Searching for Magnetic Monopoles with the MoEDAL Experiment

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MoEDAL
The MoEDAL Experiment

LHCb  MoEDAL
MoEDAL is an experiment for the search of heavy stable ionizing particles at LHC energies.

The MoEDAL experiment, the 7th LHC experiment, was officially approved by the CERN Research Board on March 3rd 2010.

MoEDAL shares the 8th LHC IP with the LHCb experiment.

MoEDAL is an array of passive Nuclear Track-Etch Detectors & Trapping Detectors, with a MediPix chip based online radiation monitor system.

The complete MoEDAL experiment has started data taking at the LHC in spring of 2015.

A 20% prototype of the full Trapping Detector was installed in the second half of 2012 and collected the first data. The results of these data are presented today.
Now 66 physicists from 16 countries and 26 institutions:

The MoEDAL Experiment

-> Three subdetector systems

- Passive Nuclear Track-Etch Detectors (NTDs)
  - 18m² of CR39 and Makrofol (for very high ionization)
  - Detection threshold is “charge/β > 5”
- Passive Trapping Detectors (MMTs)
  - 800 kg of aluminium bars
- MediPix chip based online radiation monitor system

The NTD and MMT detectors have been exchanged in December ‘15. These removed detector are being analysed
Magnetic Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac ‘31)

\[ g = \frac{q_m}{e} = \frac{n}{2\alpha_e} = n \cdot g_D \approx n \cdot 68.5 \]

- Symmetrizes Maxwell equations!
- Dirac: Charge quantization consequence of angular momentum quantization in the presence of monopole
- ‘t Hooft, Polyakov: GUT monopoles

Collider signature: pair production of very highly ionizing particles!

Monopoles will ‘burn’ through the plastic sheets of the experiment or get trapped in the dense material of the trapping detector.
Results Based on the 2012 Prototype

- Magnetic Monopole Trapper prototype deployed in September 2012 and exposed to 0.75 fb\(^{-1}\) of 8 TeV pp collisions
- 160 kg Magnetic Monopole Trapper made of 198 aluminium rods of 2.5 cm diameter and 60 cm length
Geometry Description in Geant4

- Good knowledge of material between the IP and detector essential to determine monopole stopping position. Dominating systematics!
- Implemented into XML file already containing the LHCb detector geometry.
- Then used by Geant4 within the LHCb software framework for simulating monopole propagation in the material.
Magnetometer Measurements

- Detection Method: Measure a persistent current induced in the superconducting coil of a sensitive SQUID magnetometer

Magnetometer scans
- Optimum length 20 cm
- 11 boxes (606 samples) in 7 days
- 852 independent runs (including calibration, backgrounds, and multiple measurements of candidates)

A DC-SQUID rock magnetometer (2G Enterprises model 755)
Magnetometer Measurement Procedure

- Output measured before, during and after the passage of the sample through the sensitive coil
- Calibration with a convolution method applied to a dipole sample and cross checked with thin long thin dipoles mimicking a monopole of well known charge.
- Subtract the empty holder result from the measurement.
- The difference is the persistent current. If it differs from zero we have a monopole signal candidate!!

Measurement of one 20 cm sample in 76 step through the SQUID
Measure of Magnetic Charges: Results

- All 606 sample measurements
- Some device instabilities in the last part
- Exclude a trapped magnetic charge with $|g| > 0.5 \, g_D$ at the 99.75% confidence level, in the full sample
Monopole Event Simulation

Drell–Yan Process

Two acceptance studies:

Single monopoles with flat $\theta$, $\varphi$ and $E_{\text{kin}}$ distributions

Pair production: Drell-Yan model with spin $\frac{1}{2}$ and spin-0 monopoles give different kinematics (with MadGraph)

Energy loss simulated in Geant4 & arXiv:1606.01220 (see also backup)

Note: non-perturbative!
### Acceptance for spin $\frac{1}{2}$ and spin 0

| m [GeV] | $|g| = 1.0g_D$ | $|g| = 2.0g_D$ | $|g| = 3.0g_D$ | $|g| = 4.0g_D$ |
|---------|----------------|----------------|----------------|----------------|
| spin-1/2 |                |                |                |                |
| 100     | 0.019±0.003    | 0.002±0.002    |                |                |
| 500     | 0.017±0.001    | 0.021±0.005    | 0.005±0.003    |                |
| 1000    | 0.014±0.001    | 0.022±0.004    | 0.008±0.004    | 0.002±0.001    |
| 2000    | 0.012±0.001    | 0.022±0.003    | 0.008±0.004    | 0.001±0.001    |
| 3000    | 0.016±0.001    | 0.013±0.004    | 0.002±0.002    |                |
| 3500    | 0.020±0.001    | 0.004±0.003    |                |                |
| spin-0  |                |                |                |                |
| 100     | 0.028±0.002    | 0.007±0.004    |                |                |
| 500     | 0.0082±0.0010  | 0.027±0.004    | 0.010±0.005    | 0.002±0.002    |
| 1000    | 0.0038±0.0007  | 0.022±0.002    | 0.011±0.004    | 0.003±0.002    |
| 2000    | 0.0020±0.0004  | 0.014±0.001    | 0.008±0.003    | 0.002±0.002    |
| 3000    | 0.0032±0.0007  | 0.008±0.002    | 0.002±0.002    |                |
| 3500    | 0.0069±0.0007  | 0.004±0.002    |                |                |
Acceptance for Single Monopoles

Studied for a magnetic charge of up to $6g_D$
Search for magnetic monopoles with the MoEDAL prototype trapping detector in 8 TeV proton–proton collisions at the LHC


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The MoEDAL experiment is designed to search for magnetic monopoles and other highly–ionising particles produced in high–energy collisions at the LHC. The largely passive MoEDAL detector, deployed at Interaction Point 8 on the LHC ring, relies on two dedicated direct detection techniques. The first technique is based on stacks of nuclear–track detectors with surface area ~18 m², sensitive to particle ionisation exceeding a high threshold. These detectors are analysed offline by optical scanning microscopes. The second technique is based on the trapping of charged particles in an array of roughly 800 kg of aluminium samples. These samples are monitored offline for the presence of trapped magnetic charge at a remote superconducting magnetometer facility. We present here the results of a search for magnetic monopoles using a 160 kg prototype MoEDAL trapping detector exposed to 8 TeV proton–proton collisions at the LHC, for an integrated luminosity of 0.75 fb⁻¹. No magnetic charge exceeding 0.5g₄ (where g₄ is the Dirac magnetic charge) is measured in any of the exposed samples, allowing limits to be placed on monopole production in the mass range 100 GeV ≤ m ≤ 3500 GeV. Model–independent cross–section limits are presented in fiducial regions of monopole energy and direction for 1g₄ ≤ |g| ≤ 6g₄, and model–dependent cross–section limits are obtained for Drell–Yan pair production of spin–1/2 and spin–0 monopoles for 1g₄ ≤ |g| ≤ 4g₄. Under the assumption of Drell–Yan cross sections, mass limits are derived for |g| = 2g₄ and |g| = 3g₄ for the first time at the LHC, surpassing the results from previous collider experiments.
Limits for Different Monopole Charges

Search results versus the monopole mass

- World best limits for $|g| > g_D$ (previously ~400 GeV at Tevatron)

| DY Lower Mass Limits [GeV] | $|g| = g_D$ | $|g| = 2g_D$ | $|g| = 3g_D$ |
|----------------------------|------------|------------|------------|
| spin-1/2                   | 700        | 920        | 840        |
| spin-0                     | 420        | 600        | 560        |

- Limits on masses in the range of $100 \text{ GeV} < m < 3500 \text{ GeV}
- In particular sensitive to high magnetic charges (new at the LHC!)
Limits for Different Monopole Charges

DY cross section are calculated at leading order but note that perturbative calculations are not reliable due to large coupling.
Comparison with other Measurements
MoEDAL in Run-2

MoEDAL in 2015/2016

NDTs on top of VELO, close to IP

Thin “curtain” within LHCb acceptance

TimePix chips

3 arrays trapping detectors

• Full arrays exposed to 13 TeV \( pp \) collisions
Summary

• The first results from MoEDAL, a dedicated LHC experiment for the search of heavy stable ionizing particles have been released, using a 160 kg prototype Magnetic Monopole Trapper, and based on 0.75 fb$^{-1}$ of data at 8 TeV.

• The samples have been analysed by a SQUID magnetometer.

• No monopole candidates with a magnetic charge of $\geq 0.5g_D$ were found in the full trapping sample.

• Under the assumption of a DY production at LO, mass limits are obtained for magnetic charge of up to $3g_D$.

• Model independent results put a 95% CL upper limit of 10 fb for magnetic charges up to $6g_D$.

• 2015 data (trapper and plastic foils) being analysed.

• Detector is equipped for the 2016 run and collecting data since the start of the run.
Heavy Ionizing Particles

- **Electric charge** - ionization increases with increasing charge & falling velocity $\beta$ ($\beta=v/c$) – use $z/\beta$ as an indicator of ionization

$$-\frac{dE}{dx} = K\left(\frac{Z^2}{A}\frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right] + \frac{2m_e c^2 \beta^2 \gamma^2}{I_m} + \frac{K |g|}{2} - \frac{1}{2} - B(g) \right]$$

- **Magnetic charge** - ionization increases with magnetic charge and decreases with velocity $\beta$ – a unique signature

- The velocity dependence of the Lorentz force cancels $1/\beta^2$ term

- The ionization of a relativistic monopole is $(ng)^2$ times that of a relativistic proton i.e $4700n^2!!$ ($n=1,2,3,...$)