Status of the MoEDAL & milliQan Experiments

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The Monopole and Exotics Detector at the LHC (MoEDAL) Experiment
MoEDAL Today
The MoEDAL Detector

A largely passive detector, analogous to a giant camera that 'photographs' the interaction point with the main purpose of searching for magnetic monopoles. The nominal detector system is comprised of three subdetectors: NTD, MMT, and TimePix (for radiative background monitoring; not discussed here).

MoEDAL Nuclear Track Detector (NTD)

- An array of passive material only sensitive to highly ionizing particles.
- ~200 square meters of plastic material deployed in stacks around the IP.

MoEDAL Magnetic Monopole Trapper (MMT)

- A ~1 ton array of aluminum deployed around the IP to trap MMs.
- Material is removed every 2 years, along with the NTD material, for analysis.

MoEDAL's Latest Results for Magnetic Monopole Production at the LHC (Run-2)

Considering production in $p$-$p$ collisions via Drell-Yan & photon fusion mechanisms and a total integrated luminosity of 6.46 fb$^{-1}$.


MoEDAL has also recently published the first search for dyons at a collider as, The MoEDAL Collaboration, Phys. Rev. Lett. 126, 071801 (2021).
MoEDAL's Upcoming Results

HIPs - MMs and HECOs using LHC Run-1 & Run-2 data collected with the NTDs.
*In Collaboration wide review.

MMs produced in heavy-ion collisions via the thermal Schwinger mechanism.
*Sent to Nature.

Studies of the exposed CMS beampipe for trapped MMs.
*Analyses in progress.
MoEDAL's Apparatus for Penetrating Particles (MAPP)

The MAPP Detector Upgrade
The MAPP-1 Detector System

An active scintillation based detector aimed at the search for new feebly interacting particles (FIPs). Two subdetectors: MAPP-mCP & MAPP-LLP.

MAPP-mCP (Phase-I, beginning in Run-3)
Currently under construction at the UofA!

- Inner core of MAPP-1 with a detector size of roughly 1 m x 1 m x 3 m.
- Search for minicharged particles - mCPs (Q << 1e).
- Note: Atlas and CMS are limited to \(-e/3\) or greater.

MAPP-LLP (Phase-II, in 2022 during Run-3)

- Nested outer layers of the MAPP detector (hodoscope planes).
- Search for new pseudo-stable neutral particles with long lifetimes that may decay in the detector volume.
Location of the MAPP Detector @ The LHC

Proposed placement is in the UGC1 gallery, adjacent to the MoEDAL detector region.

MAPP-1 (Phases-I & II)
- Positioned at 5° w.r.t to the beam axis. ~55 m from IP8.
- This placement has ~100 m of rock overburden and 25-30 m of rock shielding between the detector and the IP.
- Large decay zone of ~10 m is possible.

MAPP-2 (Phase-III)
- A proposed future version of MAPP which fills the entire cavern (covering from roughly 5-20° w.r.t to the beam axis).
MAPP-mCP

MAPP's minicharged particle subdetector

Active scintillation counter detector with a large path length of sensitive scintillator bars.

- 10 x 10 grid of 75cm long scintillator bars.
- 4 co-linear sections with low-noise PMTs placed in coincidence to eliminate dark and radiogenic background counts.
- Scintillator, light guides, and LED boards currently worked on @ the UofA.
- 'Outrigger' Detector extension which increases the acceptance area of MAPP-mCP considerably is in planning.
MAPP-mCP – 'Outrigger Detector' Extension

A detector extension in planning.

In planning since 2020.

- Lower sensitivity to smaller fractional charges, but much large acceptance area of ~16 square meters deployed in 4 layers.
- The goal is to increase the sensitive area of MAPP-mCP to improve the detector reach at larger values of mCP mass and minicharge.
MAPP-mCP Construction

Testing will begin this summer!
The milliQan Experiment

The search for millicharged particles at the LHC
The milliQan Experiment

A planned millicharged particle detector placed in the CMS cavern ~33m from the interaction point (IPS) and aligned towards the IP.

Early developments in the milliQan Experiment:

- **2016** - milliQan LOI submitted with a full detector design. (arXiv:1607.04669)

2018 - milliQan Demonstrator Detector Deployed

- ~1% of the full milliQan detector volume, deployed in Run-2 (2018).
- Collected 37.5 fb-1 worth of pp collision data at a C.o.M energy of 13 TeV.
- Produced the first search for mCPs at a hadron collider in 2020 with this data.
The Full milliQan Detector

A scintillation detector comprising two main detector systems, the bar and slab detectors.

### milliQan Bar Detector
- 0.2 m x 0.2 m x 3 m array of plastic scintillator bars.
- Four layers that each comprise 16 scintillator bars coupled to high-gain PMTs.
- Surrounded by an active muon VETO shield. (6 layers of 5 cm thick scintillator.)

### milliQan Slab Detector
- Comprised of 40 cm x 60 cm x 5 cm scintillator slabs.
- A total of 48 slabs separated into 4 layers with 3 x 4 slabs per layer.
- Improved reach for higher mass mCPs.
Run-3 & HL-LHC

Projected Detector Sensitivities for MAPP & milliQan to mCPs
mCPs in 'Dark QED' (Kinetic Mixing) - Model

Production via the DY mechanism through a renormalizable kinetic mixing interaction between a new $U'(1)$ gauge field ($A'$) and SM hypercharge.

Add to the SM, a new massless $U'(1)$ gauge field ($A'$, the 'dark photon') and a charged massive fermionic field $\psi$,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\psi} \left( \partial_{\mu} A'_{\mu} + i e' A' + i m_{\text{mCP}} \right) \psi - \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$$

where the Feynman slash notation has been used, $e'$ is the charge of the new gauge field $A'$, and $B$ is the SM hypercharge gauge field.

Lastly, the field strength of the dark photon is defined in the usual way as:

$$A'_{\mu\nu} = \partial_\mu A'_{\nu} - \partial_\nu A'_{\mu}$$

Removing the mixing term through a field redefinition, $A'_{\mu} \Rightarrow A'_{\mu} + \kappa B_{\mu}$, reveals a coupling between the field $\psi$ to the SM hypercharge,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\psi} \left( \partial_{\mu} A'_{\mu} - i e' B + i m_{\text{mCP}} \right) \psi$$

Consequently, the new field $\Psi$ is charged under hypercharge with a fractional charge proportional to the mixing parameter, $\epsilon$.

This can be written as: $\epsilon = \kappa e' \cos \theta_W / e$, in units of the electric charge, $e$.

Sensitivity of MAPP to mCPs - Analysis & Results

95% C.L. exclusion bounds for Drell-Yan pair-produced mCPs @ a C.o.M energy of 14 TeV using Madgraph5

Events were generated based on the x/s and analyzed to estimate the # of 'hits' in MAPP-mCP.

- This was performed across the parameter space of interest.
- A 'hit' was defined as an mCP with momenta traversing each of the co-linear sections of the MAPP-mCP detector.
- Inclusion of resonant production modes of mCPs could improve the ranges of MAPP-mCP shown.
- Outrigger detector was not included in this initial study.

No BGs and an overall detector efficiency of 100% were assumed for ease of comparison. (Simulations of detector response and efficiency are still ongoing.)


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Sensitivity of milliQan to mCPs – Analysis & Results

More detailed studied than ours, performed at a C.o.M energy of 13 TeV.

- Included production of mCPs via decays of vector mesons and Dalitz decays of light mesons as well (using Pythia6/8).
- An mCP-like signal in the detector was selected by requiring a single hit in each of the detector layers, produced in a straight path.
- Further selection criteria and BG rejection were also applied. e.g. timing and energy deposition expected for mCPs in the detector layers.
- Detailed BG estimates were performed using GEANT4 simulations.
- 95% C.L. exclusion curves were set using a signal + BG hypothesis and a modified frequentist approach.

N.B. The HL-LHC projections also include improvements to the milliQan detector, such as an increased number of scintillator bars in each layer of the bar detector and an improved active veto, thus reducing the total BG.

Conclusions & Future Outlook

**MAPP-1 is on schedule for deployment at the LHC's Run-3.**

- The MAPP-1 detector has sensitivity to significant portions of unexplored parameter space for a total of 8 models studied so far.
- **Phase-I of MAPP, MAPP-mCP**, will enable searches over unexplored regions of the mass-mixing parameter space for mCPs that can probe electric charges as low as $\sim 0.003$ over a mass range of $0.1\text{–}75$ GeV, in the best-case scenario at the LHC's upcoming Run-3. At the HL-LHC, a factor $\sim 10$ increase in the total integrated luminosity will extend this reach to charges as low as $\sim 0.001$.
- Updates to these studies including the outrigger and effects of tracking and backgrounds. Further studies involving MAPP are also underway.

**The milliQan Experiment is on schedule for Run-3 as well.**

- **Demonstrator results represent the first search for mCPs at a hh collider. New exclusion bounds** for mCP masses larger than 0.7 GeV.
- Most recent, detailed study of the future sensitivity of milliQan to mCPs shows complementary sensitivity to MAPP.
- **Funding secured** and on schedule for deployment at the LHC's Run-3 to collect 200 fb$^{-1}$ of pp collision data. With this dataset, mCPs could be excluded at the 95% C.L. for a range of masses from $0.1\text{–}45$ GeV and for charges as low as $0.003$, in the best case. At the HL-LHC, this reach could be extended to mCP masses as large as 80 GeV, and charges as low as $0.0018$, in the best case.
Thank you!
Questions?