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PTOLEMY-G^3 for Directional Detection of MeV Dark Matter

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Abstract

We propose two-dimensional targets for direct directional detection of MeV dark matter[1]. Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays, called a graphene cube (G^3), have unprecedented sensitivity to electron recoil, at the level of single charge detection. G-FETs provide tunable meV band gaps and provide high-granularity particle tracking when configured into arrays. In this experiment we look for MeV dark matter scattering events that liberate an electron from the graphene target, in the absence of any other activity in the G^3. A narrow, vacuum-separated front-gate of the G-FET imposes a kinematic discrimination on the maximum electron recoil energy, and the FET-to-FET hopping trajectory of an ejected electron indicates the scattering direction, shown to be correlated to the dark matter wind[1]. High radio-purity wafer-level fabrication[2], ultra-low ratio $^{14}C/C$ graphene growth[3], a cryogenic fiducialized volume and the coincidence of the FET-to-FET trajectories of electron recoils provide the conditions for a low background observatory of MeV dark matter interactions[4]. The evaluation of the G^3 active target and low background methods are an important step for the PTOLEMY[5] project whose long-term goal is the direct detection of the cosmic neutrino background. PTOLEMY-G^3 is the only experiment with direct directional detection capability for MeV dark matter and has a projected detection sensitivity that exceeds an equivalent mass target of low noise (5 e^- threshold) germanium cryogenic detectors.

[1]Hochberg, et. al, 2016. "Directional Detection of Dark Matter with 2D Targets", `http://arxiv.org/abs/1606.08849`.

[2]Low background contamination lithography has been demonstrated, see for example "Cryogenic Dark Matter Search detector fabrication process and recent improvements" by Jastram et. al, 2015. NIM A: 772:14-25.

[3]Litherland et. al, 2005. "Low-level ^{14}C measurements and Accelerator Mass Spectrometry" in AIP Conference Proceedings, vol. 785, p. 48. `http://dx.doi.org/10.1063/1.2060452`.

[4]The low backgrounds achieved by Xenon100 below 100 keV (`http://arXiv.org/abs/1101.3866`), parameterized with a rate formula 0.1 single scatter EM events/keV/kg/day, applied to the mean free path of 100 eV electrons in PTOLEMY-G^3 yields approximately 4 events/kg/yr.

[5]Betts, et. al, 2013. "Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield", `http://arxiv.org/abs/1307.4738`.

– With a modest, small-scale deployment of PTOLEMY-G^3, a fiducialized volume of 10^3 cm^3 will search down to approximately $\bar{\sigma}_e = 10^{-33}$ cm^2 at 4 MeV in one year, uncovering a difficult blind spot inaccessible to current experiments. This new approach will open up for the first time direct directional detection of MeV dark matter, a capability that no other light dark matter proposal has.

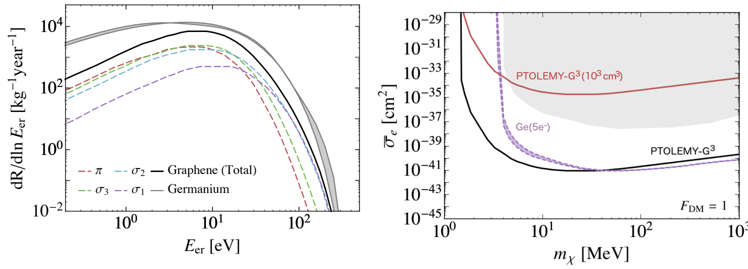

Figure 1-1. (left) *Differential rate for a 100 MeV DM particle scattering off an electron in graphene is shown with the solid black line with $\bar{\sigma}_e = 10^{-37}$ cm^2 and $F_{\rm DM}(q) = 1$.* (right) *Expected background-free 95% C.L. sensitivity for a graphene target with a 1-kg-year exposure (black). A first experiment with a G^3 volume of 10^3 cm^3 (target surface of 10^4 cm^2) will search down to approximately $\bar{\sigma}_e = 10^{-33}$ cm^2 at 4 MeV.*

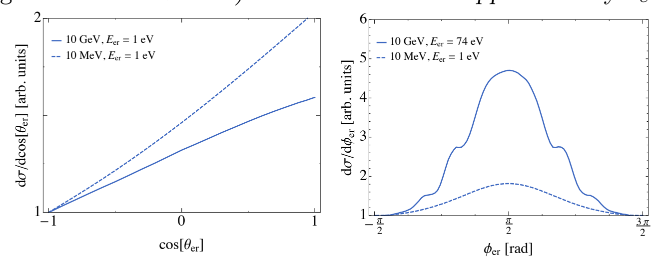

Figure 1-2. *Predicted angular distributions for DM masses 10 MeV (dashed) and 10 GeV (solid) in a DM stream with $v_{\rm stream} = 550$ km/s in the lab frame.* (left) *Polar distribution of the final-state electron when the stream is oriented perpendicular to the graphene plane and points along $\cos\theta = 1$.* (right) *Azimuthal distribution of the final-state electron when the stream is oriented parallel to the graphene plane and points along $\phi = \pi/2$. The outgoing electron direction is highly correlated with the initial DM direction.*

– The G-FET sensor has a tunable meV band gap, a full three orders of magnitude smaller than cryogenic germanium detectors. This sensitivity is used to switch on and off the conductivity of the G-FET channel by 10 orders of magnitude in charge carriers in response to the gate voltage shift from a single scattered electron. A narrow, vacuum-separated front-gate imposes kinematic discrimination on the maximum electron recoil energy, where low energy recoil electrons above the graphene work function follow FET-to-FET directional trajectories within layers of the fiducialized G^3 volume.

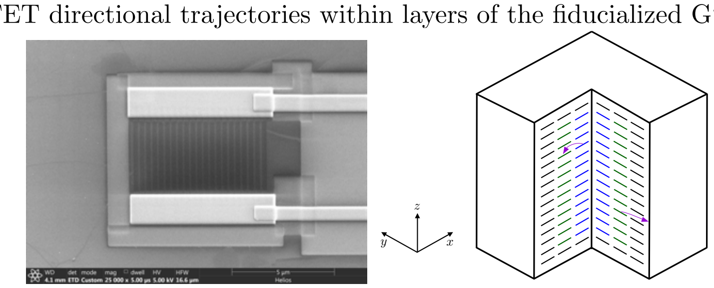

Figure 1-3. (left) *The graphene FET sensor consists of an interdigitated source and drain separated by a planar graphene layer segmented finely into ribbons.* (right) *Cutaway view of a conceptual design for graphene directional detection. When an electron is ejected from a graphene sheet, it is drifted by an electric field, where electrons follow a "FET-to-FET" trajectory.*

– PTOLEMY-G^3 is ready for a first phase experiment. Graphene sensor results are reported at this workshop and the existing PTOLEMY setup at Princeton University has the volume and cooling capacity to host PTOLEMY-G^3 with a fiducialized volume of 10^3 cm^3.

– Current, research-level production capacity of graphene exceed 200 m^2 per year with prices of approximately \$1 per cm^2. Substrate and graphene wafer costs are less than \$200 per wafer (100 mm dia.), but current research-level processing costs are an order of magnitude higher. Wafer-level processing costs are \$2,000 per wafer (100 mm dia.) to implement the G-FET array structure and applying expected yields. A 10^3 cm^3 fiducialized volume corresponds to a 100 wafer production run. This gives \$200,000 as the dominant core cost for PTOLEMY-G^3. Significant understanding of the wafer-level fabrication would be achieved with a pre-production of 10 wafers. The dominant production cost, wafer-level processing, could be furthered with an SBIR.