Journal of Physics: Conference Series **2156** (2022) 012051 doi:10.1088/1742-6596/2156/1/012051

The dark-PMT: a novel directional light Dark Matter detector based on vertically-aligned carbon nanotubes

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Abstract. We present the 'dark-PMT', a novel detector concept based around a target made of vertically-aligned carbon nanotubes. The detector is sensitive to electron recoils induced by sub-GeV dark matter, and is expected to have directional sensitivity and to be unaffected by thermal noise, even at room temperature. The key feature is that nanotubes are made of graphene, which is a two-dimensional material: therefore, if a dark matter particle transfers enough energy to an electron in the carbon lattice to overcome the work function (4.7 eV), the electron will be ejected directly into the vacuum. Because of the strong density anisotropy of nanotubes, the electrons will be capable of leaving the target, without being reabsorbed, if travelling in the direction of the tube axes. The electrons will then be accelerated, and reach an energy of 5 keV before hitting an electron sensor. We report on the most recent advancements towards the construction of a dark-PMT: a novel, state-of-the-art facility for nanotube synthesis has been recently installed in Rome, and it is being used to produce high-quality nanotubes; and detailed characterizations of silicon sensors with keV electrons have been performed.

1. Introduction

In most cosmological models about 85% of the mass of the Universe is thought to be made of non-baryonic dark matter (DM). In galaxies, DM forms a halo, centered in the galactic center and extending farther than ordinary, visible matter. In the past decades, a large number of experiments have been conducted on Earth to detect the interaction between the DM in the halo and targets of ordinary matter. A summary of the results of these searches is shown in Figure 1 (left), where the 90% confidence-level (CL) upper limits on the cross section of the interaction between DM and ordinary matter is graphed as a function of the mass of the hypothetical DM particle m_χ. The most sensitive limits (such as those from the XENON1T [1], PandaX-II [2] and LUX [3] collaborations) are the results of searches based on nuclear ionization signals produced in ton-mass tanks of liquid xenon. As can be seen, these limits quickly lose sensitivity for DM masses below 10 GeV.

However, several cosmological models (such as SIMPs [4]) predict DM to have sub-GeV mass. To extend ensitivity to this mass range, searches for nuclear recoils need to be abandoned as the target mass is too large to produce a visible recoil. Electron recoils, thanks to the light

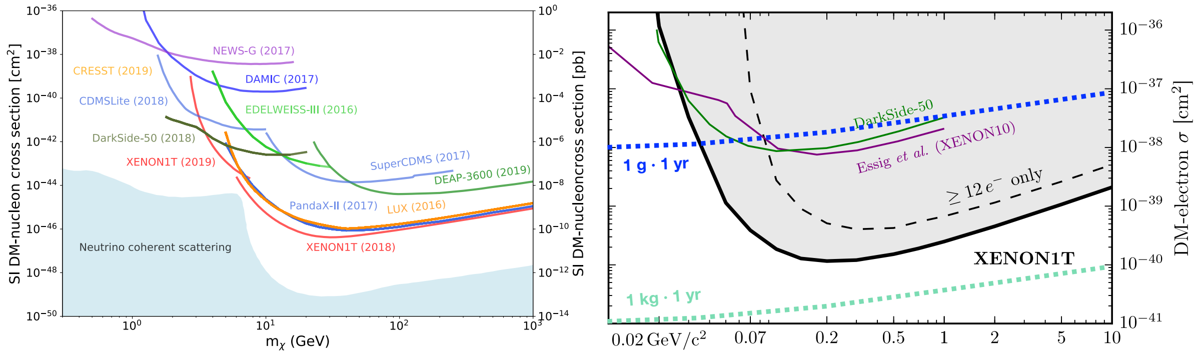

Figure 1. Summary of the 90% CL upper limits on DM-nucleon (left, taken from [5]) and DM-electron (right, adapted from [6]) cross sections, as a function of the DM particle mass m_χ.

mass of the electron, prove to be adeguate. A summary of the current best limits on the DM-electron cross section coming from electron recoil experiments is shown in Figure 1 (right). When comparing these limits to the nuclear recoil ones, it should be noticed that they are up to 10^6 times weaker: this means that to be competitive in this mass range it isn't necessary to build ton-mass targets, as gram targets could already prove to be competitive. Another feature to notice about these limits is that most experiments lose sensitivity below ≈ 100 MeV: this is because minimal thresholds are necessary in order to reconstruct the energy deposits created by electron recoil signals in the target.

2. The dark-PMT

We present a novel sub-GeV DM detector concept, the 'dark-PMT', which is built around a target made of vertically-aligned carbon nanotubes (VA-CNTs). VA-CNTs can be thought of as graphene sheets wrappen in the form of straws with a diameter of a few nanometers. The advantage of a VA-CNT target is that graphene is a 2-dimensional material: therefore if enough energy is transferred to the electrons in the carbon lattice, they are ejected directly into the vacuum. Because of the motion of the Solar system orbiting around the galactic center, the DM halo on Earth would produce a 'wind' of DM particles, traveling at non-relativistic speed ($v \approx 10^{-3}c$) originating from the direction of the Cygnus constellation: therefore, DM particles with mass between 1 and 100 MeV would have a kinetic energy in the $5-50$ eV range, which is sufficient to overcome the work function of carbon in its graphitic form (4.7 eV).

A striking feature of VA-CNTs is that they have vanishing density in the direction of the tube axes. This can be seen in Figure 2 (left), where the results of Raman analysis performed on VA-CNTs is shown [7]. These VA-CNTs have been subjected to bombardment with Ar^+ ions, in two different configurations: lateral bombardment (*i.e.* in the direction orthogonal to the tube axes), and longitudinal bombardment (*i.e.* parallel to the tube axes). As can be see in the Raman spectra in the middle of the figure (which are taken at different depths), in the case of lateral bombardment the pristine carbon spectrum is recovered already at a depth of 15 μm, meaning that the Ar^+ ions have penetrated less than that. In the case of longitudinal bombardment, on the other hand, damage is observed along the whole length of the tubes (180 μm in this case), indicating that the Ar^+ ions have penetrated the whole target.

This strong density anisotropy makes VA-CNTs an almost ideal target for DM-electron scattering: the electrons which are ejected from the lattice, in fact, are capable of exiting the target, without being re-absorbed, if they travel in the direction of the tubes. This grants the detector directional sensitivity, *i.e.* the capability of linking a signal with a specific region of the

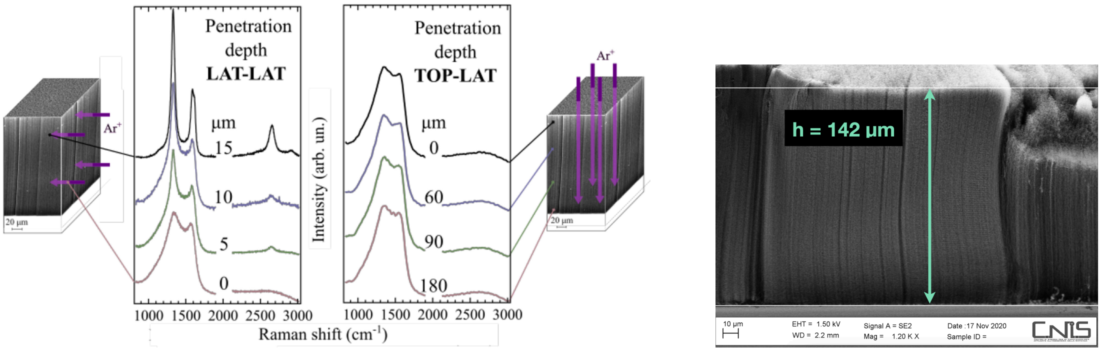

Figure 2. Left: results of Raman spectroscopy on VA-CNTs after lateral (left) and longitudinal (right) Ar^+ bombardment [7]. Right: SEM image of VA-CNTs synthesized in Rome.

sky. In fact, the ejected electrons will, on average, have a momentum parallel to that of the DM 'wind'. Therefore a dark-PMT would be sensitive to the DM wind only when it points towards the Cygnus constellation.

VA-CNTs can be efficiently grown in the laboratory through Chemical Vapor Deposition (CVD). A state-of-the-art CVD facility has been installed in Rome thanks to ATTRACT funding. The facility was commissioned in July 2020, and has been since growing VA-CNTs on differents substrates. An example growth can be seen in the SEM image in Figure 2 (right), where VA-CNTs with a length of 142 μm have been successfully grown on a fused silica substrate.

A sketch of the dark-PMT design concept is shown in Figure 3: the incoming DM particles scatter off electrons in the VA-CNT cathode, and the ejected electrons, once they leave the target, are accelerated by an external electric field and reach an energy of a few keV before hitting the anode, where an electron sensor is present. The dark-PMT is expected to have very attractive features: (i) it's portable, cheap and easy to produce; (ii) it is unaffected by thermal noise, even at room temperature, thanks to the high work function of carbon (4.7 eV); (iii) it has directional sensitivity. Dark-PMTs could be used in a search for sub-GeV DM by forming two arrays placed on a moving platform: one array would point in the direction of Cygnus, and would be sensitive to a DM signal; the other array would point in an orthogonal direction and would be used as an *in situ* measurement of the backgrounds. Figure 4 (left, taken from [8]) showns the expected rate of ejected electrons for the signal array (black) and the background array (red): as can be seen electrons with a kinetic energy as low as a few eV are expected to be capable of exiting the target: sensitivity to such low-energy recoils is a direct consequence of the fact that graphene is a two-dimensional material. The dotted lines in Figure 1 (right) show the expected sensitivity of a search based on dark-PMTs, corresponding to an exposure

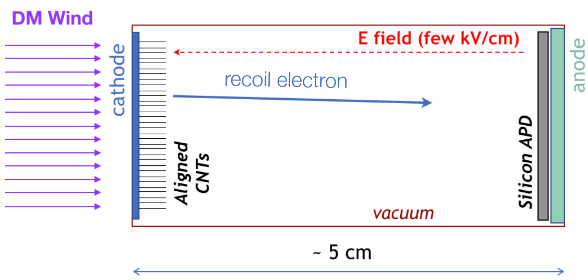

Figure 3. The dark-PMT design concept.

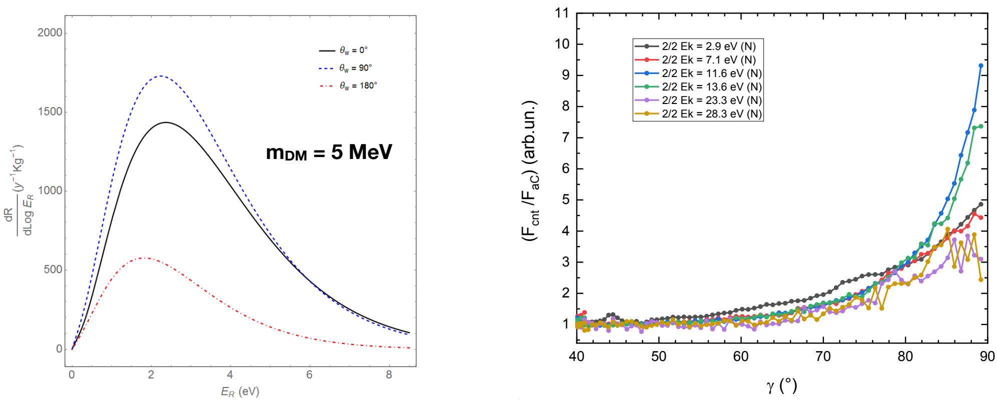

Figure 4. Left: expected rate of ejected electrons, as a function of their kinetic energy, for the case of a DM wind of particles with a mass of 5 MeV. The rate of electrons ejected in the array parallel to the wind (black) is compared to that of the array pointing in the opposite direction (red) [8]. Right: photoelectron flux emitted by a VA-CNTs, normalized to the flux of amorphous carbon, as a function of the angle γ between the incoming UV photons and the perpendicular to the target surface, for different photoelectron kinetic energies E_k.

of 1g $\times$ year (in blue) and 10g $\times$ year (in cyan). As can be seen such a search is expected to significantly extend the reach below 40 MeV.

Both sides of the dark-PMT need to be optimized: the VA-CNT cathode and the electron sensor at the anode. Detailed characterizations of VA-CNTs are being conducted at LASEC laboratories at Roma Tre University, where a large ultra-high vacuum (UHV) chamber capable of performing angular UV photoelectron spectroscopy (UPS), the results of which are shown in Figure 4, where the ratio between the photoelectron flux emitted by a VA-CNT target and the one emitted by a sample of amorphous carbon (aC) is studied as a function of the angle γ between the incoming UV radiation and the normal to the sample. As can be seen, for all of the analyzed photoelectron energies (different colors), there seems to be a significant increase (up to a factor 10) of the VA-CNT flux, compared to aC, as one approaches the grazing angle ($\gamma = 90°$). This is further proof of the anisotropy of VA-CNTs.

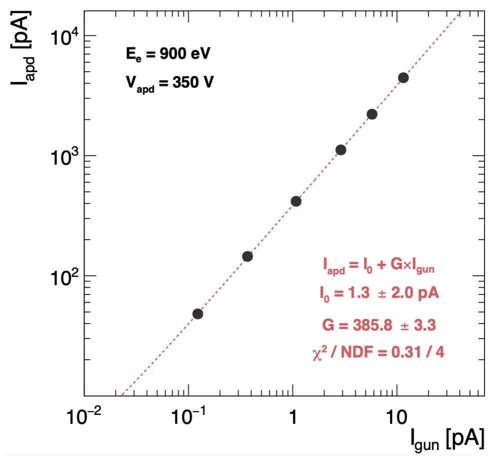

Figure 5. APD current as a function of electron gun current, for 900 eV electrons, while operating the APD at $V_{APD} = 350$ V.

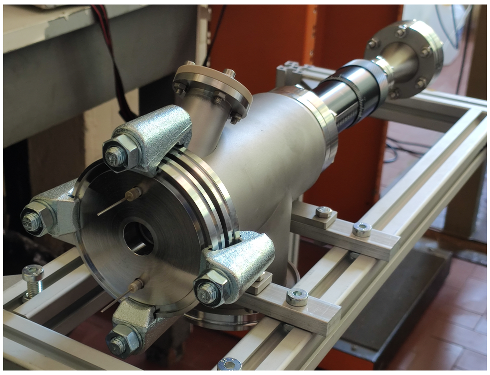

Figure 6. The dark-PMT prototype.

The characterization of the electron sensor was also performed at LASEC labs, by using the monochromatic electron beam produced by the custom electron gun present in the same UHV chamber. The gun is capable of producing beams with energy between a few eV and 1 keV, with energy dispersion below 50 meV, sub-mm beam profile and current as low as a few fA. The electron sensor we are currently considering for use in the dark-PMT is a windowless APD produced by Hamamatsu, which has a circular active area with diameter of 3 mm. Figure 5 shows the measuread APD current I_{apd} as a function of the gun current I_{gun}, when directing a beam of 900 eV electrons on the APD active area [9]. As can be seen, a clear linear correlation can be observed, and similar results are found at 90 and 300 eV. This constitutes the first time a silicon APD is shown to be sensitive to electrons of such low energy. Finally, Figure 6 shows a picture of the first dark-PMT prototype, built on the design concept shown in Figure 3, which is currently being tested in Rome.

3. Conclusions

Vertically-aligned carbon nanotubes offer exciting new possibilities in the search for light dark matter. We have presented here a design concept for a novel detector, the dark-PMT, sensitive to sub-GeV DM, built around a target made of VA-CNTs. The detector is expected to have directional sensitivity and to be unaffected by thermal noise. Considerable R&D is being performed in Rome, aimed towards the construction of such a device.

4. Acknowledgements

Some of this work has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

5. References

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