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Light Dark Matter searches with the BDX-MINI experiment

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Summary. — BDX-MINI is the first modern electron beam dump experiment aiming to probe Light Dark Matter in the MeV-GeV mass range. In the experiment, Dark Matter is expected to be produced by the interaction of CEBAF high intensity electron beam with JLab experimental Hall-A beam dump and detected by the BDX-MINI detector, located 26 m downstream. This paper describes the detector used in the experiment and reports details of (blind) data analysis. Since no positive results were found, an exclusion limit was extracted from data collected in 2020 run.

1. – Introduction

Light Dark Matter (LDM) is the new compelling hypothesis that identifies Dark Matter with new sub-GeV "Hidden Sector" states. In the most popular model, LDM particles χ are charged under a new broken $U(1)_D$ symmetry, whose mediator is a massive vector boson called A' ("Dark Photon"). The Dark Photon can kinetically mix with the Standard Model hypercharge field, resulting in SM-DM interaction. A comprehensive discussion of the LDM theory and the ongoing experimental efforts is presented in refs. [1, 2].

BDX-MINI is a Beam Dump eXperiment searching for DM particles in the MeV-GeV mass range produced by the interaction of Jefferson Lab (JLab) multi-GeV beam with the beam dump of experimental Hall-A.

This paper describes BDX-MINI experimental setup and data analysis procedure. Since no positive results were found, an exclusion limit for fermionic LDM interacting with SM through a vector mediator was extracted in the LDM parameter space.

2. – BDX-MINI experimental setup

In the BDX-MINI experiment, a high-current (up to 150 μA), 2.176 GeV electron beam impinged on the experimental Hall-A Al/water beam dump, potentially producing,

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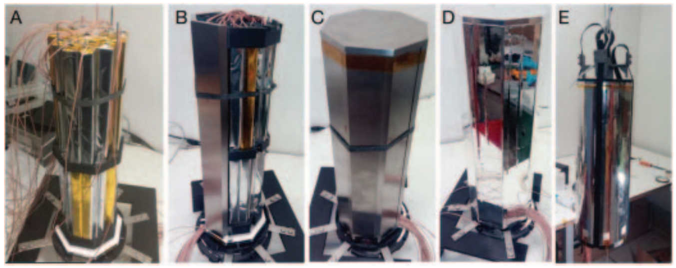

Fig. 1. – The different components of the BDX-MINI detector are shown. (A) The two modules that constitute the ECal. (B) and (C): tungsten shielding. (D) Inner Veto. (E) Outer Veto.

among many SM particles, a secondary beam of LDM χ particles. LDM particles propagate to the detector and interact with atomic electrons. The resulting few hundreds MeV scattered electrons could be identified by detecting a high energy electromagnetic shower.

The BDX-MINI detector was installed in a well at beamline height, 26 m downstream of the Hall-A beam dump. To shield the detector from beam related SM particles, a shielding of 5.4 m of concrete and 14.2 m of dirt was in place between the detector and the dump. The experimental setup was located within a field tent to protect it from weather conditions.

The core of the BDX-MINI detector is the electromagnetic calorimeter (ECal) composed of 44 parallelepiped $PbWO_4$ crystals for a total active volume of $\sim 4 \times 10^{-3}\,m^3$ (fig. 1(A)). The crystals scintillation light is read by SiPMs. The ECal is surrounded by layers of passive and active vetoes. The innermost layer consists of 0.8 cm-thick passive tungsten shielding (WS), shaped as a prism with octagonal base (fig. 1(C)). The middle (Inner Veto, IV) and outer (Outer Veto, OV) layers are made of plastic scintillators read by Wavelenght Shifter (WLS) fibers and SiPMs (fig. 1(D) and fig. 1(E)). For a detailed description of the detector and its performance, see ref. [3].

BDX-MINI accumulated data for approximately six months in 2020. During most of this time, Hall-A received a 2.176 GeV e^- beam. At this energy, no beam-related SM particles, except neutrinos, reached the BDX-MINI detector. For a short period of time, CEBAF delivered a beam with energy 10.381 GeV used for detector calibration. The cosmogenic background was also measured during beam-off periods due to the accelerator Radio Frequency (RF) trips (about 50% of the time).

3. – Data analysis

The search for LDM described in this paper uses the full data sample collected in 2020, corresponding to 2.56×10^{21} Electrons On Target (EOT). For each event, charge and time were extracted from recorded waveforms with the procedure described in ref. [3]. The ECal energy calibration was performed using muons produced in high-energy (10.381 GeV) runs [3].

Since the BDX-MINI detector operated for several months in an outdoor tent, the first step of the analysis was to study the performance over time of each detector's component using the beam-off data [3]. The veto response stability was monitored using cosmic muons crossing the detector and selected with a custom offline trigger. Figure 2 shows the response of the Outer Veto Cylinder (OV-C) as a function of run number. The

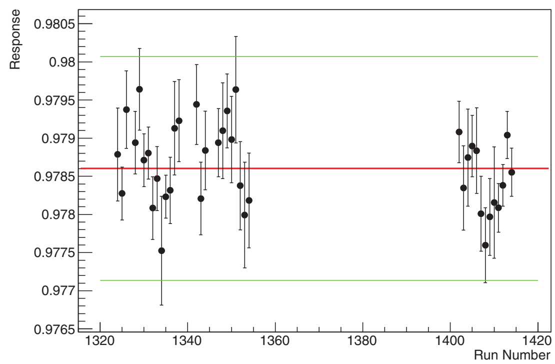

Fig. 2. – Response of the OV-C (on y-axis) as a function of time (represented by the run number on x-axis). The time between the first and last run corresponds to six months.

response is evaluated as the rate between the number of cosmic muons detected by both Inner Veto Octagon (IV-O) and Outer Veto Cylinder (OV-C) and the number of cosmic muons detected by the IV-O. The same study, repeated for all veto paddles, showed that the veto efficiency was stable within 1%.

To avoid biases in LDM selection, a fully blind analysis was performed. Beam-off data and Monte Carlo (MC) simulations (see ref. [3]) were used to optimize cuts to minimize the number of background events (neutrinos and/or cosmic rays) and maximize the number of signal events. DM production in the dump was simulated using a custom version of Madgraph, while LDM interaction in the detector was simulated using the GENIE program also used to simulate neutrinos [3]. MC studies suggested that the neutrino background was negligible.

Several selection cuts on total deposited energy, hit multiplicity and other reconstructed variables were tested by comparing the *sensitivity* curves, defined as the average expected limit calculated using the profiled likelihood method. The cosmic background was reduced requiring an anti coincidence condition between ECal and veto (see ref. [3]). The best sensitivity was achieved by selecting events with total energy deposited in the ECal >50 MeV with ECal and veto anti-coincidence condition.

4. – Results

After defining the optimal selection criteria and estimating the background yield, the beam-on data were analyzed. Since no excess of events over the background was measured, a 90% upper limit on the number of observed signal events was estimated. It was translated in an exclusion limit in the y *vs.* m_χ parameter space, being m_χ the mass of LDM candidate and y a dimensionless variable called *thermal target*: $y \equiv \alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4$, where α_D is the Dark Sector coupling constant and ϵ is the A'-SM coupling parameter.

The BDX-MINI exclusion limits for a model considering fermionic thermal DM interacting with SM through the vector portal are shown in fig. 3. The exclusion limit is mainly limited by the number of expected DM events: as the χ mass increases, less signal events are expected. In the 10 MeV range, the reach is significantly improved thanks to resonant A' production from e^+e^- annihilation in the beam dump [4, 5].

BDX-MINI results are compatible with previous experiments. Even if no new region

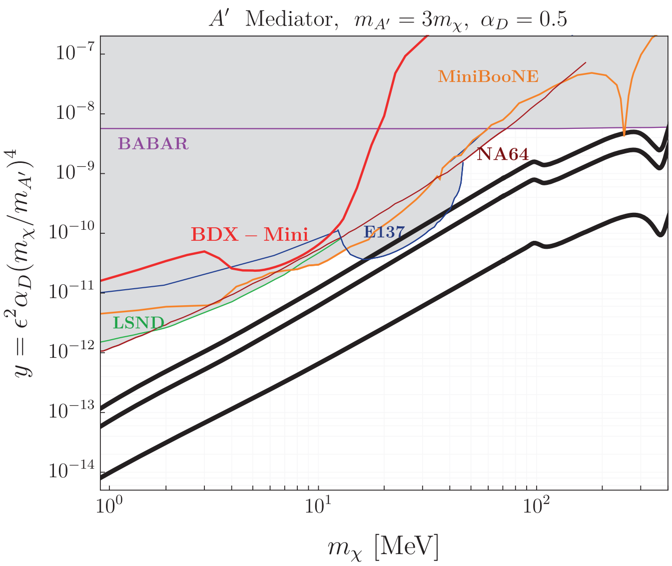

Fig. 3. – BDX-MINI exclusion limit (in red) in the (y, m_χ) plane. The other curves and shaded areas report already existing limits in the same parameter space. The bold black lines present the target values for different mediators, as expected from astrophysical constraints.

of LDM parameter space is ruled out, the successful run strengthens the prediction that BDX, the full scale experiment with an interaction volume of $1\,\mathrm{m}^3$, will improve current limits by two order of magnitude.

5. – Conclusions

BDX-MINI is the first modern beam-dump experiment searching for DM in the MeV-GeV range. This paper reports the preliminary data analysis results. The BDX-MINI detector is made by a compact $PbWO_4$ electromagnetic calorimeter, surrounded by a passive tungsten shielding and a double active veto layer. Data were analyzed applying a blind analysis that used beam-off data and Monte Carlo simulations to study detector performance and optimize the experimental reach. Since no yield excess in beam-on data was observed, an exclusion limit in the LDM parameter space was derived. Although the compact volume, BDX-MINI achieved a reach similar to flagship experiments thanks to the large accumulated charge (4×10^{21} EOT) and the optimized data analysis. BDX-MINI results suggest that a modern beam dump experiment with a larger active volume such as BDX will improve significantly the current exclusion limits in the LDM parameter space in case no DM events will be detected.

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