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Light Dark Matter search with a positron beam

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Summary. — Although the existence of Dark Matter has been confirmed by a variety of gravitational measurements, to date there are no conclusive indications about its particle nature. Light Dark Matter (LDM) particles, with mass in the range of 1 MeV–1000 MeV, represent a theoretically well-motivated solution for the Dark Matter puzzle. Among the LDM theories, the simplest model introduces a new light gauge boson called Dark Photon (A'). In this theory, the A' can be generated by the interaction of Standard Model charged particles with ordinary matter and subsequently decays into an LDM particle pair. In this scenario, an experiment making use of a positron beam impacting on a thick active target would have a unique discovery potential, since the positron annihilation process with atomic electrons provides an efficient mechanism for LDM generation. In this work, the feasibility and the potential of a missing energy experiment using a ∼10 GeV positron beam are discussed.

1. – Light dark matter

One of the most compelling arguments motivating the search for physics beyond the Standard Model (SM) is the need to explain the nature of Dark Matter (DM). In past years, theoretical and experimental efforts have been made, mainly focused on the hypothesis that DM corresponds to a Weakly Interacting Massive Particle (WIMP), with mass at the electroweak scale (∼100 GeV) interacting with SM particles via the weak force. However, despite an extensive search program that combined direct, indirect, and detection at colliders, to date no conclusive signals supporting the existence of WIMPs have been found [1]. As a consequence, searches for Dark Matter (DM) extended to new alternative models. In particular, DM particles in the mass range 1 MeV–1000 MeV (also called "Light Dark Matter" or LDM) are theoretically well-motivated if a new light mediator is introduced. Among the LDM theories, the simplest model introduces a new

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gauge boson called "Dark Photon" (A') interacting both with the SM photon and the LDM particles (χ). Such a theory can be described by the effective Lagrangian given below [2]:

$$\mathcal{L}_{LDM} = -\frac{1}{4}F'_{\mu v}F'^{\mu v} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - e_D\bar{\chi}\gamma^\mu A'_\mu\chi + \frac{\varepsilon}{2}F'_{\mu v}F^{\mu v}. \tag{1}$$

In this context, ε is the coupling constant between A' and the Standard Model photon, while $e_D \equiv \sqrt{4\pi\alpha_D}$ is the coupling constant for the χ-A' interaction. Thanks to the γ-A' mixing, an effective coupling arises between SM charged particles and the A' with intensity εq, where q represents the electric charge of the particle involved in the process. This implies that the A' can be generated by the interactions of charged particles with ordinary matter. Finally, assuming that $m_{A'} > 2m_\chi$ and $\alpha_D \gg \alpha_{EM}\varepsilon^2$, once produced, the Dark Photon decays into a LDM particle pair through the so-called "invisible decay" channel ($A' \to \bar{\chi}\chi$). According to the thermal origin hypothesis [3], the current DM density can be thought of as a thermal relic of the DM generated in the early Universe. This assumption allows constraining the LDM parameter space, identifying a target region towards which experimental efforts are focused.

2. – Accelerator-based experiments

In the last years, a broad experimental program to search for LDM at accelerators was started, with many complementary efforts [4]. Accelerator-based experiments are performed in a controlled environment allowing for optimised studies in certain regions of interest in the LDM parameter space and efficient background events evaluation. For example, changing the beam energy allows the LDM search to be focused at different m_χ values, while turning off the beam allows a dedicated study of beam-unrelated backgrounds. Among the accelerator-based experiments, fixed target experiments making use of positron beams [5] are particularly interesting, since the resonant annihilation process with electrons in the target provides an efficient mechanism for LDM generation (fig. 1). If the kinematics allows it, the resonant annihilation process is more intense than the other LDM production channel. Furthermore, this process is characterized by a unique kinematic signature due to the underlying resonant dynamics. More precisely, the A' produced via this mechanism carries a well-defined kinetic energy, equivalent to the interacting positron energy, solely depending on Dark Photon mass ($E_R = \frac{m_{A'}^2}{2m_e}$). This feature represents a powerful means to discriminate signals from backgrounds and motivated the interest in studying this LDM production channel.

3. – JPOS-LDM experiment

The JPOS-LDM is a new proposed experiment to search for LDM in the $\sim$100 MeV mass range at Jefferson Lab (JLab, Newport News, VA) [6]. The measurement is based on a positron beam impacting on a thick active target measuring the energy deposited by each positron. If an A' is generated in the target by the interaction between a positron in the electromagnetic shower and an atomic electron, the LDM decay particles may leave the detector without further interactions. This results in a measurable "missing energy", defined as the difference between the beam and the measured ("visible") energy. The target is thick enough to produce and fully absorb the electromagnetic shower generated within it. As a consequence, several secondary positrons are produced, carrying a kinetic

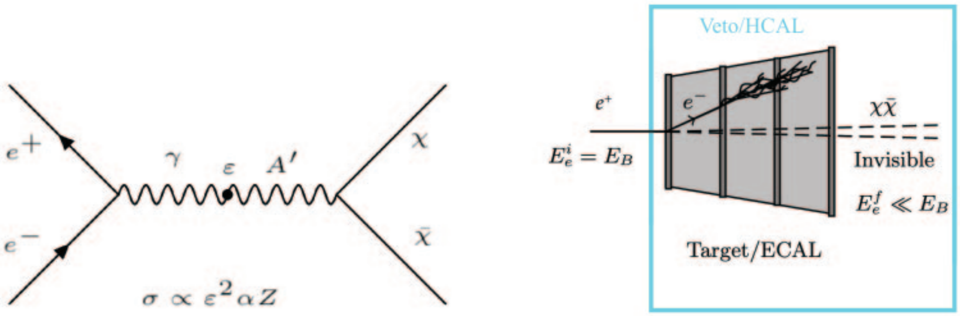

Fig. 1. – Left: the Feynman diagram for the resonant annihilation process. Right: the JPOS-LDM setup scheme. The e^+ beam impinges on a thick, active target (ECAL), surrounded by the veto system (HCAL). LDM production events present high missing energy and no veto activity.

energy lower than the primary positron energy. This means that a thick target experiment can explore a large range of values for $m_{A'}$ thanks to the resonant annihilation process of secondary positrons. In this experiment, the beam current has to be limited to reduce the pile-up effects: the time interval between the impact of two subsequent positrons has to be longer than the response time of the detector. Otherwise, overlapping between events occurs, and it is not possible to evaluate the missing energy positron by positron.

In such an experiment, an event presenting a missing energy greater than about half of the beam energy is considered a signal event candidate. Background events are mainly caused by energetic particles produced in the target and escaping from it, carrying away a large portion of the primary beam energy: these events present a high missing energy not associated with LDM particle production. Backgrounds events can be efficiently recognised by using an external veto system, surrounding the inner calorimeter, that detects these exiting particles and reject events with high energy leakage.

The JPOS-LDM will exploit the future 11 GeV positron beam foreseen at Jefferson Lab, with an expected current of about $1e^+/\mu s$. This will allow acquiring approximately 10^{13} positrons on target (POT) in a one-year measurement, avoiding pile-up effects. The proposed setup is composed of a thick active target (ECAL) surrounded by a hadronic calorimeter (HCAL) acting as a veto system (fig. 1). The ECAL must have a fast response time to reduce the pile-up effects. Its volume and density have to be sufficiently large to fully absorb the electromagnetic shower within a compact detector. In addition, a high-resolution measurement of the deposited energy is needed. To meet these constraints, the JPOS-LDM target is a homogeneous calorimeter made of $PbWO_4$ crystals. The foreseen configuration presents a target of $20 \times 20 \times 35.6\,\mathrm{cm}^3$, corresponding to a thickness of 40 radiation lengths. If a 5 GeV missing energy threshold is considered, such a target results in a signal efficiency of about 90% for $m_{A'} \sim 90\,\mathrm{MeV}$. On the other hand, the external HCAL has to detect energetic particles escaping from the ECAL (in particular long-lived neutral hadrons and penetrating particles). To minimise the total detector size, the JPOS-LDM makes use of a sampling hadronic calorimeter made of lead and plastic scintillator layers.

The detector geometry has been optimised through a dedicated study based on Monte Carlo simulations [7]. The results show that the optimal detector geometry consists of a 40 X_0 long ECAL, followed by a 20 λ_I thick downstream HCAL, also extending for 3 λ_I around the active target. The lead layer thickness is 3 cm, while the plastic scintillator

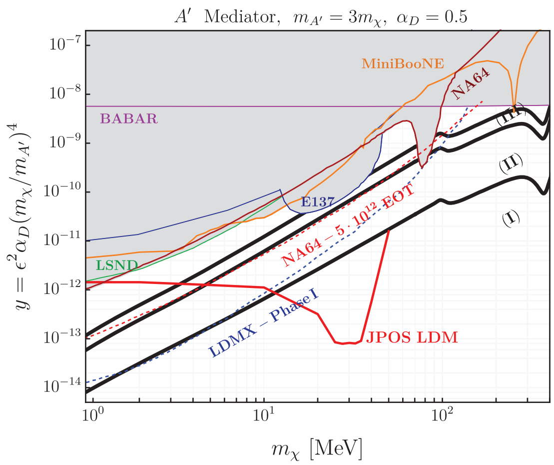

Fig. 2. – The JPOS-LDM sensitivity. The red curve shows the expected sensitivity calculated assuming 10^{13} POT and zero background. Gary areas report the most updated exclusion limits. The black lines are the predictions from the "thermal origin" hypothesis, for the following LDM models: pseudo-Dirac fermion (I), Majorana fermion (II), elastic and inelastic scalar (III). This study was performed considering $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$.

layer thickness is 2 cm. To reject all the expected background events for 10^{13} POT, it is required to discard an event whenever an energy amount greater than 0.5 MeV is deposited in at least one plastic scintillator tile. The predicted sensitivity of the JPOS-LDM experiment has been evaluated using the method described in [6]. In particular, the number of expected background events is set to zero and a signal efficiency of about 90% is considered, according to the estimate obtained from Monte Carlo simulations. The final result is reported in fig. 2, where the JPOS-LDM sensitivity is compared to the most updated upper limits quoted by other LDM experiments. This result confirms the interest in the first positron-beam missing energy experiment that will search for LDM in the multi-GeV energy range.

In conclusion, this work represents the first step towards the real detector design and construction. On-beam tests will be required to validate the simulation result and to confirm its dependence on the setup critical parameters (such as the veto thresholds applied for backgrounds rejection), significantly affecting the experimental sensitivity.

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