Compton photoproduction of axion-like, dark photon, dark scalar, and dark matter particles

Igal Jaeglé

Contact e-mail: igjaegle@gmail.com

University of Florida

Physics Division Seminar
Thomas Jefferson National Accelerator Facility
Newport News
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Based on arxiv:1903.06225 Sankha S. Chakrabarty & IJ
Outline

1. Introduction

2. Compton-like process: $\gamma + e^- \rightarrow A'(a/\phi) + e^-$

3. Tagged photon-beam fixed-target experiments

4. Implications for the beam-dump experiments

5. Conclusions
The Universe missing mass “problem”?

First observed by Fritz Zwicky in 1933 and reported in Helvetica physica acta, vol. 6, p. 110
- Missing mass problem, gravitational mass of galaxies in Coma galaxy cluster is much higher than expected
- Dunkle Materie or dark matter?

- Measure rotation curves of spiral galaxies
- Observe: outermost components of the galaxy move as quickly as those close to the center

There are different ways to solve this relation problem between mass and gravity:
- Add an extra mass (most popular solution) which is not
  - Baryonic (Standard Model of Particles does not apply)
  - Interacting with known electromagnetic force (missing force(s))
- Modify the theories of gravity, eg MOdified Newton Dynamics (MOND) theories
- Combination of the above
- None of the above

Rotation curve of NGC 2403. The points are the observed rotation curve, the dashed and dotted curves are the Newtonian rotation curves of the baryonic components (stars and gas respectively), and the solid curve is the MOND rotation curve, R. H. Sanders CJP 93 2 (2015).
Cosmic Microwave Background (CMB), emitted by the Hydrogen spin flip at different Universe ages, observed by Planck (arXiv:1807.06205) cannot be explained by MOND (so far).

Difference between data and model is an indication of the proportion of:
- Visible (luminous) matter (∼5 %)
- Non-luminous (dark) matter (∼25 %) to bind cosmic structures: Galaxies & clusters of Galaxies
- Dark energy (∼70 %) to drive cosmic acceleration: now and at primordial inflation
Criteria and list of candidates

Dark matter criteria:
- Slowly moving particle
- Does not emit light
- Produced during the Big Bang
- Does not decay

List of candidates:
- Massive AstrophysiCal Halo Object
- Weakly Interacting Massive Particle
- Dark Sector Light Dark Matter
- Sterile neutrino
- (QCD) Axion(-like)
- Something else
- A combination of the above
The (QCD) axion(-like)

To solve the neutron’s electric spin or the strong-CP violation problem
- Peccei and Quinn proposed a pseudo-particle in 1977 (“CP Conservation in the Presence of Pseudoparticles”) which
- Weinberg and Wilczek (the same year) formally introduced as the (QCD) axion (“A New Light Boson” and “Problem of Strong P and T Invariance in the Presence of Instantons”)
- Sikivie in 1984 defined the experimental principals needed to observe this hypothetical ultra-light particle: (QCD) axion can convert into photon while crossing a magnetic field perpendicular to its direction

More generally, Axion-Like pseudo-scalar Particles (ALP) appear in any theory with a spontaneously broken global symmetry and possible ALP masses and couplings to SM particles range over many orders of magnitude.
- (QCD) axion (below eV) could represent up to 30 % of dark matter
- MeV range ALPs could represent only a fraction of dark matter

\[ \Lambda / |C_{\text{eff}}| = 32 \pi^2 f_a \] where \( f_a \) and \( C_{\text{eff}} \) axion decay constant and effective coupling, respectively

Igal Jaeglé (UF)  Dark Compton photoproduction  Seminar @ JLab  6 / 39
D. Aloni and al. performed first search with a real photon-beam arXiv:1903.03585 by re-interpreting PrimEx results

- $\gamma A \rightarrow a A$ and $a \rightarrow \gamma \gamma$
- $g_{a\gamma} = c_{\gamma}/\Lambda$

No need to know form factor and photon flux

GlueX expected sensitivity is competitive compared to Belle II expected sensitivity

(Boost to re-interpret the data taken by TAPS in Bonn and Mainz since 2002 started)
Last detour in the (QCD) axion world

First axion helioscope proposed by P. Sikivie

- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field, K. van Bibber et al., Design for a practical laboratory detector for solar axions, PRD 39, 2089 (1989)
- J. Redondo, Solar axion flux from the axion-electron coupling, JCAP 1312 008 (2013)

![Diagram of axion interactions](image)

- ABC reactions responsible for the solar axion flux in non-hadronic axion models.
- Flux of solar axions due to ABC reactions driven by the axion-electron coupling ($g_{ae} = 10^{-13}$).
  The different contributions are shown as red lines: Atomic recombination and deexcitation (FB+BB, solid), Bremsstrahlung (FF, dot-dashed) and Compton (dashed). The Primakoff flux from the axion-photon coupling is shown for comparison using $g_{a\gamma} = 10^{-12}$, a typical value for meV axions having $g_{ae} = 10^{-13}$. Note that has been scaled up by a factor 50 to make it visible

One can learn a lot from these searches that are in their third decade
The Weakly Interacting Massive Particle (WIMP)

Can be naturally explained by a minimal Supersymmetry extension of the Standard Model

WIMP with a mass of 100’s of GeV/c² can explain

~80% of all matter is dark

Dark matter density at different ages of the Universe

If true, in this room there is 1 WIMP every 10 cm with a velocity of ~ 200 km/s

arXiv:1401.6085, Planning the Future of U.S. Particle Physics (Snowmass 2013)

- WIMP was not detected so far at underground laboratory
- Supersymmetry particles were not detected so far at LHC
The dark sector hypothesis to explain dark matter

Introduction of a new force mediated by a “Dark Gauge vector Boson”
- Formulated first by P. Fayet and B. Holdom in the 80’s
- Reformulated 30 years later by M. Pospelov, H. Arkani-Hamed, R. Essig, P. Shuster, N. Toro, et al. in light of the different anomalies observed
  - $e^+$ flux excess, AMS-02 Collaboration PRL 113, 221102 (2014)

\[ \alpha_D: \text{dark matter, } \chi, \text{ coupling to dark photon, } A' \ (m_{A'} \neq 0 \text{ GeV}/c^2) \]
\[ m_{A'} \text{ between 1.022 MeV}/c^2 \text{ and 10’s of GeV}/c^2 \]
\[ \epsilon = \sqrt{\alpha'/\alpha}: \text{kinetic mixing between } A' \text{ and Standard Model } \gamma \ (m = 0 \text{ GeV}/c^2) \]
  - $\alpha = 1/137$: SM electromagnetic coupling constant
  - $\alpha'$: $A'$ coupling to SM fermions

Mediator can also be a scalar (ie Higgs-like) or neutrino ie $\alpha'$ replaced by $y_e$, ...
EDGES 21-cm hydrogen signal at cosmic dawn

Experiment to Detect the Global Epoch of Reionization Signature (EDGES), Nature volume 555, pages 67–70 (2018)

- Baryon temperature cooler than expected, 3.8σ discrepancy, and not confirmed yet by another collaboration
  - More 21-cm radiation at cosmic dawn than expected (generally considered unlikely)

![Graph of Hydrogen spin temperature vs. Universe age]

- Millicharged dark matter possible if very small fraction (< 1 %) of total dark matter, mass $m_\chi$ between 0.5 and 35 MeV/c^2, and $\epsilon$ between $10^{-6}$ and $10^{-4}$, E. D. Kovetz et al. arXiv:1807.11482
- Dark matter is axions (QCD axion and/or axion-like), P. Sikivie arXiv:1805.0557
- Composite dark matter?
- Or something else?

Artistic view of the Hydrogen spin temperature vs. Universe age by Pierre Sikivie.
Meanwhile on Earth

Most accelerator based experiments are looking for sub-GeV to GeV dark particles

Produced in the processes:

(a) “Dark” Bremsstrahlung in nucleus scattering
(b) “Dark” Bremsstrahlung in $l^+l^-$ or $pp$ annihilation
(c) “Dark” resonance in $l^+l^-$ or $pp$ annihilation
(d) “Dark” meson decay
(e) “Dark” atomic deexcitation

With:

- Lepton or hadron beam on a thin or thick fixed target
  E137, E141, E774, KEK, Orsay, A1, APEX, BDX, DarkLight, (Super-)HPS, LDMX, PADME, VEPP-3, NA48, NA64, MAGIX, MMAPS, Mu3a, SeaQuest, SHIP, ATOMKI
- Lepton or hadron colliders
  KLOE, KLOE II, BABAR, Belle, Belle II, BESI/II/II, LHCb, CMS, and ATLAS
  Much less SM backgrounds than fixed target experiments
- Photon-beam on a fixed target
  GlueX (“Dark” meson decay)

Do we use all the processes capable of producing dark particles/matter in a Laboratory?
Compton-like process

\[ \gamma_{beam} + e^-_{target} \rightarrow A' / a / \phi + e^-_{recoil} \]

- \( A' \): dark photon
- \( a \): axion-like pseudo-scalar
- \( \phi \): dark scalar

Possible dark particle production mode (in Laboratory).

Always considered for calculation of axion flux or even dark photon flux in “outer-space”
γ-production of dark particles off free electrons

Electron at rest

Lagrangians:

\[ \mathcal{L}(\gamma e^- \rightarrow A'e^-) \supset \epsilon e \bar{\psi}_e \gamma^\mu \psi_e A'_\mu \]
\[ \mathcal{L}(\gamma e^- \rightarrow ae^-) \supset g_{ae} \bar{\psi}_e \gamma_5 \psi_e a \]
\[ \{ \mathcal{L}(\gamma A \rightarrow aA) \supset g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \}^* \]
\[ \mathcal{L}(\gamma e^- \rightarrow \phi e^-) \supset y_e \bar{\psi}_e \psi_e \phi \]

With

\( \epsilon \): kinetic mixing between \( A' \) and \( \gamma \) for \( m_{A'} > 0 \)
If \( m_{A'} = 0 \) millicharge scenario: \( \gamma + e^- \rightarrow \chi_e + e^- \)
\( g_{ae} \): axion-like pseudo-scalar coupling to electron
\( y_e \): dark scalar coupling to electron
\[ g_{ae} = y_e = \sqrt{\alpha} \times \epsilon \]
* Primakoff photoproduction of axion-like pseudo-scalar off nucleus highlighted by J. D. Bjorken et al. PRD 38, 3375 (1988)
**γ-production of dark particles off quasi-free electrons**

Electrons at rest do not exist in Laboratory

- Atomic electron
- Accelerator electron

We have to do the so-called **Screening and radiative corrections**

K. Mork, H. Olsen PR 140, 1661 (1965)

\[ \sigma_{\text{quasi-free}} = S(q, Z) \times \sigma_{\text{free}}(\approx Z \times \sigma_{\text{free}}) \]

where

\[ S(q, Z) = S(q) \times R(Z) \]

- \( S(q) = 1 - F^2(q) \)
  - \( F(q) = (1 + \frac{a^2 q^2}{4})^{-2} \to 0 \) if \( q \) large
  - \( a \) Bohr radius
  - \( q \) momentum transfer to the recoil electron

- \( R(Z) = Z \cdot (1 + c \frac{\sigma(\gamma A \rightarrow A e^+ e^-)}{\sigma(\gamma e^- \rightarrow e^- e^+ e^-)}) \)
  - \( c \) radiative correction which is independent of \( Z \)
  - \( \sigma(\gamma A \rightarrow A e^+ e^-) \) NIST pair cross section
  - \( \sigma(\gamma e^- \rightarrow e^- e^+ e^-) \) NIST triplet cross section


Same as in M. Dugger et al. NIMA 867 (2017) 115-127
Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac.

Von O. Klein und Y. Nishina in Kopenhagen.

(Eingegangen am 30. Oktober 1928.)

Auf Grund der neuen, von Dirac entwickelten relativistischen Quantendynamik wird die Intensität der Comptonstreuung berechnet. Das Resultat zeigt Abweichungen von den entsprechenden Formeln der alten Quantenmechanik, die bei der Rechnung vernachlässigt wurden.


In der vorliegenden Arbeit haben wir uns auf die Berechnung der Intensität der Streustrahlung in ihrer Abhängigkeit von Richtung und Wellenlänge beschränkt, das Ergebnis der Polarisation der Streustrahlung wurde zu einer späteren Zeit behandelt.

Expressions above valid if $E_\gamma \gg m_e$

$$E_\gamma \geq m_A'/a/\phi + \frac{m_2^2}{2m_e}, \text{ eg for } m_A'/a/\phi = 16.8 \text{ MeV}/c^2, E_\gamma \geq E_\gamma^\text{thres.} = 292.965 \text{ MeV}$$

* O. Klein and Y. Nishina, Z. Phys. 52, 853 (1929)

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Cross section expression

- For the different Compton-like processes:

  $$\sigma(\gamma e^- \rightarrow A'e^-) \approx 1.4 \text{ pb}\left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

  $$= \sigma^{\text{Klein–Nishina}}(\gamma e^- \rightarrow \gamma e^-)$$

  $$\approx 6.5 \text{ pb}\left(\frac{g_{ae}}{10^{-4}}\right)^2 \left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

  $$\approx 20.2 \text{ pb}\left(\frac{y_e}{10^{-4}}\right)^2 \left(\frac{0.1\text{GeV}}{\sqrt{s}}\right)^2$$

Incident photon energy must be:

- Expressions above valid if $E_\gamma \gg m_e$
\[ \gamma + e^- \rightarrow A'/a/\phi + e^- \] cross section vs. \( E_\gamma / m_{A'/a/\phi} \)

Additional points to keep in mind:
- If \( E_\gamma \gg E_\gamma^{\text{thres.}} \), cross section is independent of \( m_{A'/a/\phi} \) or \( m_{\chi e} \)
- No restriction on \( m_{A'/a/\phi} \): can be sub-eV or above-GeV
- Four tagged photon-beam experiments, based at electron accelerator, could be suited:
  - LEPS2/E949 and LEPS/BGOegg at SPring8 (8 GeV \( e^- \)), Sayo, Japan
  - FOREST at ELPH, Tohoku, Japan
  - GlueX at JLAB (12 GeV \( e^- \)), Newport News, USA

Cross section vs. \( E_\gamma \).

Cross section vs. \( m_{A'/a/\phi} \).
Comparison to other production processes

Theoretical cross section [mb] vs. $E$ [GeV]

- $m_A' = 2$ MeV/$c^2$, full line
- $m_A' = 100$ MeV/$c^2$, dashed line
- Brems. in A: $\sigma / (Z^2 \epsilon^2)$ vs. $E_p$
- Brems. in A: $\sigma / (Z^2 \epsilon^2)$ vs. $E_{e^-}$
- Res. Brems. in $e^+ e^- : \sigma / (Z^2 \epsilon^2)$ vs. $E_{e^+}$
- Non res. Brems. in $e^+ e^- : \sigma / (Z^2 \epsilon^2)$ vs. $E_{e^-}$
- Compt. $: \sigma / (Z^2 \epsilon^2)$ vs. $E_{\gamma}$
We can search for with the Compton-like processes:

- Dark photon with and w/o a displaced vertex
  - Visible $A' \rightarrow l^+l^-$ by using
    - Inv. mass of $l^+l^-$ pair
    - Missing mass of electron recoil
  - Invisible $A' \rightarrow \chi\bar{\chi}$
    - Missing mass of electron recoil

- Axion-like pseudo-scalar with and w/o a displaced vertex
  - Visible $a \rightarrow l^+l^-$ by using
    - Inv. mass of $l^+l^-$ pair
    - Missing mass of electron recoil
  - Visible $a \rightarrow \gamma\gamma$ by using
    - Inv. mass of $\gamma\gamma$ pair
    - Missing mass of electron recoil
  - Invisible $a$ or $a \rightarrow \chi\bar{\chi}$
    - Missing mass of electron recoil

- Dark scalar with and w/o a displaced vertex
  - Visible $\phi \rightarrow l^+l^-$ by using
    - Inv. mass of $l^+l^-$ pair
    - Missing mass of electron recoil
  - Visible $\phi \rightarrow \gamma\gamma$ by using
    - Inv. mass of $\gamma\gamma$ pair
    - Missing mass of electron recoil
  - Invisible $\phi \rightarrow \chi\bar{\chi}$ by using
    - Missing mass of electron recoil
Before starting, some basics maths

In a real photon-beam fixed-target experiments:

- Luminosity: \( \mathcal{L} = \frac{N}{A} \cdot \rho \cdot l_{\text{target}} \cdot \Phi_{\gamma} \cdot \Delta t \)

Assuming:

- Molar mass, \( A \)
- LH\(_2\) density: \( \rho = 0.071 \text{ g/cm}^3 \)
- Target length: \( l_{\text{target}} = 1 \text{ cm} \)
- Photon flux: \( \Phi_{\gamma} \sim \Phi_0 \frac{E^0}{E_{\gamma}} \)
- Beam-time duration: \( \Delta t = 1 \text{ month} \)
- Detection efficiency: \( \varepsilon \sim 1 \)
- Branching Ratio: \( BR \sim 1 \)
- \( E_{\gamma}^{\text{min}} = 9 \text{ GeV} \)
- \( E_{\gamma}^{\text{max}} = 11 \text{ GeV} \)
- 0 background
- No event observed, \( N_{\text{obs}}^{90\% \text{ up}} = 2.3 \)

- Expected observed event number: \( N_{\text{expected}} = \mathcal{L} \cdot \varepsilon \cdot BR \cdot \int_{E_{\gamma}^{\text{min}}}^{E_{\gamma}^{\text{max}}} \sigma(E_{\gamma})dE_{\gamma} \)

\[ \frac{\varepsilon_1^{90\% \text{ up}}}{\varepsilon_0^{90\% \text{ up}}} = \left( \frac{\mathcal{L}^0}{\mathcal{L}} \frac{\Delta M}{\Delta M^0} \frac{\varepsilon_0^0}{\varepsilon} \right)^{0.25}, \Delta M \text{ is the observable resolution} \]

<table>
<thead>
<tr>
<th>( m ) [MeV/( c^2 )]</th>
<th>( \phi_0^{\gamma} ) [( \gamma/\text{s} )]</th>
<th>( \sigma/\varepsilon^2 ) [mb]</th>
<th>( \mathcal{L} ) [mb(^{-1})]</th>
<th>( N_{\text{expected}}/\varepsilon^2 )</th>
<th>( \varepsilon^{90% \text{ up}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( 10^8 )</td>
<td>267.316</td>
<td>1.10827( \cdot 10^{10} )</td>
<td>2.96( \cdot 10^{12} )</td>
<td>8.81( \cdot 10^{-7} )</td>
</tr>
<tr>
<td>10</td>
<td>( 10^8 )</td>
<td>262.893</td>
<td>1.10827( \cdot 10^{10} )</td>
<td>2.91( \cdot 10^{12} )</td>
<td>8.88( \cdot 10^{-7} )</td>
</tr>
<tr>
<td>20</td>
<td>( 10^8 )</td>
<td>249.636</td>
<td>1.10827( \cdot 10^{10} )</td>
<td>2.76( \cdot 10^{12} )</td>
<td>9.11( \cdot 10^{-7} )</td>
</tr>
<tr>
<td>100</td>
<td>( 10^8 )</td>
<td>59.4691</td>
<td>1.10827( \cdot 10^{10} )</td>
<td>6.59( \cdot 10^{11} )</td>
<td>1.86( \cdot 10^{-6} )</td>
</tr>
</tbody>
</table>
Photon beam produced by bremsstrahlung

$$e_{\text{accelerator}}^- A \rightarrow e^- A \gamma$$

- A:
  - $\sim 100 \mu m$ Cu for unpolarized photon beam
  - $\sim 100 \mu m$ C (diamond) for linearly polarized photon beam

- Emitted (unpolarized) photon energy spectrum: $\Phi \sim \frac{1}{E_\gamma}$

- Emitted photon half-angle: $<\theta^2>^\frac{1}{2} = \frac{1}{e^-} = \frac{m_e c^2}{E_{\text{accelerator}} e^-}$

- Electrons emitting bremsstrahlung deflected downwards by dipole magnetic field onto focal plane of tagging system
  - Energy and timing extracted
  - $E_\gamma = E_{e^-}^{\text{accelerator}} - E_{e^-}^{\text{deflected}}$

Typical tagging spectrometer setup.

More details in I. Jaegle et al., EPJ A 47 (2011) 89
Photon beam produced by Laser-backscattering

\[ e^{-}_{accelerator} \gamma_{laser} \rightarrow e^{-} \gamma, \text{ inverse Compton process} \]

- Tagged photons backscattered from 8 GeV electrons reach max. energies of 2.9 GeV
- Scattered electrons momentum analyzed by last bending magnet before straight section of beam line and then detected in tagging counter

Backscattering of laser light (eV) from high energy electrons (Gev).

More details in N. Muramatsu et al. NIM A737 (2014) 184-194
Commissioned in 2015, based on BNL-E949 magnet

Physics Motivation

- Search for the missing resonances
- Search for meson-nuclei states
- Study of $s\bar{s}$ mesons
- Study of Hyperon resonances
- ...

Setup characteristics used in our fast MC

<table>
<thead>
<tr>
<th>$\phi_\gamma$ [\gamma/s]</th>
<th>$E_\gamma$ range [GeV]</th>
<th>$\Delta E_\gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^6$</td>
<td>1.5 - 2.4</td>
<td>12</td>
</tr>
</tbody>
</table>

LEPS2/E949 tagging system key numbers.

<table>
<thead>
<tr>
<th>$\theta$ range [°]</th>
<th>$\Delta P/P$ [%]</th>
<th>$\Delta \theta$ [°]</th>
<th>$\Delta \phi$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 - 110</td>
<td>1</td>
<td>$\theta \cdot \Delta P/P$</td>
<td>$\Delta \theta$</td>
</tr>
</tbody>
</table>

LEPS2/E949 detectors key numbers.
Physics Motivation

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LEPS2/E949 tagging system key numbers.

<table>
<thead>
<tr>
<th>$\theta$ range [$^\circ$]</th>
<th>$\Delta P/P$ [%]</th>
<th>$\Delta \theta$ [$^\circ$]</th>
<th>$\Delta \phi$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 20</td>
<td>0.5</td>
<td>$\theta \cdot \Delta P/P$</td>
<td>$\Delta \theta$</td>
</tr>
</tbody>
</table>

LEPS/BGOegg detectors key numbers.
Few words on the process kinematics

Correlation between momentum and polar angle

- Slow momentum $\Rightarrow$ “large” polar angle
- “Large” polar angle $\Rightarrow$ slow momentum
- eg for a 10 MeV/$c^2$ dark photon and FOREST tagged photon-beam
  - Detectable tracks on a very narrow lab. polar angle
  - Recooling Atomic electron and $e^+e^-$ pair not necessarily detectable simultaneously

- $0.8 \leq E_\gamma \leq 1.2$ GeV and $m_{A'} = 10$ MeV/$c^2$
- $E_\gamma = 1$ GeV
**Compton vs. Primakoff kinematics**

For $E_\gamma = 10$ GeV

- In Compton process most of the incident photon-energy is transferred to the recoil electron
- In Primakoff process most of the incident photon-energy is transferred to ALP

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>$c = 15$ MeV/$c^2$</th>
<th>$c = 100$ MeV/$c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$E_{\text{kin}}$ [GeV]</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$E_{\text{kin}}$ [GeV]</td>
<td>$10^3$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$E_{\text{kin}}$ [GeV]</td>
<td>$10^2$</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>

![Graph showing kinematics for $m_a = 15$ MeV/$c^2$ and $m_a = 100$ MeV/$c^2$](image)
Single electron analysis for invisible or long-lived decay

One single track measured (long-lived $\tau \sim 10^{-13}$ to $10^{-14}$ s)

- Identified as an electron
- $p \geq 100 / 200$ MeV/$c$ for LEPS2/LEPS
- Polar angle below $6^\circ / 4^\circ$
- Transverse momentum cuts to remove pair/triplet production
- Dark particle missing mass reconstructed from: $M_{A'/a/\phi}^2 = s + m_{e^-}^2 - 2E_{e^-}^* \sqrt{s}$

Efficiency (left) and resolution (right)
Expected background for single electron analysis for invisible or long-lived decay

From SM Compton, SM double Compton, SM pair, and SM triplet

- For one month beam-time and 30 cm (left/GlueX) and 5 cm (right/LEPS2) LH$_2$ target
- Background can be suppressed by a $\gamma$ and $e^+e^-$ pair veto

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Dark Compton photoproduction

Seminar @ JLab
Expected sensitivity for $A'/a/\phi \rightarrow \chi\bar{\chi}$

90% C.L. on $\epsilon/y$ for the Compton process determined by a shape experiment (peak search)

- Liquid hydrogen target
- One month of data taking
- NB: $g_{ae} = y_e = \sqrt{\alpha} \times \epsilon$
- $\alpha_D = 0.5$ and $m_{A'} = 3m_\chi$
Visible analysis

LEPS2: one track + $e^+e^-$-pair veto recording hits
LEPS: three tracks

- Identified as electron(s) and positron
- $p \geq 100 / 200$ MeV/$c$ for LEPS2/LEPS
- Polar angle below $6^\circ / 4^\circ$
- Transverse momentum cuts to remove pair/triplet production
- LEPS2, $M^2$, and LEPS: Dark particle invariant mass reconstructed from the $e^+e^-$-pair

![Graphs showing efficiency and resolution](image)

Efficiency (left) and resolution (middle and right).
Expected background for visible analysis

From $e^-e^+$-pair of pair and triplet productions

LEPS2 (up) and LEPS (down) expected background and signal ($\epsilon = 10^{-4}$) for one month beam time.
Expected sensitivity for $A'/a/\phi \rightarrow e^+e^-$

90% C.L. on $\epsilon/gae/y$ for the Compton process determined by a shape experiment (peak search)

- Liquid hydrogen target
- One month of data taking
- NB: $gae = ye = \sqrt{\alpha} \times \epsilon$

$$\begin{array}{c}
\text{e}^+\text{e}^- \text{pair, full curve} \\
\text{e}^+\text{e}^- \text{pair, dotted curve} \\
\text{e}^- \text{recoil, dashed curve} \\
\text{GlueX} \\
\text{LEPS2} \\
\text{LEPS} \\
\text{FOREST}
\end{array}$$

$Igal Jaeglé (UF)$

Dark Compton photoproduction

Seminar @ JLab
Beam-dump experiments

Electron/positron/proton beam on a heavy Z target (dump) of several 10’s of cm

- Look at $A'$ produced with a displaced vertex that decays in $L_{dec}$ region

![Diagram of beam-dump experiment]


Beam-dump experiments did not use the full possibilities that offer the electromagnetic shower, i.e. replace systematically all photons by a dark photon, as pointed out by L. Marcino et al. in PRL 121, 041802 (2018)

But, so far, even in most recent studies, the copious photon flux generated in a dump with its large electron density is not used
Parameters of past beam-dump experiments

Same than in S. Andreas et al., PRD 86, 095019 (2012)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>target</th>
<th>$E_0$ [GeV]</th>
<th>$N_{el}$</th>
<th>Coulomb</th>
<th>$L_{ab}$ [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$^{+1312}_{-126}$</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>$0^{+9}_{-0}$</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>

- S. Andreas et al. only considers Brems. in nucleus
- L. Marcino et al. considers in addition Brems. and resonance in $l^+l^-$
- We are only considering the Compton process for $E_\gamma \geq E_{\gamma \text{thres.}} \gg 10$ MeV

Geant4 distributions of particles pointing to the E141 setups.
The estimation of the expected event number, $N_{\text{expected}}(m_{A'}, \epsilon)$, is done as followed:

$$N_{\text{expected}} = L_{sh} + L_{dec} \sum_{l=L_{sh}} \sigma^{\text{th.}} \cdot \mathcal{L} \cdot BR \cdot \epsilon \cdot \frac{1}{l_{A'}} e^{-\frac{l}{l_{A'}}} \cdot \Delta l$$

$$\mathcal{L} = \frac{N_A}{A} \cdot Z \cdot \rho \cdot l_{\gamma} \cdot N_{\gamma}$$

$$N_{\gamma} = n_{\gamma MC} \cdot \frac{\text{EOT}}{\text{EOT}_{MC}}$$

where:
- $\sigma^{\text{th.}}$ is the theoretical cross section
- $\mathcal{L}$ is the luminosity
- $N_A$ is the Avogadro number
- $A$ molar mass
- $Z$ is the atomic number
- $\rho$ is the density
- $l_{\gamma}$ is the photon track length ($\sim \frac{9}{7} X_0$)
- $N_{\gamma}$ is the number of photons
- $n_{\gamma MC}$ is the number of photons produced in the dump by Geant4
- EOT is the Electron number On Target
- EOT$_{MC}$ is the simulated Electrons number On Target
- $BR$ is the Branching Ratio
- $\epsilon$ is the detection efficiency
- $l_{A'} = \gamma \beta \tau$
- $\gamma$ is the Lorentz boost and $\beta = \sqrt{1 - \frac{1}{\gamma}}$
- $\tau$ is the decay time, $\tau = \frac{1}{\Gamma}$
- $\Gamma = \frac{\alpha \epsilon^2}{4} \left(1 + 2 \frac{m_l^2}{m_{A'}^2}\right) \sqrt{1 - 4 \frac{m_l^2}{m_{A'}^2}}$
- $l$ is the decay length
- $\Delta l$ is the decay length step

Limit/sensitivity set for $N_{\text{expected}} \geq N_{\text{obs}}^{90\% \text{up}}$
90% C.L. limit on $\epsilon$ for $A' \rightarrow e^+e^-$

- Bremsstrahlung systematically better than Compton
- Bremsstrahlung + Compton combined should improve the limits
- $Be$ anomaly region can be scanned by photon-beam fixed-target experiments

Photon-beam fixed-target experiments can be tuned:

$$\frac{\epsilon_{90}\%_{up}}{\epsilon_{90}\%_{up}} = \left( \frac{\xi^0}{\xi^0} \frac{\Delta M}{\Delta M} \frac{\epsilon^0}{\epsilon} \right)^{0.25}$$

$\Delta M$ is the observable resolution

Implications for beam-dump experiments:

- Shorter beam-time
- Expand reach to higher mass
- Expand sensitivity to lower or/and higher kinetic mixing strengths

Beam energy, dump, $L_{sh}$, $L_{dec}$, and detector size have to be optimized by taking into account the dark Compton process as well
90% C.L. limit on \( y = \epsilon^2 / \alpha_D (m_\chi / m_{A'})^4 \) for \( A' \rightarrow \chi \bar{\chi} \)

And the hypothesis: \( \alpha_D = 0.5 \) and \( m_{A'} = 3m_\chi \)

- Photon-beam fixed-target experiments are competitive provided they are tuned

Equation, receipt, and input parameters used:

- Same as in L. Marcino et al.

Implications:

- Higher sensitivity at low mass
- Optimized real photon-beam fixed-target experiments implied

\( \Rightarrow \) Use missing mass technique ie do not have the \( \alpha_D \epsilon^2 \) factor

\( \Rightarrow \) Heavy Z target

\( \Rightarrow \) Veto detector

Experiment optimization should take into account the dark Compton process
One last question

Are we using all possible observables? answer in arxiv:19xx.xxxxx Sankha S. Chakrabarty & IJ & Yi-Ming Zhong

- GlueX and LEPS(2) can use in addition the linear polarization of the photon-beam
- Beam-asymmetry prediction for Primakoff photoproduction of ALP

Apart from $\Sigma_\gamma$, there is also E, F, G, H, P, and T
Conclusions

Cosmological anomalies are observed at different scales and ages of the Universe

- Dark matter could explain these anomalies but other explanations are also possible

Dark matter could be: MACHO, WIMP, Dark Sector Light Dark Matter, (QCD) Axion(-Like), ...

First study of the Compton-like photoproduction of dark photon, axion-like, or dark scalar particles off electrons with accelerator based experiments

- Did we turn on all the lamp-posts? **No, we did not.**
- Is the “dark” Compton process a lamp-post that we should turn on? **YES, in my opinion.**
- Photon-beam fixed-target experiments such as GlueX, LEPS2/E949, LEPS/BFOegg, and FOREST can:
  - Potentially detect dark photon, axion-like, or dark scalar particles of a mass below 100 MeV/c^2 and light dark matter of a mass below 50 MeV/c^2
  - Or if no signal is found, extract competitive limits on $\epsilon$, $g_{ae}$, $y_e$, and $y$

Implications for the past, present, and future beam-dump experiments:

- Combining bremsstrahlung-like processes with Compton-like process improves the sensitivity

Thank you