Monte Carlo simulation for multiple-muon distributions of cosmic rays

K. Mitsui
Institute for Cosmic Ray Research, University of Tokyo, Midori-cho, Tanashi, Tokyo 188, Japan

Y. Minorikawa
Department of Physics, Faculty of Science and Technology, Kinki University, Kowakae, Higashi-Osaka, Osaka 577, Japan

H. Komori
Department of Science, Yamanashi Gakuin University, Sakaori, Kofu, Yamanashi 400, Japan
(Received 13 February 1991)

A high-multiplicity event detected by the Kolar Gold Field (KGF) detector is examined to determine whether or not it is an abnormal phenomenon, taking into account the cosmic-ray primary composition and ordinary interaction models. Our calculation shows that a proton-dominated primary composition around the "knee" is not consistent with measurements of the multiple-muon distributions. On the other hand, taking 15–40 % for the proton fraction and 25–50 % for iron nuclei, there is satisfactory agreement. We have estimated the frequency of multiple-muon events with muons in excess of 20 taking the above primary composition. From this result, one would expect such an event per 60–100 years of operation time, and therefore the probability of observing such an event becomes a few percent for the duration of KGF experiment. Thus, we would suppose that the KGF event is a natural phenomenon in spite of their argument that it is difficult to explain it in terms of a conventional muon production mechanism even if an extreme case of heavy chemical composition of primaries is assumed.

I. INTRODUCTION

A detector, intended for the study of cosmic rays and searching for nucleon decays, has been constructed underground at a depth of 6045 m of water equivalent (mwe) at Kolar Gold Field (KGF) in India [1]. The ground above the site is nearly flat. The KGF detector, which has an area of 6 m$\times$6 m and height 6.5 m, consists of 60 layers of proportional counters. Iron plates with a thickness of 6 mm were put between the layers. During the operating period of about 3.2 yr, they have detected 12 050 single-muon, 132 two-muon, 14 three-muon, and 3 four-muon events, and one event of 20 particles (KGF event) [2,3].

The mean energy of muons going from the surface to the detector is calculated by taking into account the atmospheric muon spectrum. At the surface, it corresponds to $\sim$6.3 TeV ($\pm$1.3 TeV) for the vertical zenith angle, $\sim$8.5 TeV for 30°, and $\sim$16 TeV for 45°, respectively. Underground, the mean muon energy and full width at half maximum (FWHM) of the distribution of the muon energy are $\sim$100 and $\sim$270 GeV, respectively.

It is expected that the contribution of protons in the primary cosmic rays is not important for the production of high-energy multiple-muon events ($>$10 muons in the KGF detector) compared with heavy nuclei. For instance, taking primary iron nuclei, the mean primary energy corresponds to $\sim 10^{17}$ eV nucleus for 20 muons in the KGF detector. On the other hand, for primary protons it increases by a factor of about 2. High-energy muons as measured in KGF are found in the vicinity of the air-shower axis, and a large fraction of them ($\sim$90%) is confined to a circle with a diameter of $\sim$2 m at the surface.

The NUSEX [4], Frejus [5], and Homestake [6] experiments also reported multiple-muon distributions. The NUSEX experiment measured multiple-muon events with up to 7 muons at a depth of 5000 mwe and their results indicate a proton-poor composition. Their measured muons correspond to primary energies of $10^{13}-10^{16}$ eV. The Frejus experiment used a detector with dimension 6 m$\times$12.3 m$\times$6 m at a depth of 4850 mwe and measured multiple-muon events with up to 25 muons in a period of about 2.8 yr. For muons going through the Frejus detector, the mean muon energy at the surface is $\sim$3.3 TeV, taking into account the muon energy spectrum. On the other hand, the Homestake experiment measured multiple-muon events with up to 7 muons at a depth of 4200 mwe. From the measurements, they reported multiple-muon rates consistent with a proton-dominated (83%) primary composition in the energy range from 3×10^{13} to 3×10^{15} eV.

There is an interesting suggestion that the sphaleron will decay into $W^{\pm}$ and Z bosons, accompanied by many quarks and leptons at high energies ($\sim10^{17}$ eV) [7]. In that case, multiple-muon events observed deep underground might be interpreted as the decay products. However, because bosons have high transverse momentum, multiple muons should distribute over larger extent compared with the KGF event ($\pm\sim$1 m). Still the cross section for sphaleron production in hadron-nucleus (and also nucleus-nucleus) collisions in the atmosphere is not clear, and so we confine ourselves to interpretating the events by the mass composition of primary cosmic rays and ordinary interaction models.

In this paper we calculate multiple-muon distributions by Monte Carlo simulation and investigate what limitation is imposed on the primary composition. The primary composition around the "knee" is very important for understanding the primary cosmic-ray acceleration and origin. However, direct measurement is impossible, because of the small intensity of the primary cosmic rays. Therefore, the estimate using the muon component in air showers becomes important as one of the indirect methods.

After determining the best-fit primary composition from the multiple-muon distributions, we examine whether or not the KGF event is an abnormal phenomenon. Since there is a fair chance that the observed particles are not muons but hadrons, we also examine atmospheric muon and neutrino interactions with a rock surrounding the detector. The primary energy able to produce 20 muons in the Frejus detector, assuming primary iron nuclei, corresponds to $\sim 5\times 10^{16}$ eV nucleus. Although it is lower by a factor of ~ 2 compared with KGF, we examine whether or not the Frejus measurements contradict the KGF.

In the following section, the Monte Carlo simulation procedures are presented, and the estimates are compared with the measurements in Sec. III. We give also the discussion and conclusion in Sec. IV.

II. CALCULATION PROCEDURES

A. Primary-cosmic-ray spectrum and mass composition

In the present paper, the primary composition is divided into six groups as follows: proton, helium, medium ($12\le A\le 16$), heavy ($20\le A\le 30$), middle heavy ($31\le A\le 50$), and iron. Primary particles collide with air nuclei and mesons are produced. The muons mainly originate from meson decays. The mechanism of multiple-meson production is formulated according to the wounded-nucleon model [8] for a nucleus-nucleus interaction and the scaling model for a nucleon-nucleon interaction. In a nucleus-nucleus collision, the projectile nucleus is fragmented into other nuclei with lower mass number. The mechanism of nuclear fragmentation is formulated according to the experimental values of fragmentation parameters at low energies [9]. Measurements by a balloon [10–12] and a satellite [13] are available for primary composition and energy spectrum up to the total energy ~ 100 TeV. Above this, air-shower measurements are available [14].

We suppose the energy spectrum presents the well-known "knee" at an energy E_k, the location of the bend in the total-energy spectrum. The spectrum falls somewhat more steeply above the knee, which may reflect that the more energetic particles above the knee are able to leak out of our galaxy more rapidly (assuming their sources to be within it). $E_k(Z)$ is taken as $5\times 10^5 Z$ GeV, where Z is the atomic number of the projectile nucleus.

The differential primary-cosmic-ray intensity varies as $E^{-\gamma}$ over many decades with the exponent γ equal to 2.7 up to E_k and greater than 3 above it. However, for iron nuclei the exponent γ is assumed to be 2.55 up to E_k [13]. In the present paper, the fraction of each component at the total energy 10^{13} eV is assumed to be proton 42%, helium 23%, medium 10%, heavy 8%, middle heavy 4%, and iron 13%. And we calculate the expected multiple-muon distributions under the following two types of spectra.

(a) First type: proton,

$$E\le 2\times 10^5\ \text{GeV}\ ,\quad \gamma=2.7\ ,$$

$$2\times 10^5 < E \le 2\times 10^7\ \text{GeV}\ ,\quad \gamma=2.5\ ,$$

$$2\times 10^7\ \text{GeV} < E\ ,\quad \gamma=3.02\ [15]\ ,$$

helium–middle heavy,

$$E\le E_k\ ,\quad \gamma=2.7\ ,$$

$$E_k < E\ ,\quad \gamma=3.23\ ,$$

iron,

$$E\le E_k\ ,\quad \gamma=2.55\ ,$$

$$E_k < E\ ,\quad \gamma=3.23\ ,$$

where E is the total energy. The fractions of protons and iron nuclei amount to 50–70 % and 15–20 % for total energies between 10^{15} and 10^{17} eV, respectively.

(b) Second type: proton–middle heavy,

$$E\le E_k\ ,\quad \gamma=2.7\ ,$$

$$E_k < E \le 100E_k\ ,\quad \gamma=2.85\ ,$$

$$100E_k < E\ ,\quad \gamma=3.02\ ,$$

iron,

$$E\le E_k\ ,\quad \gamma=2.55\ ,$$

$$E_k < E\ ,\quad \gamma=3.1\ .$$

The fractions of protons and iron nuclei amount to 20–40 % and 20–25 % for total energies between 10^{15} and 10^{17} eV, respectively.

These two types of spectra are presented in Figs. 1(a) and 1(b).

B. Meson production

In this paper we adopt the wounded-nucleon model for nucleus-nucleus interaction. The mean number of wounded nucleons N_{AB} is defined to be the number of nucleons that have participated in one interaction:

$$N_{AB}=(A\sigma_{NB}+B\sigma_{NA})/\sigma_{AB}\ ,$$

where σ_{NA} and σ_{NB} are the nucleon-nucleus inelastic cross sections and σ_{AB} is the nucleus-nucleus cross section. For σ_{NA} and σ_{NB} the following energy dependence is taken:

$$\sigma_{NA}=\sigma(A)E^{0.05}\ (E\ \text{in TeV})\ ,$$

where $\sigma(A)$ is assumed as $36A^{0.74}$ mb [3]. σ_{AB} is given as

$$\sigma_{AB}=\pi(R_A+R_B-br_0)^2\ ,$$

where $R_A = r_0 A^{1/3}$, $R_B = r_0 B^{1/3}$, $r_0 = 1.29$ fm, and b represents the overlapping effect [8] and is given by $1.189 \exp[-0.0545 \min(A,B)]$. The inelastic cross sections of pion- and kaon-nucleus interactions are given [3],

$$\xi = A^{0.79} E^{0.05} \quad (E \text{ in TeV}) ,$$

$$\sigma_{\pi A} = 24.1\xi \text{ mb} ,$$

and

$$\sigma_{KA} = 20\xi \text{ mb} .$$

The mean number of mesons produced in the nucleon-nucleon interaction is taken as

$$\langle n_s \rangle = 0.177 \ln^2 s + 0.66 \ln s + 1.32 ,$$

where s is the center-of-mass energy squared in GeV^2. The multiplicity distributions are assumed to behave according to Koba-Nielsen-Olesen scaling. The ratio of the number of charged kaons to charged pions is taken as 15% and is assumed to be energy independent. The meson energy in the fragmentation region is decided according to the scaling model, and the ionization loss in the atmosphere of the muon and meson are taken into consideration. The total-energy loss of muons in the underground is determined practically entirely by the processes of ionization and excitation of atoms of the medium, bremsstrahlung, pair production, and nuclear interaction and was taken into account with multiple scattering in the present calculation.

The number of muons traversing KGF is estimated by using the second type for the primary spectrum, and their distributions are shown in Fig. 2. As can be seen from this figure, high-multiple muon events with muons in excess of 10 are produced mainly by heavy nuclei such as iron.

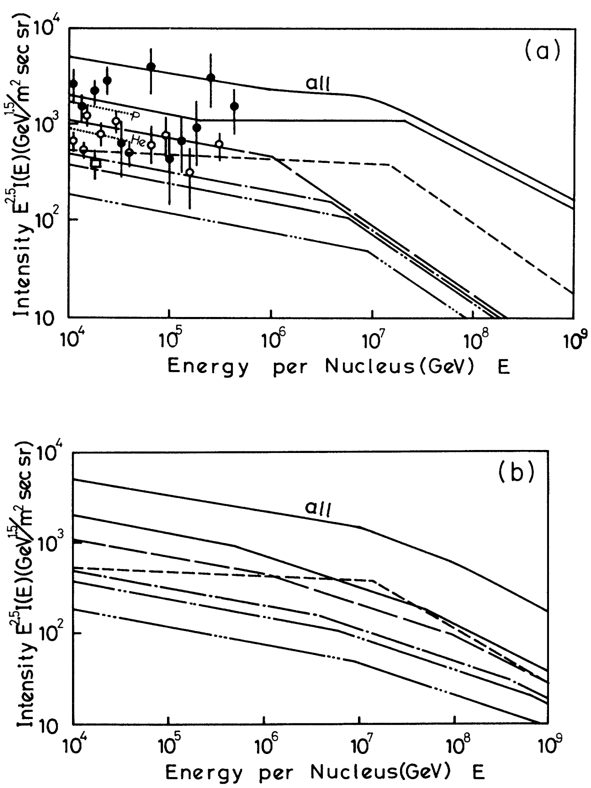

FIG. 1. Assumed differential primary spectra. The ordinate shows the primary energy (E) per particle and the abscissa shows the differential intensity multiplied $E^{2.5}$ (E in GeV). —— : proton, — — — —: helium, –·–·–·–: medium, –..–..–..–: heavy, – · · · – · · · – · · · –: middle heavy, - - - - - - - - - -: iron. The sum of the above six components is shown by *all*, which corresponds practically to the energy spectrum measured by extensive air showers. The measured data are also plotted: proton (●) (JACEE [10]), helium (○) (JACEE [10]), iron (⚈) (Grunsfeld *et al.* [13]), and oxygen (□) (Grunsfeld *et al.* [13]). Extrapolated spectra taking into account measurements by Ryan *et al.* [11] are shown by the dotted line where *p* and He represent proton and helium, respectively. (a) and (b) correspond to the first and second types mentioned in the text.

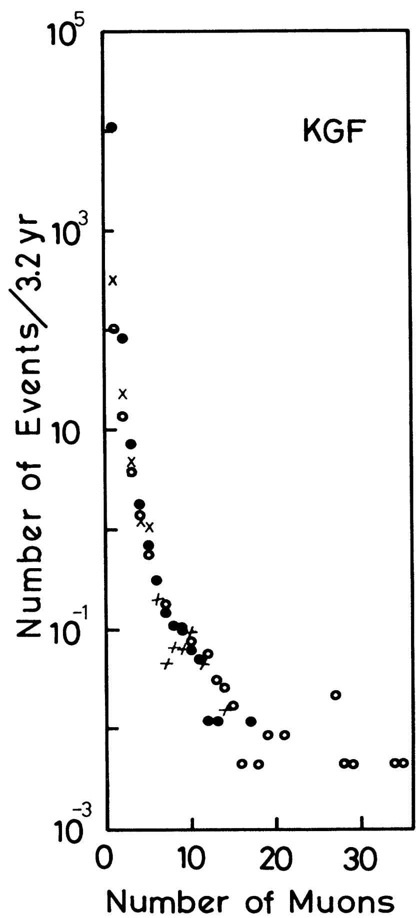

FIG. 2. Distribution of the number of the muon expected in the KGF detector. The muon distributions calculated using the following three primaries are presented individually. Each primary spectrum is given in the second type. protons (●), helium nuclei (×), and iron nuclei (○). The operation time is normalized to 3.2 yr.

C. Muon-nucleon interactions

Multiple mesons are also produced by nuclear interactions atmospheric muons with rock above the detector. Thus we estimate the contribution from this process to the high-multiple events such as the KGF event. The interaction cross section is given in the paper [16], and the total hadronic c.m.-system energy squared W^2 is presented using the four-momentum transfer squared Q^2, transferred energy ν, and nucleon mass M as

$$W^2 = M^2 + 2M\nu - Q^2 \ .$$

The mean multiplicity of charged hadrons is given from the experimental results of the European Muon Collaboration [17] as

$$\langle n \rangle = -0.30 + 1.22 \ln W^2 + 0.22 \ln Q^2 \ ,$$

and the following formula is taken as the multiplicity distribution [18]:

$$\phi(z) = \langle n \rangle p(n) = 2e^{-c}c^{cz+1}/\Gamma(cz+1) \ ,$$

where z is $n/\langle n \rangle$ and c is 7.4. We calculate the number of hadrons produced in the rock above the KGF detector and also calculate the number of hadrons (and/or muons) going through without interaction in the residual target rock and detector. In this case the muon spectrum at the surface is taken from the experimental result [19] and the thickness of the target rock above the detector is varied up to 10 m. The distributions calculated for a rock thickness of 2 m are shown in Fig. 3. As seen in the figure, the number of hadrons going through the detector without interaction is extremely small. Therefore, we can neglect the contribution from this interaction to underground events of high multiplicity.

Other processes producing muons and hadrons deep underground include the neutrino-nucleon interaction [20]. However, this contribution is completely negligible because the cross section is several orders lower than the muon-nucleon interaction mentioned above.

III. COMPARISON WITH OBSERVATIONS

A. Primary composition

Assuming two types of primary spectra as shown in Fig. 1, we first calculate the distributions of the number of muons deep underground by Monte Carlo simulation. We take into account the muon threshold energy, which depends on zenith angle and the geometry of the detector (taking the muon trajectory in excess of 1 m). The distributions calculated by using the primary spectrum of the second type are shown together with experimental data in Fig. 4 (Frejus) and Fig. 5 (KGF). For Frejus the esti-

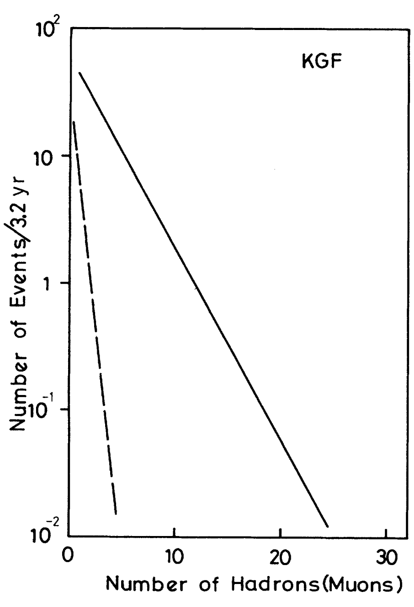

FIG. 3. Multiplicity distribution (solid line) of hadrons produced by atmospheric muon interactions with a rock above the KGF detector. Also, the distribution (dashed line) is shown for hadrons and muons (after meson decays) going through the detector and residual target without interactions. The thickness of a target rock was taken as 2 m. These distributions are almost independent on the target thickness.

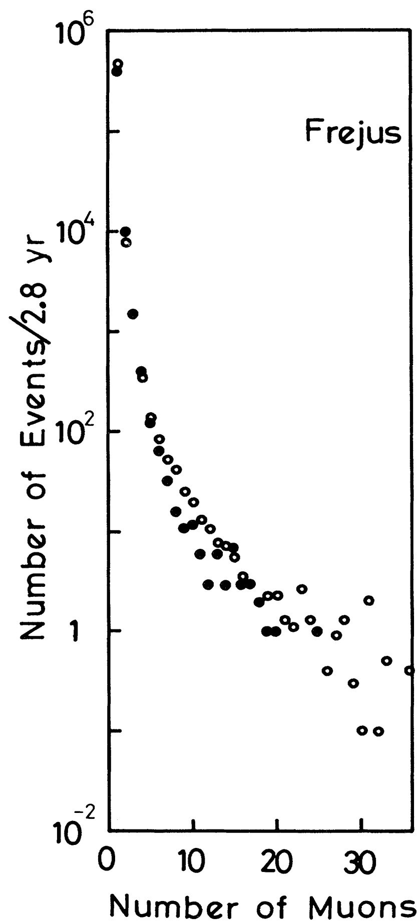

FIG. 4. Comparison between Monte Carlo simulations (○) and measurements of Frejus (●). The operation time is normarized to 2.8 yr. All muons produced by six components assumed in the text are taken in the simulation and spectra assumed in the second type are taken into account.

mates are somewhat higher than the measurements in the range of 7–12 muons, and for KGF the estimates become somewhat higher for 3–4 muons. Although there are slight discrepancies as mentioned above, the measurements of the multiple-muon distribution are in good agreement with the present estimates based on the primary mass composition in the second type.

The χ^2 value per degree of freedom between estimates and measurements is ~ 2 for the first type (all fits are with 19) and ~ 0.6 for the second type. However, if we take the primary composition of the first type without iron nuclei, the χ^2 value becomes ~ 1.9. Therefore, such a primary composition does not help the interpretation of the measurements. Further, if the number of muons is taken in the range of significant statistics (1–6), the χ^2 values become ~ 10 and ~ 1.3 for the first and second types, respectively. Thus the second type composition is better than the first type.

From these considerations, for primary energies between 10^{15} and 10^{17} eV, a proton-dominated composition

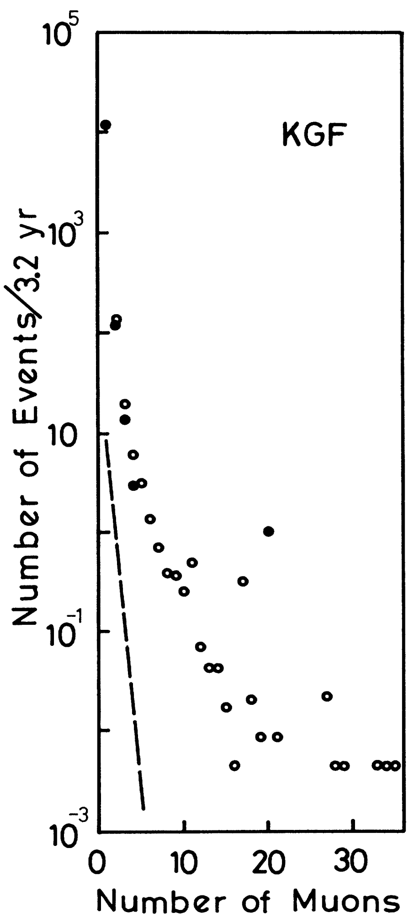

FIG. 5. Comparison between Monte Carlo simulations (○) and measurements of KGF (●). In the simulation, the operation time is normalized to 3.2 yr and all muons produced by six components assumed in the text are taken. The primary spectrum assumed in the second type is taken into account for each components. The dashed line shows the distribution expected from the muon-nucleon interactions.

seems unable to explain the measurements well, and then it is necessary to take into account the possibility that the primary cosmic rays consist predominantly of nuclei (proton fraction 20–40 %).

Further, keeping the first type spectral shape for protons and iron nuclei and varying the fractions of these two components, we calculate the multiple-muon distribution and estimate the best-fit primary composition by comparison with the KGF measurements. However, the other components are assumed to be the same as those of the first type. The estimated minimum χ^2 values and the iron fraction at this place become ~ 1.5 ($N_{\mathrm{DF}}=5$) and $(50^{+25}_{-20})\%$, respectively. This iron fraction is somewhat higher than that (30–40 % around 10^{15} eV) suggested by the γ-ray family experiment [21]. The above-estimated primary composition is called hereafter the third type (proton fraction 10–30 %).

B. Examination of high-multiplicity muon events

As a second step, we examine whether or not the KGF event with 20 tracks is abnormal.

1. Time interval between high-multiplicity muon events

We calculate the flux of high-multiplicity muon events (≥ 20 muons) by taking the second and third types for the primary composition. As shown in Fig. 5, the atmospheric muon and neutrino interactions do not contribute to such high-multiplicity muon events. Primary protons are also impossible for the production of such high-multiplicity muon events. By contrast, heavy nuclei in the primary cosmic rays can contribute to them. If we take the second type and operation time of ~ 250 yr, the number of events is zero for the primary protons (maximum multiplicity is 17) and 3 for primary iron nuclei. Also, we calculate the time interval between any two high-multiplicity muon events (≥ 20 muons). As a result, such events will be observed with the mean time interval of ~ 100 yr (curve A shown in Fig. 6). Thus the probability of observing such an event amounts to a few percent for the KGF operation time. On the other hand, for the third type the mean time interval is ~ 60 yr (curve B shown in Fig. 6) and therefore the corresponding probability becomes $\sim 5\%$.

Although the muon multiplicity of 20 in the KGF detector corresponds to ~ 50 muons in Frejus, taking account the difference of the muon threshold energy, no such event was observed during the Frejus operation time of about 3 yr.

2. Statistical treatment of the experimental value of KGF

We would like to examine whether the experimental value of KGF for $N_\mu = 20$ in Fig. 5 is able to be dismissed or not by the statistical treatment. We have 12 theoretical values (open circles) whose frequencies are all $4.5\times 10^{-3}/3.2$ yr and one experimental value (solid circle) whose frequency is $1.0/3.2$ yr for $N_\mu \geq 20$. According to the statistical treatment, if their distribution is normal and assuming that significant level α is 0.05, we present a ratio F_0, which follows the F distribution, as

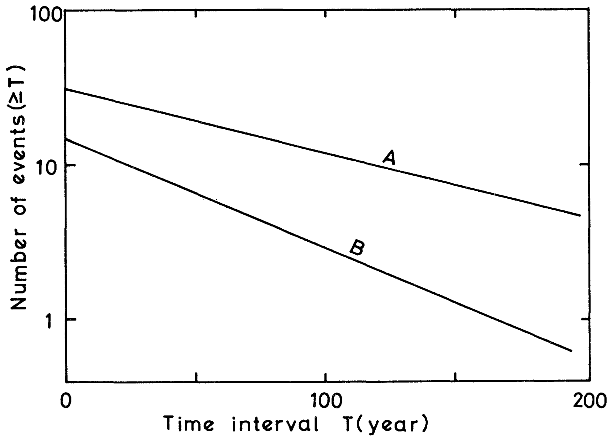

FIG. 6. Integral spectra of the time interval between any two high-multiplicity muon events (≥20 muons). These were obtained by Monte Carlo simulations. The ordinate shows the time interval (T), and the abscissa shows arbitrarily the integral number of events. Curves A and B correspond to the second and third types for the primary composition, respectively.

follows:

$$s^2=\sum_{i=1}^{n}(x_i-\langle x\rangle)^2/n \ , \tag{3.1}$$

$$a=(x_k-\langle x\rangle)/s \ , \tag{3.2}$$

$$F_0=(n-2)a^2/(n-1-a^2) \ , \tag{3.3}$$

where n is the number of data, $\langle x\rangle$ the average value of frequencies for all data, and x_k expresses the frequency to be examined. Since we have that a is 3.4641, F_0 becomes infinity. From the table of F distribution, F_{11} ($\alpha=0.05$) is to be 4.844. F_0 is greater than F_{11} (0.05); therefore, the experimental frequency can clearly be excluded. However, this does not mean that the KGF event is an abnormal phenomenon.

IV. DISCUSSION AND CONCLUSION

Very recently Saito *et al.* [22] have found in cosmic rays two abnormal events with the charge of 14 and mass number of about 370 and have identified them as strange quark matter [23] (SQM), consisting of roughly equal number of u, d, and s quarks. If this conjecture is correct, a primary glob of SQM might explode while penetrating the atmosphere and give rise to multiple-muon events through enhanced Λ and K production because of the high content of s quarks. However, their estimated relative abundance of the SQM candidate to cosmic rays is $\sim 2\times10^{-5}$ at the total energy of 10^{11} eV, and therefore if the integral energy spectrum of SQM can be extrapolated to $10^{16}-10^{17}$ eV with the exponent of cosmic rays, -1.7, the SQM contribution to high-multiplicity muon events should be neglected ($<\sim10^{-3}$ compared with that of heavy nuclei).

Although there is an interesting suggestion that the KGF event is an occurrence of a new interaction [2] in the range of 10^{17} eV, we examined how it may be possible to interpret the KGF event by taking account a primary composition and ordinary interaction models. It was confirmed in the present calculation that the high-multiplicity event detected by KGF cannot be interpreted by muon and neutrino interactions. Since these particles are probably muons, we calculated the multiple-muon distribution produced through primary-cosmic-ray interactions. The low-multiplicity muons are produced normally by protons, while high-multiplicity events originate mainly from heavy nuclei. Thus the proton contribution to the KGF event is negligible.

We assumed two types of primary spectra and calculated the multiple-muon distribution in the KGF detector. Although the second-type primary composition is in better agreement with measurements than the first type, in the region of 3–4 muons the estimations are something higher than the measurements. In order to improve the agreement, it is desirable to decrease the proton rate by making the spectral index greater than 3 for energies beyond E_k, at which the spectral slope steepens. However, such improvement introduces a discrepancy with the energy spectrum measured by extensive air showers. In any case, a proton-dominated composition ($>\sim50\%$) around the knee ($10^{15}-10^{17}$ eV) cannot explain well the multiple-muon distribution. Therefore, it is natural to assume a nucleus-dominated composition around the knee, for example, iron 25–50 % and proton 15–40 %.

We calculated the probability of observing high-multiplicity events with muons in excess of 20. We can expect one such event per 60–100 yr of operation time, and the probability becomes a few percent in the KGF operation time. Therefore, we suppose that the KGF event is not an abnormal phenomenon.

The MACRO detector [24] at the Gran Sasso has a muon threshold energy of ~1.3 TeV and an area of ~900 m^2. When it goes into operation at the full size, it will be possible to detect many events with muon multiplicities up to several hundred. Therefore, in the near future we can say more convincingly whether or not the KGF event is an abnormal phenomenon.

ACKNOWLEDGMENTS

The authors express their sincere thanks to J. R. Storey for his careful reading of this manuscript and valuable discussions. The Monte Carlo simulation was done with the computer FACOM M780 of the Institute for Nuclear Study, University of Tokyo.

[1] H. Adarkar *et al.*, Nucl. Instrum. Methods A **284**, 422 (1989).
[2] H. Adarkar *et al.*, in *Proceedings of the 21st International Cosmic Ray Conference,* Adelaide, Australia, edited by R. J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 9, p. 370; N. Itoh, in *Proceedings of the International Symposium on Underground Physics Experiments,* edited by K. Nakamura (Institute for Cosmic Ray

Research, University of Tokyo, 1990), p. 101; N. Itoh, Parity **5**, 47 (1990).

[3] Y. Muraki, in *Proceedings of the 21st International Cosmic Ray Conference* (Ref. [2]), Vol. 11, p. 257.

[4] G. Bologna *et al.*, Nuovo Cimento C **8**, 76 (1985); M. Aglietta *et al.*, in *Proceedings of the 21st International Cosmic Ray Conference* (Ref. [2]), Vol. 9, p. 352.

[5] Ch. Berger *et al.*, Phys. Rev. D **40**, 2163 (1989).

[6] D. Cebula *et al.*, Astrophys. J. **358**, 637 (1990).

[7] F. R. Klinkhamer and N. S. Manton, Phys. Rev. D **30**, 2212 (1984); A. Ringwald, Nucl. Phys. **B330**, 1 (1990).

[8] A. Bialas, M. Bleszyinski, and W. Czyz, Nucl. Phys. **B11**, 461 (1976); C. E. Navia *et al.*, Phys. Rev. D **40**, 2898 (1989).

[9] O. C. Allkofer and W. Heinrich, Nucl. Phys. **B71**, 429 (1974).

[10] JACEE Collaboration, T. H. Burnett *et al.*, in *Proceedings of the International Symposium on Cosmic Rays and Particle Physics,* Tokyo, Japan, 1984, edited by A. Ohsawa and T. Yuda (Institute for Cosmic Ray Research, University of Tokyo, 1984), p. 468.

[11] M. J. Ryan, J. F. Ormes, and V. K. Balasubrahmanyan, Phys. Rev. Lett. **28**, 985 (1972).

[12] E. Julliusson, Astrophys. J. **191**, 331 (1974).

[13] J. M. Grunsfeld *et al.*, Astrophys. J. **327**, L31 (1988).

[14] A. M. Hillas, *High Energy Astrophysics,* edited by F. K. Lamb (Benjamin, New York, 1984), p. 277; M. P. Chantler *et al.*, J. Phys. G **9**, L27 (1983).

[15] L. Linsley, in *18th International Cosmic Ray Conference, Bangalore, India, 1983, Conference Papers,* edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 12, p. 135.

[16] A. Okada *et al.*, Fortschr. Phys. **32**, 135 (1984).

[17] European Muon Collaboration, M. Arneode *et al.*, Phys. Lett. **165B**, 222 (1985).

[18] N. Schmitz, in *Neutrino 88,* Proceedings of the 13th International Conference, Boston, Massachusetts, 1988, edited by J. Schneps *et al.* (World Scientific, Singapore, 1989), p. 243.

[19] S. Matsuno *et al.*, Phys. Rev. D **29**, 1 (1984).

[20] Y. Ninorikawa and K. Mitsui, Europhys. Lett. **7**, 377 (1988).

[21] J. R. Ren *et al.*, Phys. Rev. D **38**, 1404 (1988).

[22] T. Saito *et al.*, Phys. Rev. Lett. **65**, 2094 (1990).

[23] J. D. Bjorken and L. L. McLerran, Phys. Rev. D **20**, 2353 (1979).

[24] M. Calicchio *et al.*, Nucl. Instrum. Methods A **264**, 18 (1988); R. Bellotti *et al.*, Phys. Rev. D **42**, 1396 (1990).