PROCEEDINGS OF SCIENCE

Carbon Nanostructures for Directional Light Dark Matter Detection

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Carbon nanostructures offer exciting new possibilities in the detection of light dark matter. A dark matter particle with mass between 1 MeV and 1 GeV scattering off an electron in the carbon would transfer sufficient energy to extract the electron from the lattice. In 2D materials, such as graphene or carbon nanotubes, these electrons would be released directly into the vacuum, avoiding their re-absorption in the medium. We present two novel detector concepts: a 'Graphene-FET' design, based on graphene sheets, developed at Princeton University; and a 'Dark-PMT' based on aligned carbon nanotubes, developed in University of Rome Sapienza. We discuss their light dark matter discovery potential, the status of the RD, and the recent commissioning of a state-of-the-art carbon nanotube growing facility in Rome.

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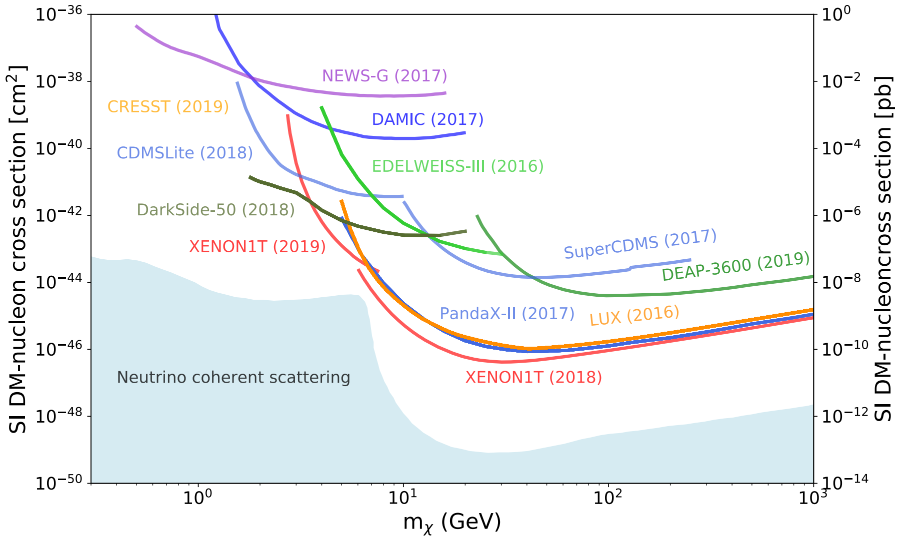

Figure 1: Exclusion limits at 90% confidence level on the DM-nucleon cross section as a function of m_{DM}. Different experiments are shown in different colors, and the cross section of neutrino-nucleon scattering is shown as a light blue shade. Figure taken from [1].

The most stringent limits on the Dark Matter (DM) interaction cross section are set by direct detection experiments based on multi-ton noble-liquid targets. The cross section exclusion limits depend on the mass of the hypothetical DM particle (m_{DM}), and are most stringent for $m_{\text{DM}} > 10$ GeV, where the XENON1T collaboration [2] has recently excluded down to $\sigma > 4.1 \cdot 10^{-47}$ cm^2, as shown in Figure 1. Experiments such as XENON1T typically base their sensitivity on DM-nucleus recoils, so rapidly lose sensitivity for $m_{\text{DM}} \lesssim 1$ GeV, because the momentum transferred to the nucleus becomes too small to be detected.

In order to extend the sensitivity to the $m_{\text{DM}} < 1$ GeV region, detectors sensitive to DM-electron scattering are needed. In the 1 MeV $< m_{\text{DM}} <$ 1 GeV region ("light DM"), cross-section exclusion limits are up to 10^{10} times weaker. Therefore detectors with much lighter targets would be able to produce competitive results.

Another crucial feature of detectors for direct DM detection is directionality, *ie.* the capability of linking a signal with a specific area of the sky. The DM 'wind' is expected to come from the direction of the Cygnus constellation, so in the event of observing a significant signal it will be important to verify that it comes from that direction to corroborate the claim. Directionality can also help contrast some sources of background, which either do not have a preferred direction (such as environmental radiation), or which come from directions different from Cygnus (such as solar neutrinos).

Assuming an average velocity of $\approx$ 300 km/s, DM particles composing the 'wind' have a kinetic energy of about $5-50$ eV (for $10 < m_{\text{DM}} < 100$ MeV). Considering a detector with a carbon target, this is enough energy to extract an electron from the lattice, as the work function of carbon in its graphitic form is about 4.6 eV. The ejected electrons would have a kinetic energy of $\approx 1-50$ eV. Electrons with such low energy have extremely low range in matter, and are therefore prone to being re-absorbed in the target before they can be extracted to produce a measurable signal. A possible approach to contrast this problem is to use targets made of 2D materials, such as graphene and

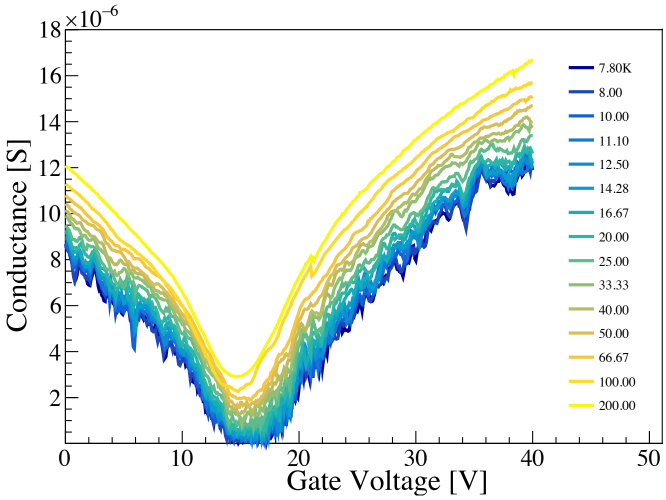

Figure 2: Conductance of a graphene nanoribbon ($W = 35$ nm) as a function of the gate voltage, for different operating temperatures.

carbon nanotubes.

Substantial RD on graphene has been carried out in Princeton University within the framework of the PTOLEMY project [3, 4]. Graphene can be engineered into ‘nanoribbons’, which are quasi-1D materials with a width of $W = 50$ nm or less, and distinctive electrical properties which depend on W. This allows for the creation of graphene Field Effect Transistors (G-FETs), in which the source and drain potentials are connected by a graphene nanoribbon [5]. As shown in Figure 2, the conductance of a nanoribbon strongly depends on the gate voltage: at low (high) bias there is a conductance region dominated by the movement of holes (electrons), while in the intermediate region there is a minimum, known as the charge neutrality point. As the temperature of the device is lowered to cryogenic values, the minimum conductance approaches zero, so the nanoribbon behaves as a semiconductor. It has been shown [6] that at the charge neutrality point, nanoribbons are sensitive to unitary changes in the number of charge carriers: the ejection or absorption of single electrons would result in measurable jumps in resistivity.

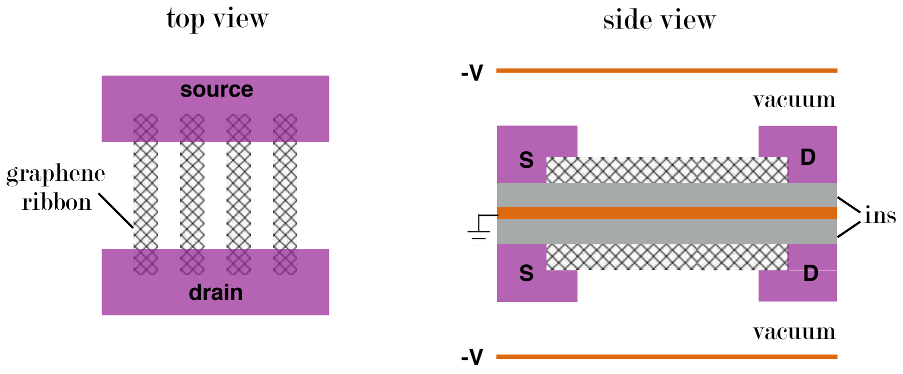

Figure 3: Left: sketch of the top view of a G-FET. Right: side view of the double-sided G-FET geometry, surrounded by electrodes.

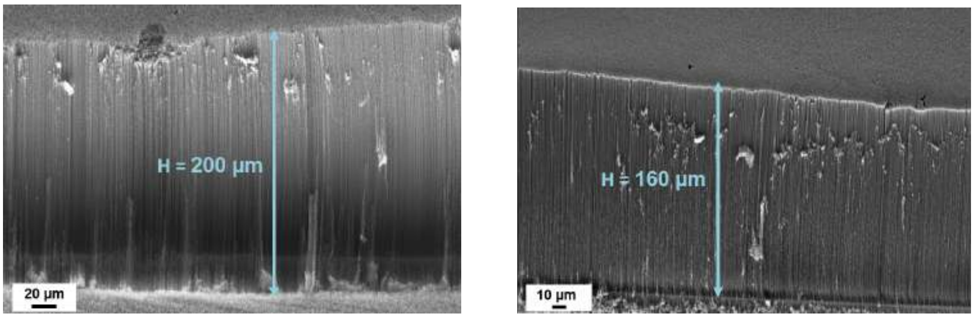

Figure 4: SEM images of successful CVD growths of carbon nanotubes achieved in 2019 at Elettra laboratories (Trieste). Left: silicon substrate. Right: fused silica substrate. The typical length of the nanotubes is reported on the figures.

A detector composed of arrays of G-FETs could achieve directional sensitivity to light DM. The G-FETs would be arranged in a double-sided geometry, surrounded by electrodes set at $V = -100$ V, as sketched in Figure 3. In this way, a DM-electron scattering event would eject an electron from the nanoribbon of a G-FET, which would then be re-accelerated by the electrodes back towards the G-FET array. A DM event would therefore correspond to the coincidence of a signal in two different G-FETs (departure and arrival). As the drift is ballistic, by adding time-of-flight sensitivity to the detector one would be able to fully reconstruct the electron velocity, whose initial direction is correlated to the direction of the DM wind. In this way the detector would have directional sensitivity.

Carbon nanotubes can be thought of as graphene sheets wrapped into straws with an internal diameter of a few nm, and are 'single-walled' when each nanotube is formed by a single graphene layer, or 'multi-walled' if multiple graphene cylinders share the same axis. Vertically-aligned carbon nanotubes can be grown through Chemical Vapor Deposition (CVD) on different substrates, with lengths up to a few hundred μm [13, 14]: some example growths of vertically-aligned multi-walled nanotubes we have performed with the CVD chamber present in the Elettra laboratories (Trieste) are shown in Figure 4. A new CVD chamber has been installed in University of Rome 'Sapienza' in July 2020, which is capable of producing both multi-walled and single-walled nanotubes.

Vertically-aligned nanotubes have been shown to be a highly anisotropic material, with close to vanishing density in the direction of the tube axes [7, 8]. Therefore, when a DM particle ejects an eletron off of the carbon lattice, the electron will be able to escape the carbon-nanotubes (and produce a signal) only if its momentum points in the direction of the nanotube axes. A detector with a target made of aligned carbon nanotubes would therefore have directionality by design.

The development of a novel light DM detector ('dark-PMT', [9–12]) with directional sensitivity is currently ongoing in Rome. The detector concept is shown in Figure 5 (left): the DM wind scatters on an electron of the vertically-aligned carbon nanotube target; the ejected electron would escape the target and be accelerated by an external electric field, reaching a kinetic energy $K \approx 1 - 10$ keV before hitting a solid-state electron counter on the other side of the detector. By building two arrays of detectors, one array pointing in the direction of the Cygnus constellation, and another pointing in an orthogonal direction, directional sensitivity to light DM would be achieved, by searching for a significant excess in the signals of the former array, relative to the latter.

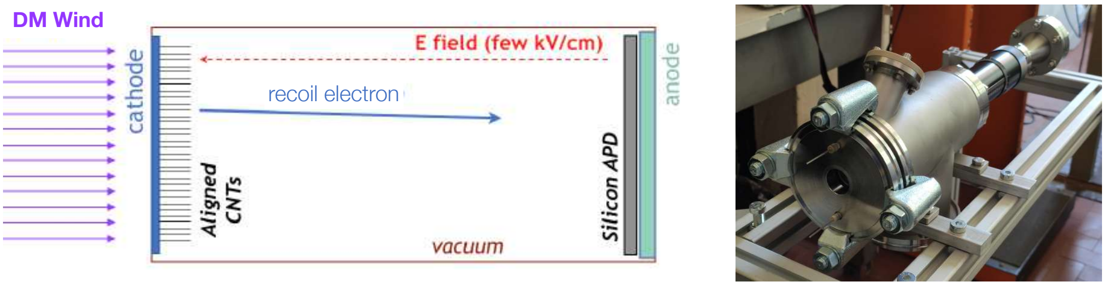

Figure 5: Left: the dark-PMT detector concept. Right: the dark-PMT prototype taking data in Rome.

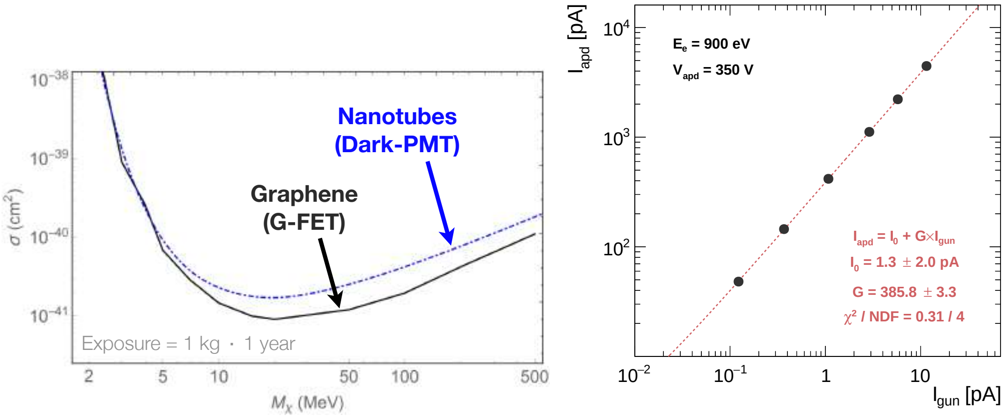

Figure 6: Left: Expected 90% cross section exclusion with an exposure of 1 kg × 1 year for the G-FET concept (black) and the dark-PMT concept (blue dashed). Right: APD characterization carried out in LASEC laboratories in University of Roma Tre: APD current (I_{apd}) as a function of the electron gun current (I_{gun}).

A comparison between the expected performance of the dark-PMT concept (blue dotted line) and that of the aforementioned G-FET concept (black line) is shown in Figure 6 (left). The plot shows the expected 90% exclusion on the DM-electron cross section, for an exposure of 1 kg × 1 year, as a function of the DM particle mass. As can be seen, the two detector concepts have similar expected performance, and they both have best sensitivity for a DM mass of about 20 MeV.

In the dark-PMT detector concept, the electrons ejected from the carbon reach a kinetic energy of about 1 keV before hitting the electron counter. The detection of keV electrons with a compact apparatus is not a trivial task. For this purpose we have explored two different technologies: silicon avalanche photo-diodes (APDs) and silicon drift detectors (SDDs). Silicon APDs constitute our benchmark technology, as they are simple and cost-effective, while SDDs are a possible upgrade, and are capable of providing ultimate single-electron resolution.

The characterization of silicon detectors with low-energy electrons has been carried out at the LASEC laboratories of University of Roma Tre. 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 [15]. The gun was directed onto the sensitive area of a Hamamatsu S11625-30N windowless APD, and the APD current I_{apd} was measured as a function of the gun current I_{gun}, for different electron energies E_e [16]. The results for E_e = 900 eV are summarized in Figure 6 (right): as can be seen I_{apd} is found to be proportional to I_{gun}.

Finally, a dark-PMT prototype has been constructed in Rome, and will be commissioned in the upcoming weeks. The detector is shown in Figure 5 (right), and will be initially equipped with an SDD detector produced by Fondazione Bruno Kessler, read out by an electronics module which was designed and constructed by Politecnico di Milano specifically for this detector.

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