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Searching for X_{17} using resonant production at PADME

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Summary. — The ATOMKI Collaboration (Debrecen, Hungary) observed an anomaly in the angular correlation of e^+e^- pairs emitted by Internal Pair Creation (IPC) in ^{8}Be, ^{4}He and ^{12}C nuclear transitions. This anomaly can be explained introducing a new neutral boson of $\sim 17\,\text{MeV}$ mass, now named X_{17}. The Positron Annihilation into Dark Matter Experiment (PADME) based at the National Laboratories of Frascati (LNF), was designed and constructed to search for dark photons A' in the interaction between positrons, provided by the local Beam Test Facility, and electrons of a fixed target. In order to probe the existence of the new X_{17} particle, PADME detector has been modified and a new data-taking run has been undertaken.

1. – Introduction

The Dark Matter (DM) problem is one of the most discussed themes of Beyond Standard Model physics and many theories are currently tested in fundamental research. The Weekly Interactive Massive Particle (WIMP) models are those that have been tested more extensively, but the absence of any experimental evidence has moved the attention to other theories that assume that DM interacts feebly with ordinary Standard Model (SM) matter through a particle generically called "portal". The simplest model alternative to the WIMP hypothesis is the "minimal" one, where the mediator is a dark photon A', that is a gauge boson of a potential $U(1)_{DM}$ symmetry. The free parameters of these models are the mass $m_{A'}$ and the coupling ϵ' with ordinary matter.

In recent years, the Hungarian ATOMKI Collaboration observed an anomaly in ^{8}Be, ^{4}He and ^{12}C nuclear transitions [1-3]. The experiment consists in the nuclear excitation of different target elements through proton capture to study the angular correlation of the e^+e^- pairs emitted by IPC using a multi-arms spectrometer. The anomaly has been observed in each nuclear de-excitation studied and it seems to be compatible with the production, and successive decay, of a neutral massive and short-lived particle now called

(*) On behalf of the PADME Collaboration.

X_{17}. According to all the measurements provided by the ATOMKI Collaboration, the expected X_{17} mass and the production cross-section are $m_{X_{17}} \simeq 17$ MeV and $\sigma(e^+e^- \to X_{17}) \simeq 5 \times 10^{-6}\sigma(e^+e^- \to \gamma\gamma)$ [4].

Feng *et al.* proposed several anomaly explanations, building models on momentum and spin-parity conservation rules. Based on the latter, the *vector* and *axial-vector* hypotheses seem to fit all the ATOMKI observations [4, 5].

1˙1. *The X_{17} resonant search at PADME.* – In order to confirm, or disprove, the presence of this new particle, the Positron Annihilation into Dark Matter Experiment (PADME), based at National Laboratories of Frascati (LNF) of INFN, dedicated the Run III data taking to the production of a X_{17} obtained through the interaction between positrons, coming from the local Beam Test Facility (BTF), and the electrons of a fixed carbon target.

The allowed X_{17}-production processes in the invariant mass range of ~ 17 MeV are:

- *Resonant annihilation*: $e^+e^- \to X_{17}$, whose cross-section is

$$\sigma_{res} = \frac{12\pi}{m_X^2}\frac{\Gamma_X^2/4}{(\sqrt{s}-m_X)^2 - \Gamma_X^2/4}, \tag{1}$$

  only accesible using a positron beam [6].

- *Radiative emission* (X_{17}-strahlung): $e^\pm Z \to e^\pm Z X_{17}$.

- *Associated production*: $e^+e^- \to \gamma X_{17}$.

The produced X_{17} is then experimentally detectable via its decay in e^+e^- pairs.

The PADME Run III data taking was devoted to the search for X_{17} through the resonant annihilation production, which becomes large if one can tune the $\sqrt{s}$ as close as possible to the new particle mass. The full analysis technique and the strategy of the PADME Run III are described in [7].

2. – PADME Run III

One of the main contributions to the e^+e^- cross-section in the X_{17} mass range is the Bhabha scattering $e^+e^- \to e^+e^-$. Referring to the studies of Feng *et al.* [4], the width of the X_{17} under the vector hypothesis is $\mathcal{O}(10^{-5}\,\text{eV})$, allowing to consider the X_{17} production prompt and making the kinematic of the process $e^+e^- \to X_{17} \to e^+e^-$ nearly the same of the Bhabha scattering (*i.e.*, s-channel). This assumption is the keystone of the PADME Run III analysis strategy: in a fixed-target experiment the kinematic of annihilation and scattering processes can be distinguished, strongly improving the sensitivity to the X_{17} research.

In order to perform the X_{17} measurement, which requires collecting e^+e^- pairs as final state particles, the PADME experimental setup underwent some variations with respect to previous runs (fig. 1) [8]: the magnet was turned off to allow all the final state particles reaching the Electromagnetic Calorimeter (ECal); a new plastic scintillator detector, called Electron Tagger (ETagger), was installed in front of ECal to distinguish charged and uncharged particles; the Small Angle Calorimeter (SAC) previously located behind ECal central hole, was replaced by the TimePix3 beam monitor and a lead glass luminometer, to control the beam condition during the whole data acquisition.

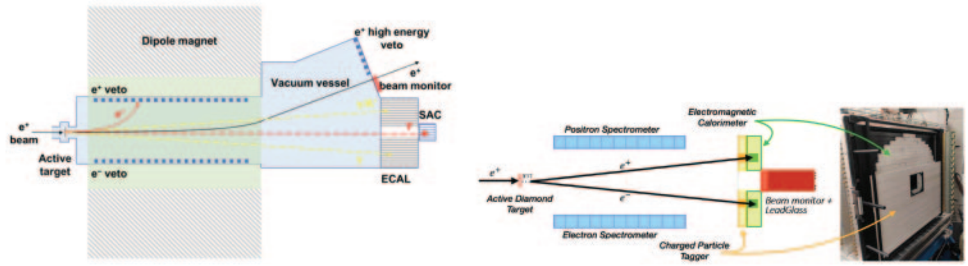

Fig. 1. – Left panel: PADME experimental setup adopted in Run I and II [8]. Right panel: modified PADME setup for Run III for X_{17} hunting.

2˙1. *Expected standard model background.* – The irreducible SM background process for the PADME measurement is the Bhabha scattering, characterised at the tree level by three different processes, the scattering (t-channel), the annihilation (s-channel) and the interference term. Contrary to what happens in colliders, in a fixed-target experiment it is possible to distinguish the annihilation contribution from the scattering one looking at the momentum of final state particles, as shown in fig. 2. The full cross-section is dominated by the t-channel, which is strongly boosted in the forward direction, while the s-channel is quite flat in the entire spectrum, then in order to minimise the t-channel background contribution, a set of cuts can be applied to select events in the central region of fig. 2. The knowlodge of Bhabha scattering kinematics allows to study the acceptance of both background (full $e^+e^- \to e^+e^-$ scattering) and signal processes.

In fig. 2 the $\gamma\gamma$-production cross-section spectrum (blue), is also shown that is another pure QED process allowed in the X_{17} invariant mass region. The presence of this other SM process is the main reason why the ETagger was installed in front of ECal.

2˙2. *Invariant mass scan technique.* – The technique adopted by PADME to investigate the production of X_{17}, requires a bump in the cross-section at $\sqrt{s} \simeq m_{X_{17}}$ in the e^+e^- invariant mass distribution,

$$\mathcal{N}_X = N^{PoT} \frac{g_{V_e}^2}{2m_e} \ell_{tar} \frac{N_A \rho Z}{A} f(E_{res}, E_{beam}), \tag{2}$$

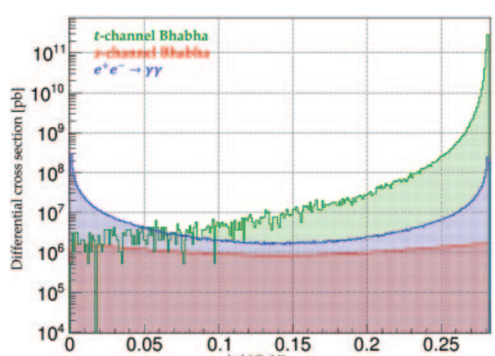

Fig. 2. – SM cross-section as a function of final state positron momentum of each background process: $\gamma\gamma$ production (blue), t-channel (green) and s-channel (red) of Bhabha scattering.

where N^{PoT} is the number of positron on target, g_{V_e} is the vector-electron coupling, ℓ_{tar} is the target thickness and $f(E_{res}, E_{beam})$ is a Gaussian describing the X_{17} production as a function of $E_{res} = \frac{m_X^2}{2m_e}$, the beam energy and its spread σ_E:

$$f(E_{res}, E_{beam}) = \frac{1}{\sqrt{2\pi}\sigma_E} e^{-\frac{(E_{beam}-E_{res})^2}{2\sigma_E^2}}. \tag{3}$$

In order to show how the signal could arise over the background, Darmé *et al.* proposed two different production scans in [7] as a function of the beam energy spread and the number of PoT (fig. 3), which are the variables entering linearly in (2).

2·3. *Collected data.* – The PADME Run III lasted three months at the end of 2022. The total integrated luminosity was $\sim 6\times10^{11}$ PoT, divided into 53 scan points: 47 points in the "*on-resonance*" region where X_{17} is expected to be, 5 points below resonance where the X_{17} production is kinematically forbidden and 1 point above resonance, where the X_{17} production is suppressed. The *on-resonance* points were collected in the beam energy range $260 \leq E_{beam} \leq 300$ MeV, corresponding to a ~ 1 MeV $\sqrt{s}$-region centered on the expected X_{17} mass value. The distance between two consecutive points is determined by the beam energy spread, which was $\simeq 0.75$ MeV for the whole run period. The "*off-resonance*" points were collected in the beam energy range $205 \leq E_{beam} \leq 212$ MeV (*below resonance*) and at 402 MeV (*above resonance*).

Regarding the *off-resonance* points, PADME collected these data, in order to perform pure SM measurements of the involved processes (Bhabha scattering and $\gamma\gamma$ production), study the SM background, make comparisons between data and the full PADME Monte Carlo simulations [9], tune the search technique and validate the luminosity measurement for the entire scan.

3. – Preliminary results

The PADME Run III data analysis on $\sim 6\times10^{11}$ PoT will set more stringent limits on both *vector* and *pseudo-scalar* hypotheses for the X_{17} than the ones plotted in fig. 4 [7].

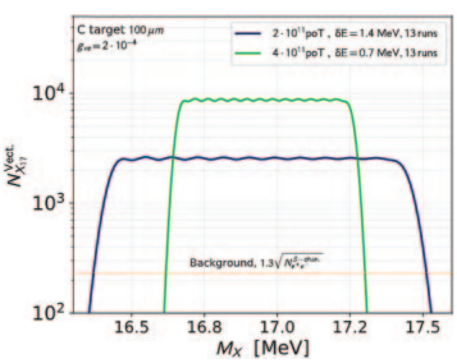

Fig. 3. – X_{17} production as a function of the invariant mass. The blue line is derived with $N^{PoT} = 2\times10^{11}$ and $\sigma_E = 1.4$ MeV, the green with $N^{PoT} = 4\times10^{11}$ and $\sigma_E = 0.7$ MeV. The orange dotted line represents the expected SM background due to the pure Bhabha s-channel process.

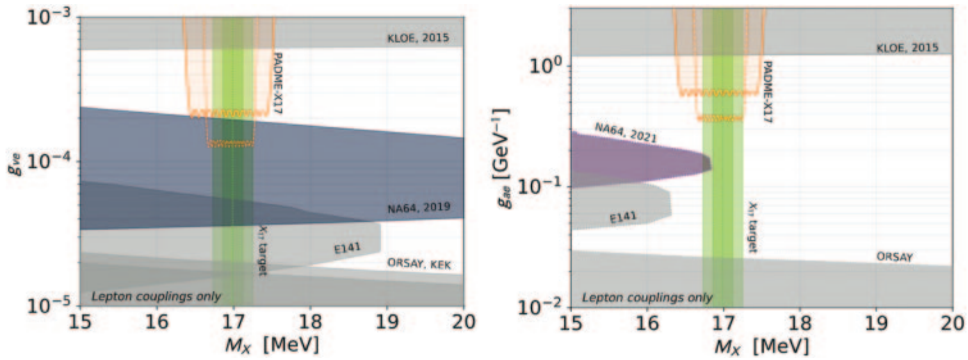

Fig. 4. – The expected 90% confidence level sensitivity for *vector* (left) and *pseudo-scalar* (right) X_{17} models [7]. The targeted space parameters for PADME Run III are shown in orange while the green band represents the constraints on X_{17} mass coming from the ATOMKI measurements [1-3].

The aim is to cover the entire free space parameters in the X_{17} invariant mass region for the *vector* boson model, ruling out or confirming the existence of such a particle (fig. 4(left)), while for the *pseudo-scalar* hypothesis (fig. 4(right)), PADME will exclude a portion of the free space parameters only for a decay into an electron-positron pair.

3˙1. *Run III data quality*. – The data analysis started from the "*below-resonance*" points. Figure 5(left) shows the energy distribution of an electromagnetic cluster in ECal as a function of the scattering angle with respect to the beam axis, for events with two clusters in ECal. The events populating the red box are those coming from a vertex inside the target, while the population on the right comes from the so-called Beam-Induced Background (BIB). The time difference between the two clusters, for events belonging to the red box, is presented in fig. 5(right). It shows a Gaussian distribution centred at zero with $\sigma \simeq 1.5$ ns, demonstrating that the experiment is not dominated by background either from out-of-trajectory beam particles or from pile-up events.

4. – Conclusions

The PADME Run III was performed to investigate the particle nature of the anomaly observed by the ATOMKI Collaboration in the study of excited nuclear states via IPC.

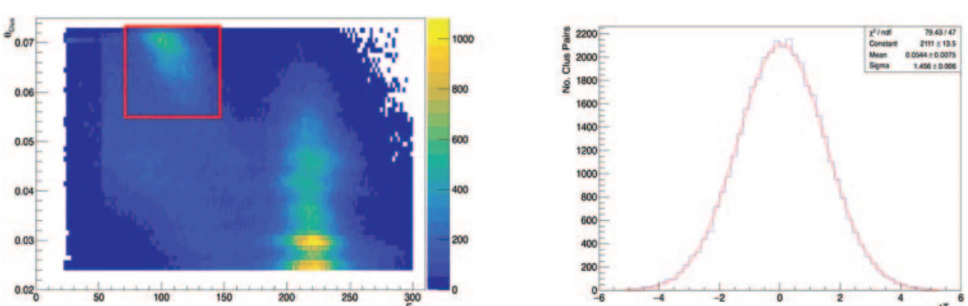

Fig. 5. – Left panel: energy of two-clusters events in ECal *vs.* theta angle to beamline. Right panel: time difference of cluster pairs within red box.

The Run III data have been collected and the preliminary analysis on the *off-resonance* regions shows that the quality of acquired data is good and that signals are well separated from the background.

The collaboration aims to set stringent limits on both *vector* and *pseudo-scalar* hypotheses, covering the entire untested region for the vector case.

Moreover, this analysis will allow new cross-section measurements of Bhabha scattering and $\gamma\gamma$ production in the $\sqrt{s}$ region below $\sim$ 20 MeV, which are currently not present in literature.

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