DarkMESA –
Light Dark Matter Search
at the MESA Beam Dump

Patrick Achenbach
Univ. Mainz
Jan. 2019

and Sebastian Baunack, Paul Burger, Mirco Christmann,
Achim Denig, Luca Doria, Frank Maas & Harald Merkel
Dark Matter Properties

Matter content of the known Universe:

- Dark matter: ~23 %
- Dark energy: ~72 %
- Atomic matter: ~5 %
- Light neutrinos: ~0.1 %

Unknown DM properties:

- Weakly charged (WIMP) or not?
- E.-m. (milli?)-charged or not?
- Hidden sector existing or not?
- Portal existing or not?
- Darkly charged or not?
- Weak-scale mass or not?

Known DM properties:

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic
Early Universe Thermal DM Freeze-Out

Freeze-out relation: $\Omega_{\text{DM}} \leftrightarrow \text{annihilation rate}$

$\Omega_{\text{DM}} \approx \frac{2 \times 10^{-37} \text{cm}^2}{\langle \sigma_{\text{annih}} v \rangle} \approx 0.23$


WIMP Paradigm: If stable WIMPs exist, they are naturally produced with a relic density consistent with the one required of dark matter.
Hidden sector composed of particles without SM interactions
- Many forms of hidden interactions seem conceivable
- The simplest form is an electromagnetism analogue
- Disclaimer: A dark sector with set of hidden interactions may seem an over-complicated solution to the dark matter problem

"Plurality must never be posited without necessity".
William of Ockham: *Sentences of Peter Lombard* (1495)
Mediators between Sectors

- Vector, Higgs, neutrino mediators in many BSM constructions
- Mediator typically is unstable (and not DM)
- Some aspects of this idea are testable and amenable to observations
- SM coupling via kinetic or mass mixing or with direct coupling

\[ \mathcal{L}_{mix} = -\frac{\varepsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{\text{dark}} \]
**Light Dark Matter Annihilation**

### Secluded Annihilation

\[ m_\chi > m_{Med} \quad \langle \sigma v \rangle \sim g_D^4 / m_\chi^4 \]

No SM coupling dependence: arbitrary coupling possible. Hard to test experimentally.

### Direct Annihilation

\[ m_\chi < m_{Med} \quad \langle \sigma v \rangle \sim \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{Med}^4} \]

There is a minimum SM coupling compatible with thermal history.

**Experimentally testable target:**

\[ y = \frac{g_D^2 g_{SM}^2}{4\pi} \left( \frac{m_\chi}{m_{Med}} \right)^4 \geq m_\chi^2 \langle \sigma v \rangle_{Relic} \]
The virtue of Dark Bremsstrahlung from Electrons

- $A'$ carries away most of an electron’s energy in the first reaction
- $A'$ emitted in a narrow forward cone
- Recoil electron is soft, *i.e.* large missing energy
- Recoil electron at large angles, *i.e.* large missing momentum

\[ \sigma \propto \frac{\epsilon^2}{E_{cm}^2} \quad \text{versus} \quad \sigma \propto \frac{Z^2 \epsilon^2}{m_{A'}^2} \]

Dark Bremsstrahlung is a simple way to get large DM yield
Two main operation modes:

1. ERL operation: MAGIX experiment
   *High beam currents, thin gas-jet targets*

2. EB operation: P2 experiment
   *High stability, thick targets, long runs, high luminosities, stable conditions*

MESA accelerator:
- Normal conducting injector
- Two superconducting cavities
- Several recirculations
- 1.3 GHz c.w. electron beam

High-power beam dump ⇒ Parasitic experiments

DarkMESA – Light Dark Matter Search at the MESA Beam Dump
The DarkMESA Concept

\[ Y_{Prod} \sim \epsilon^2/m_A^2 \]

\[ Y_{Det} \sim \epsilon^2 \alpha_D/m_A^2 \]

Target

Beam dump

Concrete walls and air

Detector

\[ \sim 12 \text{ m} \]
\[ \sim 2 \text{ m} \]
\[ \sim 23 \text{ m} \]
\[ 2.4 \text{ m} \]

Total yield: \[ Y_{TOT} \sim \epsilon^4 \alpha_D/m_A^4 \]
Beam energy $\sim 147$-$155$ MeV
Beam current $\sim 150$ $\mu$A
P2 target: 60 cm liquid hydrogen
- 3 kW beam power loss
- 17 MeV beam energy loss
- 2° multiple scattering angle
- $e\, p \rightarrow e\, n\, \pi^+$ threshold at 152 MeV
$\Rightarrow$ No pion/muon/neutrino production
- Beam dumped after 12 m
- Beam energy ~ 130–138 MeV
- Beam power ~ 20 kW
- Lateral beam width ~ dump size
- Main absorber material: 20 $X_0$ Al
- 10 000 h of operation:
  - $\sim 3 \times 10^{22}$ electrons
  - $\sim 5400$ C charge dumped
- Radiative production of (massive) dark photon $A'$ coupling with $\epsilon$
- Subsequent decay to SM particle pairs with $\epsilon$ or dark matter pairs with $\alpha_D$
- Assume dominant invisible decay channel $\Gamma(A' \rightarrow \bar{\chi}\chi)/\Gamma_{\text{total}} \simeq 1$

[Bjorken et al., Phys. Rev. D80, 075018 (2009)]

$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2x}{m_{A'}^2} \left(1 + \frac{x^2}{3(1-x)}\right)\log$$
Example simulations for $m_{A'} = 10$, 50 and 100 MeV/c²

- $m_{\chi} = 1$ MeV/c²
- $m_{\chi} = 10$ MeV/c²
- $m_{\chi} = 50$ MeV/c²
- $m_{\chi} = 100$ MeV/c²

Testing ground for DM production with $20$ MeV $\ll m_{A'} \ll 120$ MeV
Dark Matter Beam-Line

- 20 $X_0$ beam-dump, 70 $X_0$ (~ 8 m) barite concrete
- Total length of 23 m including several shielding walls
- Practically free of beam-related background
Detector needs to be sensitive to small recoil energies

$E_{\text{beam}} = 140$ MeV

$\chi$ elastic scattering kinematics

Detector acceptance: few % for small $m_{A'}$
Elements of Detector Design

Ideal Requirements:
1. Large Surface (Acceptance)
2. Large thickness (Int. Prob.)
3. High density (Int. Prob.)
4. Reliability (long running time)
5. Background rejection
   - Cosmics
   - Natural Backgrounds
   - Beam Backgrounds
   - ...

Baseline Concept
Inorganic crystal calorimeter (high density)
- Cherenkov (fast, no neutrons)
- Scintillator (higher light yield)

- 81 lead glass blocks
- $30 \times 30 \times 150 \text{ cm}^3 = 11 \text{ m}^3$
- $274 \times 274 \text{ cm}^2$ cross section
- Readout with 5 inch PMTs
Phased Approach

Phase 1

1000 (available!) PbF2 crys
Volume: 1x1x0.13 m³
5x5 crystal sub-modules
1200 kg mass

Phase 2

Addition of Pb-Glass blocks
Volume: 1m³
4100 kg mass

Phase 3

Reach maximum volume: O(10m³)

DarkMESA – Light Dark Matter Search at the MESA Beam Dump
A4 Calorimeter Recycling

- 1022 PbF$_2$ crystals
- Volume 0.15 m$^3$, 1.2 tons
- Density 7.77 g/cm$^3$

Status:
- A4 calorimeter disassembled
- Crystals and PMTs in laboratory

Phase 1 calorimeter of DarkMESA
Projected Exclusion Limits from DarkMESA

Full simulation of DarkMESA

Three detector stages:

- Stage A: existing PbF$_2$ crystals
  (A4 - 0.13 m$^3$ volume)
- Stage B: lead glass calorimeter
  (1 m$^3$ volume)
- Stage C: lead glass calorimeter
  (11 m$^3$ volume)

DarkMESA has the potential to touch the thermal relic targets!
Prototyping and Beam Tests

Measurements:
- Light Yield
- Position dependence
- PMT voltage scan

Input to Simulation

Investigated Crystals:
- SF5 (Pb-Glass, Schott AG)
- SF6 (Pb-Glass, Schott AG)
- SF57HTultra (Pb-Glass, Schott AG)
- BGO (on loan from Frascati, L3-LEP)
- PbF₂ (from A4)

Beam Position Monitor and Trigger Detector
Cherenkov Radiators
PMTs
Movable Table

Beam Energy

DarkMESA – Light Dark Matter Search at the MESA Beam Dump

Jan. 2019

P Achenbach, U Mainz
Development of a Veto System

Comics Veto System
Multiple scintillator layers
Lead / Neutron shielding

Crystal Array
Available from A4:
- PbF$_2$ crystals
- PMTs

Key questions
- Signal properties
- Backgrounds

Background rejection:
- Use of beam on/off information:
  beam-time scheduling 50% / year
- Segmenting of detector read-out:
  coincidences eliminating noise
- Use of several layers of veto detectors

Red/Blue: w/ 1 or 2 veto layers

Cosmics Background
DarkMESA can contribute to DM searches

Ideal for *light* and *weakly coupled* particles:
- Very large number of electron on target
- Extremely stable beam conditions
- Very low backgrounds
- New infrastructure
  with dedicated floor space for detector

**Conclusion**

Dark Photon thermal relic targets could be reached within a few years
Direct WIMP Searches

Assuming $m_W \sim 100 \text{ GeV}/c^2$, $v \sim 10^{-3}c$:

→ Ordinary matter recoiling with $E \sim 1–100 \text{ keV}$ from DM collisions

→ Typically ultra-sensitive detectors located deep underground

- WIMP hypothesis nowadays cornered

- Unexplored mass region $< 1 \text{ GeV}/c^2$

- Small mass and small coupling can reproduce correct relic density if $m_\chi/g_\chi^2 \sim m_w/g_w^2$

Light Dark Matter with large self-interaction and small SM coupling possible
Dark Photon Couplings and Decays

- Photon-like couplings
- If $2\ m_X < m_{A'}$ and not too small $\alpha_D$: invisible decays into DM pairs
- Else if kinematically allowed: visible decays to $ee, \mu\mu, \pi\pi, \ldots$

- Dark Bremsstrahlung: $eZ \to eZA'$ electron beam dump
- Annihilation: $ee \to \gamma A'$ electron-positron collider

- Dark Bremsstrahlung: $pZ \to pZA'$ proton beam dump
- Drell-Yan process: $qq \to A'$ proton beam
- Meson decay: $\pi \to \gamma A'$ etc. proton beam

Searches with Collider and Beam Dump Experiments

Colliders (visible/invisible decays)  Beam dumps (invisible decays)
- B-Factories (BaBar/Belle II)  - BDX@Jlab, DarkMESA
- LHC experiments  - Proton beam dump, re-analyses
- Meson decays
Recent Constraints from NA64

- 100 GeV electron beam at CERN
- Missing energy experiment
- $4.3 \times 10^{10}$ electrons on target

[NA64, Phys. Rev. D 97 (2018)]

Invisible decay exclusion limits
Extending to $< 10^{-4}$ for masses of 10 MeV
Recent Constraints from *BaBar*

- e+e- collider at B-factory
- missing energy and missing momentum
- 53 fb\(^{-1}\) from \(\Upsilon(nS)\)

[Recent constraints from *BaBar* in *Phys. Rev. Lett.* 119, 131804 (2017)]

Invisible decay exclusion limits extending to 10\(^{-3}\) at masses < 1 GeV
Proposal for BDX@JLab

- 800 recycled \textit{BaBar} crystals
  Volume: $\sim 0.5 \text{ m}^3$
  Signal: shower with $E_{thr} \sim 300 \text{ MeV}$
- JLab PAC approval
- Funding & schedule unclear

spokesperson: Marco Battaglieri
Particle Production in Beam Dump

Geant4 simulation by Mirco Christmann

Hard photon flux relates to Dark Photons flux
Energy distribution at different shower depths:

- Shower maximum within first $X_0$
- On average only ~ 3 charged particles per beam electron
- On average only ~ 1 hard photon emission per beam electron

Complementary energies to all other beam dump experiments