Graphene-based detectors for directional dark matter detection

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Dark matter detectors with directional sensitivity have the capability to distinguish dark matter induced nuclear recoils from isotropic backgrounds, thus providing a smoking gun signature for dark matter in the Galactic halo. Motivated by recent progress in graphene-related research, we propose a conceptually novel class of high directional sensitivity dark matter detectors utilizing graphene-based van der Waals heterostructures as detection materials. A proof-of-concept design of the detector based on graphene/hexagonal boron nitride and graphene/molybdenum disulfide heterostructures is developed for directional detection of dark matter. The developed detector has modular scalability, keV-scale detection threshold, nanometer position resolution, sensitivity down to GeV/$c^2$–dark matter masses, and intrinsic head–tail discrimination and excellent background rejection capabilities.

I. INTRODUCTION

A variety of independent astrophysical observations on galactic and cosmological scales strongly indicate that more than 80% of the matter in our Universe is in a form of nonluminous, nonbaryonic dark matter [1,5]. The nature of dark matter remains to date a deep mystery, and its identification is one of the major outstanding problems in both astrophysics and particle physics. Many theoretical extensions of the standard model of particle physics predict new types of stable, charge neutral particles that could be candidates for dark matter [6]. At present, the leading dark matter candidates are weakly interacting massive particles (WIMPs). They have mass in the range $\sim 1 \text{ GeV}/c^2–1 \text{ TeV}/c^2$ and only couple weakly to ordinary standard model particles. Theoretical studies show that galactic WIMPs have promising prospects for direct detection [7].

If WIMPs constitute the dark matter halo of our Galaxy, which is assumed to be nonrotating in the Galactic rest frame, the fact our Solar System revolves around the Galactic Center implies that halo WIMPs in the vicinity of the Earth may be directly detectable through their elastic scattering off atomic nuclei in terrestrial detectors [8]. In particular, the observed nuclear recoil event rates are expected to exhibit annual modulation as a result of Earth’s orbital motion around the Sun [9–11]. For decades, numerous experiments have been designed for direct detection of WIMP dark matter [12–13]. While there is so far no conclusive evidence for WIMP detection, experimental limits on the elastic WIMP-nucleon scattering cross section for various WIMP masses have been obtained [14]. The situation at the moment is more intriguing than perplexing and calls for further experimental and theoretical investigations.

The motion of the Earth and Sun relative to the Galactic Center also gives rise to a strong directional dependence in WIMP-induced nuclear recoils [14]. This is because nuclear recoils resulting from WIMP collisions will significantly peak in the direction of the WIMP flux, producing a large forward–backward asymmetry. The WIMP flux direction is opposite to the direction of the Sun’s motion around the Galactic Center, which at the current epoch points towards the constellation Cygnus. On the contrary, nuclear recoils caused by random backgrounds (e.g., alphas, electrons, neutrons, neutrinos, gammas, and cosmic rays) are expected to be isotropic and exhibit no preferred direction. Detailed studies [15–17] show that the strong directional dependence is a robust signal of Galactic halo WIMPs in that it is generic to a wide variety of halo models, WIMP parameters, detector parameters, etc. For detectors with fine angular resolution, only of order $\sim 100$ recoil events will be sufficient to distinguish a WIMP signal from isotropic backgrounds [10]. Therefore, directional signal in nuclear recoil events serves as a “smoking gun” signature for direct detection of halo WIMPs. There have been increasing experimental efforts devoted to directional dark matter detection (for a recent review see, e.g., Ref. [18]). The most notable ongoing experiments are DMTPC [19], DRIFT [20], NEWAGE [21], and MIMAC [22]. These experiments utilize various designs of the low-pressure gaseous time projection chambers (TPCs) to reconstruct the tracks of recoiling nuclei [29].

In this article, we critically analyze the existing TPC-based and recently proposed DNA-based directional detectors [24, 26]. We point out that while the feasibility of the proposed DNA-based detectors is exiguous, this detector design does have remarkable merits that may hold the key to a new generation of detection technology with nanometer accuracy. Motivated by those merits and the recent progress in nanotechnology and graphene-related research, we propose a new class of high directional sensitivity dark matter detectors using graphene-based heterostructures that are within the grasp of current technology. The proposed detector has modular scalability, keV-scale detection threshold, nanometer position resolution, sensitivity down to dark matter of mass $\sim 5 \text{ GeV}/c^2$, and intrinsic head–tail discrimination and excellent background rejection capabilities. The feasibility of the proof-of-concept design is strongly supported by a great amount of experimental evidence on the prop-
properties and fabrication of the heterostructures.

The rest of this article is organized as follows. In Sec. II, we briefly describe TPC- and DNA-based directional detectors and comment on the experimental challenges they face. In Sec. III, we highlight the merits of the design of DNA-based directional detectors, and argue that graphene-based heterostructures are far more better than DNA arrays as the detection material of a new class of directional detectors with nanometer accuracy. The conceptual design, detection principles, and directionality and background rejection capabilities of the proposed graphene-based directional detector are presented in Sec. IV. Finally, we summarize our results in Sec. V.

II. TPC- AND DNA-BASED DIRECTIONAL DETECTORS

TPCs provide three-dimensional (3D) information about the tracks of charged particles that traverse the chamber and ionize the detection material along the way. While dual phase (liquid/gas) argon and xenon TPCs have long been used in the DarkSide, XENON100, LUX, and PandaX experiments [13], they were not designed to provide recoil track information.

In the current low-pressure gaseous TPC-based directional detection experiments [19–22], the active volume of low-pressure gaseous TPCs is limited to $\sim 1 \text{ m}^3$ or less and the target gas ($\text{C}_3\text{S}_2$, $\text{CF}_4$, $\text{He}$, or mixture thereof) is pumped to a low-pressure at $\sim 40 – 150 \text{ Torr}$ [23]. This is in contrast to the TPC used in the ALICE experiment at CERN’s Large Hadron Collider, which is filled with $90 \text{ m}^3$ of detection gas at atmospheric pressure (or 760 Torr) [24]. The purpose of a low-pressure, small-volume design is twofold. First, diffusion of ionization electrons and/or ions during drift is constrained by the imposition of a maximum drift length. Second, the use of a dilute low-pressure gas ensures the tracks of the low-energy recoiling nuclei (with a typical recoil energy not more than a few tens of keV [12, 13]) to be long enough for adequate reconstruction. However, since the gas also acts as the target material, a dilute target gas would inevitably imply a low event rate and a limited scalability.

Moreover, information about the recoil tracks that is encoded in the drifting ionization electrons and/or ions is read out by a multi-wire proportional counter, charge-coupled device, micropixel chamber, or micro-mesh gaseous structure [24]. The state-of-the-art position resolution of these readout techniques is of order $\sim 10 \mu\text{m}$ [25], which however falls short of the fine angular resolution required for directional dependence. To achieve an unambiguous detection of dark matter, the existing TPC-based directional detectors would need to be improved for better scalability, sensitivity, and position resolution. An interesting idea [26] which exploits columnar recombination in a high-pressure xenon gas TPC has recently been presented to address the issues of scaling-up feasibility and detection sensitivity. Meanwhile, with so much at stake, exploration of the possibility of new directional detection technology is clearly warranted.

In a recent development, a brilliant idea of biological dark matter detectors has been proposed [24, 25]. Of particular novelty is the use of DNA in lieu of more conventional detection materials to provide high-resolution directional detection of dark matter. The basic detector unit [24, 25] consists of a thin film of metal (e.g., gold or tungsten), from which a large number of single-stranded DNA (ssDNA) strands hang down. The detector is modular in that a series of independent basic units (or modules) may be stacked on top of each other. The sequence of the ssDNA strands is known. When a WIMP scatters elastically off a nucleus in, say, a gold film, the recoiling nucleus traverses through and, whenever it hits one, breaks a few hundreds of ssDNA strands before either coming to a stop or being captured in the Mylar (i.e., polyethylene terephthalate) film on the other side of the ssDNA layer. The fragmented strands can be recovered and removed periodically and then sequenced with a single base accuracy, corresponding to a precision of 0.7 nm for straightened ssDNA strands. Thus the path of the recoiling nucleus can be tracked with nanometer accuracy.

As noted by the authors of Ref. [25], there are however several challenges to the ssDNA design that remain to be resolved. They include the need of a large amount of ssDNA strands of uniform quality, the difficulty of shrinking interstrand spacing down to nanometer scales, the ability to use homogeneous stretched ssDNA strands, and the possibility to diminish interstrand interactions. While the design is highly modular, it is conceivable that the challenges become more severe as the number of modules becomes practically large. Indeed, a total of $\sim 10^{12}$ pre-sequenced ssDNA strands will be needed for a module with a cross-sectional area of $\sim 1 \text{ cm}^2$ and an interstrand distance of $\sim 10 \text{ nm}$. Since ssDNA is a macromolecule typically composed of thousands or more atoms, manipulation of ssDNA is difficult due to the complex polymer dynamics that results in intrastrand base pairing, base stacking, and formation of diverse secondary structures [29]. Moreover, ssDNA stretching is sequence dependent [30] with multiple pathways [31] and a clear understanding is still lacking [32]. Last but not least, interstrand interactions are due largely to hydrogen bonds, the screening of which using glyoxal not only degrades ssDNA strands [25] but also introduces unwanted scatterers for the recoiling nuclei. Under current technology, contrary to those authors’ optimism [25], a resolution of the challenges would be a daunting task.

III. FROM DNA- TO GRAPHENE-BASED DIRECTIONAL DETECTORS

Since the concept of DNA-based detectors is fundamentally distinct from that of the conventional TPC-based ones, it is therefore insightful to compare the two design concepts. In fact, a thorough comparison reveals
that DNA-based directional detectors have several remarkable merits that hold the key to new directional detection technology.

The first merit is dual material design, i.e., two different materials, instead of a single one, are separately used for target and detection. In this dual material design there is a constructive division of labor. A dense high-Z material (e.g., metal or liquid noble gas) is ideal for achieving a high event rate, while a sparse low-Z material (e.g., soft or organic matter) is well suited for tracking recoiling nuclei.

The second merit is modularity in design, i.e., a large-size detector can be built up by stacking on top of each other, and/or placing side by side, a large number of independent modules. Evidently, modularity in design implies scalability. Importantly, we note that the independent modules may use a wide variety of target and detection material pairs which are sensitive to WIMPs in different mass ranges. This feature not only increases the nuclear recoil event rate but also allows WIMPs of different masses to be detected by a single detector.

The third merit is direct information encoding and delayed information decoding. Information about the recoil tracks is encoded directly in the detection material and hence has to be decoded in real time by an integral readout device. The advantages in cost and scaling-up are quite evident since only a single readout device is needed regardless of the size of the detector.

The fourth, and the most important, merit is the intrinsic nanometer structure of the detection material. Recall that for TPC-based detectors, the tracking accuracy is prone to diffusion of ionization electrons and/or ions during drift and is limited to $\sim 10\ \mu m$ by the position resolution of readout devices. In light of direct information encoding and delayed information decoding, nuclear recoil tracks can be measured with nanometer accuracy by a suitable combination of detection materials with an intrinsic nanometer structure and readout devices with a commensurate spatial resolution.

With these merits and the aforementioned drawbacks of DNA-based directional detectors in mind, we now argue that graphene-based heterostructures are ideally suited as the detection material of a new class of directional detectors with nanometer accuracy.

Graphene is a two-dimensional (2D) atomic crystal which consists of carbon atoms tightly packed into a hexagonal lattice. Since its first isolation by mechanical exfoliation in 2004 [33], graphene has been attracting tremendous interest and under intense experimental and theoretical study. Graphene has many extraordinary electronic and mechanical properties, such as high electron mobility, high thermal conductivity, excellent elastic flexibility, complete impermeability to any gases, and stability under ambient conditions [34]. Recently, growth of bilayer-free, high crystalline quality monolayer graphene by chemical vapor deposition (CVD) [35] on low-cost copper films and its clean transfer, free of metal contaminants, structural defects, and polymeric residues have been achieved [36]. More recently, large-area high-quality graphene films of dimensions $3 \times 3\ cm$ have been grown by CVD on copper films [37]. These advances are an important step towards the realization of high-performance, large-scale graphene-based materials and devices.

The advent of graphene also spurred the study of other novel 2D atomic crystals, such as hexagonal boron nitride (h-BN), molybdenum disulfide (MoS$_2$), tungsten diselenide (WSe$_2$), and many others [38]. Like graphene, these 2D materials can be obtained by methods such as mechanical exfoliation, CVD growth, and epitaxial growth. Many 2D materials have distinct properties that are suited for practical applications in electronic devices. For instance, monolayer h-BN is an optically transparent insulator, while monolayer MoS$_2$ and WSe$_2$ are direct band gap semiconductors with a strong photoluminescence [39]. Importantly, these 2D materials, including graphene, can be reassembled layer by layer in a chosen sequence by mechanical stacking or CVD growth to form new 3D materials with diverse properties and atomically precise interfaces [39]. In the resulting so-called van der Waals (vdW) heterostructures, strong covalent bonds provide in-plane stability of 2D crystals, while relatively weak, vdW-like forces are sufficient to keep the stack together with an interlayer spacing of order $\lesssim 1\ nm$. We highlight that this feature renders heterostructures mechanically far more stable than ssDNA arrays. This is because in the latter the interstrand interactions are due to hydrogen bonds, which are much stronger than vdW-like forces and hence tend to entangle neighboring strands. Recently, atomically thin photodetectors sensitive to light from the infrared to the ultraviolet have been fabricated using various vdW heterostructures [40]. With intrinsic mechanical stability, integrated designer optoelectronic functionality, and steady improvement in large-area, high-quality fabrication techniques, it is evident that vdW heterostructures are far more superior to ssDNA arrays as the dark matter detection material.

IV. CONCEPTUAL DESIGN OF THE PROPOSED DETECTOR

A. Detector configuration

We now present a conceptual experimental design of the proposed graphene-based detector that leverages currently available materials and technology. The detector consists of pixelated sheets of a thin film of metal, a stack of graphene/h-BN bilayer heterostructures, a graphene/MoS$_2$ bilayer heterostructure, and a thick layer of Mylar. Figure 1 depicts a schematic illustration of a
single “pixel” (or module) of the detector. Thanks to modularity in the design, a large-size detector array can be built up by stacking vertically, and/or juxtaposing laterally, a large number of the single pixels. Each pixel consists of four components, which will now be described in detail.

(i) The target component is a thin film of metal. The choice of metal depends on the mass of the WIMPs to be detected, and its thickness is roughly $10 – 20$ atoms thick so as to reduce multiple scattering of the recoiling nucleus in the film. Following Ref. [24], with an incoming WIMP of mass $\sim 100$ GeV/$c^2$ in mind, here we use a 5-nm-thick gold film as the target.

(ii) The detection component is a stack of graphene/h-BN bilayer heterostructures [11] with a thickness of about 7 nm. The distance between neighboring boron and nitrogen atoms in h-BN is 0.145 nm, which is only slightly larger than that of 0.142 nm between neighboring carbon atoms in graphene [12]. A graphene sheet on a h-BN surface has an interlayer spacing of about 0.34 nm [13] and is known to exhibit high performance owing to the atomically flat surface of h-BN and its lack of dangling bonds or surface charge traps [14]. The frequency-dependent optical absorbance of graphene from the infrared to the ultraviolet has been measured experimentally [15]. It takes the universal value $\pi \alpha \approx 2.3\%$ (where $\alpha \approx 1/137$ is the fine structure constant) [16] and is nearly frequency independent in the infrared region of $0.5 – 1.5$ eV, then increases smoothly and steadily by $\sim 80\%$ at 3.0 eV in the visible region, and finally more rapidly by a factor of about 2.5 up to 4.5 eV in the ultraviolet region [15]. In the same spectral regions, h-BN is optically transparent due to a sufficiently large optical band gap of 6.05 eV [47]. The total thickness of the graphene/h-BN heterostructures is chosen such that they are sufficient thick to have a good energy resolution and remain relatively optically thin in the visible and ultraviolet regions. This corresponds to a total of about 20 graphene and h-BN monolayers, or 7 nm in thickness.

(iii) The registration component is a graphene/MoS$_2$ bilayer heterostructure photodetector. A MoS$_2$ monolayer is about 0.65 nm thick, and a graphene/MoS$_2$ bilayer is about 1 nm thick. Including electrical contacts and SiO$_2$/Si passivation/substrate layers, the overall device thickness is $\sim 100$ nm [10, 18]. With current technology, such a photodetector can reach a photoresponsivity of $\sim 10^6 – 10^7$ A/W at room temperature in the visible and ultraviolet regions of 1.8 – 4.5 eV [48]. The photodetector is used to detect visible and ultraviolet bremsstrahlung photons produced by a recoiling Au nucleus when the latter collides with and knocks out atoms in the graphene/h-BN heterostructures of the detection component. Note that the event registration component should not be confused with the readout device, which will be specified in the following subsection.

(iv) The absorption component is a thick layer of Mylar [50] with a thickness of about 1 $\mu$m. Its purpose is twofold: (a) to stop the recoiling nucleus and confine the latter to its originating pixel, and (b) to block out recoiling nuclei that originate outside the pixel. Combining the four components, we arrive at a total thickness of $\sim 1.1$ $\mu$m for a single pixel in our conceptual design.

The gold thin film and bilayer heterostructures of graphene/h-BN and graphene/MoS$_2$ can be fabricated layer by layer on a substrate using CVD growth or mechanical stacking, and the back side of the substrate opposite the electrical contacts is then coated with the Mylar layer. Based on state-of-the-art fabrication technology [37, 47, 61], an estimate of the cross-sectional area of a single high-quality pixel can reach $\sim 100$ cm$^2$ or larger in the near future. While currently the area of graphene/MoS$_2$ photodetectors can only reach $\sim 50$ mm$^2$ [49], we emphasize that because of their ultrahigh photoresponsivity it should suffice to have $\sim 100$ photodetectors uniformly distributed on the substrate in each pixel, giving rise to a surface coverage ratio of about 50%. For a 1-kg target of gold, a 5-nm-thick gold film has a surface area of $10^6$ cm$^2$, corresponding to $10^6$ pixels, each with a cross-sectional area of 100 cm$^2$. Hence, the entire detector has a volume of $\sim 10^{-2}$ m$^3$, and contains 73.2 g of graphene, 73.5 g of h-BN, 16.5 g of MoS$_2$, and 14 kg of Mylar.

B. Detection principles

The detection principles of the proposed detector are based on defect formation produced by recoiling nuclei in monolayer graphene and h-BN, and on the induced bremsstrahlung of the recoiling nuclei. Vacancies in monolayer graphene and h-BN created by ion irradiation have been under extensive experimental study [52–56] and recently used as an atomic doping technique for graphene [57]. Bremsstrahlung produced by highly charged ions in nanostructures and solids is an active research topic in modern atomic physics [58, 59].

An incoming WIMP from the Galactic halo collides elastically with one of the gold nuclei and knocks it out of the film. To be quantitative, following Ref. [8], we consider a WIMP of mass $m$ and velocity $v$ scatters off a target nucleus of mass $M$. The recoil momentum is at most $2mv$ and the recoil kinetic energy is at most $E_{\text{max}} = (2mv)^2/2M$. We assume a typical recoil energy $E = E_{\text{max}}/2 = m^2v^2/M$ [24] and use the standard halo model [9] with $v = 220$ km/s for the WIMP velocity. For
a WIMP of mass \( m = 100 \, \text{GeV}/\text{c}^2 \), the typical recoil energy of a Au nucleus is \( E \sim 30 \, \text{keV} \). Specifically, we consider the situation that the WIMP–Au nucleus scattering takes place at the midpoint of 2.5 nm from the surface of the gold film. According to SRIM simulations, at this energy the stopping range of a Au nucleus in a gold target is 5.1 nm, and the stopping power of the target for the nucleus is 5.36 keV/nm (see Fig. 2). Hence, a typical recoiling Au nucleus does escape from the gold film, and its energy after the escape is roughly halved, at 16.6 keV.

The recoiling Au nucleus then traverses through and, whenever it collides with and knocks out the carbon, boron, and nitrogen atoms, creates vacancy defects in the monolayers of the graphene/h-BN heterostructures before being stopped by the thick Mylar film (see right panel of Fig. 1). The displacement threshold energies (i.e., the minimum amount of kinetic energy that, when transferred to an atom, results in ejection of the atom away from its lattice site) for carbon atoms in monolayer graphene \[65\] and for boron and nitrogen atoms in monolayer h-BN \[56\] have been measured experimentally. For ejection perpendicular to the layer, the displacement thresholds are 23.6 (carbon), 19.36 (boron), and 23.06 eV (nitrogen), respectively. Molecular dynamics simulations \[61\] show that the displacement thresholds increase gradually for oblique ejection and become almost doubled for ejection parallel to the layer. SRIM simulations were carried out for estimation of the number of vacancies produced by Au nucleus–graphene/h-BN collisions. The simulations were done by approximating the graphene/h-BN heterostructures by a 7-nm-thick layer of carbon, boron, and nitrogen with an atom stoichiometric ratio of 2 : 1 : 1. The binding energies of

the atoms were set at the above experimentally determined displacement threshold values. For a recoiling Au nucleus entering the graphene/h-BN heterostructures at 16.6 keV, there are on average about 150 primary and secondary vacancies created in the heterostructures. The result of SRIM simulations is plotted in Fig. 3. We note that the alternating arrangement of graphene and h-BN monolayers in the heterostructures (see right panel of Fig. 1) has the advantage of inhibiting possible interlayer vacancy migration \[62\] between neighboring layers of the same kind. From the SRIM simulated stopping range and stopping power shown in Fig. 2 we estimate that after leaving the graphene/h-BN heterostructures, the energy of the recoiling Au nucleus is significantly reduced to 3.5 keV, and the Au nucleus will subsequently be stopped by the substrate layer of the graphene/MoS\(_2\) photodetector.

Meanwhile, the visible and ultraviolet photons produced by nuclear bremsstrahlung \[65, 59\] when the recoiling Au nucleus collides with atoms and nuclei in the graphene/h-BN heterostructures are picked up by the graphene/MoS\(_2\) photodetector, giving rise to a pulsed photocurrent. It is noted that a quantitative analysis of the bremsstrahlung spectra and induced photocurrent has to be obtained experimentally and is beyond the scope of this article. The photocurrent is fed into a circuit connected to an external electronic device (not shown in Fig. 1) that registers the nuclear recoil event and the location of the corresponding pixel. After an exposure during which a number of nuclear recoil events are registered, the registered pixels can be removed and their component graphene/h-BN heterostructures be delaminated by mechanical exfoliation, while the gold films,
graphene/MoS$_2$ photodetectors, and Mylar layers are recycled for reuse. The position of the vacancies in the now graphene and h-BN monolayers can be determined with atomic accuracy by a separate readout device, such as the transmission electron microscope (TEM) or high-resolution TEM (HRTEM) \cite{52, 54, 57}. This position information, together with structure information of the graphene/h-BN heterostructures, allows the path of the recoiling Au nucleus to be tracked with nanometer accuracy.

Recall that the 7-nm-thick graphene/h-BN heterostructures in one single pixel consist of a total of about 20 graphene and h-BN monolayers. We define the energy threshold of the detector as the smallest energy for a recoiling nucleus to traverse one half of the heterostructures, and then the energy threshold is about $\sim 1$ keV, which is verified by SRIM simulations. This energy threshold is comparable to but lower than those ($\sim 2 - 4$ keV) of low-pressure gaseous TPC-based detectors \cite{25}. Moreover, with a suitable target material (e.g., beryllium) with appropriate target thickness, the low energy threshold also allows for directional detection of low mass WIMPs down to the $\sim 5$ GeV/$c^2$ scale, resulting in an overall detector sensitivity to WIMPs in the mass range of $\sim 5 - 100$ GeV/$c^2$. For a WIMP of mass $m = 5$ GeV/$c^2$ and a 5-nm-thick beryllium film, SRIM simulations shows that after escaping from the film the energy of a typical recoiling Be nucleus is 1.34 keV, and on average there are about 13 vacancies created in the graphene/h-BN heterostructures. Using the standard halo model with an escape velocity $v_{esc} = 500$ km/s, an energy threshold of $\sim 1$ keV gives rise to an estimated event rate of $\sim 0.1 - 1$ count per kg per year for WIMP masses from 5 to 100 GeV/$c^2$.

![Figure 3](image.png)

**FIG. 3.** Plot of SRIM simulated number of primary and secondary vacancies per nm of depth in graphene/h-BN heterostructures as a function of depth in the heterostructures. The vacancies are produced by a recoiling Au nucleus entering the heterostructures at 16.6 keV. The dotted (dashed) line is a power-law (an exponential) fit to the simulated data.

### TABLE I. Relevant beta emitters.

| Isotope | Abundance | Half-life | Mode | Energy (MeV) |
|---------|-----------|-----------|------|--------------|
| $^{3}$H | trace     | 12.32 y   | $\beta^-$ | 0.01861      |
| $^{14}$C | trace     | 5730 y    | $\beta^-$ | 0.156        |
| $^{31}$Si | trace    | 2.62 h    | $\beta^-$ | 1.495        |
| $^{32}$Si | trace     | 153 y     | $\beta^-$ | 13.020       |
| $^{35}$S | trace     | 87.32 d   | $\beta^-$ | 0.167        |
| $^{100}$Mo | 9.63% | $8.56 \times 10^{18}$ y | $\beta^-\beta^-$ | 3.04 |

### C. Directionality and background rejection

This proposed design has intrinsic head–tail discrimination and excellent background rejection capabilities. It is noted that the type of vacancies (i.e., single vacancies with one atom missing, and multiple vacancies with two or more atoms missing) created in the graphene/h-BN heterostructures directly depends on the energy of the recoiling nucleus \cite{53, 57}. The sense of a recoil track (head–tail) can be determined by information obtained from TEM or HRTEM imaging about the number of vacancies and vacancy types in individual graphene and h-BN monolayers. This is because collisions of a recoiling nucleus with target atoms and atomic crystals dissipate energy, and hence the recoiling nucleus always moves from layers with many vacancies and multiple vacancies to layers with few vacancies and single vacancies. As can be seen clearly from Fig. 3, the intrinsic head–tail discrimination of the proposed detector is verified by the SRIM simulations for a recoiling Au nucleus entering the graphene/h-BN heterostructures at 16.6 keV.

While information about the directionality of the WIMP signal provides an inherent discriminant against backgrounds, the expected low event rate requires that detectors are built from, and shielded with, radiopure materials and operated in underground laboratories. However, a background-free environment is virtually never attainable. Most primary backgrounds give rise to electron recoils \cite{12, 13} in the gold film. When a recoiling electron collides with the graphene/h-BN heterostructures and Mylar, it undergoes electron bremsstrahlung \cite{63}. The visible and ultraviolet electron bremsstrahlung photons are captured by the graphene/MoS$_2$ photodetector and a photocurrent is generated. While quantitative properties of the induced photocurrent must be determined experimentally, it is expected to be characteristically distinct from that induced by a recoiling Au nucleus undergoing nucleus bremsstrahlung. Hence, the photodetector also serves as a part of the background rejection device. Moreover, the modular design with a dense high-Z target material also allows for effective fiducialization \cite{13} in that events from pixels close to the surfaces of a large-size detector are excluded. This fiducialization is especially useful in suppressing neutron-induced background events that cannot be distinguished from a WIMP-induced signal.
According to the decay properties of relevant isotopes listed in Table I, we expect that the main irreducible backgrounds come from $^{14}$C decay in graphene and Mylar, and $^{100}$Mo decay in MoS$_2$. Accelerator mass spectroscopy during the fabrication process of graphene can reduce the $^{14}$C/C ratio to $10^{-21}$ [64]. For a detector with a 1-kg target of gold, this corresponds to $4.4 \times 10^5$ atoms of $^{14}$C in the graphene and Mylar (see Sec. IV A). With the $^{14}$C half-life of 5730 years, there are roughly 77 events per year assuming no veto, which can be subsequently rejected because of the multipixel interaction of the energetic 156-keV electrons. As for $^{100}$Mo, anion-exchange chromatography can be used to the abundance of the the most common stable isotope $^{98}$Mo to $\geq 99.9\%$ [65], corresponding to a $^{100}$Mo/Mo ratio of $10^{-4}$ or $\sim 6.2 \times 10^{18}$ atoms of $^{100}$Mo in MoS$_2$, with a half-life of 8.56 $\times 10^{18}$ years. This gives rise to 0.7 events per year, which can be easily rejected owing to the characteristic extremely energetic double-beta decay at 3.04 MeV.

V. SUMMARY

We proposed and investigated a novel dark matter detector with nanometer accuracy and high directional sensitivity using graphene-based heterostructures as detection materials. The proposed detector has modular scalability, keV-scale detection threshold, nanometer position resolution, sensitivity down to dark matter of mass $\sim 5$ GeV/$c^2$, and intrinsic head-tail discrimination and excellent background rejection capabilities. The feasibility of the proposed design is strongly supported by a great amount of experimental evidence on the properties and fabrication of the heterostructures. It is fascinating that the new graphene-based materials, devices, and technology may help solve the old problem of dark matter. We leave for future work an extended study of the nucleus bremsstrahlung spectrum in the visible and ultraviolet regions, and of the performance and optimization of the proposed detector.

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