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James E. Harrison IV
University of North Florida, n01425459@unf.edu

Faculty Mentor: Dr. Jason Haraldsen, Associate Professor
Department of Physics

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Dark Matter Detection Materials

James E. Harrison IV

Faculty Mentor: Jason T. Haraldsen, Ph.D.
Department of Physics
University of North Florida

Abstract

The purpose of this paper is to review the different methods and materials used in the detection of dark matter. Special attention is given to materials in the solid state, but other materials are briefly mentioned for the sake of completeness. After a review, I discuss the viability of each material as a detector, and determine what advantages each material has, and what method of detection works best for each material. I conclude by discussing the potential outcomes of a null detection.

I. Introduction

The search for dark matter has been ongoing for over eighty years. Dark matter was first noted in 1937 by Zwicky while attempting to estimate the masses of large clusters of galaxies [1]. While analyzing the motions of the galaxies, he determined that most of the matter in the clusters was non-luminous. Continual observations proceeded to confirm Zwicky's hypothesis, which has led to the continual search for dark matter. Countless theories have been proposed to explain dark matter, but the theories are useless unless a direct detection can be made. Despite being aware of dark matter for over eighty years, no direct detection has ever been made. This has led to some speculation about the validity of our current theories of gravity. Some have pointed to Einstein's modification of gravity that explained the orbit of Mercury. If Mercury could be explained without the need for an additional planet, perhaps galaxies could be explained without dark matter. However, the same argument exists for the support of dark matter. The discovery of Neptune in the 1900s was entirely motivated by deviations in Uranus' orbit. The same is also true for the eventual discovery of Pluto, which was motivated by deviations in Neptune's orbit (although it is worth noting that Neptune's orbital deviations were the result of a miscalculation, and therefore the discovery of Pluto was largely a coincidence). For a more detailed review of dark matter and its history see [2].

Nevertheless, for the purposes of this paper I will assume that dark matter does exist, and that it can be detected. With this stipulation in mind, the paper is setup as follows: section 2 reviews the different methods used to detect dark matter. Section 3 reviews the different materials used. Section 4 discusses how the data from the detectors is analyzed. Section 5 discusses and compares the different materials and their respective advantages. In Section 6, I present my conclusions.

II. Methods of Detection

Direct detection experiments operate under the assumption that dark matter exists as weakly interacting massive particles. These particles, as their name suggests, interact weakly with normal matter. However, it is theoretically possible to measure the interaction if a sensitive enough target material is used. The most common methods of detection used for dark matter are absorption, scattering, detection in a particle accelerator, and scintillating targets. With the exception of accelerator detection, each method is dependent on the density of dark matter around Earth and the material used.

A. Particle Accelerator Detection Method

The most insightful way to detect dark matter would be to reproduce it inside of a particle accelerator. The Compact Muon Solenoid (CMS) and A Toroidal LHC Apparatus (ATLAS) are two such experiments run by CERN. These experiments have already successfully proved the existence of the Higgs particle, and there are many more signals that the collaborations are still analyzing. Since dark matter is weakly interacting, the creation of dark matter in a particle accelerator could only be discovered if an observed event was missing some momentum or energy. If the energy loss cannot be accounted for by any standard model particles, then it would be reasonable to conclude that it escaped as dark matter. Searches for dark matter using particle accelerators have heavily constrained theoretical models at ~4 GeV for spin-independent interactions and ~700 GeV spin-dependent interactions [3].

B. Absorption

Dark matter could also be detected via absorption, which occurs when an inelastic collision between a dark matter particle and a target material results in a portion of the dark matter's energy being absorbed by the material. In semiconductors, absorption can occur in two ways. If the dark matter mass is greater than 1 eV (approximately the band gap energy of a semiconductor), then the dark matter will excite an electron into the conduction band. This will create an excess current in the target that can be directly measured. If the dark matter mass is less than 1 eV, then the dark matter will cause multiphonon excitations. Multiphonon excitations occur due to coupling between the crystal dipole moments and the phonons. The maximum energy of the lattice's phonons is approximately the Debye temperature of the material. The sensitivity of this method has been shown to be approximately 0.01 - 1 eV, and it is possible that, with some technological improvements, semiconductor absorption targets could probe dark matter emitted from the sun [4].

C. Scattering

For dark matter in the GeV mass range, it is possible to impact particles and scatter off of them. This method of detection is limited by the cross section of the target material used and by the excitation energy of that material. For light dark matter, elastic collisions can generate nuclear recoils inside of the target's crystal lattice. The energy of the recoil is given by

$$E_{nr} = \frac{q^2}{2m_n} \approx 1eV \times (\frac{m_{DM}}{100MeV})^2(\frac{10GeV}{m_N})$$

where m_N is the mass of the nucleus, $q \sim vm_{DM}$ is the momentum transferred, and $v \approx 10^{-3c}$ is the DM velocity [5]. As the equation shows, dark matter with a larger mass will produce larger disruptions in the target material's lattice structure, but larger target masses will reduce the amplitude of the disruption. Scattering is the most common method of detection due to its simplistic setup and higher potential interaction rates.

D. Scintillating Targets

A more recent method of detection has developed around the scintillator technology. When certain materials are struck by a particle, they emit a photon. The strength of the photon is dependent on the mass of the scattering particle and the material chosen. By knowing the parameters of the target material, the scattering particle can be identified. By surrounding the target material with a photosensitive diode, the photons can be converted into an electrical signal that can be measured and analyzed. This method of detection can result in less background noise in the signal and can potentially have a higher sensitivity than traditional methods [6].

III. Materials Used

There are a variety of materials used for dark matter detection. The most common materials are germanium (Ge) and silicon (Si), but other materials include liquid xenon (Xe), bis(naphthoquinone)-tetrathiafulvalene (BNQTTF), Yb_3PbO, graphene, Gallium Arsenide (GaAs), and Sapphire (Al_2O_3). There has also been some discussion surrounding the viability of super-fluid helium [7], sodium iodide, and cesium iodide [6]. The capabilities of each material are dependent on the production quality of the material, and the design of detection apparatus [8]. Samples with a higher degree of purity have a higher resolution than materials with lower purity (here and throughout this paper, the term purity refers to a lack of unwanted elements or design defects). Additionally, some materials benefit by having a specific shape. However, the exact benefits received depend heavily on the method of detection.

A. Semiconductors

Semiconductors are the most commonly used material due to their ability to detect low mass dark matter (M<1 MeV) [9] and their ease of production. Noble gas detectors can typically only detect masses greater than one GeV (although recent developments with liquid xenon and superfluid helium may render this argument invalid). Semiconductors gain their accuracy from their low band gap energy. The separation between the valence band and the conduction band is typically between 1 and 3 eV. If a particle of dark matter scatters an electron in a target semiconductor, then the electron could gain enough energy to enter the conduction band. The exact amount of energy gained by the electron is dependent on the mass of the dark matter particle. If the mass of the dark matter particle is greater than 1 MeV, then the scattered electron will enter the conduction band and produce a detectable current in the target material [10].

Semiconductors can also be used to detect nuclear recoil energy. Similar to electron ionization, a dark matter particle can inelastically collide with an atomic nucleus. This collision can cause the nucleus to vibrate, generating a phonon. The phonon's energy can be measured by recording the vibrations in the crystal lattice. This method has approximately the same resolution as ionization, so there is little motivation to use one over the other.

Several collaborations around the world are using semiconductors such as germanium and silicon. The Super Cryogenic Dark Matter Search (SuperCDMS) uses cryogenically frozen germanium to try and detect weakly interacting massive particles (WIMPs). The low temperature of the apparatus allows for a clear distinction between phonon energies and natural thermal emission [11]. The Dark Matter In CCDs (DAMIC) experiment attempts to detect the recoil energies inside of a silicon target by using charge-coupled devices (CCDs) as sensors around the target material [12]. Additionally, DAMA, EDELWEISS-II, and other collaborations are also using semiconductors in an attempt to detect dark matter.

B. Superconductors

Super conductors behave very similarly to semiconductors, except their band gap energy refers to the amount of energy required to break apart their Cooper pairs, instead of the energy required to go from the valence band to the conduction band. The binding energy of these pairs is in the meV range, which makes them highly sensitive to small changes in energy. To further increase its sensitivity, a superconductor could be combined with transition edge sensors (TESs) or microwave kinetic inductance devices (MKIDs). These devices, although sensitive to sub-meV energies, are not suitable for detection targets by themselves due to their small size and mass. However, a superconductor could be used as a baseline target that absorbs the dark matter particle, and then the TES or MKID could be placed on the edge of the superconductor to measure the scattering energy [13].

In general, there is no reason that MKIDs and TESs could not be applied to other materials (in fact, they are currently being used in some semiconductor experiments), but their use with superconductors is more widely theorized due to superconductors being less widespread than semiconductors.

An example of superconductors being used today is in the search for axions. Axions are a potential candidate for dark matter that can be probed using a slightly different method than traditional dark matter. When an axion collides with a superconductor under a strong magnetic field (~3T or more), an oscillating current is created. This current then creates a dipole radiation dependent on the axion's mass [14]. This method of detection was proposed based on the working theory for axions. Unlike traditional dark matter searches that are based on more general guidelines for generic particles, axion searches are relying on the specific properties of axions.

In addition to their use as a target material, however, superconductors are also usable as sensors. The recent development of superconducting nanowires has given rise to highly sensitive sensors. In 2019, it was theorized that a superconducting target, surrounded by superconducting nanowires, could be sensitive to sub-keV masses. Due to the recency of this development, the use of nanowires is not yet widespread. However, a schematic of their use is shown in Figure 1 [15].

C. Polar Materials

While semiconductors and superconductors are highly sensitive to low mass dark matter, it is relatively impossible for them to reveal any information regarding the direction of the dark matter particle. To overcome this hurdle, some have suggested the use of anisotropic materials such as gallium arsenide or sapphire. The anisotropic nature of these materials results in a strong directional dependence of scattering events. Additionally, polar materials are readily available and reasonably easy to produce [16].

After a dark matter particle scatters off of a polar material, phonons are produced in the lattice. When analyzing the resulting phonons, however, it is apparent that only the optical modes can reasonably be measured. The reason for this is that the acoustical modes carry very little energy at the expected interaction mass range. The energy carried by acoustical modes in this range is currently below the sensitivity range of modern sensors. Optical modes, on the other hand, carry far more energy, and should be detectable by modern sensors. By only considering the resulting optical phonons, the mass and direction of the dark matter particle can be determined. A diagram of the optical and acoustical modes in gallium arsenide is shown in Figure 2 [16].

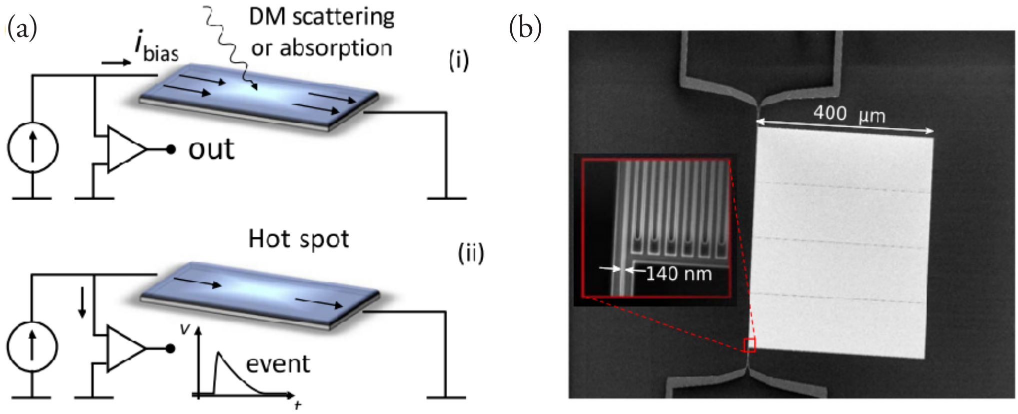
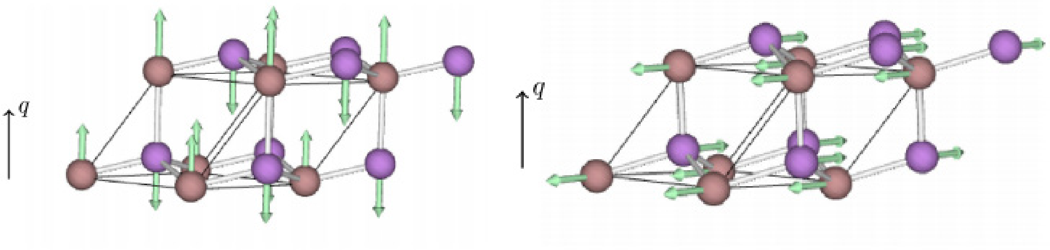


Figure 1. (a) A schematic of a superconducting nanowire single photon detector. (i) is a schematic showing a particle of dark matter scattering off of the detector while a current is run through the detector. (ii) is a schematic of the detector after a particle scatters off. The energy of the particle is absorbed by the nanowire and the electrons depart from equilibrium. They then diffuse out of the formed hot spot resulting in a resistive region that generates a measurable voltage pulse. (b) An image of a prototype device after fabrication. The active area is 400 × 400μm^2 [15].



(a) LO mode

(b) TO mode

Figure 2. Visual representation of the optical modes in GaAs. The black lines show the primitive cell. The purple atoms represent As and the brown atoms represent Ga. The primitive cell contains 1 As atom and 8 × (1/8) Ga atoms. The green arrows indicate the atomic motions while the black arrow indicates the phonon propagation direction [16].

D. 2-Dimensional Materials

2-dimensional lattice structures offer a key advantage over 3-dimensional ones. While 3-dimensional lattices can allow for a wide range of materials to be used, they are only able to determine the energy of an incoming particle, not its direction. By using a 2-dimensional lattice, the direction can be determined by recognizing that the direction of a scattered electron is strongly correlated with the direction of the incident dark matter. By utilizing a carbon nano-structure, it is possible to create a graphene dark matter target that can determine the dark matter's mass and direction [18].

E. Dirac Materials

Perhaps one of the most intriguing advancements in detector technology had been the development of Dirac materials. Dirac materials have a unique property in that elementary excitations follow the Dirac equation with a relativistic flat-metric energy-momentum relation $E_k^{\pm} = \pm\sqrt{v_F^2 K^2 + \Delta^2}$. In this equation, k denotes the lattice momentum, v_F is the Fermi velocity, and 2Δ is the band gap. This property allows for the measurement of both the energy and the direction of a scattered particle. However, Dirac materials are not easily produced, and other materials seem to offer the same benefits as Dirac materials without requiring any special production [19].

F. Liquid Materials

While most materials used for direct dark matter detection are solid, there are a few liquid detectors as well. The most prominent liquid detector is the Xenon100 detector in Italy [20]. The main advantage of liquid detectors over solid detectors is their size. Solid materials must be produced as a single slab of material, which makes it difficult to ensure a high level of purity. Liquid detectors, on the other hand, can be easily divided into smaller portions. This allows designers to easily isolate and remove impurities, and then recombine the portions in a large tank. This ensures that the target has a high level of purity, and that it has a large volume to detect dark matter with. Liquid xenon detectors are usually accurate at around 100 GeV/cm^2, and operate on the same principles as superconductors and scintillators (depending on how the apparatus is setup).

Although not technically liquid, superfluid Helium (SFH) has also been proposed as a potential target material for dark matter [21]. SFH has the potential to be sensitive at ~keV dark matter mass ranges. The key to the high sensitivity of SFH is its ability to measure multiple excitations from a single scattering event. Unlike other detectors, SFH assumes the dark matter particle will scatter off of the nucleons, rather than off of electrons. This greatly increases the cross-sectional area of the target, and thus greatly increases the chance of detection.

G. Scintillator Materials

The final set of materials commonly used for dark matter detection are scintillator materials. Scintillator materials are luminescent. When struck by an outside particle, they will emit a photon that has an amplitude dependent on the energy of the scattered particle. By surrounding the material with a photosensitive material, it is possible to detect dark matter in the sub-GeV range. The most common materials used for scintillators are sodium iodide and cesium iodide. The Korea Invisible Mass Search (KIMS) collaboration is currently utilizing cesium iodide in an underground facility located in South Korea [22].

IV. Data Interpretation

Calculating theoretical results for dark matter scattering off of a solid crystal lattice target is complex. For semiconductors, the valence electrons are delocalized and have a complicated band structure. As a result, wave functions cannot be determined analytically. Instead, wave functions must be calculated numerically. Additionally, the electron states of the lattice are quantum in nature, and the electrons have considerably larger speeds than the expected dark matter particles [10].

Another major hurdle occurs when considering neutron scattering inside of a detector. Functionally, neutron scattering looks identical to theoretical dark matter scattering. Since differentiating between them is impossible, it is necessary for designers to build a neutron veto around the detector. The veto screens the neutrons while allowing dark matter to pass through. This allows experimenters to evaluate the frequency of detections in order to determine if dark matter has interacted with the target. If the interaction rate is higher than the veto allows, then it must be dark matter [23].

While a veto or other shielding techniques can reduce outside noise, they can cause other complications. Dark matter detectors are usually located underground where they are shielded by the Earth's atmosphere and solid rock. This can cause some dark matter particles to be deflected or absorbed before they can reach a detector. This is more prevalent for slower dark matter particles due to the dark matter form factor hindering larger momentum transfers. Additionally, dark matter particles with larger cross sections (around 10^{-26} cm^2) are essentially completely removed from the system [17]. A graph showing the effects of shielding on the expected results is shown in Figure 3.

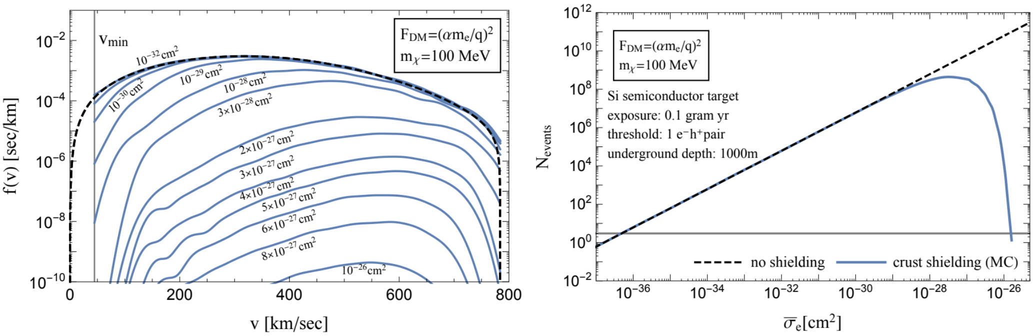


Figure 3. Left: Monte Carlo simulations of the speed distribution of dark matter for a detector 1 km underground. Each line is labeled with its respective $\sigma_e$value. Right: The attenuation of expected events for a generic semiconductor detector. The grey line indicates ~3 events, which corresponds to the number of signals with 95% CL exclusion bound in the absence of background events [17].

Despite these difficulties, estimates for dark matter detection are commonplace. The exact form of the calculation is heavily dependent on the material and method of detection used. Generally, the detection rate is dependent upon the density of dark matter in the region, the band gap energy of the material, the cross section of the target material, the temperature of the target material, and the mass of the dark matter.

V. Discussion

After analyzing each method and material, it is clear that not all materials are created equal. Super conducting materials are the most sensitive to changes, but they can be more difficult to maintain than semiconductors, and the difference in resolution has become negligible now that better sensors are available. Dirac materials are promising, but polar materials can perform marginally worse, and are far easier to produce. Additionally, polar materials can be combined with scintillators to produce a highly sensitive and directionally dependent detector. Once more, many scintillators now use TESs or MKIDs instead of photosensitive diodes. This can actually make them more sensitive than Dirac materials in certain mass ranges.

Liquid materials are easily produced in large quantities and are easier to maintain than superconductors. However, liquid materials are bound by their containers. Unlike solid materials, which can be molded into any shape, liquid materials must maintain the shape of their container. While the container could certainly be in any shape, using any shape other than a large cube or sphere would remove the main advantage of liquid materials: their size. Superfluid materials, while more sensitive than other materials, are hard to consistently maintain. Additionally, superfluid materials are still only theoretical, and no detectors currently exist which are actively using them (although there have been a few proposed detectors which are in development).

2-dimensional materials such as graphene are capable of determining the direction and mass of a scattered particle, but their resolution is comparable to polar materials, and their production cost is higher. Additionally, polar materials gain more from advancements in sensor technology. The advent of TESs, MKIDs, and superconducting nanowires has proven more beneficial for polar materials than graphene, and it is unclear what benefits graphene may have as technology improves. It is clear that the best materials are the ones which have high resolution and can be easily produced. Additionally, most detectors now use a combination setup, where one material is used as an absorber and another is used as a sensor. This setup can allow for detectors to take advantage of multiple materials at once. Superconducting nanowire detectors have a high sensitivity, which can then be combined with any absorber material. Early tests of this setup are utilizing a superconducting base, but it would be equally plausible to use a polar material or a semiconductor, depending on the desired search parameters.

In most cases, the material chosen is still mostly dependent upon the detection method. Superconductors are most common in absorption experiments due to their low band energy. Semiconductors are used for scattering events due to their ease of production and low band energy. Additionally, scattering events are best suited for lighter materials, which is why germanium and silicon are the two most common semiconductors used. Boron is not used, however, due to its lower orbital electron structure leading to higher intrinsic stability. Polar materials are not as common as superconductors or semiconductors because the direction of dark matter particles is currently of little consequence. As noted before, dark matter has never been directly detected. As such, where dark matter particles come from is of little consequence to current researchers. Because the primary goal is to prove the existence of dark matter, rather than its origin, current detectors are utilizing the most sensitive materials available rather than potentially more informative materials.

VI. Conclusion

The search for dark matter has been an ongoing quest for over eighty years. Researchers across the globe have joined together to develop theories for the nature of dark matter and how to detect it. Despite these efforts, no direct detection of dark matter has ever occurred. Even as numerous detectors probe the Universe, there has been no sign of dark matter outside of gravitational kinematics. The most common materials used for dark matter detection are semiconductors and superconductors, which are used for their high sensitivity. There are also some liquid xenon detectors that have comparable sensitivity, and polar detectors which are capable of determining the direction of scattered particles. However, as searches continue to turn up null results, perhaps it is time to review the theory. Current theories suggest that, if dark matter particles do pervade the earth, they have to be lower than 1 MeV in size. If dark matter existed above that size, then a detector would most likely have detected it by now. However, detectors that are sensitive below the 1 MeV mass range are either still in development or have not been active for long enough to produce meaningful results.

If dark matter is not detected, then it would mean that our understanding of galaxies and the Universe as a whole is flawed in some way. This would require an extensive rework of gravitational equations that would impact far more than just the kinematics of galaxies. The entire Universe is the product of gravitational interactions. An alteration of this theory would impact everything, even up to the earliest moments of the Universe. Such a massive undertaking is largely discouraged precisely because of its scale. It seems unlikely that a theory which has worked so accurately for everything else would be incorrect. A more likely solution would be that our understanding of dark matter is incorrect. Most of the current detectors for dark matter assume that dark matter exists as some weakly interacting particle that may collide with the detector. However, other theories for dark matter are currently being developed, such as primordial black hole remnants or even dark stars. While these theories are speculative, they demonstrate the possibility of alternate theories. A final potential solution would be the simplest. Similar to the accidental discovery of Pluto, it is possible that the observations are flawed in some way. There is currently no evidence outside of dark matter to suggest this, but I felt that it was worth mentioning for the sake of completeness.

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