showers initiated by heavier nuclei are expected to be richer in muons than proton-initiated showers. However, these studies have given conflicting results for the primary composition.[17–21] For example, studies of high-energy (> 5 GeV) muons by the Lebedev group[12–15] and very-high-energy (> 220 GeV) muons by the Tata group[10,11] have suggested that the composition of the primary flux at energies $\sim 10^{14}$–10^{16} GeV is proton dominant as at lower energies where direct measurements exist. On the other hand, observations on high-energy (> 10 GeV) and very-high-energy (~ 50–500 GeV) muons by the Moscow State University group[8,16] have been found to

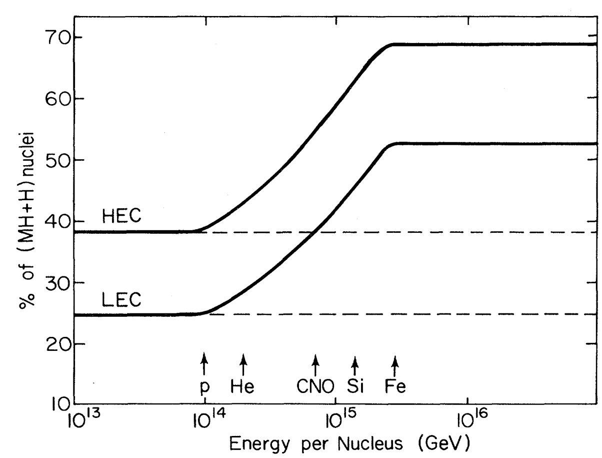

FIG. 1. Energy variation of the percentage of medium-heavy (silicon-group) and heavy (iron-group) nuclei according to the LEC and HEC models with a rigidity-dependent cutoff at 100 TeV/nucleon.

be inconsistent with such an interpretation, within the constraints of the scaling model[22–25] for particle interactions at very high energies. Although many observations related to air showers have been suggested[17,20,26] to be indicative of violation of scaling at energies $\sim 10^{15}$ eV, recent direct observations[27] at equivalent laboratory energies $\sim 1.5\times 10^{14}$ eV by CERN SPS $\bar{p}p$ collider experiments have shown these violations to be small, at least in the central region (small values of the Feynman variable x). Also results obtained from studies of cosmic-ray interactions at energies $\sim 10^{13}$–10^{14} eV with emulsion chambers have been shown[28] to be consistent with expectations from the scaling model, suggesting the absence of any large violation of scaling in the fragmentation region.

These differences in the results for primary composition obtained from high-energy muon experiments are difficult to understand except possibly in terms of differences in the details of interaction models and shower-simulation procedures used by different groups. Usually each group has attempted to compare only its own experimental data with expectations from Monte Carlo simulations of showers and very few attempts (e.g., Refs. 29 and 30) have been made to compare data from many experiments with the same set of simulated showers. Also many simulations have not taken adequate account of various experimental selection conditions, for example, small shower-size groups, zenith-angle cuts, limited geometrical-acceptance factors for the detectors, etc. We present here a detailed discussion of our attempt to find a consistent interpretation for all observations on high-energy muons with the same set of simulated showers. Some preliminary results from this study have been presented elsewhere.[31] The simulation procedure and the details of the interaction model used here are very similar to those used earlier in interpreting[7,26,32,33] various other observations. We have incorporated many of the experimental selection conditions in simulations to make the comparison with data more meaningful. Some relevant details of the simulation procedure, interaction models, and the assumptions about the primary energy spectra for various nuclear groups are discussed in Sec. II. A discussion of the effects of various changes in the interaction model and different values of the zenith angles for the showers is presented in Sec. III. A comparison of the expected characteristics of high-energy muons with data from various experiments is presented in Sec. IV along with a discussion of the primary composition required to obtain a consistent interpretation of all observations. The conclusions derived from this study are discussed in relation to the results obtained from studies of other components of air showers in Sec. V.

II. SIMULATION OF AIR SHOWERS

Hadronic interactions have been simulated with an independent-particle-emission model. Secondary momenta in the center-of-mass (c.m.) system are chosen from the probability distributions obtained from scaled invariant single-particle inclusive cross sections. Since use of the radial-scaling variable[24,25] x_R has been found to give a better agreement with the experimental data at Fermilab and CERN ISR energies compared with the Feynman scaling variable,[22] radial scaling has been used in our simulations. However, a mild violation of scaling as seen at the SPS $\bar{p}p$ collider energies[27] has been taken into consideration by putting an energy-dependent term in the x_R distribution. Hadron–air-nucleus inelastic interaction cross sections have been assumed to increase logarithmically with energy. Kaon (charged and neutral) and baryon production as well as the prominent decay modes of pions and kaons have been taken into consideration appropriately. A large-transverse-momentum component in the transverse-momentum distribution has also been included in the simulations. Showers initiated by a nucleus of mass number A and energy E_0 have been assumed to be a superposition of A showers, each of energy E_0/A. Various other details of the interaction model and the simulation procedure as well as the values of various input parameters for different distributions have been given elsewhere.[7,26,32,33]

Groups of showers have been generated for various primary energies assuming a power-law type of energy spectra with a value of -2.6 for the spectral exponent,

$$N(E,A)=K(A,E_n)(E/E_n)^{-2.6}\ .$$

The values of the constants $K(A,E_n)$ for various nuclear groups assumed to be present in the primary flux are discussed later. Here A is the average atomic number and E_n is the flux normalization energy for a primary nuclear group. Each energy group was restricted in energy between a value $E_{\min}$ and $2E_{\min}$, with the value of $E_{\min}$ selected over the energy range 1–3200 TeV. A large number, about 10 000, of showers were generated for the lower-energy groups but this number was reduced gradually with increasing energy to 10 showers of 3200–6400 TeV. This scheme allows a flexibility of choosing a different value of the spectral exponent when grouping showers according to shower size without introducing a

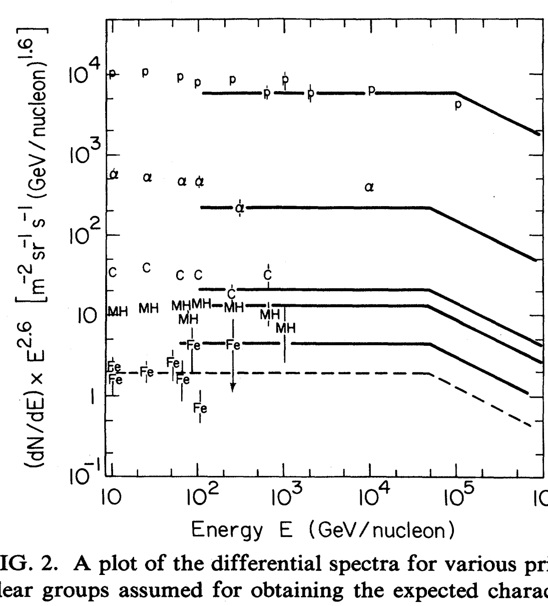

FIG. 2. A plot of the differential spectra for various primary nuclear groups assumed for obtaining the expected characteristics of muons and hadrons in showers. Points shown refer to direct measurements (Refs. 1–5).

TABLE I. Values of the constants $K(A,E_n)$ for LEC and HEC models [K in (m^2 sr s GeV/nucleon)$^{-1}$, E in GeV/nucleon]. MH and H indicate medium-heavy and heavy nuclei, respectively.

Nuclear group	Average A	LEC E_n	LEC K	HEC E_n	HEC K
Protons	1	100	0.04	1000	1.0×10^{-4}
α	4	10	1.08	250	1.1×10^{-4}
CNO	14	10	0.053	250	1.0×10^{-5}
MH	28	10	0.033	63	2.73×10^{-4}
H	56	10	5.5×10^{-3}	63	1.1×10^{-4}

large error. Showers were generated with isotropic angular distribution at the top of the atmosphere thus obviating the need for assuming any shape of the angular distribution for showers at the observational level. All the relevant details for the electron, hadron, and muon components were recorded for each shower for each of the four observational levels in the atmosphere defined to be 690 (Tien Shan), 800 (Ooty), 920 (Kolar gold fields), and 1030 g cm^{-2}. For each level the lateral distributions of the electron component, the energy and lateral distributions of all hadrons of energy larger than 2 GeV, and the energy and lateral distributions of all muons of energy larger than 5 GeV were recorded on the magnetic tape.

The values of the constants $K(A,E_n)$ for various nuclear groups depend on the normalization energy in the energy range of direct measurements. In Fig. 2 the measured energy spectra for the five nuclear groups for energies above 10 GeV/nucleon are shown. It is seen that the proton spectrum is steeper with a spectral index of -2.7 right up to energies $\sim 10^5$ GeV. Recent direct measurements by the Japanese-American Cooperative Emulsion Experiment (JACEE) collaboration[5] suggest a similar steep spectrum for He nuclei at energies above a few TeV/nucleon. The energy spectra for heavier nuclei are consistent with a value of -2.6 for the spectral index except for a suggestion of a slightly flatter spectrum for the iron-group nuclei. It may be noted that assuming a value of -2.7 for the spectral index for protons and He nuclei and -2.6 for other nuclear groups and using the normalization for flux at lower energies, say, less than 100 GeV/nucleon would lead to a discrepancy of the all-particle flux with direct measurements[1] at energies $\sim 10^{15}$ eV. This suggests that some spectral changes must be occurring in the energy range $\sim 10^3$—10^5 GeV per nucleus. However, for our present purposes, we consider two models for the energy spectra for various nuclear groups which are different only in the normalization for flux of heavier nuclei. The low-energy-composition (LEC) model assumes the flux normalization at energies ~ 10 GeV/nucleon and the high-energy-composition (HEC) model assumes the normalization energy to be about 100 GeV/nucleon for the heavier nuclei. It may be noted that these two assumptions lead to almost a factor of 2 in the flux of heavier nuclei at energies >1 TeV/nucleon. For simplicity we have assumed the spectral index to be -2.6 for all the nuclear groups in order to match the all-particle flux with direct measurements. The values of the constants $K(A,E_n)$ for these two assumed models are given in Table I. Since the all-particle energy spectrum is known[1,19,21] to become steeper at energies above 10^{16} eV, there are only two simple options available for the assumed spectra at higher energies: (i) a rigidity-dependent steepening[7,34] of all spectra above a critical value for the rigidity E_{rc} (GeV/nucleon), (ii) an energy-dependent steepening[35] of all spectra above a total energy E (GeV/nucleus). We have assumed here that the spectral

TABLE II. Characteristics of electron, muon, and hadron components of showers for various models, zenith angles, and initiating nuclei with 2×10^5 GeV/nucleus at depth of 920 g/cm^2.

σ	Scaling	θ (deg)	A	N_e	N_h $E>10$ GeV	N_μ $E>10$ GeV	N_μ $E>220$ GeV	Number of events
C^a	Y	0	1	1.35×10^5	334	1570	46.8	51
C	Y	0	56	4.1×10^4	171	3110	105	51
C	Y	<45	1	5.7×10^4	242	1830	62.5	30
C	Y	<45	56	2.3×10^4	94.7	3141	123	51
$\uparrow^b$	Y	0	1	1.1×10^5	241	1810	59	51
$\uparrow$	Y	0	56	3.3×10^4	129	3160	109	57
$\uparrow$	Y	<45	1	5.3×10^4	120	2088	78.7	30
$\uparrow$	Y	<45	56	1.57×10^4	67.3	3180	129	51
$\uparrow$	N	0	1	7.7×10^4	193	2230	71	30
$\uparrow$	N	0	56	1.59×10^4	124	3330	110.2	57
$\uparrow$	N	<45	1	5.7×10^4	147	2247	81	30
$\uparrow$	N	<45	56	0.67×10^4	60	3330	125	51

[a] C denotes constant cross section.

[b] $\uparrow$ denotes cross section increasing with energy.

index changes from -2.6 to -3.1 at a critical rigidity E_{rc} (GeV/nucleon) for all nuclear groups, and the value of E_{rc} is varied to study the variation of the expected shower characteristics.

III. SENSITIVITY OF N_μ AND N_E

The electron size, muon size, and the hadron number in a simulated shower at a given observational level depend on the values of various parameters defining the interaction model and other shower characteristics, such as the zenith angle, etc. It is therefore necessary that these parameters are well defined in any comparison of either the calculations with experimental data or one set of calculations with another set. In fact some of the differences between the results of various calculations presented by different groups are due to rather different assumptions about these parameters. We present in Table II a comparison of the average values of the shower size N_e, number of hadrons N_h ($E_h > 50$ GeV), and the number of muons N_μ ($E_\mu > 10$ and 220 GeV) in showers of a fixed energy ($E_0 = 5\times 10^5$ GeV) at an observational level of 920 g cm^{-2} for various interaction models, zenith angles, and primary nuclei. It is interesting to note from this table that the expected characteristics of muons and hadrons in showers can be quite different for the cases as listed in the table. It is therefore necessary to be cautious in comparison of expected distributions with measurements which are mostly presented for showers with sizes in a narrow range and with arrival zenith angles less than some predefined value.

IV. COMPARISON WITH OBSERVATIONS

A. Tien Shan experiment

In this experiment[12–15] the density Δ_μ of muons of energy >5 GeV has been measured in showers of size 10^5–10^7 at an observational altitude of 690 g cm^{-2} using a 30-m^2-area muon detector. The distribution of normalized $(\Delta_\mu/\bar{\Delta}_\mu)$ at a distance of 35–45 m from the shower axis in showers of average size $\sim 1.6\times 10^6$ and with zenith angles less than 30° given by Kirov *et al.*[14] is compared with the expected distribution under different assumptions in Figs. 3 and 4 obtained from our simulations. Our Monte Carlo simulated distributions are considerably different from those of Kirov *et al.* Kirov *et al.*[14] have concluded from a comparison with their calculations that a primary composition very similar to that measured at lower energies gives a better fit to the data. They have used the Cocconi-Koester-Perkins[36] (CKP) model for particle interactions which yields a considerably higher value of the average secondary particle multiplicity than that observed in SPS $\bar{p}p$ experiments.[27] A surprising part of the results given by Kirov *et al.* is the double-peak structure expected for heavy-nuclei-dominant composition. In Fig. 4(a) we display the Kirov *et al.* distribution. However, our expected distributions for $K_\mu = (\Delta_\mu/\bar{\Delta}_\mu)$ are broad enough for each nuclear species [Figs. 5(a) and 5(b)] that any mixing of nuclear groups in any reasonable proportion gives a single-peak distribution; the peak shifts to a different value of K_μ depending on the relative proportions

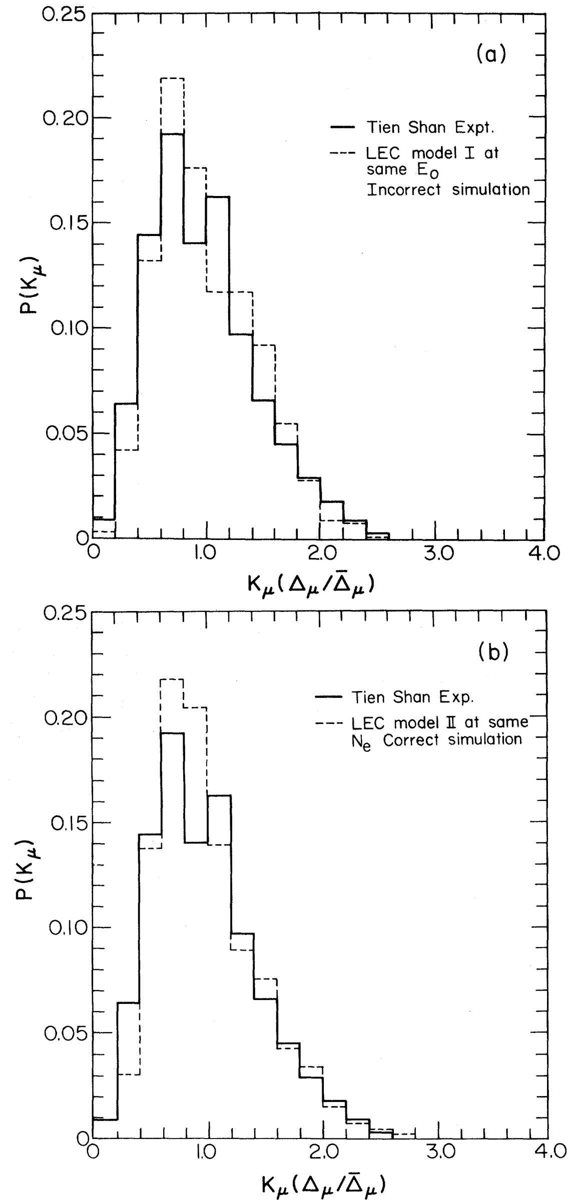

FIG. 3. A comparison of the expected distribution of density of muons of energy >5 GeV at distances of 35–45 m from axis of showers of size $\sim 1.6\times 10^6$ at Tien Shan altitude for LEC model of primary composition but assuming no rigidity-dependent steepening of energy spectra with experimental data (Ref. 14). (a) Showers due to different nuclear groups combined in relative proportions determined at same total energy E_0 (LEC I of Table III). (b) Showers due to different nuclear groups combined in relative proportions determined for same size N_e (LEC II of Table III).

of various nuclear groups. The values for the widths $\sigma/\bar{\Delta}_\mu$ for the expected distributions shown in Fig. 5(a) for protons and iron-nuclei showers are 0.34 and 0.27, respectively, which are much larger than the values according to Kirov *et al.*[14] Also the difference between these two values is much larger in their calculations. The simulated distributions shown in Fig. 4 are for vertical showers and

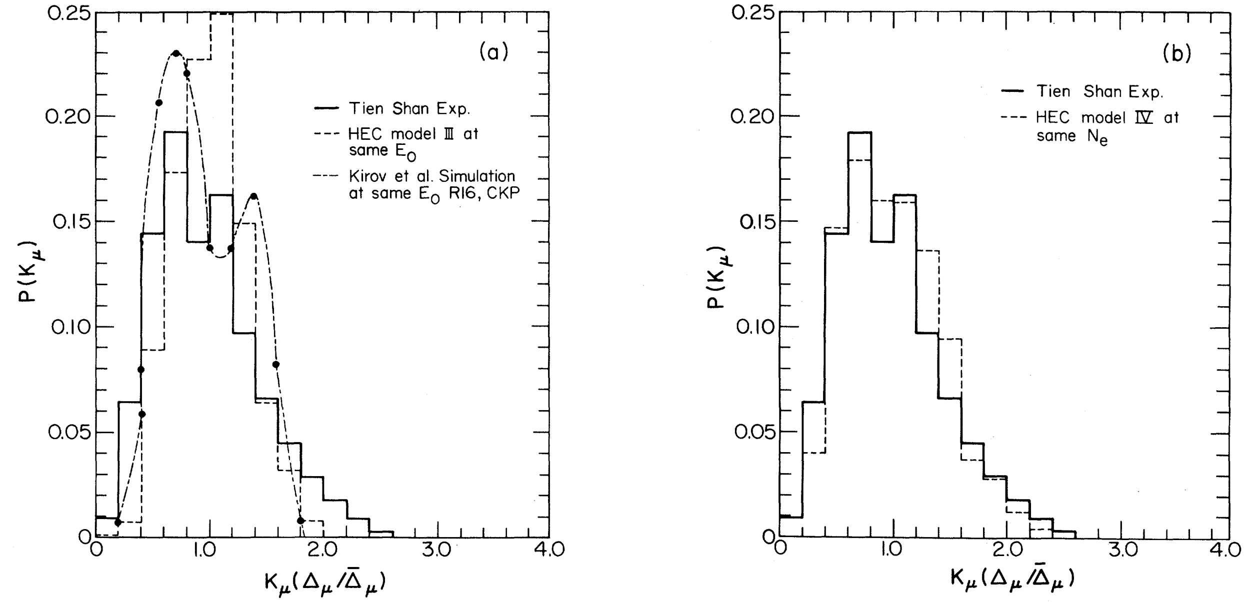

FIG. 4. A comparison of the expected distribution of density of muons of energy >5 GeV at distances of 35—45 m from axis of showers of size $\sim 1.6\times 10^6$ at Tien Shan altitude for HEC model of primary composition assuming rigidity-dependent steepening of energy spectra ($E_{\rm rc}=100$ TeV/nucleon) with experimental data (Ref. 14). (a) Showers due to different nuclear groups combined in relative proportions determined at same total energy E_0 (HEC III of Table III). (b) Showers due to different nuclear groups combined in relative proportions determined for same size N_e (HEC IV of Table III).

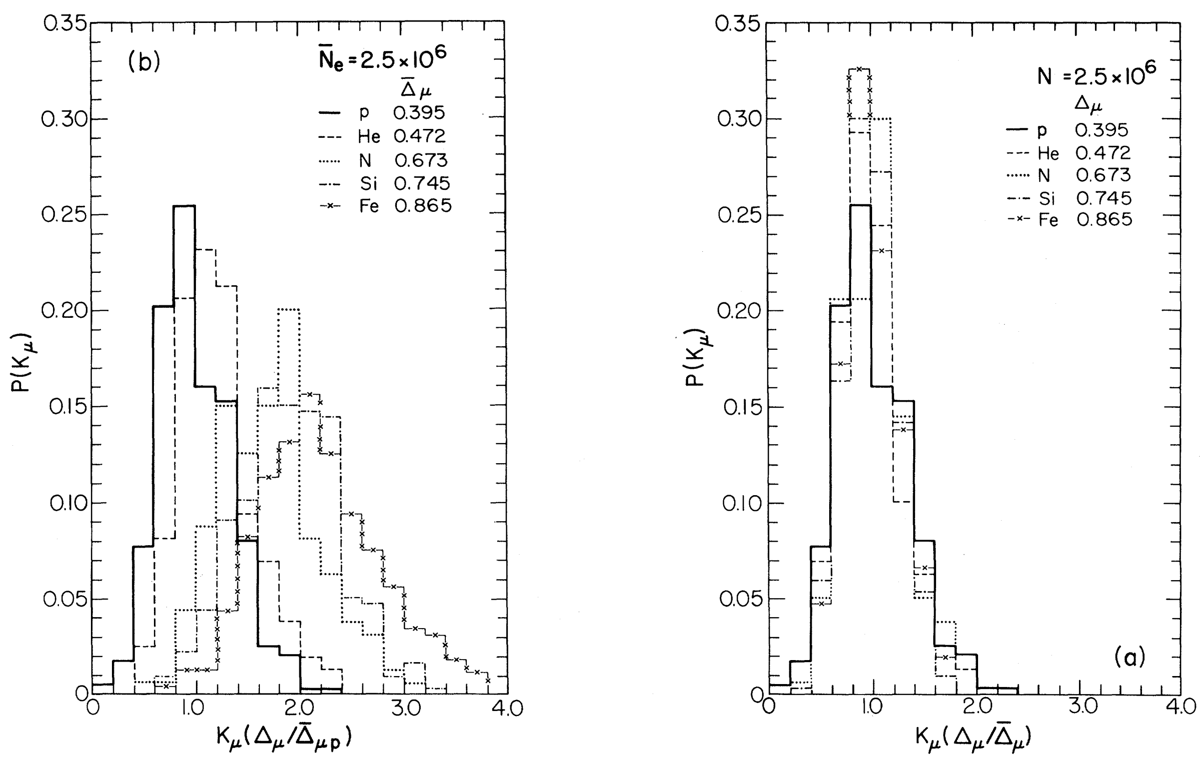

FIG. 5. A comparison of the expected distribution of density of muons of energy >5 GeV at distances of 34—45 m from axis of showers of size $\sim 1.6\times 10^6$ at Tien Shan altitude for different nuclear groups: (a) K_μ obtained using the values of $\bar{\Delta}_\mu$ for different nuclear groups, and (b) K_μ obtained using the value of $\bar{\Delta}_\mu$ corresponding to protons $K_\mu(\bar{\Delta}_\mu/\bar{\Delta}_{\mu p})$. Note that the experimentally obtained value of Δ_μ is heavily weighted towards $\Delta_{\mu p}$ due to the dominance of proton-initiated showers among showers of same size.

TABLE III. Relative composition of primary flux used in Figs. 3 and 4.

Model	Figure	p	He	CNO	MH	H
LEC I, same E_0	3(a)	0.40	0.14	0.10	0.18	0.18
LEC II, same N_e	3(b)	0.51	0.15	0.09	0.14	0.11
HEC III, same E_0 with RDS[a]	4(a)	0.16	0.08	0.10	0.27	0.39
HEC IV, same N_e with RDS[a]	4(b)	0.27	0.12	0.12	0.24	0.25

[a]Rigidity-dependent steepening of energy spectra at 100 TeV/nucleon with a spectral slope change of 0.5.

would be broader for showers arriving at larger zenith angles.

The expected distribution in Fig. 3(a) assumes the LEC model I of primary composition but assumes no rigidity-dependent steepening of the energy spectra. The relative composition of various nuclear groups assumed for obtaining this distribution is given in the first line of Table III and corresponds to the same average primary energy E_0. The distribution expected assuming rigidity-dependent spectra with rigidity cutoff at 100 TeV/nucleon, leading to a relative composition as given in the third line in Table III, is shown in Fig. 4(a). It is clear that the agreement with experimental data is better in Fig. 3(a) compared with Fig. 4(a). At this stage we point out several features of simulated showers which are important for understanding the analysis of data. Showers of the same total energy E_0 do not give the same shower size N_e for different nuclear groups. In order to have the same shower size past shower maximum, heavy-nuclei-initiated showers must have higher energy per nucleus than proton-initiated showers. This energy factor increases with the atomic number of the nucleus initiating the shower and with increasing zenith angle. Our simulations show that factor to be 1.6 for iron-nucleus-initiated showers for Tien Shan altitude in the vertical direction. Therefore, the proper relative composition of various nuclear groups for obtaining showers of the same size have to be obtained from different parts of the primary energy spectra for these groups. Therefore, the flux of iron nuclei contributing to showers of same size is reduced because it must be calculated at an energy $1.6E_0$. The expected distribution for K_μ, assuming the LEC model II but without rigidity-dependent steepening, is shown in Fig. 3(b). The relative composition chosen for obtaining this distribution is shown on line 2 in Table III and is expected to yield the same average shower size for each nuclear species. A similar distribution assuming rigidity-dependent steepening at 100 TeV/nucleon is shown in Fig. 4(b) with the corresponding relative composition shown on line 4 of Table III.

It is evident from a study of Figs. 3(b) and 4(b) that the K_μ distribution is not very sensitive to primary composition except that it can rule out a pure proton or a pure heavy-nuclei-type composition. Though Fig. 4(b) shows somewhat better agreement between the expected and measured distributions it is felt that no firm conclusion about composition can be drawn from this study of K_μ distributions.

Using the measured density of muons in showers of same size, the Tien Shan group[13] has determined the average number of muons N_μ per shower and its variation with shower size:

$$N_\mu\ (>5\text{ GeV}) = (1.26\pm0.02)\times10^4\times(N_e/10^6)^{0.80\pm0.01}\ .$$

This measurement of the N_μ-N_e relation is compared with

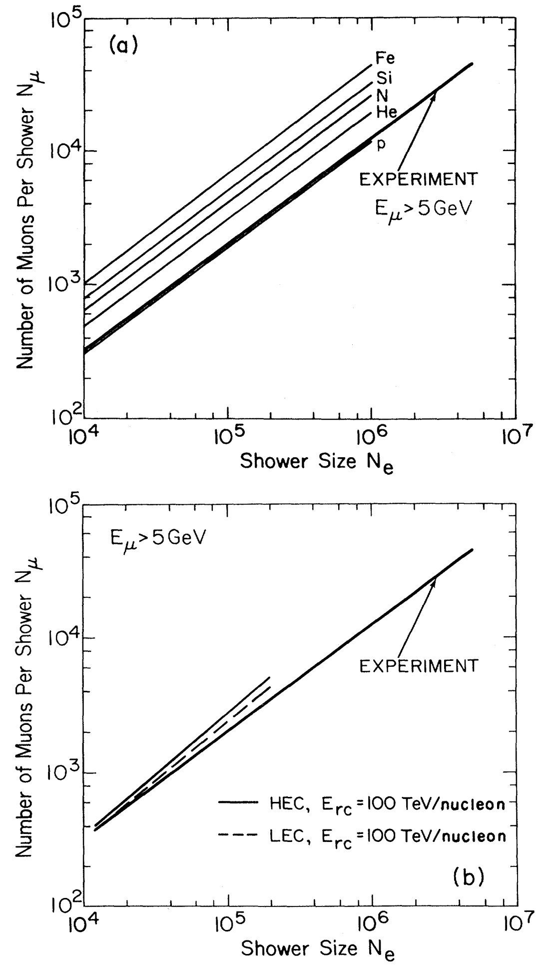

FIG. 6. A comparison of the experimental data (Refs. 14 and 15) on variation of N_μ with N_e with expectations from simulations: (a) for various primary nuclear species, and (b) for the two composition models assuming a value of 100 TeV/nucleon for the rigidity cutoff.

the expectations from our simulations in Fig. 6(a). Different lines in this figure refer to showers initiated by different nuclei. It may be noted that for this comparison an isotropic angular distribution for the primaries at the top of the atmosphere with a cutoff at a zenith angle of 30° was assumed in simulations and showers have been grouped in narrow size bins with widths of a factor of 2. It is clear from this figure that the expected slope of the N_μ-N_e relation agrees well with measurements. In Fig. 6(b) is shown the comparison of the expected relation between N_μ and N_e, assuming various models of primary composition discussed earlier, with experimental data. It may be mentioned here that the energy factor discussed earlier for heavy-nuclei showers is larger here due to the selection of showers up to zenith angles of 30°. Therefore, the contribution of heavy-nuclei showers is suppressed with respect to proton showers more severely than for vertical showers. This figure shows that most of the expected values of N_μ are larger than the measured values. Since a systematic error of about 30% cannot be ruled out in any absolute determination of N_e as well as N_μ due to various factors such as the transition effect, fluctuations in lateral distribution, etc., it seems to be difficult to choose among the models for primary composition shown in Fig. 6(b).

B. Moscow State University experiments

Khristiansen *et al.*[8] measured the lateral distribution of muons of energy > 10 GeV using a 45-m^2 detector located underground at a depth of 40 m of water equivalent (mwe) and determined the average number of muons per shower in showers of different size groups at sea level. Their results are shown in Fig. 7(a). The N_μ-N_e relations at sea level expected from our simulations of showers arriving at zenith angles $< 30°$ for different primary nuclei are also shown in Fig. 7(a) for comparison with observations. In Fig. 7(b) are shown the expected N_μ-N_e relations for various models of primary composition along with experimental data. Since heavy-nuclei showers are discriminated against by the requirement of same size to a larger extent at this observational level compared with the Tien Shan altitude, the contribution of heavy-nuclei showers to observations is expected to be considerably reduced leading to the loss of sensitivity of the muon component to primary composition. As for the Tien Shan experiment, the expected values of N_μ are larger than observations. However, for the same reason of possible systematic errors it is not possible to conclude anything about primary composition from these data.

Recently Grishina *et al.*[16] have reported the measurement of lateral distribution, energy spectrum, and total number of muons per shower of energies > 10—500 GeV using a magnetic spectrometer and a large hodoscopic counter placed at a depth of 40 mwe in showers of size $\sim 10^5$—10^6. Their integral energy spectrum for showers of average size $\sim 2\times 10^5$ is compared with expectations from our simulations in Fig. 8 for different models of primary composition. Again it is difficult to draw a firm conclusion from the results of this experiment due to the small difference between predictions for different models

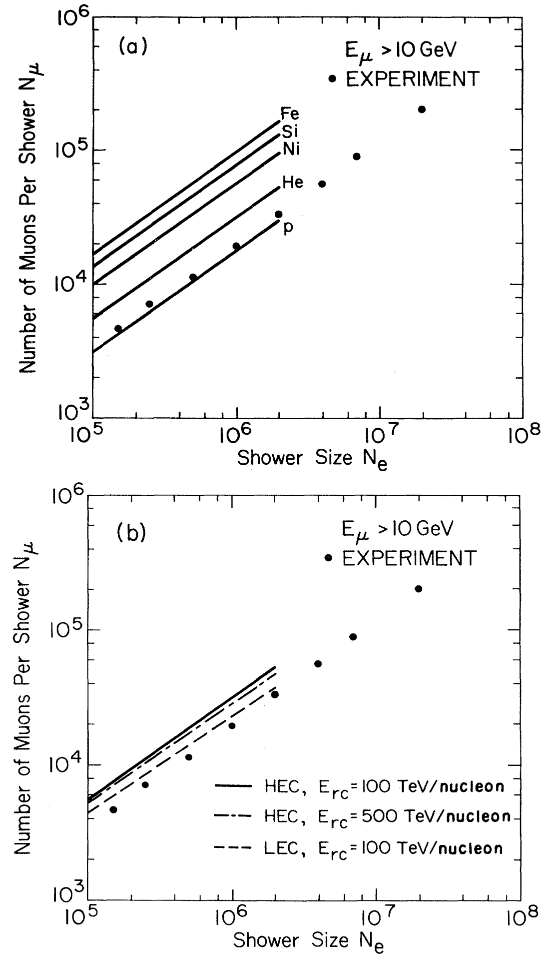

FIG. 7. A comparison of the experimental data (Ref. 8) on variation of N_μ with N_e with expectations from simulations (a) for various primary nuclear species, and (b) for the two composition models assuming different values for the rigidity cutoff.

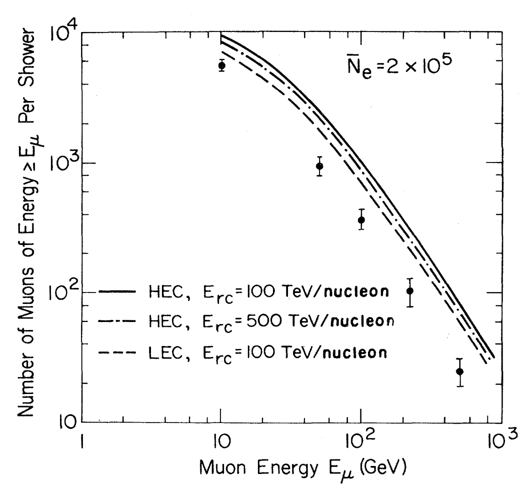

FIG. 8. A comparison of the experimental data (Ref. 16) on the energy spectrum of muons in showers of average size 2×10^5 with expectations from simulations for the two composition models assuming different values for the rigidity cutoff.

of primary composition. Although the functional dependence of N_μ on N_e is reasonably well reproduced by our simulations, the absolute values of expected N_μ are difficult to simulate due to the complex method used to obtain N_μ from limited sampling of densities.

C. Kolar-gold-fields experiment

The Tata group[10,11] has measured the lateral distribution of high-energy (>220 GeV) muons using a 4-m^2 neon-flash-tube hodoscope and scintillation counters placed underground at a depth of 810 mwe in showers of size $\sim 10^4$–10^7. Their measured lateral distribution for muons in showers of size group 10^4–(2×10^4) is shown in Fig. 9(a) along with the expectations from our simulations for showers initiated by protons and iron nuclei. As in calculations of Acharya *et al.*,[10,11] our expected lateral distribution also seems to be steeper at larger distances from the shower axis compared with observations. It is interesting to note that the shape of the observed lateral distribution is independent of shower size within experimental errors. This can be seen from Fig. 9(b) where the lateral distributions for five size groups have been plotted together after normalization with the total number N_μ per shower. Our simulations include an energy-dependent cross section for hard-scattering processes which lead to large-transverse-momentum pions. The simulations show that the inclusion of a large-p_t tail does not give rise to observable effects in the lateral distribution of 220-GeV muons. Therefore, the observed flattening of the lateral distribution at large distances could not be ascribed to hard-scattering processes in high-energy interactions. Since the observations do not show a size-dependent effect, it seems difficult to interpret the observed flattening

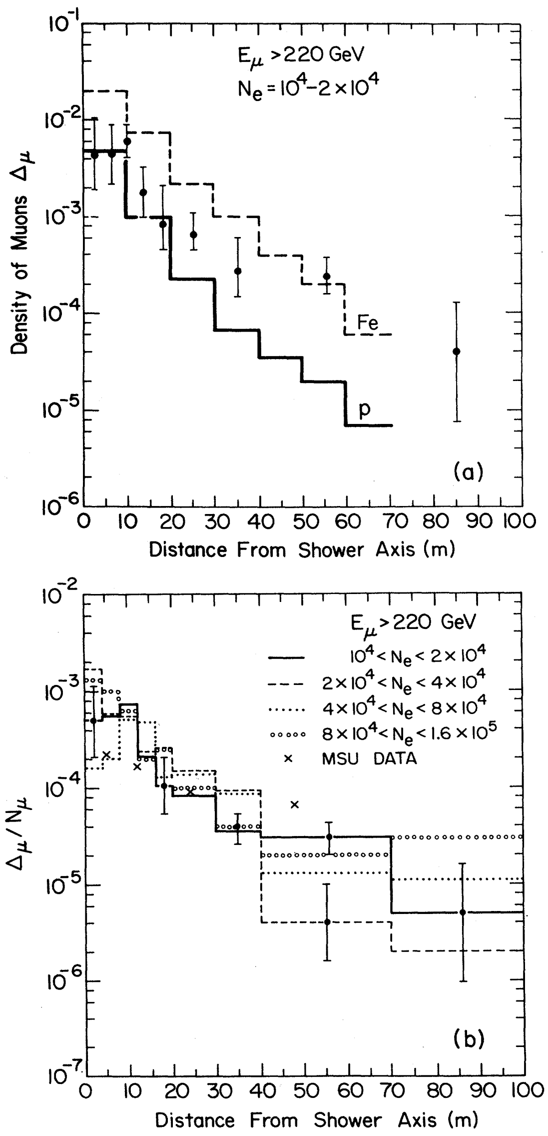

FIG. 9. Lateral distribution (Refs. 10 and 11) of high-energy muons. (a) A comparison of observations with expectations from simulations for showers of size group 10^4–(2×10^4) for protons and iron-nuclei primaries. (b) A comparison of normalized distributions for various size groups.

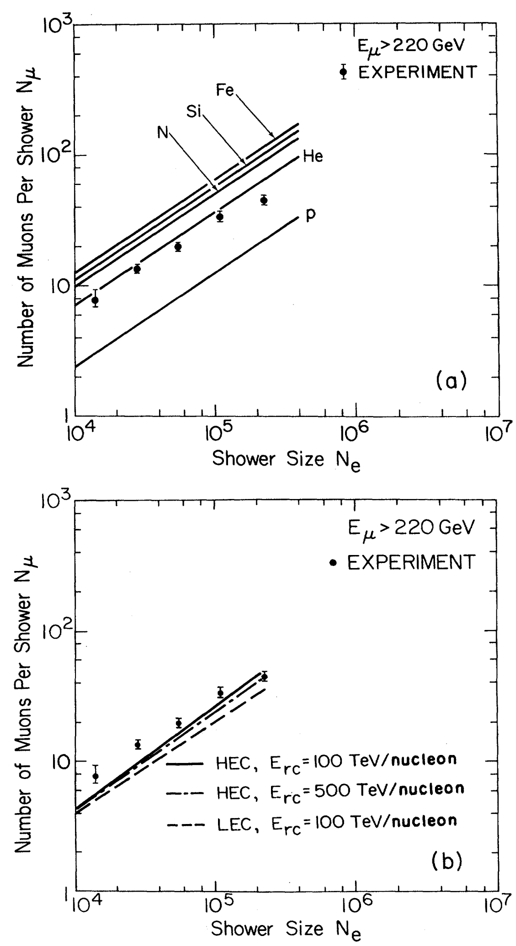

FIG. 10. A comparison of the experimental data (Refs. 10 and 11) on variation of N_μ with N_e with expectations from simulations (a) for various primary nuclear species, and (b) for the two composition models assuming different values for the rigidity cutoff.

as due to production of muons through decay of short-lived particles like charm or beauty hadrons whose production cross sections may be increasing with energy. It is felt that at least a major part of this discrepancy between expectation and observation could be due to selection effects introduced by the requirement of same shower size. Since the muon detector is located at 270-m depth and the shower axes have been required to be located within an area of 15-m radius from the center of the shower array, only near-vertical showers contribute to the muon signal close to the axis. On the other hand, showers with the muon located at distances larger than about 30 m have to be inclined by angles larger than about 10° in order to meet the selection criterion. This value of the minimum angle increases with increasing distance of the detected muon from the shower axis. Therefore, showers with muons detected at larger distances from the axis are due to higher primary energies; note the decrease of N_e with increasing angle in Table I. These showers have a larger number of muons and would give a larger muon density at any distance from the axis.

The expected variation of the number of muons N_μ with shower size N_e is compared with observations in Fig. 10(a) for showers initiated by various nuclei. The expected N_μ-N_e relations for different models of primary composition are shown in Fig. 10(b) along with experimental data. It is seen from this figure that high-energy muons in near-vertical showers have a larger sensitivity to primary composition compared with lower-energy muons in showers with an average zenith angle $\sim 20°$. It may be noted that though the observed lateral distribution of high-energy muons in the Kolar-gold-fields (KGF) experiment is affected by selection bias as discussed earlier, the estimated number of muons N_μ is not affected so strongly because of the small contribution due to muons located at large distances from the axis to N_μ. It is evident from Fig. 10(b) that the LEC model predicts fewer muons per shower and the HEC model agrees better with observations. However, it is not possible to distinguish between various values of the rigidity cutoff from this comparison. It may also be noted that the observed number N_μ may need to be increased by about 20—30 % to take into consideration the nonunity survival probability for muons of energy > 220 GeV to penetrate to the depth of 810 mwe due to catastrophic energy losses. However, detailed calculations need to be carried out to estimate this effect, taking into consideration the energy spectrum of muons in air showers of size $\sim 10^4$—10^5. It can be concluded from this discussion that the observations from the KGF experiment are consistent with the primary composition expected from the HEC model.

V. CONCLUSIONS

We have shown through simulations of experimental observations of high-energy muons in air showers that the sensitivity of these experiments to the atomic number of primaries initiating the showers is reduced when data is grouped according to shower size. Deep in the atmosphere, heavy nuclei must have higher total energy to produce the same shower size as protons; thus they are discriminated against when grouped by shower size. Experimental data on the variation of the number of muons with shower size, both for > 5 and > 10 GeV muon energies, are consistent with expectations from simulations assuming either protons-dominant or heavy-nuclei-dominant composition. Since the absolute numbers N_μ or N_e cannot be relied upon to an accuracy better than about $\pm 30\%$ due to various possible systematic errors, experimental data on low-energy muons cannot be used to distinguish between various models of primary composition. Similarly it has also been shown that the distributions of muon density are insensitive to primary composition and do not provide any reliable information on primary composition at energies $\sim 10^{15}$—10^{16} eV.

The same conclusions hold for the KGF experiment which studies > 220-GeV muons in air showers: sensitivity to composition is reduced by grouping according to shower size.

We show that the available data on muons in air showers are consistent with the heavy-nuclei-dominant composition at energies of the order of 10^{15} eV suggested by the measurements on delayed hadrons in air showers[37] and Cherenkov-photon profiles of air showers.[38]

Finally, we suggest that measurements on the high-energy muon component will be sensitive to mass composition of primaries provided the energy of each shower can be estimated independent of shower size at the observation level, for example, through observations of the total Cherenkov-photon yield in the shower.

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