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Search for highly ionizing particles in e^+e^- annihilations at $\sqrt{s}=91.1$ GeV

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We report the first result from a search for highly ionizing particles at the LEP e^+e^- storage ring at CERN. Based on CR-39 plastic track detectors, this search is sensitive to Dirac monopoles with magnetic charges in the range $0.1g_D<g<3.6g_D$, where $68.5e\equiv g_D$. New upper limits are established on the production of monopoles with charge g_D and mass up to 44.9 GeV/c^2.

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As a counterpart to the electric charge, magnetic charge fits naturally into our understanding of the electromagnetic force, completing the symmetry between the electric and magnetic fields observed in the Maxwell equations. More importantly, it was shown by Dirac in 1931 [1] that the quantization of magnetic and electric charges is coupled by quantum mechanics and that the magnetic charge quantum has a large magnitude, $|g_D|\equiv|e|/2\alpha\sim68.5|e|$. Thus far no experimental evidence has been able to confirm or deny the existence of magnetic monopoles [2]. In practice, however, the experimental sensitivity, particularly with regard to searches in bulk matter, has been limited by assumptions about properties such as mass and interaction couplings which are implicit in the procedure. In spite of the recent popularity of models which predict high mass, the charge of the magnetic monopole remains its only property which is fundamental and model independent. Searching in accelerators is the only way in which the existence and properties of monopoles (within kinematically allowed mass regions) can be investigated in a systematic way.

In addition to magnetic monopoles there are several hypothetical particles, both elementary [3] and composite [4], possessing large ($Z>20e$) electric or magnetic charge. The masses of most of these are not predicted, and there is no experimental evidence for the existence of any particles with such exotic charge.

The LEP storage ring at CERN currently provides the highest energy e^+e^- collisions and is the most sensitive probe for new particles in the region $m<45$ GeV/c^2. We report here the first result from a search for Dirac monopoles and other highly ionizing particles at LEP.

The ionization energy loss of magnetic monopoles with magnetic charge g and $\beta>0.1$, where βc is the velocity, is well established through calculations analogous to those for electrically charged particles [5]. It is found to be equivalent to that of a particle with electric charge $g\beta$. The energy loss dE/dx is thus nearly constant as a function of velocity, unlike that of an electrically charged par-

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ticle, where dE/dx is roughly proportional to β^{-2}. The ionization changes substantially only at very low velocity, $\beta < 10^{-2}$. A magnetically charged particle is thus characterized by constant ionization as a function of depth of penetration, with no rise near the end of range. It is due to the extraordinarily large charge of the Dirac monopole that its ionization is high (~ 10 GeV/g cm^{-2}).

A massive, stable, highly ionizing particle produced in a beam collision is likely to have a short range due to the combination of high ionization and relatively low kinetic energy. In order to maximize the sensitivity of a detector to such particles, it is desirable to form a multilayer tracking configuration, minimizing the material thickness of each layer, < 0.1 g cm^{-2}, so that the ionization pattern may be followed as a function of depth to the end of range. A simple system composed of track-etch detectors [6] can satisfy all of these criteria both reliably and inexpensively and is used here to detect the heavy ionization produced by Dirac monopoles and other highly charged exotics.

The monopole detector at LEP (MODAL) uses CR-39 plastic track detectors [7] in a configuration (similar to that of a previous experiment [8]) of twelve flat stacks of plastic sheets covering a solid angle $\sim 0.86 \times 4\pi$ sr surrounding the I5 interaction point at LEP. This polyhedral array is supported by a frame which is mounted on a fixed stand. The vacuum pipe at the I5 region is thin, 0.5-mm aluminum, with 0.5-mm × 6.5-mm ribs at 5.0-cm intervals for mechanical stability.

MODAL was deployed during two exposure periods: June–October 1990 and April–October 1991, which we designate (I) and (II), respectively. The run energy during this time was $\sqrt{s} = 89$–93 GeV. In the I5 region the beams are normally separated electrostatically, and luminosity was accumulated for this experiment by turning off the separators for approximately the last two hours of each beam fill. The integrated luminosity of 60 ± 12 nb^{-1}, accumulated mainly at $\sqrt{s} = 91.1$ GeV, was evaluated from accelerator run parameters and was divided nearly equally between the two runs.

The twelve detector faces were filled with several types of CR-39. One of them, which will be referred to as CR-39 (A), was of 720 μm average thickness, made by American Acrylic and doped with 1% DOP (dioctyl phthalate) plasticizer and 0.5% Naugard® antioxidant. Another (B), of 1500 μm thickness, was fabricated by Intercast Co. (Parma, Italy) with 1% DOP. A third (C), of 730 μm average thickness, was fabricated by Track Analysis Systems Limited (Bristol, UK) with 0.3% DOS [sebacic acid di(2-ethylhexyl) ester]. The detector response of all three plastics has been calibrated using heavy ions at the Bevalac (Lawrence Berkeley Laboratory) [9]. The composition of the modules used in the two runs is summarized in Table I. The use of detectors with different combinations of sensitivity and thickness enables the experiment to be sensitive to a larger range of mass and charge than can be covered with any single detector [10].

TABLE I. Detector composition and exposures.

Run	I		II	
$\int \mathcal{L}\,dt$ (nb^{-1})	30±6		30±6	
Module type	I.1	I.2	II.1	II.2
CR-39 type	*A*	*B*	*C*	*B*
Initial sheet thickness (μm)	720	1500	730	1500
No. of modules	3	9	6	6

In each exposed module the two front sheets, closest to the interaction point, were analyzed. Several different procedures were used to search for monopole candidates. In all cases at least one of the two front sheets, the "scan sheet," was etched heavily and scanned rapidly, while the others were examined only if a track passed the scanning criteria. To enable rapid scanning a sheet was etched so that a normally incident penetrating track with average Z/β (where Z is the charge in units of $|e|$) exceeding a threshold $(Z/\beta)_{\text{thr}}$ would produce a hole. Holes were located by one of two methods: an ammonia technique [11] or by microscopic inspection at low magnification (16×). Each hole was visually inspected to verify it as an ionization track rather than a flaw. The diameter of each of the tracks was measured to check that it was consistent with being of external origin, rather than originating within the sheet itself. The region of the extrapolated trajectory in the adjacent sheet, the second or the first, was then examined for a corresponding etchpit. Any penetrating track found in this way was measured to identify the particle.

A total of 28 holes corresponding to ionization tracks were found in the scanned sheets. Seventeen of these were consistent with penetrating tracks, and the adjacent sheets were inspected. None were found to continue into adjacent sheets. The etching conditions, scanning thresholds and results are summarized in Table II.

A particle satisfying the ionization criterion is detected if it falls within the geometric acceptance and has sufficient energy to penetrate all material in front of and including the detector scanned. The overall efficiency ϵ is therefore 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. In the absence of specific models which give angular and energy distributions, we calculate efficiencies and limits for isotropic, exclusive pair production of Dirac monopoles with charge g_D and $2g_D$. The efficiency is obtained via Monte Carlo simulation as a function of mass and run energy. The simulation accounts for geometric acceptance, energy losses in the beam pipe and detector, and etching and scanning criteria. Figure 1 shows the combinations of charge (both magnetic and electric) and mass for which the efficiency is finite. The cutoff mass $\mathcal{M}_n$ is defined as the mass at which the detector efficiency is greater than 10%, for monopoles with charge ng_D. The acceptance and cutoff mass for each detector sector are compiled for $n = 1, 2$ in Table II. Note that in this search no assumptions have been made about the properties of the monopole aside from the magnitude and magnetic nature of the charge. Although the sensitivity of track detectors to very slow magnetic monopoles ($\beta \ll 10^{-2}$) is not assured [12], this

TABLE II. Detector parameters, sensitivity, and results. Where there are two entries X/Y the first pertains to the scanned sheet and the second to the other sheet. $\mathcal{M}_n$ is defined in the text.

Module type	I.1	I.2	II.1	I.2	II.2
No. of modules	3	3	6	6	6
NaOH concentration	6.25N			8N/6N	
Etch temperature (°C)	50			80/70	
Etch time (h)	1080	1980	890	150/45	
Surface removed (μm)	270	560	290	650/50	
Scanning technique	Ammonia			Visual	
Z/β_{thr}	20	10	7	10	10
Scanned sheet No.	2	2	1,2	1	1
No. of holes (tracks)	10	1	13	3	1
No. of penetrating tracks	0	1	12	3	1
$\mathcal{M}_1$ (GeV/c^2)	44.9	43.8	44.9	43.8	
$\mathcal{M}_2$ (GeV/c^2)	39.3	32.9	39.2	32.9	

experiment does not depend on the details of energy loss at low velocities.

As there are no candidates for highly ionizing elementary particles, the upper limit on the cross section for production of such particles at 95% confidence level is

$$\sigma < \frac{3.0}{\epsilon \int \mathcal{L}\, dt} \equiv \sigma_{\text{lim}} \quad (95\%\ \text{C.L.}) ,$$

where $\int \mathcal{L}\, dt$ is the integrated luminosity and ϵ the detector efficiency. To obtain a conservative limit, we take $\int \mathcal{L}\, dt$ to be 48 nb^{-1}, 1σ below the central value. Where the efficiency is equal to the maximum acceptance of 0.86, σ_{lim} established using all of the data is 7×10^{-35} cm^2.

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 a single-photon production process is assumed, the lowest-order cross section $\sigma_D(m)$ for a pointlike monopole of mass m scales with the cross section for unlike-sign dimuons times a phase space factor [10]:

$$\sigma_D(m;s) = \left[\frac{g_D}{e}\right]^2 \sigma_{\mu\mu}(>2m;s) \left[1-\frac{4m^2}{s}\right]^{1/2} .$$

Our limits can then be expressed as limits on the quantity $R_D \equiv \sigma(m)/\sigma_D(m)$ which would be expected to be of order unity for pointlike Dirac monopoles with a magnetic charge g_D, at energies above threshold. Our limits on R_D are shown in Fig. 2 with the most stringent limits from previous searches [8,13,14,15]. If this naive lowest-order estimate of σ_D is valid, we may conclude that pointlike Dirac monopoles with a mass below 44.9 GeV/c^2 are ruled out. However, it has been speculated that monopoles may have nonpointlike structure, resulting in a suppression of the production cross section by many orders of magnitude [16]. Our result is able to rule out suppression factors of less than 7×10^2 at 95% confidence level.

If monopoles can be produced by a different mechanism, then the production cross section as a function of collision energy may have a different behavior from that modeled above. To allow for other possibilities, we plot

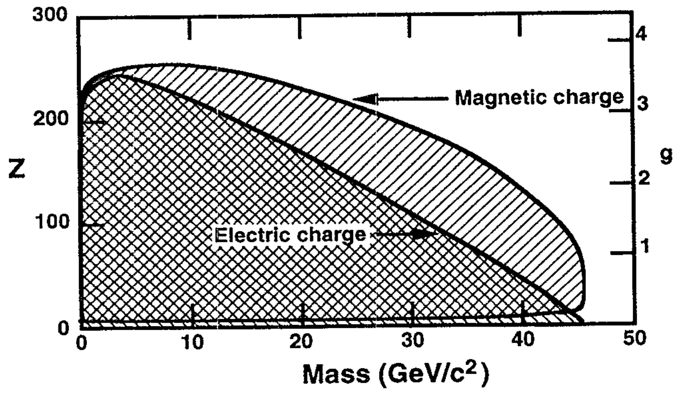

FIG. 1. Mass-charge combinations to which MODAL detectors have finite sensitivity. Regions are shown separately for magnetic and electric charge. The lower limit for sensitivity to electric charge is less than e for most of the mass range.

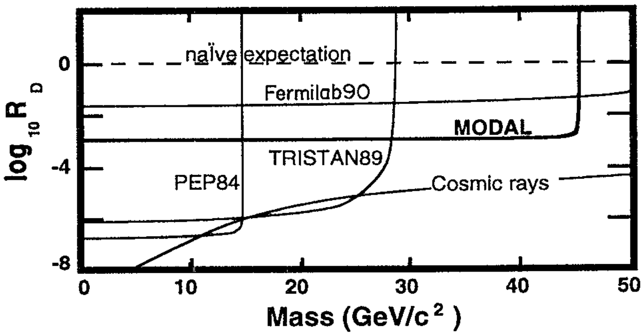

FIG. 2. Upper limits at 95% confidence on $R_D \equiv \sigma_{\text{lim}}(m)/\sigma_D(m)$ for isotropic exclusive production of monopole pairs with charge g_D. Our new results and that from KEK TRISTAN [8] include a phase space correction in the definition of σ_D (see text), which is not included in limits shown from other searches, at the SLAC e^+e^- storage ring PEP [13], the Fermilab Tevatron (Fermilab90) [14], and in cosmic rays [15].

in Fig. 3 our limit against $\sqrt{s}/2$, with corresponding limits from other experiments [8,13,14,17,18]. The limits from all of these experiments are nearly flat over the region of mass below the end point, and this is implicit in our plot. For any given monopole mass, the dependence of the cross section as a function of run energy may then be modeled and superimposed on our plot. As an example we include in Fig. 3 curves of σ_D for 40-GeV/c^2 monopoles, both in e^+e^- and pp collisions. Any experimental limit lying below the curve may then be interpreted as ruling out monopoles of the assumed mass for the given model.

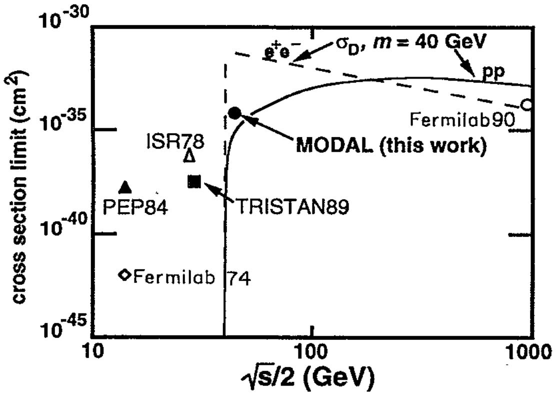

FIG. 3. Upper limits at 95% confidence level on production cross sections of monopole paris with charge g_D as a function of $\sqrt{s}/2$ for this search and previous searches. Solid symbols are used to denote searches in e^+e^- collisions [8,13] while open symbols are used for pp (Fermilab (Fermilab74) [17], CERN ISR [18]) and $p\bar{p}$ [14]. Also shown are the lowest-order pointlike electromagnetic production cross sections for 40-GeV monopoles in e^+e^- (dashed line) and pp (solid) collisions.

To summarize, the MODAL search has found no evidence for heavily ionizing particles in e^+e^- collisions at 91.1 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 up to 44.9 GeV/c^2.

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