AN INCLUSIVE SEARCH FOR FREE QUARKS AT PEP

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We report the results of a search for fractionally charged particles in e^+e^- reactions at a center of mass energy of 29 GeV. We find no evidence for such particles and present upper limits on $R_q = \sigma_{q\bar{q}X}/\sigma_{\mu\mu}$ for charge $\frac{1}{3}e$ and $\frac{2}{3}e$ which range from 1 to 8×10^{-2} for mass up to 12 GeV/c^2.

Since the time the quark theory was first proposed there have been numerous searches for free quarks at each new accelerator [1]. Although these have been uniformly unsuccessful, positive results have been reported in a stable matter search [2]. The free quark search was designed to look for fractionally charged particles in e^+e^- collisions at PEP. We have already reported [3,4] on a search for exclusively produced quarks in the reaction $e^+e^- \to q\bar{q}$ and in this letter we report the results of a search in multi-particle final states ($e^+e^- \to q\bar{q}X$). Analogous results, using different techniques, have been reported by Mark II at SPEAR [5] and JADE at PETRA [6].

An elevation view of the apparatus, which has been described in greater detail elsewhere [3,4,7–11] is shown in fig. 1. Energy loss (dE/dx) and time of flight (TOF) were measured with scintillation counters.

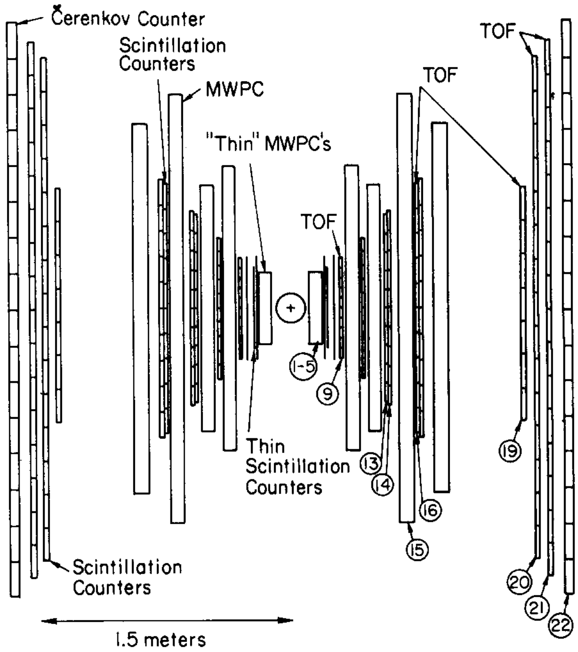

Fig. 1. Elevation view of the detector as viewed along the beam pipe. The elements are numbered sequentially from 1 to 22 moving outward from the IR (some of the layers are numbered in the figure). The innermost MWPC's (layers 1 to 5) are not shown individually. Scintillation counter layers 9, 16, 19,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

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Beta (v/c) and a truncated mean approximation $(dE/dx)_{mp}$ of the most probable dE/dx were used in an approximation of the Bethe–Bloch formula

$$\frac{dE/dx_{mp}}{dE/dx_{mp}\ (Q = 1, \beta = 1)} = \frac{Q^2}{\beta^2}[1 + f(\beta)] \qquad (1)$$

to calculate charge (Q) [12,13]. The function $f(\beta)$ is a slowly varying function ranging from 0 at $\beta = 1$ to -0.2 at $\beta = 0.1$. The detector consisted of 2 identical arms covering 2 sides of a cube centered at the interaction region (IR), subtending $\frac{1}{3}$ of 4π steradians. Each arm was comprised of 12 scintillator hodoscopes with between 7 and 16 elements. The scintillation counter elements had a photomultiplier (PMT) at both ends. In addition there were 9 layers of multiwire proportional chambers (MWPC) for reconstructing particle tracks and one layer of 16 lucite Čerenkov counters as a further check on the velocity measurement. Six scintillator hodoscopes (layers 9, 11, 13, 14, 16, 17 in fig. 1) each contained 10 counters which were arranged in 10 radial rows or "roads" covering a region of 0.2 in tan φ (the azimuthal angle). Thus the active detector solid angle was segmented into 20 regions. Five of the hodoscopes (9, 16, 19–21), at distances ranging from 30 to 150 cm from the IR, were instrumented to measure time of flight.

Our apparatus was triggered when at least 5 out of 6 counters were hit on at least one road in each arm. A hit was defined as a coincidence of the 2 counter PMT's with a threshold of 5% of the most probable dE/dx for a minimum ionizing particle, MIP_{mp} (a relativistic $Q = \frac{1}{3}e$ particle would have $dE/dx_{mp} = 0.10$ MIP_{mp}). The probability that a single relativistic quark would trigger a single arm of the apparatus was 100% for $Q = \frac{2}{3}e$ and 87% for $Q = \frac{1}{3}e$ particles. The multiwire proportional chambers were sensitive to dE/dx deposits of $\frac{1}{30}$ of MIP_{mp} [10]. The dynamic range of the ADC's used to process the counter signals was from 0.01 to 4 times MIP_{mp}.

Of the 1.5×10^6 triggers that we collected, about 20% were beam–beam interactions and the other 80% were either cosmic rays or single beam generated background. The multiprong beam–beam events were selected by the following criteria:

(1) Timing cuts were effective in suppressing both types of background. A software beam gate required that the average of the time in the innermost TOF counters (at 30 cm from the beam) be within 7 ns of the beam crossing time. In addition, to guarantee that the event progress from the inside to the outside in each arm, the average arrival time in layers 18, 19 and 20 was required to follow that of the inner layers.

(2) Three or more tracks were required. Tracks were reconstructed by correlating coordinates from the counters and the MWPC anode wire hits. Counter coordinates along the counter length (z) were found from the difference of the times measured in the PMT at each end ($\sigma = 2.5$ cm). Typical chamber resolution ranged from 3.5 mm in the inner MWPC's to 2.0 mm in the outer large MWPC's. Good tracks were defined as those which had at least 3 hits in the large MWPC's, a χ^2 per degree of freedom of the fit less than 5.0, and which extrapolated back into a rectangle (± 5 cm vertical by ± 10 cm along the beam) centered at the beam–beam crossing point.

(3) To further reduce the background from accidental tracks generated by soft photons, at least two tracks were required to have dE/dx greater than 25% of normal. This limits the possibility of finding those events in which there were 2 low mass, relativistic, $Q = \frac{1}{3}e$ quarks with only one other particle in the apparatus.

Out of the original sample of 1.5×10^6 triggers ($16\ pb^{-1}$ of integrated luminosity), 6142 events satisfied the selection criteria outlined above. Fig. 2 shows the observed multiplicity and the multiplicity predicted by a Monte Carlo model based on quantum chromodynamic (QCD) event production [14]. There is an ex-

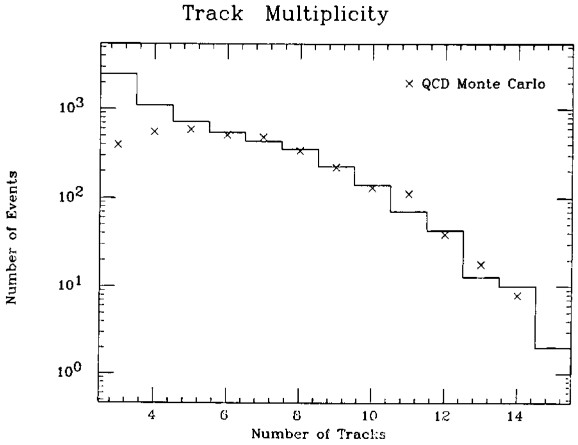

Fig. 2. Multiplicity distribution. The distribution predicted by the QCD Monte Carlo is normalized to the measured cross section.

cess of events with 3 and 4 tracks which are due primarily to beam–gas and two-photon events, but there is excellent agreement for events with 5 or more tracks.

A charge was calculated for tracks which met the following two conditions: (1) at least 5 of the road counters must have had a signal above a threshold of 3% MIP_{mp} and (2) the track must have intersected at least 2 counters with valid TOF hits. Agreement between the counter z coordinate and the extrapolated track was required for a valid TOF hit. The energy loss in each road was estimated by excluding the lowest and the two highest pulse heights in the dE/dx counters in the roads and averaging the remainder. Beta was determined from a fit of the counter times and the beam crossing time to the path length. In cases where the particle track passed near the edge (±1.5 cm) of the road counters, the estimated energy loss was corrected by adding the dE/dx of the 2 adjacent counters together. Charge could not be accurately calculated for tracks with more than 2 overflowed ADC channels.

Fig. 3 is a plot of $1/\beta$ versus dE/dx_{mp} for these tracks. The region below the $Q = 0.5$ curve would contain >95% of charge $\frac{1}{3}e$ particles. There is one point in this region which has $dE/dx_{mp} = 0.9$ and $\beta = 0.4$, but one of the counters along the track gave a very late time value, and the rest of the counters have times consistent with $\beta = 1$. In addition to this, the Čerenkov counter was hit, vetoing the low-β measurement. For these reasons this candidate was discounted.

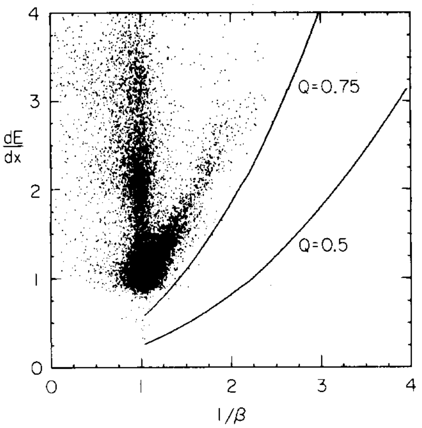

Fig. 3. dE/dx versus $1/\beta$ for tracks (13840) in events which pass the selection criteria of the search for charge $\frac{1}{3}e$ particles. $Q = 0.5$ and $Q = 0.75$ contours determined from eq. (1) are also shown. Tracks with low $1/\beta$ are accidental tracks which use very early time values in the outer counters. The tracks with high dE/dx and $\beta \approx 1$ are due to more than one particle in the road counters.

Similarly, more than 95% of the particles with a charge of $\frac{2}{3}e$ would fall below the line marked $Q = 0.75$ on fig. 3. There are 16 candidates below the contour. Many of these (7) appear to be due to low energy photons associated with background events and were eliminated by raising the threshold for hits from 3% MIP_{mp} to 20% MIP_{mp}. The remainder (9) all pass near the edges between the hodoscope counters. To guard against a possible error in the charge calculation due to the edge we cut all tracks which pass within 1.5 cm of the counter edge on 2 or more counters. This cuts only 35% of the "normal" tracks but all of the candidates, so we conclude that they are indeed due to the edges.

In order to interpret this result as a limit on the quark production total cross section we estimated our detection efficiencies with the aid of a Monte Carlo model. Since there is no specific prediction of the nature of e^+e^- events in which free quarks are produced, we have selected a simple model for this process – an all-pion two-jet Monte Carlo [15] in which 2 of the π's are replaced by a pair of quarks with specific masses and fractional charge. Events without quarks produced by this model are similar to the events we observed and also to the predicted events of the QCD Monte Carlo. The event multiplicity is recalculated with the mass of the quark pair removed. At high masses (>10 GeV/c^2) the recalculated multiplicity is very low, which decreases the number of events with at least 3 particles entering the detector.

In broad outline 45% of the multiprong (⩾3) events triggered the apparatus and satisfied the event criteria. The probability that we would detect the track of a quark in such an event is 42% (on the average $\frac{5}{12}$ of the tracks enter the apparatus), and only 46% of these quarks occupied a road unaccompanied by other particles. In addition only 65% of the tracks satisfied the more restrictive cuts for $Q = \frac{2}{3}e$. Our sensitivity to high masses is limited by the low multiplicity, the dynamic range of our TDC's (100 ns) which requires that β be greater than 0.1 and by the range of slow particles since they must penetrate to the TOF counters (layers 19–21).

Assuming two quarks per event, the Monte Carlo yields a combined efficiency which depends upon mass and ranges from 10.8% down to 5.1% for $Q = \frac{1}{3}$

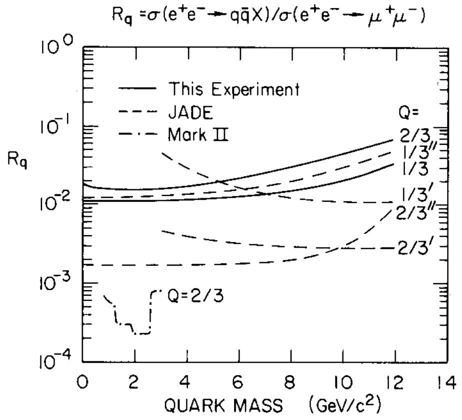

Fig. 4. Upper limits on quark production ($R_q = \sigma_{q\bar{q}X}/\sigma_{\mu\mu}$). Results from Mark II and JADE are included. In the JADE data analysis [6] two quark momentum spectra, an exponential distribution, ('), and a flat distribution, ("), were used.

(5.9% down to 1.7% for $Q = \frac{2}{3}$) for quarks with masses less than 12 GeV/c^2. Fig. 4 shows our radiatively corrected upper limit at 90% confidence level on the inclusive quark production cross section $\sigma(e^+e^- \to q\bar{q}X)$ normalized to the total μ pair cross section. The results from JADE and Mark II are also shown. We have not allowed for the possible hadronic interactions of the quark, and it should be noted that the mean thickness of our apparatus to the first outer TOF layer is 30% of a collision length.

In summary we have searched for fractionally charged particles with masses less than 12 GeV/c^2 produced in e^+e^- collisions at 29 GeV and find no evidence at the level of 1 to 3% (2–8% for $Q = \frac{2}{3}$) of the μ production cross section.

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