Exploring the low mass frontier in dark matter direct detection

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Outline

1. Why light dark matter?

2. Direct detection of light dark matter

3. Low-threshold targets for $M=\text{meV-MeV}$
   
   a. absorption in semi/super-conductors
   
   b. scattering in liquid helium
Dark matter puzzles

Solar neighborhood: $\rho_\chi \approx \frac{0.4 \text{ GeV}}{\text{cm}^3}$

Some new particle physics is needed
Directions

• Standard Model has other unresolved questions - use as a guide for dark matter.

• Look more broadly for a dark sector. Generically, this would be as rich as the Standard Model.
WIMP dark matter

WIMP (Weakly Interacting Massive Particle)

Relic abundance of dark matter today set by weak-scale interactions in the early universe

\[ M = 10 \text{ GeV} - 10 \text{ TeV} \]
Mass scale of dark matter?

10^{-22} \text{ eV} \quad \text{meV} \quad \text{eV} \quad \text{keV} \quad \text{MeV} \quad \text{GeV} \quad \text{TeV}

Light bosonic DM

Many recent theory ideas

Many proposals for detection

WIMP

coherent light boson searches (e.g. ADMX, CASPER)

Nuclear recoil in direct detection
sub-GeV dark matter

light mediators

\[ \chi \rightarrow Z' \]

3 to 2 annihilation, SIMPs

\[ \text{DM} \rightarrow \text{DM} \]

asymmetric

\[ \text{DM} \rightarrow \text{SM} \]

sub-keV non-thermal

\[ V(\phi) \]

- e.g. Fayet, Pospelov et al. 2007
- e.g. Nussinov, Barr, Kaplan et al.
- e.g. Pospelov et al. 2008, Arias et al. 2012
Mass scale of dark matter?

$10^{-22} \text{ eV}$

meV eV keV MeV GeV TeV

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Light bosonic DM

Light thermal
Asymmetric
SIMPs

WIMP

$V(\phi)$

coherent light boson searches
(e.g. ADMX, CASPER)

semiconductors

superconductors

see also: graphene, scintillators, chemical bonds, …

helium

Nuclear recoil in direct detection
2. Direct detection of light dark matter
Direct detection of WIMPs

Energy deposited from WIMP in nuclear recoil:

\[ E_R \sim \frac{\mu^2_{\chi N} v^2}{m_N} \sim 1 - 100 \text{ keV} \]

Typical dark matter velocity \( v \sim 10^{-3} \)

Heat (phonons), ionization, scintillation from recoiling nucleus
Direct detection of WIMPs

Typical threshold in experiment: > 1 keV recoil energy

![Graph showing the spin-independent elastic WIMP-nucleon cross section](image_url)

- **CDMSlite 2015**
- **SuperCDMS 2014**
- **PandaX 2015**
- **DarkSide–50 2015**
- **XENON100 2012**
- **LUX 2014**

The graph illustrates the cross-section limits for WIMPs, with the 2015 (LUX) result showing significant improvements compared to earlier experiments. The typical threshold in the experiment is set at > 1 keV recoil energy.
Detecting light dark matter

Look for electron recoils

- Below ~ 1 GeV, inefficient energy transfer to nuclei.
- Idea applied in: Xenon, semiconductors...

Essig, Mardon, Volansky 2011
Electron recoils

- Electron interactions already constrained with Xenon10 low-threshold analysis, search for DM ionization signal

\[ E_{th} \sim 12 \text{ eV} \]
Electron recoils

Electronic band structure

$E_F \sim \text{meV gap in superconductor}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Band Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>$\sim \text{eV}$</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>$\sim 10 \text{ eV}$</td>
</tr>
<tr>
<td>Insulator</td>
<td>(\text{Xe})</td>
</tr>
</tbody>
</table>

Al, Ge, Si
Gapless excitations

Long wavelength acoustic phonons have linear dispersion:

\[ \Omega = c_s |\vec{Q}| \]

- Lattice vibrations in a solid
  \[ c_s \sim 10^{-5} \quad \text{in aluminum} \]

- Density perturbations in a liquid
  \[ c_s \sim 10^{-6} \quad \text{in helium} \]
Low-threshold targets

Semiconductors

- $E_{th} \sim$ eV, electron+phonon
- Reach MeV DM (scattering)
- Used in DAMIC, SuperCDMS, …

Superconductors

- $E_{th} \sim$ meV, electron+phonon
- Reach keV DM (scattering)

Helium

- $E_{th} \sim$ meV, phonons
- Reach keV DM (scattering)
3a. Absorption of light bosonic dark matter

with:

Yonit Hochberg
Kathryn Zurek

1604.06800, 1608.01994
sub-keV bosonic dark matter

- **Candidates:**
  - Hidden photon
  - Pseudoscalar (axion)
  - Scalar

- **Coherent field below** $m \sim \text{eV}$

  Local DM density: $0.4 \text{ GeV/cm}^3$

  Occupation number is high:

  $$\frac{\rho_{DM}}{m_{DM}} \gg \lambda_{dB}^{-3}$$

- **Non-thermal relic abundance, e.g. "misalignment"**

  $$\rho_{DM} = \frac{1}{2}m_{DM}^2\phi_0^2$$

  $\phi_0$ — field amplitude today

  $$V(\phi)$$
Absorption

Absorption from halo
• mono-energetic
• doesn’t require coherent field

Solar emission
• ~keV energies
• “axio-electric” effect

Photoelectric effect:

Dimopoulos, Starkman, Lynn 1986
Pospelov, Ritz, Voloshin 2008
DM absorption in materials

Typical electron in material has $k \sim \text{keV}$. Need momentum transfer $q \sim 100 \text{ m}_X$ in absorption.

- **Atomic ionization**
  - Ex: Xenon, ionization energy = 12 eV

- **Absorption on a crystal/solid**
  - Rely on band structure
  - Phonon emission

Relate the DM absorption rate to photon absorption rate:

$$\langle n_e \sigma_{\text{abs}} v \rangle_{\text{DM}} \propto \langle n_e \sigma_{\text{abs}} v \rangle_{\gamma} = \sigma_1$$

(photon absorption, conductivity $\sigma$)
Conductivity

• Polarization tensor in medium:

\[ \Pi^{\mu\nu} = e^2 \langle J_{\text{EM}}^{\mu\dagger}, J_{\text{EM}}^{\nu} \rangle \quad \Pi^{\mu\nu}(\vec{q}, \omega) = \Pi(\omega) \sum_{i=1,2} \epsilon_i^{T\mu} \epsilon_i^{T\ast\nu} + \Pi(\omega) \epsilon_i^{L\mu} \epsilon_i^{L\nu} \]

• Related to optical conductivity

\[ \vec{J} = \hat{\sigma} \vec{E} \quad \Pi(\omega) \approx -i\hat{\sigma} \omega \]

Real part gives effective mass, imaginary part gives absorption:

\[ \text{Re} \ \Pi(\omega) \approx \omega_p^2 = \sigma_2 \omega \quad - \frac{\text{Im} \ \Pi(\omega)}{\omega} = \sigma_1 = \langle n_e \sigma_{\text{abs}} v \rangle_{\gamma} \]
**Hidden photon dark matter**

**Kinetic mixing in vacuum:**

\[ \mathcal{L} \supset - \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} \]

**Matter coupling:**

\[ A_\mu \rightarrow A_\mu - \kappa V_\mu \rightarrow \kappa e V_\mu J_{EM}^\mu \]

**Absorption rate of halo DM**

\[ R = \frac{1}{\rho} \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \kappa^2 \sigma_1 \]

**Effective kinetic mixing in a material:**

\[ \kappa_{\text{eff}}^2 = \frac{\kappa^2 m_V^4}{[m_V^2 - \text{Re} \Pi(\omega)]^2 + [\text{Im} \Pi(\omega)]^2} \]
• Existing experiments already use Germanium, Silicon targets.

• Current $E_{th} \sim 50$ eV electron recoil.

• $E_{th} \sim$eV could be reached in the near future.
Electron excitations

Optical absorption dominated by direct transitions

Band gap: 0.7 eV (germanium), 1.1 eV (silicon)
Multi-phonon excitation

Optical absorption below the band gap is allowed if (multiple) phonons are excited instead!
Hidden photon dark matter

Stellar constraints

Xenon

Xenon100

$\kappa$ vs $m_V$ (eV)

Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013
Hidden photon dark matter

Stellar constraints

DAMIC
(Si, 0.6 kg-d)

Xenon

Xenon100

CDMSlite
(Ge, 70 kg-d)

Stellar, Xenon10 constraints:
An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013
Hidden photon dark matter

Stellar constraints

An, Pospelov, Pradler 2013, 2014
Redondo & Raffelt 2013

See also:
I. Bloch, Tien-Tien Yu, etc 2016
for similar study

Stellar, Xenon10 constraints:

CDMSlite
(Si, 0.6 kg-d)
Xenon100
(Ge, 70 kg-d)
Figure 1. Schematic designs for superconducting detectors that are sensitive to DM-electron scattering.

Left: Quasiparticles produced by a recoiling electron in a large aluminum absorber are collected by tungsten quasiparticle collection fins and then their energy is sensed by a TES.

Right: Athermal phonons produced by a recoil electron in a large tantalum absorber are collected by aluminum collection fins and then their energy is sensed by a TES.

Athermal phonons and quasiparticles have very long lifetimes, and as such can potentially be collected before they thermalize. Thus in the systems we consider, detection of DM operates via the breaking of Cooper pairs in a superconducting target. We consider this idea in more detail next.

2.2 Detector design with milli-eV sensitivity

Our detector concept is based on collecting and concentrating long lived athermal excitations from DM interactions in a superconducting target absorber onto a small volume (and thus highly sensitive) sensor. The collection and concentration of long lived excitations is a general concept that has been a core principle of detector physics, from ionization in semiconductor CCDs to athermal phonon collection in CDMS. Here we propose that this general detection philosophy be applied in large volume (very pure, single crystal) superconductors to search for DM with mass as low as the warm DM limit of a keV using standard superconducting sensor technology that has been pushed to its ultimate theoretical sensitivity. A schematic of two proposed detector concepts for light dark matter, that we describe in greater detail through the remainder of this section, is shown in Fig. 1.

Detection of dark matter in such detectors is comprised of a three part process:

• Dark Matter Scattering on Target Absorber and Subsequent Excitation Production. The DM particle scatters on an electron in the target metal or superconducting absorber. In subsequent interactions, the recoil energy is converted into long lived athermal phonons and quasiparticles.

• Collection of Excitations. The resulting excitations must be collected and concentrated onto a small volume (and thus very sensitive) sensor; this is typically done via 'collection — 6 — Measurement by sensitive bolometer (TES)

• Noise is going to be an issue, backgrounds at low energies unknown.
Why superconductors?

Cooper pairing:

- Small band gap (< meV)
- Long-lived quasiparticle (electron) excitations
- Cooper pairs decoupled from thermal noise

\[ \Delta = \frac{3}{2} T_c \approx 0.3 \text{ meV} \]
Superconductors

\[ \Delta = \frac{3}{2} T_c \approx 0.3 \text{meV} \quad \text{in aluminum} \]

Because of gap, excitations (broken Cooper pairs) take a long time to recombine!
Absorption via phonon emission

The phonon can carry large momentum, with small energy.

Phonon energy:
\[ \Omega = c_s |\mathbf{Q}| \]

Speed of sound in aluminum:
\[ c_s \simeq 6320 \text{ m/s} \sim 2 \times 10^{-5} \]

Theory uncertainties:
- phonon dispersion, coupling
- impurities
Suppression in absorption rate, reduced effective kinetic mixing

\[ \kappa_{\text{eff}}^2 \approx \frac{\kappa^2 m^4_V}{\omega_p^4} \]

\[ \omega_p \approx 12.2 \text{ eV} \]

Hidden photon dark matter

Stellar, Xenon10 constraints:

An, Pospelov, Pradler 2013, 2014

Redondo & Raffelt 2013
Pseudoscalar DM

Pseudoscalar dark matter

\[ g_{\text{aaee}} = C \frac{e_m e_a}{f_a} \]

Xenon100

White dwarf

(White dwarf cooling hint?)

QCD axion

\[ a \rightarrow \gamma \gamma \]

Al, 1 kg-yr

1 kg-yr, Ge

1 kg-yr, Si

10^{-8}

10^{-9}

10^{-10}

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-3}

10^{-2}

10^{-1}

10^{0}

10^{1}

10^{2}

10^{3}

\[ m_a [\text{eV}] \]
3b. DM scattering in superfluid He

in progress, with:
Simon Knapen
Eckhard Krotscheck
Kathryn Zurek
Why superfluid Helium?

- Long-lived quasiparticle excitations
- Potential detection of meV energy depositions

![Graph showing dispersion curves for superfluid helium excitations.](image)

**FIG. 1.** Left: We compare the measured dispersion curve for single excitations in superfluid helium (solid black line) with the Bijl-Feynman relation for excitations, \( q^2 / (2m_\text{He} S(q)) \) (solid red line). The measured dispersion curve comprises the phonon modes at low \( q \) and the maxon and roton at high \( q \), but does not include the broad multi-excitation response centered around the free-particle dispersion at high \( q \). In the Bijl-Feynman theory, which does track the free-particle dispersion at high \( q \) (shown as the dotted blue line), these high \( q \) modes are treated as single-particle resonant excitations.

Right: \( S(q) \) data from neutron scattering experiments (cite). We also show \( S(q) \) for a dilute Bose gas, which misses both the roton/maxon excitations and also has the incorrect behavior at high \( q \).

[TL: It might be confusing if we include calculations with this \( S(q) \), since it gives a much lower rate and doesn't capture the region where the rate is largest due to missing the rotons/maxons.)]
Detector concept

- Operation at 10-100 mK
- Evaporation and amplification \( \times 10^{-40} \) down to 0.6 meV!
- Measure scintillation at energies \( \approx 100 \text{ eV} \)
- Superfluid helium used for ultracold neutrons, etc.
- Easy to obtain and purify
Scattering in Helium

• Neutron scattering:

\[
\frac{d^2 \sigma}{d\omega d\Omega} \equiv \frac{\sigma^n k_f}{4\pi k_i} S(Q, \omega)
\]

Dynamic structure factor:

\[
S(Q, \omega) = \frac{1}{n_0} \sum_F |\langle F | n_Q | I \rangle|^2 \delta(E_F - E_I - \omega)
\]

response of the fluid to a density perturbation with momentum transfer \(Q\), energy \(\omega\)

• Apply directly to dark matter scattering

\[
\frac{d^2 \sigma}{d\omega d\Omega} \equiv \frac{\sigma^n k_f}{4\pi k_i} S(Q, \omega)
\]

Density operator:

\[
\hat{n}_k = \frac{1}{\sqrt{N}} \sum_i e^{i k \cdot r_i}
\]
Multiphonon excitations

Dynamic structure factor $S(Q,\omega)$

Fig. 1.6. The broad high-energy $\ldots$article (or multiphonon) structure in $S(Q,\omega)$ at intermediate $Q$ at 1.1 K and SVP. The “peak” position and its width are indicated [Source: Cowley and Woods, 1971].

Kinematics allows larger energy $\omega$ deposited, even for small $Q$.
FIG. 21. The figure shows a comparison between our $S(k,\hbar\omega)$ (solid line) and the experimental one [9] (stars) at a momentum transfer of $k = 2.4 \, \text{Å}^{-1}$. The experimental values have been normalized to satisfy the $m_0$ sum rule.

Theorem vs. experiment

Dynamic structure factor $S(Q,\omega)$

FIG. 22. Same as Fig. 21. The figure shows a comparison between our calculated values for $S(Q,\omega)$ and the experimental data. The experimental values have been normalized to demonstrate the overall agreement with our theoretical results.
Sensitivity to light DM

Two-phonon scattering rate

Dominant scattering into two rotons

Extends reach to lower mass DM! (~10 meV resolution)
Conclusions

• Current direct detection experiments focus on WIMP dark matter at or above 1 GeV

• New ideas (for models and detection) explore many orders of magnitude in mass!

Absorption of bosonic DM down to meV

Scattering of < MeV DM