Illuminating a Dark Boson with DarkLight@ARIEL

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The Standard Model



Here be Dragons



- There is a lot we do not know!
- Phase space grows with complexity of model
- One either performs a broad search, or focuses on existing anomalies to illuminate the path

Dark Matter Searches

- Decades of WIMP/axion searches have not turned up results
- Community is moving towards MeV scale, not well-constrained at present
 - Models with U(1) gauge symmetry, kinetic mixing gives weak coupling to leptons
- Other experiments: APEX, BDX (MINI), HPS, LIPSS, PRad2, DarkMESA



Direct detection WIMP constraints. From: arxiv:2312.10828

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Existing and proposed dark photon searches. From: arxiv:2207.06905

Dark Photon



- Is there a dark photon? Dark partner to the EM photon?
- Proposed by B. Holdom, Phys. Lett. B 166, 196 (1986)
- Universal coupling to electric charge, but weaker by factor ϵ^2 .
- Could there be something beyond a dark photon?

Anomalies: $g_{\mu} - 2$

- Well known $(g_{\mu} 2)$ anomaly (among other μ puzzles)
- Differences in standard model values between theorists calculations
- Could be indicative of BSM physics



A. Driutti, MENU 2023

Anomalies: X17

• Excess in e^+e^- invariant mass spectra in ⁸Be and ⁴He

• Corresponds to a mass of $\approx 17 \text{ MeV}/c^2$

• Seen at different angles and different experimental setups

• Proto-phobic boson could explain excess

• Fine-tuned couplings



arxiv:1910.10459 and PRL 116, 042501 (2016)

Atomki Experiment - New Result on Carbon

- ${}^{11}B(p,e^+e^-){}^{12}C$ reaction
- E_p = 1.50, 1.70, 1.88, 2.10, 2.50 MeV
- Observe excess between $155-160^\circ$
- $m_X = 17.03 \pm 0.11 \pm 0.20 \text{ MeV}/c^2$
- Will continue to search for X17 in decay of giant dipole resonances on other nuclei
- Points to proto-phobic vector boson



PRC 106, L061601 (2022)

Dark Boson: Measurable in an Accelerator!



- Measure the produced e^+e^- spectrum and reconstruct invariant mass
- $m(e^+ + e^-) = m(X)$
- Need a high current, low energy electron accelerator
- Sensitive to leptonic-only coupling models!

Complementarity



 $g_{\mu} - 2$ and X17 points us to an area where we do not have lepton-based exclusion limits! If theory groups can bring $g_{\mu} - 2$ into better agreement with experiment, the $g_{\mu} - 2$ preferred band will move down in this figure.

Particle Physics Interest



- Recent P5 report
- Illuminate the Invisible Universe!
 - "Determine the Nature of Dark Matter"
 - Desire a "portfolio of agile projects for dark matter"

DarkLight!

















University Manitoba







TRIUMF Accelerator Complex

- Primary proton driver, 500 MeV 150 kW
- 4(+1) Cyclotrons for medical isotope production, 15-42 MeV with 100 kW total beam power
- Advanced Rare Isotope Laboratory -ARIEL
 - 30 MeV, 330 uA CW electron linac
 - Will undergo upgrade to 50 MeV



• Planned upgrades and expansions to the ARIEL hall



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- Stage 0
 - Minimal changes
 - Run at 31 MeV near beam dump



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- Stage 2
 - Run DL simultaneously with ARIEL operation



The DarkLight Experiment



DarkLight Target Vacuum Chamber

- 1 μ m thick Ta foil target
- 1 μ m C foil for calibration and parasitic measurements
- 300 μ A beam, 30 MeV \rightarrow 8 W heating
- Target ladder allows "empty space" configuration
- Design and construction underway at MIT Bates
- Characterized backgrounds in experimental hall in spring 2022



Spectrometers

- Up to 35 MeV central momentum, 0.38 T field
- $\pm 1.35^{\circ}$ in-plane, $\pm 5^{\circ}$ out-of-plane acceptance
- ± 20 % momentum acceptance
- Mass resolution \approx 120 keV
- Spectrometer angles, 20° (36°) for e⁺ (e⁻) in Phase 0 configuration



Tracking Detectors

- $25 \times 40 \text{ cm}^2$ triple-GEMs built by Hampton
- APV+MPD4 readout
- Planes constructed and already available
- Shipped to TRIUMF for commissioning and DAQ tests



Trigger Hodoscope

- Trigger via segmented scintillator hodoscope
 - Double-ended SiPM readout
 - Design resolution <200 ps
- Under construction at TRIUMF
- DAQ development underway at TRIUMF



Bump Hunt



Background Processes

- Irreducible background
 - $X
 ightarrow e^+e^-$ competes with $\gamma
 ightarrow e^+e^-$
 - γ from scattering or radiative terms
 - e^+e^- pairs from γ scales with ${\cal L}$
- Random background
 - Any e^+ with beam e^-
 - Scales with \mathcal{L}^2



• Figure of merit for bump hunt

•
$$\frac{S}{\sqrt{B}} = \frac{p_{sig}\mathcal{L}}{\sqrt{p_{irred}\mathcal{L} + p_{rand}\mathcal{L}^2}}$$

- Independent of \mathcal{L} at large \mathcal{L} !
- *p_{random}* can be optimized by moving electron spectrometer to larger angles



Projected Reach



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Current Status @ TRIUMF



Current Status @ JLab



Test Run Upcoming



Moving near the beam dump in 2024. Photo Credit: T. Planche.

Testing the Beam

🕹 🖸 E-LINAC - Mozilla Firefox	- O X
E-LINAC X +	
← → C ŵ ① A https://driverdispl	ays.triun ···· ♥ ☆ ≫ ≡
Most Visited	📽 CYCLOTRON Operat 📎
E-LINAC	
BEAM	ON
PATH	EHD:DUMP
PEAK CUR. ENERGY POWER	438 μΑ 28.2 MeV 996 W
ACCT CUR. TRANSMISSION	518 μA 84.6 %
DUTY FACTOR FREQUENCY WIDTH	8.05 % 1.10 kHz 73.2 μs

Upgraded gun equipment to improve beam stability.

The Path Forward

- Stage 0: Existing ARIEL Design
 - GEMs can be commissioned and available within 6 months
 - Can begin commissioning of spectrometers at TRIUMF in \approx Fall
 - Aim to complete Stage 0 in Winter 2024/Spring 2025
- ERL upgrade path
 - Stage 1: Recirculation to reach 50 MeV beam, potential chicane to separate 1st and 2nd pass beams
 - Stage 2: Simultaneous running of DarkLight with ARIEL

The Energy Upgrade



Summary

- PP-EEC approved for 1300 h of beamtime for DarkLight
- Progress on multiple fronts in the past year
 - Finalized detector layout and experiment design
 - Secured DOE and NSERC funding for experiment setup
 - Additional NSERC funding for energy upgrade secured!
 - Mentioned in FSNN Whitepaper for NSF LRP and in AF5 Report to Snowmass 2021
 - Detailed simulation studies underway, verifying background characterization, estimating possible resolution as detector components finalized
- Plan to have checkout and background measurements this fall

Back Up

Stepping into the Light

- Additional measurements in addition to BSM search
- Møller scattering commonly used as luminosity measurement
- Radiative Møller scattering is easily measurable in checkout period
- Multiple beam energies on C target



Radiative Bhabha Diagrams



Radiative Møller Diagrams, Phys. Rev. D 94, 033004

Stepping into the Light



Radiative Møller events from EM generator in DarkLight detector. Red line indicates central spectrometer momentum, blue lines indicate acceptance.

Thoughts in favor

- χ^2 near 1, $\approx 7\sigma$ effect
- Measured in four experimental setups with three different reactions (remeasured once)
- Bump over several bins
- Compatible couplings and masses for protophobic vector boson. J. Feng, *et al.*, PRD 102, 036016 (2020)

Thoughts against

- Needs to be finely tuned protophobic boson to escape NA48 limits
- Other possible explanations
 - B. Koch, Nucl. Phys. A 1008, 122143 (2021) Hard $\gamma + \gamma$ process
 - P. Kálmán, T. Keszthelyi, arXiv:2005.10643 Anomalous Internal Pair creation
 - A. Aleksejevs et al, arXiv:2102.01127 LO+NLO interference
 - M.Hostert and M. Pospelov, arxiv:2306.15077 Pion decay constraints on vector boson X17

Anomalies Abound: Proton Radius

- Proton radius puzzle
- Difference in extracted radius in muonic and electronic measurements
- Potential questions with lepton universality

• Could be explained by electrophobic scalar boson, Y-. S. Liu, D. McKeen, and G. Miller PRL 117, 101801



Permanent Magnets

• Permanent magnets acquired from SABR

• Incorporated in beam line optics simulation and FLUKA calculation

• Installation onto beam line planned for this fall

