3.18 E12-10-009 - APEX

An Electron Fixed-Target Experiment to Search for a New Vector Boson A' Decaying to e^+e^-

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3.18.1 Introduction

The development of the Standard Model of particle interactions is the culmination of a century of searches and analyses with fixed-target and colliding beam experiments. The Standard Model describes all known matter, and its interactions through the strong, weak, and electromagnetic forces mediated by vector bosons of the Standard Model. New forces beyond the Standard Model could have escaped detection only if their mediators are either heavier than O(TeV) or quite weakly coupled. The latter possibility can arise through a simple and generic mechanism proposed by Holdom [1], in which a new vector particle A'_μ (the *dark photon*) mixes via quantum loops with the Standard Model photon. This mixing, with a typical strength $\varepsilon \sim 10^{-2} - 10^{-6}$, in turn induces a minute charge for ordinary matter under the new force, so that the dark photons coupling to matter is smaller than that of the photon by $\alpha'/\alpha = \varepsilon^2$. In this context, MeV–GeV masses for the A' are both well-motivated and weakly constrained, with limits at $\varepsilon e \lesssim 0.3 \times 10^{-2} e$ for most A' masses between 10 MeV and 1 GeV.

Fixed-target experiments with high-intensity electron beams and existing precision spectrometers are ideally suited to explore sub-GeV forces by probing reactions in which a new A' vector particle is produced by radiation off an electron beam [2, 3]. The A' can decay to an electron and positron pair and appears as a narrow resonance of small magnitude in the invariant mass spectrum. In [2], several fixed-target experimental strategies were outlined to search for new sub-GeV vector interactions.

The C12-10-009 experiment is a concrete plan for an A' search using the CEBAF accelerator and the High Resolution Spectrometers (HRS) in Hall A [4]. This experiment, the A' *Experiment* (APEX), can probe charged particle couplings with new forces as small as $3 \times 10^{-4} e$ and masses between 65 MeV and 525 MeV — an improvement by two orders of magnitude in cross section sensitivity over present limits across most of this mass range.

Fixed-target experiments of this form are particularly timely in light of a series of recent anomalies from terrestrial, balloon-borne, and satellite experiments that suggest that dark matter interacts with Standard Model particles. Much of this data hints that dark matter is directly charged under a new force mediated by an A' and not described by the Standard Model. Theoretical as well as phenomenological expectations suggest an A' mass $m_{A'} \lesssim 1\,\mathrm{GeV}$ and $\varepsilon e \lesssim 10^{-2} e$.

Expected reach and impact APEX will be sensitive to new gauge bosons with couplings as small as $\varepsilon^2 \equiv \alpha'/\alpha \sim 9 \times 10^{-8}$ and masses in the range $65 - 525\,\mathrm{MeV}$ (here α (α') is the coupling of the photon (A') to electrically charged matter). This is about a factor of $3 - 10$ times lower in ε than existing constraints (several of which also rely on an A' coupling also to muons), and corresponds to $\sim 10 - 100$ times smaller cross-sections.

The precise mass range probed by this type of experiment can be varied by changing the spectrometer angular settings and/or the beam energies, see the APEX plan in Figure 63. The parameter range probed by APEX is interesting for several reasons. This region of mass and coupling is compatible with A''s explaining the annual modulation signal seen by the dark matter direct detection experiment DAMA/LIBRA, and also with dark matter annihilating into A's, which explains a myriad of recent cosmic-ray and other astrophysical anomalies. In addition, and independently of any connection to dark matter, the APEX experiment would be the first to probe A's of mass $\gtrsim 50\,\mathrm{MeV}$ with gauge kinetic mixing significantly below $\varepsilon \sim 10^{-3}$, the range most compatible if the Standard Model hypercharge gauge

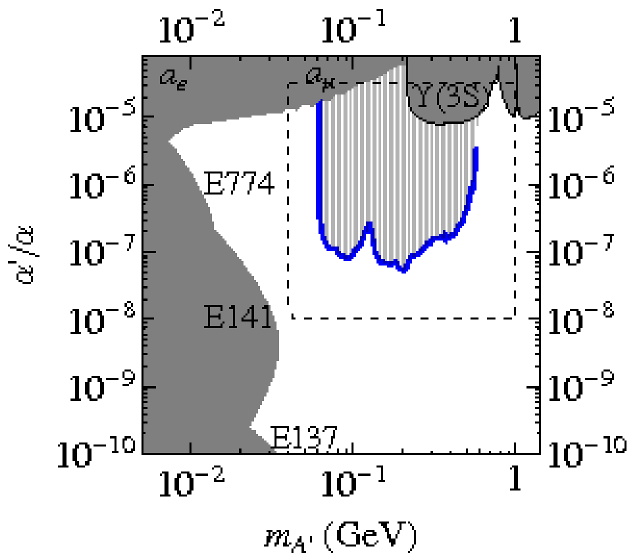

Figure 63: The reach of the APEX experiment (blue contour), existing constraints (gray shaded and hatched regions), and other proposed experiments (colored lines). The region in which an A' could explain the anomalous measurement of the muon $g-2$ is shaded in green.

force is part of a Grand Unified Theory.

The importance for fundamental physics of precision searching for new forces near the GeV scale cannot be overstated.

Concept In the APEX experiment, we are interested in collecting as many true e^+e^- coincidence events as possible, since the A' is expected to decay to e^+e^- pairs. A large background of such true coincidence events is expected also from Standard Model QED Bethe-Heitler and radiative trident processes, but the A' would appear as a narrow spike on top of this large Standard Model background. A further background is the accidental e^+e^- coincidences that come from two distinct scattering events, in which an electron scatters into the L-HRS from one event, while a positron scatters into the R-HRS in a second event within the timing window of the trigger. Lastly, there are both true and accidental $e^-\pi^+$ coincidence events. Rejection of these two backgrounds is key to the A' search and is achieved by means of a short trigger timing window and good particle identification (PID).

The other crucial factor in determining the sensitivity of this experiment is the optics, which determines the ultimate mass resolution of the experiment. Since we are looking for a narrow spike on top of a large, smooth QED background, excellent mass resolution is essential to achieve the best possible sensitivity to an A'. In the APEX experiment it is crucial to take into account the above considerations.

Figure 64 shows the layout of the APEX experiment. The central momenta of the both spectrometers are set to half of the beam energy. At such a setting the background rates are minimized. The same time most of A' events will be detected in spite of small momentum bite of the HRSs.

Our *coincidence trigger* is defined as a signal in the S2m of both the left HRS *and* the right HRS, *and* a signal in the Gas Cherenkov counters of the right HRS. The coincidence trigger based on these three signals allows us to collect true coincidence events with high efficiency and acceptable DAQ dead time. Such events are candidates for true coincident e^+e^- signal events.

The design of the target for the APEX experiment shown in Figure 65 has a number of interesting ideas including a concept of narrow ribbons, a tension mechanism, and alignment and calibration target sets.

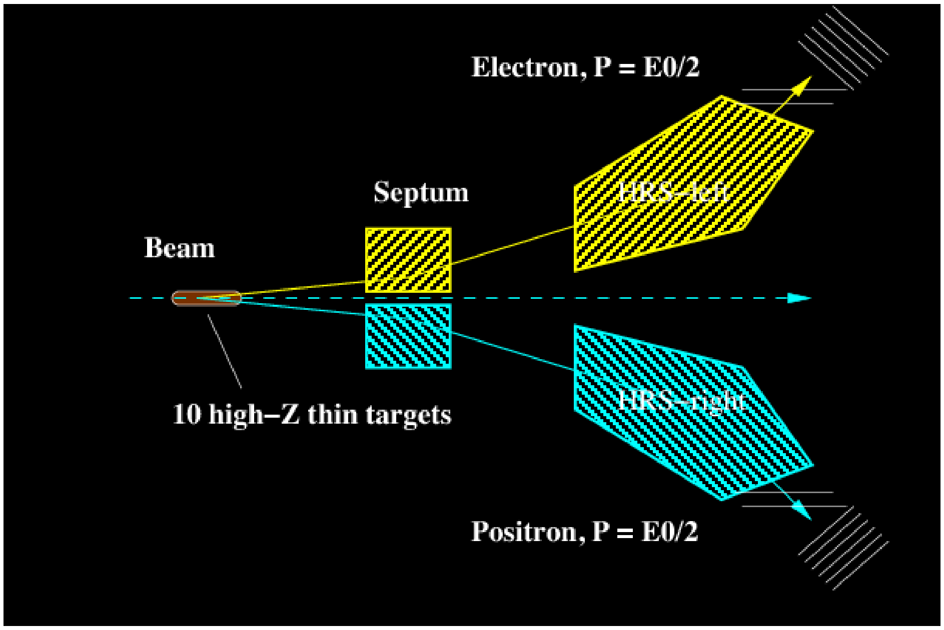

Figure 64: The layout of the APEX experimental setup.

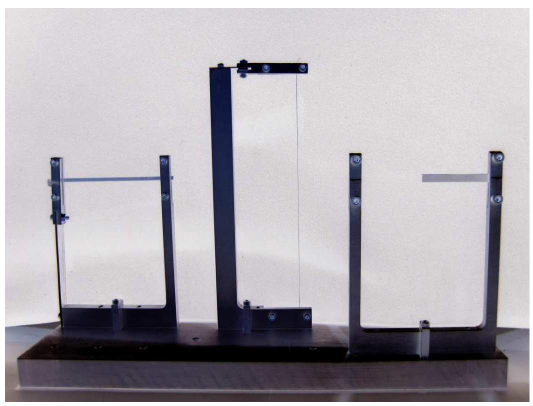

Figure 65: The components of the target for the APEX experiment.

3.18.2 Test Run Results and Future Plans

A test run was recommended by PAC35, and realized after the PREX experiment in June 2010. The primary purpose of the test-run was to demonstrate the detector performance necessary for a full APEX run, including:

1. Demonstrate that the gas Cherenkov counters can be used effectively in a coincidence trigger to reduce the pion accidental trigger rate, even at high count rates (a sufficient online rejection of $1/30$ was achieved)
2. Measure the importance of different contributions to background and their agreement with simulation (all QED backgrounds agreed within 10–20% uncertainties; pion background rates were lower than the WISER expectation by a factor of 6 at 2 GeV).
3. Prove that a successful 20 ns triple-coincidence trigger (S0-S0-C) can be achieved.
4. Prove that the vertical drift chambers (VDCs) can operate at a rate higher than 20 kHz/wire (performance was sufficient up to the anticipated 6 MHz singles rate; efforts to reduce inefficiencies at these high rates are ongoing)

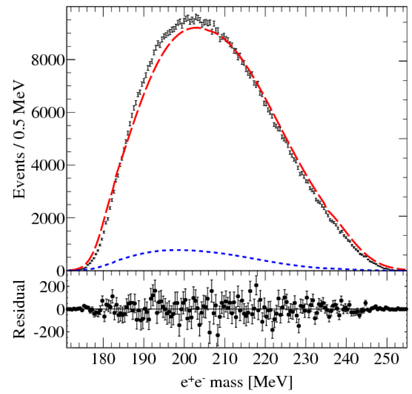

Figure 66: Upper panel: The invariant mass spectrum of e^+e^- pair events in the final event sample (black points, with error bars), accidental e^+e^- coincidence events (blue short-dash line), and the QED calculation of the trident background added to the accidental event sample (red long-dash line). Lower panel: the bin-by-bin residuals with respect to a 10-parameter fit to the global distribution (for illustration only, not used in the analysis).

The detectors were tested in all the extreme conditions expected during the APEX production run. Further results on these topics were presented at the A'-boson workshop [5] at JLab in September 2010. The observed detector performance was found to be in compliance with the APEX requirements.

In addition, a science dataset of 700,000 QED e^+e^- events (Fig. 66) was obtained during the test run. These allowed an A' search over the mass range from 175 to 250 MeV, which in the lower half of the mass range exceeds all other experiments' sensitivity by an order of magnitude [6]. As no signal was seen, an upper limit on α'/α was obtained, shown in Figure 67.

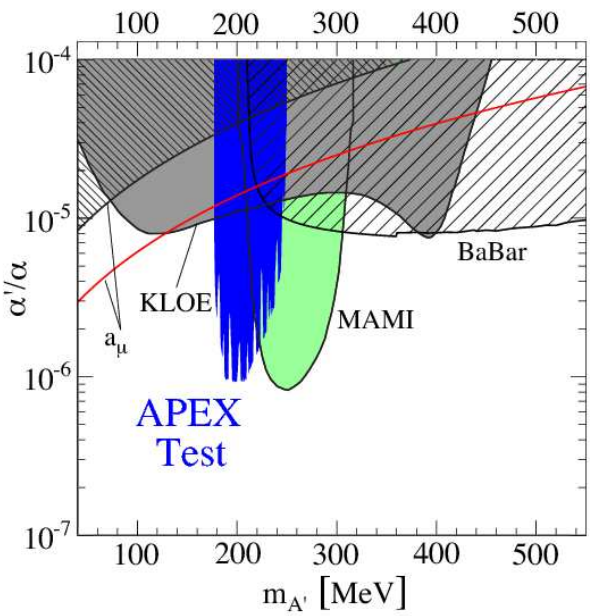

Figure 67: The 90% confidence upper limit on α'/α versus A' mass for the APEX test run (solid blue). Also shown are existing 90% confidence level limits from the muon anomalous magnetic moment a_μ (fine hatched) [7], KLOE (solid gray) [8], the result reported by Mainz (solid green) [9], and an estimate using a BaBar result (wide hatched) [2, 3, 10]. Between the red line and fine hatched region, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [7] at 90% confidence level. The full APEX experiment will roughly cover the entire area of the plot.

References

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