Axion and WIMP phenomena in atomic systems

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Phys. Rev. Lett. **113**, 081601 (2014); Phys. Rev. D **90**, 096005 (2014); Phys. Rev. D **89**, 043522 (2014).

PATRAS2015: The 11th Patras Workshop on Axions, WIMPs and WISPs,
Universidad de Zaragoza, Spain

25 June 2015

Overview:

Axions, ALPs & pseudoscalar fields

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

New linear effects

- Axion–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 Field

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

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Axion–SM Couplings

Effective couplings to SM particles:

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

$$a(t) = a_0\cos(m_a t) \qquad \frac{1}{f_a} \approx 2\times10^{-20}\ \mathrm{eV}^{-1}\left(\frac{m_a}{10^{-4}\ \mathrm{eV}}\right)$$

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: $\Rightarrow a_0/f_a \sim 4\times10^{-19}$ (QCD axion)
- (In general, DM ALP, f_a free parameter, $a_0 \sim 1/m_a$)

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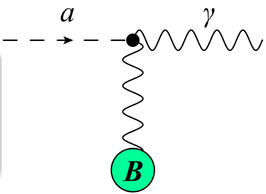
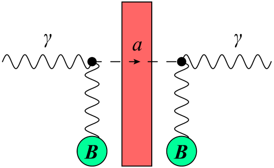
Searching for Axions

"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

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

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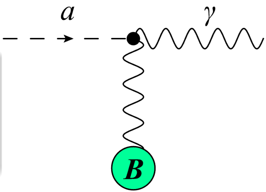

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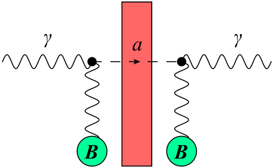

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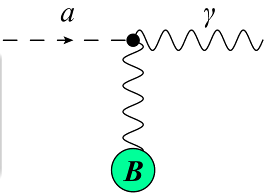

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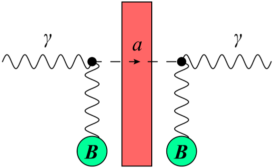

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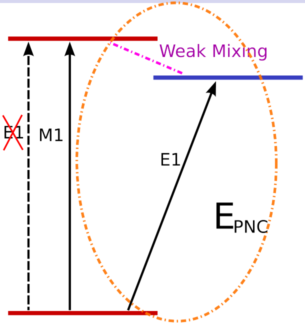
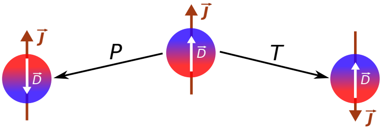
Atomic Parity & Time-Reversal Violation

Conventional sources

Mixing of opposite parity states

- *P*-Violating "*E*1" transition: $E_{\rm PNC}$
  - e-N weak interaction
- PNC in Cs: Best low-energy EW test
- *P*, *T*-Violating Electric Dipole Moments
- Nuclear EDM unobservable
  - Schiff, MQM; electron EDM, ...





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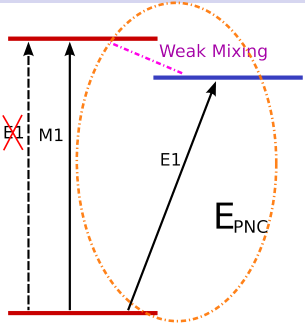

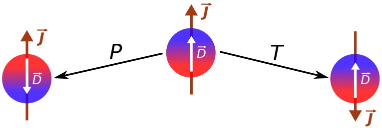

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Gluon–coupling: Axion-induced EDMs

- $d_n = 1.2 \times 10^{-16}\,\theta\ e\,\mathrm{cm}$ $\qquad \theta_{\mathrm{QCD}} \to \mathrm{a/f_a}$ [1]
- 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: (Alex Sushkov's talk Monday)

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

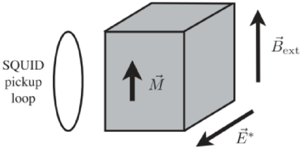

FIG. 1. Geometry of the experiment.

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Emerging Axion Searches: Gluon Coupling

Schiff Moments and CASPEr

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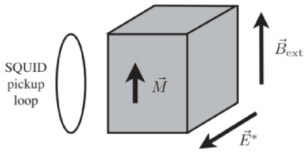

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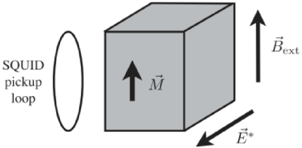

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Gluon Coupling: Magnetic Quadrupole Moments

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

Oscillating EDMs

- P & T Violating nuclear moment $\Rightarrow$ EDMs
- Much larger effect in Paramagnetic Systems
  - but shorter coherence times ...

Nuclear Enhancement

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

- Sensitivity may be roughly same; larger frequency (m_a) range!
  - (at cost of smaller f_a range)

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ALP–Fermion Interaction

General derivative-type pseudoscalar interaction:

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

P-odd effects

- Parity-mixing
- Oscillating PNC amplitudes
- Oscillating EDMs

P-even effects

- "Axion-wind" $\sigma_f \cdot p_a$
- $M1$ atomic transitions [1]

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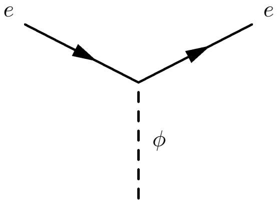
- Need non-zero J
- Non-rel limit: $\gamma^5 \to i[H, \boldsymbol{\sigma} \cdot \mathbf{r}]$



Alkali atoms:

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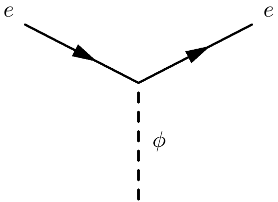

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ALP–Electron Interaction

Resonance in diatomic molecules

- Close opposite-parity levels $\Rightarrow\sim 10^4$ enhancement
- Magnetically drive resonance: $E_a - E_b = m_a$

$$d_{\rm EDM} \simeq 8\langle a|e\mathbf{r}|n\rangle\langle n|\boldsymbol{\sigma}\cdot\mathbf{r}|a\rangle\ \frac{a_0}{f_a}\ m_a\ \cos(m_a t)$$

- $d_{\rm EDM} \sim 10^{-34}\, e\,{\rm cm}$

- Independent of m_a [for ALP]! ($a_0 \propto 1/m_a$ from $\rho_{\rm DM}$)

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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

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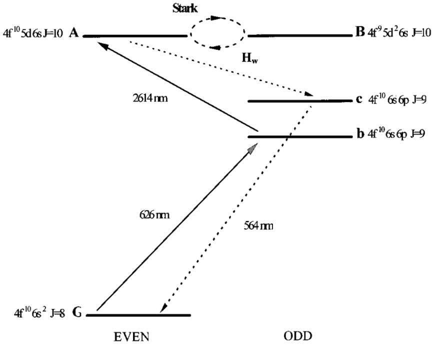

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[1] Colladay, Kostelecký, Phys. Rev. D **58**, 116002 (1998).

Fermion Interaction

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Search for parity nonconservation in atomic dysprosium

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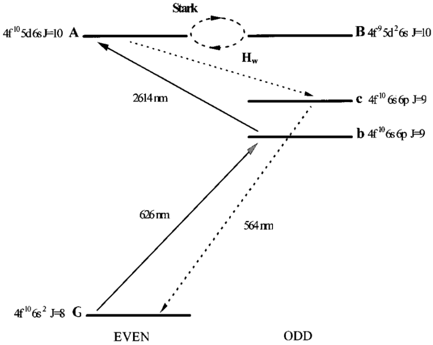

- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. D **90**, 096005 (2014)
- Roberts, Stadnik, Dzuba, Flambaum, Leefer, Budker, Phys. Rev. Lett. **113**, 081601 (2014)

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

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]

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

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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
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–

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

Tests of CPT: Fermion MDM

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

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: $4 \times 10^{-9}\ \mu_B$

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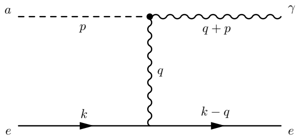
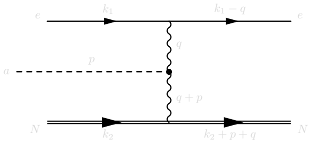
Electromagnetic Anomaly

Perturbation to Coulomb interaction

Axion–Magnetic Dipole Interaction

- Oscillating "EDM" of particles [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

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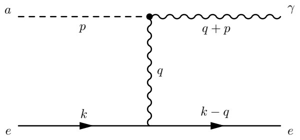

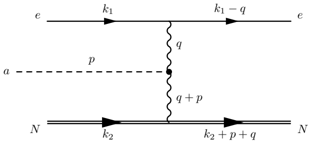

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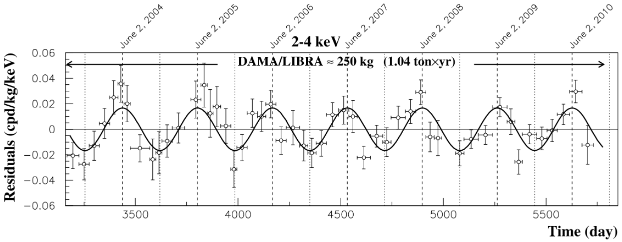
DAMA annual modulation

"Model Independent" WIMP detection: 9σ DAMA signal

Eur. Phys. J. C (2013) 73:2648



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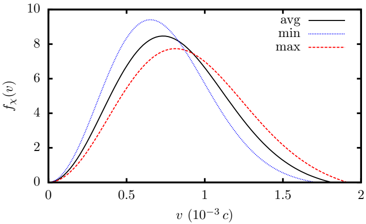
- Null results from XENON, LUX, SuperCDMS, ...
- WIMP-electron scattering? [1]



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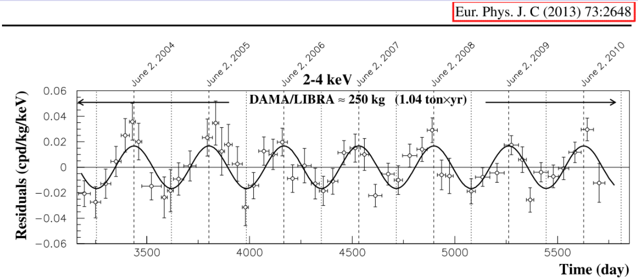

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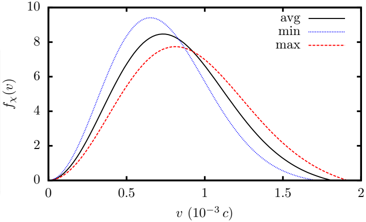

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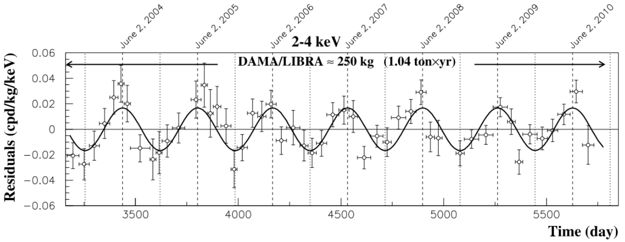

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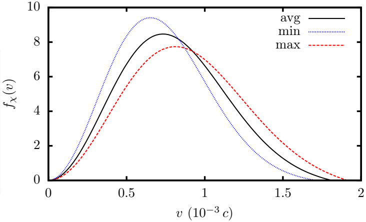

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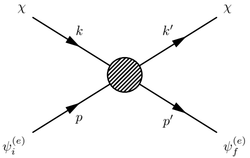
WIMP-electron Scattering

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!

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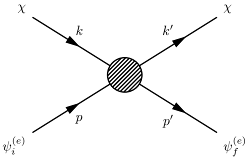

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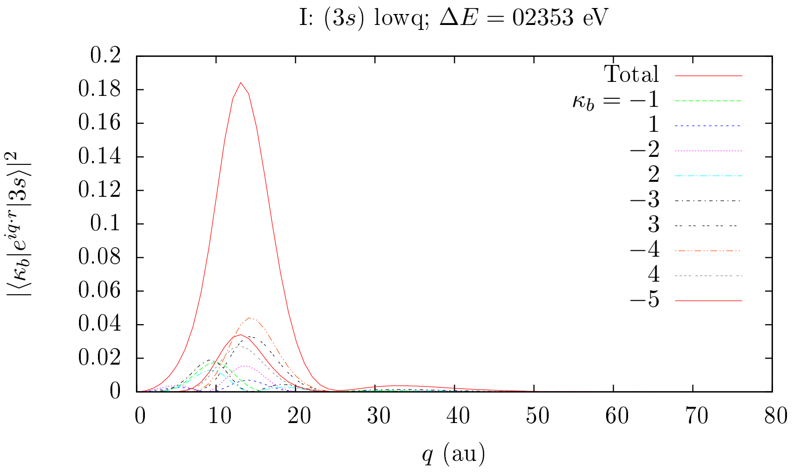
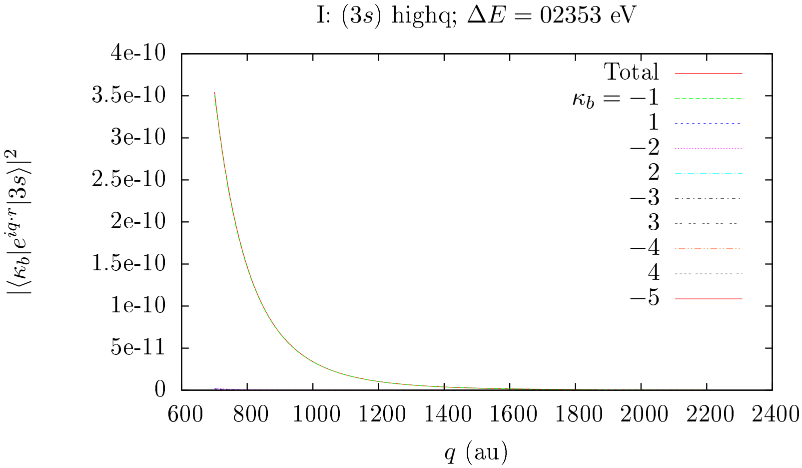
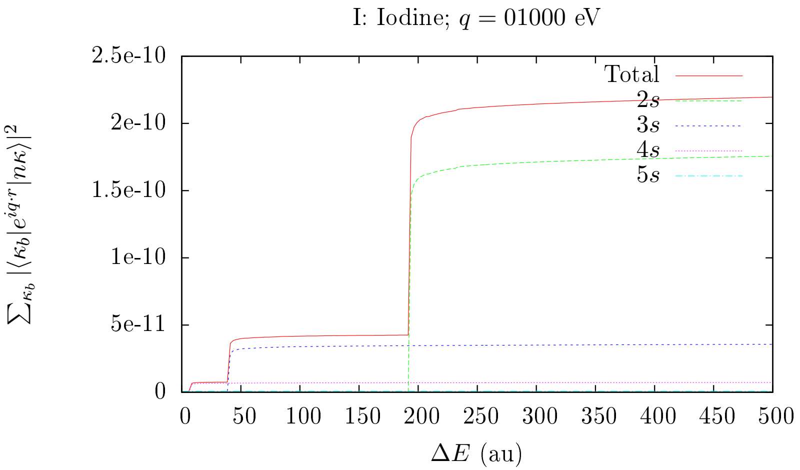
Iodine Atomic form-factor: Normal atomic momentum scale



Iodine Atomic form-factor: Relevant Momentum scale



Iodine Atomic form-factor: Function of energy deposition



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 $< \sigma v >$ depends on
  - Lorentz structure, DM mass, mediator mass,
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- Easy to implement once atomic $\sum |\langle f | \hat{V} | i \rangle|^2$ is known

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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 $\vec{\mathbf{r}}$

- 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).
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