Results from Nikko-Maru

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Abstract

At the Nikko area of the TRISTAN storage ring the Search for Highly Ionizing Particles (SHIP) Nikko-Maru employs etchable solid state track detectors to search for heavily ionizing particles produced in the e^+e^- annihilations. New results are reported from exposures to 13.9 pb^{-1} integrated luminosity at $\sqrt{s}$=57-60.8 GeV. New upper limits are established on the production of Dirac monopoles with mass up to 28.8 GeV/c^2.

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 $g_D \equiv \frac{e}{2\alpha} \sim 68.5e$. 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) has been deployed since 1986 at the Nikko interaction region of the TRISTAN e^+e^- storage ring at KEK in Japan. The results from the first two years of running, at center-of-mass energies of 50–56 GeV, have been reported previously.[3] We report here results from the past year of running, at $\sqrt{s}$=57–60.8 GeV.

The ionization deposited by magnetic monoples and the response of track detectors to them is established through calculations analogous to those for electrically charged particles.[4] The ionization rate of monopoles with velocities $\beta > 0.1$ is found to be approximately equal to that of a relativistic particle carrying electric charge of the same magnitude and is approximately constant as a function of velocity. 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] are deployed in a polyhedral configuration covering a solid angle $\sim 0.9 \times 4\pi$ sr outside the 1.5 mm thick aluminum vacuum pipe (Figure 1). Six of the detector faces are populated with stacks of

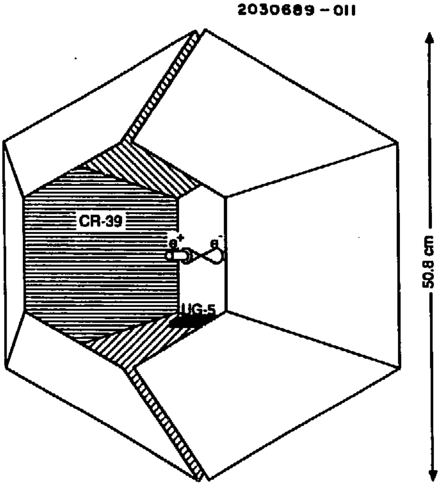

Figure 1. Configuration of Nikko-Maru detector, showing halves of CR-39 slightly separated. The UG-5 is inside the vacuum while the CR-39 is outside.

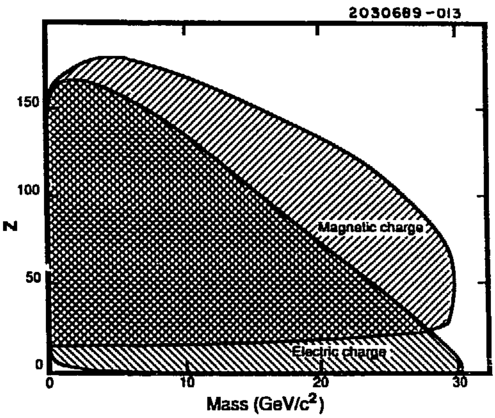

Figure 2. Mass-charge combinations to which CR-39 detector has finite sensitivity. Regions sensitive to electric and magnetic charges are indicated separately.

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) fabricated by Sola Optical 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,[6] was also deployed during early runs. The new results reported here were collected with CR-39 detectors only.

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. The detectors from all exposures have been etched and scanned. The etching and scanning procedures[3] have been uniform for all runs. The principal source of tracks in the CR-39 is spallation products from high-energy collisions of hadrons, particularly neutrons, with the beam pipe. To be considered as a candidate a particle is required to penetrate at least one detector sheet while producing high ionization. For particles with electric charge $Z|e|$ the requirement is $Z/\beta > 21$ in CR-39 (A) and $Z/\beta > 15$ in CR-39 (B) sheets. Figure 2 shows the combinations of charge and mass for which the efficiency may be finite. The ionization requirement enables the identification and rejection of the few spallation products which do penetrate a sheet. Rates were established in runs I–II and found to present no background for this search. No tracks passed the scanning criteria in any of the detectors exposed in runs V–VIII.

Run	$\sqrt{s}$	$\int \mathcal{L}dt(\text{pb}^{-1})$	$\frac{\Delta\Omega}{4\pi}$, $\mathcal{M}_1c^2$(GeV), $\mathcal{M}_2c^2$(GeV)		
			CR-39 (A)	CR-39 (B)	UG-5
I	50	0.8	0.40,* 23.2, 12.1	0.40,* 22.0, 5.6	0.05, –, 21.0
II	52	4.0	0.40,* 24.1, 13.2	0.40,* 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	–

*Solid angle overlapping UG-5 has been subtracted.

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

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:

$$\sigma < \frac{3.0}{\epsilon \int \mathcal{L}dt} \equiv \sigma_{lim} \qquad (95\%CL)$$

where $\int \mathcal{L}dt$ is the integrated luminosity. The detection efficiency ϵ 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 highly ionizing particle is detected with efficiency ≈ 1 if it has sufficient energy to penetrate the beam pipe plus enough detector material to satisfy the scanning criterion. Where the efficiency is equal to the geometric acceptance of 0.86, σ_{lim} established using all of the Nikko data is 1×10^{-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_D and $2g_D$. The efficiency is calculated via Monte Carlo simulation as a function of mass and run energy. The cutoff mass $\mathcal{M}_n$ is defined as the mass at which the detector efficiency is half the maximum geometric acceptance, for monopoles with charge ng_D. The total exposure, geometric acceptance and cutoff masses $\mathcal{M}_1c^2$ and$\mathcal{M}_2c^2$ for each detector sector are compiled in Table 1.

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

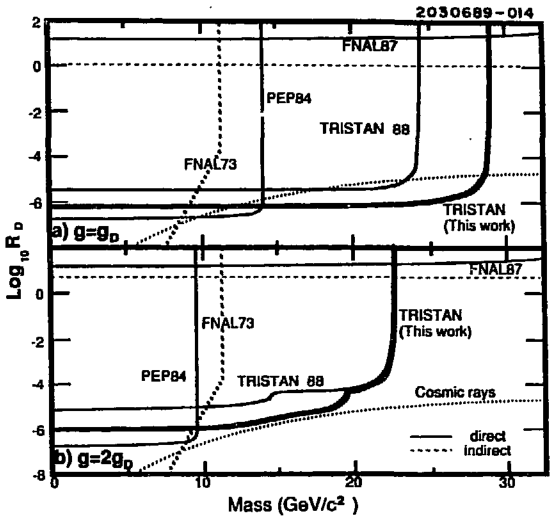

Figure 3. Limit at 95% confidence on $R_D \equiv \frac{\sigma(m)}{\sigma_D(m)}$ for isotropic exclusive production of monopole pairs with charge a) g_D and b) $2g_D$. The limit shown has been accumulated using all exposures at TRISTAN. The dashed lines indicate the naïve expectation. Also shown are selected limits from previous accelerator searches[3),8)] and from cosmic rays.[9)]

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 and details of phase space, one can then formulate a naïve pair production cross section for monopoles of mass m, $\sigma_D(m)$, 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: $\sigma_D(m) = (\frac{g_D}{e})^2 \cdot \sigma_{\mu\mu}(> 2m)$. The quantity $R_D \equiv \frac{\sigma(m)}{\sigma_D(m)}$ would then be expected to be of order unity for pointlike Dirac monopoles with magnetic charge g_D (and ~ 4, for charge $2g_D$), at energies above threshold. In e^+e^- annihilations the μ 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 or $p\bar{p}$ collisions μ 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.[7)] Our limit on R_D, accumulated over all runs, is shown in Figure 3 with the most stringent limits from previous searches.[3),8),9)] 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.

To summarize, the Nikko-Maru search has found no evidence for heavily ionizing particles in e^+e^- collisions at energies up to 50.8 GeV in the center of mass. 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.

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REFERENCES

[1] P.A.M. Dirac, Proc. Roy. Soc. London **133**, 60 (1931).

[2] R.L. Fleischer, P.B. Price and R.M. Walker, *Nuclear Tracks in Solids* (University of California Press, Berkeley, 1975).

[3] K. Kinoshita, M. Fujii, K. Nakajima, P.B. Price and S. Tasaka, Phys. Rev. Lett. **60**, 1610 (1988); K. Kinoshita, *Proc. XXIV Int. Conf. on High Energy Physics*, R. Kotthaus and J. Kühn, eds., in press.

[4] S.P. Ahlen, Phys. Rev. **D17**, 229 (1978).

[5] B.G. Cartwright, E.K. Shirk and P.B. Price, Nucl. Instr. Meth. **153**,457 (1978).

[6] P.B. Price, L.M. Cook and A. Marker, Nature **325**, 137 (1987).

[7] A.L.S. Angelis et al., Phys. Lett. **B87**, 398 (1979).

[8] R.A. Carrigan, Jr., F.A. Nezrick and B.P. Strauss, Phys. Rev. **D8**, 3717 (1973); D. Fryberger, T. Coan, K. Kinoshita and P.B. Price, Phys. Rev. **D29**, 1524 (1984); P.B.Price, Ren Guoxiao and K. Kinoshita, Phys. Rev. Lett. **59**, 2523 (1987).

[9] R.R. Ross, P.H. Eberhard, L.W. Alvarez and R.D. Watt, Phys. Rev. **D8**, 698 (1973).