The BD$\chi$ detector prototype for Dark Matter searches in a Beam Dump eXperiment @ JLAB

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LDM (MeV - GeV) is a new hypothesis to explain the observed relic abundance, alternative to the traditional WIMP (GeV - TeV range) hypothesis.

- LDM requires a "new" interaction mechanism between the SM and LDM. The simplest: LDM-SM interaction through a new U(1) gauge-boson ("dark-photon")

\[ A' \text{ acts as a "portal" between the SM and the new sector} \]

\[ g \quad W^\pm, Z \quad \gamma \quad A' \quad \epsilon \]

- Accelerator based experiments in the GeV energy range are the ideal tool to search for LDM (direct-detection experiments have limited sensitivity to LDM – too low energy recoil)
LDM is direct detected in a $e^-$ beam, fixed target setup. It consists in two steps:

- **$\chi$ production**
  - GeV - high intensity - $e^-$ beam impinging on a dump
  - $\chi$ particles pair produced via A' emission and invisible decay

- **$\chi$ detection**
  - Detector placed behind dump $O(10\text{ m})$
  - $\chi$'s scattering on atomic $e$- through A' exchange, recoil releasing visible energy
  - Signal: $O(100\text{ MeV})$ - EM shower
The experiment is designed with two goals:

Producing and detecting $\chi$
- High intensity $e^-$-beam
  $\sim 10^{22}$ EOT/year
- Energy $e^-$-beam $\geq 10$ GeV
- $\sim 1$ m$^3$ detector
- BD$\chi$ signal: $\chi$-$e^-$ scattering
  $\rightarrow$ GeV electromagnetic shower

Reducing Background
- Passive shielding between beam-dump and detector to filter beam-related backgrounds (except $\nu$s)
- Passive shielding and active vetos surrounding the active volume to reduce backgrounds
- Segmented detector for background discrimination based on event topology
BD$\chi$ setup @ JLAB

Jefferson Laboratory is home for the CEBAF electron accelerator

**Plan to run BD$\chi$ behind Hall-A beam-dump in a new, dedicated experimental Hall**

- Ideal beam conditions for the experiment: $E = 11$ GeV, $I$ up to $60 \mu A$
- Already-approved experiments with more than $10^{22}$ EOT (Moller, PVDIS)
- BD$\chi$ is compatible with these planned experiments and can run parasitically with them
BDX detector

Detector design:
- 800 CsI(Tl) crystals, total interaction 0.5 m$^3$
- Dual active-veto layer, made of plastic scintillator counters with SiPM readout

Calorimeter footprint:
- 1 module: 10 x 10 crystals, 30-cm long. Front face: 50 x 50 cm$^2$
- 8 modules: interaction length 2.6 m
- each crystal read by SiPM

Signal:
- EM-shower (threshold: 300 MeV), anti-coincidence with IV and OV
BDX Proto

Small scale prototype for detector design and technology validation in a cosmic measurement campaign @ INFN-CT and INFN-LNS

Detector components:

- EM-Calorimeter (ECal): 16 CsI(Tl) crystals read by SiPM
- Inner Veto (IV): active-veto layer, made of plastic scintillator counters with SiPM readout
- Passive shielding: 5 cm lead vault
- Outer Veto (OV): active-veto layer, made plastic scintillator counters. Tested different light read-out systems
- The dimensions of the whole setup are: $\sim 1 \times 1.1 \times 1.8$ m$^3$
BDX Prototype: ECal

- 16 CsI(Tl)\(^\alpha\) crystals assembled in a 4×4 matrix
- SiPM: 6×6 mm\(^2\) Hamamatsu MPPC (S13360-6025PE)
- Each crystal is inserted inside a regular-parallelepiped aluminum holder (5 x 5.5 x 33 cm\(^3\))

\(^\alpha\) Each crystal was assembled and tested @ INFN-GE
BDX Proto: Inner Veto

- 6 EJ200 plastic scintillator paddles, 1-cm thick, forming a nearly hermetic parallelepiped
- Top, bottom, left and right sides of the veto: 4 scintillators $35 \times 140 \text{ cm}^2$
- Upstream and downstream caps: 2 scintillators $35 \times 42 \text{ cm}^2$
- Grooves on the surface of the scintillators host two WLS fibers each ($\Phi = 1 \text{ mm}$) to convoy the scintillation light to SiPMs, mounted at the edges.
- SiPM: $3 \times 3 \text{ mm}^2$ Hamamatsu MPPC (S12572-100C)

\[ \text{caps: spiral grooves} \]

\[ \text{WLS fiber in the clear scintillator} \]

\[ ^a \text{IV} \text{ was assembled and tested @ INFN-GE} \]
BD\(\times\) Detector Prototype: Outer Veto

- Different light read-out systems
- Bottom and lateral sides are made by \(80 \times 40 \times 2\, \text{cm}^3\) NE110 scintillators
  - A fish-tail shaped PMMA light-guide + 2 inch PMT (Thorn EMI 9954A)
- Top \((184 \times 54 \times 2.5\, \text{cm}^3)\), upstream and downstream \((58 \times 66 \times 2.5\, \text{cm}^3)\) caps are made by EJ200 scintillators
  - EJ280 WLS bar + PMT (Hamamatsu R1924A)

\(a\) OV was assembled and tested @ INFN-CT
Main goals: to finalize the design of the full detector, make realistic predictions of its expected performance and estimate the cosmic background contribution

INFN-CT
- Minimal shielding: concrete roof 15 cm thick
- Detector commissioning
- Characterization of cosmic events in the ECAL
- IV and OV performances

INFN-LNS
- Similar overburden as expected @ JLab
- First version of prototype: just 1 crystal and OV no optimized
- Study of the cosmogenic background reduction in a realistic condition
Measurement campaign @ INFN-CT: Characterization of cosmic events (1)

Comparison between the rate of cosmic muons as a function of the deposited energy in each crystal and the expected values (GEANT 4 simulations)

- perpendicular muons crossing ECAL
Measurement campaign @ INFN-CT: Characterization of cosmic events (2)

Looking at three different measurable quantities...

- $E_{seed}$: the highest energy measured in a single crystal per event
- $E_{TOT}$: total energy measured in ECAL per event
- $N_{hits}$: number of crystals fired (signal over threshold)

high energy && veto anti-coincidence: most of the E contained in just 1 crystal
Veto efficiency has been studied for two class of events with a well-defined topology in the ECAL:

- **Vertical selection**

  ![Diagram of vertical selection]

- **Diagonal selection**

  ![Diagram of diagonal selection]

Efficiency_{OV,IV} > 99.9% is an index of the overall goodness of both systems in terms of hermeticity and technologies.
The background rejection efficiency as a function of event energy has been studied.

- All events
- Events with OV in anti-coincidence
- Events with IV in anti-coincidence
- Events with both OV and IV in anti-coincidence

At the MIP energy the differential counting rate is reduced by a factor: ~700 when OV and IV in anti-coincidence.

At higher energy (i.e. $E_{\text{seed}} > 350 \text{ MeV}$) the integrated background rate is suppressed by ~3 orders of magnitude.
Measurement campaign @ INFN-LNS

Main goal: to estimate conservatively the total number of cosmogenic background events expected in the full experiment

- First version of prototype: one crystal
- Detector placed inside a bunker with a surrounding overburden similar to that expected @ JLab
The majority of cosmic muons are detected and rejected by the two veto detectors.

- Measured anti-coincidence rate ($E_{\text{thr}} \sim 300$ MeV) $\sim 10^{-12}$ Hz
  - Results obtained by conservatively extrapolating from the lower-E, non-zero counts region.

- Expected cosmic bg in the BDX lifetime $< 2$ counts:
  - Projecting to the JLAB setup (800 CsI(Tl) crystals)
  - Integrating over the expected beam-on time (285 days).
Conclusions

- A prototype of the future BDX detector was designed and constructed.
- A dedicated campaign of measurements @ INFN-CT allowed us to validate the technological solution proposed for the future detector and to study the performances of the prototype.
- A dedicated campaign of measurements @ INFN-LNS, performed with the first version of the BDX-PROTO, allowed us to demonstrate the possibility to reject the cosmic background.