Neutrino Scattering Off Bound Electrons at Low Energies

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Neutrino-Electron Scattering

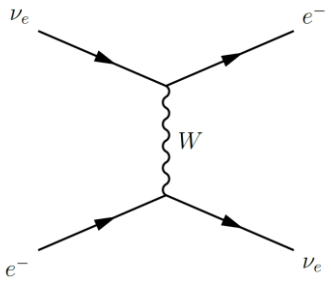
- This process led to the discovery of the weak neutral current in 1973 through the **Gargamelle experiment**.
- Today, it's used to constrain **electroweak parameters** and improve our understanding of the **Sun**.
- It represents a significant source of **background** for **direct dark matter searches**.

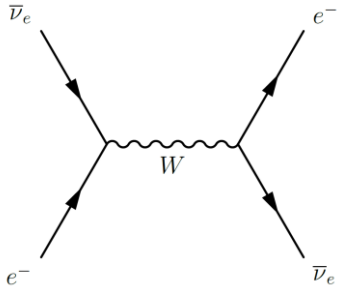
Purpose of this work:

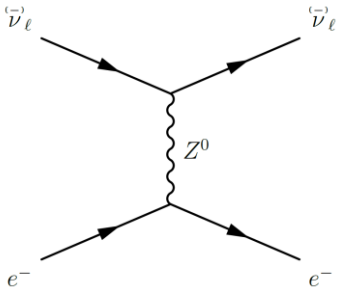
- Compute the neutrino-electron scattering cross-section for **bound electrons** using the **stepping approximation**, which accounts for the binding energy of each atomic shell.
- Evaluate the **solar neutrino background** in noble-liquid-based direct dark matter detectors, such as DarkSide, XENONnT and LZ.

Image from D. Cundy & C. Sutton, Gargamelle: the tale of a giant discovery, CERN Courier, 25 Aug. 2009. https://cerncourier.com/a/gargamelle-the-tale-of-a-giant-discovery/

Neutrino-Electron Elastic Scattering: Free Electrons







$$\mathcal{L}_{CC} = -\frac{G_F}{\sqrt{2}}[\overline{\nu}\gamma^\rho(1-\gamma^5)e][\overline{e}\gamma_\rho(1-\gamma^5)\nu] \qquad \mathcal{L}_{NC} = -\frac{G_F}{\sqrt{2}}[\overline{\nu}\gamma^\rho(1-\gamma^5)\nu][\overline{e}\gamma_\rho(g_V - g_A\gamma^5)e]$$

$$\frac{d\sigma^{free}_{\nu_{\ell-e}}}{dT_e}(E_\nu, T_e) = \frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2+(g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{T_e}{E_\nu}\right)^2-((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2)\frac{m_e T_e}{E_\nu^2}\right] \quad [*]$$

Tree level couplings:

$$g_V^{\nu_e} = 2\sin^2\theta_W + 1/2 \qquad g_V^{\nu_{\mu,\tau}} = 2\sin^2\theta_W - 1/2 \qquad g_A^{\nu_e} = 1/2 \qquad g_A^{\nu_{\mu,\tau}} = -1/2$$

Including **radiative corrections** [**]:

$$g_V^{\nu_e e} = 0.9521 \qquad g_A^{\nu_e e} = 0.4938$$
$$g_V^{\nu_\mu e} = -0.0397 \qquad g_A^{\nu_\mu e} = -0.5062$$
$$g_V^{\nu_\tau e} = -0.0353 \qquad g_A^{\nu_\tau e} = -0.5062$$

[*] Giunti C. and Kim C. W., Fundamentals of Neutrino Physics and Astrophysics, 2007, Oxford University Press, Oxford, UK.

[**] Values from M. Atzori Corona, W. M. Bonivento, M. Cadeddu, N. Cargioli, and F. Dordei, New constraint on neutrino magnetic moment and neutrino millicharge from LUX-ZEPLIN dark matter search results, Phys. Rev. D 107, 053001 (2023).

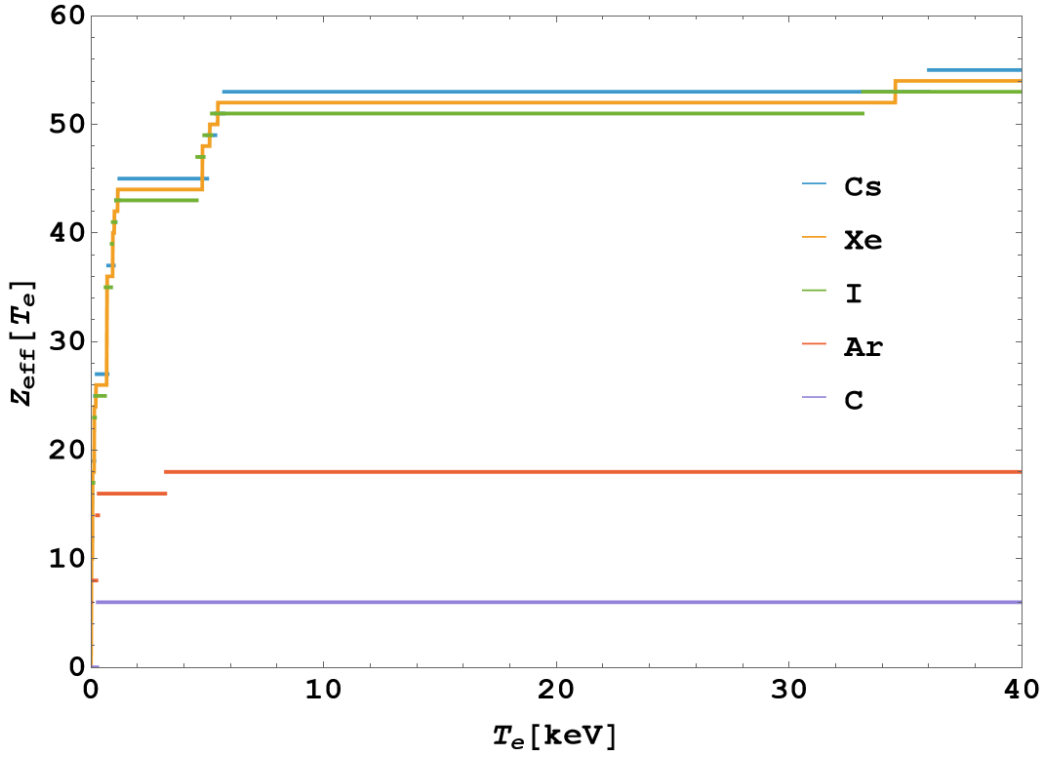
Neutrino-Electron Scattering: Atomic Electrons (Stepping Approximation)

Obtaining accurate results generally relies on *ab initio* methods, including Hartree–Fock and its extensions. Here, we employ a simplified approach known as the **stepping approximation**.

$$Z_{\text{eff}}^{\mathcal{A}}(T_e) = \sum_i n_i \theta(T_e - |E_i|) \quad [*]$$

$$\frac{d\sigma_{\nu_{\ell-e(\mathcal{A})}}}{dT_e}(E_\nu, T_e) = Z_{\text{eff}}^{\mathcal{A}}(T_e) \frac{d\sigma_{\nu_{\ell-e}}^{free}}{dT_e}(E_\nu, T_e)$$

The factor $Z_{\text{eff}}^{\mathcal{A}}(T_e)$ counts the number of electrons kinematically available for the scattering at the recoil energy T_e.



[*] Kouzakov, K. A., & Studenikin, A. I. (2014). Theory of neutrino-atom collisions: the history, present status and BSM physics. Adv. High Energy Phys., 2014, 569409. https://doi.org/10.1155/2014/569409

Differential Event Rate

The differential event rate for **solar** neutrino–electron scattering is computed by convoluting the **differential cross section** with the **SSM** neutrino flux [*]. **Neutrino oscillations** are properly considered.

$$\frac{dR^{th}_{\nu-e(\mathcal{A})}}{dT_e} = N(\mathcal{A}) \int_{E_\nu^{min}}^{E_\nu^{max}} \frac{d\Phi}{dE_\nu}(E_\nu) \sum_{\ell=e,\mu,\tau} \frac{d\sigma_{\nu_\ell-e(\mathcal{A})}}{dT_e}(E_\nu, T_e) P_{e\ell}(E_\nu) dE_\nu$$

Number of target atoms

Solar neutrino flux

Neutrino oscillation probability

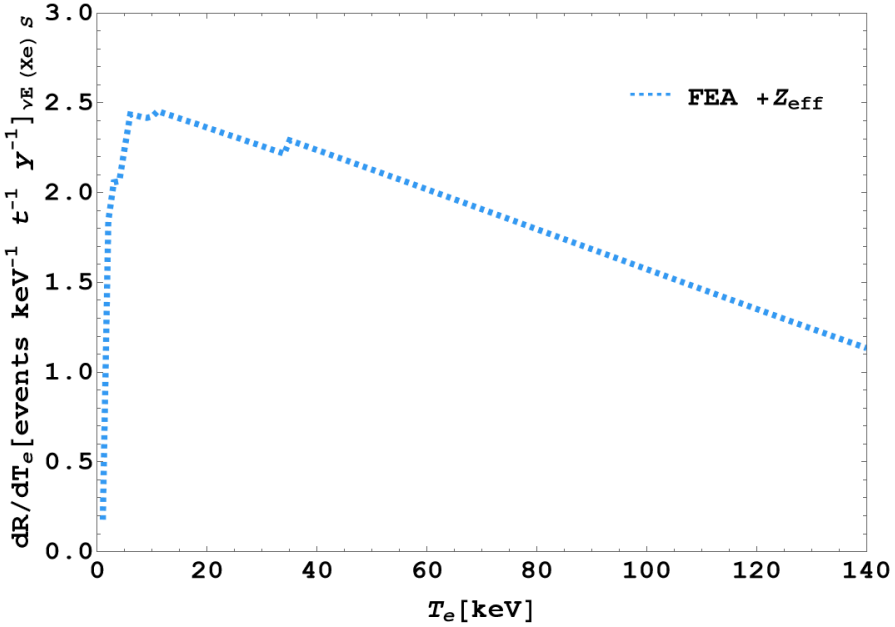
To this end, the neutrino fluxes from the main solar sources were taken to account **- pp, ^{8}B, ^{3}He-p, pep, and the two ^{7}Be lines -** finding that the dominant contributions arise from the pp continuum and the two ^{7}Be lines at 384 keV and 862 keV.

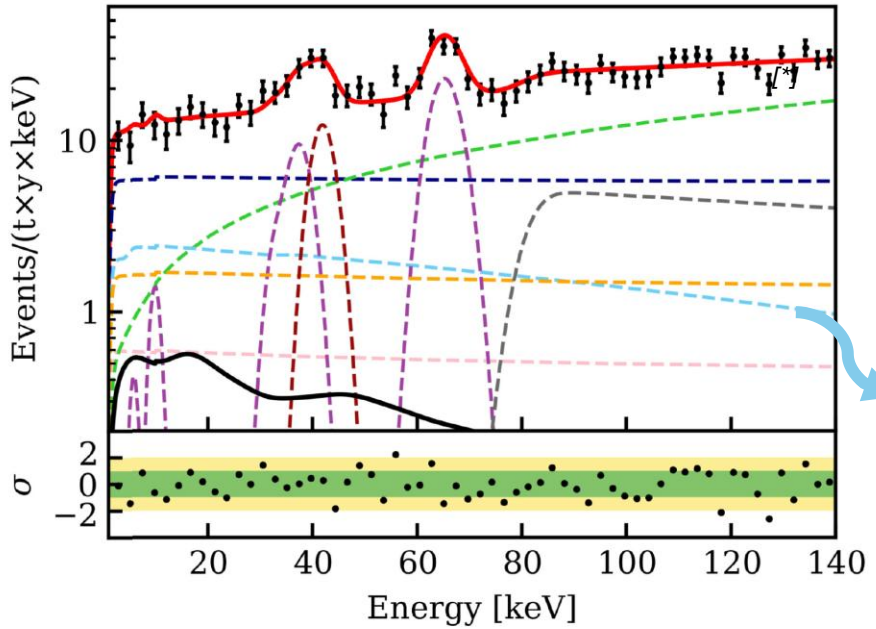
[*] J. N. Bahcall, A. M. Serenelli and S. Basu, New solar opacities, abundances, helioseismology, and neutrino fluxes, Astrophys. J. Lett. ***621*** *(2005) L85–L88, [astro-ph/0412440] – data from https://www.sns.ias.edu/~jnb/SNdata/Export/BS2005/bs2005opflux.dat*

Comparing results with XENONnT data

Finally, as a preliminary comparison, the computed differential rate - corrected for the detector efficiency - is compared against the theoretical solar neutrino rates reported by the XENONnT collaboration.

$$\frac{dR^{exp}_{\nu-e(\mathcal{A})}}{dT_e} = \eta(T_e)\frac{dR^{th}_{\nu-e(\mathcal{A})}}{dT_e}$$





Number of events for solar neutrinos between 1 and 140 keV (1.16 tonne × years exposure): ~ 298 events (left plot), 310±30 (ref. [*]).

[*] XENON Collaboration, Challenging Spontaneous Quantum Collapse with the XENONnT Dark Matter Detector, Phys. Rev. Lett. (2026), doi: https://doi.org/10.1103/2jm3-4976 .

Summary and Outlook

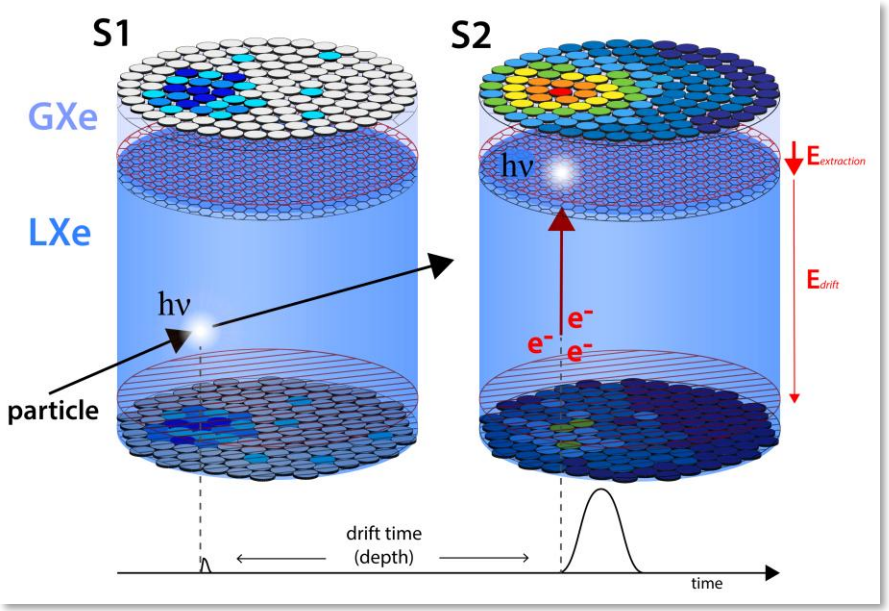
Summary

- The **vES cross-section for bound electrons** was computed using the **stepping approximation**, accounting for the binding energy of each atomic shell via $Z_{\mathrm{eff}}^{\mathcal{A}}(T_e)$.
- The **differential event rate** for neutrino-electron scattering was computed for **Xe**, incorporating the SSM flux and neutrino oscillations.
- Results were compared with the **XENONnT theoretical prediction**, providing a description of the solar neutrino background for direct dark matter searches.

Outlook

- Implementation of more accurate **ab initio methods** (e.g. Hartree-Fock) to improve the atomic structure description.
- Further **tests against experimental data** as new measurements from direct dark matter detectors become available.

Dual-Phase TPCs



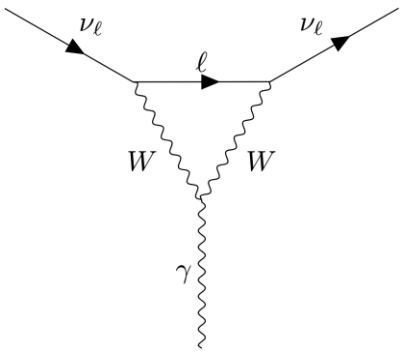
Dual-phase TPCs are filled for most of their volume with **liquid**, while the remaining volume is filled with **gas**, which constitutes the second phase of the chamber.

This technology is widely adopted in **direct dark matter research**, where one looks for possible recoil signals in the TPC by dark matter particles coming from space.

Solar neutrinos contribute significantly to the **background** signal for direct dark matter detectors as they **cannot be shielded**. For this reason, an accurate description of the **vES** process is essential for establishing the background and analyse data from direct dark matter experiments.

Image from P. Di Gangi. "The Xenon Road to Direct Detection of Dark Matter at LNGS: The XENON Project". In: Universe 7.8 (2021), p. 313. DOI:10.3390/universe7080313.

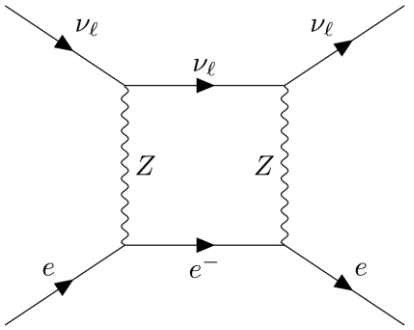
Radiative Corrections

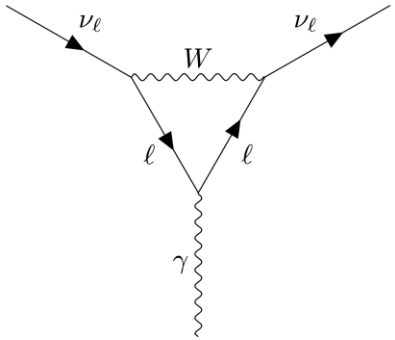


$$g_{LL}^{\nu_\ell f} = \rho\left[\frac{1}{2} - Q_f\hat{s}_0^2 + \boxtimes_{ZZ}\right] - Q_f\varnothing_{\nu_\ell W} + \boxtimes_{WW} \qquad (f = u),$$

$$g_{LL}^{\nu_\ell f} = \rho\left[-\frac{1}{2} - Q_f\hat{s}_0^2 + \boxtimes_{ZZ}\right] - Q_f\varnothing_{\nu_\ell W} + \square_{WW} \qquad (f = d, e),$$

$$g_{LR}^{\nu_\ell f} = -\rho\left[Q_f\hat{s}_0^2 + \boxtimes_{ZZ}\right] - Q_f\varnothing_{\nu_\ell W} \qquad (f = u, d, e),$$

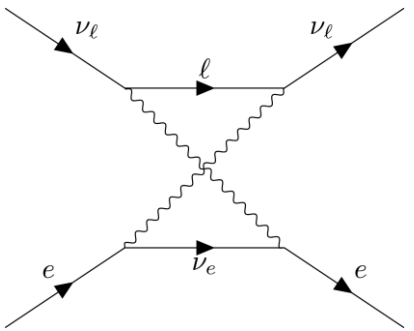




$$\varnothing_{\nu_\ell W} = -\frac{\alpha}{6\pi}\left(\ln\frac{M_W^2}{m_\ell^2} + \frac{3}{2}\right),$$

$$\square_{WW} = -\frac{\hat{\alpha}_Z}{2\pi\hat{s}_Z^2}\left[1 - \frac{\hat{\alpha}_s(M_W)}{2\pi}\right], \qquad \boxtimes_{WW} = \frac{\hat{\alpha}_Z}{8\pi\hat{s}_Z^2}\left[1 + \frac{\hat{\alpha}_s(M_W)}{\pi}\right],$$

$$\boxtimes_{ZZ} = -\frac{3\hat{\alpha}_Z}{8\pi\hat{s}_Z^2\hat{c}_Z^2}(g_{LX}^{\nu_\ell f})^2\left[1 - \frac{\hat{\alpha}_s(M_Z)}{\pi}\right].$$



$$g_V^{\nu_\ell f} = g_{LL}^{\nu_\ell f} + g_{LR}^{\nu_\ell f} \qquad g_A^{\nu_\ell f} = g_{LL}^{\nu_\ell f} - g_{LR}^{\nu_\ell f}$$

$$\rho = 1.00064, \qquad \hat{s}_0^2 = 0.23865, \qquad \hat{s}_Z^2 = 0.23126, \qquad \hat{\alpha}_Z^{-1} = 127.94$$

J. Erler and S. Su. "The Weak Neutral Current". In: Prog. Part. Nucl. Phys.71 (2013), p. 119. DOI: 10.1016/j.ppnp.2013.03.004. arXiv: 1303.5522 [hep-ph].