PROCEEDINGS OF SCIENCE

The BDX experiment at Jefferson Laboratory

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The Beam Dump Experiment (BDX) at Jefferson Laboratory (JLab) is an electron-beam thick-target experiment to search for Light Dark Matter (LDM) particles in the MeV-GeV mass range. BDX will exploit the high-intensity 10.6 GeV e^- beam from CEBAF accelerator impinging on the beam dump of experimental Hall-A, collecting up to 10^{22} electrons-on-target (EOT) in a few years time. Any LDM particle produced by the interaction of the primary e^- beam with the beam dump will be detected by measuring their scattering inside the BDX detector, an electromagnetic calorimeter surrounded by an hermetic veto system, which is to be installed in a dedicated underground facility, located 20 m downstream. Thanks to the large detection efficiency and background rejection capabilities, BDX will be able to explore a so-far unknown region in the LDM parameter space, improving current exclusion limits by one order of magnitude in case of a null observation.

In preparation to the full experiment, a small-scale version called BDX-MINI, has been built and operated at JLab with a lower energy beam. Despite the small interaction volume, the large accumulated charge of 2.2×10^{21} EOT allowed for the BDX-MINI measurement to set competitive exclusion limits on the LDM parameters space, comparable to those reported by larger-scale efforts.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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https://pos.sissa.it/

PoS(ICHEP2022)327

1. Introduction

The *Light Dark Matter* (LDM) hypothesis identifies DM with the lightest, sub-GeV stable states of a new "Dark Sector" in Nature, interfacing with Standard Model (SM) particles through a new force. A simple and theoretically founded model predicts that LDM particles (denoted as χ) are charged under a new $U(1)$ symmetry, whose mediator is a light, massive spin-1 boson, usually referred to as "heavy photon" or "dark photon" (A'). The dark photon feebly couples to the SM electric charge thanks to a kinetic mixing with the ordinary photon [1]. The corresponding lagrangian density, after fields diagonalization and omitting the LDM mass term, reads:

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} - g_D A'_\mu J^\mu_D \tag{1}$$

where $m_{A'}$ is the dark photon mass, $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu (A'_\mu$ $(F_{\mu\nu})$ is the dark photon (SM electromagnetic) field strength, $g_D \equiv \sqrt{4\pi\alpha_D}$ is the dark gauge coupling, J^μ_D is the current of DM fields and ε parametrizes the degree of kinetic mixing. In this picture, assuming a DM thermal origin in the Early Universe [2], well defined combinations of the LDM model parameters can be identified, that are compatible with the presently observed DM relic density [3].

In recent years, the LDM hypothesis promoted the development of many new experimental programs (see [3] for a recent review). In particular, accelerator-based thick-target experiments at moderate beam energy (10÷100 GeV) are the ideal tool to probe the new hypothesis since they have a very large discovery potential in a wide area of the parameters space [4].

2. The BDX experiment at Jefferson Laboratory

The goal of the Beam Dump eXperiment (BDX) at JLab (Newport News, USA) is to search for LDM particles in the MeV-GeV mass range, exploiting the high-energy CEBAF electron beam impinging on the Hall-A beam dump. The experiment will run parasitically to the scheduled Hall-A hadron physics program. Thanks to the very high CEBAF beam current (up to 65 μA), BDX plans to accumulate up to 10^{22} electrons-on-target (EOT) within a one-year time scale.

A simplified scheme of the experimental setup is shown in Fig. 1, left panel. LDM particles can be produced by the interaction of the 10.6 GeV e^- beam and its secondaries with the beam-dump material by two main mechanisms, the so-called A'-strahlung ($e^\pm N \to e^\pm N A'$) and the resonant e^+e^- annihilation ($e^+e^- \to A'$), followed by the invisible $A' \to \chi\overline{\chi}$ decay to a LDM pair [4, 5]. This results to an intense and energetic flux of forward-focused LDM particles. BDX aims to detect them through their scattering with the material of a detector located approximately 20 meters downstream of the thick target. Between the beam dump and the detector a sizable iron shielding is installed to range out all SM particles (except neutrinos) produced in thick target.

The BDX detector is a state-of-the-art electromagnetic calorimeter surrounded by a hermetic veto system. LDM particles are detected by measuring the high-energy (> 100 MeV) electron diffused after the LDM elastic interaction with the calorimeter atomic electrons ($\chi e^- \to \chi e^-$). The expected signal is a high-energy eletromagnetic shower paired with null activity in the veto. The calorimeter is based on a matrix of CsI(Tl) crystals read by SiPM, while the veto system is made by two layers of plastic scintillator counters, coupled via wavevelength-shifting fibers (WLS)

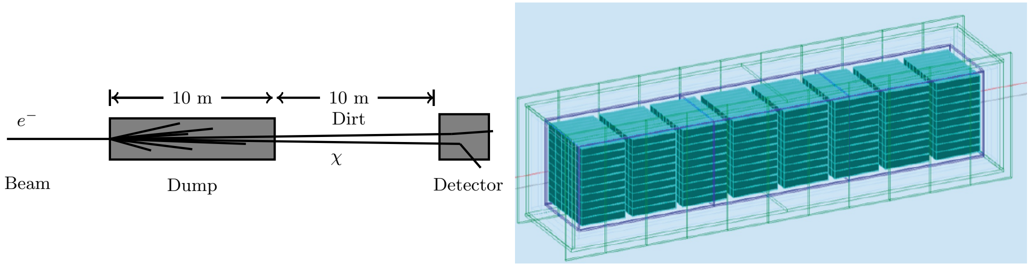

Figure 1: Left: schematic of the BDX experimental setup (see text). Right: sketch of the BDX detector, showing the full reference design composed of 8 modules of 10×10 CsI(Tl) crystals.

to SiPMs. In between the calorimeter and the veto, a 5-cm thick passive lead shielding is installed. A sketch of the full BDX detector is shown in Fig. 1, right panel. The design is based on a modular structure to allow for maximal flexibility in rearranging or increasing the interaction volume. Since the LDM beam is focused in the forward direction, the baseline solution foresees a long rectangular detector to enhance the LDM interaction probability, with 8 calorimeter modules, each being a 10×10 matrix crystals read by SiPM. This arrangement has a cross section of 50×50 cm^2 for a total length of about 3 m. The BDX detector will be installed in a new underground experimental hall, aligned to the primary CEBAF beam direction.

Two main sources of background events are expected in BDX. The beam-unrelated background is associated with cosmic-muons and cosmic-neutrons induced interactions in the calorimeter and in the surrounding materials, with a large energy deposition in the calorimeter not accompanied by any signal in the veto. To suppress this background, a sizable overburden will be installed on top of the BDX detector, corresponding approximately to 10 m of water equivalent. To evaluate the expected background yield for the full BDX experiment, and to validate the detector design, a prototye has been constructed and installed at INFN-LNS, in an experimental configuration similar to the one expected at JLab [6]. The prototype detector incorporated all the elements of the BDX detector (active veto's, lead shielding, CsI(Tl) crystals) to provides a solid basis for a realistic estimate of the expected rates [6]. The obtained result show that for an energy threshold of at least 300 MeV the number of cosmogenic background events expected in the full BDX run reduces to zero.

Beam-related backgrounds,instead, are associated with energetic particles produced in the beam-dump penetrating the shielding up to the detector location, and releasing a large enough energy in the BDX calorimeter. The expected yield for each particle species was evaluated through FLUKA and GEANT4 based Monte Carlo simulations. The simulation framework was validated through a dedicated on-site measurement campaign in the present configuration, with no iron shielding installed behind the Hall-A beam dump [7]. Monte Carlo simulations predict that all forward-emitted particles except neutrinos will be completely absorbed by the iron shielding. High-energy neutrino produced in the beam-dump, instead, can travel unperturbed to the detector and interact with it by elastic and inelastic scattering, resulting to a significant energy deposition that could mimic the LDM signal. The energy spectrum of neutrinos impinging on the BDX detector is shown in Fig. 2, left panel. The most critical background source is associated with charge-current interactions of ν_e and $\overline{\nu}_e$ with the calorimeter nuclei, resulting to a high-energy electron in the final state. This background can be efficiently reduced exploiting the different kinematics of the

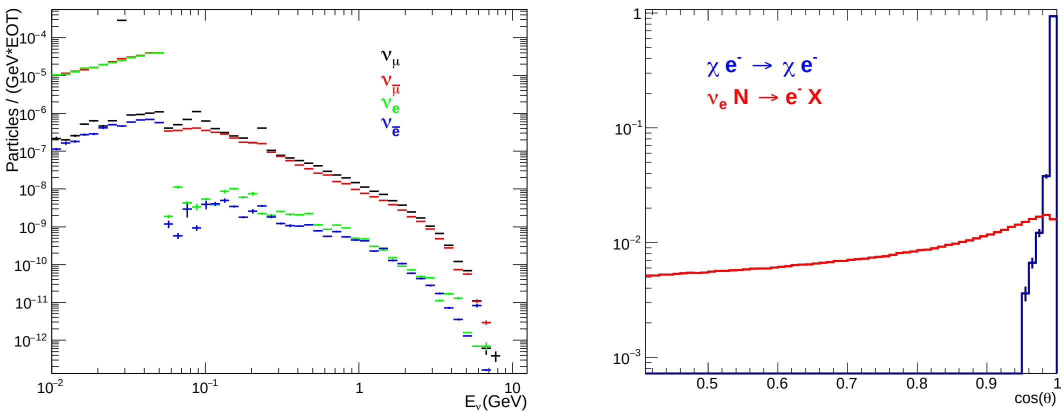

Figure 2: Left: differential energy spectrum of neutrinos impinging on the BDX detector. Right: scattered electron angle distribution for the signal ($e^-\chi \to e^-\chi$) and ν_e CC background ($\nu_e N \to e^- X$) reactions. The two histograms have been normalized to the same area.

$\nu - N$ interaction with respect to the $\chi - e^-$ scattering (see Fig. 2, right panel), by imposing an appropriate cut on the electromagnetic shower transverse dimension [8]. The expected number of neutrino-induced background events for the optimized selection cuts, including a 350 MeV selection on the EM shower seed energy, is $\simeq 5$.

The expected sensitivity of the BDX experiment is reported in Fig. 4. Thanks to the large accumulated charge and to the detector volume and efficiency, BDX will be capable to explore a large area of the LDM parameters space, improving current exclusion limits by one/two orders of magnitude in the $\simeq 10$ MeV mass range.

3. BDX-MINI

While preparing for the design and construction of the new experimental hall hosting the full BDX detector, the collaboration constructed and operated a small-scale version of the latter, BDX-MINI, exploiting the experimental infrastructure used for the Monte Carlo validation on-site measurements [9]. The BDX-MINI experiment run in spring/summer 2020, collecting a charge of 2.56×10^{21} EOT during a $\simeq$ 80-days long period, with almost equal beam-on and beam-off intervals interleaved. The detector was installed in a well 26 m downstream the beam-dump, at the beamline height. The reduced energy of the CEBAF beam delivered to Hall-A during this period (2.176 GeV) allowed the Hall-A concrete vault and the dirt between the latter and the well to range out all SM particles except ν.

The BDX-MINI detector is made by a $PbWO_4$ electromagnetic calorimeter surrounded by an inner tungsten shielding and by two active veto layers made of plastic scintillator, for a total interaction volume of about 4×10^{-3} m^3 [10]. A rendering of the BDX-MINI detector is reported in Fig. 3, left panel. The 44 crystals forming the calorimeter are arranged into two equal modules. Each veto layer is composed by an octagonal prism (inner veto, IV) / a hollow cylinder (outer veto, OV), a top cap, and a bottom cap. Crystals are read by SiPMs, directly glued on them, while plastic scintillators are coupled to SiPMs through WLS fibers mounted into grooves machined into them.

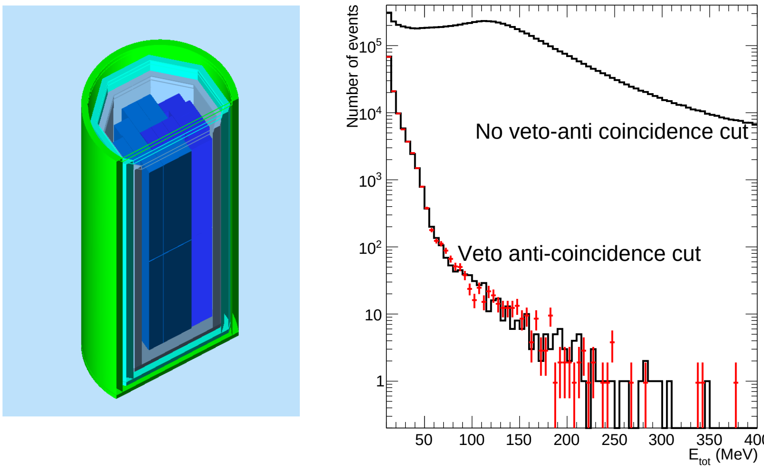

Figure 3: Left: GEANT4 rendering of the BDX-MINI detector, showing the $PbWO_4$ crystals (blue), the tungsten shielding (gray), the IV (cyan) and the OV (green). Right: in black, the calorimeter energy distribution for the beam-on data sample with and without the veto anti-coincidence cut. In red, the beam-off anti-coincidence data sample, properly normalized in time.

The crystals energy response was calibrated by exploiting data collected during a 10.38 GeV Hall-A run, in which high-energy muons were produced that could penetrate the concrete shielding and the dirt and pass through the BDX-MINI crystals. The calibration constants were derived by matching the ionization peak position in the charge distribution to the value predicted by Monte Carlo simulations. The charge of the veto SiPMs signal was normalized to the single photo-electron (phe) value, determined during dedicated random-trigger runs.

Reconstructed data were divided into two samples, corresponding respectively to beam-on and beam-off periods; the corresponding energy distributions are shown in Fig. 3, right panel. A suppression factor of up to four order of magnitudes is obtained after applying the anti-coincidence cut with the veto system, for a 5 phe threshold. A blind data analysis approach was used to optimize the analysis cuts by maximizing the experiment sensitivity. A Poisson counting model was adopted, with the background contribution from beam-related neutrinos estimated from Monte Carlo simulations and that associated with cosmic muons extrapolated from beam-off periods. To validate the extrapolation, the compatibility between the two data-sets was checked before unblinding by comparing the rate of vertical crossing muons events. The effect of systematic uncertainties was incorporated in the likhelihood through additional pseudo-measurement factors with Gaussian constraints. The optimal sensitivity was achieved for 40 MeV energy threshold on the energy deposited in the calorimeter. After unblinding, n_{on} = 3623 (n_{off} = 3822) events were found in the signal region for the beam-on (beam-off) dataset, with a beam-off to beam-on time ratio equal to 1.054. From these results, an upper limit on the LDM parameter space was set, as shown in Fig. 4.

The obtained result, despite the small detector volume and the limited accumulated charge, is comparable with those reported by flagship experiments, and demonstrates the potential of the new generation of beam dump experiments in LDM searches.

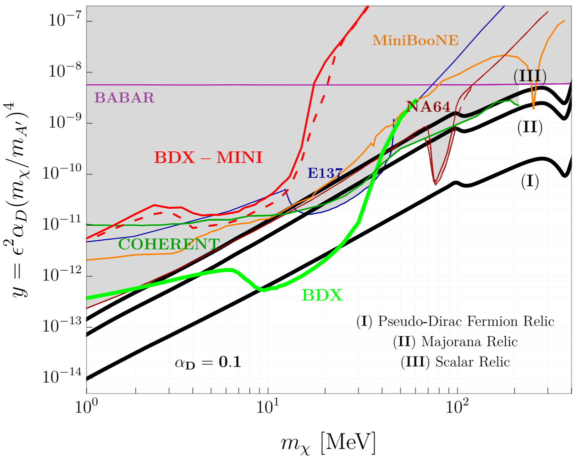

Figure 4: BDX-MINI exclusion limits assuming $\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$ for scalar LDM (continuous red line) and fermionic LDM (dashed red line), compared with the full BDX experiment sensitivity (green line). The thick black lines represent the relic target. The other colored lines show the current most stringent exclusion limits from other experiments (see e.g. [3] for further details)

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