# Search for Charge-$\frac{4}{3}e$ Particles Produced in $e^+e^-$ Annihilations

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In a search for heavy charge-$\frac{4}{3}e$ particles produced in $e^+e^-$ collisions at a center-of-mass energy of 29 GeV, no candidate events were found in 22 $pb^{-1}$ of data collected by the time projection chamber at PEP. Upper limits are established on the inclusive cross section for the production of charge-$\frac{4}{3}e$ particles in the mass range of 1–10 GeV/$c^2$.

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Fractional-cnarge searches at accelerators have largely concentrated on the production of charge-$\frac{2}{3}e$ and -$\frac{1}{3}e$ particles. In the framework of quantum chromodynamics, the inability to observe free quarks in these searches is considered strong evidence that color triplets are confined. Recently, Slansky, Goldman, and Shaw[1] have proposed a model in which color triplets are confined, yet some states with higher-order representations of $SU(3)_{\rm color}$ are unconfined. It is possible in this model to have a free charge-$\frac{4}{3}e$ dequark ($uu$). In this Letter we report the results of a search for the inclusive production of free charge-$\frac{4}{3}e$ particles at PEP.

The time projection chamber (TPC) is the central tracking chamber (Fig. 1) of the PEP-4 experiment. The detector system has been described in detail elsewhere.[2] Track ionization formed in the TPC sensitive volume drifts in parallel electric and magnetic fields to arrays of proportional wires. The track position in $z$ (parallel to the beam axis) is found from the arrival time of the ionization (drift velocity $\approx 5$ cm/$\mu$sec) at the proportional wires. Up to 183 samples of ionization per track are collected on the wires. Track coordinates in the bending plane $(x, y)$ are found from signals induced on fifteen rows of segmented cathode pads beneath the wires.

The data presented in this Letter were collected with the TPC operating at a gas gain of $10^3$, in an 8.5-atm mixture with 80% Ar and 20% $CH_4$. The drift field was 75 kV/m; the magnetic field was 4 kG. The spatial resolution for tracks was 190 $\mu$m in the bending plane $(x, y)$ and 340 $\mu$m in the drift direction $z$. The chamber had a momentum resolution, $dp/p$, of $0.035p$ ($p$ in GeV/$c$) for particles with momenta greater than 1 GeV/$c$.

The TPC identifies particle species by a simultaneous measurement of ionization and momentum. To avoid fluctuations in the measurement of track ionization resulting from close collisions

 

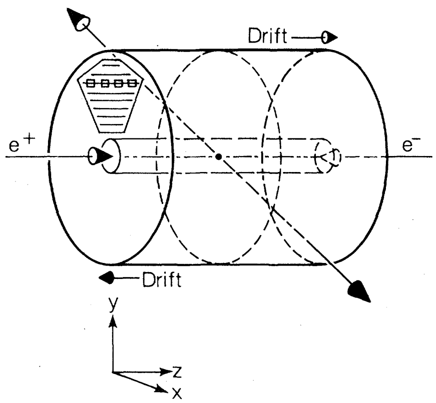


FIG. 1. Schematic view of the TPC. Track ionization formed in the sensitive volume drifts to arrays of proportional wires (only one set of wires shown). Position in the bending plane $(x, y)$ is found from signals induced on cathode pads beneath the wires.

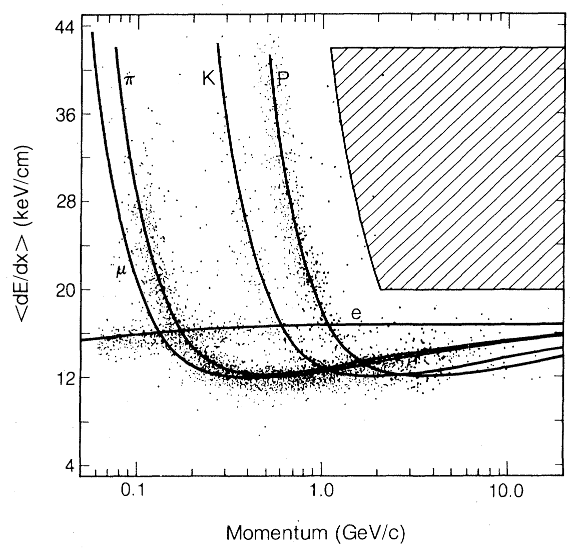


FIG. 2. Curves of expected $\langle dE/dx\rangle$ vs momentum for stable charge-1$e$ particles. The points are from a subset of the data collected. The charge-$\frac{4}{3}e$ search was performed with use of tracks found in the cross-hatched region.

with atomic electrons, the measured value of the energy loss due to ionization, $\langle dE/dx\rangle$, was defined to be the mean of the lowest 65% of the wire pulse heights. Each wire was calibrated with an $Fe^{55}$ source. The $\langle dE/dx\rangle$ resolution, measured with minimum ionizing pions ($\langle dE/dx\rangle = 12$ keV/cm), was 3.9% for tracks with at least eighty samples of ionization.

Figure 2 shows the curves of expected $\langle dE/dx\rangle$ as a function of momentum for pions, muons, protons, kaons, and electrons along with a subset of the data collected. Since the energy loss of a particle scales as the square of its charge, one would observe relativistic charge-$\frac{4}{3}e$ particles as a population in the upper right-hand region of Fig. 2 at $\frac{16}{9}$ times the ionization of a relativistic unit-charged particle. Because the curvature of a particle in a magnetic field also depends on its charge, the apparent momentum scale for charge-$\frac{4}{3}e$ objects in Fig. 2 would be shifted by a factor of $\frac{3}{4}$ relative to the charge-1$e$ particles.

In order to achieve good sensitivity, the search was performed in regions of $\langle dE/dx\rangle$ and momentum (shaded region in Fig. 2) which were not populated by known stable charge-1$e$ particles. The low momentum boundary of the search region was set at the curve of expected $\langle dE/dx\rangle$ for a charge-1$e$ particle with a mass of 1.8 GeV/$c^2$. The low $\langle dE/dx\rangle$ boundary was set at 1.2 times $\langle dE/dx\rangle$ for electrons in the same momentum range. The level at which electronic saturation begins to affect the $\langle dE/dx\rangle$ measurement is at $\langle dE/dx\rangle = 42$ keV/cm. This defines the high $\langle dE/dx\rangle$ boundary of the search region.

The data sample used in the search consisted of 22 $pb^{-1}$ of integrated luminosity at a center-of-mass energy of 29 GeV collected during the 1982–1983 running cycle of PEP. The events were selected to be one-photon annihilations of $e^+e^-$ into hadrons, satisfying the following criteria. The number of charged tracks extrapolated to within 5 cm in $(x, y)$ and 10 cm in $z$ of the beam crossing had to be greater than or equal to five. The scalar sum of the visible charged momenta had to be at least 7.25 GeV/$c$. In each event the momentum imbalance between the forward and backward hemispheres was required to be less than 40% of the visible energy. We estimate the contamination of background events to be 8%, coming from cosmic rays, beam gas, $\tau\bar{\tau}$, and two-photon events. In all, 7137 events satisfied the above criteria.

In order to retain good $\langle dE/dx\rangle$ resolution, candidates in the search region were selected only if they had at least eighty samples of ionization with no other ionization detected within 3 cm in $z$. We also required that candidates have momentum assignment errors, $dp/p$, estimated from the residuals to the fit, less than or equal to $0.1p$ ($p$ in GeV/$c$).

After applying these cuts fifty candidate tracks remained. There were two major sources of backgrounds in this sample.

Deuterons and tritons have ionization curves lying partly in the search region. Some of these particles, produced from the interactions of primary tracks with the detector material, will pass the above cuts. As a result of finite production angles, however, most of the track fits for these particles will not extrapolate through the beam crossing point. We reduced this background by requiring candidates to have an extrapolated distance of closest approach to the beam crossing point no greater than 5 cm in the bending plane $(x, y)$ and no greater than 10 cm in the drift direction $z$. Nine candidate tracks were rejected by imposing this requirement. Eight of these had values of $\langle dE/dx\rangle$ and momentum consistent with deuterons. The ninth candidate track was an overlap background of the type described below.

The second source of background came from unresolved pairs of nearby tracks. When two high-momentum tracks are emitted close together (typically with an angular separation of 25 mrad or less) often only one is reconstructed. The ionization from these tracks adds and the reconstructed track appears to have a large value of $\langle dE/dx\rangle$ and a high momentum.

The fine spatial segmentation of the TPC allowed us to develop a series of cuts to reduce the second background. The cuts were tested on heavily ionizing tracks in hadronic events both to ensure that the requirements were not overly restrictive and to measure the inefficiency created by imposing them. We based these requirements on the expectation that overlapping tracks would produce excessively wide cathode pad and wire ionization clusters and/or nearby clusters not associated with the reconstructed track.

A wire hit is imaged on two to three cathode pads. In the three-pad case (2–10 per track) we measure the width, $\sigma$, of the ionization cluster ($\langle\sigma\rangle = 3.9$ mm). From $P(\sigma)$, the probability for a cluster on an isolated track to have a width $\sigma$, we formed the quantity

$$L \equiv \frac{1}{n}\sum_{i=1}^{n} \ln P(\sigma).$$

$L$ is the logarithm of the likelihood for a track to have $n$ clusters with widths coming from the distribution $P(\sigma)$. We required candidates to have values of $L$ consistent with a single track. $L$ has no appreciable $\langle dE/dx\rangle$ dependence.

When only one of a pair of nearby tracks is reconstructed, the second track will often appear as additional ionization clusters near the first. Tracks were eliminated as candidates if they had an unusually large number of nearby pad or wire hits not associated with reconstructed tracks.

In some cases a second track or energetic delta ray may appear to merge with a track for part of its length and give approximately double the normal ionization only for the merged regions. The high density of wire information (up to 183 clusters per track) allowed us to reject these. We required candidates to have statistically uniform amounts of ionization along the track length. Partially merged tracks showed, on many contiguous wire hits, abnormally heavy ionization often correlated with large cluster widths. These were rejected.

These requirements rejected the remaining 41 candidate tracks.

The detection efficiency of the apparatus for charge-$\frac{4}{3}e$ particles was determined in two steps. First the efficiency due to event topology, momentum distribution, fiducial volume, etc., was found with use of a Monte Carlo calculation. The event generator was a modified LUND[3] generator in which a pair of oppositely charged $\frac{4}{3}e$ particles were introduced into multihadron events. These events provided input to a detector simulation. The generated $\frac{4}{3}e$ particles were given momenta chosen from one of three distributions, $dN/dp \propto P^2/E$, $dN/dp = \text{const}$, and $dN/dp \propto (P^2/E) \times e^{-3.5E}$.

We expect that if free colored objects, such as unconfined diquarks, are produced, they will be quite massive.[4] On the basis of kinematics arguments[5] the inclusive momentum spectra for such objects should be quite similar to the spectra found for heavy hadrons, such as charmed and bottom hadrons. Estimates of the inclusive momentum spectra for heavy fractionally charged particles and heavy hadrons tend to favor the first and second distributions above.[4,5] The third distribution, more typical for light hadrons (e.g., pions, protons), is presented as an alternative.

In the detector simulation we assumed that charge-$\frac{4}{3}e$ 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. The amount of material between the beam crossing and the TPC active volume corresponds to 6% of a nuclear interaction length.

We found the efficiency of the cuts used to re-

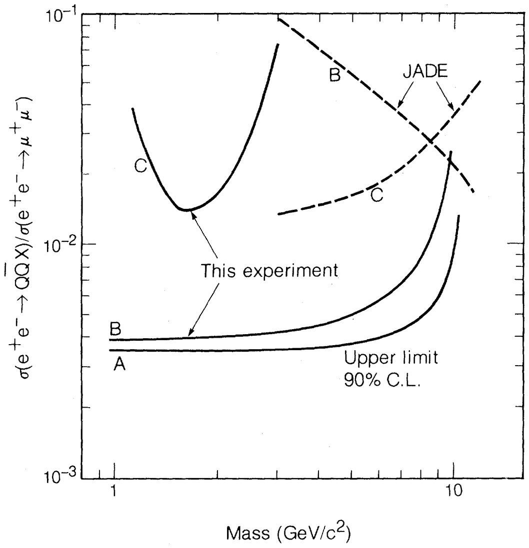


FIG. 3. Limits on the inclusive production cross section for charge-$\frac{4}{3}e$ particles $R_Q \equiv \sigma(e^+e^- \to Q\overline{Q}X)/\sigma(e^+e^- \to \mu^+\mu^-)$ for the momentum distributions (a) $dN/dp \propto P^2/E$, (b) $dN/dp = \text{const}$, and (c) $dN/dp \propto (P^2/E) \times e^{-3.5E}$. The solid curves are the limits from this search, and the dashed curves are the limits from a search performed by the JADE Collaboration (see Ref. 6).

ject overlapping tracks by applying the same requirements to heavily ionizing charge-1$e$ tracks. This efficiency was 72% with an estimated systematic uncertainty of 10%.

Our limits on $R_Q \equiv \sigma(e^+e^- \to Q\overline{Q}X)/\sigma(e^+e^- \to \mu^+\mu^-)$ are plotted in Fig. 3 along with the results of a similar search reported by Bartel *et al.*[6]

To conclude, we have seen no evidence for the inclusive production of charge-$\frac{4}{3}e$ particles in $e^+e^-$ collisions at a 29-GeV center-of-mass energy. For momentum distributions similar to those for heavy hadrons[4,5] we set an upper limit on the ratio $R_Q$ at less than 0.005 in the mass range 1–8 GeV/$c^2$. Work is currently in progress on a search for charge-$\frac{1}{3}e$ and $-\frac{2}{3}e$ particles.

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