Dark sector searches at Jefferson Laboratory

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Abstract. The nature of Dark Matter (DM) is one of the prominent open-questions in physics: although gravitational observations proove that matter in our Universe is mainly made of Dark Matter, very little is known about it. While most of "traditional" DM experiments are designed and optimized to prove the weak-force mass scale, O(100 GeV/c²), the light Dark Matter region, O(10 MeV/c² - 1 GeV/c²) is, so far, almost unexplored. This hypothesis is a compelling possibility for new physics, and a rich experimental program is currently being proposed and developed to investigate it.

The Jefferson Laboratory community joined this program with different, complementary efforts. The APEX, HPS, and DarkLight experiments are searching for a possible $U(1)$ force-mediator between the dark sector and the Standard Model (SM), the "Dark Photon". These three experiments look for the visible Dark Photon decay to Standard Model particles, mainly in the e^+e channel. The BDX experiment, instead, is a beam-dump experiment looking directly for the Light Dark Matter scattering on a detector, resulting in a visible energy release.

1. Introduction

The overwhelming evidence for the existence of Dark Matter is based on multiple, independent astrophysical and cosmological observations, such as the stellar rotation curves in galaxies, the power spectrum of Cosmic Microwave Background (CMB) fluctuations, the ratios of light element yields from Big Bang Nucleosynthesis (BBN), the morphology of galaxy cluster collisions, and astrophysical mass measurements based on gravitational lensing. All the above measurements consistently indicate that 85% of the total matter and 25% of the total energy of our Universe comprises an electrically neutral, non relativistic population of "Dark Matter" [1].

The most popular mechanism to describe the observed abundance of DM in the Universe ($\Omega_{DM} = 0.242 \pm 0.004$ [2]) is the so-called "freeze-out" process, that describes the present amount of DM as a relic left-over from the primordial era of thermal equilibrium with SM particles, made possible by a proper non-gravitational interaction mechanism. The equilibrium broke when the interaction rate dropped below the Universe expansion rate. The thermal origin sets a lower limit on the DM mass, of the order of 10 keV/c², if DM has to explain large-scale structures as observed in the Universe [3].

The simplest model deriving from the above paradigm of thermally-generated DM in the early Universe is that of "Weakly Interacting Massive Particles" (WIMPs). In this model, DM particles have mass $m_{DM} = 10 \div 1000$ GeV/c², and interact with SM particles trough the Weak Force, with a thermally-averaged cross-section $< \sigma v >$ of the order of 10^{-26} cm³s⁻¹. The fact that no additional interactions are required to yield the observed DM abundance is the so-called "WIMP miracle". At present, a large number of running and planned experiments are exploring the heavy DM region [4], but, so far, no positive signal evidences have been found.
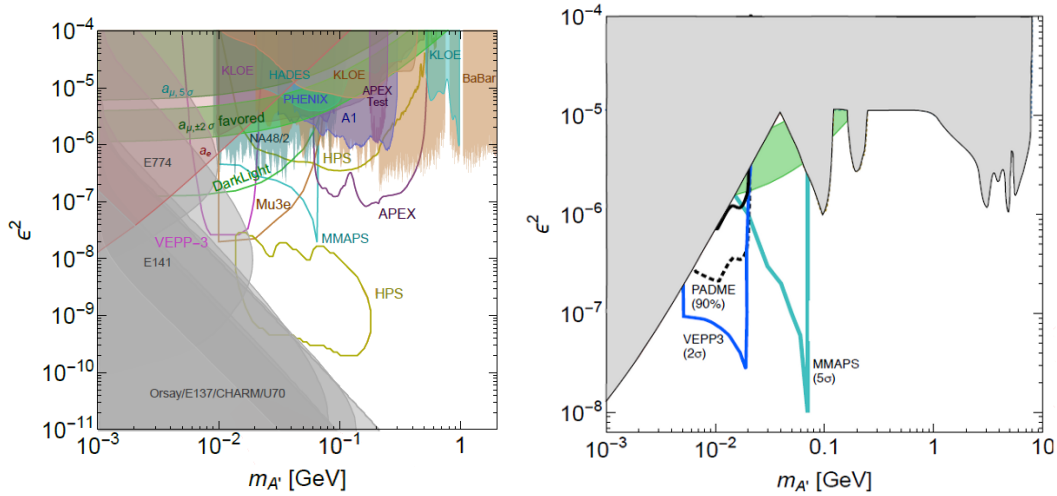
Figure 1. Exclusion limits on the dark photon parameters space from past (shaded) and planned (lines) experiments, for visibly (left) and invisibly (right) decaying A'. (Figures from [4]).

On the opposite side, the Light Dark Matter (LDM) hypothesis is, so far, almost unexplored. This scenario foresees DM particles in the mass range $m_{DM} = 10 \div 1000$ MeV/c^2, and thus is conceptually dinstinct from heavy WIMP DM: it requires a new interaction between LDM and SM particles, with a correspondingly light, sub-GeV force carrier, in order to be compatible with the DM thermal origin. The simplest mechanism to provide this interaction, the so-called "vector portal", is trough a new vector force carrier from an additional $U(1)_D$ gauge group under which LDM is charged, also called "dark photon", or A' (for a complete review of this and other possibilities, see [5]). In this model, the A' couples to ordinary photons through a "kinetic mixing" mechanism [6], i.e. through a loop-order effect, mediated by a GUT-scale massive particle that carries both the standard-model weak hypercharge and the dark-force equivalent. This induces an effective parity-conserving interaction $\varepsilon e A'_\mu J^\mu_{\mathrm{EM}}$ of the A' to the SM electromagnetic current, with coupling εe. The "vector-portal" scenario is regulated by four parameters: the LDM particles mass (m_χ), the mediator mass (m'_A), the A'-SM electric charge coupling (ε), and the A'-LDM coupling g_D. The strength of the kinetic mixing parameter is unknown, however, certain ranges can be motivated from quantum-mechanic effects of heavier particles. If the A'-SM coupling arises from a single-loop mechanism as described above, it is natural for ε to be of the order of $10^{-4} \div 10^{-2}$ [6], while higher order effects, foresee in GUT theories, predict a lower value, of about $10^{-6} \div 10^{-3}$ [7]. Similarly, the LDM thermal origin requirement set further limits on different combination of the model parameters, depending on the fine details of the interaction [4].

A comprehensive LDM experimental program has been launched in the last few years, investigating both the existance of χ particles and dark photons [4]. For the latter, these complementary searches are sensitive to different possible A' decay modes, that include both the so-called "visible" decay to SM particles, mainly lepton pairs of opposite charge, and the "invisible decay" to LDM particles. The relative strenght of the two processes depend on the actual values of the model parameters. In particular, for an on-shell A', the "visible" decay to e^+e^- pairs is the main reaction channel if $m'_A < 2m_\chi$, while the "invisible" decay dominates in the opposite case. The phenomenology of off-sheel particles is more rich [8], but still the distinction between the two regimes is governed by the particle masses.
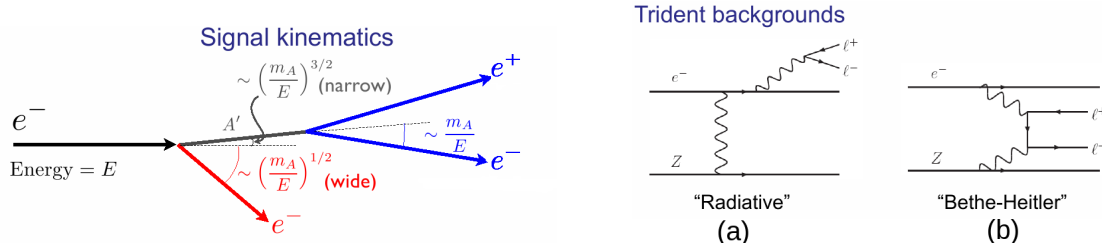
Figure 2. Left: the foreseen kinematics for the A' production by Bremsstrahlung off an incoming electron and the subsequent decay to an e^+e^- pair. Right: sample diagrams of radiative trident (γ^*) and Bethe-Heitler trident reactions that comprise the primary background to the A' search.

2. Dark photon experiments at Jefferson Laboratory

High luminosity, fixed target electron-beam experiments provide an unique way to probe the aforementioned dark photon visible-decay mode and the corresponding parameters space [9]. In these experiments, an electron beam impinges on a high Z target, producing heavy photons that subsequently decay to pairs of fermions. The A' is then reconstructed by measuring the decay products momenta. The kinematic of this process, reported in Fig. 2 (left panel), is characterized by a forward emitted A' that carries most of the incident electron beam energy E. This results in a very small opening angle of the decay products, of the order of $\theta \simeq M_A/E$. Therefore, the A' decay products are emitted at a very low angle with respect to the beam-line, and carry most of the beam energy. Furthermore, depending on the value of the parameters, long-lived A' are possible in the aforementioned parameter space, depending on the value of ε.

The main background sources associated to this reaction are QED trident processes, i.e. Bethe-Heitler trident reactions and radiative trident production (see Figure 2, right-panel). Although the Bethe-Heitler process has a much larger total cross-section, it can be significantly reduced by exploiting the very different kinematics. Instead, the radiative trident process is an irreducible background, with the same kinematic as the signal. However, it presents a smooth, continuous distribution in the e^+e^- invariant mass distribution, in contrast to the peak at the dark photon for the signal, and occurs promptly at the production target, while the signal can be displaced for small ε values.

2.1. The APEX experiment

The APEX experiment [10] is a fixed-target experiment in Hall-A, that makes use of the two High Resolution Spectrometers (HRSs) there installed [11] to search for a visibly-decaying dark photon in the e^+e^- final state. A proper dipole septum magnet between the thin Ta target and the HRS aperture allows the detection of scattered leptons down to $5°$ with respect to the incident beam. Each spectrometer is equipped with two vertical drift chambers, each with two orthogonal tracking planes, for momentum reconstruction, Cerenkov and plastic scintillator counters for particle identification and triggering, and a lead glass calorimeter.

In 2010 the APEX collaboration succesfully completed a test run, at 2.260 GeV electron beam energy, with currents up to 150 μA. The HRSs detectors were configured for central momenta of 1.13 GeV/c, with a corresponding acceptance of $\pm 4.5\%$. Events were measured by demanding a tight time coincidence (12.5 ns) between the two spectrometers and requiring good quality tracks in both drift chamber systems. Finally, a cut on the energy sum of the two particles, which can't exceed the primary beam energy, has been introduced to further reduce accidentals. The final data-set consits of $\simeq 770k$ events, with $O(7.5\%)$ contamination, mainly from accidentals. The e^+e^- mass resolution was 0.85 - 1.11 MeV/c^2, depending on the invariant mass. No events excess was measured in the e^+e^- invariant mass spectrum, on top of the QED background. Therefore,

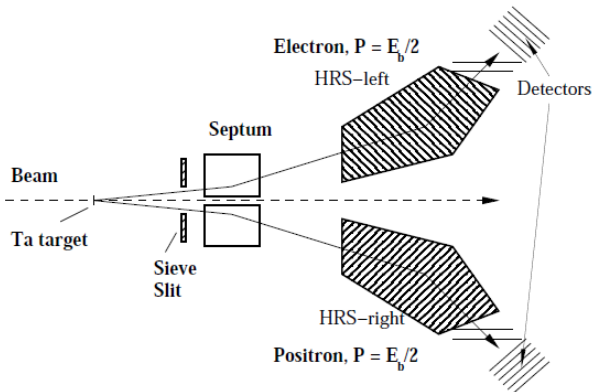**Figure 3.** Schematic of the APEX experimental setup. Figure from [10].

a sophisticated statistical technique was employed to determine the 2σ exclusion limit on the kinetic mixing parameter ε, as a function of the dark photon mass (see Fig. 1).

The APEX experiment has been fully approved by JLab, for a 34-days run period, and is scheduled to run in 2017-2018. The run plan foresees different configurations involving different beam energies and spectrometer settings, in order to cover a large area in the aforementioned parameters space.

2.2. The HPS experiment

The Heavy Photon Search (HPS) experiment [12] is a fixed-target experiment in Hall-B designed to search for dark photons in the mass range between 20 MeV/c^2 and 1 GeV/c^2 and coupling ε^2 between 10^{-5} and 10^{-10}, trough the decay to e^+e^-. HPS employes two complementary search techniques: resonance search and detached vertexing. In particular, through the latter, the experiment can explore a unique region in the parameters space corresponding to small cross sections. The foreseen reach is reported in Fig. 1.

The HPS detector (see Fig. 4) is a compact spectrometer, made by a $\simeq 1$ m long silicon tracker (SVT) inside a dipole magnet, to measure charged particle trajectories and production vertexes, and a lead-tunsgtate electromagnetic calorimeter (ECal), for particle identification and triggering. HPS employs a three-magnet system with the second dipole serving as an analyzing magnet: the thin Tungsten target ($\simeq 10^{-3}X_0$) is located in front of the analyzing magnet, at about 10 cm from the first SVT layer. To reduce beam-related backgrounds, the target and the SVT are mounted in a vacuum chamber, with the ECal being placed downstream the analyzing magnet, out of it. The SVT is made of 6 layers of Si modules, each with two sensors, mounted at a small stereo angle (100 for the first 3 layers and 50 for the others) to provide three-dimensional tracking and vertexing. The SVT is split in two modules, mounted on top and on bottom of the beam plane, leaving a central "dead-region" where the degraded beam can pass through the detector unobstructed. The edge of the sensors have to be placed at 0.5 mm from the electron beam plane to achieve the desired acceptance for low-mass dark photons. The ECal is also split into two halves, each made of 221 PbWO$_4$ crystals arranged in five rows. The light from each crystal is read out by a Large Area Avalanche Photodiode (APD), and corresponding signal is read by a custom amplier before being processed by a FADC-based DAQ system.

In July 2012, a successfull test run [13] demonstrated the feasibility of the measurement and of the detector operation. The experiment received full approval from the laboratory for a 180-day run, with different beam energy configurations, to be completed in different data-taking periods, up trough 2020. So far, two data-taking periods have been completed: in 2015, 1.7 days (10 mC) at 1.06 GeV, and in 2016, 5.4 days (92.5 mC) at 2.3 GeV.
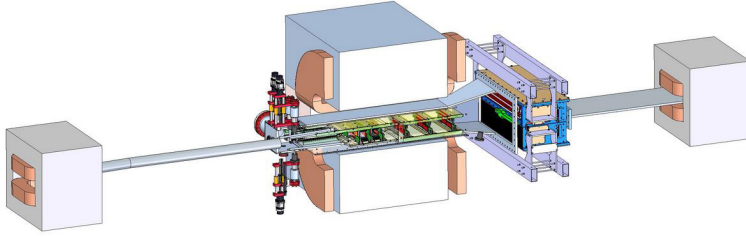
Figure 4. Schematic of the HPS detector setup. From left to right: the first dipole magnet, the target system, the silicon vertex tracker (SVT) inside the analyzing dipole magnet, the electromagnetic calorimeter (ECal), the third dipole magnet.

2.3. The DarkLight experiment

The DarkLight experiment [14] is a fixed gas target A' search, proposed at the Jefferson Laboratory Low Energy Recirculating Facility (LERF). In the experiment, the low energy (100 MeV), very high current (5 mA) electron beam will impinge on a $\simeq 10^{19}$ cm^{-2} long hydrogen target, thus reaching a luminosity of $\simeq 3 \cdot 10^{35}$ cm^{-2} s^{-1}. The experiment aims at reconstructing the complete final state in the reaction $ep \rightarrow epe^-e^+$, and, therefore, is sensitive both to the visible and to the invisible dark photon decay, the latter process being measured trough the missing mass of the final state $e - p$ system.

The DarkLight detector, cilindrically simmetric around the beam line, is made by a Si detector installed inside the target cell for low-energy recoiling proton detection, a 4-layer MicroMegas system working in conjuction with a 0.5 T solenoidal magnet for e^+ and e^- measurement, and an array of plastic scintillators acting as photon veto. The foreseen e^+e^- invariant mass resolution is $\simeq 1$ MeV/c^2.

In 2012, a crucial test demonstrated the feasibility of steering the 0.4 Megawatt electron beam trough the 2 mm diameter gas target aperture, with negligible losses [15]. The collaboration has planned a phased approach toward the final experiment: in the first phase, expected in 2016, accelerator studies will be performed, in order to understand the LERF operations in conjuction with the windowless target. At the same time, detector tests will be performed, potentially with a pilot DM search, with only a partial coverage detector. The second phase, currently under design, will consist of the full statistics measurement, with a complete detector.

3. The BDX experiment

The "Beam Dump eXperiment" (BDX) [16] is an e$^-$ beam, thick-target search at Jefferson Laboratory for LDM in the mass range $10 \div 1000$ MeV/c^2. BDX will detect dark matter particles produced by the primary e^- beam impinging on the JLab Hall-A beam dump, by measuring the scattering on a detector placed about 20 m downstream. The BDX detector will measure both $\chi-$nucleon and $\chi-$electron scattering. These two reactions have a very different signature in the detector: MeV nucleon recoil vs. GeV EM shower. Thus, the sensitivity to both is a powerful handle to control systematics.

The BDX detector is a segmented homogeneus calorimeter, made by CsI(Tl) crystals formerly used in the end cap BaBar Ecal, with an inproved SIPM-based readout. The calorimeter is made of about 800 crystals, resulting in a $0.5 \ m^3$ active volume. The crystals are arranged in a sequence of arrays, each $30 - cm$ long. In order to suppress cosmogenic and beam-related backgrounds, the calorimeter is surrounded by two active-vetos, made by plastic scintillator layers read by PMTs and SiPMs. Between the inner and the outer veto, a 5cm thick lead vault shields the calorimeter from low energy photons. The detector will be placed about 8 m undeground, in a new experimental hall, in order to shield it from cosmogenic particles and also to match the depth of the Hall-A beam dump. To shield the detector from beam-related backgrounds, about 10 m of concrete and iron will be placed between the beam dump and the new hall.

The BDX proposal has been submitted to the 2016 JLab Program Advisory Commitee, receiveing a conditional approval. With an electron current up to 60 μA, and few years of run,
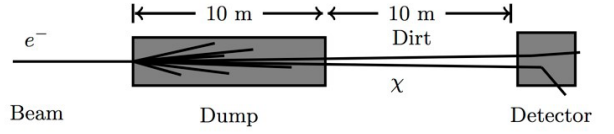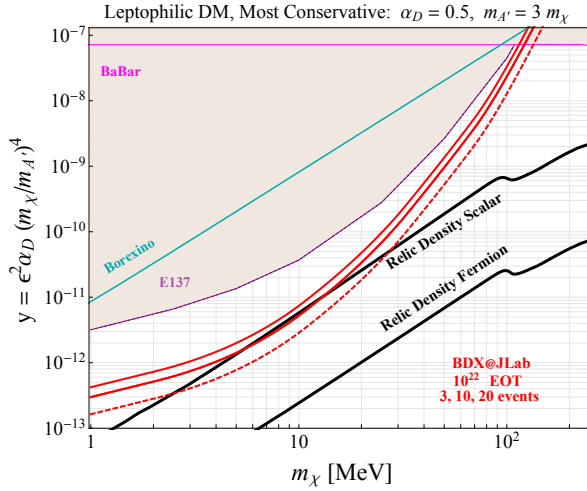
Figure 5. Top: schematic of the BDX experiment layout. Left: the foreseen BDX reach, for 10^{22} EOT. The y variable on the vertical axis is defined as $y = \varepsilon^2 \alpha_D (m_\chi/m_A')^4$.

BDX will be capable of collecting up to 10^{22} electrons on target (EOT), ruling-out a significant portion of the LDM parameters space. The expected BDX reach is shown in Fig. 5, for a leptofilic LDM: a further discussion of the reach, for different LDM scenarios, can be found in [16].

4. Conclusions

The LDM scenario (MeV to GeV range) is a compelling possibility, theoretically founded as the "traditional" WIMP paradigm, to explain the observed DM relic density. A new experimental program has been launched in the last few years to explore this so-far unexplored hypothesis. The Jefferson Lab community joined this program with four complementary efforts, searching both for light dark matter particles (BDX experiment) and for the corresponding light mediator with the SM, the so-called "dark photon" (APEX, HPS, DarkLight experiments). The results already obtained by APEX, as well as those soon expected by HPS, covered a large portion of the "dark photon" parameters space, for the visible decay to an e^+e^- pair, while the already-approved DarkLight and BDX experiments will be able to explore the invibible-decay scenario, and also to directly measure LDM particles in a so-far unexplored mass range.

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