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X_{17} anomaly and prospects for its verification with NA64 experiment

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The ATOMKI collaboration reported a 7σ excess in the angular distribution of e^+e^- events in the nuclear de-excitation of ^{8}Be, which was recently confirmed by new results on other nuclei, ^{4}He. This anomaly could be explained by the existence of a new boson X_{17} with a mass around 17 MeV and spin 0 or 1. In this work, we summarize the latest results on the searches performed by NA64 of a vector X_{17}, an example of which could be the so-called protophobic gauge boson, with predicted coupling strength with electrons $2 \times 10^{-4} \lesssim \epsilon \lesssim 1.4 \times 10^{-3}$ and lifetime in the range $10^{-14} \lesssim \tau_{X17} \lesssim 10^{-12}$s. NA64 experiment is a fixed target experiment at the CERN Super Proton Synchrotron (SPS) capable to perform an independent measurement. If such a particle exists, it can be produced via Bremsstrahlung after high energy secondary SPS electron beam collides with the active target nuclei. In the analysis of the combined 2017-2018 run, corresponding to 8.4×10^{10} electrons on target, no signal-like events have been found excluding a large fraction of the coupling parameter space able to explain the anomaly: $\epsilon < 6.8 \times 10^{-4}$. We will also briefly discuss prospects for further searches aiming to cover parameter space for models suggesting enabled explanation of the anomaly.

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1. Introduction

The fundamental nature and composition of Dark Matter (DM), its cosmological origin and how it interacts are fundamental open questions for nowadays particle physicists. The main difficulty so far is that the only established way to probe DM is through its gravitational interaction. An exciting possibility is that, in addition to gravity, a new force between the dark sector and the visible matter might exist. This very weak interaction can be transmitted by a vector mediator interacting with ordinary leptons such as electrons. These mediators, with masses below the GeV, can then decay into dark matter or back into standard model particles (see [1] for a review on this topic). An additional motivation for these searches is the 7σ excess observed in the angular distribution of e^+e^- events resulting from the nuclear de-excitation of ^{8}Be reported by the ATOMKI collaboration [2]. Recently, new results on other nuclei, ^{4}He, have confirmed a similar excess [3]. This anomaly could be explained by the existence of a new protophobic gauge boson X_{17} with a mass around 17 MeV and a coupling strength with electrons $2\times10^{-4} \lesssim \epsilon \lesssim 1.4\times10^{-3}$ $\left(10^{-14} \lesssim \tau_{X17} \lesssim 10^{-12}\text{s}\right)$ [4]. However, according to [5] this hypothesis would imply that X_{17} should be additionally produced in the Be nucleus transitions producing a signal that has not been observed by the experiment.

The NA64 collaboration aims to cover the full parameter strength allowed region in a model independent way for the scalar, pseudoscalar, vector and axial cases [6]. In this work we focus in the protophobic hypothesis. In NA64, X_{17} can be produced through Bremsstrahlung after SPS CERN secondary e^- from the H4 beamline collide with a target nuclei in the reaction:

$$e^- + Z \to e^- + Z + X_{17};\ X_{17} \to e^+e^- \tag{1}$$

Considering that the particle is penetrating and the lifetime is long enough it will decay immediately after the target into an e^+e^- pair. NA64 collaboration carried out these searches for the first time in 2017 excluding the region: $1.3\times10^{-4} \lesssim \epsilon \lesssim 4.2\times10^{-4}$[7]. The setup was improved in 2018 to cover the remaining region for short-lived X_{17}. The most important changes were the use of a shorter target and the increase of the beam energy from 100 to 150 GeV to boost the X_{17} decays outside it. In this work, the results for the combined 2017-2018 data analysis, corresponding to 8.4×10^{10} electrons on target (EOT), will be discussed (further details can be found in [8]).

2. Method of the search

A 150 GeV electron beam impinges an active target, a Tungsten-scintillator sandwich electromagnetic calorimeter (WCAL). The X_{17} produced in the e^- scattering off a target nuclei, escapes the dump and subsequently decays into an e^-e^+ pair measured in a second shashlick-type lead-plastic scintillator electromagnetic calorimeter (ECAL) downstream. The signature would be an event with one electromagnetic shower in the WCAL and the second one in the ECAL with the sum of their energies compatible with the initial beam energy.

The experimental setup used in the 2018 run is illustrated in Fig.1. The incoming e^- is measured by two scintillator counters $S_{1,2}$, a spectrometer consisting in two bending magnets and a set of Micromegas detectors which measure the particle momentum. Additional suppression in the initial hadron beam contamination is achieved using the synchrotron radiation detector located before the target. Two larger area tracker detectors, straw tubes (ST), are placed immediately after the vacuum

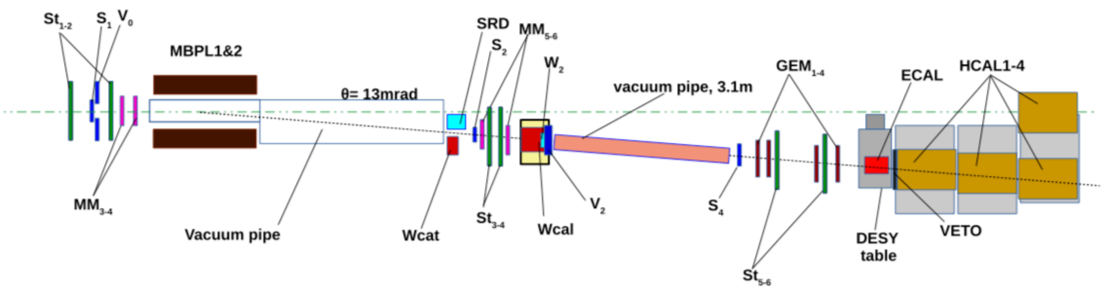

Figure 1: Experimental setup for the 2018 NA64 visible run [8].

pipe to reject large scattering beam particles from charged hadronic interactions. The active dump (WCAL) is compact, $30X_0$, to enhance the probability that X_{17} decays outside the dump. A thinner veto (W_2) was installed to minimise the probability that X_{17} decays within WCAL. To be accepted as a candidate event, the particle needs to be neutral and pass a second veto (V_2) without interactions. Then, decays in flight into e^-e^+ pair in the decay volume. An additional vacuum pipe was installed after WCAL during the 2018 run. The products of the decay are measured in a scintillator counter (S_4) located after the vacuum window, in a set of Micromega and GEM trackers located right after, and finally in the ECAL downstream. An iron-scintillator hadronic calorimeter (HCAL) consisting in three 7.5λ modules, a high efficiency veto and an HCAL module placed on axis are located at the end of the setup to suppress additional hadron contamination or energy leak. Finally, the trigger was defined requiring in-time energy deposition in the scintillator counters ($S_1 - S_3$), no energy deposition in V_0, and $E_{WCAL} \leqslant 0.7E_{beam}$.

The candidate events were selected using a Geant4 [9] based simulation chosen the criteria to maximize the signal acceptance and minimize the background. The Monte Carlo selection was cross-checked and validated with a sample of $\sim 10^5$ events from the rare QED $\mu^+\mu^-$ pair production in the target (see further details in [7] and [8]). The selection requires: 1) Energy deposited in the first five layers of the WCAL to guarantee the electron entering. 2) Sum of WCAL and ECAL energies compatible to the beam energy. 3) Minimum energy deposition in the first ECAL layers to guarantee the presence of e^+e^- pair. 4) ECAL maximum energy deposition in the central cell, minimum energy deposition of 25 GeV and compatibility with the longitudinal and lateral shape of the shower to the electron one. 5) The energy deposited in W_2 should be larger than the one of a minimum ionizing particle (MIP). 6) Charged particles measured in the decay volume requiring two MIP energy in S_4. 7) No signal on VETO (<1 MIP) and HCALs (<1 GeV in each module) to avoid hadron large scattering.

The main source of background in this search comes from $K^0_S \to \pi_0\pi_0$ events produced in the WCAL. The photons from the π_0 decay downstream the WCAL could convert into e^+e^- pairs which can deposit energy on S_4 and mimic the signal. This background has been studied using both simulations and data. To select the sample of neutral events from data, the cut on S_4 has been reversed. Fig.2 shows the sample of the resulting events from both 2017 and 2018 runs as a function of the ECAL-WCAL energy. The signal region is indicated by the shadowed areas. No events have been found in 2018 and three events fall into the 2017 region. From this the ratio between signal-like to neutral events has been calculated for the total statistics accumulated: 0.06 events for the 2017 data and 0.005 for the 2018. The number of events in 2018 is smaller because of

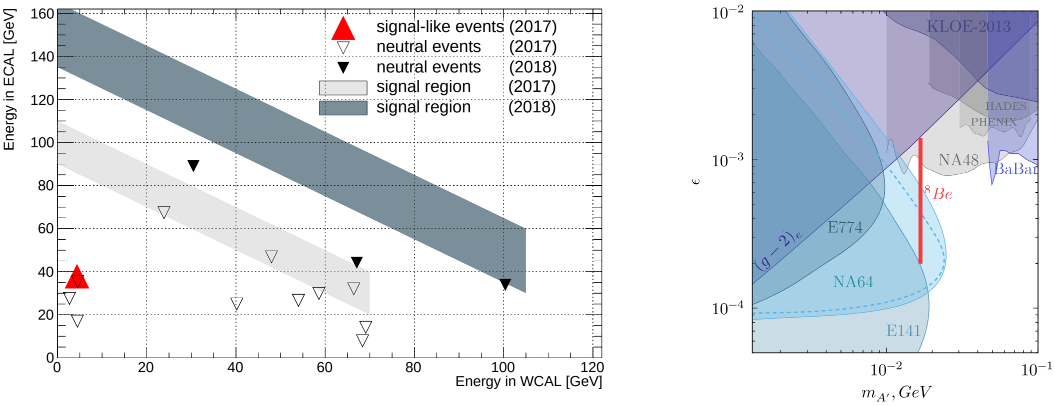

Figure 2: *Left:* ECAL vs WCAL energy distribution of signal regions in 2018 run in dark grey and 2017 in light grey. The triangles represent the neutral events measured in both runs (filled triangles for 2018 and empty triangles for 2017). The red triangle correspond to the single signal-like event recorded in 2017 run which did not fall into the signal region. *Right:* Region of the coupling and mass parameter space excluded at 90% C.L. The vertical red band represents the region where the X_{17} anomaly can be explained. The dash line corresponds to NA64 results using only 2017 data and the continuous one to the results from the 2017-2018 combined analysis. Constrains from other experiments and bounds from the electron anomalous magnetic moment, $(g-2)_e$ [16] are also shown for comparison: E774 [10], E141 [11], BABAR [12], KLOE [13], HADES [14], PHENIX [15], NA48[17] (see [8] for further details)

the vacuum pipe installed before S_4 and the increased distance between WCAL and ECAL (further details can be found in [7] and [8]).

3. Results and future prospects

After applying the selection criteria, no signal-like events were found inside the signal box. Using the modified frequentist approach we have obtained the region of the mass, $m_{A'}$, and coupling, ϵ parameter space excluded at 90% confidence level (CL). NA64 results are shown in the right panel of Fig.2 where other experimental results are also shown for comparison (further details on the derivation of the exclusion limits can be found in [7] and [8]). The red band represents the region compatible with the X_{17} anomaly. The NA64 exclusion limit obtained from the combined analysis is given by the blue shadowed region. Notice that without the setup optimisation the limits on ϵ would have improved just logarithmically with the accumulated statistics.

As can be observed in Fig.2 a large fraction of the parameter space able to explain the anomaly is excluded by NA64. To cover the remaining region and also to probe the scalar, pseudoscalar, and axial-vector cases we plan to upgrade the setup in 2021. In order to reach the short lifetime region we will use a compact active target. Moreover, in case of observing signal-like events we need to probe the X_{17} hypothesis unequivocally. For this purpose the setup will be optimised to allow the X_{17} invariant mass reconstruction with a precision of 2%. A magnet will be included in the decay volume to separate the lepton pair. Finally, a set of trackers and the electromagnetic calorimeter downstream will allow to measure the angle between the e^+e^- pair (see [18] for further details).

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