Search for Exclusive Free-Quark Production in e^+e^- Annihilation

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The products of e^+e^- annihilation at 29-GeV center-of-mass energy have been searched for free fractionally charged particles produced in exclusive two-body final states. No evidence for fractionally charged quarks was found and the upper limits on the ratio $R_{q\bar{q}} = \sigma_{q\bar{q}}/\sigma_{\mu\bar{\mu}}$ are below 1% for quarks with charges $\frac{1}{3}e$ or $\frac{2}{3}e$ and masses below about 14 GeV/c^2. This is the first reported limit for charge $\frac{1}{3}e$. Long-lived fractionally charged leptons are definitely ruled out over a significant range of masses.

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Numerous attempts to discover free fractional charge[1] have been made since the quark hypothesis was first introduced. Recent sensitive searches for fractional charge on matter provide positive evidence[2] stimulating new interest in free quarks. Searchers for isolated quarks have concentrated mostly on cosmic rays or particles produced in hadronic collisions at accelerators. Searches for quark production by the weak and electromagnetic interaction are less numerous.[3]

We have completed a search for quarks or other fractionally charged particles produced electromagnetically in e^+e^- collisions. We collected data at 29-GeV center-of-mass energy using the Stanford Linear Accelerator Center (SLAC) e^+e^- storage ring, PEP (positron electron project). Recent results of similar searches using different techniques were reported as by products of general-purpose colliding-beam detectors: Mark II at SPEAR[4] and JADE at PETRA.[5] These experiments were sensitive to exclusively produced particles with charge $\frac{2}{3}e$ as well as inclusive production for $\frac{1}{3}e$ and $\frac{2}{3}e$. The present work includes the first limit on exclusive production of charge $\frac{1}{3}e$ particles.

Our detector is specifically designed to measure fractionally charged particles produced in e^+e^- annihilation either exclusively in pairs or accompanied by hadrons. The charge (Q) of detected particles is determined through the Bethe-Bloch formula from measurements of energy loss (dE/dx) and velocity ($\beta = v/c$). In this Letter we report limits for exclusive production using two-prong collinear events collected at PEP.

The detector has two symmetric arms, each covering the face of a cube centered at the interaction region (IR). The total solid angle is $4\pi/3$ sr. Figure 1 is an elevation view. Each arm is composed of nine multiwire proportional chambers (MWPC)[6] for tracking, twelve scintillation-counter hodoscopes for sampling dE/dx, and a single Lucite Cherenkov-counter hodoscope.[7] Five of the scintillation-counter hodoscopes have time-of-flight (TOF) electronics for measuring β. The flight path for TOF is 1.5 to 2.6 m, depending on the angle of the track. The Cherenkov-counter hodoscope provides additional velocity information. The threshold velocity for the

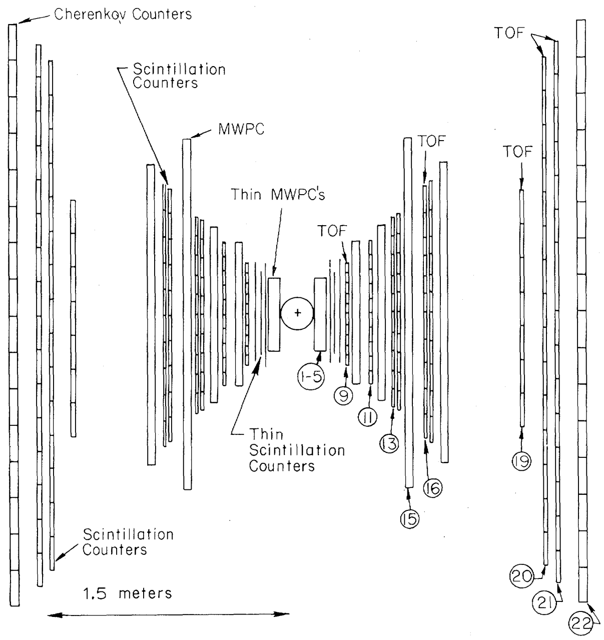

FIG. 1. Elevation view of the detector as viewed along the beam pipe. The elements are numbered sequentially from 1 to 22 moving outward from the IR (some of the layers are numbered in the figure). The "thin" MWPC's (layers 1 to 5) are not shown individually. Scintillation layers 9, 16, 19, 20, and 21 are equipped with TOF electronics.

Cherenkov counters is $\beta \approx 0.7$. All counters have two photomultipliers, one at each end.

For tracks near counter edges dE/dx is sometimes partially sampled in more than a single counter. We account for this effect by adding the dE/dx from the intersected counter and relevant adjacent counter.

For selected tracks the most probable dE/dx is estimated by a truncated average of the single layer dE/dx measurements. The Q is calculated with the relation $Q \propto \beta(dE/dx)$ and a velocity-dependent correction is introduced[8] to approximate better the Bethe-Bloch formula. We note that the ability to measure TOF extends our sensitivity to high quark masses (M_q). The TOF is also essential for reducing backgrounds.

Cosmic rays are used to calibrate and align the detector components.[9] A minimum-ionizing particle produces roughly 150 photoelectrons in each scintillation counter. After corrections for pulse-height effects the average time resolution of a TOF counter measured with cosmic rays is $\sigma \approx 150$ psec. The time resolution depends on pulse height and increases to 650 psec for $\frac{1}{10}$ of dE/dx for a $Q = 1e$ minimum-ionizing particle (MIP).

During colliding-beam runs, the detector is monitored periodically: Light-emitting diodes connected to counters via optical fibers ensure gain stability; a similar system driven by a fast flash tube monitors the TOF system; and the MWPC electronics is monitored by reading out calibration pulses induced on the anode wires and cathode strips.

The thresholds on counter discriminators and MWPC readout are set at a dE/dx level corresponding to $\frac{1}{30}$ and $\frac{1}{50}$ of MIP dE/dx, respectively. This ensures sensitivity to $Q = \frac{1}{3}e$ particles. A relativistic $Q = \frac{1}{3}e$ particle produces 3.2 primaries and 11.5 ion pairs per centimeter in our chamber gas (80% Ar – 20% CO_2). The innermost five "thin" MWPC's in each arm are 1.6 cm thick and the other four MWPC's are 2.4 cm thick. The MWPC's are determined to be better than 97% efficient for $Q = \frac{1}{3}e$ particles by procedures described by Parker.[6]

The trigger is generated by the six counter hodoscopes in layers 9 through 17 (see Fig. 1). A pretrigger requirement is that there be at least one hit in layers 9 and 16 in each arm. The ten counters in each of the trigger hodoscopes are aligned in "roads" radiating from the IR and the final trigger requirement is that at least one "road" in each arm has hits in at least five of the six possible counters. The trigger rate is typically 0.4 Hz at a luminosity of 4×10^{30} cm^{-2} sec^{-1}. Under typical conditions, 20% of the triggers are from e^+e^- interactions; cosmic rays account for 20% and the rest are from interactions with residual gas and the beam pipe.

The detector trigger is essentially 100% efficient for two back-to-back $Q = \frac{2}{3}e$ particles within the detector acceptance. For back-to-back $Q = \frac{1}{3}e$ particles the efficiency is reduced to $\approx 75\%$ for small masses (high velocity and thus low dE/dx) increasing to $\approx 100\%$ for masses above ≈ 8 GeV/c^2.

The search for exclusively produced quarks, $e^+e^- \rightarrow q\bar{q}$, is simplified by the strong requirement that there must be two back-to-back fractionally charged particles. Thus only loose cuts on the data are sufficient to eliminate backgrounds. Two-prong, collinear, e^+e^--generated events are selected according to the following criteria:

(a) *Tracking*.—Tracks are identified by correlated hits in MWPC's and scintillation counters. The counters provide y (vertical) coordinates from their positions and TOF counters also provide z (along the beam) coordinates from the difference in the hit times of the two photomultipliers. We require two and only two tracks which are back to back within $8°$ in both θ and φ, the polar and azimuthal angles with respect to the beam axis. Events generated by e^+e^- collisions are selected by requiring the track intercepts to be within 3σ of the center of the IR. The resolution $\sigma_y = 0.5$ cm and $\sigma_z = 1.5$ cm are determined from the observed distribution of track intercepts; σ_z reflects the physical size of the IR and σ_y indicates the tracking resolution.

(b) *Timing.*—The time on layer 9 is required to be within 10 ns of the beam crossing. Each track is required to be associated with at least three TOF measurements. A linear fit for the time versus path length of the particle, with the time at the IR equal to the beam crossing time, must yield a χ^2 per degree of freedom less than 9. Cosmic rays are eliminated by requiring each track to move outward from the IR.

These cuts reduce 1.5×10^6 triggers to about 1.3×10^6 events. The Q associated with each of the selected tracks is computed by use of dE/dx sampled only with scintillators in layers 9 through 16 and all available TOF information.

Figure 2 is a scatter plot of Q from each arm for selected events. The requirement that both tracks have a common fixed origin in time introduces a slight correlation in Fig. 2 but does not affect the present search. The single-arm charge distributions are projected in Fig. 2 illustrating the overall charge resolution. We require candidate events to have $Q<0.8e$ in each arm. No candidates for exclusive fractionally

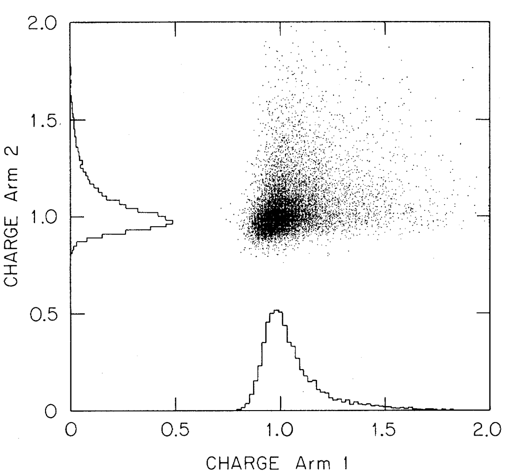

FIG. 2. A scatter plot of the measured charge in each arm of the detector for two-prong events. The charge measured in each arm of the detector is projected into a histogram illustrating the overall charge resolution. There are about 13 000 events in the figure.

charged particle production are found in Fig. 2.

The present search is independent of the presence of single tracks with $Q<0.8e$. Nevertheless we studied individually the seven examples which fall below the cut in Fig. 2. All are easily understood as consequences of showering or slowing down particles which lead to incorrect velocity determination. This gives us confidence that we understand the low-Q tail of the charge distribution. Cuts to eliminate these backgrounds are applied in an inclusive quark search now underway but these cuts are not necessary for the present exclusive search.

The luminosity is determined by two methods. The first uses wide-angle collinear pairs from the reactions $e^+e^-\to e^+e^-$ and $e^+e^-\to\mu^+\mu^-$. We subtract backgrounds from other processes by examining the distribution in collinearity angle. The angular distribution of the events agrees with QED predictions. After radiative corrections an integrated luminosity of 15.5 ± 0.4 pb^{-1} (statistical error only) is obtained. This luminosity agrees with the result of the second method, 16.0 pb^{-1}, obtained from a luminosity monitoring system which detects small-angle Bhabha scattering.

The imposed cuts are essentially 100% efficient for particles with $Q=\frac{1}{3}e$ but the requirement that $Q<0.8e$ is estimated to reduce the efficiency by 5% for $Q=\frac{2}{3}e$ because of the Landau tail. Our limit is converted into a total cross-section limit by using the angular distribution for production of pointlike fermions. The combined effect of radiative corrections and the mass dependence of the angular distribution reduces the relevant differential cross section by as much as 15%, depending on M_q. We take 15% over the entire mass range for the purpose of obtaining a limit. Finally, we state our result as a limit on the ratio of the measured total exclusive quark production cross section to the calculated total muon-pair production cross section.

The 90%-confidence-level upper limits for $R_{q\bar{q}} = \sigma(e^+e^-\to q\bar{q})/\sigma(e^+e^-\to\mu^+\mu^-)$ are

$$R_{q\bar{q}} \leq 7.7\times10^{-3},\quad M_q \lesssim 13.8\ \mathrm{GeV}/c^2,\quad Q=\tfrac{2}{3}e,$$

$$R_{q\bar{q}} \leq 9.7\times10^{-3},\quad M_q \lesssim 14.1\ \mathrm{GeV}/c^2,\quad Q=\tfrac{1}{3}e.$$

The upper limits to the range of M_q come from the requirement that the quarks have enough range to penetrate to the outer part of the detector. Figure 3 displays the mass dependence of our limits and compares them to previous experiments. We note that the effects of radiative corrections are treated differently in the various

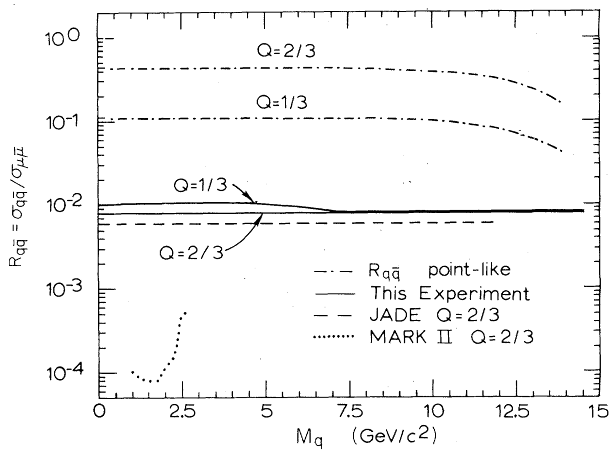

FIG. 3. Limits (90% confidence level) on exclusive quark production in e^+e^- annihilation. The limits for JADE are from Ref. 5 and the limits from Mark II are from Ref. 4.

experiments but these effects are small. Figure 3 also shows the expected cross section for pointlike fermions. Our limits are well below this expectation for both $Q=\frac{1}{3}e$ and $Q=\frac{2}{3}e$ particles. Thus, for example, long-lived ($\gtrsim 10^{-8}$ sec) fractionally charged lepton production[10] is definitely ruled out for masses below 14 GeV/c^2. Our method measures charge directly and thus within the range of sensitivity ($0.2 \lesssim Q \lesssim 0.8$) this experiment provides limits for particles with Q other than $\frac{1}{3}e$ and $\frac{2}{3}e$.

The limits on quark production obtained in any experiment of this type depend upon how the free quark interacts with matter. Our limits apply to quarks that are able to penetrate to layer 19 of the detector without interacting. Thus, a quark must penetrate $\gtrsim 0.30$ hadronic collision length.

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