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A search for highly ionizing particles produced at the OPAL intersection point at LEP

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We report the results from a search for highly ionizing and magnetically charged particles at the OPAL intersection point at the LEP e^+e^- storage ring. The search was sensitive to Dirac monopoles with magnetic charge in the range $0.9\,g_D < g < 3.6\,g_D$, where $68.5e \equiv g_D$. New upper limits are established on the production of monopoles with charge g_D and mass up to 45.0 GeV/c^2.

Many kinds of highly ionizing particles have been hypothesized, but the object in this class that has received the most attention is the magnetic monopole. This is due to the elegance of the prediction of Dirac in 1931 [1], whereby the symmetrization of the Maxwell equations and the quantization of electric charge results in the specific prediction of a fundamental magnetic charge. The magnetic charge of the monopole is expected to be $g \equiv ne/2\alpha = n \cdot 68.5e$ where n is an integer and e is the fundamental electric charge, usually assumed to be equal to the electron charge (if a free quark exists, then the magnetic charge would be three times larger). The mass of the Dirac monopole is not related to its electromagnetic properties, and predictions have varied from Dirac's first guess of 0.5 GeV/c^2 [1] to 10 GeV [2] to the huge value of 10^{16} GeV/c^2 [3]. Other hypothetical highly ionizing particles are the dyon [4], which has both electric and magnetic charge, and the nuclearite [5].

The ionization energy loss $\mathrm{d}E/\mathrm{d}x$ of magnetic monopoles with magnetic charge g and $\beta > 0.1$, where βc is the velocity, is well established through calculations analagous to those for electrically charged particles [6]. It is found to be equivalent to that of a particle with electric charge $g\beta$ and is thus nearly constant as a function of velocity, unlike that of an electrically charged particle, where $\mathrm{d}E/\mathrm{d}x$ is roughly proportional to β^{-2}. Ionization caused by a monopole changes substantially only at very low velocity, $\beta < 10^{-2}$. A magnetically charged particle is thus characterized by large constant ionization as a function of depth penetration, with no rise near the end of the range. It is due to the extraordinarily large charge of the Dirac monopole that its ionization is high (~ 10 GeV/g $\cdot$ cm^{-2}).

Assuming that the monopole anti-monopole pair is produced via a virtual photon intermediate state, and has a mass in the range 0–100 GeV, a direct search in e^+e^- annihilations is able to probe much smaller cross sections than a search in hadron collisions. In addition, a direct search minimizes assumptions made about the behaviour of monopoles in matter, and about the nature of the particle. In the case of LEP1 we are sensitive to particles with masses ranging up to 50 GeV. A null result of a monopole search at LEP would, considering the above assumptions, give the world's best direct limit on monopole production with monopole mass heavier than about 29 GeV/c^2.

A massive, stable, highly ionizing particle produced by colliding beams is likely to have a short range due to its high ionization and its low kinetic energy. To maximize the sensitivity of a detector to such particles one should form a multilayer tracking configuration. Minimizing the material thickness of each layer, which is in this case less than 0.1 $g \cdot cm^{-2}$, allows one to follow the ionization profile as a function of depth. A simple system composed of track-etch detectors [7] can satisfy all of these criteria reliably and inexpensively. Consequently, track-etch detectors are used here to detect the heavy ionization produced by Dirac monopoles and other highly ionizing particles.

A dedicated search for monopole production at LEP has already been carried out using the MODAL (Monopole Detector at LEP) detector deployed at the I6 intersection region [8]. This experiment (L6/MODAL) employed a polyhedral array of CR-39 track-etch detectors. The L6/MODAL experiment ran in 1990 and 1991 and obtained a rather limited luminosity from LEP (60 ± 12 nb^{-1}). However, new upper limits on monopoles with charge g and mass less than 45 GeV/c^2 were established. The passive OPAL monopole detector [9] described here had to fit in with the existing experimental aims of OPAL and as described below compromises had to be made in its design. Despite this the luminosity available for this search allowed the OPAL based monopole detector to obtain the world's most stringent limits on direct production of monopoles, of charge g, and mass in the range 25–45 GeV/c^2 (15–42 GeV/c^2 for monopoles with charge $2g$).

OPAL is a general purpose detector which has been described in detail elsewhere [10]. The main purpose of this detector is to study e^+e^- interactions at the LEP collider. The method of detection of monopoles reported here is based upon plastic track-etch detectors formed from three sets of three layers of Lexan wound around the OPAL beampipe between the strengthening ribs [9]. Each of the three layered sets of lexan was spot welded on a mandrel with exactly the same external diameter as the beampipe. A set of positioning holes was punched through each three layered lexan set while it was fixed on the mandrel. In addition, scribe marks were placed on the plastic in order that it could be aligned with positioning marks on the beampipe. Lastly, surveyor's dots were afixed to allow the CERN surveying team to measure the position of the foil with respect to the beampipe. In addition, two aluminized lexan sheets formed the gas seal and the inner HV foil for the OPAL vertex chamber. The lexan sheets deployed were all 0.125 mm in thickness. The geometric acceptance of this configuration was $\approx 0.99 \times 4\pi$ sr, and its total incremental thickness comprised 0.09% radiation lengths of material. The beam pipe was composed of aluminium and carbon fiber with a total thickness of 1.4 mm [10].

Lexan was chosen for three main reasons. Firstly, the threshold of UV sensitized lexan, which is discussed in more detail below, is sufficient to detect single magnetic charges ($n = 1$). Secondly, lexan can withstand a few megarads of radiation without undue damage – this is important considering the fact that it had to remain inside the OPAL detector for a period exceeding one year. Thirdly, the lexan could be obtained in thin sheets, of 125 μm thickness, with electrical and mechanical properties that suit its use as an inner foil in the OPAL vertex chamber. This last requirement arose because two aluminized lexan sheets, which served as a gas seal and as the inner HV foil of the vertex chamber, were also deployed in order to obtain additional space points. However, only access to the OPAL beampipe has been possible to date. Consequently, all the results quoted below relate to the lexan sheets wound on the beampipe.

Lexan was deployed in the OPAL experiment from October 1989 to December 1990. In this interval the detector was exposed to 8.67 pb^{-1} of integrated luminosity at the OPAL intersection region. The first three layers of lexan immediately surrounding the beam pipe were then removed, sensitized by exposure to ultraviolet light [11] and etched. The passage of such a highly ionizing particle through a dielectric track detector, or plastic track-etch detector, is revealed as a cone shaped etch pit when the surface of the plastic is etched in a controlled manner using hot concentrated sodium. The thickness of surface removed from each surface was 40 μm and 20 μm from the first and second sheets, respectively. The sheets were then scanned using an ammonia technique [11] to locate holes which would be produced by tracks with sufficiently high ionization. Four holes originating from tracks were found in the front sheets, and none were found in the second sheets. The extrapolated track locations in the adjacent sheets were examined for tracks, and none were found.

During the experiment, for a period of roughly 18 months, the lexan detectors were immersed in the OPAL vertex chamber gas, consisting of 89% Ar, 9% methane and 2% isobutane at 4 atm. It is known that a dearth of oxygen in its environment reduces significantly the sensitivity of lexan [12]. To calibrate this reduction, a detector was kept under similar conditions at Lawrence Berkeley Laboratory and exposed twice at intervals of several months to beams of Holmium with 972 MeV/amu kinetic energy ($Z/\beta \sim 78$) from the Bevalac. Lexan stacks were placed inside and outside a chamber containing a gas consisting of 90% Ar, 10% methane at 4 atm. The lexan sheets were then exposed to ultraviolet light from a mercury vapor lamp for varying periods and etched, to determine a suitable set of treatments. For the UV and etch sequence used with the detectors exposed at LEP we found a difference factor of 0.58 over published calibrations for lexan which had undergone no oxygen deprivation or exposure to UV [13]. We infer that the threshold for a normally incident track in a front sheet would be $Z/\beta \sim 64$ while for the second sheets it would be $Z/\beta \sim 84$.

A particle satisfying the ionization criterion is detected in the lexan if it falls within the geometric acceptance and has sufficient energy to penetrate all material in front of and including the sheet scanned. The overall efficiency 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, the beam pipe thickness and the magnetic field. As there are no 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 includes the magnetic field and accounts for geometric acceptance, energy losses in the beampipe and detector, and etching and scanning criteria. Fig. 1 shows the combinations of magnetic charge and mass for which the efficiency is finite (>10%). The cutoff mass $\mathcal{M}_n$ is defined as the mass at which the detector efficiency is finite, for monopoles with charge ng_D. The cutoff masses for $n = 1, 2$ are 45.0 and 41.6, respectively. 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.

The interpretation of the limit is dependent on the physical process by which the particle is presumed

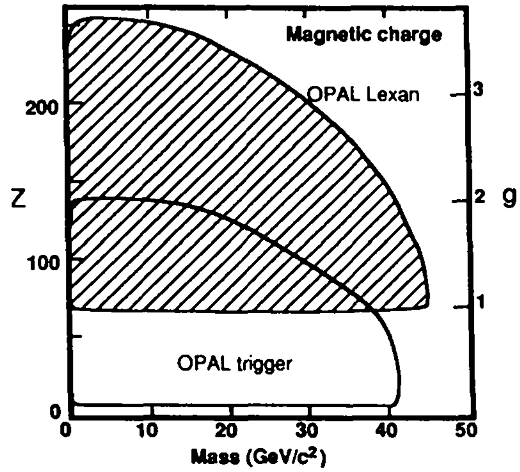

Fig. 1. Mass-charge combinations to which MODAL detectors have finite sensitivity. The region shown pertains only to magnetic charge.

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, then our limit may be compared with a lowest-order cross section $\sigma_D(m)$ for a pointlike monopole of mass m [14], which scales with the cross section for unlike-sign dimuons:

$$\sigma_D(m) = \left(\frac{g}{e}\right)^2 \sigma_{\mu\mu}^{\rm QED}(> 2m)\sqrt{1 - \frac{4m^2}{s}} .$$

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 magnetic charge g, at energies above threshold. Our limits on R_D are shown in fig. 2 along with the most stringent limits from previous searches [15].

The pointlike cross-section used here is $\sigma_{\mu\mu}^{\rm QED} = 86.8/E_{\rm cm}^2$ nb, where $E_{\rm cm}$ is the centre of mass energy. The 1989–1990 energy scan of the Z^0 resonance covered the energy range: 88.23 GeV $\leqslant E_{\rm cm} \leqslant$ 94.28 GeV. The corresponding variation in pointlike cross-section is 11.2 pb $\leqslant \sigma_{\mu\mu} \leqslant$ 9.8 pb: approximately 50% of the luminosity taken with 91.2 GeV $\leqslant E_{\rm cm} \leqslant$ 91.3 GeV. The luminosity-weighted average pointlike cross-section of 10.4 pb is taken to be the characteristic cross-section $\sigma_D(m)$.

From this analysis, we conclude that monopoles with mass below 45.0 GeV/c^2 are ruled out. However, it has been speculated that monopoles may have

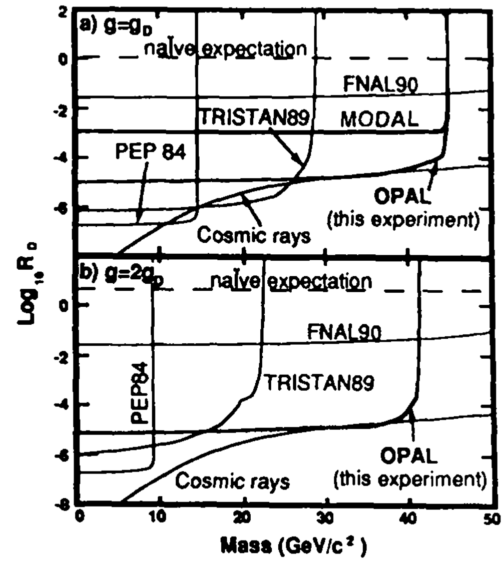

Fig. 2. Upper limits at 95% confidence on $R_D \equiv \sigma_{\text{lim}}(m)/\sigma_D(m)$ for isotropic exclusive production of monopole pairs with charge (a) g_D and (b) $2g_D$. Our new results, the MODAL result [8] and that from TRISTAN [14] include a phase space correction. Selected limits shown from other accelerator searches [15] and from cosmic rays [16] have not been adjusted for phase space.

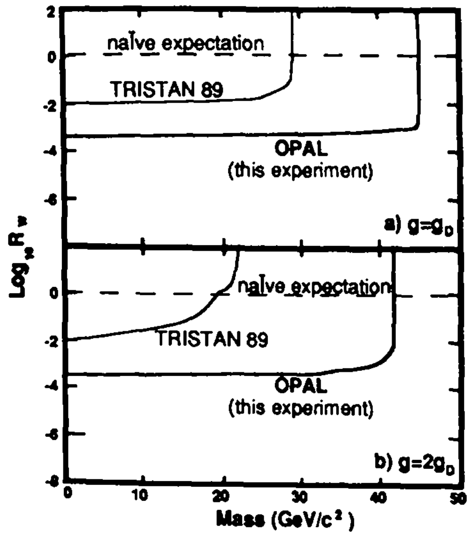

Fig. 3. Upper limits at 95% confidence on $R_W \equiv \sigma_{\text{lim}}(m)/\sigma_W(m)$ for isotropic exclusive production of monopole pairs with charge (a) g_D and (b) $2g_D$, from this experiment and from TRISTAN [14].

non-pointlike structure, resulting in a suppression of the production cross-section by many orders of magnitude by form factor effects [17]. Our result is able to rule out suppression factors of less than 5×10^4 at 95% confidence. 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

$$\sigma < \frac{3.0}{\epsilon \int \mathcal{L}\,dt} \equiv \sigma_{\text{lim}} \quad (95\%\,\text{CL}), \tag{1}$$

where $\int \mathcal{L}\,dt$ is the integrated luminosity and ϵ the detector efficiency. Where the efficiency is equal to the maximum acceptance, σ_{lim} established here is 3×10^{-37} cm^2.

These data were taken around the Z^0 mass. Thus, we are able to set excellent limits on production of pairs via the weak interaction. Assuming the coupling of monopoles to Z^0 is the same as that of leptons, then the cross section $\sigma_W(m, E_{\text{cm}})$ for a pointlike monopole of mass m is equal to the cross section for unlike-sign dimuons produced via the Z^0 times a phase space factor. In this case the magnitude of the cross-section varies from 283 ± 58 pb at $E_{\text{cm}} = 88.28$ GeV, to 1471 ± 22 pb at $E_{\text{cm}} = 91.22$ GeV [18]. The luminosity-weighted average cross-section is 1045 pb and is used as the characteristic cross-section, $\sigma^Z_{\mu\mu}$. We define a ratio $R_W \equiv \sigma(m)/\sigma_W(m)$, where we have used the average cross-section $\sigma^Z_{\mu\mu}$. The limit on R_W obtained is 7×10^{-4} over most of the mass region. The limit on R_W, as a function of monopole mass, is shown in fig. 3.

A measure on the uncertainty in the measured value of the Z^0 width is the value of $\Gamma(Z^0)^{\text{meas}} - \Gamma(Z^0)^{\text{SM}}$, where $\Gamma(Z^0)^{\text{meas}}$ is the measured width of the Z^0 [19], and $\Gamma(Z^0)^{\text{SM}}$ is the standard model prediction of the Z^0 width [20]. The predicted SM width is a function of the parameters α_s, M_t and M_{H^0} (the strong coupling constant, the top mass and the mass of the standard model Higgs boson). These were varied in the ranges $0.110 \leqslant \alpha_s \leqslant 0.126$, $89.0 \leqslant M_t \leqslant 200$ GeV/c^2 and $50.0 \leqslant M_{H^0} \leqslant 1000$ GeV/c^2, and the values that minimized $\Gamma(Z^0)^{\text{SM}}$ were used to obtain a conservative limit. The difference between the measurement and the prediction is less than 40 MeV/c^2 at the 95% confidence level. Taking the branching ratio of Z^0 to μ pairs to be 3.34×10^{-2}

[21] along with production of a new particle at a level of $7 \times 10^{-4} \times \sigma^{Z}_{\mu\mu}$ and a Z^0 (Γ_z) width of 2.487 GeV [21], results in an increase in Γ_z of less than one MeV.

In summary, we have found no evidence for production of heavily ionizing particles in e^+e^- collisions at LEP-1 centre of mass energies. New upper limits have been established on the cross section for pair production of charge g_D Dirac magnetic monopoles with masses to 45.0 GeV/c^2.

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