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ABSTRACT

We have searched the products of e^+e^- annihilation at 29 GeV center of mass energy 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 $1/3 e$ or $2/3 e$ and masses below about $14 \text{ GeV}/c^2$. This is the first reported limit for charge $1/3 e$. 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. Searches 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 SLAC (Stanford Linear Accelerator Center) 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 $2/3 e$ as well as inclusive production for $1/3 e$ and $2/3 e$. The present work includes the first limit on exclusive production of charge $1/3 e$ 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, 12 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 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 $Q \propto \beta \sqrt{(dE/dx)}$ and a velocity dependent correction is introduced⁽⁸⁾ to better approximate 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

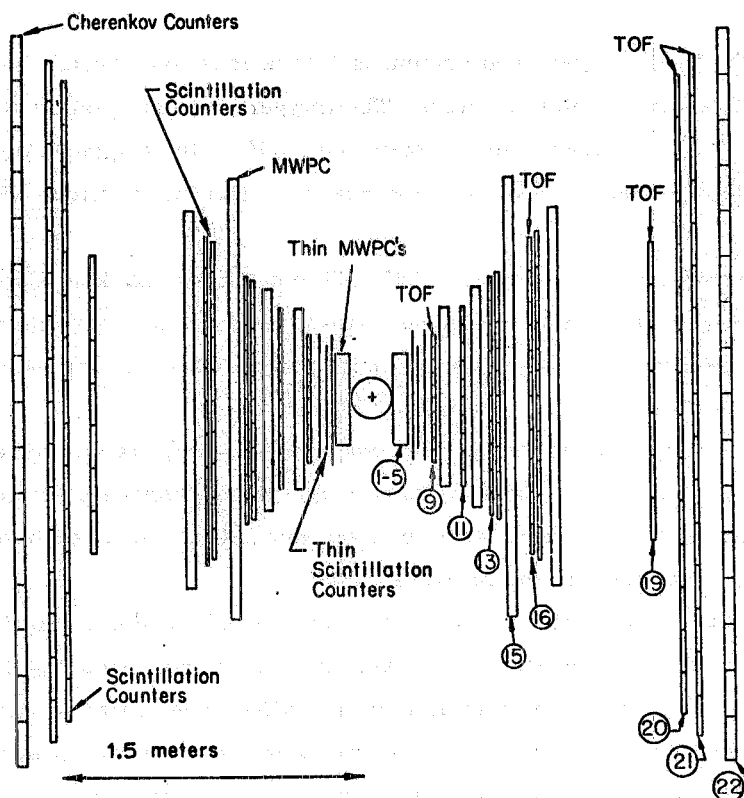


FIG. 1 - Elevation view of the detector as viewed along the beam pipe. The elements are numbered sequentially from one to 22 moving outward from the IR (some of the layers are numbered in the figure). The "thin" MWPC's (layers one to five) are not shown individually. Scintillation Layers 9, 16, 19, 20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

cosmic rays is $\sigma \approx 150$ psec. The time resolution depends on pulse height and increases to 650 psec for $1/10$ of dE/dx for a $Q = 1 e$ minimum ionizing particle (MIP). During colliding beam runs, the detector is monitored periodically: LED's 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 $1/30$ th and $1/50$ th of MIP dE/dx respectively. This ensures sensitivity to $Q = 1/3 e$ particles. A relativistic $Q = 1/3 e$ particle produces 3.2 primaries and 11.5 ion pairs per cm 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 $Q = 1/3 e$ particles by procedures described in Ref. (6).

The trigger is generated by the six counter hodoscopes in layers nine through 17 (see Fig. 1). A pre-trigger requirement is that there be at least one hit in layers nine and 16 in each arm. The 10 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 $4 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$. 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 $Q = 2/3 e$ particles within the detector acceptance. For back-to-back $Q = 1/3 e$ 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 $\approx 8 \text{ GeV}/c^2$.

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 $\sigma_y = 0.5 \text{ cm}$ and $\sigma_z = 1.5 \text{ cm}$ 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 nine 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 vs 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 nine. Cosmic rays are eliminated by requiring each track to move outward from the IR.

These cuts reduce 1.5×10^6 triggers to about 1.3×10^4 events. The Q associated with each of the selected tracks is computed using dE/dx sampled only with scintillators in layers nine 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 $Q < 0.8 e$ in each arm. No candidates for exclusive fractionally charged particle production are found in Fig. 2.

The present search is independent of the presence of single tracks with $Q < 0.8 e$. Nevertheless we studied the seven examples which fall below the cut in Fig. 2 individually. All are easily understood as consequences of showering or slowing down particles which lead to

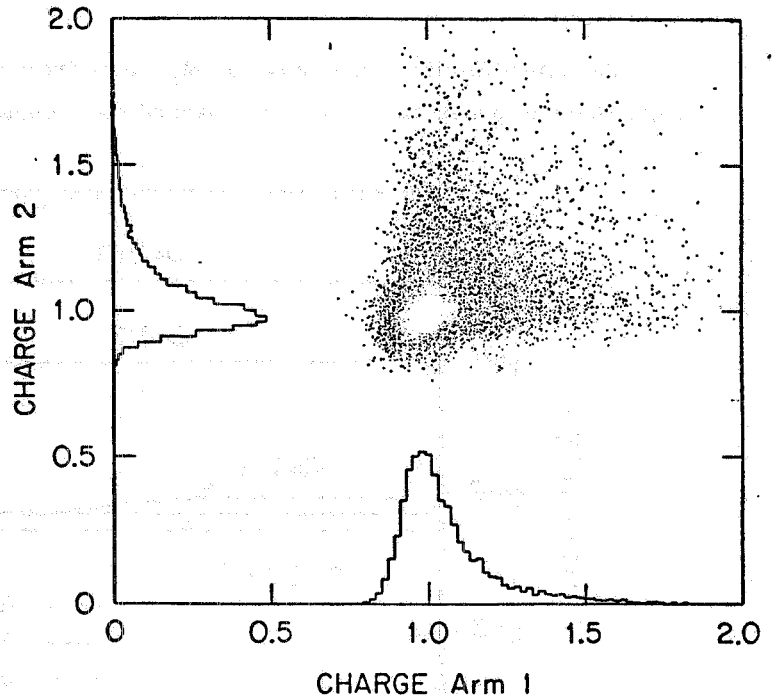


FIG. 2 - A scatter plot of the measured charge in each arm of the detector for two-prong events. The charge measured in each arm of the detector is projected into a histogram illustrating the overall charge resolution. There are about 13,000 events in the figure.

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 $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$. 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 $15.5 \pm 0.4 \text{ pb}^{-1}$ (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 $Q = 1/3 e$ but the requirement that $Q < 0.8 e$ is estimated to reduce the efficiency by 5% for $Q = 2/3 e$ because of the Landau tail. Our limit is converted into a total cross-section limit by using the angular distribution for production of point-like 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

$$R_{q\bar{q}} = (e^+e^- \rightarrow q\bar{q}) / (e^+e^- \rightarrow \mu^+\mu^-) \text{ are :}$$

$R_{q\bar{q}} \leq 7.7 \times 10^{-3}$	$M_q \leq 13.8 \text{ GeV}/c^2$	$Q = 2/3 e ;$
$R_{q\bar{q}} \leq 9.7 \times 10^{-3}$	$M_q \leq 14.1 \text{ GeV}/c^2$	$Q = 1/3 e .$

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. Fig. 3 displays the mass dependence

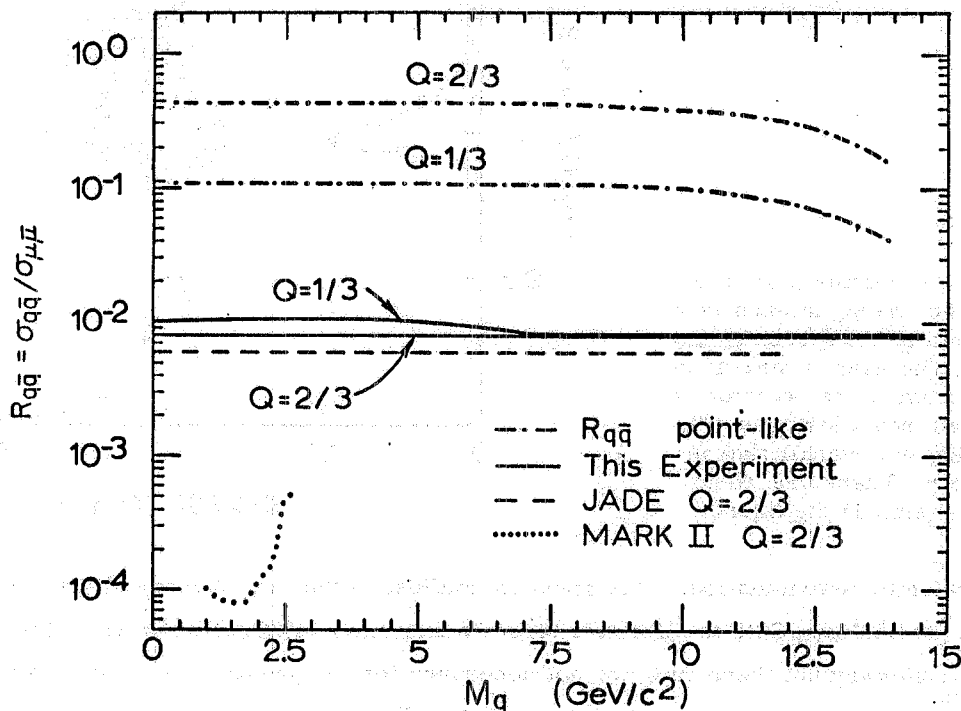


FIG. 3 - Limits (90% confidence level) on exclusive quark production in e^+e^- annihilation. The limits for JADE are from Ref. (5) and the limits from MARK II are from Ref. (4).

of our limits and compare them to previous experiments. We note that the effect of radiative corrections are treated differently in the various experiments but these effects are small. Figure 3 also shows the expected cross-section for point-like fermions. Our limits are well below this expectation for both $Q = 1/3 e$ and $Q = 2/3 e$ particles. Thus, for example, long lived ($\gtrsim 10^{-8}$ sec) fractionally charged lepton production⁽¹⁰⁾ is definitely ruled out for masses below $14 \text{ GeV}/c^2$. 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 $1/3 e$ and $2/3 e$.

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 lengths.

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