RECENT RESULTS FROM PEP ON SEARCHES FOR QUARKS, MONOPOLES, AND OTHER EXOTIC PARTICLES

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Introduction

As each new high energy particle accelerator or colliding beam facility has commenced operation, a few brave souls have continued the long search for free quarks, monopoles, and other exotic new particles. The experimental program at PEP during its first year of operation has followed this tradition.

I will report here on two experiments performed this past year at PEP at a center-of-mass energy of 29 GeV. In the "Free Quark Search Experiment", a specialized detector has been used to search in the debris of high energy e^+e^- collisions for particles with fractional electric charge. The particular reaction studied so far is the two-body process $e^+e^- \to q\,\bar{q}$. In the "Highly Ionizing Particles Search Experiment" stacks of track recording plastic sheets have been used to detect magnetic monopoles or other particles with an ionization energy loss hundreds of times greater than that due to a minimum ionizing particle.

For each of these experiments I will mention the particles looked for and the experimental technique employed. I will also give a description of the detector and, finally, the results.

The Free Quark Search Experiment

This search for fractionally charged particles at PEP has been carried out by a collaboration[1] from the Laboratori Nazionali di Frascati, the Lawrence Berkeley Laboratory, Northwestern University, Stanford University, and the University of Hawaii.

Some Possibilities for Free Fractional Charge

Free quarks, with charges $Q = \pm 1/3$ or $\pm 2/3$, are the most obvious candidates for fractionally charged particles. These might be produced in high energy e^+e^- collisions in the two-body reaction $e^+e^- \to q\,\bar{q}$. They are probably more likely to be produced (if they exist) along with hadrons in $e^+e^- \to q\,\bar{q}$ + hadrons. Of course the required energy and the cross section for the production of free quarks are completely unknown.

It has been hypothesized[2] that quarks are permanently confined within the hadrons and can never exist as free particles. This hypothesis is rooted in the assumptions that (1) Quantum Chromodynamics (QCD) provides a correct theory of the interactions (via massless gluons) between quarks and (2) the QCD interaction leads to confinement. The first assumption has not yet been experimentally verified and the second has not yet been proven theoretically. A number of theorists have proposed[3] that by giving the gluon a small mass confinement may be broken.

The hypothesis of quark confinement, as with all interesting and fundamental physical hypotheses, must be subjected to rigorous experimental verification. This is especially true in light of the measurements, reported by Fairbank *et al.*[4], "which show unambiguously the existence of fractional charges of $1/3e^-$ on niobium spheres.

Quarks are the most obvious, but not the only candidates for particles with fractional charge. For example, there may exist quarks which have integral charges.[5] These could combine together with fractionally charged quarks to produce fractionally charged hadrons. Thus we would have fractional charge and preserve quark confinement.

Another possibility is the existence of fractionally charged leptons. It has been speculated[6] that the production of lepton pairs with charge $Q = 2/3$ might account for a possible threshold behavior in $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at $\sqrt{s} \simeq 5.5$ GeV. Unlike the case of free quarks, the production cross-section for fractionally charged leptons can be calculated, for a given charge and mass, using QED.

The Experimental Technique

In the Free Quark Search Experiment the charges of particles produced at PEP are determined from measurements with scintillation counters of the ionization energy loss (dE/dx) and the velocity (β = velocity/c). The charge Q can be calculated from the approximate relation

$$dE/dx \simeq (Q^2/\beta^2)(dE/dx)_{MIP}$$

where $(dE/dx)_{MIP}$ is the ionization energy loss for a $Q = 1$ minimum ionizing particle.

The Quark Detector

A view of the quark detector along the beam-line is shown in Figure 1. The detector is constructed in two identical arms which cover two faces of a cube, 3.3 m on a side, centered on the interaction region. The solid angle coverage of the detector is thus 1/3 of 4π sr.

Each arm consists of 12 scintillation counter hodoscopes, 9 multi-wire proportional chambers, and a lucite Cerenkov counter hodoscope. A description of the detector components is given in Table I.

The scintillation counters are used for the ionization energy loss measurement. A subset of these (5 layers) also provides time-of-flight information for a determination of the particle velocity over a 1.5 m flight path. The multi-wire proportional chambers are used for tracking. The lucite Cerenkov counters give a check on the velocity determination (particles with $\beta \geq 0.7$ will trigger these). Each scintillation and Cerenkov counter has two photomultipliers — one on each end.

The inner five multi-wire proportional chambers (TM1 - TM5) plus the inner three scintillation counter hodoscopes (TS1 - TS3) form the "thin front end". The thin front end, with less than 2% of a hadronic collision length (at normal incidence), is used for the detection of highly interacting quarks. Note that the 5 chambers TM1 - TM5 provide dE/dx as well as positional information.

Experimental Checks

It is imperative in a quark search experiment to know the efficiency and response of each detector component for lightly ionizing particles. The important efficiencies and resolutions are given below. Cosmic rays were used for all the measurements.

(1) Multi-wire proportional chamber efficiency

The threshold is set at 1/50 of minimum ionizing. The operation of the chambers for lightly ionizing particles is simulated by running them on cosmic rays at reduced high voltage and therefore reduced gain. A check was made with a narrow gap chamber filled with a He(80%) - CH_4 gas mixture to show that this procedure simulates lightly ionizing particles even when statistical fluctuations on the number of primary ionizations are considered (details of this test can be found in Reference 7). From the cosmic ray running with reduced high voltage, it is found that all chamber efficiencies are greater than 97% for $Q = 1/3$ relativistic particles.

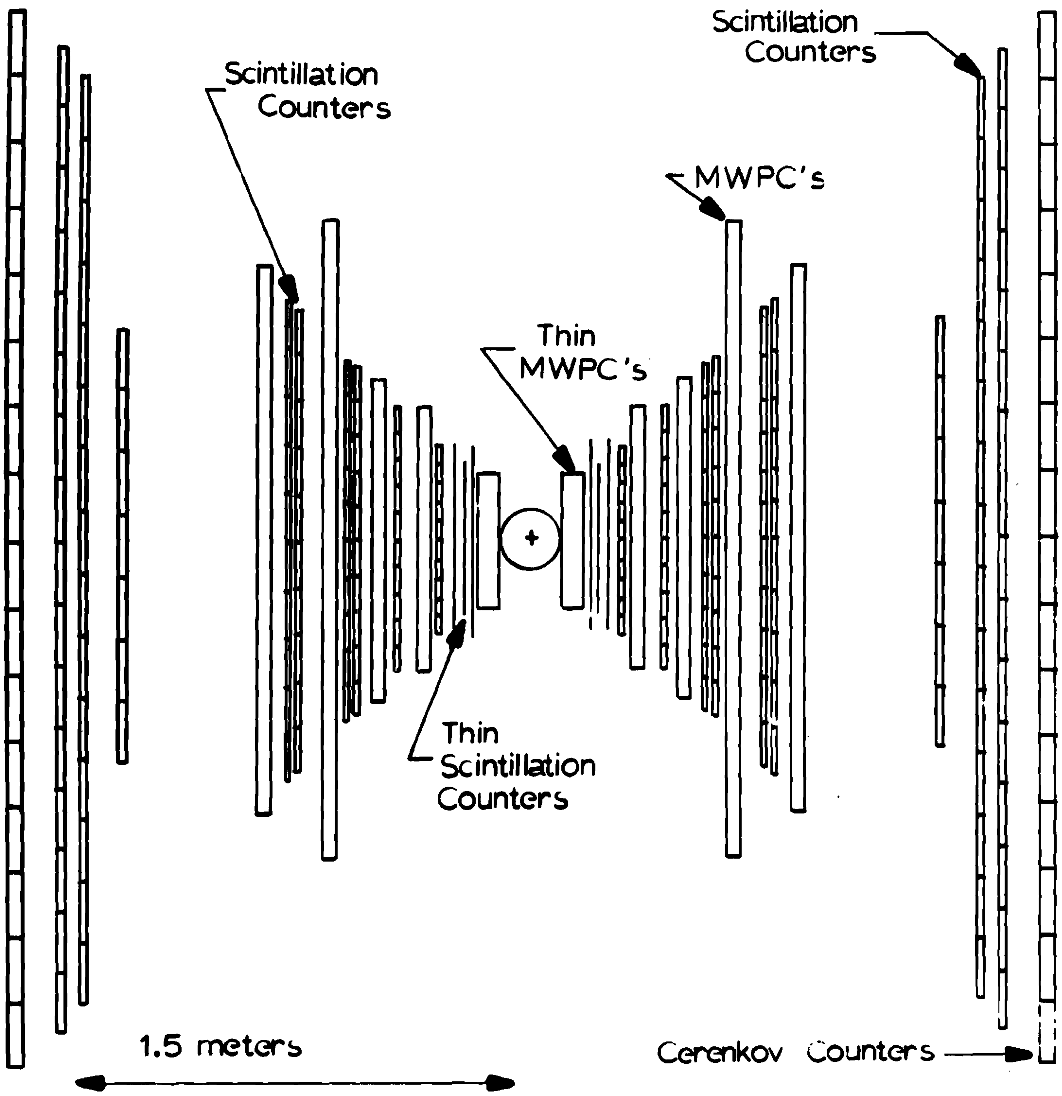

Fig. 1--A view of the PEP quark detector along the beam-line.

TABLE I

The Components of the Quark Detector

Layer	Detector Type	Orientation Angle*	# of Elements	Pulse Height	TOF	Cumulative Collision Lengths (Normal Incidence)
B1	beam pipe					
TM1	thin MWPC	+45°		Yes		
TM2	thin MWPC	-45°		Yes		
TM3	thin MWPC	90°		Yes		
TM4	thin MWPC	0°		Yes		
TM5	thin MWPC	0°		Yes		.005
TS1	thin scint.	90°	8	Yes		.008
TS2	thin scint.	0°	8	Yes		.011
TS3	thin scint.	90°	10	Yes		.014
S1	scint.	0°	10	Yes	Yes	.031
M1	MWPC	80°				.045
S2	scint.	0°	10	Yes		.072
M2	MWPC	0°				.086
S3	scint.	0°	10	Yes		.116
S4	scint.	0°	10	Yes		.145
M3	MWPC	100°				.160
S5	scint.	0°	10	Yes	Yes	.202
S6	scint.	0°	10	Yes		.243
M4	MWPC	0°				.258
S7	scint.	0°	7	Yes	Yes	.304
S8	scint.	0°	15	Yes	Yes	.351
S9	scint.	0°	16	Yes	Yes	.398
C1	Cerenkov	0°	16	Yes		.492

* For scintillation counters, 0° means the long axis is parallel to the beam-line. For MWPC's, 0° means the anode wires are parallel to the beam-line.

(2) dE/dx resolution

Each scintillation counter has a dE/dx resolution of around 28% FWHM. By fitting the cosmic ray pulse height spectrum with a Landau distribution folded with a Poisson distribution for the number of photoelectrons, it is found that each counter (2 phototubes) produces $\simeq$ 150 photoelectrons. Relativistic $Q = 1/3$ quarks would then produce about 16 photoelectrons.

(3) Time-of-flight resolution

It is important to know the time resolution of the scintillation counters for lightly ionizing particles. These are simulated by "edge cosmics" — cosmic rays which clip the edges of the counters and therefore produce low pulse heights. The time resolution of a typical counter is found to vary from $\sigma = 0.18$ nsec for pulse heights corresponding to relativistic $Q = 1$ particles (at normal incidence) up to $\sigma = 0.65$ nsec for $Q = 1/3$.

(4) Scintillation counter efficiencies for the TOF measurement

The discriminator thresholds for time measurements were set to be > 90% efficient at 1/30 of minimum ionizing, and fully efficient at 1/10 of minimum ionizing. These efficiencies were checked by increasing the discriminator threshold levels and by use of the "edge cosmics".

(5) Trigger efficiency

The trigger for the running at PEP required at least one "track" in each arm of the detector. A "track" in this context corresponds to hits in a radial roadway of counters in hodoscopes S1 - S6. Five or more out of the six counters in the roadway are required to fire with a counter threshold of 1/20 of minimum ionizing. All efficiencies are checked with "edge cosmics". In Figure 2 we show the overall trigger efficiency for the reaction $e^+e^- \rightarrow q\,\bar{q}$ as a function of the mass of q, for $Q = 1/3$ and 2/3.

Results

The data taking at PEP was at a center-of-mass energy of 29 GeV with a total integrated luminosity of 17700 nb^{-1}. I will first describe a check on the operation of the detector using the QED reactions $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, and will then present the results from the search for fractionally charged particles in the reaction $e^+e^- \rightarrow q\,\bar{q}$.

QED check

In order to gain confidence in the operation of the detector, the measured cross-section and angular distribution for the combined QED reactions are compared with the theoretical expectations. (The reactions $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ are combined together because the detector cannot distinguish electrons from muons.)

The following cuts were used to select the $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$ events:

(1) There is one and only one track in each arm of the detector

(2) These tracks must come from the interaction region

(3) The event is in-time with the beam crossing

(4) The collinearity angle between the tracks is less than 2.25°.

After background subtraction, there is a total of 4577 events. Using the QED cross-section integrated over the detector solid angle (including radiative corrections), we calculate the total integrated luminosity stated above (17700 nb^{-1}). This value agrees to better than 10% with a completely independent measurement of the luminosity by a small-angle Bhabha scattering luminosity monitor.

Next, the angular distribution of these events is compared to the QED prediction in Figure 3. There is good agreement.

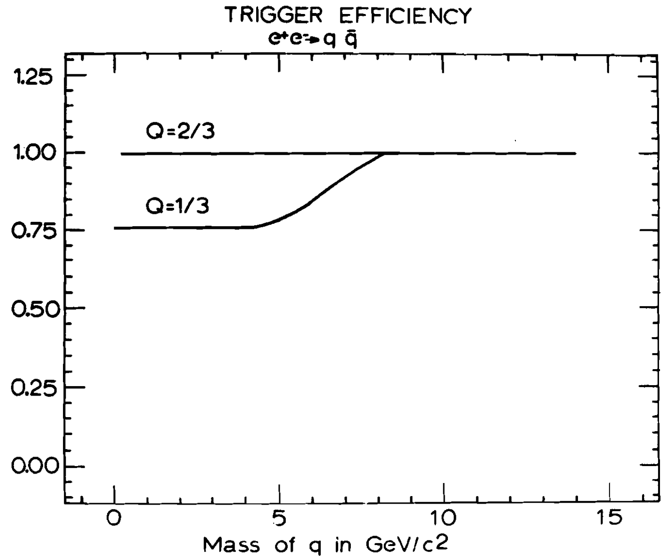

Fig. 2--The trigger efficiency for the reaction $e^+e^- \rightarrow q\ \bar{q}$ as a function of the mass of q, for charges $Q = 1/3$ and $2/3$.

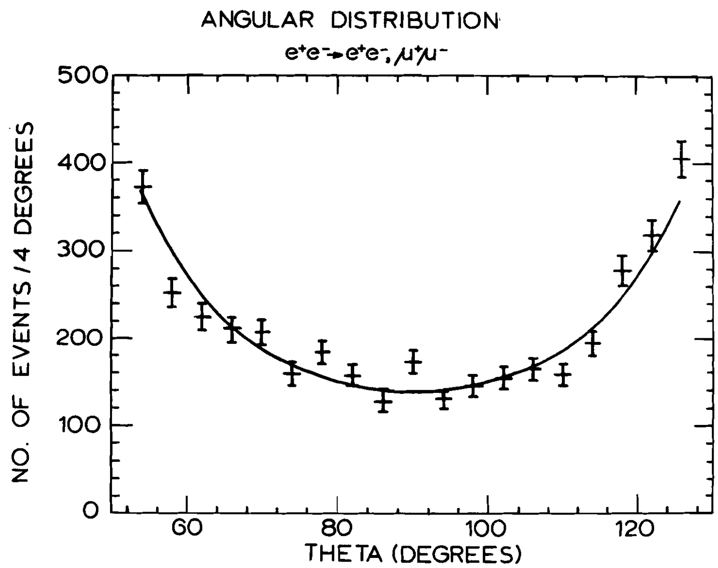

Fig. 3.--The angular distribution for the events from the combined reactions $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$, plotted in terms of the production angle θ, relative to the beam direction. The curve shows the QED prediction, normalized to the total number of events.

Search for Fractional Charge in $e^+e^- \to q\,\bar{q}$

For this search the cuts are the same as for the QED events except that the collinearity angle requirement is relaxed to 10°. For each track in the selected events a truncated mean dE/dx is calculated using the dE/dx measurements in the six scintillation counter hodoscopes S1 - S6.

In order to determine the velocity, at least three valid time-of-flight measurements are required for each track. These measurements and the beam-crossing time are fit to obtain the particle velocity. In this fit a loose χ^2 cut of $\leq$ 6 per degree of freedom is imposed.

The truncated mean dE/dx and velocity of each track are used to calculate the charge of the particle. A histogram of the measured charge is shown in Figure 4. The resolution is σ = 6.7%.

A scatter plot of the charge of the particle in one arm of the detector versus the charge of the particle in the other arm is shown in Figure 5. (There are 11.3 K events in this plot.) There are NO candidate events corresponding to $e^+e^- \to q\,\bar{q}$ with Q = 1/3 or 2/3.[8] For comparison, with the integrated luminosity of 17700 nb^{-1}, 290 $e^+e^- \to \mu^+\mu^-$ events are expected in the detector.

We will express the limit on the production of fractional charge in $e^+e^- \to q\,\bar{q}$ in terms of the ratio $R(q\,\bar{q}) = \sigma(e^+e^- \to q\,\bar{q})/\sigma(e^+e^- \to \mu^+\mu^-)$. Taking account of all efficiencies, we plot in Figure 6 the upper limit on $R(q\,\bar{q})$ at the 90% confidence level as a function of the mass of q, for charge Q = 1/3 and 2/3. We also show on this plot the limits given by the Mark II detector at SPEAR[9] and the JADE detector at PETRA.[10] The PEP experiment gives the first reported limit on $e^+e^- \to q\,\bar{q}$ for Q = 1/3.

Also shown in Figure 6 are the expected values for $R(q\,\bar{q})$ assuming point-like production. The PEP limits rule out any production at this level up to masses of 14 GeV/c^2, for charge values $1/3 \leq Q \leq 2/3$. Thus long-lived ($\tau > 10^{-8}$ sec) fractionally charged leptons in this mass and charge range are definitely ruled out.

In order to compare these results with searches performed using electromagnetic reactions different than $e^+e^- \to q\,\bar{q}$ we introduce the quantity $\rho(Q,M)$. This is defined as the ratio:

$$\rho(Q,M) = \sigma_{\text{exp. limit}}(Q,M)/\sigma_{\text{QED}}(\text{point-like, spin } 1/2,\ Q,M)$$

where $\sigma_{\text{exp. limit}}(Q,M)$ is the experimental limit on the cross-section for production of a particle of charge Q and mass M, and σ_{QED}(point-like, spin 1/2, Q,M) is the theoretical electrodynamic cross-section for production of a point-like, spin 1/2 particle of charge Q and mass M in the same type of reaction. In Figure 7, $\rho(Q,M)$ is plotted for the e^+e^- limits shown in Figure 6. In addition, we plot the limits from the most sensitive previous electromagnetic experiment (a photoproduction experiment at SLAC[11]) as well as the limits from searches using hadronic collisions assuming electromagnetic production of $q\,\bar{q}$ via the Drell-Yan process. Clearly, for the electromagnetic production of $q\,\bar{q}$ with masses above a few GeV, the recent e^+e^- experiments have improved the previous limits by many orders of magnitude.

The Future

Data taking for the quark detector has been completed and the detector has been removed from the interaction region. Data analysis for the multi-particle reaction $e^+e^- \to q\,\bar{q}\,X$ is underway, as well as the search for highly interacting quarks using the "thin front end".

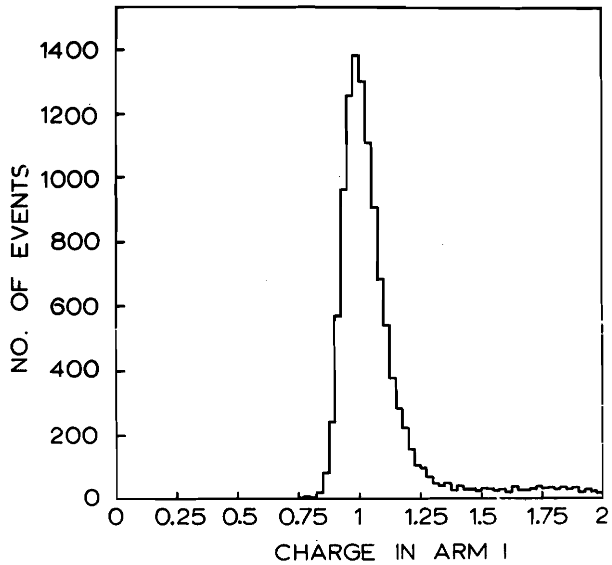

Fig. 4--The charge distribution of the particles in one arm of the detector for back-to-back events.

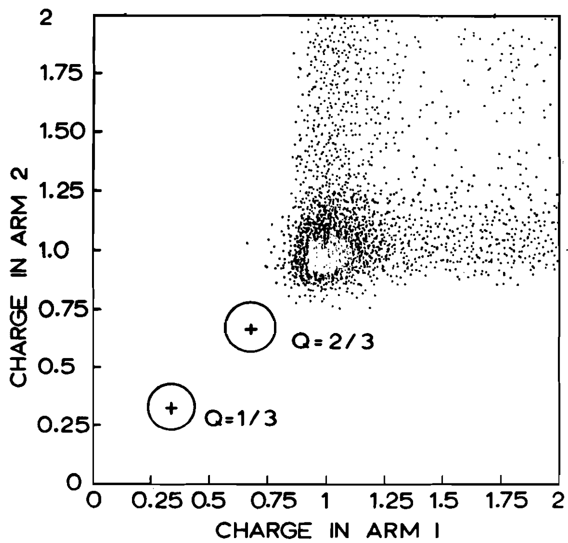

Fig. 5--A scatter plot of the charge of the particle in one arm versus the charge of the particle in the second arm for back-to-back events.

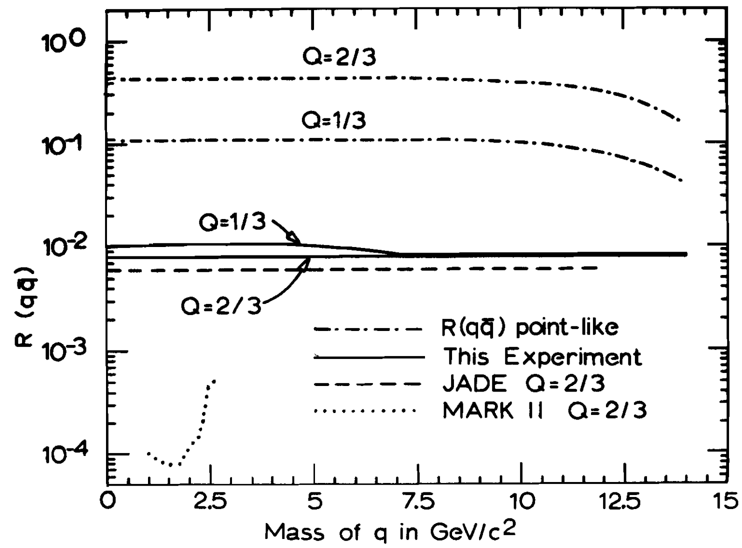

Fig. 6--The upper limits (90% confidence level) for $R(q\,\bar{q}) = \sigma(e^+e^- \to q\,\bar{q})/\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of the mass of q, for the PEP, Mark II, and JADE experiments. $R(q\,\bar{q})$ assuming point-like production is also shown.

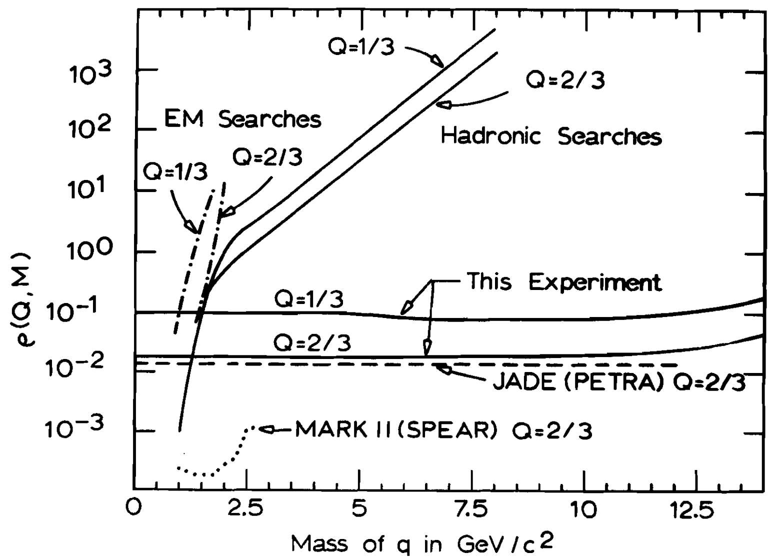

Fig. 7--The upper limits (90% confidence level) for $\rho(Q,M)$ (defined in the text) as a function of the mass of q. Limits from e^+e^- reactions, photoproduction, and hadronic reactions (assuming production via the Drell-Yan process) are shown.

The Highly Ionizing Particles Search Experiment

This search for magnetic monopoles or other highly ionizing particles has been carried out by a collaboration[13] from the University of California at Berkeley and SLAC.

Highly Ionizing Particles

We consider electrically charged particles as well as magnetic monopoles.

(1) Electrically charged particles

These might be, for example, highly charged quarked matter. The ionization energy loss is given once again by:

$$dE/dx \simeq (Q/\beta)^2 (dE/dx)_{MIP}.$$

The present experiment is sensitive to values of $Q/\beta \geq 16$.

(2) Magnetic Monopoles

The ionization energy loss for relativistic magnetic monopoles is given by:

$$dE/dx \simeq (g/e)^2 (dE/dx)_{MIP}. \qquad (\beta \simeq 1)$$

where g is the magnetic charge. The charge quantization condition gives:

$$g/e = n/2\alpha \simeq \frac{137}{2} n$$

with n = ± 1, ± 2, ... for a Dirac Monopole. This is an enormous ionization energy loss. For n = 1, it is 4700 times minimum ionizing, or about 9.4 GeV/gm/cm^2. For non-relativistic monopole velocities, the dE/dx (expressed in terms of the equivalent value of Q/β) is plotted as a function of β in Figure 8.[14] The sensitivity of the present experiment is indicated on this figure.

The Experimental Technique

Thin sheets of plastic, with the tradenames CR-39 and Lexan, are used to record the tracks of highly ionizing particles. The method is illustrated in Figure 9. In (a), a highly ionizing particle passes through a plastic sheet and leaves a microscopic trail along its trajectory which is susceptible to chemical etching at an accelerated rate.

The latent track is made visible by etching the plastic sheet in a concentrated solution of sodium hydroxide. This is shown in (b). Let V_G be the general etch rate for exposed surfaces and let V_T be the accelerated rate for etching along the trajectory. The ratio V_T/V_G is a rapidly increasing function of the ionization energy loss of the particle. Due to this differential etch rate, in analogy with the formation of a conical wavefront in Cerenkov emission, conical etch pits are formed in the plastic. The half-angle θ of the cone is given by arc sin $\theta = V_G/V_T$ ($\theta = 42°$ in CR-39 when $Q/\beta = 16$).

As shown in (c), if the etching process is continued for a sufficient length of time, a hole will be formed in the plastic sheet. These holes can be detected with a simple and ingenious technique. The plastic sheet is placed on top of the blueprint paper and taped around the edges. It is then exposed to ammonium vapor. Each hole in the plastic is then indicated by a blue spot on the blueprint paper.

Figure 10 shows the conical etch pits formed in a sheet of CR-39 after exposure to a beam of neon ions incident at an angle of 60° with respect to the normal to the surface.

The Detectors

This past year there were stacks of track recording plastic sheets in two interaction regions at PEP. In IR-6 there were two stacks located 9 cm from the beam-line. Each stack consisted of 15 x 46 cm^2 of Lexan (75 μ thick) and CR-39 (600 μ thick). The Lexan and CR-39 sheets alternated for a total of 20 sheets. This was followed by 5 sheets of CR-39. The total solid angle subtended was 40%

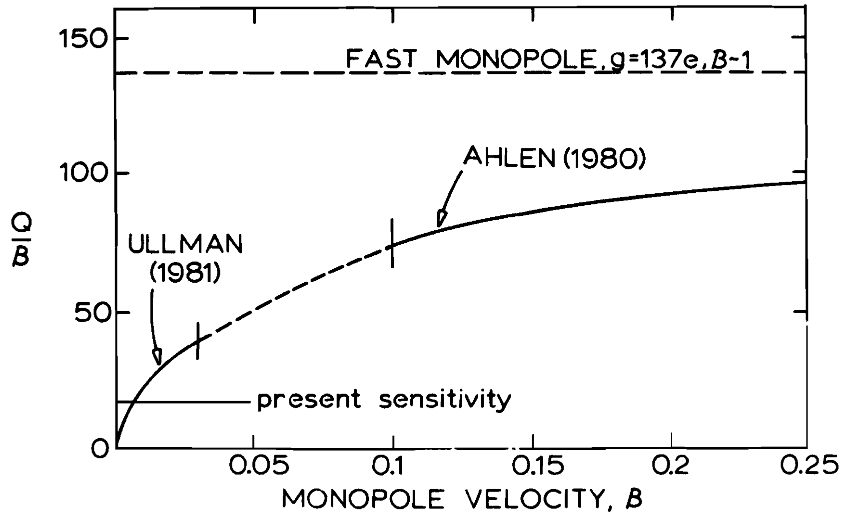

Fig. 8--The ionization energy loss, expressed in terms of the equivalent value of Q/β, for a magnetic monopole with velocity β in water. The charge of the monopole is taken to be g = 137 e. The present sensitivity of the experiment, Q/β > 16, is indicated.

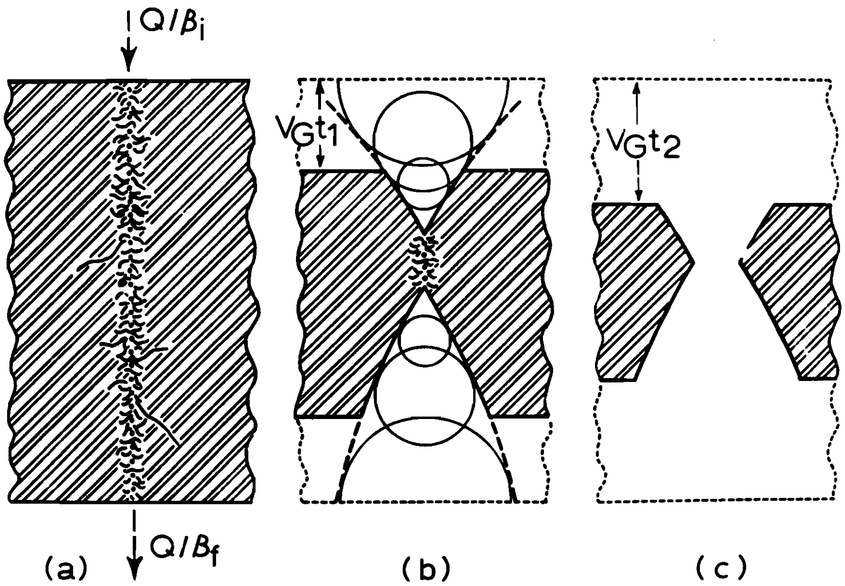

Fig. 9--Sketch of the passage of a highly ionizing particle through a plastic track recording sheet (a) and the subsequent formation of conical pits (b) and holes (c) by etching.

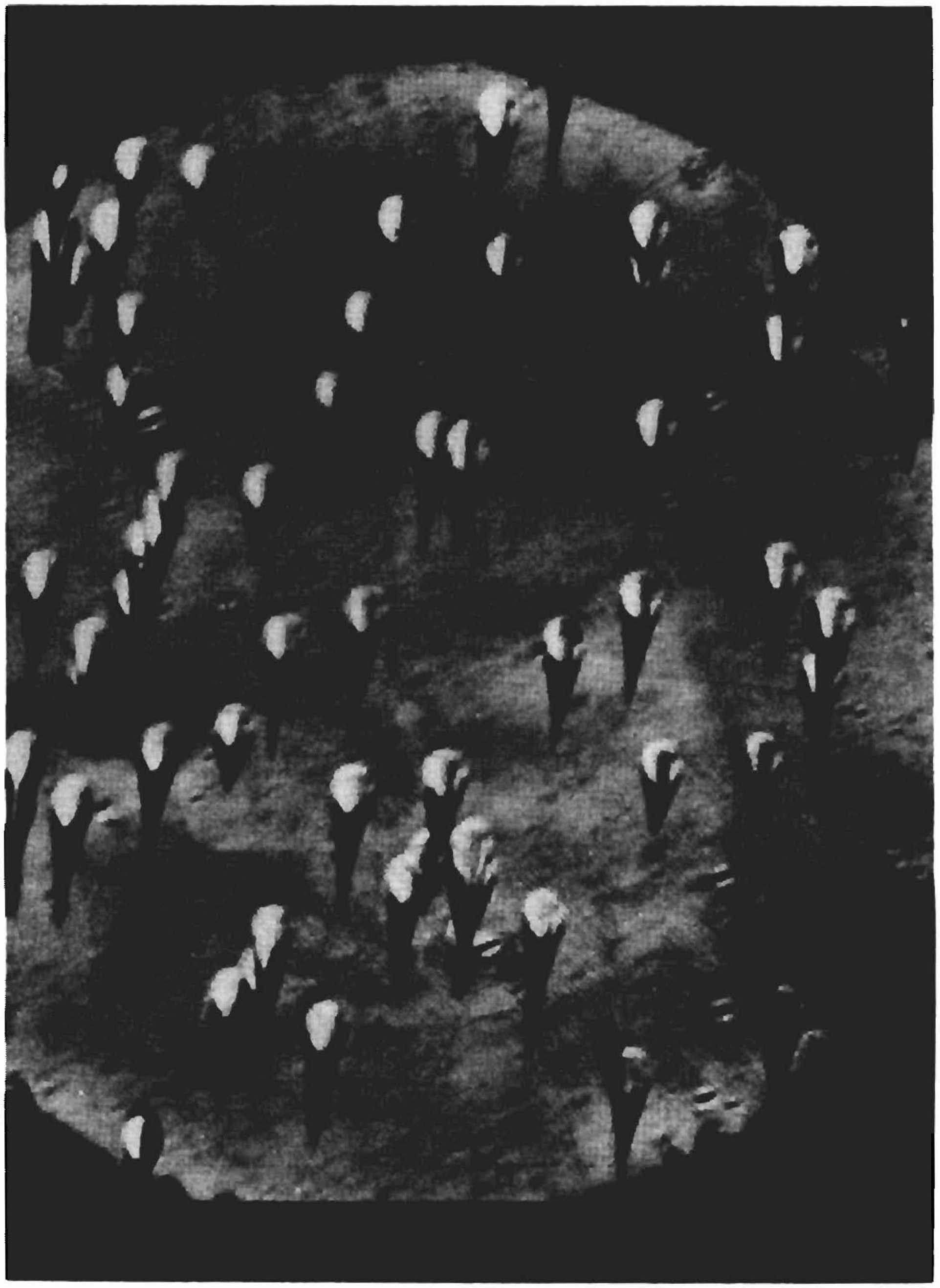

Fig. 10--An optical micrograph of the conical etch pits formed in a sheet of CR-39 after exposure to a beam of neon ions incident at an angle of 60° with respect to the surface normal. The etch pits are ≈ 20μ in diameter.

of 4π sr. The corrugated beam pipe had an average thickness at normal incidence of 265 μ of stainless steel plus 25 μ of copper.

In IR-10 there were two stacks 5 cm from the beam-line. The sheets were 3 x 6 cm^2. Each stack had alternate layers of Lexan and CR-39 for a total of 10 sheets. The solid angle subtended was 11% of 4π sr and the corrugated beam pipe had an average thickness of 160 μ of stainless steel.

Results

All data taking was done at a center-of-mass energy of 29 GeV. The sheets closest to the beam-line were etched and examined for holes using the ammonia vapor technique. No holes were found. Note that detection of a highly ionizing particle coming from the collision point requires $Q/\beta \geq 16$ sustained for 0.3 gm/cm^2 in IR-6 or 0.2 gm/cm^2 in IR-10 (assuming normal incidence). The integrated luminosities, solid angles, and inclusive cross-section limits for the IR-6 and IR-10 detectors are summarized in Table II.

TABLE II

Summary of Highly Ionizing Particles Search Results

	IR-6	IR-10
$\int L dt$	6.1 pb^{-1}	8.4 pb^{-1}
$\Delta\Omega/4\pi$	40%	11%
inclusive cross-section limit (90% C.L.)	0.94 pb	2.5 pb

The combined limit is 0.7 pb at the 90% confidence level. This corresponds to 0.7% x $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

Due to its finite range, the maximum detectable mass of a magnetic monopole is less than the beam energy. This maximum detectable mass is given in Table III for two different values of the magnetic charge.

TABLE III

Maximum Detectable Magnetic Monopole Mass

(Normal Incidence)

g	IR-6	IR-10
e/α	9.5 GeV/c^2	11.5 GeV/c^2
$e/2\alpha$	13.7	14.0

These limits are based on monopole production with an energy equal to the beam energy, as in $e^+e^- \rightarrow M\bar{M}$.

Conclusions

(1) There is no production of fractional charge in $e^+e^- \rightarrow q\,\bar{q}$ for charges in the range $1/3 \leq Q \leq 2/3$ and a mass $M < 14$ GeV/c^2, at the level of 1% or greater of $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

(2) Long-lived fractionally charged leptons with $1/3 \leq Q \leq 2/3$, $M < 14$ GeV/c^2 are ruled out.

(3) There is no production of highly ionizing particles in $e^+e^- \rightarrow M$ + anything, with $Q/\beta > 16$ sustained for 0.2 - 0.3 gm/cm^2 at the level of 0.7% or greater of $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

References and Footnotes

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1. The members of this collaboration are: A. Marini, I. Peruzzi, M. Piccolo, F. Ronga, Laboratori Nazionali di Frascati; D. Chew, R. P. Ely, T. P. Pun, V. Vuillemin, Lawrence Berkeley Laboratory; R. Fries, B. Gobbi, W. Guryn, D. H. Miller, M. C. Ross, Northwestern University, D. Besset, S. J. Freedman, A. M. Litke, J. Napolitano, T. C. Wang, Stanford University; F. A. Harris, I. Karliner, S. I. Parker, D. E. Yount, University of Hawaii.

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5. L. Susskind, private communication.

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7. S. I. Parker et al., Physica Scripta 23 (1981) 658.

8. There is one event corresponding to a particle in arm 1 with a measured charge = 0.69 and a particle in arm 2 with measured charge = 1.03. We have looked carefully at the track in arm 1. We find that the TOF measurements are not consistent. It appears that a particle with $Q = 1$, $\beta \simeq 1$ left the interaction region and interacted and produced in scintillation counter layer S5 a slow moving particle with $Q = 1$, $\beta \simeq 0.60$. With the very loose time-of-flight χ^2 cut of ≤ 6 per degree of freedom, these five time-of-flight measurements were accepted as due to a single track. The result was an incorrect low β measurement, and hence a low value for the charge.

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13. This collaboration consists of K. Kinoshita and P. B. Price, University of California at Berkeley and D. Fryberger, SLAC.

14. S. P. Ahlen, Rev. Mod. Phys. 52 (1980) 121; J. D. Ullman, Phys. Rev. Lett. 47 (1981) 289.

Discussion

W. Selove, Univ. of Pennsylvania: Am I correct in believing that present theory does not give a limit on the production of fractionally charged quarks which would emerge not as isolated particles but as fractionally charged members of jets?

A. Litke: There are a number of theoretical estimates for the production of free quarks along with hadrons in e^+e^- annihilation. Defining

$$R(q\bar{q}X) = \sigma(e^+e^- \to q\bar{q}X) / \sigma(e^+e^- \to \mu^+\mu^-) \ ,$$

for a quark mass of 10 GeV, Bjorken estimates $R(q\bar{q}X) \sim 10^{-4}$ (with the exponent not known to better than a factor of 3-10). DeRujula, Giles, and Jaffe give a range for $R(q\bar{q}X)$ of $10^{-16} - 5 \times 10^{-9}$ and Steigman and Wagoner estimate $R(q\bar{q}X)$ $R(q\bar{q}X) \sim 10^{-44}$. This will give you an idea of the theoretical uncertainties.

W. Bartel, DESY: Are there any reasons not to put the plastic sheets for the monopole search into the vacuum?

A. Litke: I believe that the PEP vacuum cigar would not allow this.

R. Hofstadter, Stanford University: Can we do the simple conclusion that your limit on a fractional charge measurement was 1/5 or 1/6 of a unit charge?

A. Litke: I would say that for the $e^+e^- \to q\bar{q}$ reaction we start getting into trouble with our trigger efficiency when $Q \leq 1/4$.