PROCEEDINGS OF SCIENCE

Lohengrin — a proposed experiment in the search for dark bremsstrahlung and a portal to the dark sector

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We present a proposal for a future light dark matter search experiment at the Electron Stretcher Accelerator ELSA in Bonn: Lohengrin. It employs the fixed-target missing momentum based technique for searching for dark-sector particles. The Lohengrin experiment uses a beam of electrons that is extracted from the ELSA accelerator and shot onto a thin target to produce mainly Standard Model bremsstrahlung and possibly new particles coupling feebly to the electron. A well motivated candidate for such a new particle is the dark photon. The dark photon is a new, possibly massive gauge boson arising from a new gauge interaction in a dark sector and mixing kinetically with the Standard Model photon. The Lohengrin experiment is estimated to reach sensitivity to couplings small enough to explain the relic abundance of dark matter in various models for dark photon masses between $\sim 1\,\text{MeV}$ and $\sim 100\,\text{MeV}$.

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1. Dark Sector and Dark Photons

The nature of dark matter (DM) is unexplained in the Standard Model (SM) of elementary particle physics. Many different models for DM have been put forward and some of these models have been experimentally tested. So far searches for DM have produced only negative or non-reproducible results (for an overview see [1–7]). Weakly interacting, massive particles (WIMPs) with a mass in the GeV-TeV range have been considered excellent candidates for DM. However, with the direct DM search experiments and the indirect bounds from the LHC experiments providing ever stronger limits on the WIMP parameter space, other, more complex explanations for DM are being studied more closely. One class of such models introduces either scalar or fermionic DM particles χ that interact through a new gauge interaction, based on a spontaneously broken symmetry. The associated gauge boson can couple to the SM sector through a mechanism that is called kinetic mixing, effectively introducing a feeble interaction between the dark sector and the SM. Assuming a simple, broken $U(1)_D$ gauge symmetry for the interaction in the dark sector, the new gauge boson is called dark photon and its mass/gauge eigenstates are labelled A'/A_D. The relevant terms that are added to the SM Lagrangian through this extension are given by

$$\mathscr{L} \supset -\frac{1}{4}F_{\mathrm{D}\mu\nu}F_{\mathrm{D}}^{\mu\nu} + \frac{1}{2}m_{A_{\mathrm{D}}}^2 A_{\mathrm{D}\mu}A_{\mathrm{D}}^{\mu} - \frac{\sin\varepsilon_Y}{2}F_{\mathrm{D}}^{\mu\nu}B_{\mu\nu} - g_{\mathrm{D}}A_{\mathrm{D}\mu}J_{\mathrm{D}}^{\mu}\,, \tag{1}$$

where the parameter m_{A_D} is the massterm for the A_D and ε_Y parametrises the mixing to the SM, here between the SM B-field and the new gauge field. For energies well below the electroweak scale, this leads to a new coupling between the charged SM fermions and the new gauge boson:

$$\mathscr{L} \supset \sum_f iQ_f\varepsilon\,\bar{f}\gamma^\mu f A'_\mu, \tag{2}$$

where $\varepsilon = \varepsilon_Y \cdot \cos\theta_W$ is the reduced mixing parameter. The thermally averaged dark matter annihilation cross-section can be calculated from the dark photon mass $m_{A'}$ and the dimensionless quantity

$$\Upsilon \equiv \varepsilon^2 \frac{g_D^2}{4\pi}\left(\frac{m_\chi}{m_{A'}}\right)^4. \tag{3}$$

Here, g_D is the coupling constant of the new gauge interaction in the dark sector. For a given value of Υ, the mass m_χ of the dark matter particles must have a well defined value in order to get the right relic abundance due to the fact that the annihilation cross-section is given by

$$\langle\sigma v\rangle \sim \Upsilon/m_{\mathrm{DM}}^2. \tag{4}$$

The precise value depends further on the nature, i.e. the spin, of the dark matter particle. An interesting consequence of Eq. (2) is the possible emission of *dark bremsstrahlung* as part of the interactions of a charged particle with matter. The process is analogous to the emission of SM bremsstrahlung, and only modified by the reduced mixing parameter ε and the mass of the dark photon. This enables a search for the dark photon by means of a relatively simply experiment: a beam of electrons is shot onto a high-Z target, producing ample amounts of bremsstrahlung and, occassionally, a dark photon. The expected number of dark photons that are produced when directing a 3.2 GeV electron beam onto a 10% X_0 tungsten target is shown for 10^{13}, 10^{14} and 10^{15}

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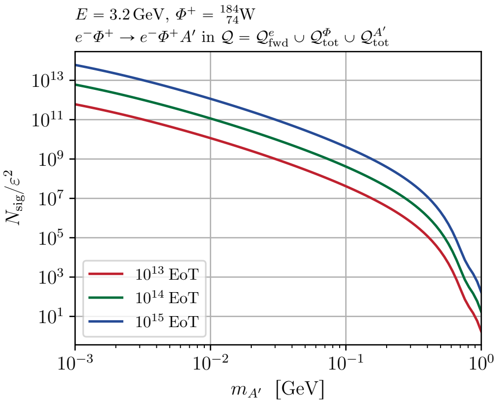

Figure 1: Expected number of dark photon events as function of the dark photon mass for a 3.2 GeV electron beam being shot onto a 10%X_0 target for 10^{13}, 10^{14} and 10^{15} electrons on target (eot).

$m_{A'}$	Scalar χ	Majorana χ	Pseudo-Dirac χ
4.5 MeV	$4.3 \cdot 10^{-11}$	$2.2 \cdot 10^{-11}$	$2.9 \cdot 10^{-12}$
10 MeV	$2.0 \cdot 10^{-11}$	$9.8 \cdot 10^{-11}$	$1.3 \cdot 10^{-11}$
100 MeV	$2.6 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$	$1.2 \cdot 10^{-9}$
1 GeV	$5.4 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$	$2.5 \cdot 10^{-8}$

Table 1: Target values of the squared reduced mixing parameter ε^2 that yield the correct relic abundance of dark matter in our universe, as a function of the dark photon mass (assuming $m_{A'} = 3m_\chi$) for different choices of the nature of the dark matter particle.

electrons on target in Fig. 1. The plot is normalised to $\varepsilon = 1$, i.e. the numbers extrapolated from the plot must be scaled with the target $\varepsilon^2 \ll 1$ for any physically relevant scenario [8]. The target values can be calculated assuming that the entirety of dark matter in our present universe consists of a single particle type, the χ, which can either be a scalar, a Majorana fermion, or a pseudo-Dirac fermion. Assuming a fixed relation between the masses of the only two relevant particles in the dark sector, $\frac{m_{A'}}{m_\chi} = 3$ (a commonly used benchmark for this scenario), these target values are shown as a function of the dark photon mass and the nature of the dark matter particle in Table 1. For any relevant scenario, and for dark photon masses at the order of a few MeV, approximately 10 – 100 dark photon events are expected for 10^{15} electrons on target.

2. The Lohengrin Experiment at ELSA

The ELSA accelerator in Bonn [9, 10] can provide a beam of single electrons with an energy of up to 3.2 GeV and a low energy spread. For the Lohengrin experiment, this beam is shot onto a target of tungsten (or another suitable material) with a thickness of approximately 10% of a radiation length. A schematic setup of the experiment is shown in Fig. 2. The target is placed inside of a tracking detector, with 3-4 planes to tag incoming electrons in front of the target and 6 planes behind the target to measure the momentum of scattered electrons (and other charged particles emerging from the target) in a magnetic field $B \approx 1$ T. Two calorimeters, an ECAL and a HCAL are placed in the forward direction to measure the energy of charged or hadronic particles that emerge from the target in the forward direction. The magnetic field is strong enough to bend the trajectories of the electrons around the ECAL, such that in first order, only photons that are emitted in the target or tracker produce clusters in the ECAL. Events in which a dark photon is produced would feature a single electron in the final state, with no additional tracks and no significant energy deposits in the calorimeters. Depleted, monolithic active pixel sensors like the TJMonopix2 ASIC [11, 12], are currently considered for the tracking detector, as they allow the construction of a low material budget tracker, which is crucial for the reconstruction of low momentum electrons. The tracking

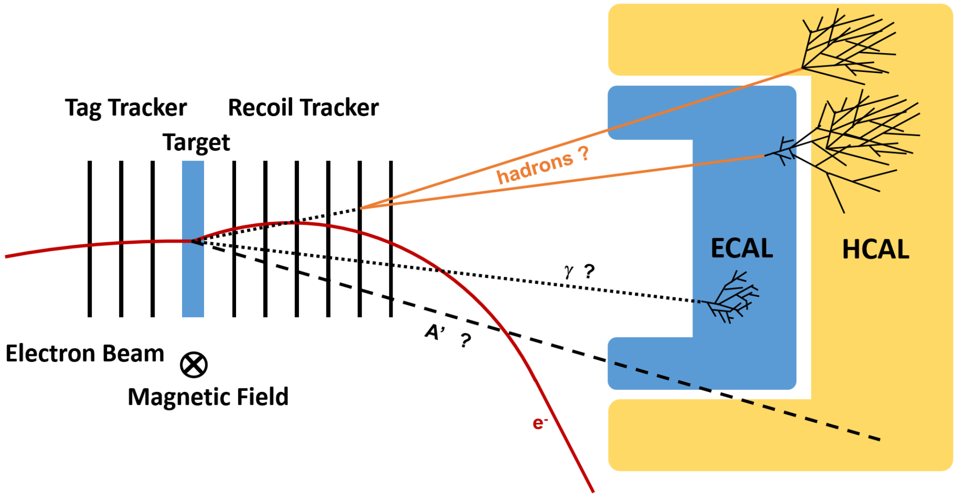

Figure 2: Schematic representation of the Lohengrin experiment.

detector also enables the installation of a fast track trigger that will select events with low energy electron tracks in the final state. A silicon-tungsten calorimeter [13] is considered for the ECAL, as this enables the construction of a highly segmented and fast calorimeter with triggered readout. The HCAL can be considerably coarser and does not have to provide excellent energy resolution. Steel absorbers paired with scintillating tiles, read out by photomultipliers, are a good candidate for the construction for this calorimeter.

3. Backgrounds and Expected Sensitivity

The most important background processes from SM processes include the emission of a photon outside of the acceptance of the calorimeter, as well as electronuclear and photonuclear interactions in which a large fraction of the energy of the incoming electron is carried away by hadrons that are emitted from a nucleus in the target or the tracking detector and do not reach the HCAL. Assuming an ECAL size of $48 \times 48\,\mathrm{cm}^2$ located 3.5 m behind the target, and considering out-of-acceptance photons as the dominant background source, the LOHENGRIN experiment achieves the highest sensitivity in the final state phase space where the recoil electron energy is below 75 MeV and emerges from the target at small or moderate polar angles with respect to the beam axis. This is shown for a dark photon mass of $m_{A'} = 10\,\mathrm{MeV}$ in Fig. 3 and Fig. 4.

A tentative signal region for the LOHENGRIN experiment is hence defined by the presence of a single track in the final state, consistent with an electron with an energy $E_{\mathrm{e,min}} < E_{\mathrm{e}} < E_{\mathrm{e,cut}}$, no additional track candidates and no significant energy deposition in the calorimeters. The upper limit is motivated by the optimisation of the discovery reach, the lower limit is motivated by the fact that the reconstruction efficiency for electrons in the final state drops sharply at low energies. This is due to the strong magnetic field that limits the number of hits in the tracking detector, as the trajectories of low energy electrons are bent outside of the tracking volume before they reach the third or fourth plane in the recoil tracker. In addition, multiple scattering dilutes the measurement of the electron tracks, in particular for low energy electrons. For the feasibility study presented here,

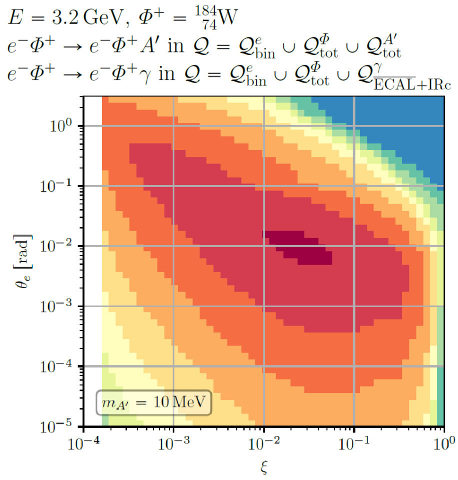

Figure 3: Expected sensitivity in bins of the recoil electron energy fraction $\xi = \frac{E_{\mathrm{e,f}}}{E_{\mathrm{e,i}}}$ and the recoil electron scattering angle θ for $m_{A'} = 10\,\mathrm{MeV}$, normalised to $\varepsilon = 1$.

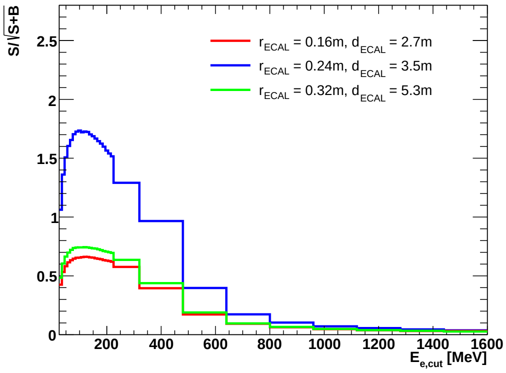

Figure 4: Expected sensitivity in inclusive signal regions as a function of the upper cut on the recoil electron energy in MeV, for three different layout scenarios for $m_{A'} = 10\,\mathrm{MeV}$ for an arbitrary value of ε.

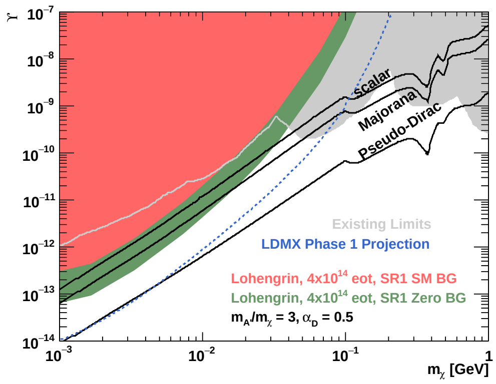

Figure 5: Expected sensitivity in the dark matter mass and coupling space in a pessimistic scenario.

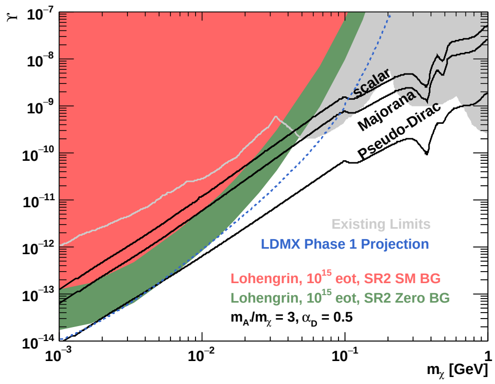

Figure 6: Expected sensitivity in the dark matter mass and coupling space in an optimistic scenario.

values of $E_{\mathrm{e,min}} = 25\,\mathrm{MeV}$ and $E_{\mathrm{e,max}} = 75\,\mathrm{MeV}$ were chosen. Using the Lohengrin++ code for the generation of signal events, and Geant4 [15] for the simulation of SM bremsstrahlung events, the expected sensitivity of the Lohengrin experiment for $4 \cdot 10^{14}$ electrons on target is shown in Fig. 5. Reducing the lower bound for the electron reconstruction and increasing the number of electrons on target, the discovery reach of the experiment can be significantly enhanced, as shown in Fig. 6.

4. Conclusions

The Lohengrin experiment can cover a significant fraction of the parameter space in dark matter models with a new, broken U(1) gauge interaction in the dark sector. The construction of suitable detectors, while challenging, is within reach. A more complete overview is given in [14].

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