Search for Highly Ionizing Particles in e^+e^- Annihilations at $\sqrt{s}=50$–52 GeV

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We report the first result of a search for highly ionizing particles in e^+e^- annihilations at the KEK storage ring TRISTAN. CR-39 and UG-5 dielectric track detectors were exposed to 4.8 pb^{-1} integrated luminosity at total energies of 50–52 GeV in the center of mass. This search is sensitive to Dirac magnetic monopoles and yields 95%-confidence-level upper limits of 8×10^{-37} and 1.3×10^{-35} cm^2 on the cross section for production of monopoles with magnetic charges $g=68.5e\equiv g_D$ and $g=2g_D$ and respective maximum masses 24.1 and 22.0 GeV/c^2.

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The existence of elementary particles with large charges has been speculated ever since the demonstration by Dirac in 1931[1] that magnetic charge, quantized in units of $g_D\equiv e/2\alpha\simeq68.5e$, would explain the quantization of electric charge. Since that time our view of elementary particles and their interactions, inspired by the subsequent discoveries of many new particles, has evolved dramatically. However, no experimental evidence has been able to confirm or deny the existence of magnetic monopoles, and Dirac's original hypothesis still stands. Any search for a new particle such as the magnetic monopole, with distinctive electromagnetic coupling yet with few or no predictions about mass, strong or weak interaction coupling, or ability to bind to matter, is limited in sensitivity by assumptions about these properties which are implied in experimental parameters. These limitations are highlighted by the emergence in recent years of theories containing particles which are not readily produced or detected, through either rarity, high mass, or lack of interaction with normal matter. For example, the extremely high mass of magnetic monopoles in grand unified theories ensures that it is not only well beyond the reach of any accelerator but also rare in nature as a result of measurable gravitational effects of even a low density of such particles.[2] In addition, its complex structure may suppress production cross sections by many orders of magnitude.[3] However, a large fraction of the known elementary particles was not predicted by theory, and this underscores the importance of searching for new particles in as many different and general ways as possible. We report here on a search for heavily ionizing particles such as magnetic monopoles in e^+e^- annihilations at $\sqrt{s}=50$–52 GeV.

The data were collected with the Nikko-Maru search for highly ionizing particles in the Nikko interaction area of the TRISTAN storage ring at the National Laboratory for High Energy Physics (KEK) in Japan. Integrated luminosities of 0.8 and 4.0 pb^{-1} were delivered to the detector at total center-of-mass energies of 50 and 52 GeV, respectively. The luminosity in the Nikko area was measured with a small-angle Bhabha counter based on lead-glass calorimeters.

The detector was composed of two types of etchable track-recording solids[4] with well established response, CR-39 plastic[5] and UG-5 glass.[6] This class of detectors is characterized by high ionization thresholds and, consequently, complete insensitivity to relativistic singly charged particles. The ionization response of these materials to magnetically charged particles has been well established by suitable analogy to electrically charged particles.[7] In this accelerator environment, etchable tracks are produced mainly by slow nuclear fragments generated from spallation in the detector and surrounding material by energetic particles, primarily neutrons.[8] Although they are easily distinguished from particles with truly exotic charge and mass, an extremely high density of spallation tracks can greatly intensify the scanning process. The sensitivity to spallation recoils is controlled by the choice of a suitable combination of detector sensitivity and sheet thickness.[8] The UG-5, relatively insensitive and readily deployed in high vacuum, was formed into a stack of two 7.5×7.5-cm^2 sheets, each of 0.9-mm thickness, and placed 7 cm below the interaction point, in vacuum. The placement of this detector inside rather than outside the vacuum chamber expands significantly our capability to search for particles with short range and very high ionization, such as a Dirac monopole with charge $2g_D$, which would lose $\simeq10$ GeV of energy in the 1.5-mm-thick aluminum beam pipe. Outside the vacuum twelve flat stacks of the more sensitive CR-39 were deployed in a polyhedral configuration. Etchable track detectors are most sensitive to particles at normal incidence, and the shape was chosen to obtain high detector acceptance. This polyhedral shape covers a solid angle $\simeq 0.9\times 4\pi$ sr and is shown schematically in Fig. 1. Six of the detector faces were populated with three-sheet stacks of 680-μm-thick CR-39, designated (A), doped with 1% dioctyl phthalate plasticizer and 0.5% Naugard antioxidant. The remaining six modules consisted of four-sheet stacks of 1600-μm-thick CR-39 (B) doped with 0.5% dioctyl phthalate and 0.01% Naugard.

To minimize sources of neutrons, no shielding material was placed within 2 m of the detector area. The CR-39 detector was mounted on a moving assembly which separates the two halves of the detector away from the beam pipe and lowers them to the floor area during beam injection and tuning. In the retracted position the detector is about 4 m below the beam line, where the average flux of particles has been measured to be 2 orders of magnitude lower than in the exposure position.

In order to discriminate against spallation tracks, which are almost all of very short range, < 20 μm, a particle was required in all three materials to penetrate at least one sheet of detector. The passage of a heavily ionizing particle is manifested, upon etching, as a pair of collinear etch pits, one at each surface, which is easily matched under microscopic examination. Because the incidence angle and location of a particle trajectory may be extremely well determined, the likelihood that two short tracks will align themselves from opposite surfaces to simulate a penetrating track is negligible. The occasional spallation product which has sufficient energy to penetrate a sheet is easily identified because of a measurable change in speed. The UG-5 glass was microscopically scanned under 200× magnification to search for pairs of tracks produced by a penetrating particle. The CR-39 (A) sheets were etched until a track with average $Z/\beta > 25$ penetrating a sheet with normal incidence would produce a hole. Any holes in these sheets were then located by an ammonia scanning technique.[4] Each hole thus located was then examined microscopically and required to be consistent with a pair of conical etch pits on line intersecting the interaction point. The reconstructed trajectory of each track passing this requirement was then extrapolated to adjacent sheets, which were examined for a corresponding etch pit. Any penetrating track thus identified was then measured to identify the particle. The CR-39 (B) sheets from each stack were numbered 1–4, starting with the sheet closest to the interaction point. Odd- and even-numbered sheets were etched for long and short times, respectively. The first and third sheets from each module were then examined under a stereomicroscope at (5–50)× magnification. Penetrating tracks thus found were measured for identification. The etching conditions and scanning techniques used for the three detectors are summarized in Table I.

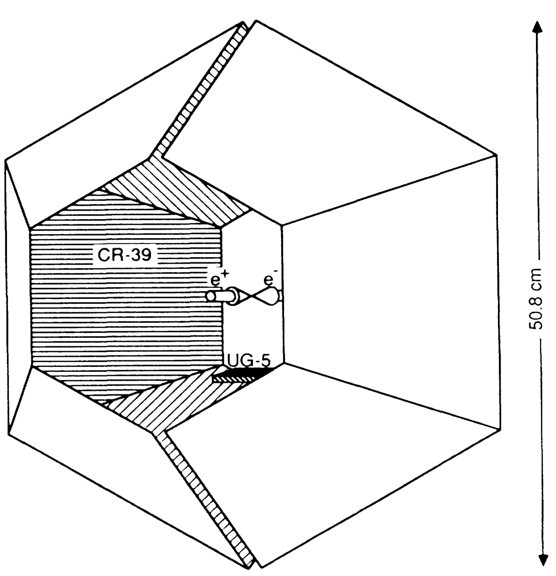

FIG. 1. Schematic representation of CR-39 and UG-5 detector configuration, showing halves of CR-39 slightly separated. The UG-5 is inside the vacuum while the CR-39 is outside.

No penetrating tracks were found in the UG-5 glass. One hole created by a track was found in the first sheet of a stack of CR-39 (A). It was produced by a particle which penetrated $\simeq 460$ μm before coming to rest and was identified as having $Z=3$ and 28 MeV/nucleon kinetic energy. No tracks passed the scanning criteria in the CR-39 (B).

The track found in CR-39 is consistent with having been produced by spallation in the beam pipe. This is reasonable, since only the most energetic hadrons produced in interactions of stray beam particles with surrounding matter ($E \gg 100$ MeV) are able to produce spallation fragments with sufficient energy to penetrate a CR-39 sheet, and, because hadrons are readily attenuated outside the vacuum, their effect is most important at the beam pipe near the interaction point. Since the detector is then compared to a nuclear interaction length, the density of fragments produced within the CR-39 detector itself can be expected to be uniform as a function of depth in the detector. The density of tracks is less than 10^2 cm^{-2} on all of the detector surfaces and is consistent with predominantly internal production. An observed enhancement of $\simeq 10$ cm^{-2} etch pits in the topmost surface of each stack can be attributed to fragments ejected from the beam pipe. Using accelerator data for spallation recoil spectra,[9] and assuming that all of the excess tracks observed at the front surface originate from spallation by high energy hadrons, we estimate that 1–10 tracks will pass scanning criteria in our detector, consistent with our observation of one.

The detector's efficiency as a function of particle charge, mass, and energy depends on the geometry of the

TABLE I. Detector parameters, sensitivity, and results for three materials. M_c and $\sigma_{\rm lim}$ are defined in the text.

	CR-39 (A)	CR-39 (B)	UG-5
Initial thickness (μm)	680	1600	900
(Solid angle)/4π	0.40[a]	0.40[a]	0.05
Etchant	6.25N NaOH	7N–8N NaOH	49% HBF_4
Etch temperature (° C)	50	73–83	70
Etch time (h)	912	30–98	100
Surface removed (μm)	213	114–1196	35
Scanning technique	Ammonia	Visual, (5–50)×	Visual, 200×
Minimum Z/β	25	≃15	≃85
$M_c c^2$ (GeV): $g=g_D, 2g_D$	24.1, 13.2	23.3, 7.3	⋯ , 22.0
$\sigma_{\rm lim}(10^{-36}\ {\rm cm}^2)$: $g=g_D$, $2g_D$	1.6, 1.6	1.6, 2.2	⋯ , 13

[a] Solid angle overlapping UG-5 has been subtracted.

detector, the sheet thickness, the response of the detector as a function of ionization rate, the scanning method used, and the beam-pipe thickness. This efficiency, determined by Monte Carlo simulation of the detector and scanning criteria for exclusive isotropic pair production of Dirac monopoles with charges g_D and $2g_D$, is approximately constant at low masses and falls rapidly as the mass approaches the beam energy. The cutoff mass M_c is defined as the mass at which the detector efficiency is half the geometric acceptance.

As we have no candidates for highly ionizing elementary particles, we can set an upper limit on the cross section for production of such particles at 95% confidence level,

$$\sigma < \frac{3}{\epsilon \int \mathcal{L}\, dt} \equiv \sigma_{\rm lim}\ (95\%\ {\rm C.L.}),$$

where $\int \mathcal{L}\, dt$ is the integrated luminosity and ϵ is the detection efficiency. Listed in the lower part of Table I are the limits established by each detector, with respective values of the cutoff mass M_c. Combining the results from the two CR-39 detectors for $g=g_D$, we find a limit of 8×10^{-37} cm^2 for most of the accessible masses. For pointlike particles the cross section for production via the electromagnetic interaction is proportional to the square of the charge. For comparison of results pertaining to different energies and particles, we therefore define R_D, the cross section for production of charge-g_D monopoles normalized to the μ-pair cross section multiplied by $(g_D/e)^2$, which has a naïve expectation value of order unity. In e^+e^- annihilations the μ pairs are produced with invariant mass equal to the center-of-mass energy,

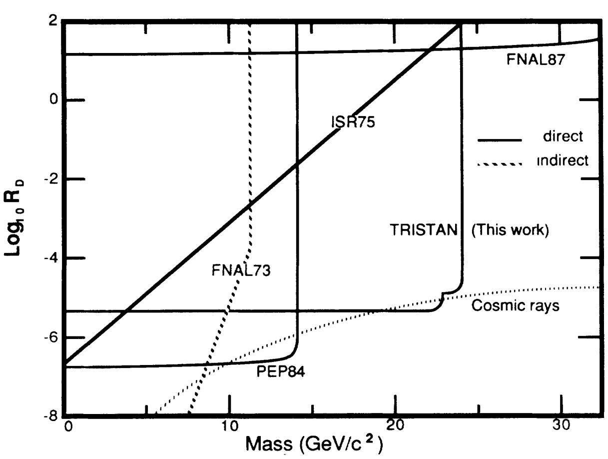

FIG. 2. Limit at 95% confidence level on the ratio $R_D \equiv \sigma_{\rm lim}(m)/\sigma_{\mu\mu}(>m)(g_D/e)^2$ for isotropic exclusive production of monopole-antimonopole pairs with charge g_D. Shown are results from this search, from the most restrictive accelerator searches (Ref. 11), and from cosmic rays (Ref. 12). By direct we refer to searches for which no assumptions are made about the particle properties except for the magnetic charge.

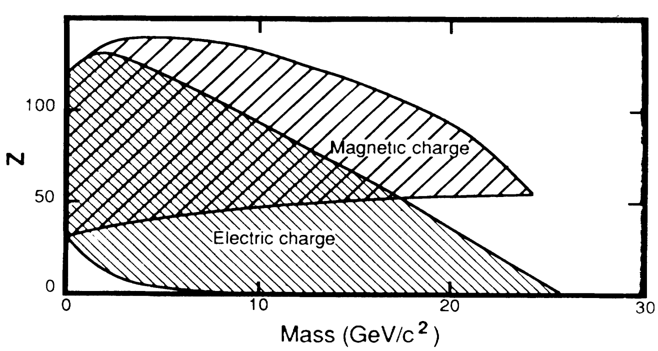

FIG. 3. Combination of mass and charge to which at least half of the CR-39 detector is sensitive. Sensitive regions are shaded and indicated separately for electrically and magnetically charges particles. The limit for this region is at most 1.6×10^{-36} cm^2 (95% C.L.).

and the cross section is well approximated by lowest-order QED. In $p\bar{p}$ collisons μ pairs are produced with a distribution of invariant mass which is obtained from data. At a given mass the normalization cross section is calculated by the integration of the measured production cross section above the threshold energy.[8] For $p\bar{p}$ collisions at $\sqrt{S}=1800$ GeV, no dimuon data are available, but, since the data at lower energies exhibit approximate scaling,[10] the cross section is estimated by extrapolation. Our limit on R_D, together with limits from other accelerator searches[11] and from cosmic rays,[12] is shown in Fig. 2. This search is classified as "direct" in that no assumptions have been made about the properties of the monopole aside from the magnitude and magnetic nature of the charge. This is the first search to explore the region $R_D < 1$, in the mass range 14.0–24.1 GeV/c^2.

This search is sensitive not only to Dirac monopoles but also to a more general class of heavily ionizing particles with $Z/\beta > 25$. In Fig. 3 we show the combinations of mass and charge to which at least half of the CR-39 detector is sensitive, for both electric and magnetic charge. The cross-section limit for these combinations is at most 1.6×10^{36} cm^2 (95% C.L.).

We have searched for heavily ionizing particles in e^+e^- collisions at energies up to 52 GeV in the center of mass. No candidates were found, and upper limits have been established on the cross section for pair production of Dirac magnetic monopoles with masses to 24.1 GeV/c^2 for charge g_D and to 22.0 GeV/c^2 for charge $2g_D$.

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