Is There Strange-Quark Matter in Galactic Cosmic Rays?

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In the analysis of background events from a counter-technique experiment to study cosmic-ray nuclei above 8-GV rigidity, two events were observed which are consistent with the assumption of $Z \sim 14$, $A \sim 350$, and 450 MeV/nucleon and which cannot be accounted for by more conventional background. Such events may be explained by the hypothesis of strange-quark matter (SQM). It is concluded that the existence of SQM has not been excluded by experiment at a flux level of $\sim 6 \times 10^{-9}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$.

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There have been studies[1] of properties of strongly interacting matter in bulk. Witten[2] has proposed the possibility that matter consisting of a roughly equal number of up, down, and strange quarks may be stable at zero temperature and pressure. Stable strange matter has been studied by several authors[3] on the basis of the MIT bag model. The strange matter created in the early Universe would have evaporated and could not survive to the present time.[4] Possible sources of the strange matter would be in the collision of neutron stars, or in neutron stars with a superdense quark surface and in quark stars with thin nucleon envelopes.[5] If strange-quark matter is really stable, it must be an abundant component in cosmic radiation. On the other hand, Bjorken and McLerran[6] have sketched a hypothesis that the "Centauro" events[7] were caused by the explosion of a glob of highly dense matter. If the Centauro events are of a cosmic origin and they are accelerated with a mechanism similar to that for cosmic rays, they should be detected at the top of the atmosphere.

Have existing direct experiments ruled out the scenario for the existence of cosmic quark matter or placed a certain restriction on the scenario? Along this line, we analyzed again the cosmic-ray data which were obtained with a counter telescope in 1981, and found a new type of event in galactic cosmic rays.

Figure 1 shows a schematic view of an instrument, consisting of an acrylic Cherenkov counter (C, two channels C_1 and C_2) and a scintillation counter (S, two channels S_1 and S_2) for measuring the primary charges with an accuracy of 0.35 unit of charges, a liquid Cherenkov counter of fluorocarbon (L, four channels L_1, L_2, L_3, and L_4) for measuring the particle energies around cutoff rigidities (10 GV) and two pairs of X-Y crossed multitube proportional counters[8] (MTPCs) for determining particle trajectories within an accuracy of 0.5 cm for single-particle as well as multiple tracks. For vertically incident carbon nuclei, about 195 photoelectrons were collected with the four combined 5-in. photomultiplier tubes (per channel) from the acrylate Cherenkov counter and about 35 photoelectrons with the three combined photomultiplier tubes (per channel) from the liquid Cherenkov counter. The geometric factor of this instrument is 6049 cm^{2}sr and the total payload weighs 291 kg. It was flown in September 1981 from Sanriku Ballon Center, Japan. The instrument was rotating at 1 rpm in order to measure arrival directions of particles. Triggering by a coincidence pulse satisfying the condition of $C\,[(C_1+C_2)\cdot S(S_1+S_2)]$, eight signals of C_1, C_2, L_1, L_2, L_3, L_4, S_1, and S_2, the trajectory data from the MTPCs, and housekeeping data were transmitted to the ground base. The trigger rate of $C\cdot S$ is about 11 particles/s and the rate of $C_1\cdot C_2\cdot L_1\cdot L_2\cdot L_3\cdot L_4\cdot S_1\cdot S_2$ is 1.3 particles/s. About 127 000 cosmic-ray nuclei of $Z \geq 6$ were recorded during 28 h at an atmospheric depth of 9 g/cm^2.

In the scatter plots of two outputs from the same counter, C_1:C_2, L_1:L_2/L_3/L_4, and S_1:S_2, data within 4 standard deviations (σ) from a response line of cosmic

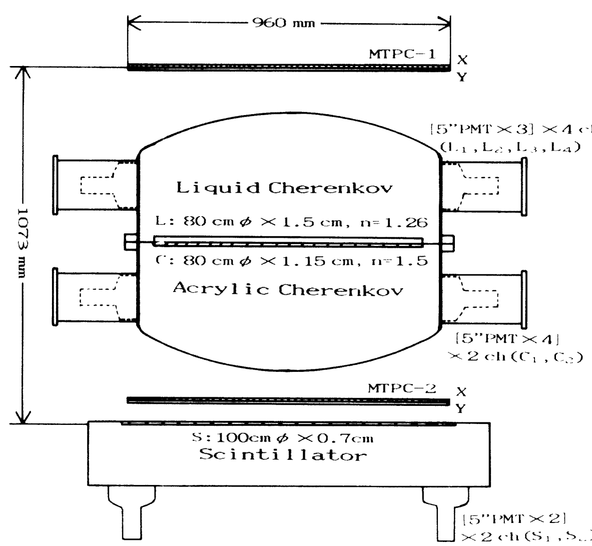

FIG. 1. Schematic cross section of the instrument.

rays were accepted in order to eliminate counter noises and other backgrounds. Particles hitting the photomultiplier were also eliminated by tracking the particles with the MTPCs. Projectile fragments produced in the Cherenkov detectors or in the vessel wall were identified by detecting the multiple tracks in MTPC-2. Figure 2 shows the scatter plot of average pulse heights of C $[(C_1+C_2)/2]$ and S $[(S_1+S_2)/2]$, after correcting the differences of path length and removing the multiple-track events, the fragment events, and other noise events. Events outside 5σ from the distribution of cosmic rays in Fig. 2 were abandoned *a priori* as backgrounds in the previous analysis for studies of chemical abundances and rigidity spectra of cosmic rays.[9] It was found that all the events, except two events, giving signals of $C<S$ in Fig. 2 were produced by particles crossing the lateral face of the Cherenkov radiator, that is, the clipping particles. The two events are shown by the solid circles and the clipping particles by the open circles in Fig. 2. The two events were distributed within 1σ from the response line in the scatter plots of the same counter and were passing through the center of detectors. Namely, they are survivors from twofold coincidences with the plastic Cherenkov counter, fourfold coincidences with the liquid Cherenkov counter, twofold coincidences with the scintillator, and the trajectory checks with the MTPC. The dependences of S and C on β $(=v/c)$ are shown by the solid curves and the corresponding energies are shown by the dotted lines in Fig. 2, where $S=Z^2/\beta^2$ and $C=Z^2\times(1-1/n^2\beta^2)$. The chain line shows the outputs due to the wavelength shifter in the Cherenkov counter which was calibrated with proton beams at KEK. Energies of the two events are obtained as 440 and 460 MeV/nucleon from Fig. 2, respectively.

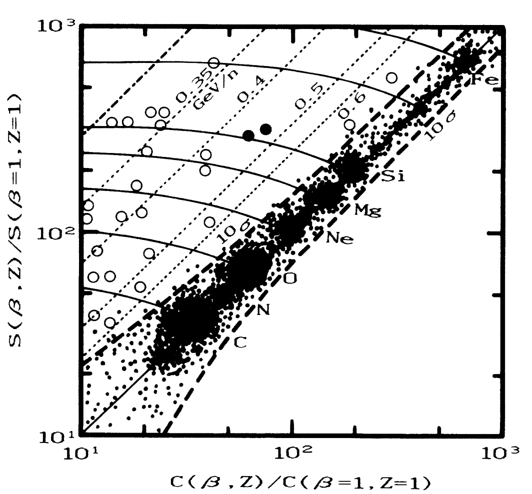

FIG. 2. Scatter plot of Cherenkov output C vs scintillator output S. The broken curves show the 10σ line from the distribution of cosmic rays. The solid curves show the energy dependences of C and S. The novel events are shown by solid circles and the clipping particles by open circles.

Before introducing exotic particles, possible cases were studied within the conservative considerations. The first is the possibility that nuclei with $Z=8$ or 9 interacted with the material of the scintillator, C_8H_8, and the secondary particles gave energy deposits of about $400S_m$ into the scintillator, where S_m is the scintillation output by a minimum-ionizing particle passing through the 7-mm thickness of the scintillator. Unfortunately, the present instrument has no detector to measure the secondary particles from the scintillator. It was stipulated that projectile and target fragments never make scintillation output more than $40S_m$. The production probability of high-energy fragments from nonthermal processes which produce an output greater than $150S_m$ is negligible in the $^{16}O+C$ collisions.[10] In order to make the scintillation output of $400S_m$, it is necessary to produce 400

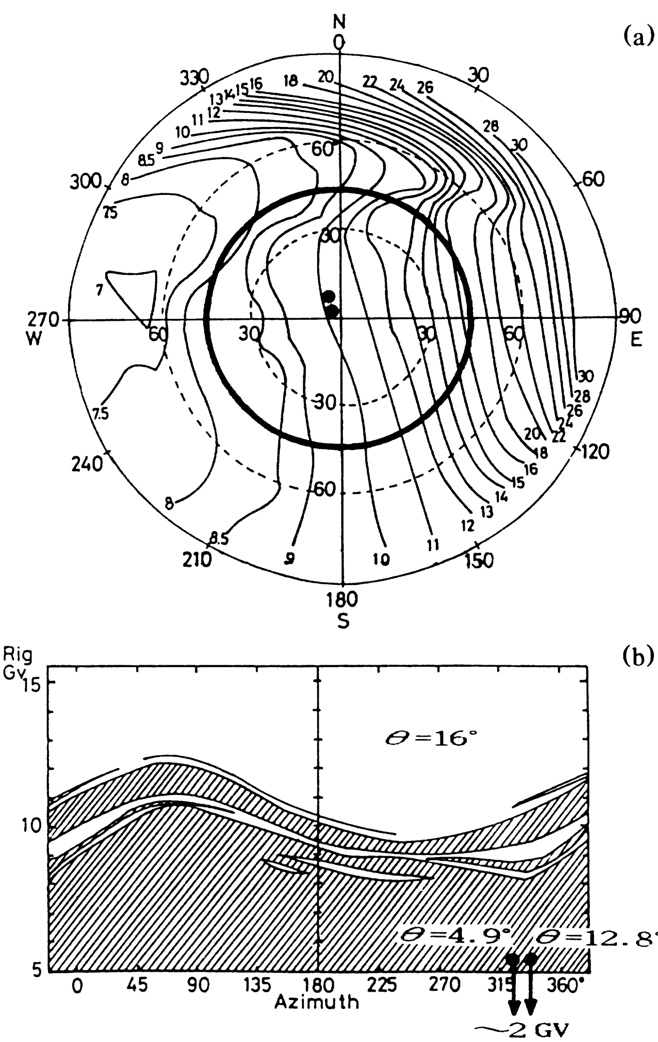

FIG. 3. (a) Contour map of cutoff rigidities at balloon altitude (Ref. 13). The circle of solid line shows the rigidity region viewed by the instrument. (b) Forbidden rigidity region of particles with arrival zenith angle of $\theta=16°$. The two novel events are shown by solid circles.

relativistic particles at the smallest and 800 particles in the case of collisions occurring at half the depth of the scintillator. However, the highest multiplicity was 180 in the 200-GeV/nucleon $^{16}O+C$ collisions at the CERN SPS.[11] Assuming that the shape of the multiplicity spectrum at 200 GeV/nucleon[11] folds at higher energies and that the average multiplicity increases with $E^{1/4}$, the 400 multiplicity events are expected in $^{16}O+C$ collisions at 8 TeV/nucleon. The probability of producing the output of $400S_m$ in the present experiment is estimated to be $< 10^{-9}$ when considering the collision probability of oxygen with the scintillator $< 10^{-1}$, the flux ratio of cosmic rays at 8 TeV/nucleon to that at 4.2 GeV/nucleon to be 2.6×10^{-6}, and the ratio of cross sections of average to the highest multiplicity $< 10^{-3}$. Hence it is rather improbable that the novel events were caused by secondary particles produced in the scintillator.

There is no possibility that the events are albedos because the silicon nuclei have to travel in the atmosphere for about 14 interaction mean free paths without interaction in order to decrease their energies from 4.2 GeV/nucleon to 450 MeV/ nucleon. Another possibility is that of normal nuclei of $Z=14$ with 450 MeV/nucleon, which corresponds to 2 GV for $A/Z=2$, because of the geomagnetic cutoff of 10 GV. Figure 3(a) shows the contour map of cutoff rigidities and Fig. 3(b) the forbidden region of particles with an incident zenith angle of $\theta=16°$ at the balloon altitude around Sanriku.[12] Arrival directions of two particles are shown by solid circles in Fig. 3. The observed rigidity spectra for Ne+Mg+Si are shown in Fig. 4. As can be deduced from Figs. 3 and 4, it is impossible for cosmic-ray nuclei of 2 GV to get over the geomagnetic filter of 10 GV. One may consider the possibility that the partially ionized silicon nuclei penetrated the geomagnetic field and then lost their electrons in the atmosphere. It is impossible to detect the so-called anomalous cosmic rays[13] at balloon altitude. Even if the existence of the partially ionized iron nuclei of > 50 MeV/nucleon is true,[14] energies of galactic cosmic rays slowing down to a few MeV will reach only several tens of MeV, at most 100 MeV/nucleon, by the reacceleration processes.[15] It is concluded that the galactic cosmic rays with energies of several hundred MeV/nucleon are fully stripped.

The mass of the events is given by $A=RZ/(E^2+2mE)^{1/2}$, where R is rigidity, E is energy per nucleon, and m is the nucleon mass. The lower limit of mass is given as $A>110$ for the measured values of $Z=14$ and $E=0.45$ GeV/nucleon, and $R_{min}=8$ GV, the detectable minimum rigidity in the experiment. The probable mass of the events is given as $A=370$ by substituting the relation for the mean rigidity which is derived from $R_{mean}=R_{cut}b/(b-1)=27.2$ GV, where R_{cut} is the effective cutoff rigidity, 10 GV, and b is the exponent of the rigidity spectrum, 1.58. It is possible to introduce the matter having strangeness per baryon of order unity in

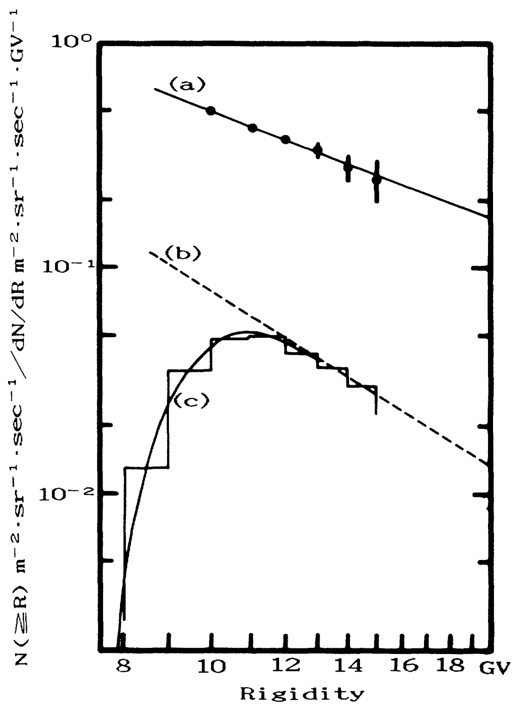

FIG. 4. Rigidity spectra for Ne+Mg+Si nuclei. (a) Integral spectrum, $N(\geq R)=19.0R^{-1.58}$; (b) differential spectrum, $dN/dR=30.2R^{-2.58}$; (c) number spectrum, $(dN/dR)\times D(R)$, where $D(R)$ is rigidity dependence of detection efficiency.

order to understand the high baryon-to-charge-number ratio, $A/Z\approx26$, of the events. The charge of stable strange matter[3] increases as $A^{1/3}$ with constant C, $Z=CA^{1/3}$, in sharp contrast to $Z=A/(2+0.015A^{2/3})$ for ordinary nuclei. The constant C depends on the bulk properties of strange matter. The constant C is equal to 2 according to our observed values of $Z=14$ and $A=370$. This observed value of C is in surprisingly good agreement with the predicted value of Farhi and Jaffe,[3] 1.77 for $Z=12$ and $A=316$, which was derived on the basis of physically simple models.

In Fig. 5, the fluxes of quark-matter candidates at the balloon altitude are shown by the solid circle at 10 GV and by the open circle at the total energy. Relative abundances of the events to cosmic rays are 2.6×10^{-7} at the same rigidity, about 2.2×10^{-9} at the same energy per nucleon, and about 2.1×10^{-5} at the same total energy. The dotted line shows the integral energy spectrum of strange-matter candidates with the exponent of cosmic rays, -1.7.

If our events are real, there must be similar types of events in the other experiments. We propose to examine the past cosmic-ray data to search for the events. Although both charges and masses were measured in the experiments using magnetic spectrometers, the collecting power, 0.2 m^2sr h, might be too small to find strange-

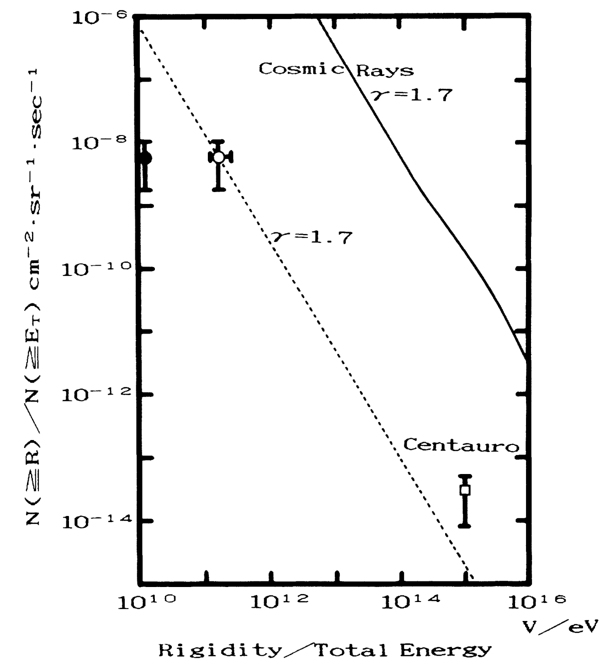

FIG. 5. Flux of the quark-matter candidates. The solid circle shows the value at 10 GV and the open circle that at the total energy. The rectangle shows the flux of Centauro events. The dotted line shows the expected total-energy spectrum of strange-matter candidates.

quark-matter events.[16] There is the possibility of finding the candidate events in the balloon experiments at the high and constant rigidity,[17] although their exposure factor, 2.6 m^2sr h, is $\frac{1}{4}$ of ours.

It is concluded that the existence of cosmic quark matter has never been excluded by direct observations. In order to confirm the events as strange-quark matter conclusively, a new instrument of 1 m^2sr combining the counter system with photosensitive passive detectors is under construction. The mass of the candidates will be determined by measuring the changes of dE/dX and residual range. If the particles interact in the detector, projectile fragments from strange matter might be observed as V particles.

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