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APEX: THE A PRIME EXPERIMENT AT JEFFERSON LAB

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Abstract

APEX is an experiment at Thomas Jefferson National Accelerator Facility (JLab) in Virginia, USA, that searches for a new gauge boson (A') with sub-GeV mass and coupling to ordinary matter of $g' \sim (10^{-6} - 10^{-2})e$. Electrons impinge upon a fixed target of high-Z material. An A' is produced via a process analogous to photon bremsstrahlung, decaying to an e^+e^- pair. A test run was held in July of 2010, covering $m_{A'} = 175$ to 250 MeV and couplings $g'/e > 10^{-3}$. A full run is approved and will cover $m_{A'} \sim 65$ to 525 MeV and $g'/e > 2.3 \times 10^{-4}$.

1 Introduction

A U(1)$'$ extension of the gauge group of the Standard Model of particle interactions is a common feature of many theories. To have thus far evaded detection, the new gauge mediator, A', must either have a large, $\mathcal{O}$(TeV), mass or be very weakly coupled to ordinary matter. This second scenario can be tested at fixed target facilities such as the Thomas Jefferson National Accelerator Facility (JLab). APEX, The A Prime EXperiment, searches for an A' at JLab and is described in brief here. For a full description of the experiment see Ref. [1] and for a detailed description of the results of the test run see Ref. [2]. The information in the current document also appears in a condensed form in Ref. [3].

2 Motivations

The Standard Model (SM) of particle interactions is described by the gauge group $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$, where the forces are mediated by vector bosons. An extension of this model can have thus far evaded identification if the corresponding gauge boson is very weakly coupled to ordinary matter, with a coupling strength g' suppressed relative to the electromagnetic charge e by $\epsilon \equiv g'/e \sim 10^{-6} - 10^{-2}$ [4] (or, equivalently, $\alpha'/\alpha = \epsilon^2$). A new gauge boson, A', corresponding to a $\mathrm{U}(1)'$ extension of the SM can acquire an effective interaction with electromagnetism via kinetic mixing, where quantum loops of arbitrarily heavy particles provide a means by which the hidden $\mathrm{U}(1)'$ sector couples to the visible sector; see, e.g., Refs. [5, 6, 7].

In addition to the general interest in discovering an extension of the SM, a hidden gauge sector with a gauge boson with mass in the MeV to GeV range could address dark matter anomalies. The PAMELA experiment sees a positron excess but no antiproton excess, which could be explained by a sub-GeV mass hidden gauge boson coupling to dark matter and preferentially decaying into leptons. A similar scenario could explain the e^+e^- excesses seen by Fermi, ATIC, and HESS, and the effects observed by DAMA/LIBRA, INTEGRAL, CoGeNT, and others. A complete description of these possibilities is in Ref. [8].

Moreover, the anomalous magnetic moment of the muon could be explained by the existence of a sub-GeV mass A' with a weak effective interaction with the SM. The presence of this A' provides extra higher-order diagrams that contribute to the calculation of $(g-2)_\mu$ and can bring it into agreement with experimental measurements [8].

3 Existing Constraints

Aside from these suggestive motivations, the coupling strength and mass of the A' are not predicted. Thus, searches for this new gauge boson must be conducted over wide ranges of both. As a result, prior to 2009, the areas of parameter space probed by APEX were remarkably weakly constrained. Following the observation [8] that much of this range could be probed at existing experimental facilities, a renewed interest in such experiments has led to the current constraints and planned experimental sensitivities shown in Figure 1.

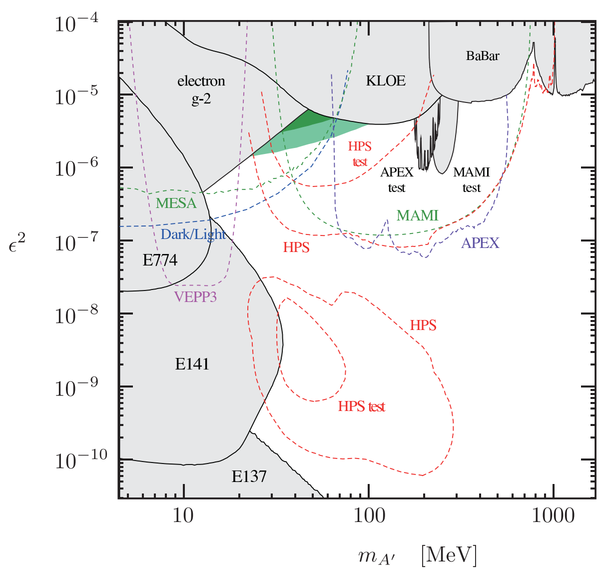

Figure 1: Existing and planned constraints in the $\epsilon - m_{A'}$ plane, as of late 2012. From [10].

The existing constraints in this range are from beam dump experiments and measurements of the $g-2$ of the electron, as well as a search for $\phi \to \eta A'$, $A' \to e^+e^-$ with the KLOE detector [9] and a search at BaBar for $\Upsilon(3S) \to \gamma\mu^+\mu^-$ that can be reinterpreted [8] as a limit on the coupling and mass of the A'. For a more comprehensive description of these constraints, see Ref. [10] and references therein.

As seen in Figure 1, APEX covers a large portion of this area of parameter space, from $m_{A'} \sim 65$ to 525 MeV and with coupling reach to $g'/e > 2.3 \times 10^{-4}$. A test run for APEX was performed in July of 2010 and demonstrated the feasibility of the full experiment.

4 APEX at Jefferson Lab's Hall A

APEX is designed to take full advantage of JLab's Continuous Electron Beam Accelerator Facility and the two High Resolution Spectrometers (HRSs) in Hall A. For the test run, an electron beam of energy 2.260 GeV and an intensity of up to 150 μA was used, incident upon a tantalum foil of thickness 22 mg/cm^2. The central momentum of each HRS was $\simeq$ 1.131 GeV with a momentum acceptance of $\pm$ 4.5%.

An A' is produced via a process analogous to photon bremsstrahlung and decays to an e^+e^- pair; thus, the A' signal will appear as a small, narrow bump in the invariant mass spectrum of e^+e^- pairs from background QED processes. The diagrams for signal and irreducible backgrounds are shown in Figure 2.

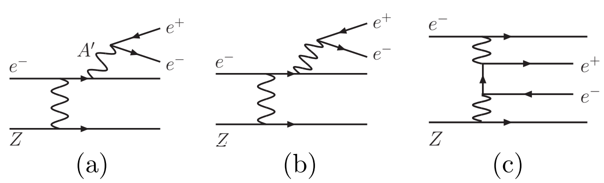

Figure 2: A' signal process (a) and irreducible QED backgrounds (b) and (c).

The opening angle Θ_0 of the e^+e^- pair is set by $m_{A'}$ and the incident electron beam energy as $\Theta_0 \sim m_{A'}/E_b \approx 5°$, with no such expectation for the QED backgrounds. This motivates a symmetric HRS configuration with both spectrometer arms positioned far forward. To optimize sensitivity to A' decays, dipole septum magnets are placed between the target and the HRS aperture.

The Hall A HRSs consist of several different components to allow for the measurement of the position and momentum of charged particles to a high degree of accuracy. Vertical drift chambers, two orthogonal planes containing anode wires immersed in an argon-CO_2 mixture, allow for an accurate determination of the full 3D track of an incoming particle. The rate of electron singles for APEX ranges up to 5.8 MHz, and the APEX test run achieved a VDC rate of 5 MHz, higher than had ever been used in Hall A. Two separate sets of scintillators provide timing information, to identify coincident e^+e^- pairs. Online particle ID is provided by a gas Cherenkov detector and a lead glass calorimeter allows for further offline rejection of pion backgrounds.

Accurate determination of the momentum of a produced particle requires knowledge of the position of the particle at the target in addition to position as it enters the HRS. Since Hall A is used by several different experiments, a reliable method by which to calibrate optics is necessary. For the APEX test run, a method known as sieve-slit was used. A metal sieve with a characteristic pattern of holes drilled into it is placed just beyond the target enclosure, and elastic scattering events are collected during a calibration run. Since the position at the target is known very well, the pattern of incident particles that enter the VDC provide an optics matrix which is used for momentum calibration.

Excellent mass resolution is required to enable the identification of an A' resonance. The HRSs are designed to achieve high momentum resolution at the level of $\delta p/p \sim 10^{-4}$, providing a negligible affect upon the mass resolution. Angular resolution and multiple scattering in the target are the dominant contributions to the mass resolution, as shown in Table 1.

For the test run, APEX achieved a mass resolution of $\sigma \sim 0.85 - 1.11$ MeV, varying over the full $m_{A'}$ range.

mrad	Optics	Tracking	MS in target
σ(horiz)	0.11	$\sim$0.4	0.37
σ(vert)	0.22	$\sim$1.8	0.37

Table 1: Contributions to APEX mass resolution.

Reducible backgrounds were rejected using a combination of different triggers. These backgrounds include electron singles from inelastic or electron-nucleon scattering, pions from virtual photon decays, proton singles, accidental e^+e^- coincidences, and e^+e^- pairs from real photon conversions. The ratio of positron to charged pion production in the right HRS was greater than 1/100; this pion contribution was reduced online by a factor of 30 and the necessary rejection was achieved offline using both gas Cherenkov and calorimeter information.

The final event sample trigger for the test run required a double coincidence gas Cherenkov signal within a 12.5 ns window in each arm. The resulting data sample consisted of 770,500 true e^+e^- coincident events with 0.9% (7.4%) meson (accidental e^+e^- coincidence) contamination.

5 Bump Hunt / Resonance Search

The final data sample was analyzed as an invariant mass spectrum of e^+e^- pairs. A bump hunt for a small, narrow resonance was performed. A probability model of the form

$$P(m_{e^+e^-}|m_{A'},\sigma,S,B,a_i) = \frac{S\cdot N(m_{e^+e^-}|m_{A'},\sigma) + B\cdot Polynomial(m_{e^+e^-},a_i)}{S+B} \tag{1}$$

was used, where S is the number of signal events, N is a Gaussian distribution with width σ corresponding to the mass resolution, B is the number of background events, and the a_i are coefficients of a polynomial that encode the shape uncertainty on the background. This model formed the basis of a likelihood function and a test statistic, the profile likelihood ratio, that was then used to calculate p-values for the null hypothesis and upper limits on S.

A scanning-window approach was adopted, where a window around each $m_{A'}$ hypothesis is formed before performing a likelihood test. Based on extensive simulations, a 7th order polynomial and a 30.5 MeV window was chosen to maximize sensitivity and simultaneously minimize pull. The resonance search was performed on the invariant mass spectrum with 0.05 MeV binning and the procedure was repeated in steps of 0.25 MeV for each candidate A' mass.

6 Test Run Results

No significant excess was found over the invariant mass range of $m_{A'} = 175$ to 250 MeV; see Figure 3. The most significant excess was at 224.5 MeV with a p-value of 0.06%. Out of ~1000 pseudoexperiments based on the test run data, 40% yielded a p-value at least as extreme as 0.06% somewhere in the mass range.

The upper limit on number of signal events, S, compatible with a background fluctuation at the 90% CL was translated into an upper limit on the A' coupling, α'/α, by exploiting the kinematic similarities between A' and γ^* production. The cross sections for the two processes are simply related [8] within a 1 MeV window around the A' mass, and thus the signal-to-background ratio is independent of detector acceptance in this mass window. Based on Monte Carlo simulations, the ratio f of the radiative-only cross section to the full QED background cross section varies linearly from 0.21 to 0.25 across the APEX mass range and, thus, all backgrounds can be normalized to the radiative background. The final expression relating S_{max} and $(\alpha'/\alpha)_{max}$ is

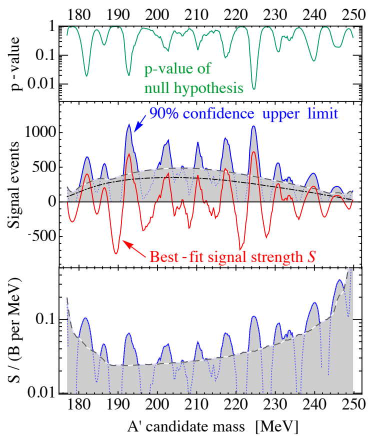

Figure 3: Results of the resonance search.

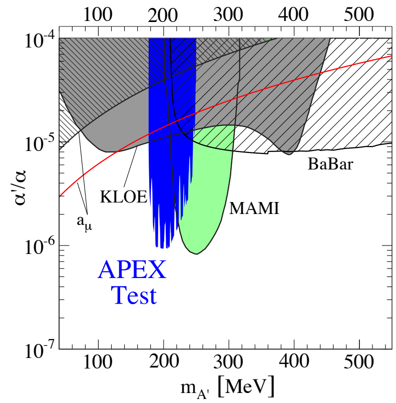

Figure 4: Upper limit on coupling.

$$\left(\frac{\alpha'}{\alpha}\right)_{max} = \left(\frac{S_{max}/m_{A'}}{f \cdot \Delta B/\Delta m}\right) \times \left(\frac{2N_{eff}\alpha}{3\pi}\right), \tag{2}$$

and the upper limit on coupling is shown in Figure 4.

7 Full Run Plans

The APEX full run is approved and will be ready to run when JLab switches on in 2014 after an upgrade of the beam energy from 6 to 12 GeV. The full run will take data for ∼34 days at four different energy and spectrometer settings, and will cover a larger mass range, $m_{A'}$ = 65 to 525 MeV, using a 50 cm long multifoil target. The full run statistics will be ∼200 times larger than the test run, allowing sensitivity to α'/α 1-2 orders of magnitude below current limits. A new optics calibration method is currently being tested and data acquisition rates are being improved, to allow for up to 5 kHz. A complete description of the full run is in Ref. [1].

8 Acknowledgments

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