Karlsruher Institut für Technologie

# Migdal effect in helium

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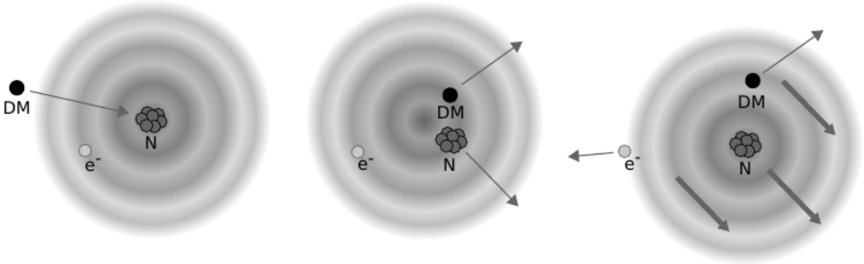
# Migdal effect in direct dark matter detection

- NR: atom recoils as a unit
- Reality:
  - High recoil velocity
  - Electrons only follow the atom after some time
  - QM yields ionization (and excitation) probability
- Migdal effect: ionization of an atom via nuclear recoil






Dolan, Kahlhoefer & McCabe

# Kinematics

- Energy conservation:

$$\frac{\vec{p}\vec{q}}{m_\chi} = \frac{pq}{m_\chi}\cos\theta = \frac{q^2}{2\mu_{\chi N}} + E_{EM}$$

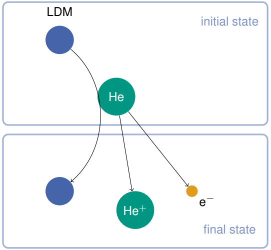
- Minimal velocity:

$$v_{min} = \frac{q}{2\mu_{\chi N}} + \frac{E_{EM}}{q}$$
$$= \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}} + \frac{E_{EM}}{\sqrt{2m_N E_R}}$$

- Condition for dark matter detection:

$$v_{\text{min}} < v_{\text{max}} = v_{\text{esc}} + v_{\text{E}}$$

$$E_i = \frac{p^2}{2m_\chi} = \frac{1}{2}m_\chi v^2$$




$$E_f = \frac{(\vec{p}-\vec{q})^2}{2m_\chi} + \frac{q^2}{2m_N} + E_{\text{EM}}$$

# Migdal effect: motivation

$$v_{max} = \frac{q}{2\mu_{\chi N}} + \frac{E_{EM}}{q}$$

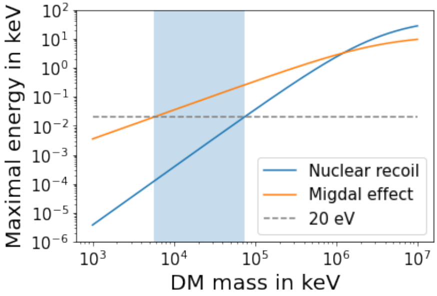
$$= \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}} + \frac{E_{EM}}{\sqrt{2m_N E_R}}$$

Nuclear recoil:

$$E_R^{\text{max}} = \frac{2\mu_{\chi N}^2 v_{\text{max}}^2}{m_N}$$

Migdal effect:

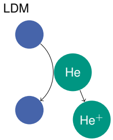
$$E_{EM}^{\text{max}} = \frac{1}{2}\mu_{\chi N} v_{\text{max}}^2$$




| $E_{\text{th}}$ | $m_{NR}^{\text{min}}$ | $m_{Mig}^{\text{min}}$ |
|---|---|---|
| 20 eV | 74 MeV | 5.7 MeV |
| 10 eV | 52 MeV | 2.9 MeV |

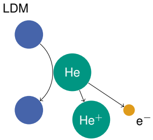
# Dark matter direct detection: nuclear recoils

Nuclear recoil




$$R = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_{E_R^{\mathrm{min}}}^{E_R^{\mathrm{max}}} |F_N|^2 g\left(v_{\mathrm{min}}\right) \mathrm{d}E_R$$

Migdal effect




$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_0^{E_R^{\mathrm{max}}} |F_N|^2 \boxed{\sum_{n\kappa} \frac{\mathrm{d}p_v\left(n\kappa \to E_e\right)}{\mathrm{d}E_e}} g\left(v_{\mathrm{min}}\right) \mathrm{d}E_R$$

# Differential event rate per deposited EM energy

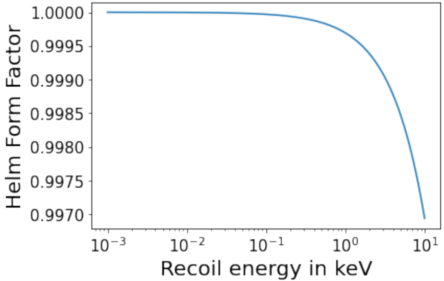
$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \boxed{\frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2}} \int_0^{E_R^{\max}} \boxed{\left|F_N\right|^2} \sum_{n\kappa} \boxed{\frac{\mathrm{d}p_v\left(n\kappa \rightarrow E_e\right)}{\mathrm{d}E_e}} \boxed{g\left(v_{\min}\left(E_R, E_{EM}\right)\right)} \mathrm{d}E_R$$

### Dark matter physics and target atom

- This term is a prefactor which depends on the physics of dark matter and the target atom

### Helm form factor

- This term contains the properties of interactions with an atom
- Helm form factor: analytical expression from [Lewin & Smith]

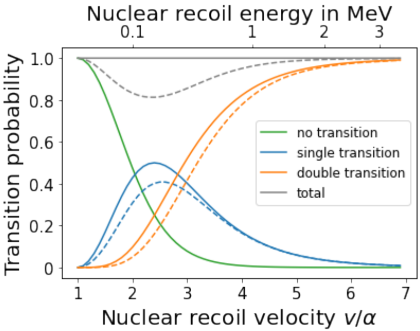


# Differential event rate per deposited EM energy

$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_0^{E_R^{\max}} |F_N|^2 \sum_{n\kappa} \frac{\mathrm{d}p_v\left(n\kappa \to E_e\right)}{\mathrm{d}E_e} g\left(v_{\min}\left(E_R, E_{EM}\right)\right) \mathrm{d}E_R$$

Migdal effect

- This term reduces the rate compared to the NR case and contains all information regarding the Migdal effect
- 3 cases:
  - Single ionization (SI)
  - Single ionization and excitation (SE)
  - Double ionization (DI)
    $\rightarrow$ integration over energy of the 2nd electron
- Data from Cox et al.
- Derivation in Ibe et al.



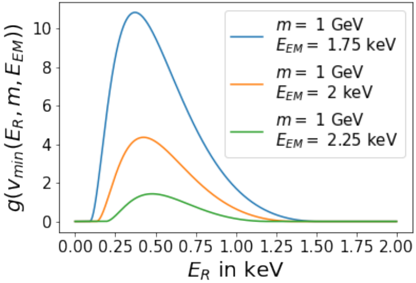
# Differential event rate per deposited EM energy

$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_0^{E_R^{\max}} |F_N|^2 \sum_{n\kappa} \frac{\mathrm{d}p_v\left(n\kappa \to E_e\right)}{\mathrm{d}E_e} \boxed{g\left(v_{\min}\left(E_R, E_{EM}\right)\right)} \, \mathrm{d}E_R$$

## Halo velocity distribution

- This term contains all of the purely kinematic constraints
- Placement in the sum ($E_{EM}$ depends on the binding energy of the Migdal electron)
- Standard halo model (Barger et al.) with:
  - $v_{\text{obs}} = 250\,\text{km}\,\text{s}^{-1}$
  - $v_0 = 238\,\text{km}\,\text{s}^{-1}$
  - $v_{\text{esc}} = 544\,\text{km}\,\text{s}^{-1}$

$$g\left(v_{\min}\right) = \int_{v_{\min}}^{v_{\text{esc}}} \frac{f\left(\vec{v}_\chi + \vec{v}_{\text{obs}}\right)}{\left|\vec{v}_\chi\right|} \mathrm{d}^3 \vec{v}_\chi$$



# Result

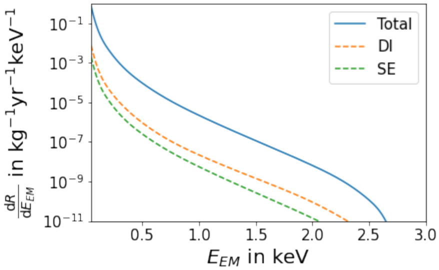
$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_0^{E_R^{\max}} |F_N|^2 \sum_{n\kappa} \frac{\mathrm{d}p_v\,(n\kappa \to E_e)}{\mathrm{d}E_e} g\left(v_{\min}(E_R, E_{EM})\right)\, \mathrm{d}E_R$$

Assumptions

- $\rho_\chi = 0.3\,\mathrm{GeV\,cm^{-3}}$
- $\sigma_n = 1 \cdot 10^{-40}\,\mathrm{cm}^2$
- $m_\chi = 1\,\mathrm{GeV}$

Observations:

- SI dominates
- DI and SE suppressed by more than one order of magnitude
- Different assumptions affect scaling and shape

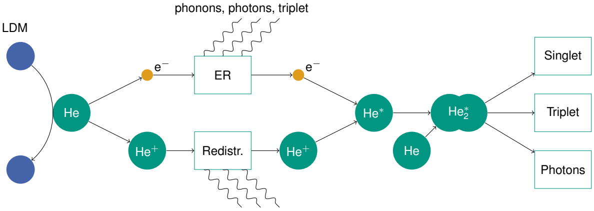


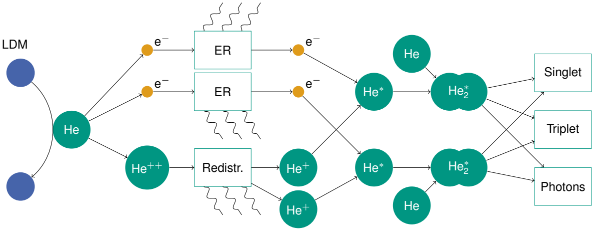
# Migdal effect: signals in helium

- ER for every ionized electron
- Excimer for every recombination
- Current assumption: nucleus at rest after recoil

Processes:

- SI: excimer + ER
- SE: SI + energy from deexcitation (problem: energy is not quantified in the data)
- DI: double SI (looks most likely like one SI)



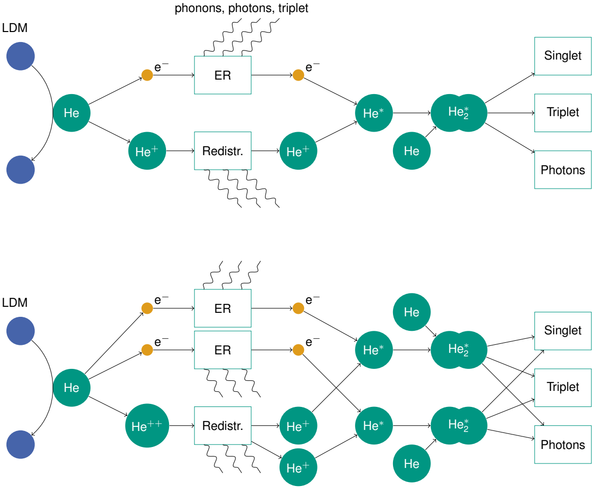
# Migdal effect: signals in helium

Signal:

- Triplet: no sensitivity (due to large timescale)
- Singlet: decays -> photons
- ER: produces triplet, singlet, quasipaticles and photons

**Note**

One excimer will always be produced. Lowering the threshold further than the binding energy will not result in access to smaller DM masses.



# Reconsideration: motivation

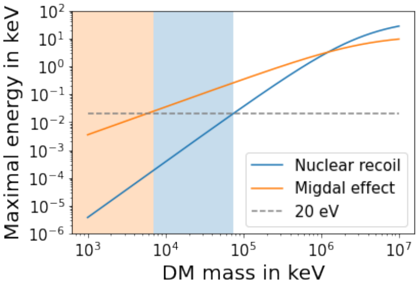
Threshold:

$$E_{EM} = E_e + E_b \geq E_{th}$$
$$E_e^{\min} = E_{th} - E_b \geq 0$$

This gives the minimal mass:

$$m_{Mig}^{\min} \geq 5.7\,\mathrm{MeV}$$

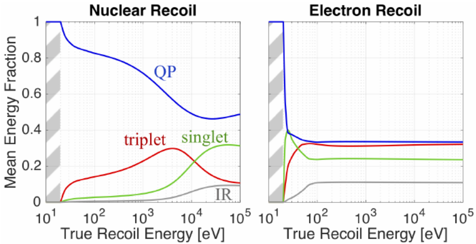
| $E_R^{\min}$ | $m_{NR}^{\min}$ | $m_{Mig}^{\min}$ |
|---|---|---|
| 20 eV | 74 MeV | 5.7 MeV |
| 10 eV | 52 MeV | ~~2.9 MeV~~ 5. 7 MeV |



# Exclusion plot

Assumptions:

- NR and ER energy partition according to Hertel et al.
- No triplet detection
- Singlet:triplet ratio is 1:1
- Photons are always detected
- Gaussian energy resolution with $\sigma = 5\,\text{eV}$ (not used in the following plot)



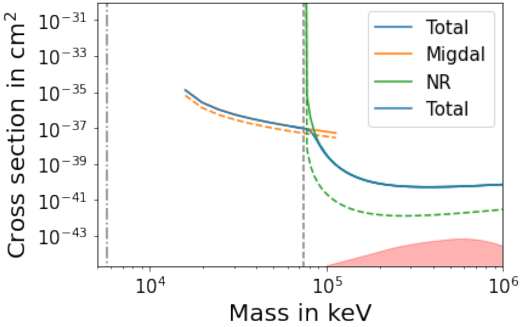

Hertel et al.

$$s_m^{\text{Mig}}\left(E_{EM}, E_R\right) = \left(\sum_{i \in S_{\text{ER}}} p_{i,\text{det}} p_i(E_e) + \frac{1}{2} p_{\text{singlet,det}}\right)$$

$$s_m^{\text{NR}}\left(E_{EM}, E_R\right) = \sum_{i \in S_{\text{NR}}} p_{i,\text{det}} p_i(E_e)$$

# Exclusion plot

- Exposure of 1 kg yr
- $E_{th} = 20\,\mathrm{eV}$
- Dashed lines: cross section with perfect detector
- Neutrino floor O'Hare



# Conclusion

- Migdal effect enhances the accessible parameter space depending on the energy threshold
- The energy threshold can improve the detection up to the binding energy
- Improvements on the signal model?
  - Form factor
  - Ionization probabilities (wavefunction, electron energies in SE)
  - Signal channels
  - Detector resolution
- The Migdal effect can be included in the neutrino floor

# Literature

- Migdal effect
  - Ibe et al.: Migdal Effect in Dark Matter Direct Detection Experiments.
  - Dolan, Kahlhoefer, McCabe: Directly detecting sub-GeV dark matter with electrons from nuclear scattering.
  - Cox et al.: Precise predictions and new insights for atomic ionisation from the Migdal effect.
- Halo model
  - Barger et al.: Electromagnetic properties of dark matter: dipole moments and charge form factor.
  - Fitzpatrick, Zurek: Dark Moments and the DAMA-CoGeNT Puzzle.
- Form factor
  - Lewin, Smith: Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil.
- Energy partition
  - Hertel et al.: A Path to the Direct Detection of sub-GeV Dark Matter Using Calorimetric Readout of a Superfluid 4He Target.
- Neutrino floor
  - O'Hare: Fog on the horizon: a new definition of the neutrino floor for direct dark matter searches.
  - Herrera: A neutrino floor for the Migdal effect.

# Exclusion plot: short mention of statistics

Statistical Assumptions:

- No events observed
- No background events observed

Poisson distribution gives the condition:

$$0.1 < p(N_{obs} = 0) = \exp(-N_{exp}) = \frac{N_{exp}^{N_{obs}}}{N_{obs}!} \exp(-N_{exp})$$

$$N_{exp} \gtrapprox 2.3$$

# Treatment of energies

Nuclear recoil

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \left|F_N\right|^2 g\left(v_{\min}\left(E_R, E_{EM}\right)\right)$$

$$R = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_{E_{\text{th}}}^{E_R^{\max}} \left|F_N\right|^2 g\left(v_{\min}\left(E_R, E_{EM}\right)\right) s_m^{\text{NR}}\left(E_R\right) \, \mathrm{d}E_R$$

Migdal effect

$$\frac{\mathrm{d}R}{\mathrm{d}E_{EM}} = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_0^{E_R^{\max}} \left|F_N\right|^2 \sum_{n\kappa} \frac{\mathrm{d}p_v\left(n\kappa \to E_e\right)}{\mathrm{d}E_e} g\left(v_{\min}\left(E_R, E_{EM}\right)\right) \, \mathrm{d}E_R$$

$$R = \frac{\rho_\chi A^2 \sigma_n}{2 m_\chi \mu_{\chi N}^2} \int_{E_{\text{th}}}^{E_{EM}^{\max}} \int_0^{E_R^{\max}} \left|F_N\right|^2 \sum_{n\kappa} \frac{\mathrm{d}p_v\left(n\kappa \to E_e\right)}{\mathrm{d}E_e} g\left(v_{\min}\left(E_R, E_{EM}\right)\right) s_m^{\text{Mig}}\left(E_{EM}\right) \, \mathrm{d}E_R \mathrm{d}E_{EM}$$