Search for Light Dark Matter with Vertically-Aligned Carbon Nanotubes

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The vast majority of experiments which have searched for direct detection of DM particles are sensitive to particles with a mass larger than a few GeV, so this is the region where the most stringent experimental limits have been placed on the interaction cross section between DM particles and ordinary matter. The most stringent limits are set by underground noble liquid experiments ([1], [2], [3]) which operate with multi-ton targets. By contrast, the mass range below a few GeV is much less explored, with up to 10^{10} times weaker exclusion limits on the cross section. This means that a detector with only grams of target mass could be able to produce competitive results.

In the search for DM, an important detector characteristic is directionality, *ie* the capability to link a signal to a given direction in the sky. In fact, because of the motion of the Solar system in the galaxy, on Earth we are expected to experience a DM 'wind', coming approximately from the direction of the Cygnus constellation. Most backgrounds, on the other hand, either don't have a specific direction (*eg* environmental radioactivity) or originate from different parts of the sky (*eg* solar neutrinos).

We propose to develop a novel detector (a 'dark-PMT') to be employed in the search for DM with mass in the range between approximately 1 MeV and a few GeV ('light DM'). The detector concept is shown schematically in Figure 1 (left). The detector is designed to be sensitive to DM-electron interactions in the target, which is made of vertically-aligned carbon nanotubes.

Carbon nanotubes (CNTs) can be thought of as a single graphene sheet wrapped in the shape of a straw, with an internal diameter of a few nm. Vertically-aligned CNTs can be grown through Chemical Vapor Deposition (CVD) techniques [4].

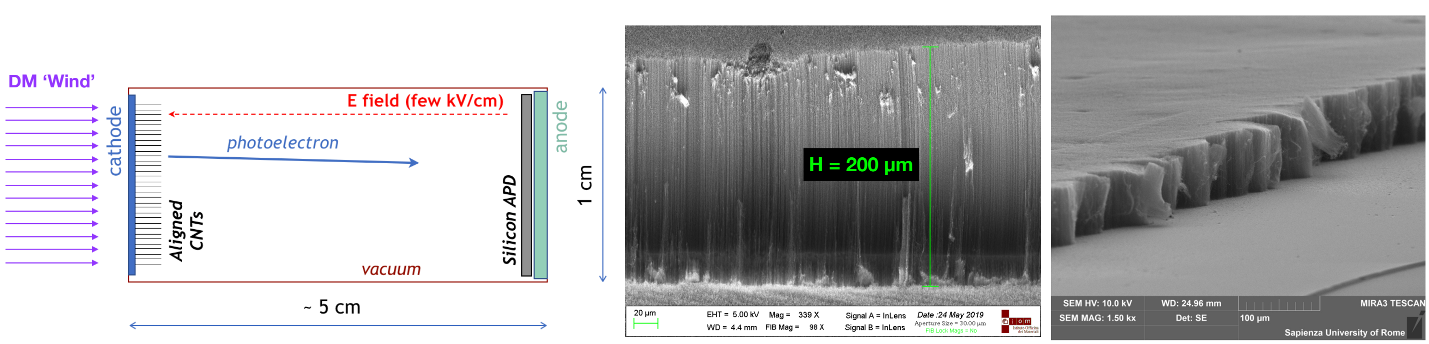

Figure 1: Left: Schematic view of the 'dark-PMT' detector concept. Center: vertically-aligned CNTs grown in 2019 with the CVD chamber present in Elettra (Trieste, Italy). Right: first synthesis of vertically-aligned CNTs achieved in August 2020 at University 'Sapienza' of Rome.

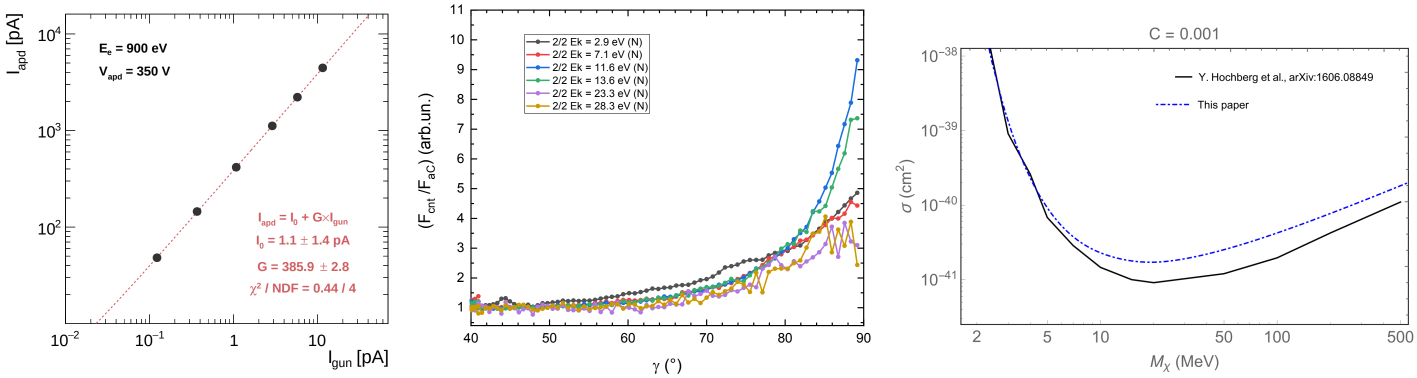

Figure 2: Left: APD current as a function of the electron gun current, for electrons with energy of 900 eV. Center: flux of emitted photo-electrons when illuminating CNTs with UV radiation, as a function of the angle of the incoming photons; the flux is normalized to the flux obtained on amorphous Carbon. Right: Expected sensitivity on the DM interaction cross section, assuming an exposure of 1 kg × 1 year.

Growth parameters, such as pressure, temperature, exposure time, substrate material, catalyst metal, precursor gas will determine the CNT length, density, and will determine if the CNTs are single-walled (each nanotube is formed by a single graphene layer) or multi-walled (each nanotube is formed by multiple graphene cylinders sharing the same axis). A scanning-electron microscope (SEM) image of a CVD growth of vertically aligned multi-walled CNTs is shown in Figure 1 (center). These CNTs were grown in 2019 in the Elettra (Trieste) CVD chamber, and are about 200 μm in length. Since July 2020, a new CVD chamber was installed in University of Rome 'Sapienza', capable of growing both multi-walled and single-walled CNTs. The first growths were carried out in August 2020, and produced vertically-aligned CNTs of 80 - 100 μm in length, as can be seen in the SEM image shown in Figure 1 (right).

The interaction of light DM particles in the CNT target would result in the ejection from the carbon lattice of an electron with a kinetic energy in the 1-10 eV range. Vertically-aligned CNTs have been shown [5, 6] to have close to vanishing density in the direction of the tube axis. Therefore, the ejected electrons will be able to exit the target if their momentum points in the direction of the CNT axes, which is what happens when the tubes are aligned with the DM wind. This detector would therefore have directionality by design [7, 8, 9], and being sensitive to electrons in the eV range would also be practically unaffected by limitations related to reconstruction thresholds.

Once the ejected electrons leave the target, they will be accelerated by an external electric field and reach a kinetic energy of a few keV before hitting a solid-state silicon detector placed on the other side of the detector. These detectors could be either Silicon Drift Detectors (SDD), Low-Gain Avalanche Detectors (LGAD), or even Avalanche Photo-Diodes (APD), depending on which trade-offs between energy resolution performance and cost-effectiveness will be deemed necessary. Recent results [10] have shown that SDD detectors can be employed to reconstruct keV electrons with excellent resolution, but also APDs have been employed with certain success in that same energy range [11].

Extensive characterization of the response of APDs to low-energy electrons has been carried out in 2020, in the LASEC laboratories of Roma Tre [12]. The experimental apparatus consists of a ultra-high vacuum (UHV) chamber with a hot-filament electron gun capable of producing mono-energetic electron beams with energy between 90 and 900 eV [13]. The bias current I_{apd} produced by the APD when shooting with the gun on its sensitive surface, as a function of the gun current I_{gun}, can be seen in Figure 2 (left) for electrons with energy of $E_e = 900$ eV. As can be seen I_{apd} is found to be proportional to I_{gun} over the entire analyzed I_{gun} range. Similar results were observed for $E_e = 90$ eV and $E_e = 500$ eV.

We have performed extensive characterization of CNTs in the UHV chamber present in LASEC laboratories, with both X-ray and UV sources. Figure 2 (center) shows the flux of emitted photo-electrons, when illuminating the CNTs with a Helium UV lamp ($h\nu = 40.8$ eV), as a function of the incidence angle γ of the UV radiation with respect to the CNT axis direction. The flux is divided by same flux measured on amorphous carbon (aC), and the ratio is normalized to be equal to unity around $\gamma = 40°$. As can be seen, for all different photo-electron energies (shown in different colors), a significant enhancement of the flux of photo-electrons emitted by CNTs is observed around $\gamma = 90°$, which corresponds to light hitting the CNTs at grazing angle. This is a further indication of the anisotropy of this material.

We therefore propose to search for light DM with detectors based on vertically-aligned CNTs. The experiment will be composed of an array of dark-PMTs pointing towards Cygnus, and another array pointing in an orthogonal direction of the sky. A DM signal would be seen as a significant excess of counts in the first array of detectors, compared to the second. The detector performance is likely to be affected by the CNT target characteristics (density, length, as well as single-wall versus multi-wall tubes) so these parameters need to be optimized appropriately. An estimate of the sensitivity on the interaction cross section of light DM is summarized in Figure 2 (right, taken from [7]), as a function of the DM mass M_X. Here an exposure of 1 kg × 1 year is assumed, and results (blue dashed) are compared to Ref. [14] (black solid).

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