Brief Reports

Brief Reports are short papers which report on completed research which, while meeting the usual **Physical Review** *standards of scientific quality, does not warrant a regular article. (Addenda to papers previously published in the* **Physical Review** *by the same authors are included in Brief Reports.) A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Search for highly ionizing particles in e^+e^- collisions at $\sqrt{s}=29$ GeV

D. Fryberger
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

T. E. Coan, K. Kinoshita,* and P. B. Price
Department of Physics and Space Sciences Laboratory, University of California, Berkeley, California 94720
(Received 31 October 1983)

The results of the analysis of data taken in the continuation of a previously reported search for highly ionizing particles at PEP are presented. Assemblies consisting of Lexan and CR-39 plastic track detectors were exposed in two runs to integrated luminosities of 30×10^{36} cm^{-2} and 150×10^{36} cm^{-2}. The search was sensitive to particles with magnetic charge $20e \leq g \leq 200e$ or electric charge $3 \leq Z \leq 180$. A combined (95% C.L.) upper limit on the production cross section of $\sigma < 3.2\times10^{-38}$ cm^2 is obtained, improving our previous limits by more than an order of magnitude.

The purpose of this paper is to present the results of the analysis of data taken in the continuation of a previously reported search[1] (hereafter referred to as I) for highly ionizing particles at the Stanford Linear Accelerator Center PEP e^+e^- storage-ring facility. The new data reported here were all taken in interaction region 10 (IR-10) with beam energy $E_B = 14.5$ GeV ($\sqrt{s}=29$ GeV; the same as in I).

As in I, this search used plastic track detectors comprised of interleaved sheets of Lexan and CR-39. These sheets were 80 and 610–725 μm thick, respectively, and arrayed in an assembly of stacks as depicted in Fig. 1. A set of holes was drilled in all of the sheets to allow alignment between individual sheets to ≤ 100 μm. The total solid angle Ω subtended by the stacks of sheets in this detector was 0.51 of 4π or 6.4 sr. The full area of the sheets is considered effective for the detection of Dirac magnetic monopoles.[2] As described in I, however, for electrically charged particles, the maximum acceptable zenith angle (the angle between the track trajectory and a vector normal to the plastic surface) is set at 30°, which in this case reduces the effective Ω to 5.0 sr.

There is a considerable background in IR-10 due to the production of neutrons (see I for discussion) by the (uncaptured) e^- injection beam. This problem was circumvented by mechanically locating the detector assembly in a shielded cave during injection and beam tuning. For the apparatus used to collect the data reported in this paper the mechanical configuration was considerably improved over that of I. The detector assembly used here was mounted on the outer circumference of a wheel of 147 cm diameter. Before each injection, the wheel was rotated by 180° around its axis, which was parallel to the axis of the beam pipe and 91.5 cm directly below it, carrying the detector assembly into a shielded cave constructed around the lower half of the wheel. A slot in the detector (see Fig. 1) permitted it to be moved past the vacuum pipe.[3] The wheel was in the form of a partitioned drum whose sections were filled with a mix of sand and water. This drum was 28.6 cm wide and shielded the retracted detector (with an estimated 150 g/cm^2)

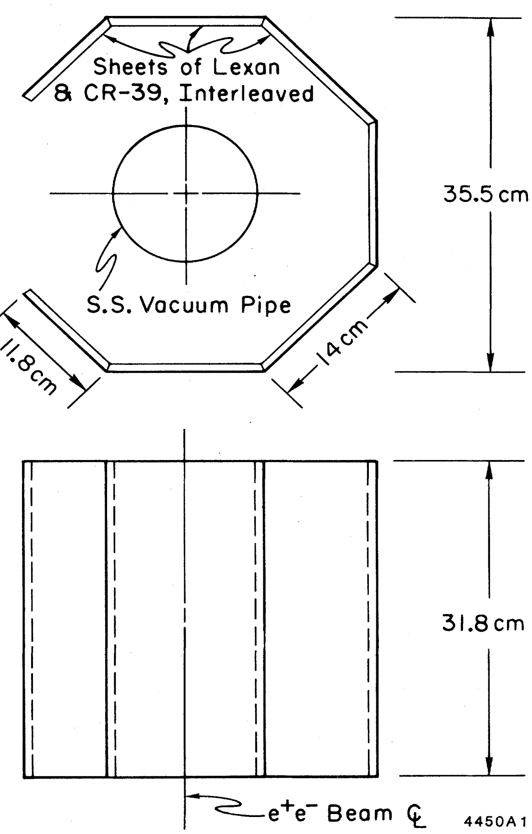

FIG. 1. Schematic depiction of the assembly of Lexan and CR-39 plastic track detectors used in this search for highly ionizing particles. Each of the seven sides contained a stack of interleaved sheets of Lexan and CR-39. The sheets were 31.8 cm long with widths as indicated (11.8 and 14 cm). The eighth side of the octagonally shaped detector was missing so that, prior to injection and beam tuning, the detector assembly could be rotated away from the beam pipe into a shielded cave located near the floor level.

TABLE I. Summary of experimental parameters and (95% C.L.) upper limits to production cross sections. $E_B = 14.5$ GeV. $g_0 \equiv e/2\alpha = 68.5e$, the Dirac charge. Note that the QED point cross section $= 10^{-34}$ cm^2 at $\sqrt{s} = 29$ GeV.

			Ref. 1 IR-6	Ref. 1 IR-10	Run 1 IR-10	Run 2 IR-10	Combined limit
	$L_i t_i$ (10^{36} cm^{-2})		6.1	8.4	30.3	150	
	Pipe thickness (μm)		200	100	200	200	
Magnetic monopole	mass limit (GeV),	$g = g_0$	13.7	14.0	13.7	13.7	
Magnetic monopole		$g = 2g_0$	9.5	11.5	9.5	9.5	
Magnetic monopole	solid angle (sr)		4.6	2.0	6.4	6.4	
Magnetic monopole	σ (10^{-36} cm^{-2})		< 1.4	< 2.3	< 0.19	< 0.039	< 0.032
Electric, $Z/\beta > 20$	solid angle (sr)		1.7	1.7	5.0	5.0	
Electric, $Z/\beta > 20$	σ (10^{-36} cm^2)		< 3.7	< 2.7	< 0.25	< 0.050	< 0.041

from above. Upstream shielding (toward the e^- injection point) consisted of 31.8 g/cm^2 of polyethylene plastic, 138 g/cm^2 of Pb, and 425 g/cm^2 of concrete blocks. Downstream shielding consisted of 29.3 g/cm^2 of plastic, 138 g/cm^2 of Pb, and 265 g/cm^2 of concrete blocks. This shielding eliminated the problem of neutron-generated background tracks[4] in the detector. At the beginning of each fill, and after injection and tuning were complete, the wheel was rotated back by the 180°, putting the detector into its data-taking position surrounding the corrugated, 15.2-cm-diameter, 200-μm-thick[5] stainless-steel vacuum pipe at the interaction point. This rotation took about 1 min, which is $\simeq 1\%$ of the running time allocated to a typical e^+e^- fill.

The data for the analysis reported here were taken using two different loadings[6] of the detector assembly. Each loading was exposed during a nine-month period. These two runs yielded integrated luminosity accumulations of 30.3×10^{36} and 150×10^{36} cm^{-2}, respectively.[7]

The plastic sheets from these data runs were analyzed as described in I. Briefly, each CR-39 sheet was etched in 6.25 N aqueous solution of NaOH at 70 °C such that a penetrating track at normal incidence with an average $Z/\beta > 16$ would produce a hole. The ammonia-scanning technique was used to search for holes in the etched plastic. Each hole was examined through a stereomicroscopic at 15× magnification. This step enables one to eliminate holes due to flaws in the plastic or, if there is an associated track, to determine its orientation. Since the ionization rate of a particle with given electric charge increases with decreasing β (except at the very end of its range), a particle might produce an etchable track above the ammonia-detection threshold in one sheet and produce a latent track below the ammonia threshold, but above the etching threshold, $Z/\beta \simeq 8$, in an immediately preceding one. Hence, if any possibly interesting track was found by the ammonia technique, the corresponding area in the previous sheet was also examined through the use of the drilled alignment holes. This coincidence technique discriminates against particles with $Z < 3$. For magnetic monopoles with a given g, the ionization rate decreases as β decreases, so any putative monopole track would have to have an etching signature consistent with this expectation.

Neither data sample produced any candidate for highly ionizing particles produced at PEP.

The formula

$$\sigma < \frac{3}{\sum_i (L_i t_i \Omega_i / 4\pi)} , \qquad (1)$$

where Ω_i is the solid-angle acceptance and $L_i t_i$ is the integrated luminosity, was used to give the 95%-confidence-level upper limit on the production cross section.

The results of the three years of data taking are summarized in Table I. For comparison to the limits set here,[8] we note that at this energy a generic[9] weak cross section is $\sim 3 \times 10^{-37}$ cm^2, and the QED point cross section is 1×10^{-34} cm^2; our upper limits for monopoles and particles with large electric charge are lower than these cross sections by factors of ~ 10 to 3000.

We thank the PEP staff for efficient operation and delivery of good luminosity. We thank A. Baumgarten, R. Adamson, D. Nevius, and W. Smith for engineering support, T. Jenkins for assistance in the background measurements, and participants in the free-quark-search experiment for their cooperation enabling us to install a detector and take data in IR-6. This work was supported in part by the National Science Foundation under Grant No. PHY-8024128 and by the Department of Energy under Contract No. DE-AC03-76SF00515.

---

*Present address: Department of Physics, Harvard University, Cambridge, Massachusetts 02138.

[1] K. Kinoshita, P. B. Price, and D. Fryberger, Phys. Rev. Lett. 48, 77 (1982).

[2] The assumption of a (back-to-back) pair-production process was made in I, which had the effect of doubling the effective solid angle for the IR-10 configuration of I (there would be two particles to detect). This assumption did not affect the IR-6 configuration of I, which was symmetrically disposed about the vacuum pipe, and which presumably would detect both particles. The pair-production assumption is not made for the new data, but rather the more conservative assumption of a general (isotropic) single-particle production process. In any case, for the configuration depicted in Fig. 1 there is little practical difference between these two assumptions; the slot in the detector is only $\simeq 20\%$ of the full 2π in azimuth.

[3]The diameter of this pipe was 15.2 cm vs 5 cm in the IR-10 configuration of I. The increase in diameter reduced the amount of background generation by scattering both during injection and data collection.

[4]The majority of the background tracks were due to knock-on protons. Since these knock-on protons had very low velocity, they registered very short background tracks (more appropriately described as pits) in the plastic track detectors. (Except at the very end of the range, electrically charged particles have a response that increases as β decreases, going like Z/β.) These background tracks, being very short, would not be confused with tracks produced by a highly charged particle emanating from the interaction point.

[5]This 200 μm was comprised of 150 μm of corrugated stainless steel, which furnished the mechanical strength, and a 50-μm liner of Cu-plated stainless steel (25 μm stainless steel + 25 μm Cu) for the suppression of heating due to higher-order-mode losses from the circulating beams.

[6]The specific stack content for run 1 was two initial sheets of Lexan followed by eleven to thirteen (depending upon the specific module) sheets of CR-39. Analysis of the data from this detector indicated that the improved configuration of shielding and vacuum pipe obviated the need for the redundancy furnished by $\sim$ a dozen CR-39 sheets. Thus the stack content for run 2 was set at an initial sheet of Lexan, two sheets of CR-39, and a final sheet of Lexan. During the etching process two CR-39 sheets (from different modules) suffered damage from the stirring paddle. The redundancy furnished by the second CR-39 sheet in these modules enabled the maintenance of track sensitivity over the detector solid angle, the calculation of which is described in the text.

[7]The total PEP integrated luminosity for run 2 was recorded (in the "official" IR-12 luminosity monitor) as 157×10^{36} cm^{-2}. For the purpose of Eq. (1) this total was rounded down to 150×10^{36} cm^{-2} to account approximately for the detector insertion time plus other minor systematic effects.

[8]It is also relevant to note here that there are two recently published searches using Kapton detectors at storage-ring interaction points. A search using e^+e^- collisions at DESY PETRA [P. Musset, M. Price, and E. Lohrmann, Phys. Lett. 128B, 333 (1983)] reports an upper limit on the pair production of monopoles of 4×10^{-38} cm^2 (95% C.L.) in the range of $67e \leq g \leq 337e$ and masses up to 10–16 GeV/c^2. A search using antiproton-proton collisions at the CERN SPS collider [B. Aubert, P. Musset, M. Price, and J. P. Vialle, Phys. Lett. 120B, 465 (1983)] reports upper limits between 10^{-32} and 10^{-31} cm^2 depending upon monopole mass, which ranges as high as ~ 250 GeV/c^2. Representative plots of limits are given for monopole charges $g=g_0$ and $g=3g_0$.

[9]Estimated on dimensional grounds by the equation $\sigma_{\text{weak}} \sim (\hbar G E_B/2\pi c^3)^2$, where $G=10^{-5}/m_p{}^2$ is the universal Fermi constant. This estimate is within a factor of 2 of a calculated $\sigma(e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-)$ at $E_B=14.5$ GeV. See, e.g., C. Quigg, *Gauge Theories of the Strong, Weak, and Electromagnetic Interactions* (Benjamin/Cummings, Reading, MA, 1983), p. 126.