PHYSICAL REVIEW D VOLUME 40, NUMBER 1 1 JULY 1989

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication in **Physical Review D** *should be no longer than five printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but because of the accelerated schedule, publication is not delayed for receipt of corrections unless requested by the author or noted by the editor.*

Search for the production of fractionally charged particles in e^+e^- annihilations at $\sqrt{s} = 10.5$ GeV

T. Bowcock,[a] K. Kinoshita,[a] P. Mauskopf,[a] F. M. Pipkin,[a] M. Procario,[a] Richard Wilson,[a] J. Wolinski,[a] D. Xiao,[a] P. Baringer,[b] P. Haas,[b] Ha Lam,[b] A. Jawahery,[c] C. H. Park,[c] D. Perticone,[d] R. Poling,[d] R. Fulton,[e] M. Hempstead,[e] T. Jensen,[e] D. R. Johnson,[e] H. Kagan,[e] R. Kass,[e] F. Morrow,[e] J. Whitmore,[e] W.-Y. Chen,[f] J. M. Dominick,[f] R. L. McIlwain,[f] D. H. Miller,[f] C. R. Ng,[f] E. I. Shibata,[f] W.-M. Yao,[f] E. H. Thorndike,[g] M. S. Alam,[h] N. Katayama,[h] I. J. Kim,[h] W. C. Li,[h] X. C. Lou,[h] C. R. Sun,[h] D. Bortoletto,[i] M. Goldberg,[i] N. Horwitz,[i] P. Lubrano,[i] M. D. Mestayer,[i] G. C. Moneti,[i] V. Sharma,[i] I. P. J. Shipsey,[i] T. Skwarnicki,[i] S. E. Csorna,[j] T. Letson,[j] I. C. Brock,[k] T. Ferguson,[k] M. Artuso,[l] C. Bebek,[l] K. Berkelman,[l] J. Byrd,[l] D. G. Cassel,[l] E. Cheu,[l] D. M. Coffman,[l] G. Crawford,[l] J. W. DeWire,[l] P. S. Drell,[l] R. Ehrlich,[l] R. S. Galik,[l] B. Gittelman,[l] S. W. Gray,[l] A. M. Halling,[l] D. L. Hartill,[l] B. K. Heltsley,[l] J. Kandaswamy,[l] R. Kowalewski,[l] D. L. Kreinick,[l] Y. Kubota,[l] J. D. Lewis,[l] N. B. Mistry,[l] J. Mueller,[l] R. Namjoshi,[l] S. Nandi,[l] E. Nordberg,[l] C. O'Grady,[l] D. Peterson,[l] M. Pisharody,[l] D. Riley,[l] M. Sapper,[l] A. Silverman,[l] S. Stone,[l] H. Worden,[l] M. Worris,[l] A. J. Sadoff,[m] P. Avery,[n] D. Besson,[n] L. Garren,[n] and J. Yelton[n]

[a]*Harvard University, Cambridge, Massachusetts 02138*
[b]*University of Kansas, Lawrence, Kansas 66045*
[c]*University of Maryland, College Park, Maryland 20742*
[d]*University of Minnesota, Minneapolis, Minnesota 55455*
[e]*Ohio State University, Columbus, Ohio 43210*
[f]*Purdue University, West Lafayette, Indiana 47907*
[g]*University of Rochester, Rochester, New York 14627*
[h]*State University of New York at Albany, Albany, New York 12222*
[i]*Syracuse University, Syracuse, New York 13210*
[j]*Vanderbilt University, Nashville, Tennessee 37235*
[k]*Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[l]*Cornell University, Ithaca, New York 14853*
[m]*Ithaca College, Ithaca, New York 14850*
[n]*University of Florida, Gainesville, Florida 32611*

(Received 29 March 1989)

We report the results of a search for particles with electric charge $Q = \frac{2}{3}e$ produced in e^+e^- annihilations at $W = 10.5$ GeV. The ratio of the cross section for the inclusive production of fractionally charged particles (q) to the dimuon point cross section, $R_q = \sigma(e^+e^- \to qX)/\sigma(e^+e^- \to \mu^+\mu^-)$, is found to have an upper limit at 90% confidence level of 1.0×10^{-4} for masses less than 3.5 GeV/c^2.

In the standard model of electroweak interactions the fundamental objects are quarks and leptons. Mesons contain quark-antiquark ($q\bar{q}$) pairs and baryons contain three quarks (qqq) or three antiquarks ($\bar{q}\bar{q}\bar{q}$). The (anti)quarks have electric charges $(-)+\frac{2}{3}e$ and $(+)-\frac{1}{3}e$ and account for the observed hadron charges. It is believed that quarks are confined within the hadrons; however, the standard model of strong interactions, quantum chromodynamics, contains no rigorous proof of this hypothesis. Observation of particles with charge $\frac{1}{3}e$ or $\frac{2}{3}e$ could be evidence for the existence of unbound (free) quarks or new stable forms of matter (e.g., qq) and would challenge our ideas of quark confinement. Many accelerator searches for free quarks have been made[1-5] and no evidence for their existence has been found.

Below, we report the results of a search for particles with charge $\frac{2}{3}e$ produced in e^+e^- annihilations at a center-of-mass energy of 10.5 GeV using the CLEO

detector at the Cornell Electron Storage Ring (CESR). We looked for evidence of fractional charge using measurements of the ionization along the tracks left by charged particles. The energy loss due to ionization per unit distance traveled, dE/dx, for a particle of velocity β and electric charge Q may be described by the relation[6]

$$\frac{dE}{dx} = Q^2 \frac{\mathcal{F}(\beta)}{\beta^2} .$$

The minimum energy loss $(dE/dx)_{\text{m.i.}}$ for a particle with unit electric charge is approximately independent of particle mass. Thus, a track whose measured dE/dx is much less than $(dE/dx)_{\text{m.i.}}$ has the distinctive signature of a fractionally charged particle.

The CLEO detector has been described elsewhere.[7,8] Here, we summarize the features that are important to this analysis. Charged-particle tracks were reconstructed using information from a cylindrical drift chamber which is immersed in a 1-T magnetic field. The drift chamber is composed of two detectors: a 10-layer vertex detector and a 51-layer main drift chamber. The vertex detector is operated with a (50-50)% mixture of argon-ethane at 1.4-atm pressure, and the main drift chamber is operated with the same gas mixture at 1-atm pressure. Both detectors are instrumented to make measurements of track coordinates and energy loss in every layer. The average dE/dx for a track is calculated separately in the vertex detector and the drift chamber using the lower 50% of the energy-loss measurements for that track in each device. The detectors are calibrated using Bhabha-scattering events. The vertex detector has a dE/dx resolution

$$\sigma(dE/dx)/(dE/dx) = 0.14 ,$$

and the main drift chamber has a dE/dx resolution

$$\sigma(dE/dx)/(dE/dx) = 0.065 .$$

The momentum resolution σ_p for charged particles using both chambers is

$$\sigma_p/p = [(0.007)^2 + (0.0023p)^2]^{1/2} \quad (p \text{ in GeV}/c) .$$

The apparent (reconstructed) momentum p_a of a track with charge Q is related to the true momentum p by $p = Qp_a$.

We looked for fractionally charged particles in both exclusive two-body events, $e^+e^- \rightarrow q\bar{q}$, and inclusively in multihadron events, $e^+e^- \rightarrow qX$. Events were selected for analysis if they passed our standard criteria for two-prong or hadronic events.[8]

The data sample used for the inclusive search consisted of 213 pb^{-1} taken at the $\Upsilon(4S)$ energy and 101 pb^{-1} of data taken at energies below the $\Upsilon(4S)$. Tracks were regarded as candidates for fractionally charged particles if the energy loss was within 3σ of the minimum energy loss expected for charge $\frac{2}{3}e$ tracks. To ensure good dE/dx resolution in both chambers, each track was required to have at least 7 samples of dE/dx in the vertex detector, and at least 30 samples in the main drift chamber. In addition, we demanded that the angle θ between tracks and the beam direction satisfy $|\cos\theta| < 0.7$. The measured dE/dx for tracks in the vertex detector is shown in Fig. 1(a) and for the main drift chamber in Fig. 1(b). Separate bands corresponding to pions, kaons, and protons are clearly visible.

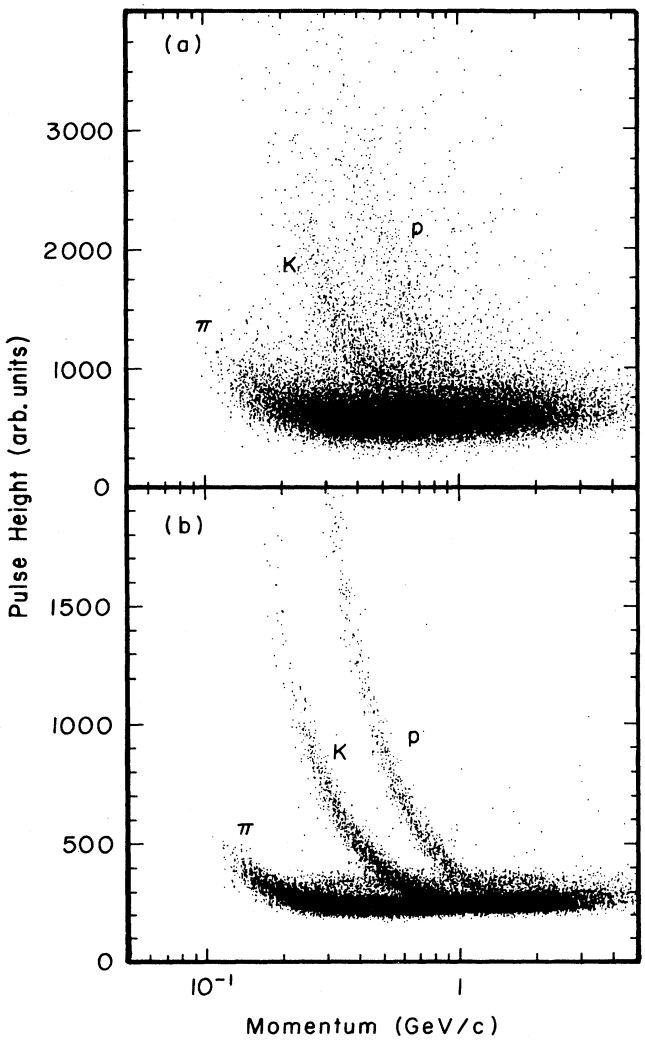

FIG. 1. Truncated mean of the ionization loss of tracks in (a) the vertex detector and (b) the drift chamber vs the apparent measured momentum, p_a.

In Fig. 2 we show the measured dE/dx in the drift chamber relative to minimum-ionizing energy loss for each track in our hadronic data sample: a total of 3.1×10^6 tracks. Only one candidate for a charge $\frac{2}{3}e$ particle was observed in our hadronic-event sample. This is consistent with what is expected from statistical fluctuations in the dE/dx measurements of singly charged particles. In addition, no evidence of correlation between very low measurements of dE/dx in the drift chamber and very low measurements of dE/dx in the vertex detector was observed.

We also searched for evidence of exclusive production of fractionally charged particles. For this part of our

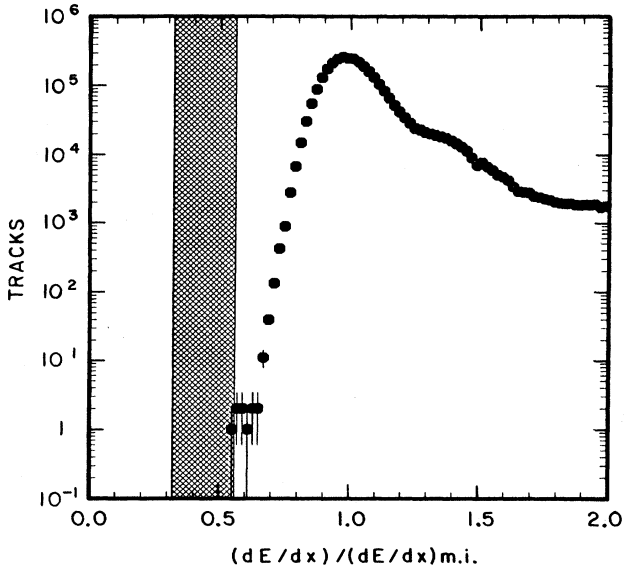

FIG. 2. From the hadronic data sample, the distribution of the truncated means of the pulse heights of tracks as measured in the drift chamber relative to the minimum-ionizing pulse height. The region of selection for quark candidates, $(\frac{4}{9} \pm 3\sigma)dE/dx_{\text{m.i.}}$ is shown as the hatched region.

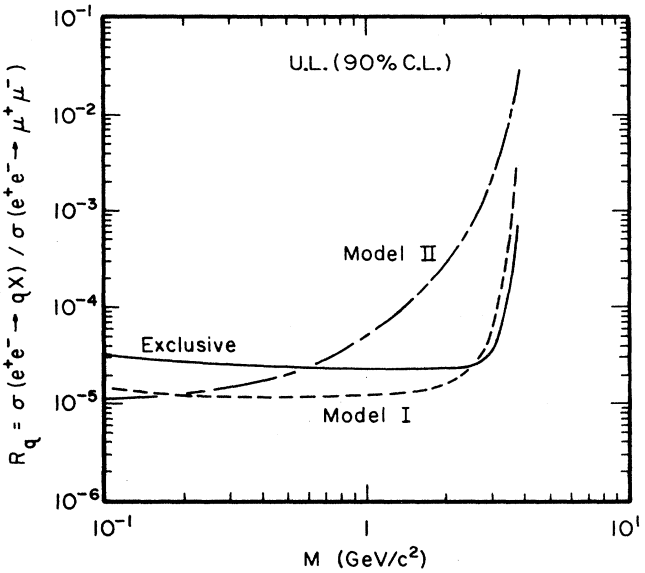

FIG. 3. Upper limits at 90% confidence level of the cross section for the production of charge $Q = \frac{2}{3}e$ particles relative to the dimuon point cross section from the inclusive search assuming two different models for the quark momentum spectrum: Model I and model II (see text). Also shown is the upper limit from the search for the exclusive production of pairs of fractionally charged particles.

analysis we used a subset of the data from which the hadronic data were selected. The data sample consisted of 153 pb^{-1} of data taken at the $\Upsilon(4S)$ energy and 68 pb^{-1} taken at energies below the $\Upsilon(4S)$. The selection criteria for candidates were the same as those used for the inclusive search. Both tracks in the event were required to pass the dE/dx cuts. In addition, so that the event be consistent with the hypothesis of exclusive two-body production, the angle between the two tracks is required to be greater than 175°. After these cuts, none of the candidate two-prong events remained.

The efficiency $\epsilon_m^Q(e^+e^- \to qX)$ for detecting a fractionally charged particle of charge Q and mass m in an hadronic event is model dependent and is given by

$$\epsilon_m^Q(e^+e^- \to qX) = \int_0^{p_{\max}} D_q(p)\epsilon_m^Q(p)dp \Big/ \int_0^{p_{\max}} D_q(p)dp ,$$

where $p_{\max} = (E_{\text{beam}}^2 - m_q^2)^{1/2}$. The efficiency of detecting a charged particle at momentum p, $\epsilon_m^Q(p)$, is estimated using a Monte Carlo simulation. The momentum spectrum $D_q(p)$ of the fractionally charged particles is model dependent. We have computed the efficiency for two

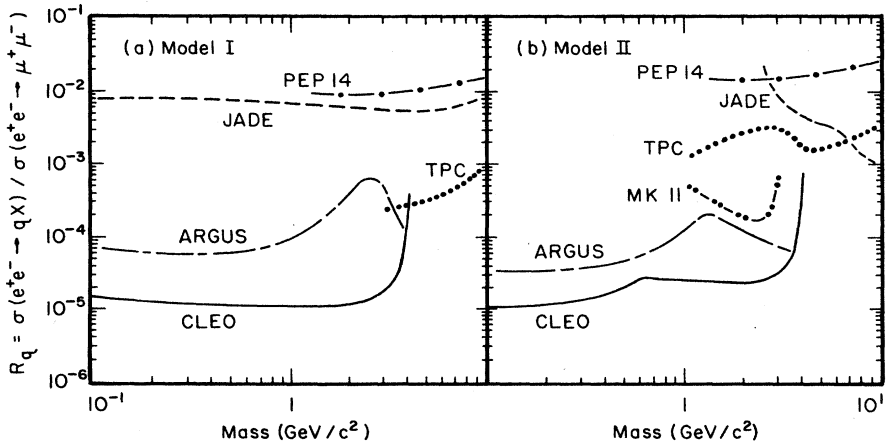

FIG. 4. Upper limit at 90% confidence level of the cross section for the production of charge $Q = \frac{2}{3}e$ particles from the inclusive and exclusive searches combined in (a) model I; (b) model II. Also shown are the limits set from other experiments.

different assumptions[5] about the form of D_q:

$$\text{Model I,}\quad D_q(p) \propto p^2/[(p^2+m_q^2)]^{1/2};$$

$$\text{Model II,}\quad D_q(p) \propto \frac{p^2}{E}\exp(-3.5E)\quad (E \text{ in GeV}).$$

The efficiency $\epsilon_m^Q(e^+e^- \to q\bar{q})$ for reconstructing and selecting the events, $e^+e^- \to q\bar{q}$, was determined by a Monte Carlo simulation of the production and passage through the detector, of a pair of particles with charge $|Q| = \frac{2}{3}e$ as a function of mass m_q.[9] The angular distribution of the $q\bar{q}$ pair was assumed to be $(1+\cos^2\theta)$. The trigger efficiency for pairs of charge $\frac{2}{3}e$ particles was estimated (by a study of the pulse-height distributions of muons in our trigger counters) to be 98% of that for $e^+e^- \to \mu^+\mu^-$.

The upper limit at 90% confidence level on the cross section for inclusive production, as a function of quark mass, was computed for models I and II. The results are shown in Fig. 3. The cross sections are presented as a ratio R_q, relative to the dimuon point cross section $\sigma(e^+e^- \to \mu^+\mu^-)$. Also shown in Fig. 3 is the upper limit (at 90% confidence level) that we place on the exclusive production of fractionally charged particles as a function of m_q. In Figs. 4(a) and (b) we have combined the results from both methods (by choosing the lower of the two limits) for each model in order to compare with results from other experiments. For particles of charge $\frac{2}{3}e$ and masses < 3.5 GeV/c^2 we set an upper limit (at 90% C.L.) of $R_q < 1\times10^{-4}$. The upper limit rises rapidly above $m_q = 3.5$ GeV/c^2 due to the increase in dE/dx as β decreases.

In summary, we observed no candidates for free quarks of charge $\frac{2}{3}e$. Our limits are significantly lower than previously existing limits for quarks of mass less than 3.5 GeV/c^2.

We are grateful for the efforts of the CESR staff which made this work possible. R. Kass wishes to thank the Office of Junior Investigator program of the Department of Energy (DOE) for support. P.S.D. is grateful for the support from the Presidential Young Investigator program of the National Science Foundation (NSF). R.P. thanks the A.P. Sloan Foundation for support. This work was supported by the NSF and the U.S. DOE under Contracts No. DE-AC02-76ER01428, No. DE-AC02-76ER03066, No. DE-AC02-76ER03064, No. DE-AC02-76ER01545, No. DE-AC02-76ER05011, and No. FG05-86-ER40272. The Cornell National Supercomputing Facility, funded in part by the NSF, New York State, and IBM, was used in this research.

[1]W. Bartel *et al.*, Z. Phys. C **6**, 295 (1980).
[2]J. M. Weiss *et al.*, Phys. Lett. **101B**, 439 (1981).
[3]H. Aihara *et al.*, Phys. Rev. Lett. **52**, 2332 (1984).
[4]W. Guryn *et al.*, Phys. Lett. **139B**, 313 (1984).
[5]H. Albrecht *et al.*, Phys. Lett. **156B**, 134 (1985).
[6]B. Rossi, *High Energy Particles* (Prentice-Hall, Englewood Cliffs, NJ, 1961), p. 17.
[7]D. Andrews *et al.*, Nucl. Instrum. Methods **211**, 47 (1983).
[8]S. Behrends *et al.*, Phys. Rev. D **31**, 2161 (1985).
[9]It was assumed that fractionally charged particles would not shower in the outer detector. If showering were to occur, then due to our event selection procedures, the upper limit for exclusive $q\bar{q}$ production should be 5 times higher.