Search for $Q=\frac{2}{3}e$ and $Q=\frac{1}{3}e$ Particles Produced in e^+e^- Annihilations

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In a search for heavy $Q=\frac{2}{3}e$ and $Q=\frac{1}{3}e$ particles produced in e^+e^- collisions at a center-of-mass energy of 29 GeV, no candidate events were found in 77 pb^{-1} of data collected by the time projection chamber at PEP. Upper limits are established on the inclusive cross section for the production of $Q=\frac{2}{3}e$ and $Q=\frac{1}{3}$ particles in the mass range 1–13 GeV/c^2, improving upon previously established limits.

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Only in the past few years have experimental limits been reported on the production of free quarks in e^+e^- annihilations.[1-3] Estimates of the inclusive-production cross section of free quarks (and diquarks) in e^+e^- annihilations indicate that if they are produced, the cross section should be highly suppressed relative to typical hadronic processes.[4,5] This underscores the need for clean, high-statistics searches for fractionally charged particles. In this Letter we report the results of a search for the inclusive production of $Q=\pm\frac{2}{3}$ and $Q=\pm\frac{1}{3}e$ particles in e^+e^- interactions at a 29-GeV center-of-mass energy. We have previously reported a limit on the production of $Q=\pm\frac{4}{3}e$ particles.[6] In this Letter we will use units in which $e=1$.

The search was performed with the use of data collected by the PEP-4 time projection chamber (TPC) facility at the positron-electron storage ring (PEP) at the Stanford Linear Accelerator Center. The data used in this analysis came primarily from the TPC, the central tracking chamber of the PEP-4 apparatus. A detailed description of the TPC and PEP-4 experiment has been given elsewhere.[7] Track ionization formed in the TPC drifts in axial electric and magnetic fields to twelve sectors (six per end cap) consisting of arrays of 183 proportional wires per sector. Track coordinates in the bending plane are found from the signals induced on rows of segmented cathode pads (fifteen rows per sector) beneath the wires. The data were collected under conditions identical to those described in an earlier Letter.[6]

Charged-particle species are identified in the TPC through a simultaneous measurement of momentum and track ionization. To a good approximation, the energy loss of a charged particle in a gas scales as[8]

$$\left\langle\frac{dE}{dx}\right\rangle \sim \frac{Q^2}{\beta^2}\left[\ln\left(\frac{\kappa(\beta\gamma)^2}{I^2+(h\nu_p\beta\gamma)^2}\right)-\beta^2\right],$$

where I, κ, and ν_p are constants which depend on the gas, β and γ are the usual kinematic variables,

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and Q is the charge of the particle. Qualitatively, this gives a curve that falls as $1/\beta^2$ at low velocities, reaches a minimum (for the TPC, this is at $\beta\gamma \approx 3.6$), and then rises logarithmically until it reaches a constant value (about 1.4 times the minimum for the TPC). In this analysis, the measured value of the track energy loss due to ionization, $\langle dE/dx \rangle$, is defined to be the mean of the lowest 65% of the ionization samples collected at the sectors. For the data under discussion, the TPC had a $\langle dE/dx \rangle$ resolution of 3.7% for tracks with at least eighty samples of ionization. The momentum resolution of the TPC is

$$(\delta p/p) \approx [(0.06)^2 + (0.035p)^2]^{1/2}$$

(p in GeV/c) for $Q=1$ particles. Figure 1 shows a scatter plot of $\langle dE/dx \rangle$ versus measured momentum for tracks in a 40% subset of the multihadron data. The bands are due to the stable $Q=1$ particles (e,π,K,P). Since $\langle dE/dx \rangle$ scales as Q^2, one would expect free $Q=\frac{1}{3}$ and $Q=\frac{2}{3}$ particles to have ionization scales $\frac{1}{9}$ and $\frac{4}{9}$ times for $Q=1$ particles. Because the curvature of a particle in a magnetic field also depends on Q, the apparent momentum (also referred to as rigidity), p/Q, will be shifted relative to $Q=1$ particles by factors of 3 and 1.5

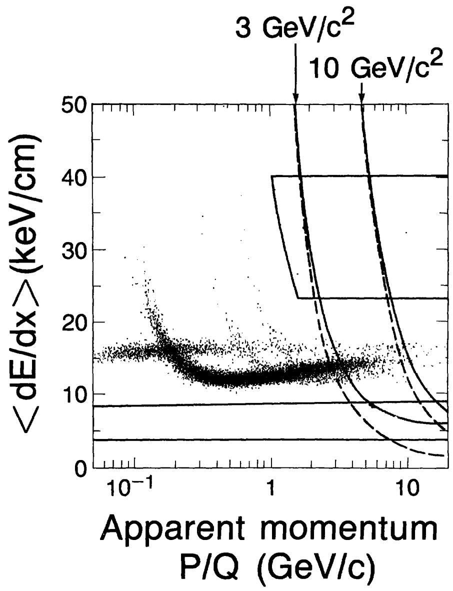

FIG. 1. Scatter plot of $\langle dE/dx \rangle$ vs apparent momentum (p/Q) for tracks in the data sample. The shaded regions are the search regions defined in the text. The lines are the expected ionization curves for $Q=\frac{2}{3}$ (solid lines) and $Q=\frac{1}{3}$ (dashed lines) particles with masses of 3 and 10 GeV/c^2.

for $Q=\frac{1}{3}$ and $Q=\frac{2}{3}$ particles, respectively. Shown in Fig. 1 are the curves of $\langle dE/dx \rangle$ versus apparent momentum for $Q=\frac{1}{3}$ (dashed lines) and $Q=\frac{2}{3}$ (solid lines) particles with masses of 3 and 10 GeV/c^2.

The search was performed in regions of $\langle dE/dx \rangle$ and apparent momentum not populated by stable $Q=1$ particles. This consisted of two regions (shaded in Fig. 1), one below minimum ionization for $Q=1$ tracks, and one at high apparent momentum and high $\langle dE/dx \rangle$. The lower region is bounded by the lines $\langle dE/dx \rangle = 4.0$ keV/cm and $\langle dE/dx \rangle = 8.0$ keV/cm (for $Q=1$ tracks at minimum ionization, $\langle dE/dx \rangle = 12.1$ keV/cm). As described later, the lower boundary of this region was chosen in a place where the detector efficiency was well understood. It must be pointed out that this region does not include the region of minimum ionization for $Q=\frac{1}{3}$ particles; we are only sensitive to these particles at essentially nonrelativistic velocities. The upper region is bounded by the curve of ionization for 1.8-GeV/c^2 $Q=1$ particles, by the line $\langle dE/dx \rangle = 40.0$ keV/cm, and by the line $\langle dE/dx \rangle = 24$ keV/cm. The upper boundary of this region was imposed by electronic saturation.

The data sample used in the search represented 77 pb^{-1} of integrated luminosity. We used an event sample consistent with the reaction $e^+e^- \rightarrow \gamma^* \rightarrow$ hadrons, with selection criteria identical to those described in an earlier Letter.[6] In all, 29 094 events passed the multihadron selection. Candidate tracks were selected from this event sample if they had a $\langle dE/dx \rangle$ and apparent momentum in the sensitive regions defined above. All candidates were required to extrapolate to within 5 cm in the bending plane and to within 10 cm in the drift direction of the beam-beam crossing point. To ensure reasonable $\langle dE/dx \rangle$ resolution all candidate tracks had to satisfy two requirements. Candidate tracks had to have at least eighty samples of unstable ionization along the track length with no other identifiable sources of ionization within 3 cm. Because the wire gain falls off sharply near the edge of the TPC sectors, tracks found close to the edge (within ≈ 1 cm) usually had unreliable $\langle dE/dx \rangle$ measurements. We defined a restricted fiducial volume by requiring candidates to have an average distance from the edge of the sectors greater than 2 cm.

In the search region below minimum ionization for $Q=1$ particles no candidate tracks were found. In the search region above minimum ionization for $Q=1$ particles, in addition to the above requirements, candidate tracks were required to have momentum errors $\delta p/p$ less than or equal to $0.1p$ (p in GeV/c). In all, 96 tracks were found passing these criteria. Most of these tracks were actually pairs of nearby tracks which were reconstructed by the analysis software as single tracks, and thus appeared to have an anomalously large $\langle dE/dx \rangle$. This background was identified by the presence of nearby hits not associated with known tracks and by abnormally wide ionization clusters. A set of cuts were developed based on these properties to eliminate overlapping tracks pairs as candidates. These requirements, described in detail in our Letter on $Q=\frac{4}{3}$ particles,[6] rejected all 96 tracks.

As a test of the detection efficiency of the TPC for tracks below minimum ionization for $Q=1$ particles, we made several runs at reduced wire gain. We used these runs to measure how the electronics and track reconstruction software responded to tracks with a low apparent ionization. Data were taken at two different wire voltages, corresponding to apparent values of $\langle dE/dx \rangle$ for minimum-ionizing tracks of 6.9 and 5.0 keV/cm. From the number of reconstructed tracks, the number of wire and pad hits per track, and the ionization spectrum, we have determined that there is no loss of detection efficiency for tracks with values of $\langle dE/dx \rangle$ as low as 4 keV/cm. Electronic noise begins to affect track detection efficiency for $\langle dE/dx \rangle$ below 4 keV/cm. We measured the inefficiency of the requirements used to eliminate overlapping track pairs by applying the same cuts to heavily ionizing $Q=1$ tracks. This inefficiency, included in the limit calculation, reduced the acceptance by $\approx 20\%$ in the region above minimum ionization for $Q=1$ tracks.

The detection efficiences for $Q=\frac{1}{3}$ and $Q=\frac{2}{3}$ particles were determined by a Monte Carlo calculation. The event generator was a modified LUND[9] generator in which a pair of oppositely charged $Q=\frac{1}{3}$ or $Q=\frac{2}{3}$ particles were introduced into multihadron events. These events provided input to a detector simulator. The generated fractionally charged particles were given momenta chosen from one of two distributions, $dN/dp \sim p^2/E$ and $dN/dp \sim (p^2/E)e^{-3.5E}$ (E in GeV). We expect that if free quarks are produced, they will be quite massive.[4] Because of this expectation and kinematics arguments,[4,10] the inclusive production spectra should be quite similar to the first distribution above. The second distribution, more typical for light hadrons such as pions and protons, is presented as an alternative model. In the detector simulation we assumed that $Q=\frac{1}{3}$ and $Q=\frac{2}{3}$ particles do not have larger than normal nuclear cross sections. We note that some estimates of nuclear cross sections for free fractionally charged particles[4] give values 2–3 times that for protons. There is 6% of a nuclear interaction length between the beam-beam crossing and the TPC active volume.

Our limits on

$$R_Q = \sigma(e^+e^- \to Q\bar{Q}X)/\sigma(e^+e^- \to \mu^+\mu^-)$$

are shown in Fig. 2 for $Q=\frac{2}{3}$ particles and in Fig. 3 for $Q=\frac{1}{3}$ particles, along with the results of similar searches reported by the JADE,[1] the Mark II[2] (for $Q=-\frac{2}{3}$ only), and the PEP-14[3] collaborations. Our results represent a substantial improvement on the previously established limits. Because the search regions in $\langle dE/dx \rangle$ and momenta are separated by the region populated by $Q=1$ particles, there exist combinations of masses and momenta for $Q=\frac{2}{3}$ particles for which we have relatively low sensitivity. This local loss of sensitivity is reflected in the structure of the limit curves in Fig. 2.

To conclude, we have seen no evidence for the inclusive production of $Q=\frac{1}{3}$ or $Q=\frac{2}{3}e$ particles in e^+e^- annihilations at a 29-GeV center-of-mass

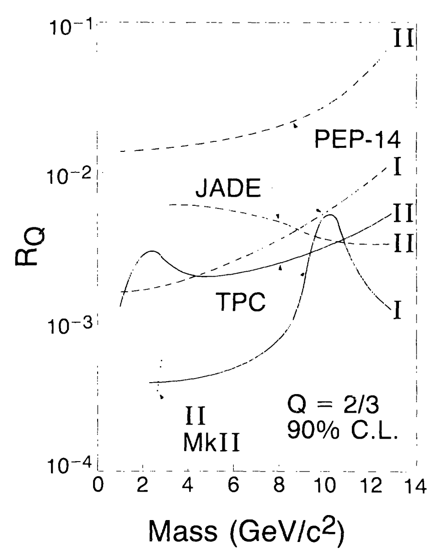

FIG. 2. Upper-limit curves (90% C.L.) for

$$R_Q \equiv \sigma(e^+e^- \to Q\bar{Q}X)/\sigma(e^+e^- \to \mu^+\mu^-)$$

for the production of $Q=\frac{2}{3}$ particles. The assumed momentum distributions are (I) $dN/dp \sim p^2/E$, and (II) $dN/dp \sim (p^2/E)e^{-3.5E}$. Also plotted are the results of similar searches by the Mark II Collaboration (Ref. 2, dotted line, for $Q=\frac{2}{3}$ only), the JADE Collaboration (Ref. 1, dashed lines), and by the PEP-14 Collaboration (Ref. 3, dash-dotted lines).

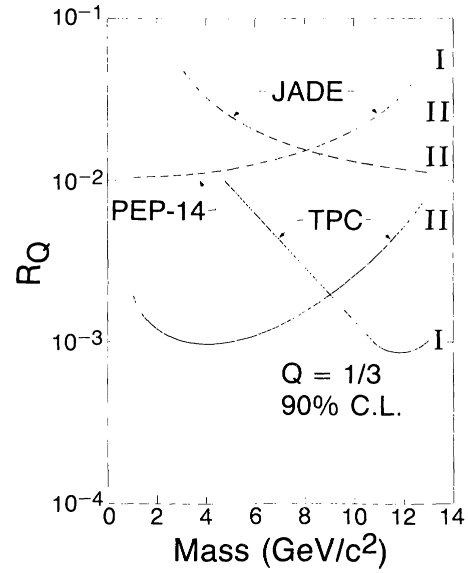

FIG. 3. Upper limit curves (90% C.L.) for the production of $Q=\frac{1}{3}$ particles. Also plotted are the results of similar searches by the JADE Collaboration (Ref. 1, dashed lines), and by the PEP-14 Collaboration (Ref. 3, dotted line). The Roman numerals refer to the same production hypotheses as in Fig. 2.

energy. In the mass range of 1 to 13 GeV/c^2, we set an upper limit on the ratio R_Q for these particles between 4.0×10^{-4} and 1.0×10^{-2} depending on mass, charge, and production hypothesis. A search is in progress for exclusively produced (i.e., in the reaction $e^+e^-\rightarrow Q\bar{Q}$) fractionally charged particles.

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[1]J. Bürger, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Bonn, 1981,* edited by W. Pfeil (Physikalisches Institut, Universität Bonn, Bonn, 1981), p. 115.

[2]J. M. Weiss *et al.* (Mark II Collaboration), Phys. Lett. **101B**, 439 (1981).

[3]M. C. Ross *et al.* (PEP-14 Collaboration), Phys. Lett. **118B**, 199 (1982).

[4]A. De Rújula, R. Giles, and R. Jaffe, Phys. Rev. D **17**, 285 (1978).

[5]R. Slansky, T. Goldman, and G. Shaw, Phys. Rev. Lett. **47**, 887 (1981).

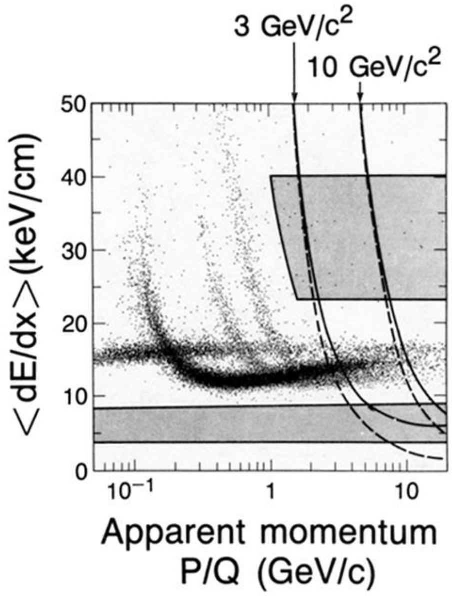
[6]H. Aihara *et al.* (PEP-4 TPC Collaboration), Phys. Rev. Lett. **52**, 168 (1984).

[7]H. Aihara *et al.* (PEP-4 TPC Collaboration), IEEE Trans. Nucl. Sci. **30**, 63, 76, 162 (1983).

[8]For a detailed treatment of dE/dx in gas-filled detectors, see, for example, F. Lapique and F. Piuz, Nucl. Instrum. Methods **175**, 297 (1980); W. Allison and J. Cobb, Annu. Rev. Nucl. Part. Sci. **30**, 253 (1980).

[9]B. Andersson and G. Gustafson, Z. Phys. C **3**, 223 (1980).

[10]M. Suzuki, Phys. Lett. **71B**, 139 (1977); J. D. Bjorken, Phys. Rev. D **17**, 171 (1978).



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