A Hunt for Hidden Photons with the LZ Experiment

Athoy Nilima
University of Edinburgh
LZ Collaboration

LUX-ZEPLIN

- Dark Matter Direct Detection Experiment
- Detector Located at Sanford Underground Research Facility (SURF), South Dakota, USA
- 37 institutions, 250 scientists, engineers, and technicians
LZ Detector

- liquid xenon Time Projection Chamber (LXe-TPC)
- 7 tonnes of LXe
- Gd loaded outer detector
- 494 PMTs
- (Additional veto) 131 xenon “skin” PMTs
- science run to start in 2020
- 1000 live days * 5.6 tonnes planned exposure

Detail overview and status: See Benjamin Krikler’s slides from yesterday!!
Detector Principle

• Signals due to particle interactions:
  • S1: Primary Scintillation Signal (prompt photons, directly measured by PMTs)
  • S2: Secondary Ionisation Signal (from electroluminescence of electrons extracted in gaseous phase)
• Energy and Position Reconstruction by S1-S2 Signals
**Projected Sensitivity: WIMPs**

- Weakly Interacting Massive Particles (WIMPs): An well-motivated Dark Matter candidate
- What LZ mainly Looks For: WIMP- Nuclear Recoils
- for 1000~live days and a 5.6~tonne fiducial mass.
- The best sensitivity of $1.6 \times 10^{-48}$ cm$^2$ is achieved at a WIMP mass of 40 GeV/c$^2$.
- The -2σ expected region is omitted based on the expectation that the limit will be power constrained [8]

![Fig.3. LZ projected sensitivity to SI WIMP-nucleon elastic scattering for 1000~live days and a 5.6~tonne fiducial mass [9]](image)
But....What if Dark Matter is not a WIMP?

- A vast possible scenario.....
- Hence a vast possible searches.....

Fig.4. A Vast Possible Theories
Gauge group of EM interaction:
- 1 charge (e.g. electron)*
- 1 gauge boson (photon)

Gauge group of Weak interaction:
- 2 charge types (2 weak isospin charges)
- 3 Gauge bosons ($W^+, W^-, Z$)

Gauge group of Strong interaction:
- 3 charge types (colour charges)
- 8 gauge bosons (gluons)

Is this structure that Obvious? **No!**
Then….Can there be any additional gauge forces?
• Dark Matter (DM) is secluded from SM
• extra $U'(1)$ gauge boson as a mediator of SM-DM interactions: **Hidden Photons**
• Minimal Model: broken U(1) symmetry and a massive hidden photon
• Coupling through the mechanism of kinetic mixing
• Correct DM relic abundance can be obtained automatically (M. Pospelov et al. [6])
• Several Other models incorporating U(1) extensions also exist
Hidden Photoelectric Effect

\[ \frac{\sigma_{\text{abs}} v}{\sigma_{\text{pe}} (\omega = m_{\text{HP}}) c} = \frac{\alpha'}{\alpha} \]

- \( v \) = velocity of the HP,
- \( \epsilon = (\alpha'/\alpha)^{1/2} \) = Kinetic mixing
- \( \sigma_{\text{abs}} \) = Hidden p.e. cross-section
- \( \sigma_{\text{pe}} \) = (ordinary) p.e. cross-section

Electromagnetic Fine Structure Constant

\[ \alpha = \frac{e^2}{4\pi} \]

Hidden Fine Structure Constant

\[ \alpha' = \frac{g_D^2}{4\pi} \]

- Analogous to the photoelectric effect in SM
- HP completely absorbed
- Line Spectra

Event Rate: (in LXe)

\[ R_{\text{HP}}[1/\text{kg/day}] = \frac{4 \times 10^{23} \alpha' \sigma_{\text{pe}}[\text{barn}]}{A \alpha m_{\text{HP}}[\text{keV}]} \]

\( A = 131.3 \) is an atomic mass of xenon of natural composition
Connection to Axion Like Particle (ALP) Searches

Hidden Photoelectric Effect for HPs

\[ R_{HP}[1/\text{kg/day}] = \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \sigma_{pe}[\text{barn}] \frac{m_{HP}[\text{keV}]}{A} \]

Axio-electric effect for ALPs

\[ R_{ALP}[1/\text{kg/day}] = \frac{1.2 \times 10^{19}}{A} g_{Ae}^2 \sigma_{pe}[\text{barn}] \cdot m_{ALP}[\text{keV}] \]

\[ R_{HP}/R_{ALP} = 3.3 \times 10^4 (\alpha'/\alpha) x (g_{Ae})^{-2} x (1/m_{HP} \cdot m_{ALP}) \]

Once we have a constraint on (\alpha'/\alpha) for HP we can convert that to a constraint on \( g_{Ae} \) for ALPs
Analysis Framework

Theoretical Rate Calculation

\[ R_{\text{HP}}[1/\text{kg/day}] = \frac{4 \times 10^{23} \, \alpha' \, \sigma_p[\text{barn}]}{A} \, \frac{\alpha}{m_{\text{HP}}[\text{keV}]} \]

PDF Generation

Signal

Background

Analysis Workspace

Statistical Analysis: PLR

Merge, Stich and Analyse

RESULT

Convert into \((\alpha'/\alpha)\) Limit

NEST version 2
**Background Model**

- Vast Majority of Backgrounds in ER band
- This Analysis: Used the same Background Models as in WIMP search
- ER Background Model up to 100 keV

<table>
<thead>
<tr>
<th>Background</th>
<th>Components</th>
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</thead>
<tbody>
<tr>
<td>ER</td>
<td>Solar pp+Be7 Neutrinos</td>
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<tr>
<td></td>
<td>Xe136 2vBB Decay</td>
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<td></td>
<td>Kr85</td>
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<td>Rn-222</td>
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<td></td>
<td>Rn-220</td>
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<tr>
<td></td>
<td>Detector ERs</td>
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</tbody>
</table>

![Fig.6. ER Background Model](image)

Table 1. ER Background Components
HP Signal Model

- Investigated Hidden Photon Masses from 2 keV to 85 keV
- Theoretical event rates calculated according to Slide 13
- Signal Models generated using NEST (Nobel Element Simulation Technique) version 2

Energy Reconstruction

For Projected Detector:

\[ g_1 = 0.118735 \text{ phd/photon,} \]

\[ g_2 = 79.2291 \text{ phd/electron} \]
LZ Projected Sensitivity: Hidden Photons

- Sensitivity Estimation: Hidden Photons
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- Hidden Photon Mass (This Work) 2-85 keV
- Experimental limits taken from XMASS 2018 paper [3]
LZ Projected Sensitivity: ALPs

- Sensitivity Estimation: ALPs
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- ALP Mass (This Work) 2-85 keV
● Hidden Photon Sensitivity: (over the mass 2-85 keV/c²)
  ○ we expect more than ~2 order of magnitude improved sensitivity for (α'/ α)
  ○ (α'/ α) no larger than 2.9 x 10⁻²⁹ (Highest value at 34 keV, atomic binding effect)

● ALP sensitivity: (over the mass 2-85 keV/c²)
  ○ g_{Ae} no larger than 2.8 x 10⁻¹⁴ (Highest value at 34 keV, atomic binding effect)
  ○ ~2 order of magnitude improvement
Questions?
References

5. Paul Langacker, Reviews of Modern Physics, vol. 81,(2009)
Backup Slides
• Minimal Model: single new broken U(1) gauge symmetry
• models with unbroken U(1) gauge symmetry result in a massless dark photon carrying a long-range interaction.
• A massless dark photon, however, will experimentally be hard to distinguish from the Standard Model photon.

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_{A'^{}}^2 A'^{\mu} A'^{\mu} + \epsilon e A'^{\mu} J_{\mu}^{EM} \]

- \( F'_{\mu\nu} \) dark photon field
- \( m_{A'} \) dark photon mass, generated by the Higgs or Stueckelberg mechanism
- \( J_{\mu}^{EM} \) EM current with coupling \( \epsilon \)
- \( \epsilon \) Kinetic Mixing Factor
Kinetic Mixing

- Tree level SM photon $\gamma$- hidden photon $\gamma'$ interaction is forbidden
- Simplest Case: by a loop of non-SM charged heavy particles, $\psi'$
- $\gamma$ and $\gamma'$ couple to them with strengths $e$ and $g_D$
- Properties of $\psi'$ particles:
  - they are charged; hence sensitive to EM interaction
  - have not been detected yet in experiments like LHC: mass scale should be above the weak scale
  - this mass scale constrains the coupling strength of $\gamma'$ to $\gamma$
  - At Lower Energies < Weak Scale: $\psi'$ can be integrated out.

\[ L_{\text{mediator}} = \varepsilon e j^\mu A'_\mu \]

Fig. 5. Feynman diagram of kinetic mixing

Below Electroweak Scale
LZ Projected Sensitivity: ALPs

- Sensitivity Estimation: ALPs
- Statistical Analysis: Profile Likelihood Ratio (PLR) Method
- ALP Mass (This Work):
  - $2-85 \text{ keV}$
  - $g_{Ae}$ no larger than $2.8 \times 10^{-14}$
- Previous Work by LZ:
  - $1-40 \text{ keV}$
  - $g_{Ae}$ no larger than $5.9 \times 10^{-14}$