Search for a Heavy Photon

Bogdan Wojtsekhowski, Jefferson Lab

• Motivation
  • Possible new forces
  • Dark matter observations/indications
  • A theory of DM (one of them)
  • Heavy photon
• Axion-like/Heavy photon searches
• Experiments under preparation
• Proposal for the storage ring VEPP-3
Where is new physics

In the middle of the 18\textsuperscript{th} century:

Clairaut suggested that the strength of gravity was proportional not to \( \frac{1}{r^2} \), but the more complicated

\[
\frac{1}{r^2} + \frac{c}{r^4}
\]

for some constant \( c \). Over large distances, the \( c/r^4 \) term would effectively disappear, accounting for the utility of the inverse square law over large distances. He then began...
Where is new physics

Table I. Results of various tests of Coulomb’s law and tests for a nonzero photon rest mass.

<table>
<thead>
<tr>
<th></th>
<th>Coulomb’s Law violation of form $r^{2+q}$</th>
<th>Photon rest mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q$</td>
<td>$\mu^2 = \left(\frac{m_0 c}{\hbar}\right)^2$</td>
</tr>
<tr>
<td>Cavendish (1773)</td>
<td>$2 \times 10^{-2}$</td>
<td>$\leq 3.4 \times 10^{-44}$ g</td>
</tr>
<tr>
<td>Coulomb (1785)</td>
<td>$4 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Maxwell (1873)</td>
<td>$4.9 \times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Plimpton and Lawton (1936)</td>
<td>$2.0 \times 10^{-9}$</td>
<td>$1.0 \times 10^{-12}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Cochran and Franken (1967)</td>
<td>$9.2 \times 10^{-12}$</td>
<td>$7.3 \times 10^{-15}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Bartlett, Goldhagen, Phillips (1970)</td>
<td>$1.3 \times 10^{-13}$</td>
<td>$1 \times 10^{-16}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Williams, Faller, Hill (1970)</td>
<td>$(2.7 \pm 3.1) \times 10^{-16}$</td>
<td>$(1.04 \pm 1.2) \times 10^{-19}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Schroedinger (1943)</td>
<td></td>
<td>$3 \times 10^{-19}$ cm$^{-2}$</td>
</tr>
<tr>
<td>Gintsburg (1963)</td>
<td>Test of Ampere’s Law from Geomagnetic Data</td>
<td>$\sim 2 \times 10^{-47}$ g</td>
</tr>
<tr>
<td>Nieto and Goldhaber (1968)</td>
<td></td>
<td>$\leq 8 \times 10^{-48}$ g</td>
</tr>
<tr>
<td>Feinberg (1969)$^a$</td>
<td>Dispersion of light</td>
<td>$\leq 4 \times 10^{-48}$ g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{-44}$ g</td>
</tr>
</tbody>
</table>
SM tests, constraints on new physics (per PDG)

column denoted Pull gives the standard deviations for the principal fit with $M_H$ free, while the column denoted Dev. (Deviation) is for $M_H = 124.5$ GeV [215] fixed.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Standard Model</th>
<th>Pull</th>
<th>Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.4 \pm 1.0$</td>
<td>$173.5 \pm 1.0$</td>
<td>$-0.1$</td>
<td>$-0.3$</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>$80.420 \pm 0.031$</td>
<td>$80.381 \pm 0.014$</td>
<td>$1.2$</td>
<td>$1.6$</td>
</tr>
<tr>
<td></td>
<td>$80.376 \pm 0.033$</td>
<td></td>
<td>$-0.2$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>$g_V^{\nu e}$</td>
<td>$-0.040 \pm 0.015$</td>
<td>$-0.0398 \pm 0.0003$</td>
<td>$0.0$</td>
<td>$0.0$</td>
</tr>
<tr>
<td>$g_A^{\nu e}$</td>
<td>$-0.507 \pm 0.014$</td>
<td>$-0.5064 \pm 0.0001$</td>
<td>$0.0$</td>
<td>$0.0$</td>
</tr>
<tr>
<td>$Q_W(e)$</td>
<td>$-0.0403 \pm 0.0053$</td>
<td>$-0.0474 \pm 0.0005$</td>
<td>$1.3$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>$Q_W(Cs)$</td>
<td>$-73.20 \pm 0.35$</td>
<td>$-73.23 \pm 0.02$</td>
<td>$0.1$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>$Q_W(Tl)$</td>
<td>$-116.4 \pm 3.6$</td>
<td>$-116.88 \pm 0.03$</td>
<td>$0.1$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>$\tau_\tau$ [fs]</td>
<td>$291.13 \pm 0.43$</td>
<td>$290.75 \pm 2.51$</td>
<td>$0.1$</td>
<td>$0.1$</td>
</tr>
<tr>
<td>$\frac{1}{2} (g_\mu - 2 - \frac{\alpha}{\pi})$</td>
<td>$(4511.07 \pm 0.77) \times 10^{-9}$</td>
<td>$(4508.70 \pm 0.09) \times 10^{-9}$</td>
<td>$3.0$</td>
<td>$3.0$</td>
</tr>
</tbody>
</table>
SM tests, constraints on new physics (per PDG)

\[ g - 2 \quad \text{for the muon} \]

Largest contribution: \[ a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800} \]

Other standard model contributions:

QED \hspace{2cm} \text{hadronic} \hspace{2cm} \text{weak}

from STORY05, Y. Semertzidis
The motivation is the nature of dark matter

Dark Matter: In 1933 by F. Zwicky. This plot from D. Clemens, 1985
The motivation is the nature of dark matter

Our galaxy is inside a halo of dark matter particles

Image by R. Powell using DSS data
The motivation is the nature of dark matter

The DAMA/LIBRA experiment

Bernabei et al.
250 kg radiopure NaI(Tl)
the Gran Sasso

NIM A592:297-315,2008
The DAMA/LIBRA experiment

DAMA/NaI (0.29 ton\*yr) (target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton\*yr) (target mass = 232.8 kg)

DAMA collab., arXiv:0804.2741
The DAMA/LIBRA experiment

2-6 keV

Residuals (cpd/kg/keV)

DAMA/NaI (0.29 ton×yr) (target mass = 87.3 kg)
DAMA/LIBRA (0.53 ton×yr) (target mass = 232.8 kg)

Recoil detection of the massive particle.

Where is the gauge boson?
The theory of DM

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov & Ritz

$\sigma v \propto \frac{1}{v}$

$m_{DM} \sim \text{TeV}$

$m_{A'} \sim \text{GeV}$

no anti-protons

also: $A'$ generates long-range force
(Sommerfeld enhancement)
Motivation for light dark photon

- Large interest in $A'$ search
- Number of considerations naturally give $A'$ mass $\sim 1 - 100s$ MeV

DM annihilation

\[ \alpha' \equiv \frac{g'^2}{4\pi} \]
Motivation for light dark photon

\[ e^+ \xrightarrow{g'} A' \quad (\text{"dark photon"}) \]

\[ e^- \quad \text{small coupling} \]

\[ \alpha' \equiv \frac{g'^2}{4\pi} \]

- Large interest in \( A' \) search
- Number of considerations naturally give \( A' \) mass \( \sim 1 - 100 \text{s MeV} \)

Positron/electron intensity ratio

![Graph showing positron fraction vs. energy (GeV)]
Motivation for light dark photon

- Large interest in $A'$ search
- Number of considerations naturally give $A'$ mass $\sim 1 - 100\text{ s MeV}$

Antiproton/proton intensity ratio

\[ \alpha' \equiv \frac{g'^2}{4\pi} \]
Motivation for light dark photon

- Large interest in $A'$ search
- Number of considerations naturally give $A'$ mass $\sim 1 - 100\text{ s MeV}$

DM annihilation  Positron/electron  Antiproton/proton

$e^+ \rightarrow g' A'$ ("dark photon")

small coupling

$$\alpha' \equiv \frac{g'^2}{4\pi}$$
Motivation for light dark photon

\[ e^+ + e^- \rightarrow A' \ (\text{"dark photon"}) \]

small coupling

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

DM annihilation        Positron/electron        Antiproton/proton

- Large interest in \( A' \) search
- Number of considerations naturally give \( A' \) mass \( \sim 1 - 100 \text{ MeV} \)
How to search for new physics

The photon and $A'$ can mix!

Standard Model
quarks, leptons
$g \ W^{\pm}, Z \ \gamma$

Hidden Sector
dark matter?
$A'$ (massive)

mixing induces coupling between
ordinary matter and hidden sector matter

Holdom
Galison, Manohar
How to search for new physics

Generated by heavy particles $X$ interacting with $\gamma$ and $A'$

$\epsilon = \text{mixing strength}$

$\Delta \mathcal{L} = \frac{\epsilon}{2} F_{\gamma,\mu\nu}^{Y,\mu\nu} F'_{\mu\nu}$

"Kinetic Mixing"

$\epsilon$ could even be $\mathcal{O}(1)$ (theoretically)
How to search for new physics

\[ \varepsilon \]

Generated by heavy particles \( X \) interacting with \( \gamma \) and \( A' \)

\( \varepsilon = \) mixing strength

\[ \varepsilon \sim 10^{-8} - 10^{-2} \]

natural from quantum fluctuations of heavy particles

our photon \( \gamma \) \( \times \) \( A' \) “heavy photon”
Where to search for new physics

Report of the Workshop held December 2011 in Rockville, MD


New studies
Beam on fixed target
Recent summary of the searches

- $g$-$2$ of muon and electron
- Missing particle in $e^+e^-$ to ..
- Decay to SM ($e^+/e^-$) -
    Beam Dump
    Mass reconstruction

S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

B. Wojtsekhowski, April 12, 2013 seminar at LEPP, Cornell
Recent summary of the searches

- g-2 of muon and electron

- Missing particle in $e^+e^-$ to $\gamma A'$

- Decay to SM ($e^+/e^-$) - Beam Dump
- Mass reconstruction

S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083
Recent summary of the searches

No mass reconstruction

Statistics limitation

S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083
Recent summary of the searches

g-2 of muon and electron

Missing particle in e+e- to ..

Decay to SM (e+/e-) -
Beam Dump
Mass reconstruction

S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083
Ways to search for a new particle

\[ e^+e^- \leftrightarrow \gamma^* \text{ and } e^+e^- \leftrightarrow A' \]

- Search for a bump in the mass spectra
- As it was done - Vector Mesons, Z, H
- Required beam: energy, intensity, duty factor
- How small is the e+e- decay branching fraction?
Ways to search for a new particle

\[ e^+ e^- \leftrightarrow \gamma^* \text{ and } e^+ e^- \leftrightarrow A' \]

- Maximize production rate of virtual photons, $\gamma^*$
- Optimization of the mass resolution, $\sigma m_{\gamma^*}$
- Optimization of the detector acceptance
How look for $A'$ with MeV-GeV mass?

$e^+e^-$ colliders

Rare meson decays

$\phi \rightarrow \eta A'$

$\pi^0 \rightarrow \gamma A'$

slide from R.Essig lecture at PATRAS2012
How look for $A'$ with MeV-GeV mass?

New $e^-$ fixed target experiments

Detect both $e^+$ and $e^-$: mass reconstruction

Experiments done/planned at
- Jefferson Lab (APEX, HPS, DarkLight)

slide from R.Essig lecture at PATRAS2012
Searches for a gauge boson A’ at JLab

Jefferson Lab site
Searches for a gauge boson $A'$ at JLab

APEX

Direct production at JLab

- Produce low mass hidden gauge bosons with weak coupling to SM via high energy electron beam incident on fixed high-Z (Ta) target
- $A'$ decays to $e^+e^-$ pair with opening angle $\sim m_{A'}/E_b$

\[ \Theta_0 \approx 5^\circ \]
Searches for a gauge boson A’ at JLab

APEX

Experimental signature

Signal

QED backgrounds

Looking for a small, narrow bump on top of a smooth histogram of QED processes

Excellent mass resolution required

APEX Test Run Data, ~770K evts
Searches for a gauge boson A’ at JLab

APEX

Bump hunt / resonance search

Final invariant mass spectrum QED radiative trident / Bethe-Heitler events

› Bump hunt for small, narrow resonance

Test run mass resolution: $\sigma \sim 0.85 - 1.11$ MeV

Window size = 30.5 MeV
7th order polynomial fit

TestRunData_6_30_10_27, Wind 30, Cheb O(7), $m_{A'} = 224.525$, edm=0.000204, CQ=3

Probability model and profile likelihood ratio

$\lambda(S) = L(S, \hat{B}, \hat{a}_i)$
Searches for a gauge boson A’ at JLab

Heavy Photon Search

- Compact large forward acceptance spectrometer
- Silicon tracker/vertexer, inside magnet close (10cm!) to target

All detectors split vertically to avoid "sheet of flame"
- Primary beam, degraded electrons, bremsstrahlung photons, etc.
Searches for a gauge boson $A'$

only $g-2 = a_e, a_\mu$,

VEPP-3 and
a portion
of DarkLight

are sensitive
to “invisible”
$A'$ decay modes
Searches for a gauge boson $A'$

The recent meeting

The part of Snowmass 2013

The Intensity Frontier Workshop at Argonne on 4/25-4/27, 2013

http://www.lnf.infn.it/conference/dark
Options for an $e^+e^-$ experiment at low $s$

A “very” low energy, $s^{1/2} \sim 10\text{-}30$ MeV

a) $5$ MeV x $5$ MeV head-head collider of $e^+e^- \Rightarrow \mathcal{L} \sim 10^{24}$

b) Sliding beams of $e^+e^-$ (250 MeV x 250 MeV)$\Rightarrow$
   Project needs a specialized accelerator with two rings

c) Our approach is a positron beam + atomic electrons
Luminosity of the colliders

from W. Panovsky’s article in BEAM LINE

For $E_{cm} = 100$ MeV \hspace{1cm} \mathcal{L} \sim 10^{26} - 10^{29} \text{cm}^{-2}/\text{s}
Luminosity using initial state radiation

\[ \Delta L \propto L \times \frac{\Delta s}{s_{\text{max}}} \]

when \( s_{\text{max}} = 10 \text{ GeV} \) and \( \Delta s \sim 100 \text{ MeV} \) (APEX)

\[ \Delta L \sim 10^{-4} L \]

\[ s \sim 4E_+ \cdot (E_- - E_\gamma) \]
BABAR search using initial state radiation

PRL 107, 221803 (2011)
Search for Hadronic Decays of a Light Higgs Boson in the Radiative Decay
BABAR search using initial state radiation

M = 500 MeV

10k events/10 MeV
Where to find a positron beam?

- A beam of 25 nA 400 MeV was produced at Saclay in 1980s
- Beam of 1 μA was used for SLC (120 Hz)
- SLAC positron damping ring up to 1.2 GeV, 200 mA
- DORIS
- VEPP-3 energy of 0.5-2 GeV, 50 mA
A few pictures of VEPP-3

Bend magnets
RF cavity
Injector
Fix target expt.
The photo-production processes

Basic QED: \( e^+e^- \rightarrow \gamma\gamma \) (mono-energetic)
Search for: \( e^+e^- \rightarrow \gamma U \) (peak below main)
Basic QED: \( e^+Z \rightarrow \gamma \) (smooth brems.)

- Detect \( \gamma \) at fixed angle with the beam:
  - reconstruct the mass
- Variation with the angle:
  - control systematic
- Target Z
  - Hydrogen vs. \(^{12}\text{C}\)

![Gamma background](image-url)
Concept of an experiment with a positron beam

Kinematics

B. Wojtsekhowski, April 12, 2013  seminar at LEPP, Cornell
Concept of an experiment with a positron beam

500 MeV beam

Proposal of an experiment at VEPP-3:
BW, Nikolenko, Rachek, arXiv:1207.5089
Experimental layout

\[ \mathcal{L}_{e^+e^-} \sim 10^{32} \]
Positron beam on internal Hydrogen target

Physics background is the bremsstrahlung radiation

Anti-coincidence with the positron counters reduce QED background
Positron beam on internal Hydrogen target

Projected event rate

A bump is $e^+e^- \rightarrow 2\gamma$

Projected for an electron beam for systematic check
VEPP-3 operation during
Two-Photon Exchange experiment

VEPP-3: experiment | E = 1600 MeV | November 22, 7:00

Current, mA

01:00 02:00 03:00 04:00 05:00 06:00 07:00

Lifetime, s

0 10 100 1000 10000

I = 35.6 mA  –- electrons  –- positrons  –- lifetime  LT = 1039 s
Photon detector

The photon detector can be placed at a distance of between 4 m and 8 m from the target. The requirements for the detector are:

- Energy resolution on the level of $\frac{\sigma_E}{E} = 5\%$ for photons with energy $E_\gamma = 100 - 450$ MeV.
- Angular resolution on a level of 0.1°.
- Angular acceptance as defined by a requirement to detect both photons from two-photon annihilation:
  - in $\phi$: either total $2\pi$, or two symmetrical sectors, e.g. $(\phi_1, \phi_2)$ and $(\phi_1 + \pi, \phi_2 + \pi)$;
  - in $\theta$: symmetrical range in $\theta_{CM}$ around 90°, e.g. $\theta_{CM} = 60° - 120°$, which corresponds to $\theta_{LAB} = 1.5° - 4.5°$.
- The detector should be able to sustain a modest photon rate of several hundred kHz over its whole area.

Potential source of crystals:

The electromagnetic calorimeter of the CLEO-II detector consists of 8000 CsI(Tl) crystals of $5 \times 5 \times 30$ cm$^3$ size (16.2X$_0$). It is used to measure electron and photon energy in a wide range; therefore, a direct measurement of its performance at a photon energy of interest for the proposed experiment is available:

$$\delta E/E = 3.8\% \quad \text{and} \quad \delta x = 12 \text{ mm} \quad \text{for} \ E_\gamma = 180 \text{ MeV}$$

One can see that in the energy range of the proposed experiment, a CsI(Tl)–based calorimeter provides better energy resolution but a worse spatial one than that based on PbWO$_4$–crystals. Therefore, the CsI(Tl)–calorimeter must be placed as far as possible from the target, i.e. about 8 m. In this case it would take about 800 crystals to cover the required angular ra
Internal target for Two-Photon Exchange experiment

target thickness $= 1 \div 2 \cdot 10^{15}$ at/cm$^2$
Kinematical correlation

\[
\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)
\]

\[
N_{U\gamma} = 2\frac{\alpha'}{\alpha} \cdot N_{\gamma\gamma}
\]

\[
E_{\gamma, \text{LAB}}^{\text{lab}}(A'\gamma) = E_{\gamma(\gamma\gamma)}^{\text{lab}} \cdot (1 - M_{A'}^2/s)
\]

The U(or A’) mass resolution \( \sim 3\% \)
Projected sensitivity in the parameter space

Projected sensitivity for the VEPP-3 measurement at $L_{ep} = 10^{32} \text{ cm}^{-2}/\text{s}$ (aver. current of 25 mA) in the six-month run
Projected sensitivity in the parameter space

These searches are sensitive to “invisible”

DarkLight (to “invisible”)
Y. Kahn, J. Thaler, arXiv:1209.0777

Projected sensitivity for VEPP-3 (at 500 MeV) measurement at
$L_{ep} = 10^{32} \text{ cm}^{-2}/\text{s}$
(aver. current of 25 mA)
in the six-month run

- - - with 5 GeV beam
Summary

- Search for the A’/U boson in the photon recoil spectra is possible using a positron beam and internal hydrogen target in the 500 MeV storage ring.

- Available luminosity (~$10^{32}$) allows a 10-100+ improvement over the (g-2) limit in mass range 7-15 MeV. The range could be extended to 50 MeV with 5 GeV beam.

- Segmented high-resolution electromagnetic calorimeter is a key new part of the setup.