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Search for magnetically charged particles produced in e^+e^- annihilations at $\sqrt{s}=10.6$ GeV

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Energetic particles carrying magnetic charge can be identified by their trajectory in a magnetic field. We report here the first application of this property to a search in e^+e^- annihilations. By tracking the paths of particles in the CLEO magnetic spectrometer at the Cornell Electron Storage Ring we place upper limits on the production of magnetically charged particles with mass $m<5$ GeV/c^2.

Interest in the existence of magnetic charge arises from the possibility of symmetrizing Maxwell's equations. In 1931, Dirac advanced theoretical arguments which demonstrated that the existence of magnetic monopoles would explain simply the observed quantization of electric charge.[1] The Dirac quantization condition for a magnetic charge (g) is $ge = n\hbar c/2$, where n is an integer. Setting $n=1$ and using the fine-structure constant, $e^2/\hbar_c = \frac{1}{137}$, defines the Dirac charge, which has a magnitude $g/e = 68.5$.

The numerous experiments which have searched for Dirac monopoles using accelerators can be broadly classified as "direct" and "indirect" experiments. Direct experiments[2] aim to detect monopoles immediately after production, before they come to rest, the experimental signature relying only on the magnetic charge or its large magnitude. Indirect searches[3] assume monopoles have stopped and have subsequently been bound in a target material. After exposure, the material is examined for evidence of magnetic charge. Most searches have been sensitive only to a large magnetic charge; no direct experiment has been sensitive to charges $g < 30e$.

We report here a new direct method to search for the production of light monopoles and dyons[4] by identifying trajectories with nonzero acceleration along magnetic-field lines. The data were collected using the CLEO detector at the Cornell Electron Storage Ring (CESR). We have looked for the process $e^+e^- \rightarrow M\overline{M}$, where M may carry electric as well as magnetic charge. This search was conducted using 25 pb^{-1} of data taken in the region of the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.6$ GeV). Results from a search for purely magnetically charged particles using 159 pb^{-1} of data are also reported.

The CLEO detector has been described in detail elsewhere.[5] For this analysis the most important components are the vertex detector and central drift chamber, which are inside a superconducting solenoid that provides a uniform longitudinal 1-T magnetic field. For a charged track, a maximum of ten measurements of position $\hat{\mathbf{z}}$ along the direction of the magnetic field is available. The information is provided by cathode strips ($\sigma \approx 600$ μm) on the inside and outside layers of the vertex detector and by eight layers of stereo wires ($\sigma \approx 3$ mm) in the drift chamber. Outside the magnet coil are time-of-flight (TOF) scintillators. The trigger demanded one hit in each of two TOF counters.

The trajectory of electrically charged particles in a uniform magnetic field ($\mathbf{B} = B\hat{\mathbf{z}}$) may be parametrized by $z = a_0 + a_1 s$, where s is the length of the projection of the trajectory in the plane perpendicular to $\hat{\mathbf{z}}$, and z is the projection on $\hat{\mathbf{z}}$. For a magnetically charged particle there is a constant force along the direction of the magnetic field, so the orbit will be better parametrized by $z = a_0 + a_1 s + a_2 s^2$. We have attempted to identify monopole candidates by searching for events in which the fit to the quadratic form is significantly better than the fit to the linear form. To quantify the difference between a linear (electrical charge) and a quadratic (magnetic charge) hypothesis we evaluate the standard statistical quantity F (Ref. 6), which is defined for a set of N hits to be

$$F = \frac{\chi_L{}^2 - \chi_Q{}^2}{\chi_Q{}^2/(N-3)} ,$$

where $\chi_L{}^2$ and $\chi_Q{}^2$ are the χ^2's of a linear and quadratic fit, respectively. A high value of F corresponds to a low probability that a track has a linear path in (s,z). Magnetically charged particles usually have large values of F, while those of electrically charged particles are small. The value of F is not itself sufficient to determine the significance of the deviation of a track from a linear hypothesis. It is also necessary to require that the $\chi_L{}^2$ be large, i.e., that the hypothesis that the track fits a straight line yields a poor fit.

The following procedure was used to search the exclusive production of monopole-antimonopole pairs. To remove events with high track multiplicity, only events containing four or fewer charged tracks, as found by the standard CLEO track-finding algorithm, were retained for further analysis. This track-multiplicity requirement was determined by maximizing the efficiency of selecting $e^+e^- \rightarrow M\overline{M}$ events generated by Monte Carlo simulation using the standard tracking algorithm. A modified version of this algorithm capable of reconstructing tracks with curvature in the plane containing the magnetic field was then used to select events with exactly two tracks, each with at least six measurements of z. The fitting parameters could then be used to calculate the value of F associated with each track (F_1, F_2 are chosen so that $F_1 > F_2$). The fits of both tracks to straight lines were required to be poor: $\chi_L{}^2/\mathrm{DF} > 12$.

To select events consistent with the production of a pair

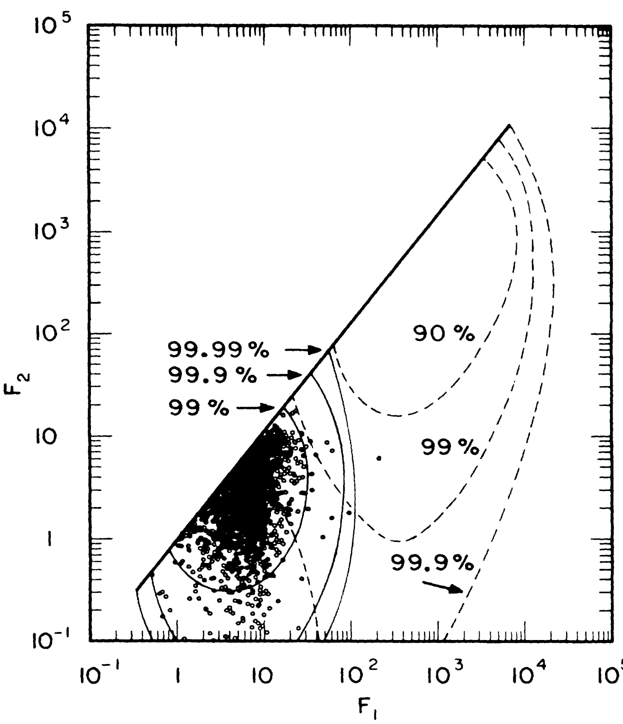

FIG. 1. Monte Carlo F_1 vs F_2 distributions. The contours bound the area containing the given percentage of generated events, for Bhabha events (solid lines) and particles with no electric charge and magnetic charge $g = 8e$, $m = 3$ GeV/c^2 (dashed lines). Superimposed on this plot is the distribution of F_1, F_2 from our data.

of magnetically charged particles, and to remove cosmic-ray and beam-gas events, the following cuts were applied. The time difference Δt between the triggering hits in the TOF counters was required to be $\Delta t < 5$ ns, i.e., less than the time $\Delta t \approx 16$ ns required for a cosmic ray to traverse the distance between azimuthally opposite TOF scintillators. We also demanded that the reconstructed vertex of the event be within 0.6 cm of the average beam position in the transverse plane and within 5 cm along the beam direction. To be consistent with the hypothesis of pair production we required that the angle (θ) between the particles at the vertex satisfy $\cos\theta < 0.0$. Events in which the two tracks had values of a_2 with opposite sign (hence opposite acceleration along the magnetic-field direction) were kept as candidate events.

The efficiency for these cuts was calculated using a Monte Carlo simulation of the passage of magnetically charged particles through our detector.[7,8] The distributions of F_1,F_2 for Monte Carlo Bhabha events and Monte Carlo events with magnetic charge $g=8e$ and electric charge $q=0$ are shown in Fig. 1. The Monte Carlo data are represented by density contours labeled with the percentage of simulated events contained within. The mean values of F rise as a function of the magnetic charge.

On the basis of these simulations we selected events as monopole candidates if the F values of the two tracks satisfied $F_1 > 100$ and $F_2 > 10$. The data are shown as points in Fig. 1. No events compatible with the production of magnetic charge were found.

Upper limits for the electromagnetic production of monopoles may be computed using the detection efficiencies estimated by Monte Carlo simulation.[9] This efficiency, as a function of mass and magnetic charge for particles with zero electric charge, is shown in Fig. 2. The two most important factors are the F_1,F_2 cut efficiency and the trigger efficiency. Because of energy lost by ionization in traversing about 30 g cm^{-2} of material prior to the TOF, the trigger requirement limits our acceptance to $g < 10e$. The uncertainty in the maximum charge observable due to the calculation of the energy loss is about 5%. Without the TOF requirement (a possibility for future runs) our acceptance would extend to $g=70e$. The ratio of efficiencies $\varepsilon(g,q,m)/\varepsilon(g,0,m)$ for the detection of dyons relative to the detection of monopoles is shown in Fig. 3 for the magnetic charges $g=(2e,5e,8e)$ as a function of mass m and electric charge q.

Using these efficiencies, the upper limits at 90% confidence level are derived for the production of magnetically charged particles as a function of mass and charge. Upper limits as a function of mass for magnetic monopoles with

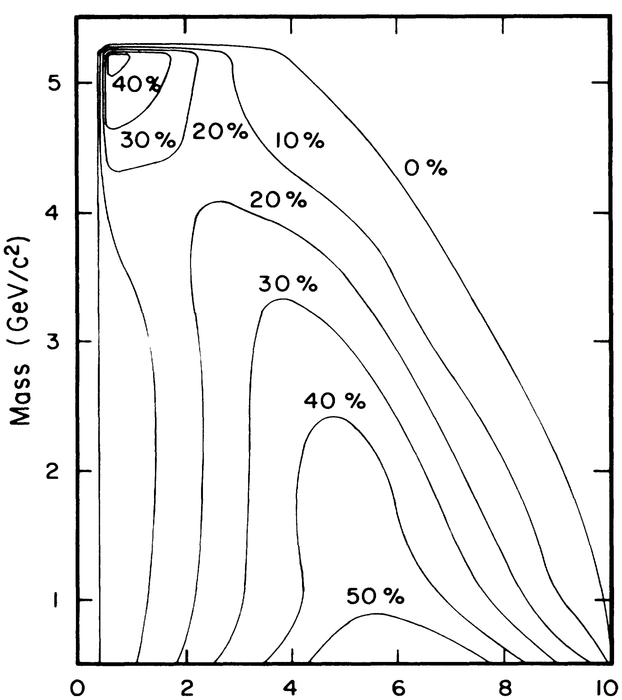

FIG. 2. Efficiency of reconstructing monopole candidates (zero electric charge) from a Monte Carlo study with the TOF trigger.

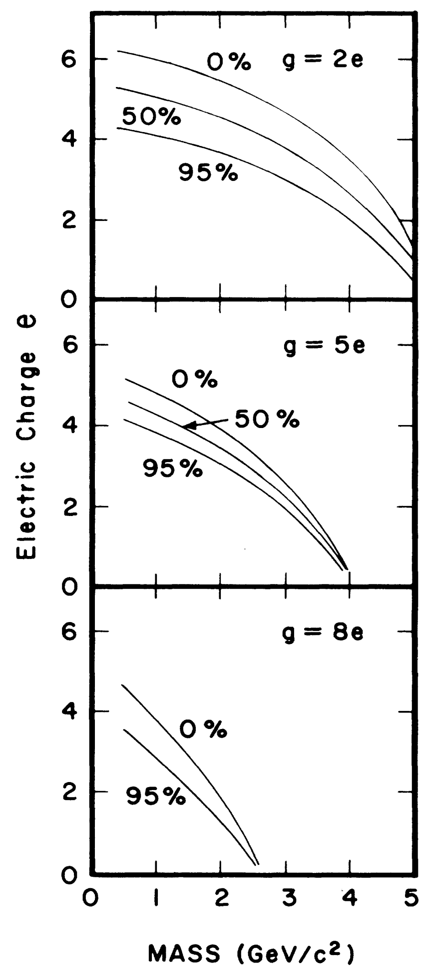

FIG. 3. Efficiency of dyon detection relative to monopole detection for magnetic charges $g=2e,5e,8e$ as a function of electric charge and mass.

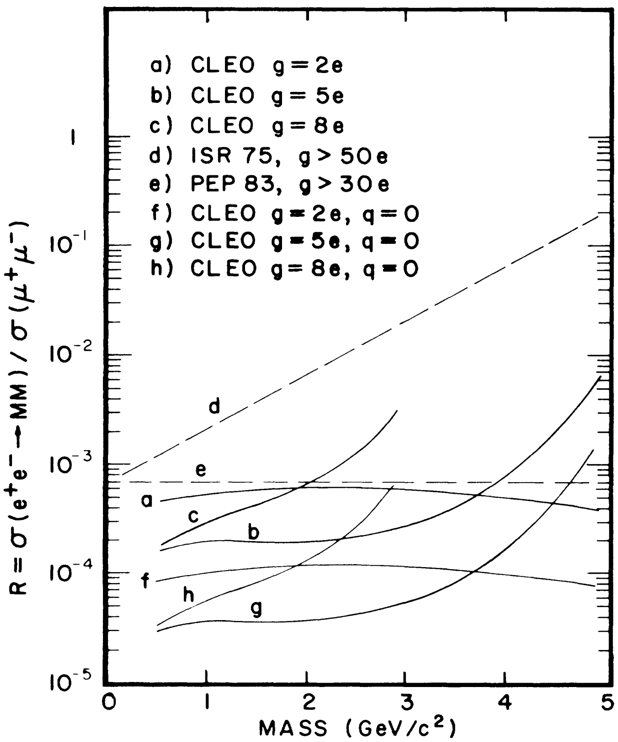

FIG. 4. Upper limits on monopole production from CLEO compared with results from ISR and PEP (d and e). Results from 25 pb^{-1} data (a–c) may be used to derive upper limits on dyon production. Also shown are upper limits on monopole production from 159 pb^{-1} data (f–h).

charge ($2e$,$5e$,$8e$) as well as those from two searches[2] performed at the ISR (CERN) and PEP (SLAC) are shown in Fig. 4. The limits are shown relative to the dimuon production rate. Limits for dyons with the same magnetic charges may be inferred using Fig. 3.

In addition to the analysis presented above, 159 pb^{-1} of data taken at the $\Upsilon(1S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ resonances were combined and used to look for purely magnetically charged particles. The procedure was identical to that described above except that the events were selected for analysis only if they contained exactly two tracks, each with more than 7 GeV/c momentum. This utilizes the fact that the trajectory of an ionizing particle with zero electric charge would have no curvature in the plane transverse to the magnetic field and would therefore appear as an infinite momentum track. No events at any value of F_1,F_2 were found. The upper limits are also shown in Fig. 4.

In summary, we have used a new technique to set limits on the direct production of magnetic charge for values of $g < 10e$ and masses less than 4 GeV/c^2. No previous limits from direct measurements exist in this range of magnetic charge and mass.

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