Review on searches for light dark matter at fixed target electron accelerators

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Hidden Sectors

Is it made by a "Dark Sector" of new particles and interactions?

A Hidden Sector not charged under SM gauge groups:

- Light Dark Matter $\chi$ in MeV - GeV mass range
- "New" interaction between LDM and SM particles in order to be compatible with the DM thermal origin
- Can explain some puzzling observations
Possible connection between Hidden sector and SM: “Vector” portal

Consider a theory in which nature contains an additional Abelian gauge symmetry $U'(1)$


This gives rise to a Kinetic Mixing term where the photon mixes with a new gauge boson ("Dark/Heavy Photon" or $A'$) through the interactions of massive fields:

$$\mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon}{2} F'_{\mu\nu} F_{\mu\nu} + \frac{m'^2}{2} A'_\mu A'^\mu + g_D A'_\mu J^\mu_\chi + e A_\mu J^\mu_{EM}$$

Mixing induces an effective weak coupling $\varepsilon e$ to electric charge

$A'$ acts as a “portal” between the SM and the new sector

4 parameters: $M_{A'}$, $M_X$, $\varepsilon$, $g_d$
Dark Photon production

Since dark photons couple to electric charge, they can be produced through.....

**Bremsstrahlung** $eN \rightarrow eN\gamma$. In a fixed target configuration the $A'$ is produced very forward, carrying most of the beam energy, while $e^-$ emerges at a larger angle.

**Annihilation** $e^+e^- \rightarrow \gamma A'$

**Meson decays**
Dark photon decays

Invisible decay

\[ A' \rightarrow \chi \bar{\chi} \]
- Requires \( m_{A'} > 2 m_\chi \)
- Independent on \( \epsilon \)

Visible decay

\[ A' \rightarrow e^- e^+ \]
- Decay regulated by \( \epsilon^2 \)
- Independent on \( m_\chi \)
- Requires \( m_{A'} < 2 m_\chi \)

A broad international program of accelerator experiments is currently focused on exploring light dark matter and associated new force.
**Direct dark photon searches:** focused on identifying the mediator through its decay into SM particles. The production mechanism is $eZ \to eZA'$ or neutral meson decays, and the mediator is reconstructed through its leptonic decays $A' \to e^+e^-$

**Missing mass:** The DM is produced in exclusive reactions and identified as a narrow resonate over a smooth background in the recoil mass distribution

**Missing momentum/energy:** The DM is produced in $eZ \to eZ(A' \to XX)$ and identified through the missing energy/momentum carried away by the escaping DM particles

**Electron Beam Dump:** The DM is produced via $eZ \to eZ(A' \to XX)$ and typically detected via $eX \to eX$ or $NX \to NX$ scattering in a downstream detector
Direct Dark Photon search

**APEX**

- Fixed target experiment at HALL A @ JLAB
- Detection strategy is mA' bump hunt
- Engineering run to demonstrate method done (2010)
- Sensitivity: $\epsilon^2 > 10^{-7}$ in the mass range $60\text{ MeV} < m_{A'} < 550\text{ MeV}$

**HPS**

- Fixed target experiment at HALL B @ JLAB
- Detector: SVT + ECAL (I. Ballossino et al. (HPS coll.) NIMA 854 (2017) 89)
- Two complementary search techniques: resonance search and detached vertexing.
- Sensitivity: $10^{-10} < \epsilon^2 < 10^{-5}$ in the mass range $20\text{ MeV} < m_{A'} < 1\text{ GeV}$
- Full approval from the laboratory for a 180-day run with different beam energy configurations
- Two data-taking periods have been completed: in 2015, 1.7 days (10 mC) at 1.06 GeV and in 2016, 5.4 days (92.5 mC) at 2.3 GeV

**Missing Mass**

It aims to use annihilation production \((e^+e^- \rightarrow \chi(A' \rightarrow XX))\) and missing mass searches.

**PADME experiment**

- Small scale fixed target experiment
- 550 MeV \(e^+ @ BTF\) in INFN-LNF
- Thin active diamond target
- Charged particle detectors
- Calorimeter
- Expected to collect \(\geq 10^{13}\) positron on target

**Sensitivity:** \(\epsilon^2 > 10^{-7}\) in the mass range \(m_{A'} < 24\) MeV in a complete model independent way (Independent from the \(A'\) decay mechanism, \(A'\) lifetime, nature and mass of the dark matter).
Fixed target experiment combining the active beam dump technique with missing energy measurement

100 GeV e– secondary beam from the SPS beam line @ CERN

A typical signature for a signal will be missing energy in the ECAL and no activity in the VETO and HCAL.
Missing momentum/energy

J. Mans, EPJ Web of Conferences 142, 01020 (2017)

LDMX collaboration: https://confluence.slac.stanford.edu/display/MME/Light+Dark+Matter+Experiment

LDMX experiment

- Missing momentum experiment
- A Low current, multi-GEV e- beam with high-repetition rate
- The experimental signature consists of a soft wide angle scattered electron, characteristic of DM production at an electron fixed-target reaction, plus missing energy
1 Step: LDM production

- Xs produced via $A'$ emission and invisible decay
  - GeV – high intensity e– beam

2 Step: LDM detection

- X scatter off nucleons, nuclei, or electrons in the detector volume, giving rise to a detectable signal.

The eternal fight in physics: signal vs background
The Beam Dump eXperiment (BDX)

Past e- beam dump experiment: E137 @ SLAC

PRL 113, 171802 (2014)

LDM results are a re-analysis of old data
the experiment itself was not optimized for this research

An optimized e- beam-dump experiment can explore new territories in the LDM space:

BDX


Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

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BDX Universities

INFINITY-Italy: Genova, Catania, Roms, Bologna, Torino, LNS, LNE Padova, Roma TV, Sasso R, Ferrara, Bari, Lecce
Jefferson Lab, BNL
FNAL
Occidental College
University of New Mexico
SLAC
Ohio University
Stony Brook
Canisius College
University of New Hampshire
Mississippi State University
Hampton University
Old Dominion University
Northwestern University
Manz University
Guelph
Glasgow University
IPN-Orsay

BDX Institutions

BDX collaboration
✓ High electron beam current ~ 65 μA (integrated charge $10^{22}$ EOT in 41 weeks)
✓ Energy beam available: 11 GeV
✓ Parasitic to experimental program. Use electrons that are otherwise thrown away.
✓ New underground experimental Hall
**X detection**

**What?** BDX experimental signatures: $X-e^-\rightarrow EM$ shower

~ GeV energy

**How?** EM Calorimeter: A homogenous crystal-based detector

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**EM Calorimeter**

- 8 Blocks (10x10 crystals each)
- 800 CsI(Tl) crystals
- 50 x 55 x 295 cm$^3$
- 6x6 mm$^2$ Hamamatsu SiPMs

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**Background rejection**

**What?** Cosmic and Beam-on backgrounds

**How?** Active Veto: Two layers of plastic scintillator

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**Inner Veto**

- Plastic scint + WLS fibers
- SIPM readout

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**Passive shielding**

- 5 cm thick lead bricks

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**Outer Veto**

- Plastic scint
- light guide + PMT readout
- WLS + PMT/SiPM
**BDX prototype**

*CsI(Tl) crystals + SiPMs*

Inner Veto: plastic scint. + WLS + SiPM

Inner Veto in the lead vault

Outer Veto: plastic scint. + Light guide + PMT

Outer Veto: plastic + WLS plastic + PMT
Full assembled @ INFN - CATANIA

CsI(Tl) crystals + SiPM

Inner Veto: plastic scint. + WLS + SiPM

Outer Veto: plastic scint. + Light guide + PMT

Veto: plastic + PMT

BDX prototype
Cosmic-ray backgrounds

- Cosmic background measured with the BDX detector prototype at INFN -CT and INFN -LNS, with similar overburden of the JLAB configuration
- Geant4 simulations (GEMC framework) in very good agreement with data
- The majority of cosmic muons are detected and rejected by the two veto detectors
- Cosmogenic background eliminated with Veto anticoincidence and Ethresh>0.3 GeV: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLAB setup
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Crystal energy deposition

Data

MC
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Count rate measured in 1 crystal

All cosmics IV + OV anti-coincidence
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Cosmogenic background eliminated with Veto anti-coincidence and Ethresh > 0.3 GeV: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLAB setup (800 CsI(Tl) crystals).

Cosmogenic background is negligible with high-energy threshold. It will be measured on-site when beam is off.
The interaction of the 11 GeV electron beam in the dump was simulated and the flux of secondaries was studied as a function of the distance from the dump.

- Photon and neutron cascades absorbed in shielding
- Muons ranged out in Fe
- Neutrinos survives to the detector → For a simulated statistics of $2.2 \times 10^8$ EOT we obtained, after all rejection cuts and extrapolation to $10^{22}$ EOT $\sim 10 \, \nu$.

**Neutrino irreducible background** is the ultimate limitation for BDX.
BDX is an optimized beam-dump experiment that can be conclusive for some Light Dark Matter scenarios. Obtained results will guide future second-generation experiments.

BDX @ JLAB: Reach

Fermion or Scalar DM, $e^-$ scattering, $m_A \ll m_{A'}$, $\alpha_D = 0.1$

$\chi - e$ elastic scattering

Leptophilic DM, Most Conservative: $\alpha_D = 0.5$, $m_{A'} = 3 m_\chi$

$\chi - N$ inelastic scattering

BDX can be 10-100 times more sensitive than previous experiments excluding a significant area of the parameter space.
Dark matter in the MeV-to-GeV range is largely unexplored.

Growing worldwide interest for LDM searches: many on-going experiments and future initiatives

Beam Dump eXperiment at JLab: search for Dark sector particles in the 1 ÷ 1000 MeV mass range.

✓ Full proposal submitted to JLab PAC 44 – conditionally approved: to run parasitically at Jefferson Lab for 41 weeks at ~11 GeV, which will allow it to collect $\sim 10^{22}$ electrons on target.

✓ BDX can be 10-100 times more sensitive than previous experiments

✓ BDX update submitted to JLAB-PAC45: Test plan to measure muon flux behind HALL A beam dump to validate MC

BDX can produce important physics results, exploring unknown territories in the LDM space, and providing directions for future activities in this field
Beam-related μ: on-site measurement

Measurement campaign to characterize the flux of high-energy μ produced in the Hall-A beam dump.

**GOAL**: validate MC simulations

- Measure the muon flux behind the Hall A beam-dump in 2 different positions (B and C) with BDX-HODO

- BDX-HODO: 1 CsI(Tl) coupled 6x6 mm$^2$ Hamamatsu S13360-6025 and sandwiched between a set of segmented plastic scintillators.

- From the FLUKA (GEANT4) simulations a drop in rate by about one order of magnitude when moving from one location to the next

- **Rate of beam-on muons** measured by BDX-Hodo are expected to be sizable for a beam current of 10 μA: ~3.7kHz for B and ~0.5kHz for C.