

Beam Dump eXperiments with electron beams

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Beam dump experiments at the intensity frontier are a powerful tool to explore the Dark Sector. We present two proposals that will make use of the high-intensity electron beams of Jefferson Lab (up to 11 GeV) and MESA at Mainz (155 MeV) to produce and detect Light Dark Matter in the MeV to GeV mass region. The two experiments share a common detector concept: an electromagnetic calorimeter surrounded by an active veto, optimized to their respective mass and energy ranges. An alternative option, using a low-pressure, negative-ion TPC is also proposed. With a year of beam, BDX and DarkMesa will explore unexplored regions of the parameter space of dark-matter coupling versus mass, exceeding the discovery potential of existing and planned experiments by up to two orders of magnitude. Both experiments were approved by the Program Advisory Committees of their respective labs and are waiting to move into the construction phase.

Introduction

If the dark and visible matter have sufficiently large interactions to achieve thermal equilibrium during the early universe, the resulting DM abundance greatly exceeds the observed density in the universe today; thus, a thermal origin requires a sufficient DM annihilation rate to deplete this excess abundance and agree with observation at later times. For thermal dark matter below the GeV scale, this requirement can only be satisfied if the dark sector contains comparably light new force carriers to mediate the necessary annihilation process. Presently there are significant regions of parameter space that are uncovered by existing experiments. We present a program of beam dump experiments that are sensitive to such new light-force carriers. See Ref. (1) for details.

Such “mediators” must couple to visible matter and be neutral under the Standard Model (SM) gauge group, so the options for possible mediators can be enumerated in an economical list. A popular representative model involves a so-called “dark photon” A' with mass $m_{A'}$ and Lagrangian in the in-

teraction basis(2)

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + g_D A'_\mu J_D^\mu$$

where $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength, $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength, $g_D \equiv \sqrt{4\pi\alpha_D}$ is the dark gauge coupling, J_D^μ is the current of DM fields, and ϵ parametrizes the degree of kinetic mixing between dark and visible photons. Although the interaction basis Lagrangian initially has no coupling between the A' and SM particles, diagonalizing the kinetic term induces an ϵ proportional coupling between A' and the EM current of SM particles f with charges Q_f . The phenomenology of the DM interaction depends on the DM/mediator mass hierarchy and on the details of the dark current J_D^μ . If there is only one dark sector state, the dark current generically contains elastic interactions with the dark photon. However, if there are two (or more) dark sector states the dark photon can couple to the dark sector states off-diagonally. This latter scenario can lead to distinct signatures, for which beam-dump experiments are especially suited.

In the paradigm of a thermal origin for DM, it would have acquired its current abundance through direct or indirect annihilation into SM. If the mediator is heavier than the DM, the thermal relic abundance is achieved via direct annihilation $\chi\bar{\chi} \rightarrow ff$, where f are SM fermions, with a corresponding annihilation rate scaling as $\sigma v_{\chi\bar{\chi} \rightarrow ff} \propto y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{\text{MED}}}\right)^4$. This scenario offers a predictive target for discovery or falsifiability, since there is a *minimum* SM-mediator coupling compatible with a thermal history that experiments can probe.

The BDX experiment at JLab The fixed target phenomenology of stable LDM particles is well-described by the simple case presented in the previous section (for further details see Ref. (1)). In an electron beam-dump experiment, LDM par-

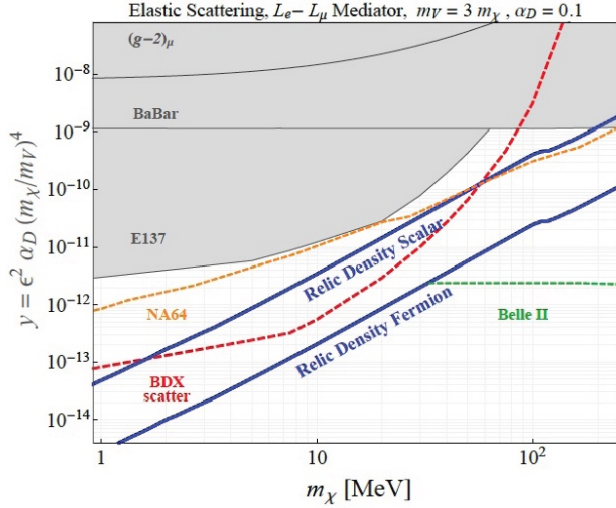


Fig. 1. Plot of BDX yield projections for elastic DM scattering $\chi e^- \rightarrow \chi e^-$ for 10^{22} electrons on target. The thermal targets are shown as blue lines.

ticles are pair-produced in the thick target and traverse unimpeded through sufficient shielding that eliminates all SM particles aside from neutrinos. BDX will detect LDM through the scattering on atomic electrons in a state-of-the-art electromagnetic calorimeter with excellent forward geometric acceptance located ~ 20 meters downstream of the Jefferson Lab Hall-A beam dump. The experiment will run parasitically, making use of the high-energy (up to 11 GeV), high-current (up to $65 \mu\text{A}$) electron beam delivered to Hall A for its scheduled hadron physics program. Unlike other efforts, **BDX is the only proposed experiment that features both DM production and detection utilizing only its coupling to electrons.** It can therefore test viable models which do not require any couplings to baryons (which SBND, COHERENT, MiniBooNE, and SHiP all require) and it can directly observe the DM scatter (or iDM decay) in the downstream detector (which LDMX, NA64, and Belle II cannot). Furthermore, BDX is unique even among other electron-based approaches in its ability to observe the particles produced in the fixed-target, whereas other electron-beam experiments rely on missing energy signatures, which indirectly infer the production of signal events, thus being exposed to unknown backgrounds.

The BDX detector The BDX detector consists of two main components: a homogeneous electromagnetic calorimeter used to detect signals produced by the interacting dark matter, and a veto system used to reject the cosmic background. The detector has a modular construction to allow for future flexibility in rearranging or increasing the interaction volume. A sketch of the detector is shown in Fig. 2.

The electromagnetic calorimeter is the main component of BDX. The detector uses CsI(Tl) crystals, which are available from the decommissioned BaBar EM calorimeter. It is compact and achieves the large target thickness required for the experiment. BaBar crystals have different shapes and tapering: they will be inserted in new regular-shaped parallelepiped aluminum alveoli for ease of assembly. Since the

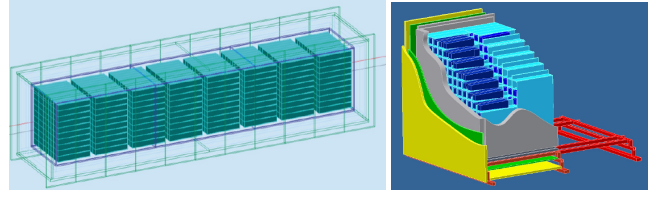


Fig. 2. A sketch of the BDX detector. On the left, the full reference design composed of 8 modules of 10x10 CsI(Tl) crystals is shown. On the right the single module drawing showing the crystals (dark blue), Al alveoli (light blue), lead vault (grey), Inner Veto (green) and Outer Veto (yellow).

LDM beam is focused in the forward direction, a rectangular detector provides a long target length along the LDM beam. The reference setup foresees 8 modules of 10x10 crystals each, arranged with the long dimension along the beam direction. This arrangement has a cross section of $50 \times 55 \text{ cm}^2$ for a total length of 295 cm. See Fig. 2. Crystals will be read-out by SiPM for fast time coincidence with the plastic veto counters.

In order to reject cosmic-rays, the EM calorimeter is operated inside two hermetic layers of plastic scintillator veto and a 5-cm thick lead vault. The design of the active and passive vetos is driven to achieve the highest hermeticity in order to shield and/or track and reject SM particles entering in the EM calorimeter detection volume from outside. The inner and outer vetos are based on plastic scintillators, which are read out with SiPMs.

Background measurements and prototyping The concept of the BDX detector has been tested by means of a prototype (BDX-PROTO) consisting of a matrix of 16 BaBar CsI(Tl) crystals, a lead vault and a veto system (Inner and Outer). The detector was deployed in 2017 at LNS-CT (Italy) to assess the cosmic background under similar conditions (overburden and acquisition time) expected for the full BDX experiment. The results showed that with a sufficiently high threshold on the energy deposited in the crystals ($\sim 100 \text{ MeV}$) the background counts can be reduced to zero. Another prototype detector (BDX-HODO), based on the same technology (a single BaBar CsI(Tl) crystal surrounded by plastic scintillator counters), was deployed in 2018 in two wells dug $\sim 20\text{m}$ downstream of the Hall-A beam-dump at the location of the planned BDX facility. The test measured the muon flux produced by the interaction of the 10.6 GeV electron beam with the dump and propagating to the detector through the present concrete and dirt shielding (3). The good agreement with predictions from the BDX simulation framework (based on GEANT4 and FLUKA) gives us confidence in our ability to design a shielding configuration to eliminate all beam-related backgrounds except for neutrinos.

The BDX-MINI experiment A small, compact version of the BDX detector (BDX-MINI) consisting of 44 high-density PbWO_4 crystals¹ enclosed in a tungsten vault and two concentric cylindrical veto systems, has been constructed and installed in one of the wells, and is currently taking data. Fig-

¹The compact PbWO_4 crystals are used as a substitute for CsI(Tl) in order to fit into the well.

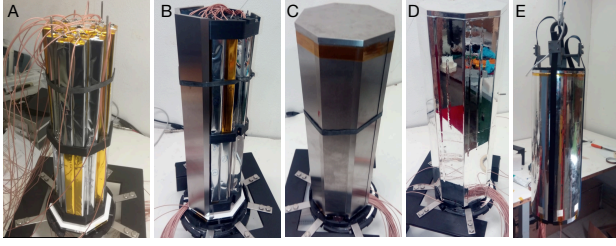


Fig. 3. The different components of BDX-MINI are shown while they were assembled. Panel A shows full assembled ECal, Panel B and C the tungsten shielding, Panel D the inner veto, and Panel E the outer veto.

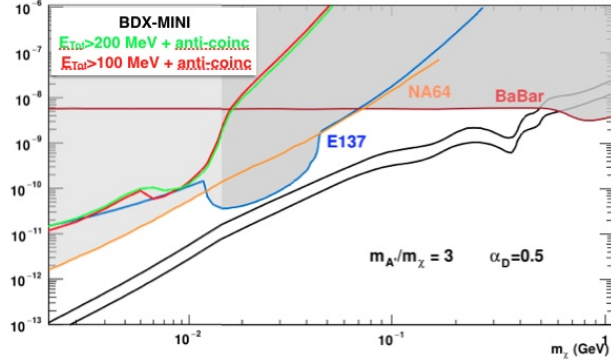


Fig. 4. The expected sensitivity of the BDX-MINI experiment.

Figure 3 shows the different component of the BDX-MINI detector. During the low-energy experiments in Hall-A ($E_{beam} \simeq 2$ GeV), the existing dirt between the dump and detector becomes an effective shield to all penetrating radiation. This allows for a beam-induced background-free measurement at low energy. BDX-MINI has already collected 2×10^{21} EOT and we expect to double the statistics in 2020, thereby collecting a data set comparable to that expected for the BDX experiment (10^{22}) over a similar time period (~ 1 year). **This test run will validate the capabilities of BDX in a realistic experimental setup over an extended period.** Figure 4 shows the expected sensitivity of BDX-MINI experiment compared to the existing limits.

The BDX-DRIFT experiment In parallel to the leading calorimetric option, we developed an alternative option for the BDX experiment based on a low-pressure, negative-ion, time-projection-chamber detector. The Directional Recoil Identification From Tracks (DRIFT) technology grew out of the requirements to detect a directional signal from halo dark matter recoils (4). It is ideally suited to search for light dark matter recoils behind a beam-dump. Despite its low mass the BDX-DRIFT detector has sensitivity rivaling and complementary to the BDX experiment due to its low threshold and low background, and provides information on the directionality of light dark-matter-recoil candidates (5).

The DarkMesa experiment The Johannes Gutenberg University Mainz is currently building a new continuous-wave, multi-turn energy recovery linac for precision experiments in the beam energy range of 100–200 MeV called MESA (6). One of the approved experiments, DarkMESA (7, 8), will consist of a calorimeter based on Cherenkov light radiators placed 23 m downstream of a beam dump in a radiation

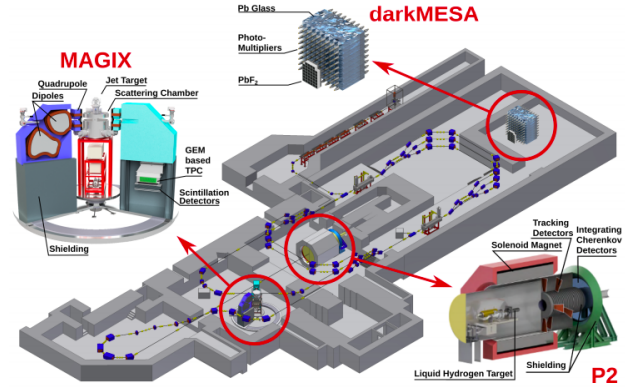


Fig. 5. The MESA (Mainz Energy-Recovery Superconducting Accelerator) facility with the three foreseen experiments: P2, MAGIX, and DarkMESA.

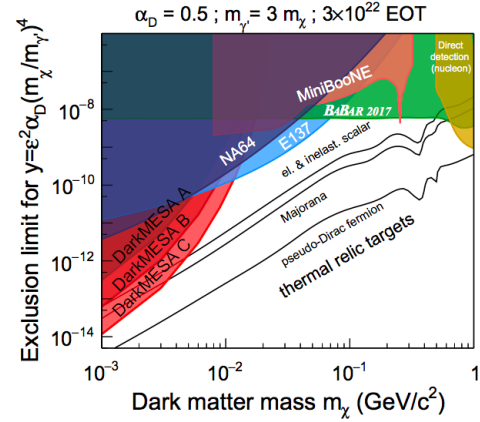


Fig. 6. DarkMESA projected exclusion limits for y as function of the DM particle mass m_χ for a dark photon decaying to dark matter particles.

shielded area (Fig. 5). The construction will be divided in three phases in which the detector volume will be successively increased. Phase A will employ already existing PbF_2 crystals for a $(1 \times 1 \times 0.13) \text{ m}^3$ detector. Phase B will add more than 1000 existing lead glass blocks, while in Phase C the full available volume will be exploited, reaching a total detector volume of $(2.7 \times 2.7 \times 1.5) \text{ m}^3$. Within the scheduled operation time of few years, a total of 3×10^{22} electrons on target will be delivered to DarkMESA. Simulated upper limits for the standard minimal dark photon model for the three foreseen phases of the experiment are shown in Fig. 6.

Conclusions Despite their conceptual simplicity, beam dump experiments showed in the past to be highly effective in setting stringent limits in Light Dark Matter searches. Making use of the high intensity electron beam available nowadays, a new generation of beam dump experiments have been proposed in world leading labs. BDX and DarkMesa are approved experiments at Jefferson Lab and MESA at Mainz, respectively, waiting for the construction phase. Both experiments are based on a solid and reliable detection technology and, collecting an unprecedented accumulated charge in a $\sim$ year time will be able to extend current limits on LDM by one/two order of magnitude.

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