**APEX: A Search for Dark Photons in Hall A**

R. Essig (SUNY), P. Schuster (SLAC), N. Toro (SLAC), B. Wojtsekhowski (JLab)

**Goal:** Search for a new $\sim 100$ MeV gauge boson ($A'$) with very weak coupling to electrons

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

$A'$ is motivated from theory and anomalies related to dark matter

- $A'$ can be a force carrier of new Abelian force (*ubiquitous* in extensions of Standard Model)
- New high-energy physics *generically* mixes $A'$ with the photon giving $\alpha'/\alpha \sim 10^{-6}-10^{-8}$
- Dark Matter charged under $A'$ may explain *famous* data “anomalies” (PAMELA, Fermi, DAMA)

**Discovery potential in Hall A:**

- $A'$ can be a force carrier of new Abelian force (*ubiquitous* in extensions of Standard Model)
- New high-energy physics *generically* mixes $A'$ with the photon giving $\alpha'/\alpha \sim 10^{-6}-10^{-8}$
- Dark Matter charged under $A'$ may explain *famous* data “anomalies” (PAMELA, Fermi, DAMA)

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

**APEX**

- APEX will achieve unprecedented statistics $\sim 10^9 e^+e^-$ trident events $\sim 10,000$-fold gain
- All equipment is ready for measurements

★★ Beam Dump Experiments at SLAC & Fermilab

- **Discovery potential in Hall A:**
  - $A'$ can be a force carrier of new Abelian force (*ubiquitous* in extensions of Standard Model)
  - New high-energy physics *generically* mixes $A'$ with the photon giving $\alpha'/\alpha \sim 10^{-6}-10^{-8}$
  - Dark Matter charged under $A'$ may explain *famous* data “anomalies” (PAMELA, Fermi, DAMA)

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

**APEX**

- APEX will achieve unprecedented statistics $\sim 10^9 e^+e^-$ trident events $\sim 10,000$-fold gain
- All equipment is ready for measurements
Searches for a gauge boson $A'$ – APEX Test Run Result

Electroproduction of $A'$

Published results:
- Beam dump searches: SLAC:E137, 141; FNAL: E774
- Electron and muon (g-2), limits
- BaBar, $\Upsilon(3s)\rightarrow \gamma$ and $\mu^+\mu^-$ (inferred limit)
- KLOE, mass of $e^+e^-$ pair (bump search)
- APEX test run, mass of $e^+e^-$ pair – in publication
- MAMI – APEX type scheme

Future searches for a new force carrier:
- APEX – electron-nucleus fixed-target, a $e^+e^-$ pair in two focusing spectrometers
- HPS – same, the $e^+e^-$, $\mu^+\mu^-$ pairs in a custom Si-tracker magnetic spectrometer
- DarkLight – an internal target with an electron beam in Jefferson Lab ERL, detect a $e^+e^-$ pair and $e'p$
- VEPP3 – a positron beam incident on an internal $H_2$ target, missing mass in $(e^+e^-, \gamma X)$
- MAMI – APEX type scheme with lower beam energy

Mont’s slide in 2011
A’ Production and Background Kinematics

Nucleus

\[ N \sim \alpha' \times \text{Branching} \sim O(1) \]

(rates before angular cuts)

Nucleus

\[ N \sim \alpha^2 \]

A’ products carry full beam energy!

- Distinctive kinematics
- \( \Delta p/p \) assists in background suppression

Best kinematics to select events for A’ search

J.Bjorken, R.Essig, P.Schuster, N.Toro, PRD 80 (2009)
Spectrometer Acceptance and S/N Ratio

Background vs. Signal Kinematics

When the productivity reaches the limit of the detector/DAQ capabilities, a modest momentum range is better!
Angular Range and Smooth Mass Acceptance

Electrons

Positrons

Beam 0.5x5 mm

0.015 mm thick 2.5 mm wide W ribbons

Angular acceptance

$D > 1.5 \text{ mm} / \sin \theta_{\text{min}}$

Electron, $P = E_0/2$

Positron, $P = E_0/2$

HRS–right

HRS–left

Septum

Sensitivity of Proposed Run Plan

$a'/a$ (2$\sigma$ sensitivity)

$e^+e^-(A')$ Mass (GeV)

10$^{-8}$

10$^{-7}$

10$^{-6}$

10$^{-5}$

0.1

0.3

0.5

0.1

0.3

0.5

C

D

B

A

SLAC, Dark Sectors 2016.

Wojtsekhowski for the collaboration
Readiness Review Process – Flow Chart

PROPOSAL PHASE
• Submitting Proposals
• TAC & PAC Process
• Director’s Decision

PRELIM. PLANNING PHASE
• Exp. Description and Requirements
• Exp. Readiness Review Calendar

DESIGN PHASE
• PESAD, specific equipment reviews
• Complete Conceptual Designs &
  “1st” Readiness Review

CONSTRUCTION PHASE
• Fabrication of the equipment
• Test of the individual elements of
  the equipment (OSP/TOSP)

SCHEDULING OF EXPERIMENT
• Construction near-completed,
  designs frozen
• “2nd” Readiness Review before
  scheduling request submission
by JLab

EQUIPMENT INSTALLATION

RUN THE EXPERIMENT

“Final” readiness review

http://www.jlab.org/user_resources/PFX/NP-PFX/
Readiness Review Process – Flow Chart

PROPOSAL PHASE

PRELIM. PLANNING PHASE

DESIGN PHASE

CONSTRUCTION PHASE

SCHEDULING OF EXPERIMENT by JLab

EQUIPMENT INSTALLATION

RUN THE EXPERIMENT

APEX test run 6/2010

APEX 4/2016

APEX 2018!

• Submitting Proposals
• TAC & PAC Process
• Director’s Decision

• Exp. Description and Requirements
• Exp. Readiness Review Calendar

• PESAD, specific equipment reviews
• Complete Conceptual Designs & “1st” Readiness Review

• Fabrication of the equipment
• Test of the individual elements of the equipment (OSP/TOSP)

• Construction near-completed, designs frozen
• “2nd” Readiness Review before scheduling request submission

“Final” readiness review

http://www.jlab.org/user_resources/PFX/NP-PFX/
Nominal Dates for Scheduling Requests

Please see the information for the requirements before scheduling can be requested

You can only request scheduling when construction of all major components of the experiment are
completed, as at this stage the experiment layout and components are considered frozen, and any
design modifications will require a change control, approved by the Division Management.

June 1 Call for Scheduling (Beam Time) Request
June 30 Deadline for Scheduling Request Submissions
September 1 Draft 18-Month Schedule Released
September 15 Deadline for Input of User Community on Draft Schedule
October 1 18-Month Schedule Released

Year 1 January - June Schedule Reaffirmed
Year 1 July - December Firm Schedule
Year 2 January - June Tentative Schedule

March 1 Draft 18-Month Schedule Released
March 15 Deadline for Input of User Community on Draft Schedule
April 1 18-Month Schedule Released

Year 1 July – December Schedule Reaffirmed
Year 2 January - June Firm Schedule
Year 2 July - December Tentative Schedule
APEX specialized equipment

- W Sieve Actuators
- SciFi Sieve Actuators
- Septum Magnet
- Target Chamber
New Septum Magnet

- New Septum magnet required. Magnet procured by Collaboration; StoneyBrook U. Septum Magnet has been fabricated and delivered to Jlab.
- In process of implementing test plan for magnet in the TestLab at 10-20% operating limit.
- Magnet is a water-cooled iron septum. Magnet operates at 2100 A, 120V, 250 KW for integral of 0.95 T-m. Experiment will utilize SBS power supply to operate the septum magnet.
- At dP=100 psi, dT =25 C. Preliminary analysis indicates sufficient water flow in Hall A for cooling magnet with other LCW dependencies.
- Fringe fields determined to be 100 G at target and 80 G at 1.5 meters from center of septum. Field range above 5 G to be indicated, ~ 5 meters out from magnet.
Corrector magnets

- Corrector magnets are required upstream and downstream of the septum magnet to reduce field effects on the beam line.
- Upstream corrector design is complete and ready for procurement. Water-cooled coils, 122A, dP=100 psi gives dT=14C. Sufficient LCW available in Hall A for cooling.
- Downstream corrector to be re-evaluated with use of SOS Q1 magnets. Conceptual design exists. Require 4 MW engineering and 8 MW design to complete design. Fabrication estimated as 12 weeks.
- Corrector magnets can be powered with existing Hall A power supplies.
Shielding

- Lead shielding is planned to be placed in open area of SOS Q1 magnets facing beam line and downstream of SOS Q1 magnets where diameter of pipe changes.
- Analysis indicates no additional radiation shielding is required.
- Requires 2 MW design to complete lead layout and support.
Radiation damage to electronics

2 m radius boundary for $1.0E + 13 n_{eq} \text{ cm}^{-2}$
DAQ rates and dead time
2.2 GeV full luminosity

- A 20 ns coincidence gate would acquire a rate of 3.1 kHz
- DAQ dead time is 10% for 4 kHz
- Full rate capability has been demonstrated in the APEX test run

20 ns coincidence time easily achievable
Ideally 10 ns could be used
Mass Resolution:

\[ \left( \frac{\sigma_M}{M} \right)^2 = \frac{1}{2} \left( \frac{\sigma_P}{P} \right)^2 + \left( \frac{\sigma_\theta}{\theta} \right)^2 \]

Mass Resolution Goal:

\[ \frac{\sigma_M}{M} \leq 0.5\% \]

HRS Resolution:

\[ \frac{\sigma_P}{P} < 10^{-3} \quad (\text{Not a problem}) \]

Thus goal requires:

\[ \frac{\sigma_\theta}{\theta} \leq 0.5\% \]

For \( \theta = 10^0 \), requires:

\[ \sigma_\theta < 0.9 \text{ mrad} \]

Target multiple scattering:

\[ \sigma_{\theta-\text{targ}} \approx 0.5 \text{ mrad} \quad (p_{\text{beam}} = 2.2 \text{ GeV}) \]
Angular Range and Smooth Mass Acceptance

Electron, $P = E_0/2$

Positron, $P = E_0/2$

Beam
0.5x5 mm

W target

Septum

HRS–left

HRS–right

Angular acceptance

$\theta_{\text{min}}$

$D > 1.5 \text{ mm} / \sin \theta_{\text{min}}$

Electrons

0.015 mm thick
2.5 mm wide W ribbons

0.1
0.3
0.5

$\alpha'/\alpha$ (2$\sigma$ sensitivity)

$e^+e^-(A')$ Mass (GeV)

Sensitivity of Proposed Run Plan

C
A
D
B

SLAC, Dark Sectors 2016.

Wojtsekhowski for the collaboration
Summary

- The APEX equipment is designed and construction is under way. All equipment is delivered or ordered.

- The APEX experiment is ready to run on 6 months’ notice.

- The data taking run will likely be in spring 2018.
A high luminosity electron-positron collider for the search for (or study of) a Dark Force Mediator (including invisible decay)

Bogdan Wojtsekhowski, Jefferson Lab

presented at

Intense Electron Beams workshop, Cornell, June 2015
Luminosity of the colliders

from W. Panovsky’s article in BEAM LINE

For $E_{cm} = 100$ MeV \[ \mathcal{L} \sim 10^{26} - 10^{29} \text{cm}^{-2}/\text{s} \]
Options for e⁺e⁻ experiment at low s

A “very” low energy s ~ 10-30 MeV

a) Search in existing data from good detector =>
   problem with resolution at low s
b) 5 MeV x 5 MeV collider of e⁺e⁻ =>
   very low luminosity
c) Sliding beams of e⁺e⁻ (200 MeV x 200 MeV) =>
   need specialized accelerator with two rings
d) Positron beam and atomic electrons
A new concept: Very Asymmetric Collider

CESR and ERL

An electron beam of 100 mA in the ERL is focused to match the e⁺ CESR beam

up to 5 GeV x 0.3 GeV
Goal: 4-turn FFAG ERL at 16MV/m
Options for a $e^+e^-$ experiment at low $s$

A “very” low energy $s^{1/2} \sim 30\text{-}300$ MeV

a) 15 MeV x 15 MeV head-to-head collider
   The problem is a very low luminosity $\mathcal{L} \sim 10^{26}$

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

c) CESR’s 2-5 GeV positron beam and a 60-300 MeV ERL
   looks like an ideal combination for a new device:
   a Very Asymmetric Collider @ Cornell

$\mathcal{L} \sim 10^{34}$? at least to keep $L \sim 10^{33}$ - the level of
5 GeV x 5 GeV regime
VAC for precision physics

A Very Asymmetric Collider @ Cornell with a positron beam of the CESR ring and an electron beam of ERL could be the ultimate device for study of the Dark Photons in the mass range up to 1-2 GeV.
Very Asymmetric Collider using $e^+$ storage ring & $e^-$-ERL

David Douglas, 4/22/2016

next 6 slides
Notional System Configuration

- $e^+e^-$ colliders now run with high $e^+$ currents
  - e.g. CESR (365 mA in 36 bunches)
- $e^-$ ERLs are poised for significant increase in beam power
  - e.g. C$\beta$ (Cornell-BNL FFAG test ERL): 250 MeV x 25 mA
- What luminosity might be achieved with a Very Asymmetric Collider made from a C$\beta$ class ERL and a CESR-like $e^+$ ring?

Confession: this is a genetically modified clone of the collider discussed by Bisognano et al. at LINAC’88
Luminosity: Comes from Charge, Frequency, and Beam Size…

- **Cβ parameters:**
  - $E=250$ MeV
  - $Q_{e^{-}}$ bunch = 77 pC ($N_{e^{-}} \sim 5 \times 10^8$); $f=325$ MHz $\Rightarrow I_{e^{-}}=25$ mA,
  - $\varepsilon_H=\varepsilon_V < 1$ mm-mrad

- **CESR parameters** ([link](http://www.lepp.cornell.edu/Research/CESR/OperatingParameters.html))
  - $E \sim 5$ GeV
  - $I_{e^+} \sim 365$ mA (in up to 45 bunches: 9 trains of 5 bunches)
  - $\varepsilon_V < \langle \varepsilon_H \rangle \sim 0.3$ mm-mrad, $\beta_H^*=0.019$ m $\Rightarrow \sigma_x \sim 75\mu$m
Miracles

- Note that all successful experiments have a Benson Index of unity
  - The “Benson Index” is the number of miracles required for the experiment to work…

- Here we invoke 2 miracles
  1. We assume CESR e+ bunch charge and timing can be reworked to give 365 mA at 325 MHz
     a. Change of ring frequency needed to match $C \beta$ RF frequency (1.3 GHz/4) – not impossible, but incurs cost
     b. With change to 325 MHz, $Q_{e+\text{bunch}} = 0.365 \text{ A} / 325 \text{ MHz} \sim 1.1 \text{ nC}$
        \[ \Rightarrow N_{e+} = 7 \times 10^9 \]
  2. ERL beam is ~round, so invoke flat beam transform (FBT) at IR to “round up” the ring beam
     a. Then $\varepsilon_v = \varepsilon_H \sim 0.15 \text{ mm-mrad}$; $\beta_x^* = \beta_y^* = 1.9 \text{ cm}$ (yes, a third miracle) \[\Rightarrow \sigma_x = \sigma_y = 50 \mu\text{m}\]
     b. spot sizes readily matched with e- beam in $C \beta$ (as in DarkLight test runs at JLab)
Luminosity

- Bisognano *et al.* LINAC-88 (http://accelconf.web.cern.ch/AccelConf/l88/papers/th3-23.pdf) describe linac/ring collider, noting

- Here

\[ N_{e^+}=7 \times 10^9 \quad N_{e^-}=5 \times 10^8 \quad f=3.25 \times 10^8 \text{ Hz} \]

\[ \sigma_x=\sigma_y=50 \ \mu m \]

\[ H_D = \text{disruption factor} \sim 1 \ (\text{no enhancement}) \]

- With these values \( \sim 3.6 \times 10^{34} \text{ cm}^{-2}\text{sec}^{-1} \sim 100 \text{ times of DAΦNE} \)
Machine Issues

- $e^+$ single bunch effects less dramatic than at lower frequency/higher charge
- Shallow-angle crossing (few mrad) provides notional avenue for higher collision frequency/closer bunch spacing
- Can use electostatic separation on low energy $e^-$ beam to greater effect than at high energy
- Positron tune shift mitigated by low electron bunch charge; electron tune shift tolerable due to ERL architecture
Conclusions

- High energy $e^+$ on low energy $e^-$ provides avenue to high luminosity at low $s$
- CESR $e^+$ on $C\beta$ a promising possibility for realization of novel system configuration