Search for fractionally charged particles in Kamiokande II

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A search has been made for fractionally charged particles with $|Q|=\frac{1}{3}$ and $|Q|=\frac{2}{3}$ which might have passed through the Kamiokande II detector. No positive evidence for such particles is observed in 1009 days of observation. The 90%-C.L. upper limits obtained on the fluxes of fractionally charged particles are 2.1×10^{-15} $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ for $|Q|=\frac{1}{3}$ and 2.3×10^{-15} $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ for $|Q|=\frac{2}{3}$, improving the existing limits by two orders of magnitude.

It was proposed in 1964 that quarks of charge $\frac{2}{3}e$ and $-\frac{1}{3}e$ might be the fundamental constituents of hadrons.[1,2] The quark model explains well many of the experimental results on hadron spectroscopy[3] and hard-scattering processes.[4] Free fractionally charged particles that would be direct evidence of the model have been searched for by several methods[5] using accelerators, cosmic rays, and detection in bulk matter. Although none of the experiments found positive evidence for free quarks, the stringent limits on the existence of such particles led to the idea of quark confinement and to partially successful QCD theories. Searches for fractionally charged particles are still necessary because they test for a possible breakdown of confinement.

In this paper, we report the results of a search in the Kamiokande II water Cherenkov detector for charged particles with $|Q|=\frac{1}{3}$ and $|Q|=\frac{2}{3}$ produced by primary cosmic rays, where Qe is the charge of the particle. The Kamiokande II detector is located 2700 m of water equivalent underground in the Kamioka mine, about 300 km west of Tokyo (36.42° N, 137.31° E). A cylindrical steel tank contains 2400 tons of water viewed by 948 20-in. photomultiplier tubes (PMT's) covering 20% of the tank inner surface. This inner detector is surrounded by a 4π steradian water anticounter at least 1.2 m thick, viewed by 123 20-in. PMT's. A more detailed description of Kamiokande II is given in Ref. 6.

In the Kamiokande II detector, fractionally charged particles can be distinguished from unit charged particles such as cosmic-ray muons by the emitted Cherenkov light intensity. The number of Cherenkov photons per unit path length and unit wavelength emitted by a charged particle of $\beta > 1/n$, $d^2N/dx\,d\lambda$, is given by

$$\frac{d^2N}{dx\,d\lambda}=2\pi|Q|^2\alpha\left[1-\frac{1}{(n\beta)^2}\right]\frac{1}{\lambda^2}\ , \qquad (1)$$

where n is the refraction index of water, β is the velocity of the charged particle relative to the light velocity, and α is the fine-structure constant. Equation (1) indicates that the number of Cherenkov photons associated with charged particles is proportional to $|Q|^2$. Therefore, the total Cherenkov emissions of $|Q|=\frac{1}{3}$ and $|Q|=\frac{2}{3}$ particles, $(d^2N/dx\,d\lambda)_{|Q|=1/3}$ and $(d^2N/dx\,d\lambda)_{|Q|=2/3}$, are related to the total Cherenkov emission of normal ($|Q|=1$) cosmic-ray muons, $(d^2N/dx\,d\lambda)_\mu$, by the factors $\frac{1}{9}$ and $\frac{4}{9}$, respectively.

Figure 1 shows the correlation of path length of cosmic-ray muons that penetrated the Kamiokande II detector with the total yield of Cherenkov light measured in number of photoelectrons. The total number of photoelectrons can be written as

$$(P_{\rm tot})_\mu \approx (1000L)\text{p.e.} \ , \qquad (2)$$

where L is the path length of the muons in meters. The deviation of $P_{\rm tot}$ from Eq. (2) is less than 10% for muons with $L \geq 10$ m. In fact, the minimum total photoelectron yield of the *a* muon with path length 10 m is about 9000 p.e. Therefore charged particles that penetrate the detector with path length larger than about 10 m and with a total photoelectron yield less than 7000 p.e. might be considered to be fractionally charged particles. Such events are searched for in the total photoelectron range 750 p.e. $\leq P_{\rm tot} \leq 2000$ p.e. for $|Q|=\frac{1}{3}$ and 3000 p.e. $\leq P_{\rm tot} \leq 7000$ p.e. for $|Q|=\frac{2}{3}$.

Data from 9 December 1986 through 11 April 1990, corresponding to 1009 days of observation time, were analyzed. A total of 7.1×10^7 events were accumulated during this data-taking period. Among them, 1.4×10^6 events satisfy the criteria 750 p.e. $\leq P_{\rm tot} \leq 2000$ p.e., and 4.9×10^6 events have 3000 p.e. $\leq P_{\rm tot} \leq 7000$ p.e. Most of these events are penetrating muons with relatively short path length in the detector or muons which stopped in the detector. No path length cut was utilized at this stage of the analysis. To remove them, an initial data reduction program utilizing only the charge and timing information from each PMT was developed. The algorithm essentially examines the correlation between the

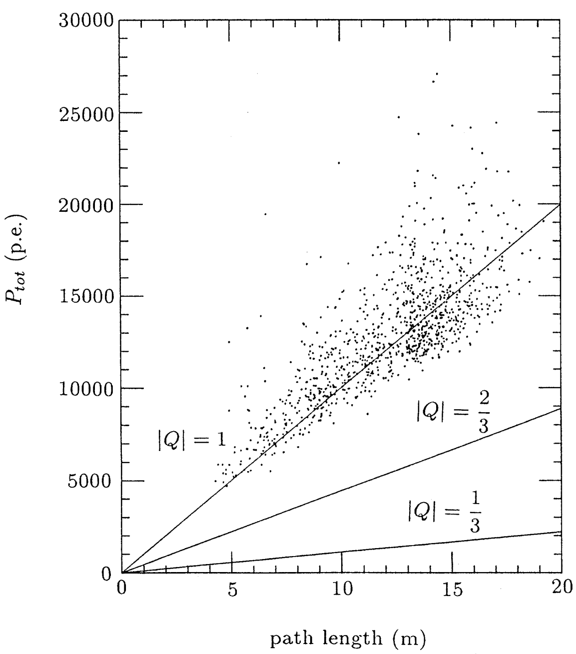

FIG. 1. Correlation between the total Cherenkov light yield measured in photoelectrons and the path length of radiating particles in the detector. The scattered points are for a selected, reconstructed sample of muons $|Q|=1$, and the solid lines for $|Q|=\frac{1}{3}$ and $|Q|=\frac{2}{3}$ particles.

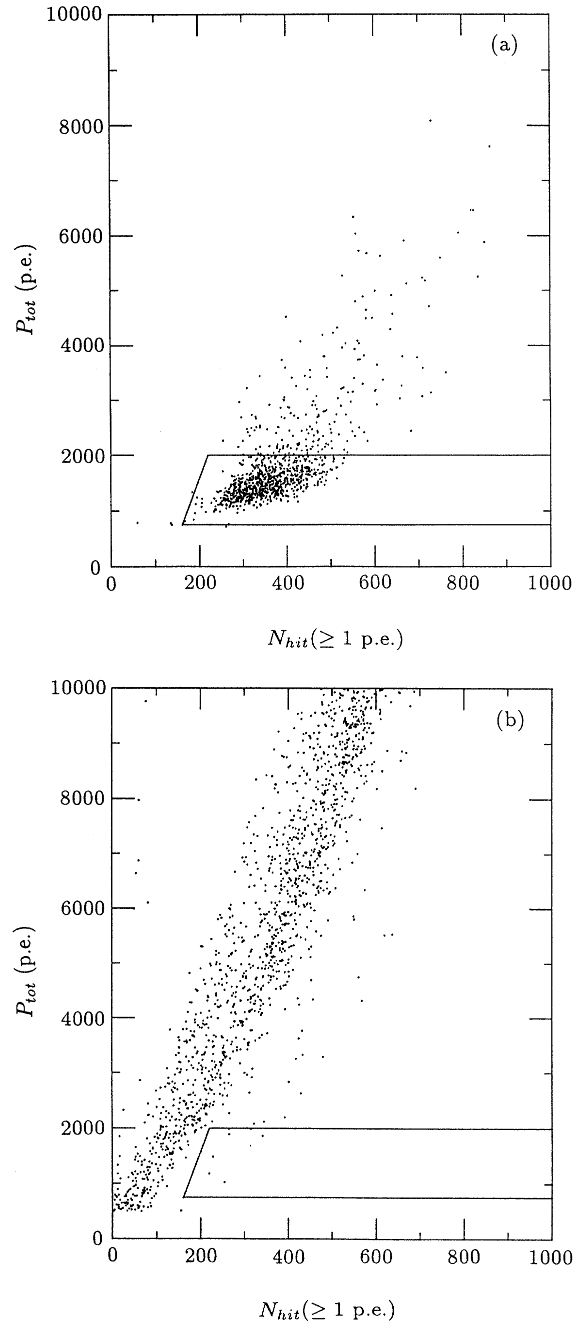

FIG. 2. Correlation between number of hit PMT's (≥ 1 p.e.) and total photoelectron number in an event for (a) $|Q|=\frac{1}{3}$ particles, simulated from real muon events by multiplying their photoelectron yield by $\frac{1}{9}$, and for (b) typical muon raw data sample obtained in a one hour exposure. The selection criteria are shown by the solid lines.

number of hit PMT's and the total photoelectron number in the event, which is shown in Figs. 2 and 3. One finds that fractionally charged events appear as a large number of hit PMT's each with relatively low ($\gtrsim 1$ p.e. for $|Q|=\frac{1}{3}$ and $\gtrsim 4$ p.e. for $|Q|=\frac{2}{3}$) photoelectron yield, whereas a short path length and stopped muon events are characterized by a small number of hit PMT's each with a relatively large ($\gtrsim 10$ p.e.) photoelectron yield. Events within the solid lines in Figs. 2 and 3 are selected. There are 2.8×10^3 events for $|Q|=\frac{1}{3}$ and 16.5×10^3 events for $|Q|=\frac{2}{3}$. Events remaining at this stage are reconstructed using timing information. Those with short (<10 m) path lengths or stopped trajectories are removed. Finally, 1945 events with 750 p.e. $\le P_{\rm tot} \le$ 2000 p.e. and 2863 events with 3000 p.e. $\le P_{\rm tot} \le$ 7000 p.e. cannot be rejected at this stage in the analysis.

Most of the remaining events are muons with more complicated behavior. About 70% of the remaining

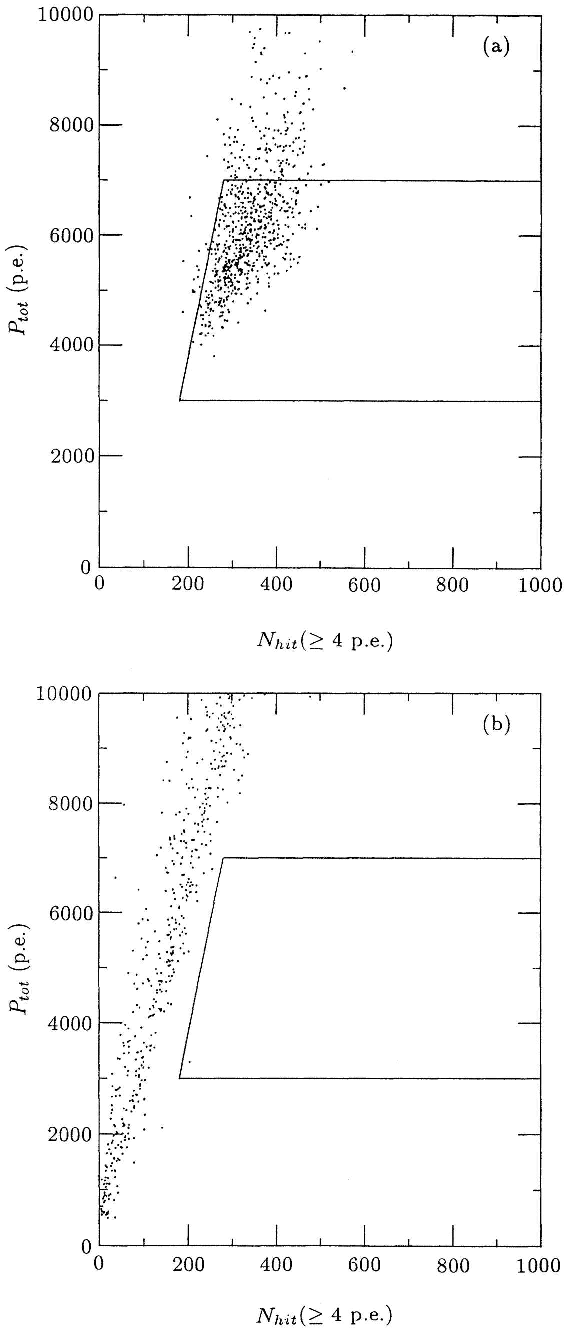

FIG. 3. Correlation between number of hit PMT's (≥ 4 p.e.) and total photoelectron number in an event for (a) $|Q|=\frac{2}{3}$ particles, simulated from real muon events by multiplying their photoelectron yield by $\frac{4}{9}$, and for (b) typical muon raw data sample obtained in a one hour exposure. The selection criteria are shown by the solid lines.

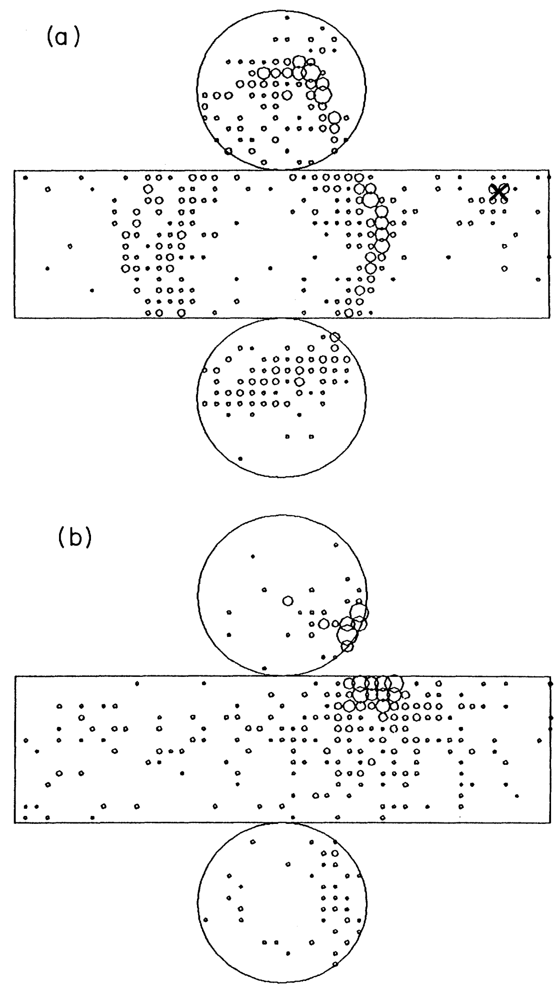

FIG. 4. Exploded view of typical events which are selected by the $|Q|=\frac{1}{3}$ event selection criteria. The top and bottom PMT planes are cut and attached to the barrel PMT plane which is open flat. Hit PMT's are shown by open circles whose areas are in proportion to photoelectrons. (a) a stopped muon with appreciable multiple scattering. Entrance position of the muon is denoted by $\times$. The total photoelectron of the event is 1451 p.e. (b) a muon accompanied with hadronic interactions clipped the top corner of the detector. The total photoelectron of the event is 1147 p.e.

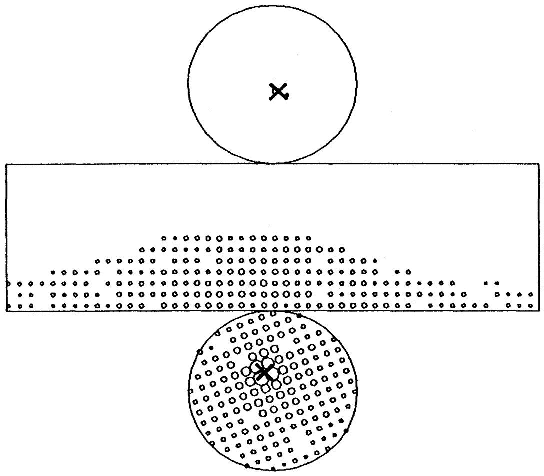

FIG. 5. An exploded view of typical $|Q|=\frac{1}{3}$ particle simulated from a real penetrating muon event by multiplying their pulse height by $\frac{1}{9}$. Entrance and exit position are denoted by $\times$. The total photoelectron of the event is 1297 p.e.

events are stopped muons with appreciable multiple scattering, 20% are muons with short path lengths accompanied with an hadronic interaction in the detector, and 10% are multiple muons both of which have short path lengths or stop in the detector. Some of the survived events are shown in Fig. 4. These events are easily distinguished from fractionally charged events shown by Fig. 5. The remaining events were visually scanned one by one and no candidate was observed with a track length greater than 10 m and $P_{\rm tot}$ in the intervals given above.

The selection efficiency of the data-reduction program was studied using real penetrating muon events by multiplying the pulse height of each PMT by $\frac{1}{9}$ ($|Q|=\frac{1}{3}$) or $\frac{4}{9}$ ($|Q|=\frac{2}{3}$). The selection efficiency (ϵ) is calculated to be $\epsilon=76\%$ for $|Q|=\frac{1}{3}$ and $\epsilon=71\%$ for $|Q|=\frac{2}{3}$. The 90%-C.L. upper limits on the fluxes (Φ) can be calculated from the nominal detection area $S=130$ m^2, observation time $T=1009$ days, and selection efficiency ϵ. The results are

$$\Phi(|Q|=\tfrac{1}{3})=2.1\times10^{-15}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} \tag{3}$$

and

$$\Phi(|Q|=\tfrac{2}{3})=2.3\times10^{-15}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}\ . \tag{4}$$

Here, the angular acceptance of the detector is taken as 4π. These upper limits are lower by more than two orders of magnitude than the present limits on fractionally charged particles in cosmic rays, 6.2×10^{-13} cm^{-2} s^{-1} sr^{-1}, obtained from the deep-underground monopole search experiment.[7]

Given the known primary proton spectrum and the upper limits on the quark fluxes in (3) and (4), an upper limit on the production cross section of quarks (σ_q) by cosmic-ray protons can be obtained. Following an early, simplified model[8,9] one finds

$$\sigma_q \le 1.6\times10^{-40}\left[\frac{\Omega}{4\pi}\right]^{-1} M_q^{3.33}\ \text{cm}^2 \tag{5}$$

with 90% confidence, where M_q (GeV) is the quark mass. Ω is the angular acceptance related to the mountain shape and the quark survival probability between the production point and the detector site, which cannot be calculated without knowledge of the interaction cross section with rock. The limit is valid for the quark-mass range $M_q \le 110(\Omega/4\pi)^{1/5.33}$ GeV, which in the simplified model is obtained from the additional relation between Φ and M_q, viz.,

$$M_q^{5.33} \le 1.7\times10^{-4}\Phi^{-1}\left[\frac{\Omega}{4\pi}\right]\ \text{cm}^{-2}\,\text{s}^{-1}\ . \tag{6}$$

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