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Searching for Light Dark Matter with Aligned Carbon Nanotubes: the ANDROMeDa Project

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Abstract. The ANDROMeDa (Aligned Nanotube Detector for Research On MeV Dark matter) project aims to develop a novel Dark Matter detector based on carbon nanotubes: the "Dark-PMT". The detector is designed to be sensitive to dark matter particles with mass between 1 MeV and 1 GeV. The detection scheme is based on dark matter-electron scattering inside a target made of vertically-aligned carbon nanotubes. Vertically-aligned carbon nanotubes have reduced density in the direction of the tube axis, therefore the scattered electrons are expected to leave the target without being re-absorbed only if their momentum has a small enough angle with that direction, which is what happens when the tubes are parallel to the dark matter wind. This grants directional sensitivity to the detector, a unique feature in this dark matter mass range.

1 Introduction

During the last decades several experiments have searched for dark matter (DM), typically for DM with mass $M_\chi > 10$ GeV [1]. In those experiments a high mass target has been used in order to have sensitivity for high mass DM particles. In fact, the detection scheme is based on measuring the interaction between the DM particle and the nucleus of the atom target. In a light DM scenario, instead, we have low sensitivity with current experiments because the momentum transferred to the nucleus from the DM-nucleus scattering is too small to be detected. In the low mass region the DM wind is expected to have kinetic energy T_χ in the range of $5 < T_\chi < 50$ eV for $10 < M_\chi < 100$ MeV, we also expect that DM particles come from the direction of the Cygnus constellation [2]. The ANDROMeDa project aims to measure DM in the low mass region by exploiting the important property of directionality of direct DM detection, this is done by using vertically-aligned Carbon NanoTubes (CNT) as target for DM-electron scattering. To do such measurement the project aims to develop a new detector: the "Dark-PMT".

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2 Carbon Nanotube

CNT can be described as graphene layer wrapped around an orientation axis with the property to be a 2D material with 1D properties and vanishing density along the axis. By exploiting this property the ANDROMeDa project aims to detect directly light DM, in fact the DM wind has a kinetic energy greater than the carbon work function ($\phi \simeq 4.7$ eV) and so it is possible to extract a recoil electron from the CNT lattice. As this is a non-relativistic scattering, the direction of the recoil electron will be, on average, parallel to the incoming DM wind. Vertically-aligned CNTs have vanishing density in the direction of the tubes and so the recoil electron is capable of exiting the target, without being re-absorbed, only if the tubes are aligned in the direction of the DM wind. This is shown in Figure 1 where it is depicted the distribution of the rates of recoil electrons that escape from the target at different kinetic energy for different θ_w [3], as can be noted the distributions for $\theta_w = 0°$ and $\theta_w = 90°$ have different rates and so it is possible to distinguish them.

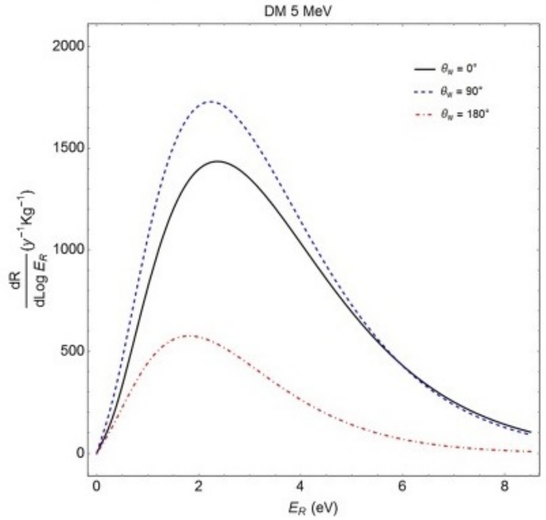

Figure 1. Electron energy recoil spectra (per year per kilogram target) for $M_\chi = 5$ MeV. Three relative orientations θ_w between the nanotube axes and the DM wind are shown: $\theta_w = 0°$ (in black, solid), $\theta_w = 90°$ (in blue, dashed) and $\theta_w = 180°$ (in red, dot-dashed) [3].

With this experimental idea it is important to produce well vertically aligned CNT, otherwise electron re-absorption can occur. CNT can be grown in forest of the surface of O(8 cm^2) with Chemical Vapor Deposition (CVD) technique in the facility that has been assembled and installed by INFN in 2020 in Rome la Sapienza, the CNT sample has a length of almost 260 μm as can be seen in Figure 2. During the growing process of the CNT sample two undesired effects can happen: the waviness modulation of the CNT and the formation of a crust layer at the top of the CNT forest. Considering the low kinetic energy of the recoil electron, the two effects described above increase the possibility of electron re-absorption. This concept of CNT target has been tested by measuring the degradation due to positive ions bombardment for transverse and longitudinal direction with respect to the CNT orientation axis [4]. The most important R&D activity of the ANDROMeDa project is to grow vertically aligned CNT samples minimizing both the undesired effects.

A possibility to minimize the waviness of the CNT sample is to optimize the growing process by increasing the seeds density with uniform seeds and to grow the CNT in an electric field, the crust layer, instead, can be removed by using a plasma etching [5].

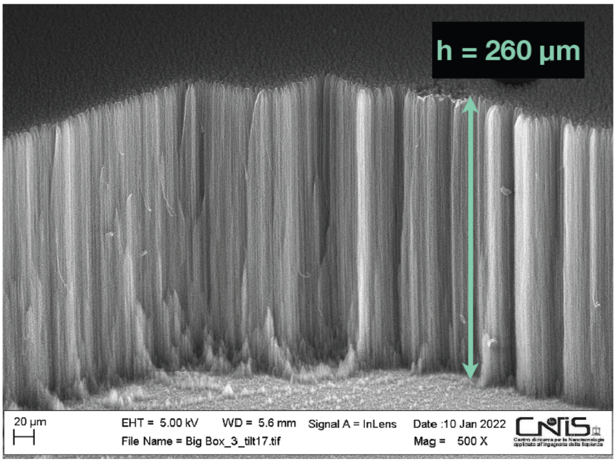

Figure 2. Typical growth of vertically aligned CNT forest, as imaged by Scanning Electron Microscopy.

3 ANDROMeDa Dark-PMT

The usage of CNT as target for light DM detection can be exploited by developing a "Dark-PMT" detector. The scheme of the Dark-PMT prototype is shown in Figure 3. When the DM wind interacts with the target produces a recoil electron, this electron escapes from the target if the DM wind is aligned with the CNT target. In this case the electron has a kinetic energy of almost 5 eV and it is then accelerated to 5 keV by using an electric field. The electron's energy is measured by using silicon avalanche photodiode (APD) that are adjusted for electron usage. APD has been characterized for electron detection by using a monoenergetic electron gun of energy $[90, 900]$ eV in the LASEC laboratory of Roma Tre university [6]. In the Dark-PMT setup it is important to being able to distinguish each single electron from the target, in this way it is possible to reject events from cosmic rays. In fact a cosmic ray event could generate various ionization electrons in the target while a DM event just one electron. The good point of this setup is that the device grant directional sensitivity, is cheap and easy to produce, has compact size and can be used at room temperature because it is not affected by thermal noise. This detector can be used for a future experiment by assembling various arrays of two Dark-PMTs, one towards the opposite direction of the other. By pointing the array towards Cygnus, it is possible to measure the rates of electrons that exit from the target as is shown in Figure 1 while the PMTs oriented in the opposite direction measure the background. Considering a CNT density of $\rho = 1$ mg/cm^2 with 10 cm^2 surface, with 100 Dark-PMTs ANDROMeDa aims to reach the expected sensitivity for 1 g× yr exposure that is shown in Figure 4. As can be noted with just 1 g target (red line) the experiment is competitive with XENON exclusion limits [7] for $M_\chi \sim 40$ MeV while with future upgrade with a target mass of 1 Kg (blue line) the exclusion limits are below for the entire mass range that is shown in Figure 4 .

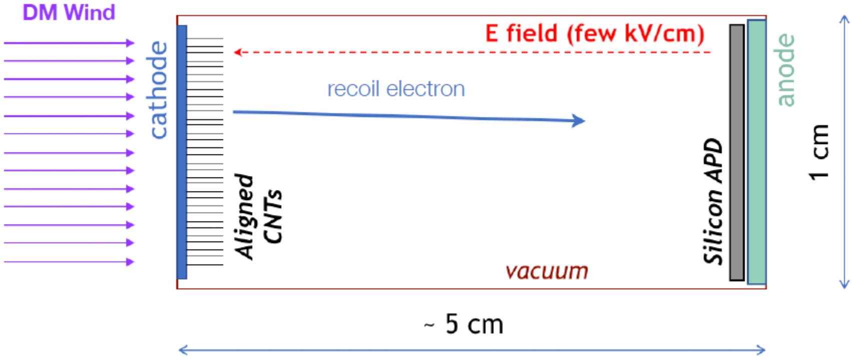

Figure 3. ANDROMeDa scheme of a "Dark-PMT". The DM wind interact with the CNT target and then the recoil electron is accelerated to 5 keV and is detected by using silicon APD.

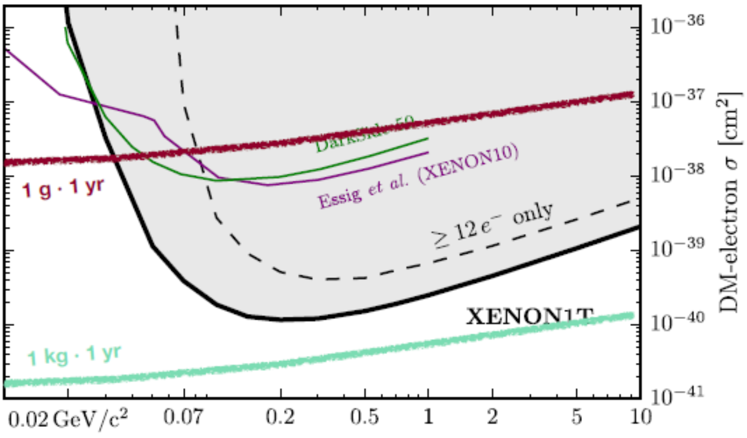

Figure 4. ANDROMeDa expected exclusion limits (red and blu lines). On the x axis is shown the DM mass while on the y axis is shown the DM-electron cross section. Figure adapted from [7].

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