Searching for the magnetic monopole and other highly ionizing particles at accelerators using nuclear track detectors

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A R T I C L E   I N F O

Article info:
Received 22 October 2008
Accepted 19 October 2009

Keywords:
Magnetic monopole
Dyon
Nuclear track detectors
Accelerators
Highly ionizing
black hole remnants
Heavy stable particles
SUSY
LEP
LHC

A B S T R A C T

The use of nuclear track detectors at accelerators to directly search for the magnetic monopole and other highly ionizing objects is discussed. Recent searches at LEP are used as examples. Finally, the MoEDAL experiment, which is designed to continue the search at the LHC, is described.

1. Introduction

In 1931 Dirac introduced the Magnetic Monopole (MM) in order to explain the quantization of electric charge, which follows from the existence of at least one free magnetic charge (Dirac, 1931, 1948). He established the basic relationship between the elementary electric charge \( e \) and the basic magnetic charge:

\[
e = n g D, \quad g = n g D.
\]

where \( n \) is an integer, \( n = 1, 2, \ldots \). The magnetic charge is

\[
g = n g D; \quad g D = \frac{Z e}{2c} = 68.5e
\]

is called the unit Dirac charge.

The existence of magnetic charges and of magnetic currents would symmetrize the form of Maxwell’s equations, but the symmetry would not be perfect since \( e \neq g \). But if the couplings are energy dependent they could converge to a single common value at very high energies (De Rujula, 1995). There is no real prediction of the mass of classical Dirac MM. One may have a rough estimate assuming that the classical MM radius is equal to the classical electron radius, we have

\[
r_M = g^2/(m_M c^2) = r_e = e^2/m_e c^2
\]

from which

\[
m_M = g^2 m_e c^2 \approx 4700 \cdot m_e \approx 2.4 \text{ GeV}/c^2.
\]

Thus the mass should be relatively large and even larger if the basic charge is \( e/3 \) and if \( n > 1 \).

Grand Unification MMs, with masses of the order of \( 10^{15} \) GeV are well beyond the reach of any presently conceivable man-made accelerator. Never-the-less there are models where MMs could appear in a mass range accessible to the LHC. Examples include: the electroweak Cho-Maison MM (Cho and Maison, 1997); the Troost-Vinciarelli MM (Troost and Vinciarelli, 1976) with mass that depends on the matter field (10^4 GeV/c^2 with IVB matter fields, 10^2 GeV/c^2 with \( \rho \) matter fields and 50 GeV/c^2 with spin-1/2 matter fields; and a Superstring model (Banks et al., 1988) where in principle, MMs/dyons with a mass low enough (<1 TeV/c^2) to be detected at the LHC are hypothesized.

Since 1931 searches for classical Dirac MMs were carried out at every new accelerator using mainly relatively simple experiments, and recently also large collider detectors (Abbott et al., 1998; Acciarri et al., 1995; Gamberg et al., 1999; Giacomelli, 1984; Giacomelli and Patrizii, 2001; Giacomelli and Sioli, 2002; Giacomelli et al., 2007; Kalbfleisch, 2000; Milton et al., 2000). Searches at the Fermilab collider seem to exclude MMs with masses up to 850 GeV. Experiments at the LEP2 collider exclude masses below 10^2 GeV (Cozzi, 2007).

The LHC presents the best opportunity to date to observe massive quasi-stable exotic particles at the TeV scale (Nisati et al., 1997). The design of the ATLAS and CMS detectors may turn out to be flexible enough to allow the detection of this interesting class of exotic particles. The challenges presented are the trigger...
acceptance, the track reconstruction and the particle identification of the heaviest particles. The MoEDAL detector at the LHC plans to deploy Nuclear Track Detector (NTD) arrays in the LHCb interaction region in order to search for MMs and other highly ionizing particles. Nuclear track detectors present an attractive alternative to conventional collider detector techniques when the $Z/\beta$ of the massive quasi-stable particles is greater than ~15 where $Z$ is the charge of the particle and $\beta$ is the velocity of the particle compared with that of light. Such exotic particles might also be multiply charged such as, for example, the doubly charged Higgs boson (Grifols et al., 1989; Abbiendi et al., 2002; Acton et al., 1992), or a microscopic black hole remnant (Koch et al., 2005; Hossenfelder et al., 2005).

2. Monopole properties

The main properties of MMs are obtained from the Dirac relation. Many of the important properties of MMs are obtained from the Dirac relation. Most of the important MM properties are summarized here. We recall that the Dirac relation may be easily summarized here. We recall that the Dirac relation may be easily

- *Basic magnetic charge*: If $n = 1$ and the basic electric charge is that of the electron, then the magnetic charge, $g_0 = e/2$, in general, $g_0 = n\hbar c/2e$. The magnetic charge is larger if $n > 1$ and/or if the basic electric charge is $e/3$.

- *Electric charge*: Electrically charged MMs (dyons) may arise as quantum mechanical excitations or as $M-p$, $M$-nucleus composites.

- *Dimensionless magnetic coupling constant*: In analogy with the fine structure constant, $\alpha = e^2/\hbar c \approx 1/137$, the dimensionless coupling constant is $g_0 = \beta^2/\hbar c \approx 34.25$. As it is greater than one, perturbative calculations cannot be used.

- *Spin*: The spin of the MM is usually taken to be 1/2 or 0.

- *Energy W acquired in a magnetic field B*: $W = ng_0 B l = 20.5$ keV/G cm. In a coherent galactic length ($l < 10^6$ kpc, $B < 3 \mu$G), the energy gained by a MM with $g = g_0$ is $W = 1.8 \times 10^{10}$ GeV. Classical poles and intermediate mass MMs in cosmic rays may be accelerated to relativistic velocities. GUT poles should have low velocities, $10^{-4} < \beta < 10^{-1}$.

- *Bending in a solenoidal field*: Detectors at colliders usually employ a solenoidal field, as MMs accelerate along field lines MM trajectories will curve in the non-bend plane of the solenoidal field (conventionally the $r-z$ plane) and will not curve in the bend plane (conventionally the $r-z$ plane) of the magnetic field.

- *Trapping*: MMs may be trapped in ferromagnetic materials by an image force, which could reach values of $< 10$ eV/Å.

3. Monopole energy loss

The detectors used in MM search experiments are used to measure either the induction effects or the ionization or excitation of a medium by the passage of a MM. A relativistic MM with magnetic charge $g_0$ and velocity $v = \beta c$ behaves like an equivalent electric charge $(Ze)_\text{eq} = g_0 e$; the energy losses of fast MMs are thus very large. In fact, the ionization caused by an ultra relativistic MM is ~4700 times that of a minimum ionizing particle. Also, $dE/dx$ should increase as an electrically charged particle passes through a detector but decrease for a MM.

In the case of a slow MM, with $10^{-4} < \beta < 10^{-2}$ it is important to distinguish the energy lost in ionization or excitation of atoms and molecules of the medium (“electronic” energy loss) from that lost to recoiling atoms or nuclei (“atomic” or “nuclear” energy loss). Electronic energy loss predominates for electrically or magnetically charged particles with $\beta > 10^{-3}$. The $dE/dx$ of MMs with $10^{-4} < \beta < 10^{-3}$ is mainly due to excitations of atoms. In an ionization detector using noble gases there would be, for $10^{-4} < \beta < 10^{-3}$, an additional energy loss due to atomic energy level mixing (Drell effect) (Drell et al., 1982).

At very low velocities, $\beta < 10^{-4}$, MMs cannot excite atoms; they can only lose energy in elastic collisions with atoms or with nuclei. The energy is released to the medium in the form of elastic vibrations and/or infra-red radiation (Derkaoui et al., 1998, 1999). Fig. 1 shows a sketch of the energy losses in liquid hydrogen of a singly magnetically charge MM versus its $\beta$ (Giacomelli and Patrizii, 2001).

The interaction of the MM magnetic charge with nuclear magnetic dipoles could lead to the formation of MM-nucleus bound systems. This may affect the energy loss in matter and the cross-section for magnetic MM catalysis of proton decay. A MM-proton bound state may be produced via radiative capture, $M + p \rightarrow (M + p)$ bound $+ \gamma$. MM-nucleus bound states may exist for nuclei with a large gyromagnetic ratio.

Typically, the method of detection using induction effects is based on the long-range electromagnetic interaction between the magnetic charge and the macroscopic quantum state of a superconducting loop. A MM, moving through the loop, induces an electromotive force and a current (\(\Delta I\)). If the coil has $N$ turns and its inductivity is $L$, the current is $\Delta I = 4\pi Ng_0 L = 2\Delta I_{\text{e}}$, where $\Delta I_{\text{e}}$ is the current change corresponding to a change of one unit of the flux quantum of superconductivity. A superconducting induction detector consists of the detection coil, which is coupled to a SQUID (Superconducting Quantum Interference Device). If a MM passes through a superconducting loop there will be a magnetic flux change of $\phi_{\text{e}} = 2\pi \hbar c/\alpha$, which is independent of the MM velocity. This type of detector is sensitive only to the magnetic charge of the MM and not to the MM mass or velocity.

4. Monopole detection using nuclear track detectors

NTDs are the favoured method for detecting heavily ionizing particles like MMs at accelerators. They are able to record the passage of heavily ionizing particles which leaves an invisible damage zone along its trajectory in the plastic. The damage zone is revealed as a cone shaped etch-pit, when the surface of the plastic detector is etched in a controlled manner using an etchant such as hot sodium hydroxide (NAOH) solution. The depth of the etch-pit is...
an increasing function of the $Z/\beta$ of the particle, where $Z$ is a particle charge and $\beta$ is velocity. A schematic picture of the etching process is shown in Fig. 2 (SLIM Collaboration, 2008).

The formation of an etchable track in a nuclear track detector is related to the Restricted Energy Loss (REL), which is the fraction of the total energy loss which remains localized in a cylindrical region with about 10 nm diameter around the particle trajectory. Both the electronic and the nuclear energy losses contribute to REL. It was shown (Cecchini et al., 1996) that both are effective in producing etchable tracks in a CR39 nuclear track detector. NTD detectors comprised of CR39 can have a threshold as low as $Z/\beta \approx 5$: it is the most sensitive NTD and it allows to search for MMs with one unit Dirac charge ($g = g_D$) for $\beta$ around $10^{-3}$, for $\beta > 10^{-3}$ and the whole $\beta$-range of $4 \times 10^{-2} < \beta < 1$ for MMs with $g \geq 2 g_D$ (Derkaoui et al., 1998, 1999). The Lexan and Makrofol polycarbonates have a threshold at $Z/\beta > 50$; thus they are sensitive only to relativistic MMs. Last, but not least, there are glass NTDs, a good example is UG-5 (a Cobalt rich phosphate glass). The threshold for UG-5 is several times higher than CR39 rendering it useful only for searches for multiply charged magnetic MMs. But, because tracks are formed in glass by a mechanism that does not require oxygen fixation this type of detector can be deployed indefinitely in a vacuum system.

After etching, the NTDs are scanned using manually controlled or computer controlled optical scanners which, with special dowel-pin marker holes, allow the determination of hole position with accuracy better than $\sim 20 \, \mu m$ in the multilayered NTDs stack used in the experiments. The response of track-etch detectors versus REL can only be established by a calibration performed using ions of different charges and energies, where the calibration is dependent on the etching conditions. A typical calibration set-up at an ion beam accelerator includes a fragmentation target and nuclear track detector foils in front of and behind a target. After exposure the detector sheets are etched in standard conditions. The measured base areas of the etch-pit cones (tracks) increase with increasing ion charges. Thus nuclear fragments may be detected as a change in the base area of the tracks. The trajectory of each detected nucleus is reconstructed by tracking the etch cones successively through the stack. This multiple measurement can be exploited to achieve a charge resolution adequate to separate individual fragments. The results of the measurements of the track areas on two sheets (4 faces) of CR39 (4 independent measurements) exposed to a 158 A GeV $^{207}$Pb$^{82+}$ beam at the CERN-SPS is shown in Fig. 3 (SLIM Collaboration, 2008).

A GeV $^{207}$Pb$^{82+}$ beam at the CERN-SPS is shown in Fig. 3 (SLIM Collaboration, 2008).

If the etching process is continued for a sufficient length of time, a hole will be formed in the plastic NTD sheet. These holes can be detected using the “ammonia technique” (Fleischer et al., 1975) where the plastic sheet is placed on top of sensitive blueprint paper and the two are sealed around the edge with tape. This package is then exposed to ammonia vapour. Each hole in the plastic is then revealed by a blue spot. The spotted blueprint paper can then be used as a map to define corresponding regions in accompanying sheets in the detector stack that can be etched with greater care.

The desirable properties of plastic NTDs for the detection of highly ionizing particles at accelerators are as follows:

- **Sensitivity to MMs:** MMs with $n = 1$ will be detectable in CR39 provided that $\beta > 0.1$ and in Lexan for $\beta > 0.85$. Highly ionizing particles with $Z/\beta$ as low as 10− can be detected by CR39, depending on the etching conditions.
- **Insensitivity to MIPs:** CR39, Lexan and UG-5 are totally insensitive to normally ionizing particles. For example with
a luminosity of $|\mathcal{L}|dt = 10^{40} \text{cm}^{-2}$ and a rapidity interval of $\Delta y = 2$, there will be $\sim 10^{16}$ MIPS passing through the detector. Nonetheless, with NTDs, we will still be able to pick out the signal from one MM.

- **Solid angle coverage**: it is relatively easy to cover the full solid angle with stacks of NTDs.
- **Trigger**: as NTDs are always sensitive to MMs and yet insensitive to normal hadronic events, no trigger is necessary (nor possible) with these devices. This is very useful in the search for very heavy stable particles whose time of flight to, say, the muon counters of an LHC experiment could exceed the trigger time allocated for each beam crossing.
- **MM Properties**: the measurement of the detailed shape of the conical etch-pit produced on each side of the plastic or glass sheet gives information on the particle trajectory as well as the equivalent Z/\beta. In a multi-sheet stack detector, the position and direction information from individual pits can be combined to give a very precise trajectory and the Z/\beta values can be used to determine the change in ionization energy loss as the particle loses energy passing through the detector (dE/dx should increase for electrically charged particles but decrease for a MM). Showing that the candidate track comes from the interaction region and has consistent dE/dx values will be important checks.
- **Radiation Resistance**: the radiation resistance of track-etch detectors is examined in reference (Price, 1987). CR39 is the most sensitive being able to stand a does of around 2 MRads, Lexan/Makrofol can withstand around 200 MRads and UG-5 around a GigaRad. Thus NTDs are relatively radiation hard. Moreover, as the material is inexpensive, compared to usual electronic detector technology, it can be replaced when necessary.
- **Placement Inside a Beam Pipe**: plastic detectors require oxygen fixation to retain their sensitivity, but glass detectors do not. Thus UG-5 can be used inside a beam pipe.
- **Cost**: both the cost of the mechanical structure required to hold the plastic NTD stacks and the plastic NTD themselves cost very little when compared to the electronic detectors designed to do the same job with the same coverage.

## 5. Monopole detection using nuclear track detectors at LEP and the LHC

No MM has found in the experiments performed so far. The first accelerator based MM search was performed in 1959 (Bradner and Isbell, 1959) the latest published result was in 2008 (Abbiendi et al., 2008). Of the roughly 32 searches performed nearly one half have used NTDs as the detecting media. The first MM search experiment to use NTDs (Giacomelli et al., 1975) was performed in 1975 at the CERN ISR complex. In this experiment the exposure was made at the CERN ISR complex. In this experiment the exposure was made at two energy domains of the LEP machine: at LEP1 ~ 90 GeV and at LEP2 ~ 206.3 GeV (Giacomelli, 2006). The OPAL detector was sensitive to Dirac MMs with magnetic charge in the range 0.9 $g_0 < g < 3.6$ $g_0$, where $g_0 = 68.5e$. The OPAL detector is a general purpose set-up with the main task of $e^+e^-$ interactions studies at the LEP collider. MM detectors based upon plastic track-etch foils, assembled as three sets of three layers of Lexan, were wound around the OPAL beam pipe during LEP1 running only (Pinfold et al., 1991). Each of the three layered sets of Lexan was spot welded on a mandrel with exactly the same external diameter as beam pipe. 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 beam pipe. Lastly, surveyor’s dots were affixed to allow the CERN surveying team to measure the position of the foils with respect to the beam pipe. 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 $\sim 0.99 \times 4\pi$ sr, and its total incremental thickness comprised 0.09% radiation lengths of material. The beam pipe was composed of aluminum & carbon fibre with a total thickness of 1.4 mm.

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 (Fleischer et al., 1975) 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 removed from each surface was 40 $\mu$m and 20 $\mu$m from the first and second sheets, respectively. The sheets were then scanned using an ammonia technique (Fleischer et al., 1975) 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.

The detection efficiency calculation was performed for MMs of charge $g_0$ and 2 $g_0$ assuming isotropic and exclusive pair production and taking into account the acceptance and energy losses in the beam pipe and the detector and etching and scanning criteria. The mechanism for MM production assumed annihilation and pair production via the Electromagnetic interaction. If a single photon production process is assumed the limit can be compared with a lowest-order cross-section $\sigma_0$ for a point-like MM of mass (Kinoshita et al., 1988, 1989), which scales with the cross-section for...
muon-pairs: \[ \sigma_D(m) = (g_D/e)^2 \sigma_{\text{had}}(>2 \text{ m}) \cdot (1-4 \text{ m}^2/s) \]. The limits obtained can then be expressed in terms of the quantity \( R_D = \sigma(m)/\sigma_D(m) \) which would be expected to be of the order of one for point-like Dirac MMs with magnetic charge \( g_D \). From this analysis the authors concluded that MMs with mass less than 45 GeV/c^2 were ruled out. However, it has been speculated that MMs may have non-point-like structure, resulting in a suppression of the production cross-section by many orders of magnitude by form factor effects (Drukier and Nussinov, 1982). This result is able to rule out suppression factors of less than \( 5 \times 10^{-4} \) 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 \( \sigma < 3/eL \), where \( L \) is the integrated luminosity and \( e \) the detector efficiency, that is \( 3 \times 10^{-27} \text{ cm}^2 \).

6. The MoEDAL experiment

A future experiment, MoEDAL (Pinfold et al., 1999), aims to use NTDs to search for MMs at the CERN LHC accelerator complex. The LHC will operate an energy of \( \sqrt{s} = 14 \) Tev in the proton–proton mode and will accelerate lead ions to \( \sqrt{s} = 5.5 \) TeV energy per nucleon in the heavy ion mode. The maximum expected proton–proton luminosity will reach \( \sim 10^{-34} \text{ cm}^{-2} \text{s}^{-1} \). There is also an LHC upgrade project that if implemented is envisaged to increase the maximum LHC energy tenfold. This unprecedented energy and luminosity scale presents a challenge to look for heavier MMs with masses up to several TeV.

The MoEDAL experiment will be housed in the open intersection region of the LHCb experiment at point 8 on the LHC ring, with the MoEDAL array elements deployed on the walls of the VELO Cavern, as shown in Fig. 4. The maximum surface area available for detectors is 25 m². A MoEDAL detector element consists of 3 sheets of CR39 and 3 sheets of Makrofol interleaved with three sheets of Lexan, to make 9 layers of NTDs as shown in Fig. 5. Six of these detector elements are housed in a thin (0.5 cm thick) aluminium envelope of size 50 cm × 75 cm. These housings are mounted a flat aluminium mounting framework attached to the walls and ceiling of the VELO cavern.

The Technical Design Report (TDR) of the MoEDAL experiment will be submitted to the Large Hadron Collider Committee (LHCC) in July of 2009. If the TDR is accepted by the LHCC, the experiment will go forward for final approval by the Research Board of CERN. If approved, MoEDAL is envisaged to deploy its first test detectors in 2009, with a full deployment in the expected long shutdown in the Winter of 2010/2011. It will run in pp mode at a luminosity of \( 10^{32} \text{ cm}^{-2} \text{s}^{-1} \) – the highest available luminosity at point 8 where the LHCb detector is housed, but a factor of 100 less than that available to the general purpose detectors ATLAS and CMS. If possible, MoEDAL will also take data in heavy ion running. The MoEDAL detector is designed to detect up to a \( \sim 7 \) TeV mass MM. MoEDAL will also have good sensitivity to multiply charged MMs with \( g_D \) as high as \( \sim 4 \).

Acknowledgments

I would like to acknowledge the assistance of the SLIM and MoEDAL collaborations in the preparation of this document.

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