The Migdal Effect in H_2^+

Ian Harris

University of Illinois at Urbana-Champaign

Yoni Kahn, Carlos Blanco, Jesus Perez Rios, Benjamin Lillard

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Outline

Dark Matter

- 27 % of the universe
- (Very) wide range of masses predicted

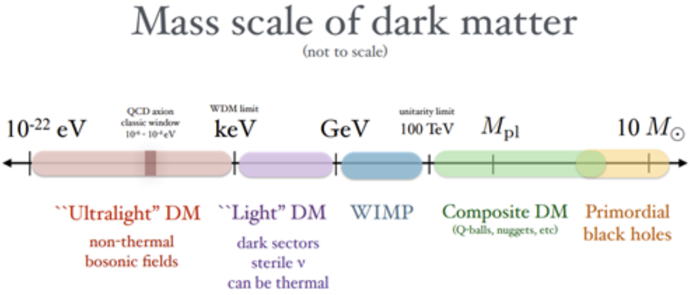


Figure: DM mass scale.[1]

[1] Lin; arXiv:1904.07915v1

Daily Modulation

- Great way to distinguish signal from background
- Sidereal vs. Earth day
- Standard Halo Model (SHM) ansatz for DM velocity distribution[2]
  - Gives time dependence over a sidereal day

[2] Evans, O'Hare, McCabe; arXiv:1810.11468v2

Migdal Effect

- Particle-nucleus scattering
  - Momentum transfer displaces nucleus, induces electronic transition probability

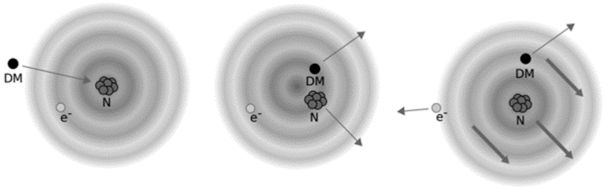


Figure: Migdal effect for a single atom. In this case, the electron is emitted.[3]

- Electron can be emitted or transition to a higher energy state
  - Need to determine initial, final wavefunctions

[3] Dolan, Kahlhoefer, McCabe; arXiv:1711.09906v2

Semiconductor Migdal Effect

- Nucleus is not a free particle, so qualitatively different in bound systems

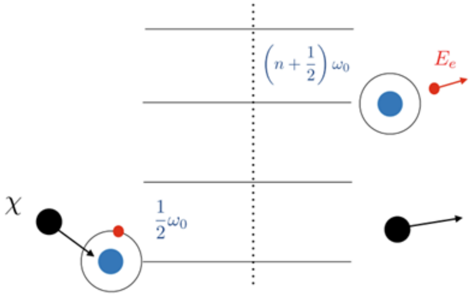


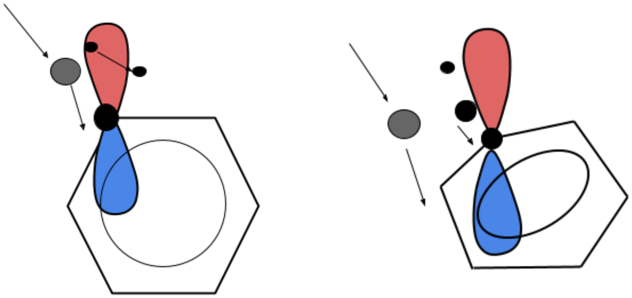
Figure: Migdal Effect in a lattice, approximated by a harmonic potential[4]

[4]Kahn, Krnjaic, Mandava; arXiv:2011.09477v1

Electron Scattering vs. Migdal Effect

- DM can couple to electrons and/or nuclei
- Electron, Migdal scattering have identical final state: recoiling atom, excited electron
- Migdal rate can exceed electron scattering rate[5]:

$$\frac{dR_M/d\vec{q}}{dR_e/d\vec{q}} > Z^2 \left(\frac{m_e}{m_N}\right)^2 (\vec{q}r_a)^2 \tag{1}$$



[5] Baxter, Kahn, Krnjaic; arXiv:1908.00012v3

Electron Scattering: Organic Molecules and Anisotropy

- Organic crystals can show directional dependence in scattering rate
  - Improves detection ability
- Linear Combination of Atomic Orbitals (LCAO) method for electronic states[6]

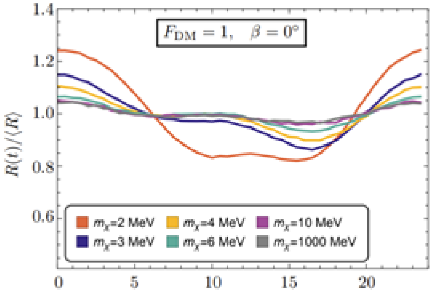


Figure: Daily modulation of electron scattering in trans-stilbene crystals[7]

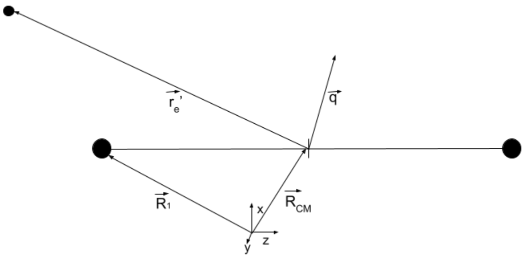
- Goal: Exploit anisoptropy for the Migdal Effect

[6] Blanco, Kahn, Lillard, McDermott; arXiv:2103.08601v2

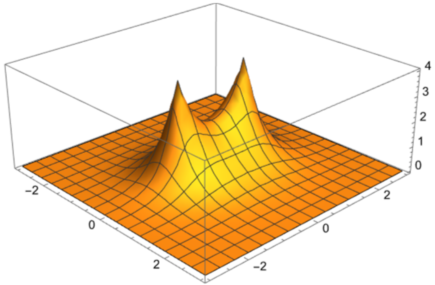
[7] Blanco, Kahn, Lillard, McDermott; arXiv:2103.08601v2

H_2^+ Wavefunctions

- H_2^+ is a toy model; goal is to generalize results to realistic detector molecules
- Electronic wavefuntions numerically determined using the ”shooting method”[8]



(a) Coordinate diagram for H_2^+



(b) Ground state of H_2^+

[8] Grivet, The Hydrogen Molecular Ion Revisited

Center of Mass Recoil

- General probability amplitude $\langle f| \exp\left[i\vec{q}\cdot\vec{R}\right]|i\rangle$ becomes

$$M(q) \simeq 2\,\langle \phi_{e'[\rho_0]}|\exp\left[i\frac{m_e}{2m_N+m_e}\vec{q}\cdot\vec{r}'_e\right]|\phi_{e[\rho_0]}\rangle \tag{2}$$

- Nuclear coordinate contains relative electron coordinate

Center of Mass Results

- Directional dependence yields time dependence in a crystal

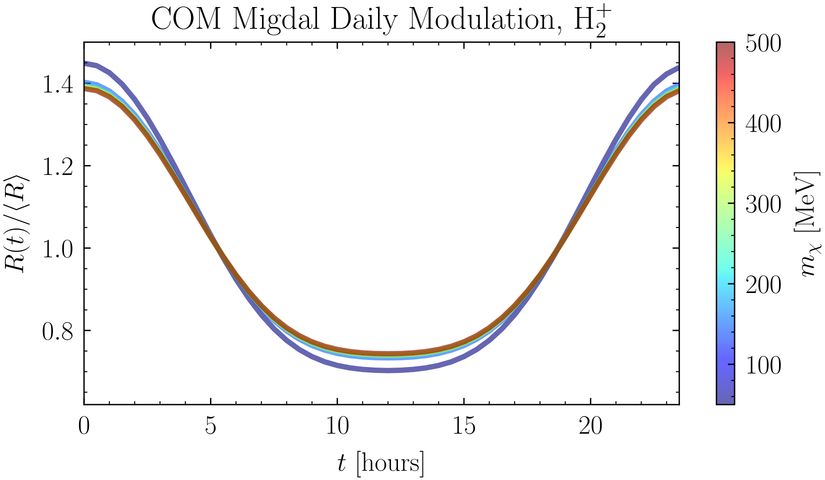


Figure: Daily modulation for center of mass recoil calculations. Across an order of magnitude in mass, $\mathcal{O}(1)$ modulation is expected.

Non-Adiabatic Coupling

- Factorize 3-body Schrodinger equation:[9]

$$\frac{1}{m_e}\nabla^2\Psi + \frac{1}{m_N}\Sigma_k\nabla_k^2\Psi + 2(E - V)\Psi = 0 \tag{3}$$

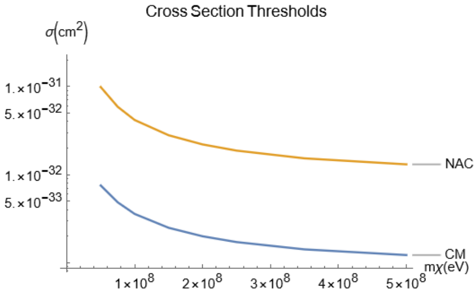
$$\Psi(\vec{r}) = \psi(\vec{r})\chi(\vec{r}) \tag{4}$$

- Terms beyond Born-Oppenheimer treated as perturbations
- If we sum over all states, transition probability is isotropic!

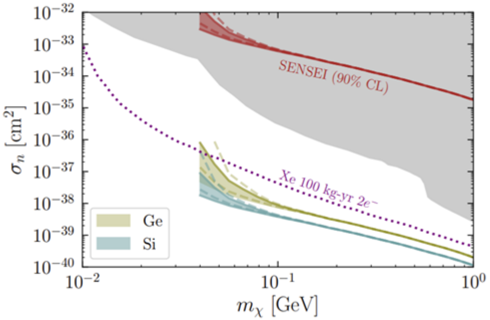
$$P(\text{any electronic transition})_{\text{NAC}} = \frac{q^2}{M_{\text{total}}^2\omega^2}\int d^3r'_e \left(\frac{\partial\psi_0(\vec{r'_e})}{\partial\rho}\right)^2_{\rho=\rho_0} \tag{5}$$

[9] Lovesey, Bowman, Johnson; Z. Phys. B - Condensed Matter 47, 137-147 (1982)

Thresholds for H_2^+ and Semiconductors



(a) H_2^+ (preliminary)



(b) Semiconductor

Figure: H_2^+ vs. semiconductor[10] detection thresholds

[10] Knapen, Kozaczuk, Lin; arXiv:2011.09496v1

Summary

- The Migdal Effect, alongside electronic scattering, can be used to study sub-GeV dark matter
- Daily modulation in anisotropic systems helps to distinguish signal from background
- The two distinct physical effects that I studied in H_2^+ could eventually be studied in real detector molecules