Investigation of a light Dark Boson existence : The New JEDI project

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Abstract. Several experiments around the world are looking for a new particle, named Dark Boson, which may do the link between the Ordinary Matter (which forms basically stars, planets, interstellar gas...) and the Hidden Sectors of the Universe. This particle, if it exists, would act as the messenger of a new fundamental interaction of nature. In this paper, the underlying Dark Sectors theory will be introduced first. A non-exhaustive summary of experimental studies carried out to date and foreseen in the incoming years will be presented after, including the ^{8}Be anomaly. The last section will provide a status of the New

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JEDI[****] project which aims to investigate the existence or not of a Dark Boson in the MeV range.

1 The Dark Sectors theory as a new alternative scenario to the standard direct Dark Matter detection approach

Understanding the composition and functioning of our Universe are among the most fundamental and challenging questions in Physics. Despite its apparent complexity, ordinary matter (OM) is in reality composed of just a few elementary particles (quarks and leptons). These particles, together with the force carrying and the Higgs Bosons constitute the main components of the Standard Model of Particle Physics [1]. This theory is able to describe 5% of the Universe (made of OM). 26% of the Universe is made of Dark Matter that does not emit light and whose existence has been inferred as necessary to explain, e.g., the star's rotational velocity within galaxies or the gravitational lensing effects observed in space. The remaining 69% of the Universe is made of Dark Energy, distributed uniformly, acting as a repulsive force counterbalancing gravity. The existence of Dark Energy could explain the accelerated expansion of the Universe. The relative composition of the Universe was deduced from the Cosmic Microwave Background anisotropy [2], in accordance with the prediction of Jim Peebles, awarded the 2019 Nobel Prize in Physics [3]. This is our current and conventionally accepted description of the structure of the Universe. To date, the real composition of the classical Dark Sectors remains a mystery. We still do not have a clear answer to the question "of what is Dark Matter composed?". There are some indications, several candidates, but, despite all the efforts over the last three decades all around the world [4], none of the dedicated experiments has proved the existence of dark particles. To date, the intrinsic nature of dark matter remains a mystery.
To address this issue, several models have been developed and in recent years particular attention is paid to studies of so-called Dark / Hidden Sectors, introduced in refs. [5][6][7][8] but poorly tested [9]. It is based on the idea that we may also consider an indirect interaction between Ordinary Matter and Dark Sectors of the Universe. In this framework, Dark Sectors can be defined as hypothetical sets of relatively light particles with interaction orders of magnitude lower than the electromagnetic interactions. These Dark Sectors may or not include Dark Matter particles. We will keep this definition of Dark Sectors in the following text. From a theoretical point of view, Dark Sectors are composed of one or more particles, that couple to the Visible Sector - Ordinary Matter well described by the Standard Model - through portals, as described in Fig. 1. A Dark Boson will act as the messenger of this interaction. It is the Dark Force carrier. This leads to the fundamental question of the existence of a fifth force of nature (in addition to the gravitational, electromagnetic, strong and weak forces). Different portals could be possible, depending on the quantum nature of the Dark Boson (spin and parity). Nuclear Physics experiments allow the study of scalar, pseudo-scalar, vector and pseudo-vector hypothesis.
Non-trivial dynamics in the hidden sectors model can lead to novel phenomenology, whose thorough characterization has only begun (see next section).

2 Dark Sectors experimental studies : state-of-art and ^{8}Be anomaly

Currently, there is much activity in both North America and Europe, evaluating various proposals attempting to see how different experiments can better probe Dark Sectors [9][10]. In

[****]acronym of New Judicious Experiments for Dark sectors Investigations

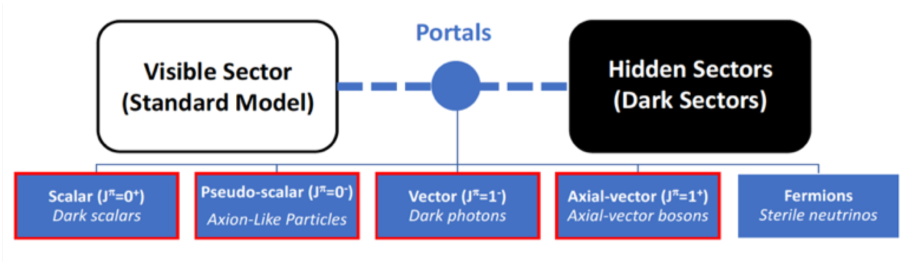

Figure 1. Illustration of the Standard Model coupling to Dark Sectors through given portals. Portals that might be studied though nuclear physics experiments are indicated with a red frame.

the US, experiments at Jefferson lab, SLAC and Fermilab facilities have been discussed. In 2016, CERN launched the "Physics Beyond Colliders" study group to assess the possibility of using the CERN facility for physics not necessarily related to the LHC. One of the physics goals of these exercises is to look at the sensitivity of various proposals for the study of Dark Sectors.

From this prospective works, one may see that, up to now, many experiments using different techniques have just provided exclusion zones, ruling out certain masses and interaction strengths of the possible Dark Boson. An example is given in Fig. 2 of [11] concerning the Dark Photon (vector) portal hypothesis (see Fig. 1). Until now, the scientific community that conducts experimental studies on Dark Sectors is mainly the High Energy Physics one. However, during the last years, there is a Nuclear Physics experiment that has caught the scientific community's attention, performed by a Hungarian research team [12]. Our investigation is further motivated by the recent claim that the anomaly they observed in the electron-positron pair decays of excited states in ^{8}Be can be interpreted as the signature of a hypothetical Dark Boson : a bump appears when looking at the e+ e- angular correlation spectrum. It has been interpreted as the possible signature of a Dark Boson decay, which was named X17. This experiment provides the main constraint on the Dark Boson mass : m_X=16.70 ± 0.35(stat) ± 0.5(syst) MeV/c^2. From this experiment, the following branching ratios were also extracted: proton decay, γ-decay, internal pair creation and ejection of a new (X17) particle. Has a Dark Boson finally been observed? It is not very clear yet. First, the given result is not compatible with the conclusions from the NA48 complementary experiment performed at CERN [13]. Compatibility might be enforced if some extreme hypothesis are considered, such as a protophobic dark photon [11]. But, the ATOMKI group has also later studied the signature of a Dark Boson in ^{4}He and ^{12}C, claiming the existence of a similar anomaly [14][15][16]. However, the synthesis made by J.L. Feng *et al.* [17] underlines (see Tab. III of the article) very well that it is difficult to build up a coherent conclusion concerning the quantum nature of the X17 particle based on all the ATOMKI experimental results. A possible explanation could be a X17 production mechanism rather proceeding through a direct capture process than through any nuclear resonance, as suggested by ref. [18]. Therefore, an independent measurement is needed.

There are lots of experimental programs that started recently to study the X17 anomaly. Even if they look like providing very promising sensitive probes, one may see that experiments conventionally used for high energy physics such as LHCb need major updates and could provide a first experimental run very later on (final detector expected 2025) [19]. NA64 managed to realize an additional experimental run in 2018. The results obtained did not allowed to conclude about the X17 anomaly but allow to improve the sensitivities of their previous measurement [20] and will need an upgrade of the setup to go further on this topic [21]. PADME, as for it, could search for this dark photon with a few proper experimental set-up changes [22]. In parallel, new emerging Nuclear Physics experimental programs, including New JEDI, are under development or reached the commissioning phase, even some have carried out already a first experiment [23][24][25][26][27]. The diversity of the detection technologies and reaction mechanisms envisaged for all these experimental programs should provide, in the near future, an unambiguous clarification on the existence or not of the hypothetical X17 particle. This joined effort of the Nuclear Physics community should allow to investigate, in a general manner, the existence of any Dark Boson in the MeV *terra incognita*. In the next section, we will provide details concerning the New JEDI project, on the way to realize its first long experimental run on ^{8}Be at the ANDROMEDE facility [28].

3 The New JEDI project : presentation and status

The New JEDI project aims to provide, in a general manner, quick and reliable tests of the existence of a light Dark Boson (MeV range) that couples the Standard Model to Dark Sectors. Fig. 2 shows the mechanical scheme (at the center) of the New JEDI setup first version and pictures of its components (chamber, detectors, target holder and units). This version has been used during the commissioning that took place in June 2020 at the tandetron facility located at Řež, in Czech Republic [29]. It was developed based on test experiments conducted at the ARAMIS facility (Orsay, France) [30] and Geant 3 simulations, carried out since 2017.

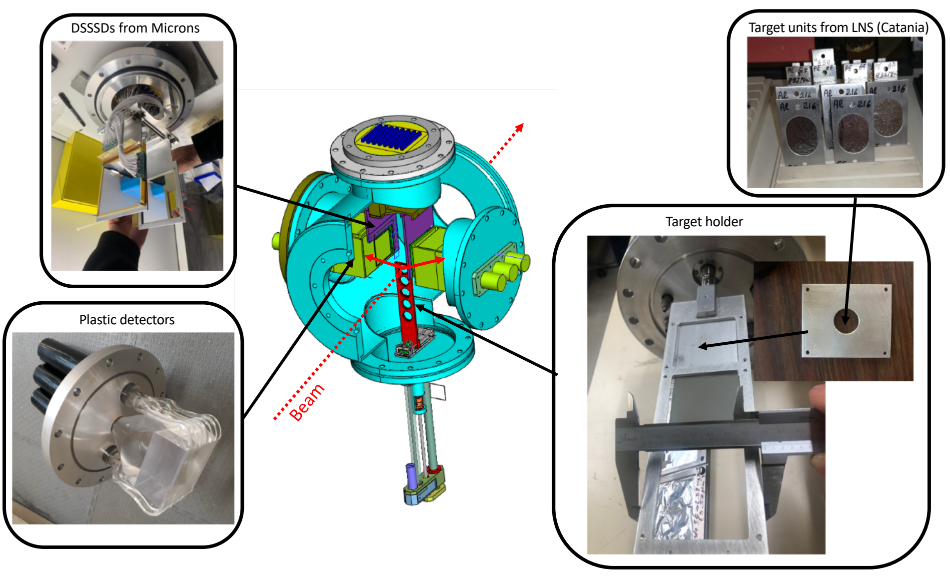

Figure 2. Mechanical scheme (at the center) of the New JEDI setup (first version) and pictures of its components (chamber, detectors, target holder and units).

The set of Double-Sided Silicon Strips Detectors (DSSSDs) of the New JEDI setup provides energy losses and angles of the detected electrons and positrons. In addition, the sets of plastic detectors is used to measure the residual energy of electrons and positrons. They are also

used to veto external background events. The detection system is coupled to the new generation NUMEXO2 digitizers [31]. A specific charge integration firmware and a coincidence cross-check mode have been developed for the project. It is worth noting that the New JEDI detection system appears to be close to the new version developed in parallel by the ATOMKI group. The geometry chosen here is more focused on the detection of X17-like events.
For the commissioning, we used mainly a proton beam of 470 keV (also 1070 keV) impinging onto a LiF target of typically 150 μgr/cm^2 thickness, having a carbon backing with a thickness of 30 μgr/cm^2. The conclusions from the commissioning are the following: there is a major contribution of the ^{19}F(p,α)^{15}O reaction in the DSSSDs that needs to be stopped using a thick (aluminized mylar) foil in front of the detector. The Lithium target emits also a lot of electrons that can be stopped in this front foil providing it is a conductive one, to avoid charge and discharge effects. Surprisingly, there is also a need to protect the back of the DSSSDs as well which see also electrons (from back-scatterings with plastic detectors...). We observed multi-scattering processes that need to be investigated more in details in the next experiment. From simulations, we identified that the electron-electron and electron-nucleon interactions play an important role (same behavior for positrons). The methods developed to measure and to check the proper coincidences between the different detectors seem to work properly. Moreover, we studied the behaviour of CaF and PTFE targets developed by the INFN-LNS laboratory, part of the New JEDI collaboration. They can be useful to disentangle the contribution of reaction from F in the spectra. They showed very promising characteristics online. We realized that we need to refine the optimal target thicknesses to get benefit of the full beam intensity expected from the simulations. In this configuration, a reasonable efficiency of 10% is estimated for the X boson electron-positron pair decay, if it exists. We also observed interesting geometrical effects (e.g. shadow effects in the DSSSDs and from the target ladder). All this will be investigated and optimized for the first experimental run foreseen at the ANDROMEDE facility.
We plan to develop a long-term research program in the MeV *terra incognita* energy range at the new SPIRAL2 facility (Caen, France) [32], that will deliver unique high-intensity beams of light, heavy-ions and neutrons in Europe. In practice, three experiments using the New JEDI setup concerning the existence or not of the X17 Dark Boson are envisaged between 2022 and 2025: two at the ANDROMEDE facility and one at SPIRAL2 looking for the signature in ^{8}Be and ^{3}He quantum systems, respectively. To start off, we plan for example to populate "excited" non-resonant state in ^{3}He around 18 MeV using the high-power pulsed proton beam of the LINAC impinging onto a thin CD2 target. In addition, one crucial experiment (not using the New JEDI detector) focused on ^{8}Be spectroscopic decay study is foreseen at iThemba LABS using the unique coupling of low-energy beam from the tandetron accelerator and the half-AFRODITE multi-detectors array (FASERED project). The aim is to investigate deeply if the X17 signal can be an artefact linked to an experimental error or a subtle nuclear physics effect in ^{8}Be, which has a complex nuclear structure.

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