Dark Photon search with an electron beam dump near large liquid scintillator detector at underground

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Model for Dark Photon and Dark Matter

- A simple model to include the dark matter by introducing an extra U(1)’
  - **Contains Dark photon (A’) and Dark matter**

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_A^2 A'^2 - \sum_f q_f e (A_\mu + e A'_\mu) \bar{f} \gamma^\mu f + \mathcal{L}_{DM}, \]

- Dark Photon and EM charged matter coupling: \( e e \)

**Dark matter sector:**

\[ \mathcal{L}_{DM} = \begin{cases} 
\bar{\chi}(i\not{D} - m_\chi)\chi, & \text{fermionic DM (} \chi \text{)}, \\
|D_\mu \varphi|^2 - m_\varphi^2 \varphi^* \varphi, & \text{bosonic DM (} \varphi \text{)} 
\end{cases} \]

\[ D_\mu = \partial_\mu + ig' A'_\mu \]

- Dark Photon and DM coupling: \( g' \) (U(1)’ charge)
Worldwide map for Dark photon search

Ongoing and proposed experiments

- Mainz (Germany)
- Orsay (France)
- GSI (Germany)
- VEPP (Russia)
- CERN (Europe)
- INFN (Italy)
- KEK (Japan)
- BES (China)
- FNAL (USA)
- SLAC (USA)
- BNL (USA)
- JLab (USA)
Constraints for $A'$

Astrophysics and other non-accelerator exps. ($m_{A'} < 1$ MeV)

**Accelerator exps ($m_{A'} > 1$ MeV)**

$A' \rightarrow$ Standard Model

**Usually look for $A'$ decays:**

Ex) $A' \rightarrow e^+ e^-$
A' production with electron accelerator (I)

Production rate: $\sim \varepsilon^2 \sigma_{\text{brem}}$

- $m_{A'} > 2 m_e$: $A' \rightarrow e^+ e^-$
- $m_{A'} < 2 m_e$: $A' \rightarrow 3 \gamma$ (Highly suppressed)

$\sim 10 \text{ keV} < m_{A'} < 1 \text{ MeV}$ -> Dark-Photon Dark Matter
A’ production with electron accelerator (II)

- A’ production rate in a thick target approximation:

\[ N_{A’} \sim 10 \times N_e \epsilon^2 \frac{m_e^2}{m_{A’}^2} \]

\( N_e \): No. of incident electrons on target

- Decay length of A’ for \( m_{A’} > 2 m_e \)

\[ L_{dec} \sim 10^{-3} m (\gamma/10)(10^{-4}/\epsilon)^2 (100 \text{MeV}/m_{A’}) \]

For \( m_{A’} =1 \text{ MeV} \) and \( \epsilon =10^{-7} \), \( L_{dec} > 10 \text{ km} \)
# Electron beam dump experiments (I)

## Old e-beam dump experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>target</th>
<th>$E_0$ [GeV]</th>
<th>$N_{el}$ electrons</th>
<th>$N_{el}$ Coulomb</th>
<th>$L_{sh}$ [m]</th>
<th>$L_{dec}$ [m]</th>
<th>$N_{obs}$</th>
<th>$N_{95%up}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E141 [47]</td>
<td>W</td>
<td>9</td>
<td>$2 \times 10^{15}$</td>
<td>0.32 mC</td>
<td>0.12</td>
<td>35</td>
<td>1126$_{-1126}^{+1312}$</td>
<td>3419</td>
</tr>
<tr>
<td>E137 [48]</td>
<td>Al</td>
<td>20</td>
<td>$1.87 \times 10^{20}$</td>
<td>30 C</td>
<td>179</td>
<td>204</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>E774 [49]</td>
<td>W</td>
<td>275</td>
<td>$5.2 \times 10^9$</td>
<td>0.83 nC</td>
<td>0.3</td>
<td>2</td>
<td>0$_{-0}^{+9}$</td>
<td>18</td>
</tr>
<tr>
<td>KEK [39]</td>
<td>W</td>
<td>2.5</td>
<td>$1.69 \times 10^{17}$</td>
<td>27 mC</td>
<td>2.4</td>
<td>2.2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Orsay [40]</td>
<td>W</td>
<td>1.6</td>
<td>$2 \times 10^{16}$</td>
<td>3.2 mC</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>
Electron beam dump experiments (II)

E137@SLAC (1988)

- 20 GeV
- Target: Aluminum plates
  - Al target was cooled with cooling water
- 179 m for shielding
- 204 m for decay region

Decay region in air (204 m)
Electron beam dump experiments (III)

KEK (1986)

- 2.5 GeV
- 3.5-cm-thick tungsten
- 2.4 m for shielding
- 2.2 m for decay region
Electron beam dump experiments (IV)

DarkLight Experiment @ Jlab FEL

- Use the Energy Recovering Linac (ERL)
- Gaseous hydrogen target inside beam pipe.
- 100 MeV, 10 mA -> 1 MW of power

Target design
We are considering the following features for the proposal,

- A large scale detector is located at a deep underground lab.
  - 1 kton of LS with \( \sim 200 \) keV threshold
  - Good detection efficiencies for e and \( \gamma \) events
- Electron accelerator near by the detector
  - 1 MW power with continuous beam
  - e-beam energy: 20 MeV -> 100 MeV upgradable.
Energy and angular distribution

- GEANT 4 simulation: $e^- + $ tungsten $\rightarrow$ gamma +X
- $\sim$ 10 photons/1 $e^-$ for $E_\gamma > 1$ MeV
A’ and Dark matter detection

- We are searching for $m_{A'} < 1$ MeV
  - $A'$ detection with Compton-like process

$$\sigma \sim \alpha^2 \epsilon^2$$

- $X$-section is dominant in $\sim 1$ MeV

- Dark matter detection

  - Electron recoil
  - Nuclear recoil
Back-of-envelope estimation for $A'$ search

1 MeV-mass $A'$ with 1 MW and 20 MeV e-beam

• Sensitivity for 1 year running:

$$N_{A'} \times \sigma_{\text{comp}} \times N_e \sim \epsilon^4 \rightarrow \epsilon < 1.8 \times 10^{-8} \text{ @ 90% C.L.}$$

$N_e$: number of electron in fiducial mass (100 ton) of LS.

Energy spectra in Borexino

1: Raw spectrum

4: Fiducial Cut
Beam line consideration

- e-beam size: < 1 mm\(^2\)
- Tungsten target: \(\sim 1 \text{ cm} \times 1 \text{ cm} \times 20 \text{ cm long}\)
- Beam shield with iron: \(1 \text{ m} \times 1 \text{ m} \times \sim 2 \text{ m}\)
- Concrete: \(\sim 1 \text{ m thick}\)
- Beam window and target can be melted with 1 MW beam power: 
  \(1 \text{ MW}/1 \text{ mm}^2\)

- Defocusing e-beam on beam window and target: > 10 cm\(^2\)
- Target with cooling: \(10 \text{ cm} \times 10 \text{ cm} \times 20 \text{ cm}\)
  - \(1 \text{ MW/mm}^2 \rightarrow 100 \text{ W/mm}^2\)
High power electron accelerator near by large detector would provide an unique program for CUP in future.

- Dark photon mass below 1 MeV is difficult region in over ground experiment.
- Low mass dark matter search

Before starting this experiment at underground, we need to check whole system at over ground
- accelerator
- target system
- beam dump, background and radiation safety