Atomic ionization by scalar dark matter and solar scalars

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Relativistic Hartree-Fock calculations corrected several orders of magnitude error. Born approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions.

New limits on electron-scalar coupling from Xenon1T data.


Calculations for Na, I, Tl, Xe, Ar, Ge atoms
Atomic ionization by scalars

\[ \mathcal{L}_{\phi \bar{e}e} = \sqrt{\hbar} c g_{\phi \bar{e}e} \phi \bar{\psi} \psi \]

- \( \phi \): scalar familon, sgoldstino, dilaton, relaxon, moduli, Higgs-portal DM, etc.
- Absorption of scalar causes atomic ionization (similar to photoelectric effect)\( \rightarrow \) detectable by current DM and solar axion searches.
Pitfall: wrong wave functions → wrong results

• Orthogonality condition → Born approximation does not work!


• Pitfall also exists for axioelectric effect → affects low-energy cross section only.

• Relativistic Hartree-Fock calculations for scalars and axions.
Results: cross sections for Na, Ar, Ge, I, Xe, Tl

- With and without 1 keV cutoff.
- Accuracy a few %, up to 10% near threshold.

\[
\sigma_{\phi} = g_{\phi ee}^2 (c/\nu) Q(\epsilon) a_0^2
\]

\[
\frac{\sigma_{\phi}(m_\phi = 0)}{\sigma_\gamma(\epsilon_\gamma = \epsilon_\phi)} \approx \frac{g_{\phi ee}^2}{4\pi\alpha}
\]

Check against photoelectric experimental data
Scalar DM and solar scalar limits from Xenon1T data

• Detection rate for scalar DM:

\[ R \approx \frac{4.8}{A} \frac{\hat{Q}(m = \frac{c}{c^2})}{\text{year}} \left( \frac{g_{\phi\bar{e}e}}{10^{-17}} \right)^2 \left( \frac{\text{keV}}{mc^2} \right) \left( \frac{M}{\text{ton}} \right) \]

• Detection rate for solar scalar:

\[ R \approx \frac{8.3}{A} \frac{\hat{Q}(m = 0)}{\text{year}} \left( \frac{g_{\phi\bar{e}e}}{10^{-15}} \right)^4 \left( \frac{\text{keV}}{\epsilon} \right)^2 \left( \frac{M}{\text{ton}} \right) \]

• New limits from Xenon1T data:

\[ |g_{\phi\bar{e}e}|_{\text{DM}} \approx 8.2 \times 10^{-15} \quad |g_{\phi\bar{e}e}|_{\text{solar}} \approx 1.0 \times 10^{-14} \]

\[ g_{\phi\bar{e}e} = \sqrt{4\pi} d_{m_e} m_e / m_P \quad |d_{m_e}|_{\text{solar}} \leq 6.8 \times 10^7 \]
Comparison with astrophysical bounds

- Direct limits well inside naturalness region.
- Always better than fifth-force & comparable to HB star cooling.
- An order of magnitude less stringent than RG star cooling → similar to Xenon1T axion limit.
Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude!

Ionization of atoms by slow heavy particles, including dark matter


Relativistic Hartree-Fock calculations for Na, I, Xe, Tl, Ge atoms, scalar and vector portals. Annual modulation due to variation of velocity of WIMPs 20 - 50%
WIMP-Electron Ionising Scattering

- Search for annual modulation in $\sigma_{\chi e}$ (velocity dependent)

- Previous analyses treated atomic electrons non-relativistically. Plane wave for outgoing electron, $Z_{\text{effective}}$ for bound electrons.

- Non-relativistic treatment of atomic electrons inadequate for $m_{\chi} > 1$ GeV. Coulomb interaction is important for outgoing electron.
Why are electron relativistic effects so important?


- Slow heavy particle produces an adiabatic perturbation of atom. Usually transitions produced by an adiabatic perturbation are suppressed exponentially, as \( \exp(-q^2 R^2) \), \( q \) is the momentum transfer. No ionization?

- However, the singular Coulomb potential produces a cusp of electron wave function near the nucleus or even infinity for the relativistic Dirac s-wave function at \( r=0 \) for a point-like nucleus. As a result, the exponential suppression is replaced by a power suppression \( q^{-n} \). The effect comes from small distances where the electron is ultra-relativistic.
Why are electron relativistic effects so important?

[Roberts, Flambaum, Gribakin, PRL 116, 023201 (2016)],
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, PRD 93, 115037 (2016)]

- Non-relativistic and relativistic contributions to $\sigma_{\chi e}$ are very different for large $q$ (for scalar, pseudoscalar, vector and pseudovector interaction portals):

  Non-relativistic [$s$-wave, $\psi \propto r^0(1 - Zr/q_B)$ as $r \rightarrow 0$], tends to constant as $r \rightarrow 0$:
  \[
  d\sigma_{\chi e} \propto \frac{1}{q^8}
  \]

  Relativistic [$s_{1/2}$, $p_{1/2}$-wave, $\psi \propto r^{-1}$ as $r \rightarrow 0$, $v^2 = 1 - (Z\alpha)^2$], increases as $r \rightarrow 0$:
  \[
  d\sigma_{\chi e} \propto \frac{1}{q^{6-2(Z\alpha)^2}}
  \]

- Relativistic contribution to $\sigma_{\chi e}$ dominates by several orders of magnitude for large $q$!
Accurate relativistic atomic calculations

- Performed accurate \((ab\ initio)\) Hartree-Fock-Dirac relativistic atomic calculations of \(\sigma_{\chi e}\) for Na, Ge, I, Xe and Tl, and event rates of various experiments: DAMA, XENON10, XENON100

- Outgoing electron in the Hartree-Fock field (not plane wave, the problem is not reduced to momentum distribution of atomic electrons!)

- 3 parameter problem: \(m_{\chi}, m_{\nu}, \alpha_{\chi};\) vector or scalar interaction vertex

\[
\langle d\sigma v_{\chi} \rangle = \frac{4\alpha_{\chi}^2}{\pi} \int_0^\infty dv \frac{f_{\chi}(v)}{v} \int_{q^+}^{q^-} dq \frac{q}{(q^2 + m_{\nu}^2 c^2)^2} \times \sum_{n,\kappa} m_e \sqrt{2m_e(\Delta E - I_{nk})} K_{nk} d(\Delta E)
\]

\[
K_{nk}(\Delta E, q) = \sum_{\kappa'} \sum_{m,m'} |\langle \epsilon_{\kappa'} m' | e^{iqr} | n\kappa m \rangle |^2 \quad q_{\pm} = k \pm \sqrt{k^2 - 2m_{\chi}\Delta E}
\]
Why are electron relativistic effects so important?

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Calculated atomic-structure functions for ionisation of I from 3s atomic orbital as a function of $q$; $\Delta E = 4$ keV, vector interaction portal
Accurate relativistic atomic calculations


Calculated differential $\sigma_{\chi e}$ as a function of total energy deposition ($\Delta E$); $m_\chi = 10$ GeV, $m_\nu = 10$ MeV, $\alpha_\chi = 1$, vector interaction portal. Annual modulation due to variation of velocity of WIMPs 20 - 50%
Constraints from XENON Collaboration using our atomic calculations

[XENON Collaboration, PRL 118, 101101 (2017)]
Conclusion

• Relativistic Hartree-Fock calculations correct several orders of magnitude error for the dark matter scalars and solar scalars.
• Plane wave approximation does not work due to violation of orthogonality condition between bound and continuum electron wave functions → Error up to 8 orders of magnitude!
• Such effect also exists for axions but the error is significant for small axion energies only.
• New limits on electron-scalar coupling from Xenon1T data.
• Relativistic effects increase ionisation by WIMP scattering on electrons by up to 3 orders of magnitude. Plane wave approximation does not work. Annual modulation due to variation of velocity of WIMPs is 20 - 50%. Results for DAMA/LIBRA and XENON collaborations.
Why are electron relativistic effects so important?


- Slow heavy particle produces an adiabatic perturbation of atom. Usually transitions produced by an adiabatic perturbation are suppressed exponentially, as \( \exp(-q^2 R^2) \), \( q \) is the momentum transfer. No ionization?

- However, the singular Coulomb potential produces a cusp of electron wave function near the nucleus or even infinity for the relativistic Dirac s-wave function at \( r=0 \) for a point-like nucleus. As a result, the exponential suppression is replaced by a power suppression \( q^{-n} \). The effect comes from small distances where the electron is ultra-relativistic.
Can the DAMA result be explained by the ionising scattering of WIMPs on electrons?

[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, *PRD* 93, 115037 (2016)]

- Using results of XENON10 and XENON100, we find no region of parameter space in $m_\chi$ and $m_V$ that is consistent with interpretation of DAMA result in terms of “ionising scattering on electrons” scenario.
Why are electron relativistic effects so important?

- Consider $m_\chi \sim 10$ GeV, $<v_\chi> \sim 10^{-3}c$
- $<q> \sim <p_\chi> \sim 10$ MeV $\Rightarrow$ $m_e = 0.5$ MeV
  $\Rightarrow$ Relativistic process on atomic scale!
- Large $q \sim 1000$ a.u. corresponds to small $r \sim 1/q \ll a_B/Z$
- Largest contribution to $\sigma_{xe}$ comes from innermost atomic orbitals – for $<\Delta E> \sim <T_\chi> \sim 5$ keV:
  - Na (1s)
  - Ge (2s)
  - I (3s/2s)
  - Xe (3s/2s)
  - Tl (3s)

Relativistic effects increase ionisation by dark matter WIMP scattering on electrons by up to 3 orders of magnitude!

[Roberts, Flambaum, Gribakin, PRL 116, 023201 (2016)]

• Important for numerous existing and future dark matter detectors.
• Detailed relativistic many-body calculations in
[Roberts, Dzuba, Flambaum, Pospelov, Stadnik, Phys. Rev. D 93, 115037, 2016,
Roberts, Flambaum, Phys. Rev. D 2019,]
• DAMA collaboration claims detection of dark matter, others – no detection. Possible explanation: scattering of dark matter on electrons (instead of scattering on nuclei).
• Our calculations show tension between DAMA and XENON results. XENON used our calculations in PRL 2017.