Axion-induced EDMs in paramagnetic systems

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Overview:

Axions, ALPs & pseudoscalar fields

- Conventional searches: axion–photon coupling
  - Quadratic (+higher) in coupling

Axion–Gluon Coupling: Linear effects
[Graham, Rajendran, PRD **84**, 055013 (2011)]

- Oscillating EDMs in diamagnetic systems: CASPEr
  [Budker, Graham, Ledbetter, Rajendran, Sushkov, PRX **4**, 021030 (2014)]

New linear effects

- Axion/ALP–Gluon, –Fermion, *and* –Photon
- Oscillating EDMs in paramagnetic systems

Tests of *CPT*

- Limits on SME parameters

WIMP–electron scattering: atomic ionisation

- Implications for DAMA annual modulation

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Axions

Strong *CP* Problem

- Observed lack of *CP*-violation in QCD ($\theta < 10^{-10}$)
- Resolution: Pseudoscalar particle "Axion" [1]

Axion Condensate

- Classical, oscillating field $a(t) = a_0 \cos(m_a t)$
- Cold dark matter candidate [2]

[1] Peccei, Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[2] Preskill, Wise, Wilczek, Phys. Lett. B **120**, 127 (1983); Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); Dine, Fischler, Phys. Lett. B **120**, 137 (1983).

Axion–SM Couplings

Anomalous effective couplings to SM particles:

$$\overbrace{\frac{a}{f_a}F^{\mu\nu}\widetilde{F}_{\mu\nu}}^{\textit{Photon}} \qquad \overbrace{\frac{a}{f_a}G^{\mu\nu}\widetilde{G}_{\mu\nu}}^{\textit{Gluon}} \qquad \overbrace{\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi}^{\textit{Fermion}}$$

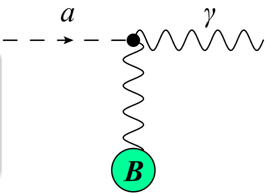
$$a(t) = a_0\cos(m_a t) \qquad \frac{1}{f_a} \approx 2\times 10^{-20}\ \mathrm{eV}^{-1}\ \left(\frac{m_a}{10^{-4}\ \mathrm{eV}}\right)$$

Classical Region: $m_a \sim 10^{-6}\ -\ 10^{-4}$ eV (∼MHz – GHz)
Anthropic Region: $m_a \sim 10^{-10}\ -\ 10^{-8}$ eV (∼kHz – MHz)

- Saturates DM density: $\Rightarrow a_0/f_a \sim 4\times 10^{-19}$ (QCD axion)
- (In general, DM ALP, f_a free parameter, $a_0 \sim 1/m_a$)

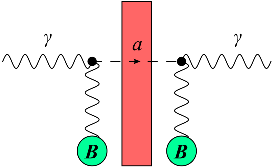
Searching for Axions

"Standard" Searches: Axion–photon coupling



Axion–photon conversion

- e.g. ADMX, CAST, IAXO, ...
- $P_{a\to\gamma} \sim (1/f_a)^2$ *Quadratic*



Light shining through a wall

- e.g. ALPS, BMV, CROWS, ...
- $P_{\gamma\to a\to\gamma} \sim (1/f_a)^4$ *Quartic*

- Good for $\sim$ $f_a < 10^{13}$ GeV

- Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).
- e.g. : depts.washington.edu/admx/, cast.web.cern.ch/CAST/, alps.desy.de/

Emerging Axion Searches:
Schiff Moments and CASPEr

Gluon–coupling: Axion-induced EDMs

- $\theta_{\rm QCD} \to a/f_a \quad \Rightarrow \quad d_n = 1.2 \times 10^{-16}\, \theta \; e\,{\rm cm}$ [1]
- Also produces observable **Nuclear Schiff Moments**
- Dominated by a-induced inter-nucleon force [2]
- Linear in a_0/f_a! Good for $f_a >\sim 10^{16}$ GeV

CASPEr

- Precision magnetometry [3]
- Solid-state, diamagnetic atoms

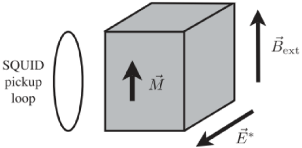


FIG. 1. Geometry of the experiment.

[1] Graham, Rajendran, Phys. Rev. D **84**, 055013 (2011); **88**, 035023 (2013).
[2] Stadnik, Flambaum, Phys. Rev. D **89**, 043522 (2014).
[3] Budker, Graham, Ledbetter, Rajendran, Sushkov, Phys. Rev. X **4**, 021030 (2014).

Magnetic Quadrupole Moments

- As for Schiff moments, $\theta_{\mathrm{QCD}} \to a/f_a \;\Rightarrow$ MQMs

Oscillating EDMs

- P & T Violating nuclear moment $\Rightarrow$ EDMs
- Need $I > 1/2$
- Much larger effect in Paramagnetic Systems

Nuclear Enhancement

- Quadrupole deformation $\Rightarrow$ enhancement (most nuclei!)
- (Schiff moment needs Octopole)

- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. D **90**, 096005 (2014).
- Roberts, Stadnik, Flambaum, *In Preparation*

MQM Sensitivity

$$M \approx np\ \mu\ E\ D_A\ \frac{\sin[(2\mu B_e - mc^2)t/\hbar]}{(2\mu B_e - mc^2)/\hbar}\sin(2\mu B_e)$$

- $\mu_N \rightarrow \mu_e \Rightarrow 10^3$
- $S \rightarrow D_{\rm MQM} \Rightarrow 10^{3\,\rm or\,4}$ (potentially more in special systems)

But:

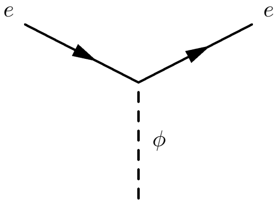
- Paramagnetic $\Rightarrow \tau/\tau = 10^{-6}$

ALP–Electron Interaction

$$\mathcal{L}_{\text{int.}} = \underbrace{\frac{\partial_t a}{f_a}\bar{\psi}\gamma^0\gamma^5\psi}_{P\text{-odd effects (This Work)}} + \underbrace{\frac{\boldsymbol{\nabla}\phi}{f_a}\cdot\bar{\psi}\boldsymbol{\gamma}\gamma^5\psi}_{P\text{-even effects}}$$

Pseudoscalar field – atomic electrons

- Dynamic field: parity-mixing
- Oscillating EDMs (Paramagnetic)
- Need non-zero J



Alkali atoms:

$$d \approx \frac{a_0}{f_a}\alpha_0 m_a^2 \cos(m_a t) \sim 10^{-38}\, e\,\text{cm}$$

- Stadnik, Flambaum, Phys. Rev. D **89**, 043522 (2014); Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. Lett. **113**, 081601 (2014); Phys. Rev. D **90**, 096005 (2014).

ALP–Electron Interaction

Resonance

- Dysprosium, Radium, Diatomic molecules
- Close opposite-parity levels $\Rightarrow\sim 10^4$ enhancement
- Magnetically drive resonance: $E_a - E_b = m_a \Rightarrow$ more?

$$d_{\rm EDM} \simeq -2i \frac{\langle A|e\mathbf{r}|B\rangle\langle B|\gamma^5|A\rangle}{(E_A - E_B + i\Gamma/2)^2 - m^2}\, m^2\, \frac{a_0}{f_a}\, \cos(m_a t)$$

- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. D **90**, 096005 (2014).
- Roberts, Stadnik, Flambaum, *In Preparation*

ALP–Electron Interaction

However, exact relation:

$$\langle a|\gamma^5|n\rangle = i\Delta E_{an}\langle a|\Sigma\cdot r|n\rangle + \langle a|2\gamma^5\hat{K}|n\rangle$$

- Main term, on resonance: $\Delta E = m \gg \Gamma$
  - $D_A \sim \frac{a_0 m}{2f_a}$
  - Independent of m_a (for ALP Dark Matter)
- Main term, off resonance: $\Delta E, \Gamma \ll m$
  - $D_A \sim -\Delta E\frac{2a_0}{f_a}$
- Other terms: $\Delta E' \gg \Gamma, m$
  - $D_A \sim -\frac{m^2}{\Delta E'}\frac{2a_0}{f_a}$

Enhanced by $(m_a/eV)^{-1}$ c.f. alkali $\Rightarrow$ several orders of magnitude

Paramagnetic measurements

Oscillating EDMs in Paramagnetic Systems

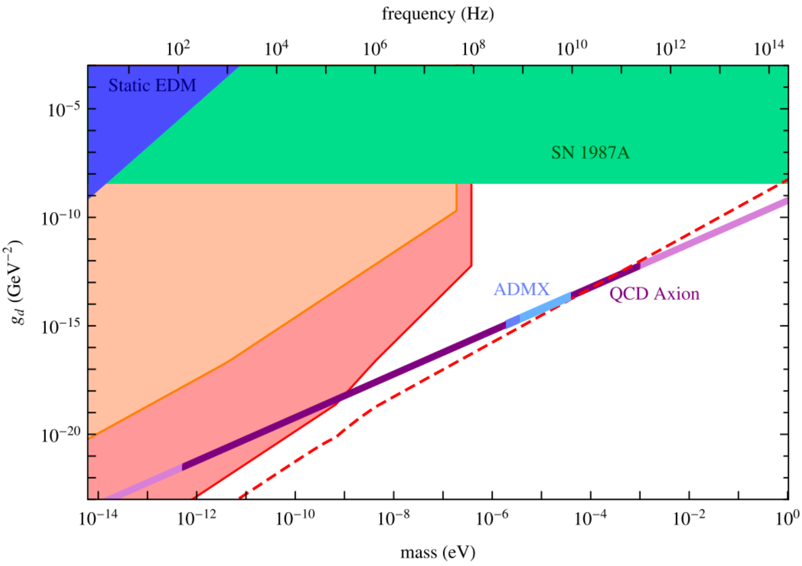
- Axion–Electron dominant mechanism in atoms
- MQM dominant mechanism for solid state (resonance)
- Different parametric dependence

Potential benefits

- Much larger effects than diamagnetics
- ..unpaired spins ⇒ higher systematics

• Different dependence on m_a to CAPSEr
⇒ Complementary!

▶ Roberts, Stadnik, Flambaum, *In Preparation*



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Fermion Interaction

Atomic Parity-Violation

Pseudoscalar field (e.g. axions)

- Oscillating PNC amplitudes
- Observable in Dysprosium?

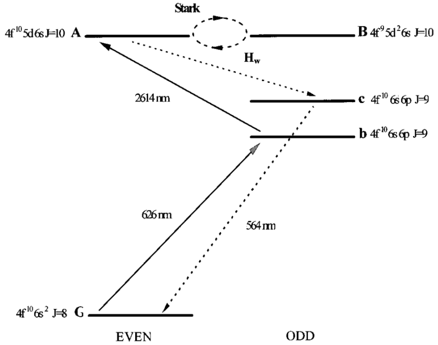
Pseudovector field (from SME[1])

- A static or oscillating field
- Limits from PNC experiments!
- b_0^e from Dy; $b_0^{p,n}$, $d_{00}^{p,n}$ from Cs

Phys. Rev. A 56, 3453 (1997)

Search for parity nonconservation in atomic dysprosium

A. T. Nguyen,[1] D. Budker,[1,2] D. DeMille,[1,*] and M. Zolotorev[3]



▶ Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. D **90**, 096005 (2014)

▶ Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. Lett. **113**, 081601 (2014)

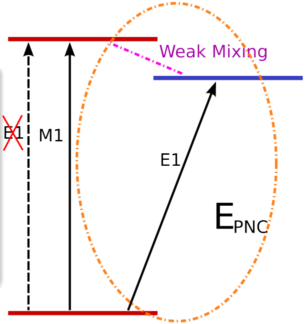
[1] Colladay, Kostelecký, Phys. Rev. D **58**, 116002 (1998).

Atomic Parity & Time-Reversal Violation

Conventional sources

Mixing of opposite parity states

- P-Violating "$E1$" transition: $E_{\rm PNC}$
  - e-N interaction: Q_W
  - N-N interaction: Anapole Moment
- P, T-Violating Electric Dipole Moments
  - e-N interaction; electron EDM



- Zeldovich, Zh. Eksp. Teor. Fiz. **36**, 964 (1959); Bouchiat & Bouchiat, Phys. Lett. B **48**, 111 (1974).
- Sandars, Phys. Lett. **14**, 194 (1965).
- Recent Review: Roberts, Dzuba, Flambaum, Annu. Rev. Nucl. Part. Sci. **65**, 63 (2015).

"Cosmic Field"-induced Parity Violation

$$\langle a|\gamma^5|n\rangle = i\Delta E_{an}\langle a|\Sigma\cdot r|n\rangle + \langle a|2\gamma^5\hat{K}|n\rangle$$

- $\Sigma\cdot r$: $\sim 1/c$; No PNC effect; Main EDM effect

Pseudoscalar field

- Static field $\Rightarrow$ no effects
- Oscillating field (e.g. axions, ALPs) $\Rightarrow$ Oscillating PNC
- $E_{\rm PNC} = i\ (a_0/f_a)\ m_a\ \sin(m_a t)\ K_{\rm PNC}$
- Atomic structure: $K_{\rm PNC} \sim 10^7\ |e|\ {\rm GeV}^{-2}$

Pseudovector field: $\mathcal{L} = b_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$ [1]

- $b_0\ \Rightarrow$ Static *and* oscillating PNC
- $E_{\rm PNC} = i\ b_0\sin(\omega_b t)\ K_{\rm PNC}$

▶ Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. Lett. **113**, 081601 (2014)

[1] Colladay, Kostelecký, Phys. Rev. D **58**, 116002 (1998).

Tests of CPT: Limiting pseudovector field

Limit on electron-field coupling

- From PNC experiment in Dy [1]

$$|b_0^{(e)}| < 7 \times 10^{-15} \text{ GeV}$$

Limit on nucleon-field coupling

- From Cs anapole moment measurement [2]

$$|b_0^{(p)}| < 4 \times 10^{-8} \text{ GeV} \qquad |b_0^{(n)}| < 2 \times 10^{-7} \text{ GeV}$$

- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. Lett. **113**, 081601 (2014); Phys. Rev. D **90**, 096005 (2014).

[1] Nguyen, Budker, DeMille, Zolotorev, Phys. Rev. A **56**, 3453 (1997).

[2] Wood, Bennett, Cho, Masterson, Roberts, Tanner, Wieman, Science **275**, 1759 (1997).

Fermion Interaction

Lead to limits on several other previously unconstrained parameters

Table S2. Maximal sensitivities for the matter sector

Coefficient	Electron	Proton	Neutron
$\tilde{b}_X$	10^{-31} GeV	10^{-33} GeV	10^{-33} GeV
$\tilde{b}_Y$	10^{-31} GeV	10^{-33} GeV	10^{-33} GeV
$\tilde{b}_Z$	10^{-29} GeV	10^{-28} GeV	10^{-29} GeV
$\tilde{b}_T$	10^{-26} GeV	10^{-7} GeV	10^{-26} GeV
$\tilde{b}^*_J$, $(J = X,Y,Z)$	10^{-22} GeV	–	–
$\tilde{d}_+$	10^{-27} GeV	10^{-7} GeV	10^{-27} GeV
$\tilde{d}_-$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_Q$	10^{-26} GeV	10^{-7} GeV	10^{-26} GeV
$\tilde{d}_{XY}$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{d}_{YZ}$	10^{-26} GeV	–	10^{-26} GeV
$\tilde{d}_{ZX}$	10^{-26} GeV	–	–
$\tilde{d}_X$	10^{-22} GeV	10^{-27} GeV	10^{-28} GeV
$\tilde{d}_Y$	10^{-22} GeV	10^{-27} GeV	10^{-28} GeV
$\tilde{d}_Z$	10^{-19} GeV	–	–
$\tilde{g}_T$	10^{-27} GeV	10^{-7} GeV	10^{-27} GeV
$\tilde{g}_c$	10^{-26} GeV	–	10^{-27} GeV
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–

- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. D **90**, 096005 (2014); Phys. Rev. Lett. **113**, 081601 (2014)

[1] Kostelecký, Russell, Rev. Mod. Phys. **83**, 11 (2011) [Up-to-date: arXiv:0801.0287v8].

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Tests of CPT: Fermion MDM

$$\mathcal{L}_{\rm int.} = -f^{\nu}\bar{\psi}\gamma^{\lambda}\gamma^{5}\tilde{F}_{\lambda\nu}\psi$$

CPT-odd background field

- Splits g-factors of fermion/anti-fermion
- $[a = (g-2)/2]$.

$$\delta a = \frac{2f^0 m}{e}\left(1 - \frac{\gamma^2 v^2}{(\gamma+1)^2}\right)$$

Limits on f^0

- Muon: $8 \times 10^{-11}\ \mu_B$
- Electron: $2.3 \times 10^{-12}\ \mu_B$
- Proton: $4 \times 10^{-9}\ \mu_B$

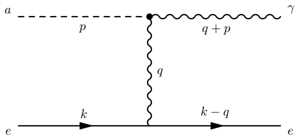
▶ Stadnik, Roberts, Flambaum, Phys. Rev. D **90**, 045035 (2014).

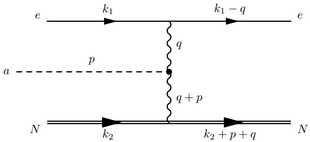
Electromagnetic Anomaly

Perturbation to Coulomb interaction

Axion–Magnetic Dipole Interaction

- Oscillating "EDM" for any MDM [1]
- Requires phase&frequency locked $\vec{\mathbf{E}}$
- Not observable





Axion-perturbed Coulomb Interaction

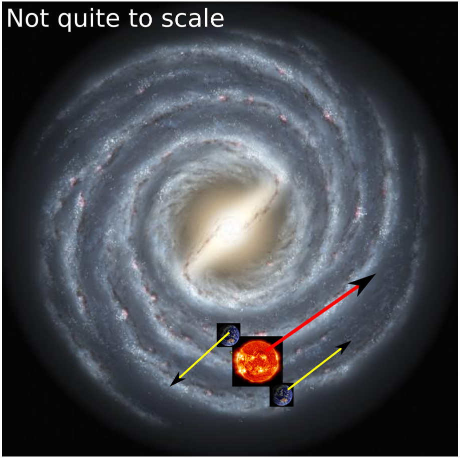
- Collective atomic EDMs
- Measured with static $\vec{\mathbf{E}}$; no reversals
- Significantly smaller than other effects

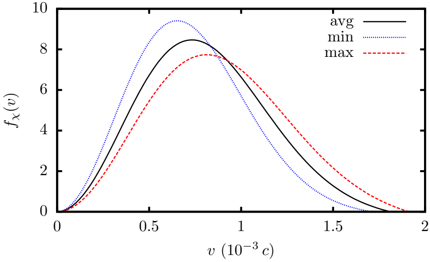
[1] Hill, arXiv:1504.01295 (2015).

- Roberts, Stadnik, Flambaum, *In Preparation*

DAMA Experiment

- Scintillation experiment; search for annual modulations

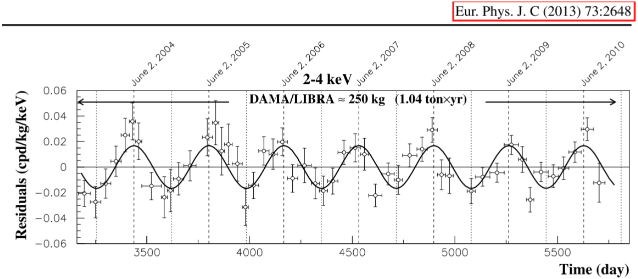




- DAMA: Bernabei *et al.*, Eur. Phys. J. C **73**, 2648 (2013).

DAMA annual modulation

"Model Independent" WIMP detection: 9σ DAMA signal



WIMP-Nucleus scattering?

- Null results from XENON, LUX, SuperCDMS, ...
- WIMP-electron scattering? [1]

▶ DAMA: Bernabei *et al.*, Eur. Phys. J. C **73**, 2648 (2013).

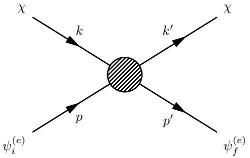
[1] For example: Bernabei *et al.* (DAMA), Phys. Rev. D **77**, 023506 (2008); Kopp, Niro, Schwetz, Zupan, Phys. Rev. D **80**, 083502 (2009).

WIMP-electron Scattering

Atomic ionisation & DAMA annual modulation

Due to electron scattering?

- Atomic ionisation
- *ab initio* Relativistic calculations

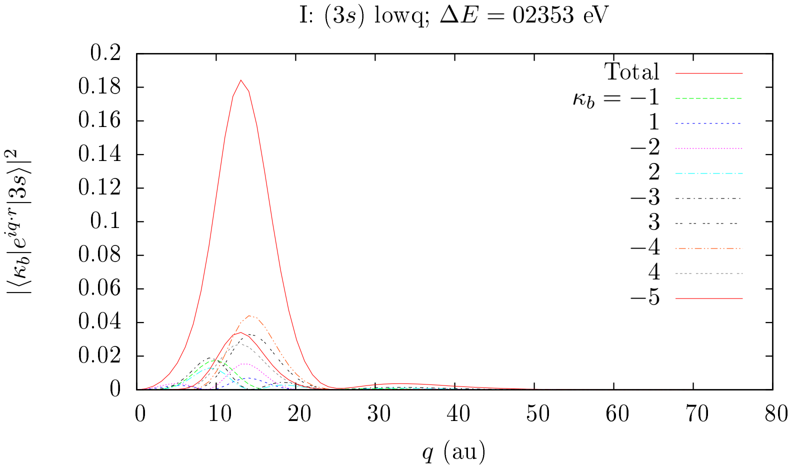


Preliminary calculations

- Dominated by very low $\vec{\mathbf{r}}$: relativistic + FNS important
- Entirely due to *s*-states
- Exponential suppression $\rightarrow$ power due to *s*-state cusp!

▶ Roberts, Stadnik, Dzuba, Flambaum, Gribakin, Pospelov, Yavin, *In Preparation*

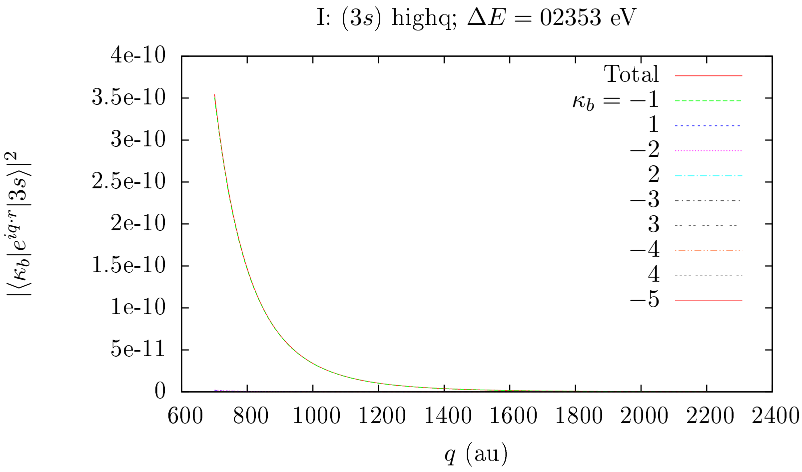
Iodine Atomic form-factor: Normal atomic momentum scale



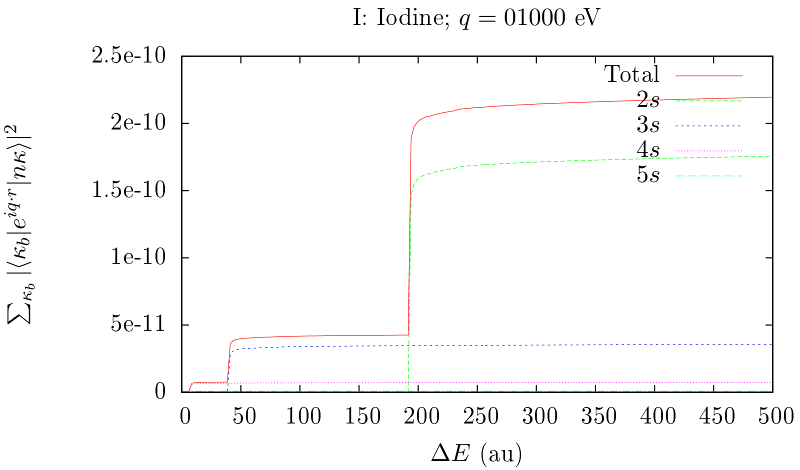
WIMP-electron Scattering

Atomic ionisation & DAMA annual modulation

Iodine Atomic form-factor: Relevant Momentum scale



Iodine Atomic form-factor: Function of energy deposition



WIMP-electron Scattering

Atomic ionisation & DAMA annual modulation

Aim:

- Combine high-accuracy numerical results +
- Simple analytic results (w/ scaling factors)
- Present simple Z-dependent model that others can implement

Simple–but accurate–model:

- Important because $d\sigma$ depends on
  - Lorentz structure, DM mass, mediator mass,
  - DM velocity distribution
- Easy to implement once atomic $\sum|\langle f|\hat{V}|i\rangle|^2$ is known

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▶ Roberts, Stadnik, Dzuba, Flambaum, Gribakin, Pospelov, Yavin, *In Preparation*

Conclusion

Axion–Induced Oscillating EDMs

- New effects, *linear* in interaction
- Axion–gluon, –fermion, *and* –photon couplings
- Complementary to existing searches; different parameter space

Tests of CPT

- New limits on SME parameters

DAMA annual modulation

- Electron scattering: *s*-states, very small $\vec{\mathbf{r}} \to$ simple usable model

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- Roberts, Dzuba, Flambaum, Annu. Rev. Nucl. Part. Sci. **65**, 63 (2015).
- Stadnik, Flambaum, Phys. Rev. D **89**, 043522 (2014).
- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker,
  Phys. Rev. Lett. **113**, 081601 (2014); Phys. Rev. D **90**, 096005 (2014).
- Roberts, Stadnik, Flambaum, *In Preparation*.
- Roberts, Stadnik, Dzuba, Flambaum, Pospelov, Yavin, *In Preparation*.

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