# SEARCH FOR HIGHLY IONIZING PARTICLES IN $e^+e^-$ ANNIHILATIONS AT $\sqrt{s}=50$–60.8 GeV

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Received 25 July 1989

New results are reported from a search for highly ionizing particles at the TRISTAN ring at KEK. Employing dielectric track detectors, this search is sensitive to Dirac monopoles with charge $g=68.5e\equiv g_D$ and $g=2g_D$. New upper limits are established on the production of monopoles with charge $g_D$ and mass up to 28.8 GeV/$c^2$. Cumulative results from 30.2 $pb^{-1}$ data at $\sqrt{s}=$ 50–60.8 GeV are discussed.

Within the framework of our current understanding of the elementary particles which is formalized in the standard model, no particles exist which have either electric charge greater than that of the electron or nonzero magnetic charge. Although experimental observations to date support this aspect of the model, the motivation to search for particles with unorthodox charge is significant and fundamental. As early as 1931, it was shown by Dirac [1] that the quantization of magnetic and electric charges is coupled by quantum mechanics and that the magnetic charge quantum has magnitude $g_D=e/2\alpha\sim 68.5e$. Searches for particles carrying such a charge have failed to produce any evidence for their existence. In practice the sensitivity of searches is limited by assumptions about the particle's properties which are implicit in the experimental procedure, and theories of grand unification have served to emphasize the restrictions placed by such assumptions on the scope of any given experimental search. A search for production in $e^+e^-$ annihilation is the most direct and sensitive way to search for particles with electromagnetic charge, within the kinematically allowed regions.

Employing etchable solid state track detectors [2], the Nikko–Maru Search for Highly Ionizing Particles (SHIP) was deployed during the period November 1986–March 1989 at the Nikko interaction region of the TRISTAN $e^+e^-$ storage ring at the National Laboratory for High Energy Physics (KEK) in Japan. The result from the first 4.8 $pb^{-1}$ of data at center-of-mass energies of 50–52 GeV has been published [3]. In subsequent running 25.4 $pb^{-1}$ of integrated luminosity has been accumulated at $\sqrt{s}=55$–60.8 GeV. Integrated luminosities at the different run energies for all data accumulated by Nikko–Maru are summarized in table 1. The luminosity in the Nikko area was measured using a small-angle Bhabha counter based on lead glass calorimeters. A large-angle counter, based also on lead glass and sensitive to scattering angles of 20°–50°, was used during runs III–VIII.

The ionization produced by magnetic monopoles and the response of track detectors to them is established though calculations analogous to those for electrically charged particles [4]. The ionization rate of magnetically charged particles with velocities $\beta>0.1$ is found to be approximately constant and equal to that of a minimum ionizing particle carrying electric charge of the same magnitude. For fast particles carrying greater than $\sim 0.2g_D$ magnetic charge, solid state track detectors are an effective and inexpensive method of detection.

The Nikko–Maru detector has been described in an earlier publication [3]. Briefly, twelve flat stacks of CR-39 detectors [5] deployed in a polyhedral con-

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Table 1
Integrated luminosity, geometric acceptance $\Delta\Omega/4\pi$ and cutoff masses for individual detector sectors at each run energy.

| Run | $\sqrt{s}$ | $\int \mathscr{L}\,dt$ (pb$^{-1}$) | $\Delta\Omega/4\pi$, $\mathscr{M}_1c^2$ (GeV), $\mathscr{M}_2c^2$ (GeV) | | |
|---|---|---|---|---|---|
| | | | CR-39 (A) | CR-39 (B) | UG-5 |
| I | 50 | 0.8 | 0.40[a], 23.2, 12.1 | 0.40[a], 22.0, 5.6 | 0.05, –, 21.0 |
| II | 52 | 4.0 | 0.40[a], 24.1, 13.2 | 0.40[a], 23.3, 7.3 | 0.05, –, 22.0 |
| III | 55 | 4.0 | 0.43, 25.7, 15.1 | 0.43, 24.9, 9.9 | – |
| IV | 56 | 7.5 | 0.43, 26.3, 15.7 | 0.43, 25.4, 10.6 | – |
| V | 57 | 4.7 | 0.43, 26.8, 16.4 | 0.43, 25.9, 11.3 | – |
| VI | 58 | 2.7 | 0.43, 27.6, 17.2 | 0.43, 26.7, 12.3 | – |
| VII | 60 | 3.4 | 0.43, 28.4, 18.1 | 0.43, 27.5, 13.2 | – |
| VIII | 60.8 | 3.1 | 0.43, 28.8, 18.5 | 0.43, 27.9, 13.8 | – |

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

figuration cover a solid angle $\sim 0.9\times 4\pi$ sr outside the 1.5 mm thick aluminum vacuum pipe (fig. 1). Six of the detector faces are populated with stacks of 680 μm thick CR-39, designated (A), doped with 1% dioctyl phthalate (DOP) plasticizer and 0.5% Naugard[TM] antioxidant, fabricated by American Acrylic. The remaining six modules consist of stacks of 1600 μm thick CR-39 (B) doped with 0.5% DOP and 0.01% Naugard, fabricated by Sola Optical Japan. During run IV 0.5% hexachloro butadiene (HCB) was substituted for DOP as the plasticizer in

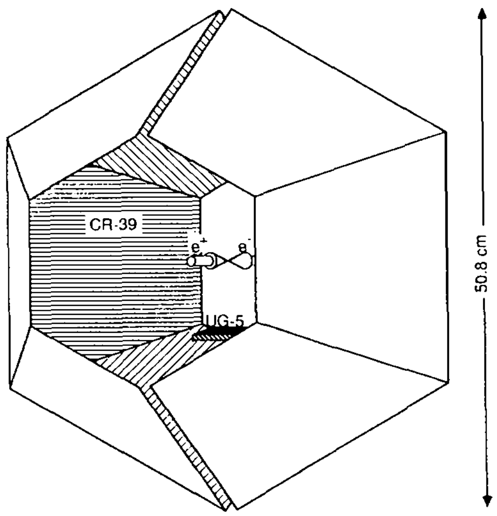


Fig. 1. Configuration of the Nikko–Maru detector, showing halves of CR-39 slightly separated. The UG-5 is inside the vacuum while the CR-39 is outside.

the CR-39(B) sheets [6]. The detector response of both plastics has been calibrated using heavy ions, the CR-39(A) at the Bevalac (Lawrence Berkeley Laboratory) [7] and the CR-39(B) at the Ring Cyclotron (Institute of Physical and Chemical Research, Japan). The polyhedral CR-39 array is 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. UG-5, a relatively insensitive detector [8], was additionally deployed inside the vacuum chamber during runs I and II. The new results reported here were collected with CR-39 detectors only.

The detector etching and scanning procedures [3] have been uniform for all runs and will be discussed only briefly here. To be considered as a candidate a particle is required to penetrate at least one detector sheet while producing high ionization. The CR-39(A) sheets were etched such that a normally incident penetrating track with average $Z/\beta > 21$ would produce a hole. Holes in the etched sheets were located by an ammonia scanning technique [2] and each hole thus located was examined microscopically and required to be consistent with a penetrating track originating at the interaction point. The region of the extrapolated trajectory in each adjacent sheet was then examined for a corresponding etchpit. Any penetrating track found in this way was measured to identify the particle. In the CR-39(B) stacks alternating sheets were etched for long and short times, and the more heavily etched sheets examined under a stereomicroscope at 5–50X magnification. Any penetrating track with $Z/\beta > 15$ located in this way was measured for identification [9]. Fig. 2 shows the combination of charge and mass for which the efficiency is finite.

The principal source of tracks in the CR-39 is spallation products from high-energy collisions of hadrons, particularly neutrons, with the beam pipe [10]. The ionization requirement enables the identification and rejection of the small fraction of the spallation products which do penetrate a sheet. Rates for such particles were established in runs I and II and found to present no background for this search. In the CR-39(A) exposed during runs III–VIII, five holes were observed to pass the first step of the scanning, and each was identified as having been produced by a Li ion. For each of the five the locations of the extrapolated trajectory in adjacent sheets were examined for corresponding etchpits. None were found. There were thus no tracks which passed our scanning criteria. No penetrating tracks were found in any of the CR-39(B) sheets.

Since there are no candidates for highly ionizing elementary particles, we may set an upper limit on the cross section for production of such particles at 95% confidence level:

$$\sigma < \frac{3.0}{\epsilon \int \mathscr{L}\, dt} \equiv \sigma_{\rm lim} \quad (95\%\ \mathrm{CL}) ,$$

where $\int \mathscr{L}\, dt$ is the integrated luminosity. The detection efficiency $\epsilon$ is a function of particle charge, mass and energy and depends on the geometry of the detector, the sheet thickness, the response of the detector as a function of ionization rate, the scanning method used and the beam pipe thickness. A particle satisfying the ionization criterion is detected with efficiency $\approx 1$ if it has sufficient energy to penetrate the beam pipe plus two sheets of detector material. Where the efficiency is equal to the geometric acceptance of 0.86, $\sigma_{\rm lim}$ established using all of the Nikko data is $1 \times 10^{-37}$ cm$^2$. The overall efficiency for a particle of a given mass depends on the energy spectrum of the produced particles. In the absence of specific models of production, we calculate efficiencies and limits as a function of mass for isotropic, exclusive pair production of Dirac monopoles with charge $g_{\rm D}$ and $2g_{\rm D}$. The efficiency is calculated via Monte Carlo simulation as a function of mass and run energy. The cutoff mass $\mathscr{M}_n$ is defined as the mass at which the detector efficiency is half the maximum geometric acceptance, for monopoles with charge $ng_{\rm D}$. The total exposure, geometric acceptance and cutoff masses $\mathscr{M}_1 c^2$ and $\mathscr{M}_2 c^2$ for each detector sector are compiled in table 1. 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.

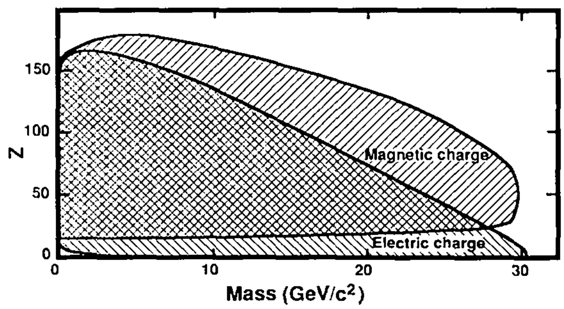


Fig. 2. Mass–charge combinations to which CR-39 detector has finite sensitivity. Regions sensitive to electric and magnetic charges are indicated separately.

The significance of the limit is dependent on the physical process by which the particle is presumed to be produced. For Dirac monopoles the most obvious mechanism is annihilation and pair production via the electromagnetic interaction. If one assumes a single-photon production process, then the amplitude for pair production is proportional to the magnetic charge. Ignoring higher order effects, one can then formulate a naïve pair production cross section for monopoles of mass $m$, $\sigma_{\rm D}(m)$, by multiplying the cross section for production of a $\mu^+\mu^-$ pair with invariant mass greater than $2m$ by the square of the charge ratio and a phase space correction: $\sigma_{\rm D}(m) = (g_{\rm D}/e)^2 \times \sigma_{\mu\mu}(>2m) \times (1-4m^2/s)$. The phase space term has not been included in previous reports. The quantity $R_{\rm D} = \sigma(m)/\sigma_{\rm D}(m)$ would then be expected to be of order unity for pointlike Dirac monopoles with magnetic charge $g_{\rm D}$ (and $\sim 4$, for charge $2g_{\rm D}$), at energies above threshold. In $e^+e^-$ annihilations the $\mu$ pair cross section is well approximated by lowest order QED, where they are produced with invariant mass equal to the center of mass energy. In pp of p$\bar{\rm p}$ collisions $\mu$ pairs are produced with a distribution of invariant mass which is well measured for pp up to $\sqrt{s} = 60$ GeV and may be extrapolated to higher energies by scaling [11,12]. Our limit on $R_{\rm D}$, accumulated over all runs, is shown in fig. 3 with the most stringent limits from previous searches [3,13,12,14]. From this analysis we conclude that pointlike Dirac monopoles with mass below 28.8 GeV/$c^2$ are ruled out.

For monopoles with nonpointlike structure the production cross section may be suppressed by many orders of magnitude by form factor effects [15]. This does not a priori rule out the possibility that a weaker interaction to which the monopole couples in a pointlike manner could then dominate the production process. If this process occurs via fermion–antifermion annihilation to a neutral vector or scalar gauge boson with mass $M_B$, and its strength is of the order of that for the electroweak force, the cross section $\sigma_B$ scales with the μ pair cross section: $\sigma_B \sim \sigma_{\mu\mu}(>2m) \times (1-4m^2/s) \times s/(s-M_B^2)$, and our null result implies a lower limit on the mass scale of such an interaction. Fig. 4 shows this limit as a function of monopole mass.

To summarize, the Nikko-Maru search has found no evidence for heavily ionizing particles in $e^+e^-$ collisions at energies up to 60.8 GeV in the center of mass. New upper limits have been established on the cross section for pair production of charge $g_D$ Dirac magnetic monopoles with masses to 28.8 GeV/$c^2$. This result may be interpreted as placing a lower limit on the possible mass scales of production mechanisms.

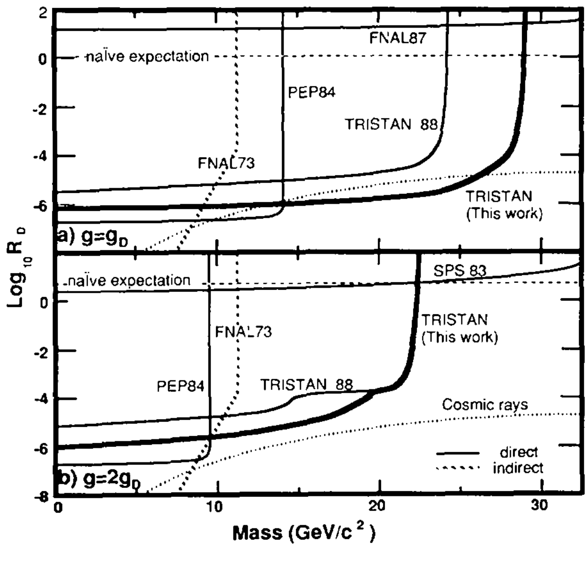


Fig. 3. Upper limit at 95% confidence on $R_D \equiv \sigma(m)/\sigma_D(m)$ for isotropic exclusive production of monopole pairs with charge (a) $g_D$ and (b) $2g_D$. The thick line indicates our limit accumulated using all exposures. Both TRISTAN results shown include a phase space correction, as described in the text. Selected limits shown from previous accelerator searches [13] and from cosmic rays [14] have not been adjusted for phase space.

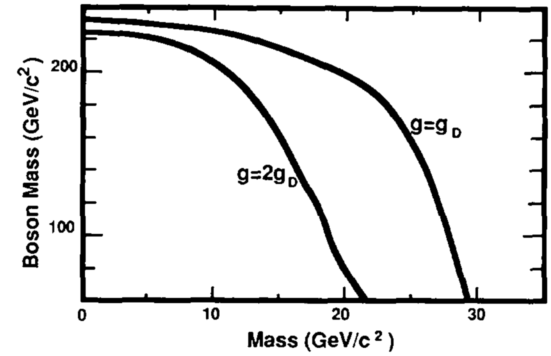


Fig. 4. Lower limit (95% confidence) on mass scale for monopole pair production processes, assuming that the coupling constant is equal to α, as described in the text.

We would like to thank the TRISTAN staff, whose efforts have made this work possible. This work has been supported in part by KEK, the US National Science Foundation grants PHY8512876 and PHY8702763, Research Corporation and the Mary Ingraham Bunting Institute. We would also like to thank P. Mauskopf, H. Saito and M. Solarz for assistance.

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