The calculation of inelastic neutrino/dark matter nucleus scattering

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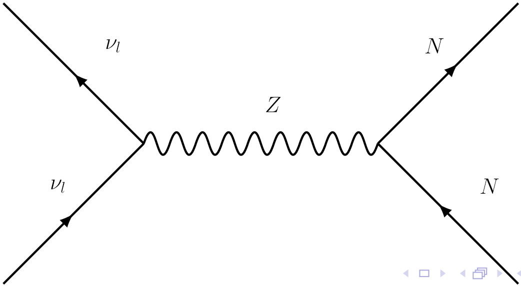
νN scattering: Elastic cross section

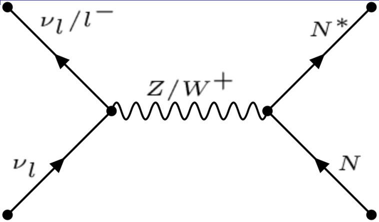
Standard Model CEνNS (coherent elastic neutrino-nucleus scattering) cross section **Drukier, Stodolsky, PRD, 1984** **Barranco, Miranda, Rashba, JHEP, 2005** **Patton, Engel, McLaughlin, Schunck, PRC 2012**

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} m_N \left(1 - \frac{E_r}{E_i} - \frac{m_N E_r}{2E_i^2}\right)[(1-4sin^2\theta_W)Z - N]^2 F_W^2$$

where m_N target nucleus mass, E_i incoming neutrino energy, E_r recoil energy, Z atomic number, N neutron number, F_W form factor, $sin^2\theta_W \approx 0.23$ Weinberg angle



νN scattering: Inelastic cross section



$$\frac{d\sigma}{d\omega d\Omega} = \sigma_W E_f k_f \zeta^2(Z', E_f)\ FF(2m_N E_r)$$

$\sigma_W^{CC} = \left(\frac{G_F cos\theta_c}{2\pi}\right)^2$, $\sigma_W^{NC} = \left(\frac{G_F}{2\pi}\right)^2$

E_f / k_f outgoing lepton energy/momentum

Coulomb field correction $\zeta^2(Z', E) = \frac{E_{eff} k_{eff}}{E\ k}$

effective energy $E_{eff} = E_f \pm \frac{3}{2}\frac{Z' \alpha \hbar c}{R}$, effective momentum k_{eff}^2

$$Z' = \begin{cases} Z+1 & \text{for } \nu \\ Z-1 & \text{for } \bar{\nu} \end{cases}$$

Nikolakopoulos, Pandey, Spitz, Jachowicz, PRC, 2021

νN scattering: Inelastic cross section

$$FF(2m_N E_r) = \sum_{J\geqslant 1, spin} \left[\frac{1}{2}(\vec{l}\cdot\vec{l}^* - l_3 l_3^*)\left(|\langle J_f||\mathcal{T}^{mag}||J_i\rangle|^2 + |\langle J_f||\mathcal{T}^{el}||J_i\rangle|^2\right)\right.$$

$$\left. - i(\vec{l}\times\vec{l}^*)_3 Re(|\langle J_f||\mathcal{T}^{mag}||J_i\rangle||\langle J_f||\mathcal{T}^{el}||J_i\rangle|)^*\right] + \sum_{J\geqslant 0, spin}\left[l_0 l_0^* |\langle J_f||\mathcal{M}||J_i\rangle|^2\right.$$

$$\left. + l_3 l_3^* |\langle J_f||\mathcal{L}||J_i\rangle|^2 - 2Re\left(l_3 l_0^* |\langle J_f||\mathcal{L}||J_i\rangle||\langle J_f||\mathcal{M}||J_i\rangle|^*\right)\right]$$

Neutrino current $l_\mu = \bar{\nu}\gamma_\mu\frac{(1-\gamma_5)}{2}\nu$, recoil momentum q

Hoferichter, Menéndez, Schwenk, PRD, 2020

$$\mathcal{M} = \mathcal{M}_{LM} + \mathcal{M}^5_{LM} = \left\{F_1^N M_L^M + \frac{\mathbf{q}^2}{4m_N^2}(F_1^N + 2F_2^N)(\Phi_L''^M - \frac{1}{2}M_{LM})\right\} + \left\{-i\frac{|\mathbf{q}|}{m_N}G_A^N\left[\Omega_L^M + \frac{1}{2}\Sigma_L''^M\right]\right\}$$

$$\mathcal{L} = \mathcal{L}_{LM} + \mathcal{L}^5_{LM} = \left\{\frac{q^0}{|\mathbf{q}|}\mathcal{M}\right\} + \left\{i\left[G_A^N(1-\frac{\mathbf{q}^2}{8m_N^2}) - \frac{\mathbf{q}^2}{4m_N^2}G_P^N\right]\Sigma_L''^M\right\}$$

$$\mathcal{T}^{el} = \mathcal{T}^{el}_{LM} + \mathcal{L}^{el5}_{LM} = \left\{\frac{|\mathbf{q}|}{m_N}\left[F_1^N\Delta_L'^M + \frac{F_1^N + F_2^N}{2}\Sigma_L^M\right]\right\} + \left\{iG_A^N(1-\frac{\mathbf{q}^2}{8m_N^2})\Sigma_L'^M\right\}$$

$$\mathcal{T}^{mag} = \mathcal{T}^{mag}_{LM} + \mathcal{L}^{mag5}_{LM} = \left\{-i\frac{|\mathbf{q}|}{m_N}\left[F_1^N\Delta_L^M - \frac{F_1^N + F_2^N}{2}\Sigma_L'^M\right]\right\} + \left\{G_A^N(1-\frac{\mathbf{q}^2}{8m_N^2})\Sigma_L^M\right\}$$

$$\langle f|\hat{H}_W|i\rangle = \frac{G_F}{\sqrt{2}}\int d^3x \langle f|j_\mu^{lep}\hat{\mathcal{J}}^\mu(\vec{x})|i\rangle$$
$$= \frac{G_F}{\sqrt{2}}\int d^3x\, e^{-i\vec{q}\cdot\vec{x}} \left(l_0\mathcal{J}^0(\vec{x}) - \vec{l}\cdot\boldsymbol{\mathcal{J}}(\vec{x})\right)$$

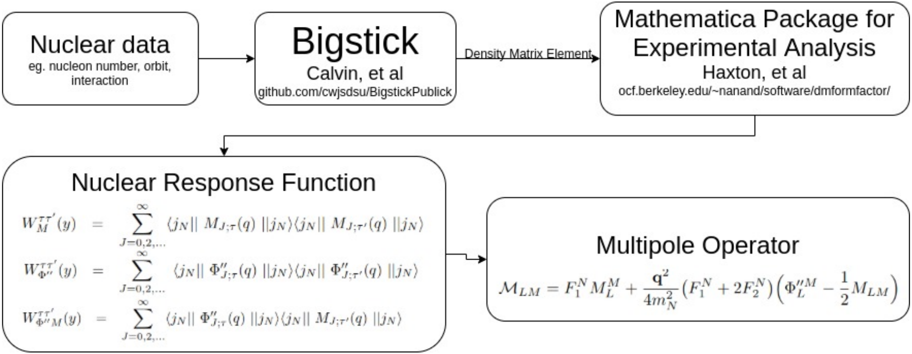
Spherical decompsition

Multipole operator $\hat{\mathcal{M}}_{JM}(q) \equiv \int d^3x\,[j_J(qx)Y_{JM}(\Omega_x)]\,\hat{\mathcal{J}}^0(\vec{x})$

Nuclear response function $M_{JM}(q\vec{x}_i) \equiv j_J(qx_i)Y_{JM}(\Omega_{x_i})$

Bessel spherical harmonics Y_{JM}
Dirac form factor F_1^N, Pauli form factor F_2^N, pseudoscalar form factor G_P^N, axial vector form factor G_A^N

νN scattering: Program calculation

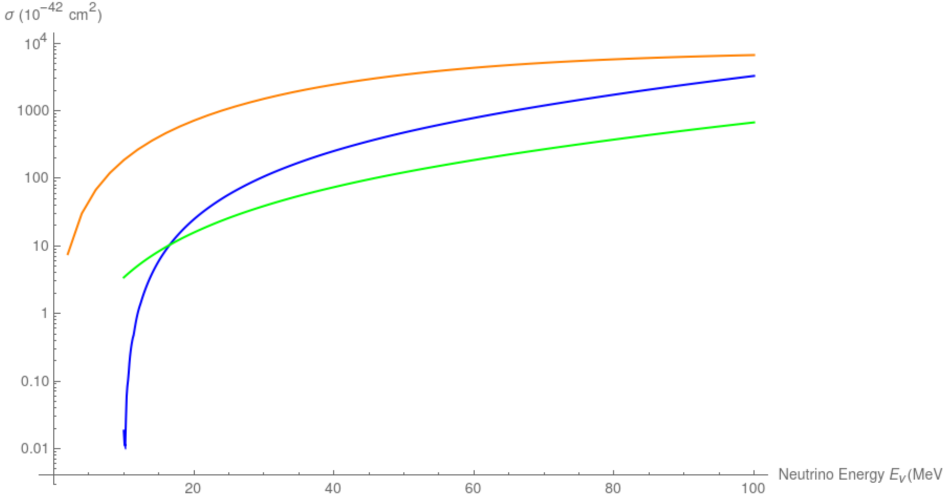


Anand, Fitzpatrick, Haxton, PRC. 2014

Johnson, Ormand, McElvain, Shan, 2018

νN scattering: Calculation result (Ar40)

Orange is CEνNS, green is NC, blue is CC (up to 5 states are calculated)



- It's possible to calculate cross section of photon production

χN scattering: Elastic and inelastic cross section

Pions ($\pi^0, \pi^\pm$) are produced after protons hit a target and dark photon $A^{'}$ is produce and decays to 2 DM (χ). We set a constant mass ratio $\frac{m_{A'}}{m_\chi} = 3$

- $A^{'} \to 2\chi$ **Dutta, Kim, Liao, Park, Shin, Strigari, Thompson, PRL, 2020**
- $\pi^0 \to \gamma + A^{'}$ **Deniverville, Pospelov, Ritz, PRD, 2015, Ge, Shoemaker, JHEP, 2018**
- $\pi^{-/+} + p/n \to n/p + A^{'}$
- dark Bremsstrahlung: $e^{\pm *} \to e^\pm + A^{'}$
- Our Lagrangian $\mathcal{L} = g_D A'_\mu \bar{\chi}\gamma^\mu \chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$

$$\frac{d\sigma}{dE_r}\bigg|_{el} = \frac{e^2\epsilon^2 g_D^2 Z^2}{4\pi(E_\chi^2 - m_\chi^2)(2m_N E_r + m_{A'}^2)^2}\Big[2E_\chi^2 m_N(1 - \frac{E_r}{E_\chi} - \frac{m_N^2 E_r + m_\chi^2 E_r}{2m_N E_\chi^2}) + E_r^2 m_N\Big]|F(2m_N E_r)|^2$$

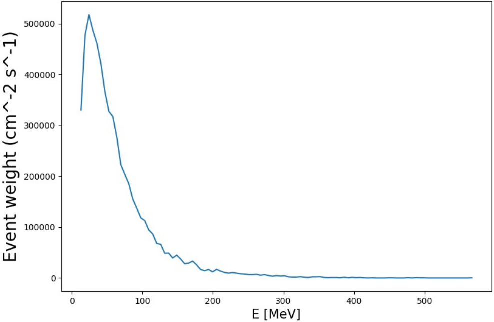
$$\frac{d\sigma}{dE_r}\bigg|_{inel} = \frac{2e^2\epsilon^2 g_D^2}{(1 - \frac{m_\chi^2}{E_\chi^2})(2m_N E_r + m_{A'}^2)^2}\frac{m_N}{2\pi}\frac{4\pi}{2J+1}\; FF(2m_N E_r)$$

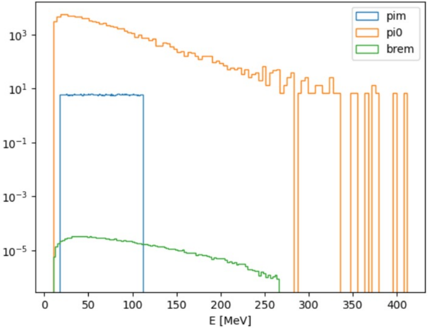
E_χ incoming DM energy, J target nucleus spin, $e \approx 0.303$

χN scattering: DM Energy spectra

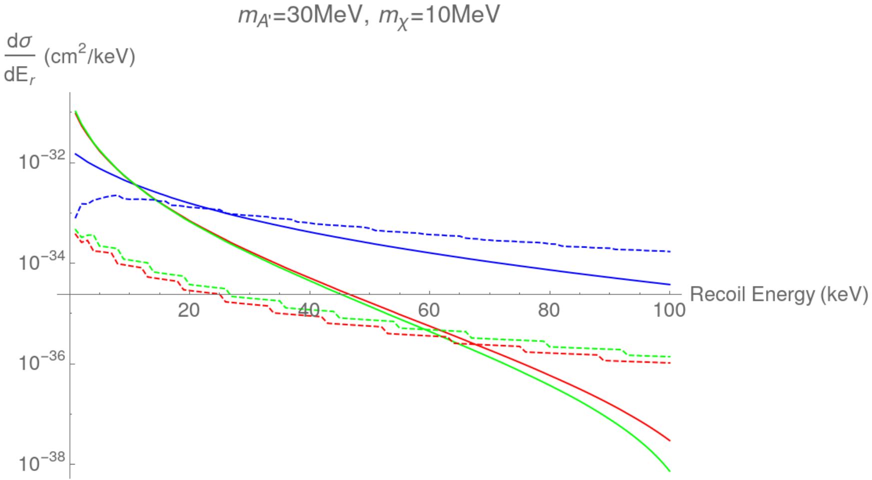
- Coherent Captain-Mills (CCM) experiment (LANL). [800 MeV protons hit a tungsten target, total 7 tons (fiducial) LAr of detector 20m from the target. $\sim 10^{22}$ POT (protons-on-target) per year, currently ongoing] **Aguilar-Arevalo, et al, 2021**
- COHERENT experiment (ORNL) [1 GeV protons hit a mercury target, 14.6kg CsI of detector 19.3m from the target, $\sim 10^{23}$ POT per year] **Akimov, et al, 2017**

$m_{A'} = 30MeV$, $m_\chi = 10MeV$





χN scattering: Calculation result



- Blue is Ar40, Red is Cs133, Green is I127
- Solid line is elastic, Dashed is inelastic
- Plots don't change significantly when mass of $m_{A'}$ changed

Conclusion

- We calculate the inelastic cross-section for neutrino and DM nucleus scattering
- The calculation results give us an insight about inelastic scattering cross section compared to CEνNS, which has been observed by COHERENT experiment. And CCM is currently in operation.
- For neutrino-nucleus scattering, the inelastic contribution is 1% compared to CEνNS for COHERENT and CCM measurements
- The DM normalization of the curves depends on the coupling parameter ϵ.
- The DM inelastic contribution can be significant for larger recoil energy

Backup

Dirac form factor $F_1^N = Q^N + \frac{< r_1^2 >^N}{6} q^2$

Pauli form factor $F_2^N = \kappa^N$

with charge Q^N, magnetic moment $\kappa^p \approx 1.796, \kappa^n \approx -1.913$

and charge radius $< r_1^2 >^N = < r_E^2 >^N - \frac{3\kappa_N}{2m_N^2}$

with $< r_E^2 >^p \approx 0.707 fm^2, < r_E^2 >^n \approx -0.116 fm^2$

Pseudoscalar form factor $G_P = -\frac{4 m_N g_{\pi NN} F_\pi}{q^2 - M_\pi^2} - \frac{2}{3} g_A m_N^2 < r_A^2 >$

Axial vector form factor $G_A = \frac{g_A}{(1 - q^2/M_A^2)^2}$ with $F_\pi \approx 92.28 MeV$

$\frac{g_{\pi NN}^2}{4\pi} \approx 13.7, < r_A^2 > \approx 0.46 fm^2, g_A \approx 1.276, M_A \approx 1 GeV$

Backup

$$
\begin{aligned}
\hat{\mathcal{M}}_{JM}(\kappa) &\equiv \hat{M}_{JM} + \hat{M}^5_{JM} = \int d^3x [j_J(\kappa x) Y_{JM}(\Omega_x)] \hat{\mathcal{J}}_0(\mathbf{x}) \\
\hat{\mathcal{L}}_{JM}(\kappa) &\equiv \hat{L}_{JM} + \hat{L}^5_{JM} = \frac{i}{\kappa} \int d^3x \{\nabla [j_J(\kappa x) Y_{JM}(\Omega_x)]\} \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x}) \\
\hat{\mathcal{T}}^{\mathrm{el}}_{JM}(\kappa) &\equiv \hat{T}^{\mathrm{el}}_{JM} + \hat{T}^{\mathrm{el5}}_{JM} = \frac{1}{\kappa} \int d^3x [\nabla \times j_J(\kappa x) \boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)] \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x}) \\
\hat{\mathcal{T}}^{\mathrm{mag}}_{JM}(\kappa) &\equiv \hat{T}^{\mathrm{mag}}_{JM} + \hat{T}^{\mathrm{mag5}}_{JM} = \int d^3x [j_J(\kappa x) \boldsymbol{\mathcal{Y}}^M_{JJ1}(\Omega_x)] \cdot \hat{\boldsymbol{\mathcal{J}}}(\mathbf{x})
\end{aligned}
$$