Search for Highly Ionizing Particles in e^+e^- Collisions at $\sqrt{s} = 29$ GeV

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In a search for highly ionizing particles at PEP, Lexan and CR-39 plastic track detectors were exposed to an integrated luminosity of $\sim 10^{37}$ cm^{-2} at an energy of 29 GeV in the center of mass. The search was sensitive to particles with magnetic charge $20e \lesssim g \lesssim 200e$ or electric charge $3 \lesssim Z \lesssim 180$. An upper limit on the production cross section of $\sigma < 0.9 \times 10^{-36}$ cm^2 (95% C.L.) is obtained.

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Dirac hypothesized the existence of the magnetic monopole in 1931,[1] as a way to symmetrize the Maxwell equations and explain the quantization of electric charge. In the intervening half century, this hypothesis has survived, unsupported by experimental evidence.[2,3] Although its magnetic charge is generally agreed to be an integral multiple of $g_0 \equiv e/2\alpha = 68.5e$,[1,4] its predicted mass has risen from an initial estimate of ~0.5 GeV,[1] as accelerator searches have continued to yield null results. Present predictions vary from large (~10 GeV)[5] to very large (5–10 TeV)[6] to colossal (~10^{15} GeV).[7] The current theories are discussed by Goddard and Olive.[8] Most accelerator searches have been "indirect," i.e., the particles were observed not when they were produced, but much later, after some process of extraction and acceleration of magnetic charge from matter in which the particle was assumed to have come to rest. Their results have consequently depended on assumptions made about the behavior of magnetic monopoles in matter. Other particles of high charge—both electric and magnetic—have been hypothesized.[9] Our search is free of restrictive assumptions and is sensitive to particles from PEP with electric charge $3 < Z < 180$ as well as magnetic charge $0.3g_0 < g < 3g_0$, and mass approaching the beam energy of 14.5 GeV.

In each of several exposures at the Stanford Linear Accelerator Center–Lawrence Berkely Laboratory positron-electron colliding-beam storage ring (PEP), our detector modules consisted of flat stacks of 75-μm Lexan and 600-μm CR-39 plastic sheets. A complete discussion of dielectric track detectors is given by Fleischer, Price, and Walker.[10] Cone-shaped pits locating the path of a highly ionizing particle are revealed at a sheet surface by etching the sheet in a controlled, hot, concentrated sodium hydroxide solution. The depth of the etch pits, or *tracks*, is an increasing function of the parameter Z/β, with Ze the electric charge and $\beta \equiv v/c$. These detectors are well suited to a search of this type, as they record no tracks for the bulk of particles in an accelerator environment, with $Z/\beta \sim 1$. Lexan records only tracks of very highly ionizing particles ($Z/\beta \geq 70$) and is able to withstand more than 100 Mrad general radiation damage. CR-39 is sensitive to particles with $Z/\beta \geq 6$ but cannot tolerate doses above a few megarads. The resultant increase in its general etch rate can, in fact, be used to measure doses in this regime.[11] The unexcelled positional and angular resolution of track detectors enables a track produced by a penetrating particle to be recognized by matching the etch pits at each detector surface. A background of short tracks originating both from natural ^{222}Rn and PEP is dealt with by demanding that a track penetrate at least one sheet to be considered. The detector is thus defined *a priori* to be insensitive to particles with range shorter than one sheet thickness. Although Lexan is quite insensitive, the thinness of the sheets used permits low-energy normal nuclei as light as $Z = 7$ to satisfy the criterion of detectability. The CR-39, being much more sensitive, may be used to detect penetrating ions down to $Z = 2$. In our detector modules, Lexan was placed closest to the beams, followed by alternating sheets of CR-39 and Lexan. The relative location of sheets in a stack was fixed by drilling several holes through it, making possible ≤ 100-μm localization from sheet to sheet.

Our search was conducted in two different PEP interaction regions. The first, IR-10, is plagued by backgrounds due to its position directly downstream from the electron injection point; in three weeks, CR-39 samples left near the interaction point received $\sim 10^5$-cm^{-2} track background. We consequently devised a motorized system, which automatically retracts the detector into a shield during beam tuning and injection. The detector used in this system consisted of two modules, each 3.2×5.7 cm^2 with thickness ~0.3 g/cm. These modules were exposed to 8.4×10^{36} cm^{-2} integrated luminosity at 5 cm from the interaction point, directly under the beam, subtending a solid angle ~2.0 sr. The beam pipe was made of 100-μm-thick stainless steel. We placed a second detector at IR-6, in a portion of solid angle unoccupied by the free-quark-search detector. Because IR-6 has an elaborate shielding system and is far from either injection point, the background is much lower there than at IR-10 and two modules were simply mounted directly above and below the 200-μm stainless-steel beam pipe and left in place for the duration of the exposure, to 6.1×10^{36} cm^{-2}. These modules, each 15×46 cm^2, covered ~4.6 sr solid angle, with total thickness ~1.3 g/cm^2. The uncertainty in the position of the interaction point was ~1 cm in the longitudinal direction and much less in the radial direction.

After exposure at PEP, each CR-39 sheet was etched such that penetrating, normally incident tracks with an average $Z/\beta > 16$ would produce a hole. An ammonia scanning technique[10] was used to locate any holes thus produced. Each hole was microscopically examined at 15× magnification to eliminate those due to flaws in the plastic and to observe each track's orientation. Tracks not consistent with a particle originating at the interaction point were eliminated. For each of the remaining tracks, the corresponding locations in the adjacent CR-39 sheets were examined. Any particle produced by PEP and recording a track detected in this way would produce an etchable track in at least the immediately preceding sheet. An electrically charged particle produces its greatest ionization at the Bragg peak, just before the end of its range. Since Z/β increases as a particle slows, it could conceivably be detected by the ammonia method in a single sheet in the middle of our detector stack. By looking in preceding sheets it is possible to see the pairs of tracks that are below the ammonia threshold, yet above the etching threshold, $Z/\beta \geq 6$. This criterion discriminates strongly against particles with $Z<3$. A track produced by a magnetic monopole would be characterized by a slow decrease in ionization, from an apparent $Z/\beta = g/e$ at $\beta = 1$, approaching zero as the particle comes to rest. At very low velocities the ionization for magnetic charge g_0 would fall below our detector threshold, but the residual range would be only a few microns, for masses accessible to PEP.

Although track detectors do not record the singly charged, miminum-ionizing particles so abundant in this environment, they do record the low-energy nuclear fragments produced in collisions of energetic particles with nuclei in and near the detector. Although these fragments almost never produce tracks long enough to penetrate a single CR-39 sheet, a high density of short tracks would reduce drastically the efficiency of scanning. To determine the track-producing efficiency of various particles, we exposed CR-39 samples to four beams (Table I), which simulated the principal types of sources expected: low- and high-energy hadrons and leptons. Each sample was first etched for a short time and scanned to determine the ratio of the density of short tracks to integrated particle flux. To determine the efficiency for production of longer tracks which could be revealed by ammonia scanning, the samples were then etched for the same length of time as our detectors and scanned for holes. We note that to produce 10^4/cm^2 of short tracks in CR-39, electrons deposit a general dose ~1 Mrad, while protons deposit much less.

To identify track background sources in IR-10, pieces of CR-39 were exposed at various locations for periods of about three weeks, then etched, and track densities were measured. At IR-6 the density varied inversely with distance from the beam line, which is consistent with a line source at the beam. At IR-10, it was much higher and almost independent of location, which suggests that the principal source is much farther away. The source is most likely related to the electron injection, which occurs about 50 m up-

TABLE I. Background calibration exposures.

Facility	Beam	Energy	Track efficiency Short	Penetrating
SLAC	e^-	20 GeV	10^{-9}	$<10^{-13}$
LLNL	e^-	95 MeV	10^{-9}	$<10^{-13}$
LBL	p	2 GeV	10^{-4}	10^{-6}
LBL	p	25 MeV	10^{-3}	$<10^{-8}$

stream of IR-10. Except at points very close to the beam line in IR-10, high track densities were accompanied by general radiation doses well below 1 Mrad, indicating a predominantly hadronic rather than leptonic source. Each full-energy electron which escapes from the beam pipe produces several neutrons and protons in depositing its energy in the surrounding matter.[12] Most of these hadrons are produced in the excitation of giant dipole resonances in target nuclei by virtual photons and have energies less than 20 MeV. The attenuation length in concrete of neutrons with these energies is approximately 30 g/cm^2, whereas protons are stopped through ionization in ~0.4 g/cm^2. A CR-39 sample in IR-10 surrounded by 23 g/cm^2 of water with an additional 100 g/cm^2 of concrete in the injection direction registered a twentyfold reduction in track density compared to an unshielded sample. This attenuation is consistent with the conjecture that our track background is caused mainly by giant-resonance neutrons originating upstream.

No candidates were found for highly ionizing particles produced by PEP. The density of short background tracks in each CR-39 sheet was ~10^3/cm^2. Because of its fixed position, the detector at IR-6 was exposed to a large flux of energetic particles during injection periods. From the resultant density of penetrating tracks we estimate that the detector was exposed to ~10^7/cm^2 of high-energy hadrons. Of ~200 tracks revealed by the ammonia technique, 18 were found which appeared to originate at or near the interaction point. One of these tracks corresponded to a particle entering the stack from the interaction area; the rest appeared to have been produced locally. The one event recorded a nearly normally incident penetrating track in the first two sheets of CR-39, producing a hole detected by the ammonia method in the second. It was identified as an α particle with initial energy ~56 MeV. This one event is consistent with the estimated event density from α particles produced by interactions of energetic hadrons with the beam pipe. The estimated production rate for lithium ions which might be detected in a similar manner is lower by 2 orders of magnitude. To estimate an upper limit to the production cross section, we assume isotropic production in the reaction

$$e^- + e^+ \rightarrow X + \bar{X}. \qquad (1)$$

The total particle energy is equal to the beam energy. To be observed, a particle would need sufficient kinetic energy to penetrate the first sheet of CR-39. An electrically charged particle would, in addition, have to slow enough so that Z/β exceeded the threshold before reaching the last sheet in the stack. The range of a magnetic monopole was calculated as a function of mass for 14.5-GeV beam energy and $g = 68.5e$, using the stopping power given for $\beta < 0.1$ by Ullman[13] and for $\beta \geq 0.1$ by Ahlen.[14] The mass at which a magnetic monopole would just penetrate a 100-μm beam pipe and one sheet of CR-39 is ~14.0 GeV/c^2, our upper limit. For the 200-μm beam pipe the mass is ~13.7 GeV/c^2. The threshold value of Z/β for detection by the ammonia method rises with the incident zenith angle of the penetrating particle so that the solid angle acceptance rises with Z/β. A significant portion of the detector at IR-6 is exposed to the interaction point at large zenith angles, up to 65°. The sensitivity to Dirac monopoles is essentially unaffected by this condition, but for other less highly ionizing magnetically and electrically charged particles we set the threshold $Z/\beta > 20$, to accept zenith angles out to ~30°. Because center-of-mass pair production is assumed, the effective collecting power is doubled where opposite sides of the interaction point are not covered, as at IR-10. The upper limit at 95% confidence level is then

$$\sigma < 3/\sum (L_i t_i \Omega_i / 4\pi),$$

where Ω_i is the solid angle acceptance and $L_i t_i$ is the integrated luminosity; the sum is over the two interaction regions. The range as a function of particle mass was calculated for different electric charges to find the charge-mass combinations accessible to our detector, shown in Fig. 1. The

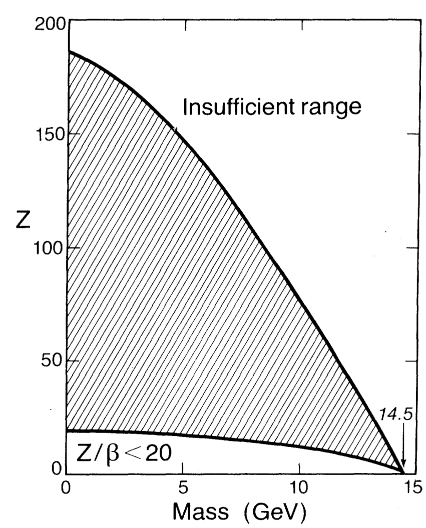

FIG. 1. Shaded region shows electric charge and mass combinations accessible to this detector.

TABLE II. Experimental parameters and upper limits to production cross sections (95% C.L.) ($E_B = 14.5$ GeV).

	IR-6	IR-10	Combined limit
$L_i t_i$ (10^{36} cm^{-2})	6.1	8.4	
Pipe thickness (μm)	200	100	
Magnetic Monopole			
Mass limit (GeV), $g = g_0$	13.7	14.0	
$g = 2g_0$	9.5	11.5	
Solid angle (sr)	4.6	2.0	
σ (10^{-36} cm^2)	<1.4	<2.3	<0.85
Electric, $Z/\beta \gtrsim 20$			
Solid angle (sr)	1.7	1.7	
σ (10^{-36} cm^2)	<3.7	<2.7	<1.6

detector parameters and cross-section limits are summarized in Table II. For comparison, it is noted that the QED point cross section at this energy is 1.0×10^{-34} cm^2, and the weak cross section is $\sim 10^{-35}$ cm^2.

If it is assumed that pairs are produced via a virtual-photon intermediate state, our search using $e^- e^+$ annihilation carries a significant cross-sectional advantage over the only other "direct" search, performed at the CERN-intersecting storage rings (ISR).[15] (Figure 4 in Ref. 3 compares recent upper limits for monopole production via nucleon-nucleon collisions.) The cross section for massive virtual-photon production at the ISR[16] is of the order of our QED point cross section for photon masses, ~4 GeV, but falls exponentially with rising mass. Extrapolating the exponential dependence, we conclude that a search at the ISR would have to accumulate a factor $\sim 10^5$ more integrated luminosity to match our limit set at PEP for the production of particles with 13-GeV mass.

This search will continue in IR-10 during the next year, with use of a detector with larger solid angle. With the expected increase in luminosity and energy at PEP, we expect to decrease our cross-section limit by at least 1 order of magnitude and extend our mass limit by several gigaelectronvolts.

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