Compton photo-production of dark particles

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Outline

▪ Theory
▪ Photon beam experiments
▪ Background processes
▪ Sensitivities
• Production of dark photon \((A')\), axion-like particle (ALP) \((a)\) and dark scalar \((\phi)\) in Compton-like scattering processes.

• Relevant coupling terms:

\[
\Delta \mathcal{L} \equiv \epsilon e \bar{\psi}_e \gamma_\mu \psi_e A'^\mu
\]

\[
\Delta \mathcal{L} \equiv g_{ae} \bar{\psi}_e \gamma_5 \psi_e a
\]

\[
\Delta \mathcal{L} \equiv \gamma_e \bar{\psi}_e \psi_e \phi
\]
• For low-mass dark photons \((M \lesssim m_e)\), the behavior is Compton-like.

• For 10 GeV photon beam hitting Hydrogen atom and producing 10 MeV ‘dark’ particle:

\[
\sigma(\gamma e \rightarrow A'e) \sim 1.4 \text{ pb} \left( \frac{\epsilon}{10^{-4}} \right)^2
\]

\[
\sigma(\gamma e \rightarrow ae) \sim 6.5 \text{ pb} \left( \frac{g_{ae}}{10^{-4}} \right)^2
\]

\[
\sigma(\gamma e \rightarrow \phi e) \sim 20.2 \text{ pb} \left( \frac{y_e}{10^{-4}} \right)^2
\]
$m_A' = 2 \text{ MeV}/c^2$, full line
$m_A' = 100 \text{ MeV}/c^2$, dashed line

Brems. in $A$: $\sigma / (Z^2 e^2)$ vs. $E$

Brems. in $A$: $\sigma / (Z^2 e^2)$ vs. $E$

Res. Brems. in $e^+e^-$: $\sigma / (Z e^2)$ vs. $E$

Non res. Brems. in $e^+e^-$: $\sigma / (Z e^2)$ vs. $E$

Compt.: $\sigma / (Z e^2)$ vs. $E$

Theoretical cross section [mb] vs. $E$ [GeV]
- Corrections for atomic electrons:

\[
\sigma = \sigma_{\text{free}} Z \left( 1 + R \frac{\sigma(\gamma A \rightarrow A e^+ e^-)}{\sigma(\gamma e_A^- \rightarrow e^- e^+ e^-)} \right) (1 - F^2(q))
\]

\[
R = 0.0093 \text{ (Z-independent radiative correction)}
\]

\[
F(q) = \left( 1 + \frac{a^2 q^2}{4} \right)^{-2} \text{ (Hydrogen form factor)}
\]

\(a:\text{ Bohr radius, } q:\text{ momentum transferred to the recoil electron}\)
GlueX:

- Located at Hall-D, Jefferson Laboratory, USA
- Photon beam is produced by bremsstrahlung technique.
- Tagged between $E_\gamma = (9 - 11)$ GeV with a resolution of $\Delta E_\gamma = 50$ MeV.
- Target: 30 cm long liquid Hydrogen cell
- Photon flux: $\Phi_\gamma = 50$ MHz.
- Charged particles and photons are tracked between polar angles of $1^\circ$ and $120^\circ$.
- Data acquisition is triggered if 600 MeV is deposited in the FCAL.
- Track momentum resolution: $\frac{\Delta p}{p} \sim 3\%$. 

Photon beam experiments
LEPS2:

- Located at Spring-8, Sayo, Japan.
- Photon beam is produced by *laser back-scattering technique*.
- Tagged between $E_γ = (1.4 - 2.5)$ GeV with a resolution of $ΔE_γ = 12$ MeV.
- Target: 5 cm long liquid Hydrogen cell
- Photon flux: $Φ_γ = 5$ MHz.
- Charged particles are tracked between polar angles of $7°$ and $120°$ and photons between $40°$ and $120°$.
- $e^+e^-$ veto counter between $0°$ and $7°$.
- Charged particles with momenta $>100$ MeV trigger data acquisition.
- Track momentum resolution: $\frac{Δp}{p} \sim 5%$. 
In this set-up, LEPS2 has no sensitivity to Compton-like scattering due to lack of tracking at lower polar angle. We have assumed charged particles at polar angles between 1° and 120° can be tracked.

- \(e^+e^-\) veto counter between 0° and 7°.
- Charged particles with momenta >100 MeV trigger data acquisition.
- Track momentum resolution: \(\frac{\Delta p}{p} \sim 5\%\).
LEPS:

- Located at Spring-8, Sayo, Japan.
- Photon beam is produced by laser back-scattering technique.
- Tagged between $E_\gamma = (1.4 - 2.5)\text{ GeV}$ with a resolution of $\Delta E_\gamma = 12\text{ MeV}$.
- Target: 5 cm long liquid Hydrogen cell
- Photon flux: $\Phi_\gamma = 5\text{ MHz}$.
- Charged particles are tracked between polar angles of $-20^\circ$ and $20^\circ$ in the x-direction and between $-10^\circ$ and $10^\circ$ in the y-direction.
- Charged particles with momenta $>400\text{ MeV}$ trigger data acquisition.
- Track momentum resolution: $\frac{\Delta p}{p} \sim 0.6\%$. 
FOREST:

• Located at ELPH, Tohoku, Japan.
• Photon beam is produced by bremsstrahlung technique.
• Tagged between $E_\gamma = (0.8 - 1.2)$ GeV with a resolution of $\Delta E_\gamma = 1$ MeV.
• Target: 5 cm long liquid Hydrogen cell
• Photon flux: $\Phi_\gamma = 4.5$ MHz.
• Charged particles are tracked between polar angles of $-0.6^\circ$ and $0.6^\circ$ in the x-direction and between $-1.2^\circ$ and $1.2^\circ$ in the y-direction.
• Charged particles with momenta $>400$ MeV trigger data acquisition.
• Track momentum resolution: $\frac{\Delta p}{p} \sim 0.6\%$. 
### TABLE I. Tagged-photon-beam characteristics

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$\phi_\gamma$ [(\gamma/s)]</th>
<th>$E_\gamma$ range [GeV]</th>
<th>$\Delta E_\gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GlueX</td>
<td>$5 \times 10^7$</td>
<td>9 - 11.5</td>
<td>50</td>
</tr>
<tr>
<td>LEPS2</td>
<td>$5 \times 10^6$</td>
<td>1.4 - 2.4</td>
<td>12</td>
</tr>
<tr>
<td>LEPS</td>
<td>$5 \times 10^6$</td>
<td>1.4 - 2.4</td>
<td>12</td>
</tr>
<tr>
<td>FOREST</td>
<td>$4.5 \times 10^6$</td>
<td>0.8 - 1.2</td>
<td>1</td>
</tr>
</tbody>
</table>

### TABLE II. Existing setup characteristics

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\theta$ range [$^\circ$]</th>
<th>$\Delta p/p$ [%]</th>
<th>$p_T^{\text{track}}$ [MeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GlueX</td>
<td>1 - 120</td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>LEPS2</td>
<td>7 - 120</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>LEPS</td>
<td>0 - 10</td>
<td>0.6</td>
<td>400</td>
</tr>
<tr>
<td>FOREST</td>
<td>0 - 0.6</td>
<td>0.6</td>
<td>400</td>
</tr>
</tbody>
</table>
Kinematics:

• The recoil electron with a certain momentum cannot be emitted at arbitrarily large polar angle.

• Also, momentum and polar angle are strongly correlated for $A' \rightarrow e^+e^-$. 

For 10 MeV dark photon
Background processes

- Standard Model Compton: $\gamma + e^- \rightarrow \gamma + e^-$. 
- Pair production: $\gamma + A \rightarrow e^+e^- + A$. 
- Triplet photoproduction: $\gamma + e^- \rightarrow e^+e^- + e^-$. 

- Measuring a single track 
- Assuming one month of beam time. 
- Reconstructing the missing mass squared: 
  \[ M^2 = s + m_e^2 - 2E_e^*\sqrt{s} \]  
  ($\sqrt{s}$: total energy in the COM frame, $E_e^*$: energy of the recoil electron in the COM frame) 
- Cuts to maximize signal to background: transverse momentum of $A'$ is below 60, 26, 25, 10 MeV for GlueX, LEPS2, LEPS, FOREST.
Remaining background and signal for $\epsilon = 10^{-4}$

**GlueX**

- Expected background
- $\gamma + N \rightarrow e^- e^+ N$
- $\gamma + e^- \rightarrow e^- e^+ e^-$
- $\gamma + e^+ \rightarrow \gamma + e^+$

**LEPS2**

- Expected background
- $\gamma + N \rightarrow e^- e^+ N$
- $\gamma + e^- \rightarrow e^- e^+ e^-$
- $\gamma + e^+ \rightarrow (\gamma) \gamma + e^-$

![Graphs showing remaining background and signal for $\epsilon = 10^{-4}$](image)
LEPS

- Expected background
- $\gamma + N \rightarrow e^+e^- + N$
- $\gamma + e^- \rightarrow e^+e^- + e^-$
- $\gamma + e^- \rightarrow \gamma + e^-$

Count / 0.8 MeV$^2$/c$^4$

$M^2_{A/\phi} [GeV^2/c^4]$

FOREST

- Expected background
- $\gamma + N \rightarrow e^+e^- + N$
- $\gamma + e^- \rightarrow e^+e^- + e^-$
- $\gamma + e^- \rightarrow \gamma + e^-$

Count / 0.8 MeV$^2$/c$^4$

$M^2_{A/\phi} [GeV^2/c^4]$
Expected sensitivities
Similar sensitivities for invisible decay
For Beam Dump Experiments