Search for Light Dark Matter with the DarkMESA Experiment

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Abstract. The search for Dark Matter is an integral part of New Physics searches, however, Dark Matter has yet to be observed directly. Theoretical models provide a large parameter space for Dark Matter and allow for different properties of the particles. Models incorporating so-called portal interactions, where Dark Matter interacts with Standard Model particles through a mediator particle, are of special interest. Examples for these are Dark Photon and Axion models, which can be studied at low energy accelerator facilities.

The DarkMESA experiment is a beam dump experiment located at the upcoming accelerator MESA at the JGU Mainz. The accelerator provides an electron beam of 155 MeV and 150 μA in extracted beam mode, which, along with the high-power beam dump of the P2 experiment, provides an ideal environment for Light Dark Matter searches.

To accurately predict the expected reach and the impact of the detector design of the DarkMESA experiment on it with respect to different Dark Matter models, most notably Dark Photon and Axion mediated models, a GEANT4 simulation is used. Here, the current status of the simulations is discussed.

1 Introduction

Baryonic matter makes up only 5% of the energy density of the universe. The rest is attributed to Dark Matter with 25%, and Dark Energy with 70%, respectively. Although a multitude of astrophysical and cosmological observations suggest the existence of Dark Matter, it has yet to be detected. Complementary efforts have been made at collider and fixed-target experiments, as well as underground direct detection facilities in the last decades, however, Dark Matter still remains elusive.

Theoretical models cover a broad energy range for Dark Matter [1]. A large group of models assume thermal equilibrium between Dark Matter and Standard Model (SM) matter, in which the observed Dark Matter abundance today is a relic of the early universe . This is due to the so called *freeze-out* process [2], where the annihilation rate of Dark Matter to Standard Model particles becomes smaller than the expansion rate of the universe. These models allow for a mass range of Dark Matter between keV/c^2 to TeV/c^2. *Light Dark Matter* (LDM) models with Dark Matter masses on the sub-GeV/c^2 scale are becoming increasingly more interesting, as searches for WIMPs (Weakly Interacting Massive Particles) at high energy accelerator facilities and direct detection experiments yielded no result.

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In the case of Light Dark Matter, the introduction of a new force is required in order to fit the thermal origin model [3]. The new force acts as a mediator between Dark Matter and Standard Model matter and opens up a *Dark Sector*. Dark Sector Models are typically classified by the mediator type. Of special interest are the vector *Dark Photon* [4] and the pseudoscalar *Axion/Axion-like-particle* (ALP) models [5].
The search for Light Dark Matter requires different detection strategies compared to experiments looking into the high mass range, as high energy colliders are not optimized for the low mass range and are therefore not as effective. In the case of direct detection experiments, the recoil of Light Dark Matter particles eventually becomes too small for detection. Fixed target experiments at low energy accelerators with high intensity beams however prove to be ideally suited for Light Dark Matter searches, as Dark Matter particles can be produced with enough momentum to be detected.

2 The MESA Accelerator

The Institute for Nuclear Physics in Mainz is currently expanding its experimental facilities with the new *Mainz Energy recovering Superconducting Accelerator* (MESA), shown in figure 1 [6]. It is expected to start operation in 2025.

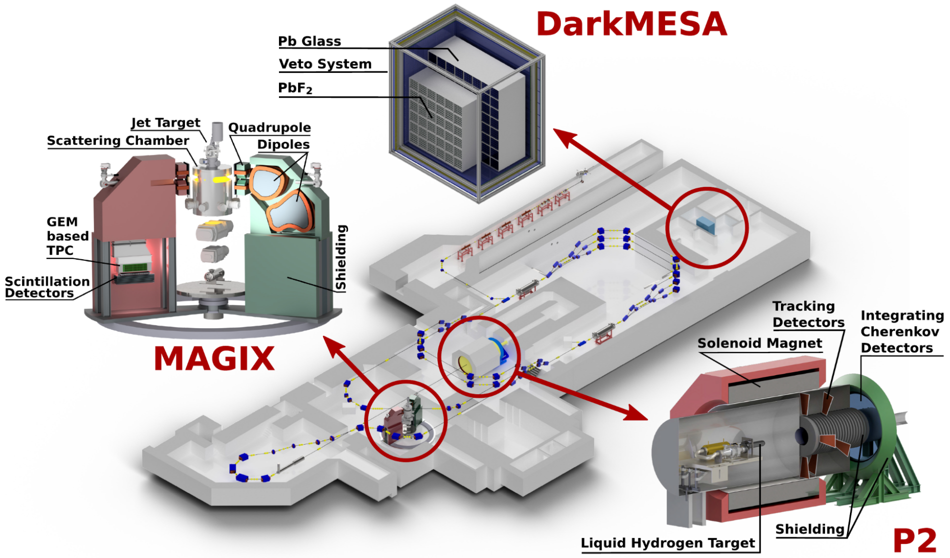

Figure 1. Schematic design of the MESA experimental facilities [6]. The experiments P2 [7], MAGIX [8] and DarkMESA [9] are shown in an enlarged view.

MESA is a *cw* electron accelerator with two operating modes. The energy-recovering LINAC (ERL) mode has a maximum beam energy of 105 MeV and a beam current of 1 mA and serves the MAGIX experiment. After interaction with the target of the MAGIX experiment, the energy of the electrons is returned to the cavities by deceleration of the beam.
The extracted beam (EB) mode provides a maximum beam energy of 155 MeV with a beam current of up to 150 μA and serves the P2 and DarkMESA experiments.

3 The DarkMESA Experiment

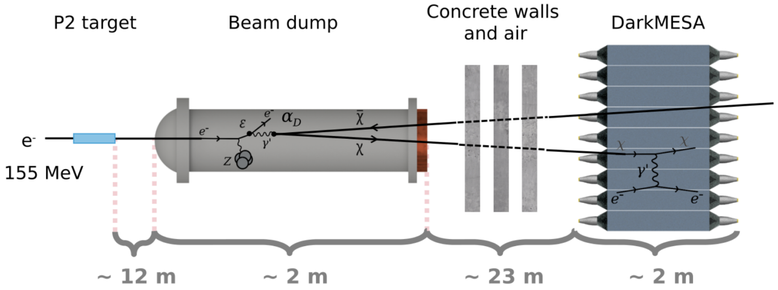

Figure 2. Schematic drawing of the DarkMESA experiment. The electron beam passes through the P2 target before impinging on the beam dump. Inside the beam dump, bremsstrahlung-like processes can occur. The mediator particle can then decay into a Dark Matter pair $\chi\bar{\chi}$, which can be detected inside the DarkMESA calorimeters through scattering processes.

The DarkMESA experiment is a beam dump experiment located about 23 m behind the aluminum beam dump of the P2 experiment [10, 11]. The setup is shown in figure 2.
The P2 beam dump serves as a target for the electron beam. In the case of the Dark Photon γ', production occurs through the bremsstrahlung-like process $eZ \rightarrow eZ\gamma'$, where Z denotes a heavy nucleus, or e^+e^- annihilation [12]. If $m_{\gamma'} > 2m_\chi$, where m_χ is the mass of the Dark Matter particle, the Dark Photon can decay into Dark Matter, $\gamma' \rightarrow \chi\bar{\chi}$. Dark Matter can then be detected inside the calorimeter through scattering processes inside the detector.
The DarkMESA experiment will be set up in three phases [13]. In Phase A, a prototype calorimeter module consisting of 5×5 PbF_2 Cherenkov crystals with a total volume of $0.004\,m^3$ and a veto system for cosmic rays will be used [14, 15]. The prototype will be tested at an energy of $E_{beam} = 55\,MeV$. For Phase B, the setup will be expanded to a volume of $0.7\,m^3$. For this, a total of 36 PbF_2 and 64 SF5 lead glass modules will be used. The development of the Phase C setup is still ongoing. The current design assumes the usage of a $1\,m^3$ negative ion TPC in addition to the Phase B setup. Both Phase B and Phase C will utilize the full available beam energy of $E_{beam} = 155\,MeV$ of the EB mode.

4 Expected Reach of the DarkMESA Experiment

In order to evaluate the experimental reach of the DarkMESA experiment, a simulation using Geant4 [16] and MadGraph [17] frameworks has been developed by Mirco Christmann [13, 18]. It includes the full geometry of the experimental halls, as well as the P2 experiment, the beam dump and the DarkMESA detector setups for the three stages.
In a first step, the energy and angular distributions of e^+e^- particles produced in the beam dump are simulated. The resulting four-vectors are then used as an input for the MadGraph simulation, which calculates the Dark Photon production, as well as its subsequent decay to Dark Matter particles. The input parameters include the mass of the mediator and the Dark Matter particles, the coupling constants for the Dark Photon coupling to SM matter, ε, and to Dark Matter, α_D, as well as the beam energy of the initial electron beam. Upon submitting the final state four-vectors of the Dark Matter particles to the Geant4 simulation, the detector response is simulated. Following the calculations described in [12], the cross section and the total number of detected Dark Matter particles are determined.

Table 1. The staged approach of DarkMESA and the envisioned number of electrons on target (EOT) for each stage.

Phase	Detector	Energy	Time	EOT
A	PbF_2 prototype module	55 MeV	2200 h	$7.42 \cdot 10^{21}$
B	PbF_2 and SF5 crystals	155 MeV	6600 h	$2.22 \cdot 10^{22}$
C (DRIFT)	Phase B + DRIFT TPC	155 MeV	13200 h	$4.45 \cdot 10^{22}$

Table 1 shows the proposed measurement strategy. To calculate the experimental reach as shown in figure 3, a confidence level of 90% is assumed. The detection efficiency is set to 95% and no background is considered. For an event to be accepted, the electron recoil needs to be larger than 10 MeV. The simulation is performed for $m_{\gamma'} = 3\,m_\chi$ and $\alpha_D = 0.5$, which produces more conservative constraints on Dark Matter searches as motivated in [19] and is in agreement with the limits obtained from the other experiments shown in figure 3. A value of $m_{\gamma'} > 2\,m_\chi$ is necessary in order to ensure that an invisible decay to Light Dark Matter is possible. Together with $\alpha_D \gg \alpha\epsilon^2$, this assumption leads to $\gamma' \to \chi\bar{\chi}$ being the dominant decay [4].

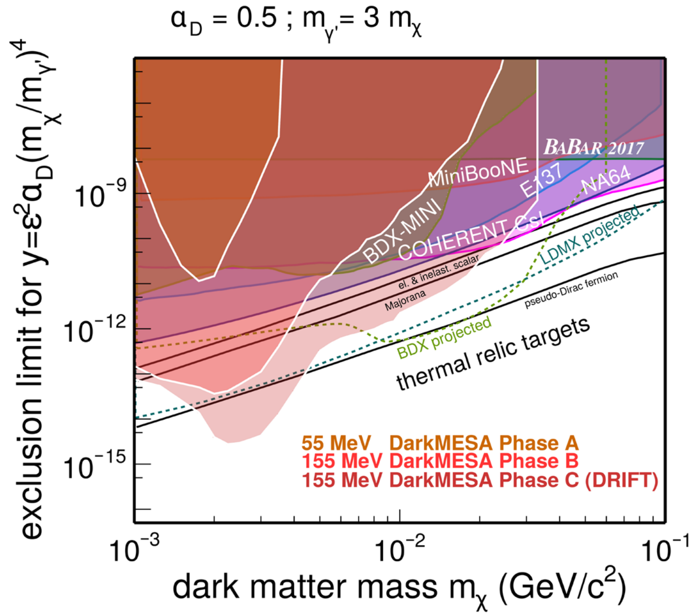

Figure 3. Projected experimental reach of the DarkMESA experiment for the invisible Dark Photon model. Dark Photon production is simulated under consideration of both bremsstrahlung-like processes and e^+e^- annihilation. Cross sections are calculated after [12]. Other limits taken from BaBar [21], E137 [22], COHERENT CsI [23], MiniBooNE [24], NA64 [25] and BDX-MINI [26]. Projected limits are shown for LDMX [27] and BDX [26]. $m_{\gamma'} = 3\,m_\chi$ and $\alpha_D = 0.5$ for all limits.

Figure 3 shows the Dark Matter mass m_χ plotted against the *yield* parameter y, which is directly connected to the thermal relic abundance [20] and less dependent on the nature of the Light Dark Matter particles [1].
Both bremsstrahlung-like processes and e^+e^- annihilation have been considered for Dark Photon production.

While the Phase A setup is not able to cover new areas in the available parameter space, Phase B and Phase C are able to reach till now untouched parameter regions. Both Phase B and C are able to reach the thermal relic targets, which have been calculated assuming the minimum possible couplings to achieve the observed abundance of Dark Matter. This allows DarkMESA to provide more stringent limits in the low mass range for m_χ. DarkMESA is the most sensitive around $m_\chi = 2.5\,\mathrm{MeV/c^2}$. For $m_\chi > 5\,\mathrm{MeV/c^2}$, its experimental reach is complemented by the proposed experiments BDX at JLAB [26] and LDMX [27], which operate at higher beam energies.

5 Outlook

The current GEANT4 simulation is limited to the study of invisible Dark Photon decays. In order to study a possible expansion of the current research program of the DarkMESA experiment, other Dark Sector models, such as Axions or ALPs, need to be considered.

To easily incorporate different Dark Matter models, the DMG4 package [28] is used. DMG4 is a fully compatible GEANT4 package, which allows for direct integration into the existing GEANT4 simulation, therefore reducing the computation time. It includes a variety of Dark Matter models and covers both visibly and invisibly decaying Dark Matter.

One such model are Axions or Axion-like particles, which have been rising in interest in the last years. Axions/ALPs are able to solve the strong CP problem [29] and are yet to be ruled out in the MeV mass range [30]. Axions/ALPs are produced through the Primakoff process $\gamma N \rightarrow aN$, where a denotes the Axion/ALP particle, and decay into two photons $a \rightarrow \gamma\gamma$.

The DarkMESA GEANT4 simulation is currently being upgraded to include the DMG4 package in order to expand the DarkMESA research program to other Dark Matter models such as Axions/ALPs, and thus make full use of the excellent experimental conditions available.

References

[1] J.L. Feng, Annual Review of Astronomy and Astrophysics **48**, 495 (2010)

[2] J. Alexander, M. Battaglieri, B. Echenard, R. Essig, M. Graham, E. Izaguirre, J. Jaros, G. Krnjaic, J. Mardon, D. Morrissey et al., *Dark sectors 2016 workshop: Community report* (2016), `1608.08632`, `https://arxiv.org/abs/1608.08632`

[3] C. Boehm, T.A. Enßlin, J. Silk, Journal of Physics G: Nuclear and Particle Physics **30**, 279 (2004)

[4] M. Fabbrichesi, E. Gabrielli, G. Lanfranchi (2020), `2005.01515`

[5] M. Giannotti, Journal of Physics: Conference Series **2502**, 012003 (2023)

[6] F. Hug, K. Aulenbacher, R. Heine, B. Ledroit, D. Simon, *MESA - an ERL Project for Particle Physics Experiments* (2017), https://doi.org/10.18429/JACoW-LINAC2016-MOP106012, `http://jacow.org/linac2016/papers/mop106012.pdf`

[7] D. Becker, R. Bucoveanu, C. Grzesik, K. Imai, R. Kempf, M. Molitor, A. Tyukin, M. Zimmermann, D. Armstrong, K. Aulenbacher et al., The European Physical Journal A **54**, 208 (2018)

[8] B. Schlimme, S. Aulenbacher, P. Brand, M. Littich, Y. Wang, P. Achenbach, M. Ball, J. Bernauer, M. Biroth, D. Bonaventura et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1013**, 165668 (2021)

[9] M. Christmann, P. Achenbach, S. Baunack, P. Burger, A. Denig, L. Doria, F. Maas, H. Merkel, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **958**, 162398 (2020), proceedings of the Vienna Conference on Instrumentation 2019

[10] M. Christmann et al. (MAGIX), PoS **EPS-HEP2021**, 129 (2022)
[11] L. Doria, Journal of Physics: Conference Series **2391**, 012005 (2022)
[12] J.D. Bjorken, R. Essig, P. Schuster, N. Toro, Phys. Rev. D **80**, 075018 (2009)
[13] M. Christmann, Ph.D. thesis, Mainz (2023)
[14] M. Lauß, P. Achenbach, S. Aulenbacher, M. Ball, I. Beltschikow, M. Biroth, P. Brand, S. Caiazza, M. Christmann, O. Corell et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1012**, 165617 (2021)
[15] M. Christmann, P. Burger, P. Achenbach, S. Aulenbacher, M. Ball, S. Baunack, J. Bernauer, M. Biroth, P. Brand, S. Caiazza et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **960**, 163665 (2020)
[16] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **506**, 250 (2003)
[17] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, JHEP **07**, 079 (2014), `1405.0301`
[18] M. Christmann, P. Achenbach, S. Baunack, P. Burger, A. Denig, L. Doria, F. Maas, H. Merkel, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **958**, 162398 (2020), proceedings of the Vienna Conference on Instrumentation 2019
[19] E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Physical Review Letters **115** (2015)
[20] J. Beacham, C. Burrage, D. Curtin, A. De Roeck, J. Evans, J.L. Feng, C. Gatto, S. Gninenko, A. Hartin, I. Irastorza et al., Journal of Physics G: Nuclear and Particle Physics **47**, 010501 (2019)
[21] J.P. Lees, V. Poireau, V. Tisserand, E. Grauges, A. Palano, G. Eigen, D.N. Brown, M. Derdzinski, A. Giuffrida, Y.G. Kolomensky et al. (BaBar Collaboration), Phys. Rev. Lett. **119**, 131804 (2017)
[22] B. Batell, R. Essig, Z. Surujon, Phys. Rev. Lett. **113**, 171802 (2014)
[23] D. Akimov, P. An, C. Awe, P.S. Barbeau, B. Becker, V. Belov, I. Bernardi, M.A. Blackston, C. Bock, A. Bolozdynya et al., *First probe of sub-gev dark matter beyond the cosmological expectation with the coherent csi detector at the sns* (2023), `2110.11453`
[24] A.A. Aguilar-Arevalo, M. Backfish, A. Bashyal, B. Batell, B.C. Brown, R. Carr, A. Chatterjee, R.L. Cooper, P. deNiverville, R. Dharmapalan et al. (MiniBooNE-DM Collaboration), Phys. Rev. Lett. **118**, 221803 (2017)
[25] Y.M. Andreev, D. Banerjee, B.B. Oberhauser, J. Bernhard, P. Bisio, A. Celentano, N. Charitonidis, A.G. Chumakov, D. Cooke, P. Crivelli et al. (2023), `2307.02404`
[26] M. Battaglieri, M. Bondí, A. Celentano, P.L. Cole, M. De Napoli, R. De Vita, L. Marsicano, N. Randazzo, E.S. Smith, M. Spreafico et al., Phys. Rev. D **106**, 072011 (2022)
[27] T. Åkesson, N. Blinov, L. Brand-Baugher, C. Bravo, L.K. Bryngemark, P. Butti, C. Doglioni, C. Dukes, V. Dutta, B. Echenard et al., *Current status and future prospects for the light dark matter experiment* (2023), `2203.08192`
[28] M. Bondi, A. Celentano, R. Dusaev, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, L. Marsicano, D. Shchukin, Computer Physics Communications **269**, 108129 (2021)
[29] R.D. Peccei, H.R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977)
[30] D.S.M. Alves, N. Weiner, Journal of High Energy Physics **2018**, 92 (2018)