

The APEX experiment at JLab

Searching for the vector boson A' decaying to e^+e^-

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Abstract. Jefferson Lab's A' Experiment (APEX) will search for a new vector boson, the A' , in the mass range $65 \text{ MeV} < m_{A'} < 550 \text{ MeV}$, with sensitivity for the A' coupling to electrons of $\alpha' > 6 \times 10^{-8} \alpha$, where $\alpha = e^2/4\pi$. New vector bosons with such small couplings arise naturally from a small kinetic mixing of the “dark photon”, A' , with the photon — one of the very few ways in which new forces can couple to the Standard Model — and have received considerable attention as an explanation of various dark-matter related anomalies. In this experiment, A' bosons produced by radiation off an electron beam could appear as narrow resonances with small production cross-sections in the e^+e^- invariant mass distribution. The two Jefferson Lab HRS spectrometers will provide a reconstructed invariant-mass resolution for the A' of $\delta M/M < 0.5\%$. With a 33-day run, the experiment will achieve high sensitivity by taking advantage of this mass resolution and high statistics of the e^+e^- pairs, which will be orders of magnitude larger than in previous searches for the A' boson in this mass range. This paper will review the key concepts of the experiment and the status of the preparations for running APEX. The results of a completed pilot run will be presented.

1 Introduction

The APEX experiment [JLab Exp. E12-10-009][1] will search for a dark photon — a new massive vector boson that couples weakly to ordinary matter— by looking for a signature of the A' produced through a bremsstrahlung-like process as JLab's electron beam passes through a high-Z target, illustrated in Fig. 1. The experiment is based on the concepts presented in J.D. Bjorken *et al.* [2]. The APEX collaboration consists of upwards of 100 researchers from about 26 institutions.

The A' production is forward peaked, with a production angle $\sim (m_{A'}/E)^{3/2}$. The experiment will search a kinematic regime in which the A' can decay to an electron-positron pair; electron-positron pairs will be detected in the twin High Resolution Spectrometers positioned at small angles relative to the Hall A incident electron beam. APEX is designed to reach the required invariant mass resolution, 0.5%, for forward-peaked lepton pairs by using three key ingredients: 1) JLab's twin high-resolution spectrometers (HRS left and HRS right) with improved rate capability trackers, 2) a septum magnet, shown schematically in Fig. 1, that will bend the electron-positron pairs produced around $\pm 7.5^\circ$ outwards and into the acceptance of the spectrometers, and 3) a novel multi-foil tungsten target.

2 The APEX reach

The production cross-section can be calculated using a QED-like Feynman diagram shown in Fig. 2, in which

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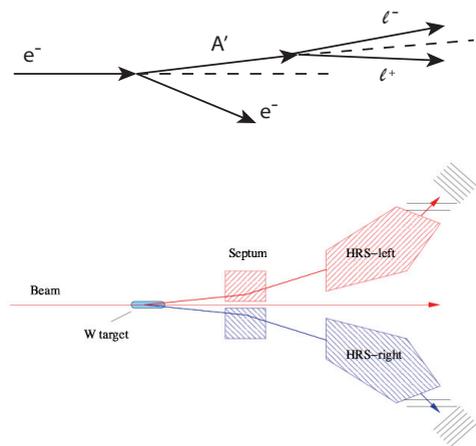


Figure 1. The APEX experiment will attempt to produce the A' through a bremsstrahlung-like process (top diagram) and search for a subsequent decay into an electron-positron pair using JLab's High Resolution Spectrometers. (bottom diagram).

we assume the coupling constant e' can be written as an unknown dimensionless parameter ϵ times the electron charge e . This gives a production cross section that is proportional to $\epsilon^2/m_{A'}^2$. Thus, the production rate is param-

terized by $m_{A'}$ and ϵ^2 , or, equivalently, it is customary to write ϵ^2 as α'/α where $\alpha = e^2/4\pi$.

The background processes include trident diagrams of a very similar nature and are larger by order $1/\epsilon^2$, but this background is broadly distributed in mass so APEX can take advantage of the fact that the signal will be a very narrow invariant-mass peak sitting on top of this broad background.

Since the background is known and the signal is a function of α' and m , we have designed an experiment that has a region of sensitivity down to $\alpha'/\alpha = 9 \times 10^{-8}$ over an A' mass region of 65 MeV to 525 MeV. Reaching this level of sensitivity requires an invariant-mass resolution of 0.5% or better.

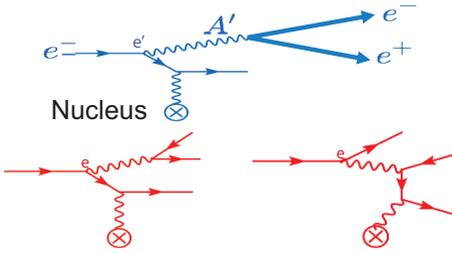


Figure 2. The Feynman diagram for production of the A' involves the coupling constant $e' = \epsilon e$ (top diagram) while the background Bethe Heitler pair production processes, shown in the bottom diagrams, are larger by a factor of ϵ .

The High Resolution Spectrometers have excellent resolution but relatively small kinematic acceptances compared to an apparatus based on large open geometries. However, the proposed search region of 65 MeV to 525 MeV can be covered with only four kinematic settings, shown in Fig. 3, due to the strong forward peaking of both the A' and the subsequent lepton decay pairs. Figure 3 shows that APEX can reach a sensitivity of ϵ^2 down to about 10^{-7} with just 30 days of production running.

The multi-foil target is shown in Fig. 4. The incident electron-beam passes through a series of tungsten foils. These foils are arranged so that the outgoing positron-electron pairs produced in one foil do not pass through any of the downstream foils on their way to the septum magnet. This minimizes the multiple scattering and is required to reach the desired mass resolution. In addition, the spatial distribution of the foils actually increases the experiment's angular acceptance and mass coverage.

3 Achieving $\delta m/m = 0.5\%$

The experiment is based on reconstructing the invariant mass of lepton pairs using the two four-momenta measured in the High Resolution Spectrometers (HRSs).

$$M^2 = (p_1^\mu + p_2^\mu)^2 \approx 2|\vec{p}_1||\vec{p}_2| - 2\vec{p}_1 \cdot \vec{p}_2 = 4p_1 p_2 \sin^2 \frac{\theta}{2} \approx p_1 p_2 \theta^2.$$

Uncertainty in the energy of the incident beam does not affect the experiment. The errors in the pair of lepton

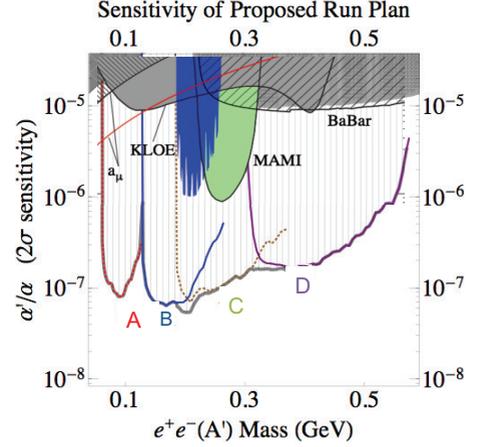


Figure 3. The predicted region of sensitivity and reach of the APEX experiment assuming 6 days at 1.1 GeV electron-beam energy (region A), 6 days at 2.3 GeV (region B), 6 days at 3.3 GeV (region C), and 12 days at 4.5 GeV (region D). The exclusion region of the APEX test run is shown in blue along with the exclusion regions from KLOE, MAMI and BaBar.

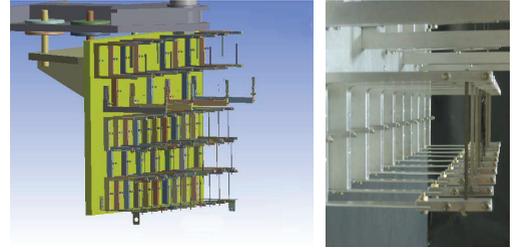


Figure 4. Left: The foil production target ladder design with three foil production targets at bottom and auxiliary targets used for alignment and optics calibrations at top. Right: Photo of a production target showing line of vertical tungsten target foils.

momenta and opening angle would introduce an error in the extracted invariant mass,

$$\frac{\delta M}{M} = \frac{\delta p_1}{2p_1} + \frac{\delta p_2}{2p_2} + \frac{\delta \theta}{\theta}.$$

The trajectories of the out-going decay leptons are measured by the instrumentation packages located at the back of each of the two HRS spectrometers. Determination of the lepton-pair opening angle θ for each event is complicated by the need to track back through the 23 meters of the QQDQ magnetic optics and then further back through the septum to determine the lepton trajectories as they exit the target foils. Our ability to reconstruct the lepton trajectories back to the target region was demonstrated during the APEX test run. As part of the HRS calibration procedures, two tungsten sieves (tungsten plates containing a pattern of holes) were used. The sieves were inserted in each spectrometer arm in front of the septum magnet during low intensity running with both spectrometer arms

tuned for electrons. The analysis magnetic-optics parameters were then tuned to accurately reconstruct the hole pattern using the trajectories of the electrons that had passed through the holes. This calibration data demonstrated that the opening angle between two outgoing particles (one in each arm) was determined to 0.3 mrad. A systematic error in the decay-lepton opening angle of this size would correspond to a reconstructed mass shift of only 0.17%.

This uncertainty in the determination of the absolute mass is not important for APEX, but the resolution of the mass measurement is important since we are taking advantage of the HRS's ability to provide a signature of a narrow peak sitting on a broad background. It is the projected APEX resolution that will give the experiment its sensitivity compared with the competition. Assuming both spectrometers have the same fractional rms resolution, σ_p/p , and using σ_θ/θ for the accuracy of the reconstructed opening angle, the expected width of the peak is

$$\left(\frac{\sigma_M}{M}\right)^2 = \frac{1}{2}\left(\frac{\sigma_p}{p}\right)^2 + \left(\frac{\sigma_\theta}{\theta}\right)^2.$$

The APEX experiment is designed to achieve an invariant mass resolution of $\delta m/m = 0.5\%$. At better than 10^{-3} , the HRS momentum resolution does not contribute significantly to our error budget so the missing mass resolution is determined by our ability to reconstruct the opening angle of the outgoing lepton pair. The multiple scattering of the leptons as they exit a single target foil contributes an uncertainty of around 0.5 mrad for the worst-case kinematics setting, so we need to measure the outgoing angles to about 0.7 mrad. The reconstruction of the sieve holes during the APEX test run demonstrated that we can achieve a resolution of 0.54 mrad for the opening decay angle and, in turn, this indicates that APEX can achieve a resolution of $\delta M/M < 0.5\%$.

4 Preparation for the APEX run

As discussed above, the APEX reach in ϵ^2 is achieved through its excellent invariant mass resolution and this, in turn, is determined by our ability to reconstruct the lepton-pair opening angle at the target. The tungsten-sieve calibration data are used for tuning the magnetic optics parameters and provide a direct measurement of our ability to determine the lepton trajectories as they leave the target. The APEX test run analysis demonstrated that we achieved a resolution of $\delta\theta < 0.54$ mrad. However, this angular resolution measurement is extracted from data taken with both spectrometers tuned for electrons. Additional uncertainties arise from the need to reverse the field in one spectrometer arm to accept positrons after the sieve-based optics calibration is completed; aberrations that may arise when one half of the septum magnetic is reversed may reduce the experiment's resolution. In principle, it would be best to calibrate with one arm tuned for positrons, but the analysis of the test run data taken with this configuration was not able to clearly identify positrons coming from the sieve holes. This observation agrees with Monte Carlo simulations showing that positrons produced in the target

and passing through the sieve holes cannot be separated from positrons produced in the sieve itself. For the test run, the limit on the degradation of the angular resolution caused by reversing the fields had to be estimated.

For the actual APEX production runs, we plan to calibrate the positron-arm with positrons by implementing active sieves based on arrays of scintillating fibers, shown in Fig. 5. This will avoid uncertainties associated with reversing the fields. There will be one active sieve for each of the two arms. Each active sieve will consist of two planes of 1 mm diameter scintillating fibers with 32 fibers per plane. The scintillator fibers will be coupled to multi-anode PMTs whose signals will be processed by JLab's F250 16-channel 250 MHz flash ADCs after amplification by x10 signal amplifiers. The active sieves will be located inside the target vacuum housing and can be inserted into the spectrometer acceptance regions using remotely controlled linear actuators.

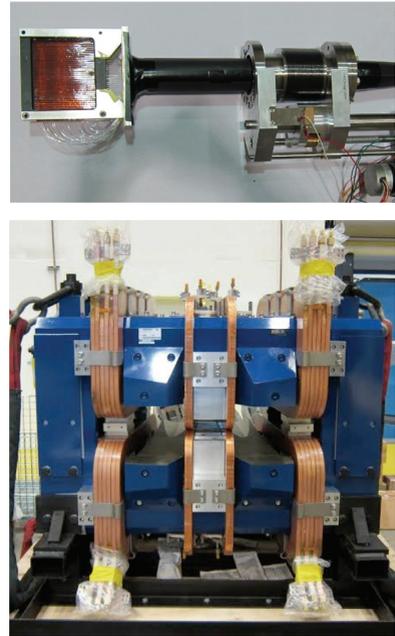


Figure 5. Top: An active sieve attached to a linear actuator and vacuum bellows. Bottom: The APEX septum magnet.

The APEX production run will take advantage of the well-understood Hall A equipment, data acquisition, and analysis software associated with the High Resolution Spectrometers. The active-sieve and the septum magnet (shown in Fig 5) are both complete and ready for installation on short notice. In addition, we plan to make small modifications to the high voltage electronics used for the spectrometer's vertical drift chambers. These modifications will allow us to run with higher luminosity during the APEX production running.

5 APEX test run and upcoming production running

When reviewing the preparations for the APEX run, the most important point to make is that the collaboration already ran a test run in July of 2010 that not only verified all key aspects of the experiment, but also produced respectable results around $m_{A'} \sim 200$ MeV and these results have already been published as a Physical Review Letter[3]. The test run was performed using an existing, but non-optimal, septum magnet and a 22 mg/cm² tantalum foil. The two spectrometer arms were positioned for central acceptance of $\pm 4.5\%$ and the incident electron beam was delivered at 2.26 GeV. The data collected contained 770,000 coincidence events. The analysis showed that 7.4% of these events were accidental coincidences between the two arms and 0.9% were due to meson contamination, leaving 700,000 good trident events.

The e^+e^- invariant mass spectrum obtained from the test run data, shown in Fig. 6, shows no visible sign of a narrow peak that would correspond to A' production. A quantitative peak search algorithm, described in detail in Ref. [3], was used to produce the 90% confidence upper limit shown in Fig. 7. It can be seen that the test run data saw no evidence for $A' \rightarrow e^+e^-$ and set an upper limit of $\alpha'/\alpha \simeq 10^{-6}$.

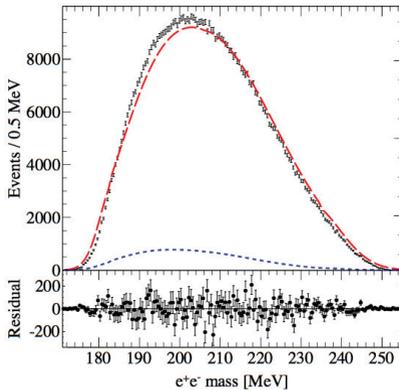


Figure 6. Invariant mass spectrum obtained from the APEX test run data. The upper panel shows the data (black points, with error bars), the contributions from e^+e^- coincidence events (blue short-dash line), and the calculated QED trident background added to the accidental event sample (red long-dash line). The lower panel shows the bin-by-bin residuals with respect to a 10-parameter fit to the global distribution.

The APEX 90% confidence level reach for 30 days of production running with the improved equipment is shown in Fig. 8. The landscape of exclusion zones based on the results of other experiments has been filled in considerably since the APEX experiment was first proposed. However, the APEX calculated reach, down to $\alpha' \sim 6 \times 10^{-8}\alpha$, remains an order of magnitude better than our current state of knowledge in the mass region $65 \text{ MeV} < m_{A'} < 550 \text{ MeV}$.

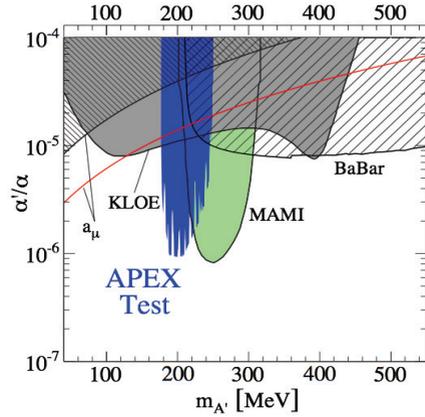


Figure 7. The 90% confidence upper limit on α'/α vs the A' mass for the APEX test run (solid blue). Also shown are the exclusion regions known at the time of the test-data publication: from the muon anomalous magnetic moment a_μ (fine hatched) [4], KLOE (solid gray) [5], Mainz (solid green) [6], and BABAR (wide hatched) [2, 7] as presented in Ref. [3]. Calculations indicate that the A' could explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment if (α'/α) lies below the fine-hatched region and above the red line.

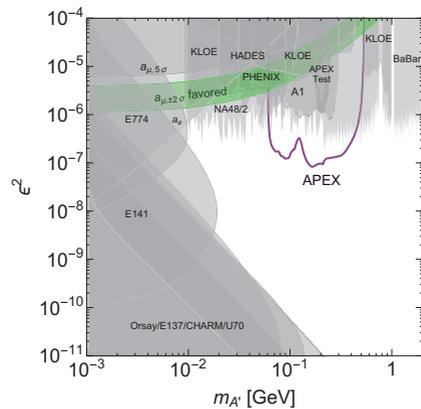


Figure 8. The predicted reach of the APEX experiment assuming 30 days of production running compared to existing results.

Although the experiment was prepared to run in the spring of 2016, the run did not take place due to complications with the Jefferson Lab 12 GeV-era accelerator turn on. It now appears that the earliest likely running of APEX would be in the fall of 2018.

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