Probing Light New Mediators on Coherent Elastic Neutrino-Nucleus Scattering

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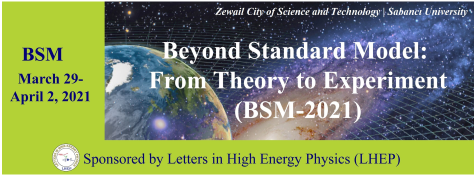

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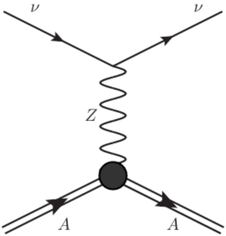
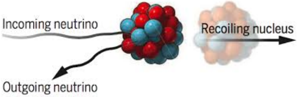
Outline

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

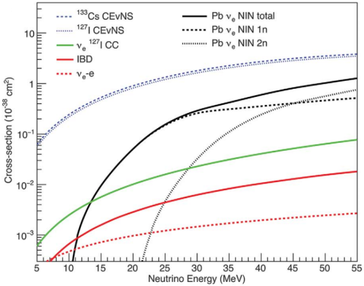
Brief Introduction to CEνNS

- A standard Model (SM) process, theoretically proposed in 1974.[Freedman, PRD 9 (1974)]
- Neutrinos collide with nucleus via the neutral Z boson followed by recoil nucleus.
- ν and N interact as a whole without changing internal state.
- CEνNS recoil energy is similar with the dark-matter direct detection.





- To occur: $\lambda \geq r_N$ and $E_\nu \leq 50$ MeV.
- It provides relatively large σ among other neutrino interaction processes.



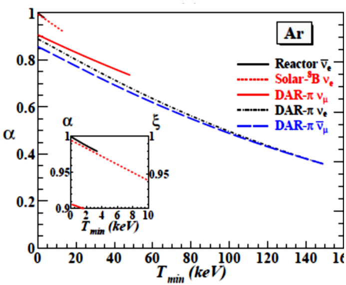
- Hard to detect; the nuclear recoil energy, T_N, is around a few keV.
- Successfully observed in 2017 by COHERENT Col. within 6.7σ using CsI target

  [D. Akimov *et al.*, Science 357 (2017)].
- Advancement using Ar last year

  [D. Akimov *et al.*, PRL 126 (2020)].

- COHERENT still unable to reach the full coherency criteria, $E_\nu \approx 4MeV$, smaller T_N.
- Best coherency would be available from reactor.
- Full-coherency from CONUS have been observed recently using Ge target

[H. Bonet, et.al., PRL 126, (2021)].



[S. Kerman, *et al.*,PRD 93 (2016)]

CEνNS Differential Cross-Section

- For SM $\nu(p_1) + N(p_2) \to \nu(p_3) + N(p_4)$ (spinless nucleus),

$$\mathscr{M} = \frac{2G_F}{\sqrt{2}} g_L^\nu \bar{\nu}(p_3)\gamma^\mu(1-\gamma^5)\nu(p_1)\langle N(p_4)|J_{NC_\mu}|N(p_2)\rangle. \quad (1)$$

- The differential cross section as a function of nucleus recoil energy is then

$$\left(\frac{d\sigma}{dT_N}\right)_{SM} = \frac{G_F^2}{4\pi} Q_{SM}^2 M|F(q^2)|^2\left(1 - \frac{T_N}{E_\nu} - \frac{MT_N}{2E_\nu^2}\right) \quad (2)$$

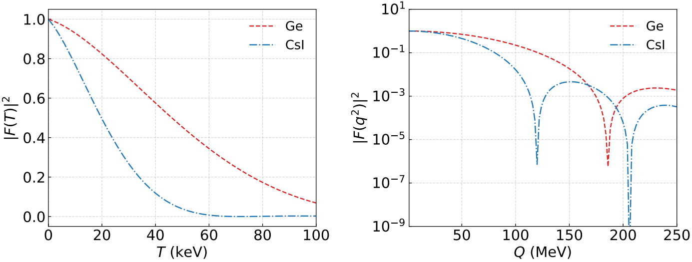
$$Q_{SM}^2 = \left(N - (1 - 4\sin^2\theta_W)Z\right)^2 \approx N^2, \quad (3)$$

or, using $\sigma_{SM} = G_F^2/(4\pi)Q_{SM}^2 M^2|F(q^2)|^2$

$$\boxed{\left(\frac{d\sigma}{dT_N}\right)_{SM} = \frac{\sigma_{SM}}{M}\left(1 - \frac{NT_N}{2E_\nu^2}\right)}. \quad (4)$$

- $F(q^2)$ describes the structure of the nucleus.
- Here we use the Helm form factor ($Q^2 \equiv -q^2 = 2MT_N$):

$$F_{Helm}(Q^2) = \frac{3J_1(qR_0)}{qR_0} e^{-\frac{1}{2}(qs)^2} \tag{5}$$



- Could be utilized using neutrino from accelerator, reactor, and astrophysical neutrino.
- Some facilities: COHERENT, CONUS, TEXONO, CONNIE, RED, etc.
- Other subject related:
  - Nuclear physics [D.K. Papoulias, et.al. PLB 800 (2020)],
  - CP violating [D.A. Sierra, V. D. Romeri, N. Rojas, JHEP 09 (2019) 069],
  - Non-standard interaction [C. Giunti, PRD 101 (2020)],
  - Exotic interaction [M. Lindner, W. Rodejohann, X. Xu, JHEP 03 (2017) 097],
  - Light mediator [Y. Farzan, et.al. JHEP 05 (2018) 066],

SM Extension: Simplified Model

Simplified Model

- Introduced to explain solar neutrino and dark matter interaction with matter.
- The neutral current are introduced with S, P, V, A, [D. G. Cerdeno, *et al.*, JHEP (2015)] and T [JHEP (2015), J. Barranco, *et al.*, Int.J.Mod.Phys.A (2012)] new interactions.
- Parameterization assumes very low energy, below electroweak symmetry breaking scale.
- Favourable proposal according to data from recent and advanced low energy neutrino experiment.

- General form of Lagrangian:

$$\mathscr{L}_S \supset [(g_{\nu S}\bar{\nu}_R \nu_L + h.c.) + g_{qS}\bar{q}q]\mathcal{S}, \quad (6)$$

$$\mathscr{L}_P \supset [(g_{\nu P}\bar{\nu}_R \nu_L + h.c.) - i g_{qP}\bar{q}\gamma^5 q]\mathscr{P}, \quad (7)$$

$$\mathscr{L}_V \supset [g_{\nu V}\bar{\nu}_L \gamma^\mu \nu_L + g_{qV}\bar{q}\gamma^\mu q]\mathscr{V}_\mu, \quad (8)$$

$$\mathscr{L}_A \supset [g_{\nu A}\bar{\nu}_L \gamma^\mu \nu_L - g_{qA}\bar{q}\gamma^\mu \gamma^5 q]\mathscr{A}_\mu, \quad (9)$$

$$\mathscr{L}_T \supset [g_{\nu T}\bar{\nu}_R \sigma^{\mu\nu} \nu_L - g_{qT}\bar{q}\sigma^{\mu\nu} q]\mathscr{T}_{\mu\nu}, \quad (10)$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu] = \frac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$.

- Any deviation from this proposal to the SM would be an evidence of new physics.

- Matching from quark to nucleon $\mathscr{n}$, and then to nucleus level $\mathscr{N}$:

$$\mathscr{L}_{X\mathscr{n}} = \langle \mathscr{n} | \mathscr{L}_X | \mathscr{n} \rangle \to \mathscr{L}_{XN} = \langle N | \mathscr{L}_{X\mathscr{n}} | N \rangle \tag{11}$$

where in general

$$\mathscr{L}_{XN} = g_{XN} \bar{N} \mathscr{O}_X N X F_X(q^2) \tag{12}$$

with $x = S, P, V, A, T$. Note that X before the F_X is the new field.

- We use $F_X = F_{Helm}$.
- Accordingly, with $\sigma_0 = G_F^2 m_N |F(q^2)|^2 / 4\pi$, we find

$$\left[\frac{d\sigma}{dT_N}\right]_S = \sigma_0 \frac{Q_S^2 m_N T_N}{E_\nu^2 (2m_N T_N + m_S^2)^2}, \tag{13}$$

$$\left[\frac{d\sigma}{dT_N}\right]_{SM+V} = \sigma_0 \Big(Q_{SM} + \frac{2\sqrt{2} Q_V}{2m_N T_N + m_V^2} \Big)^2 \Big(\frac{2E_\nu^2 - m_N T_N}{2E_\nu^2} \Big), \tag{14}$$

$$\left[\frac{d\sigma}{dT_N}\right]_A = \sigma_0 \frac{Q_A^2 (2E_\nu^2 + m_N T_N)}{E_\nu^2 (2m_N T_N + m_A^2)^2}, \tag{15}$$

$$\left[\frac{d\sigma}{dT_N}\right]_T = \sigma_0 \frac{32 Q_T^2 (4E_\nu^2 - m_N T_N)}{E_\nu^2 (2m_N T_N + m_T^2)^2}. \tag{16}$$

with $Q_X = g_{\nu X} g_{NX} / G_F$; $g_{\nu X} \rightarrow$ neutrino, while $g_{NX} \rightarrow$ nucleus.

- For each interaction we find (Cirelli, 2013)

$$g_{NS} = \mathscr{Z} \sum_{q=d,u,s} g_{qS} f_{Tq}^{p} \frac{m_p}{m_q} + \mathscr{N} \sum_{q=d,u,s} g_{qS} f_{Tq}^{n} \frac{m_n}{m_q}, \qquad (17)$$

$$g_{NV} = 3 g_{qV} (\mathscr{Z} + \mathscr{N}), \qquad (18)$$

$$g_{NA} = \mathscr{Z} S_p \sum_{q=d,u,s} g_{qA} \Delta_q^p + \mathscr{N} S_n \sum_{d,u,s} g_{qA} \Delta_q^n, \qquad (19)$$

with S_p and S_n related to nucleon spin as $S_{p,n} \equiv 2 s_\mu$, and for the tensorial case:

$$g_{NT} = \mathscr{Z} \sum_{q=d,u,s} g_{qT} \delta_q^p + \mathscr{N} \sum_{q=d,u,s} g_{qT} \delta_q^n. \qquad (20)$$

- Special to the pseudoscalar case:

$$\left[\frac{d\sigma}{dT_N}\right]_P = 0, \quad \text{since} \quad \sum_{q=u,d,s} \langle N|\bar{q}i\gamma^5 q|N\rangle = 0 \tag{21}$$

- If it is not, then

$$\left[\frac{d\sigma}{dT_N}\right]_P = \sigma_0 \frac{Q_P^2 T_N^2}{2E_\nu^2(2m_N T_N + m_P^2)^2}, \tag{22}$$

where

$$\begin{aligned} g_{NP} = \mathscr{Z} \sum_{q=d,u,s} g_{qP} \frac{m_p}{m_q}\left(1 - \frac{\bar{m}}{m_q}\right) \\ + \mathscr{N} \sum_{q=d,u,s} g_{qP} \frac{m_n}{m_q}\left(1 - \frac{\bar{m}}{m_q}\right), \end{aligned} \tag{23}$$

with $\bar{m} = (m_u + m_d + m_s)/(m_u m_d m_s)$.

- The value for each parameters are

Param.	Value	Source
$f^p_{T_u}$	0.0208	[M. Hoferichter, *et al.*, PRL 115 (2015)]
$f^n_{T_u}$	0.0189	"
$f^p_{T_d}$	0.0411	"
$f^n_{T_d}$	0.0451	"
$f^p_{T_s} = f^n_{T_s}$	0.043	[P. Junnarkar, A. Walker-Loud, PRD 87 (2013)]
$\Delta^p_u = \Delta^n_u$	0.842	[J.R. Ellis, K. Olive, C. Savage, PRD 77 (2008)]
$\Delta^p_d = \Delta^n_d$	-0.427	"
$\Delta^p_s = \Delta^n_s$	-0.085	"
$\delta^p_u = \delta^n_d$	0.84	[G.Bellanger, *et.al.*, CPC 180 (2009)]
$\delta^p_d = \delta^n_u$	-0.23	"
$\delta^p_s = \delta^n_s$	-0.05	"

Numerical Results

Event Rates and Event Numbers

- Event rates:

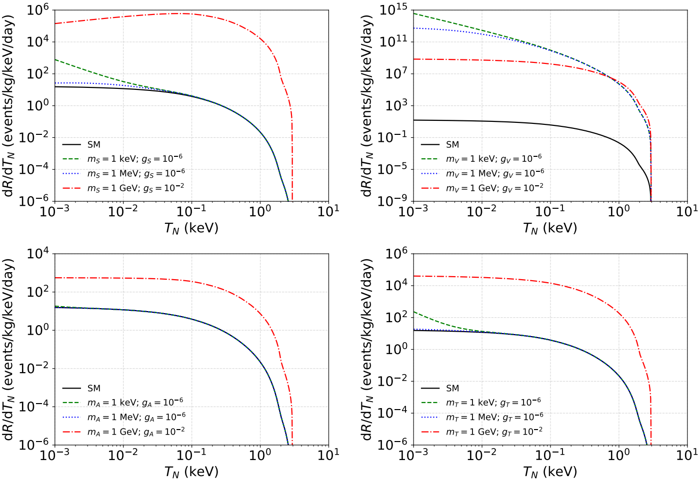
$$\frac{dR}{dT} = \int_{E_{\nu min}}^{E_{\nu max}} dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma}{dT} \frac{1}{m_N}. \tag{24}$$

- Event numbers:

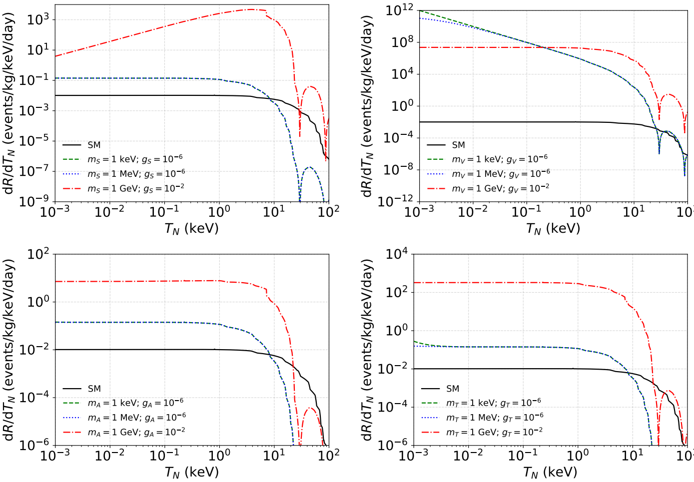
$$N = Nt \int_{T^i}^{T^{i+1}} \int_{E_{\nu min}}^{E_{\nu max}} dT dE_\nu \left[\frac{dR(T, E_\nu)}{dT} \right]_\nu \epsilon(T) \tag{25}$$

- We consider $d\phi/dE_\nu$ from detector (CHOOZ) and neutrino accelerator (SNS).

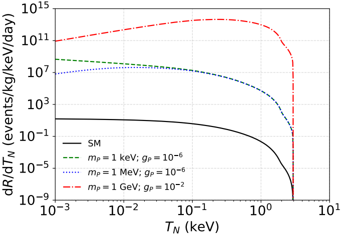
- Detector (Scalar, Vectorial, Axial, Tensor)

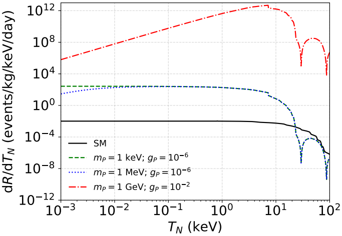


- Accelerator (Scalar, Vectorial, Axial, Tensor)



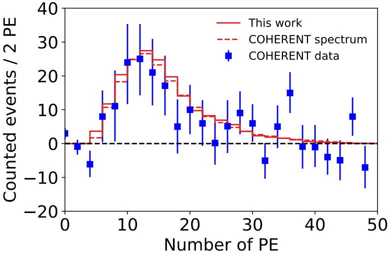
- Detector and Accelerator: Pseudoscalar





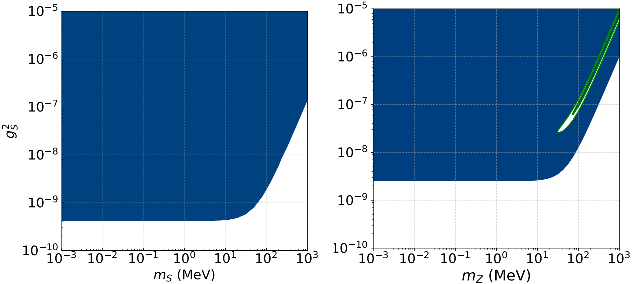
Bound Constraint

- Our preliminary work.
- Predicted number of event:



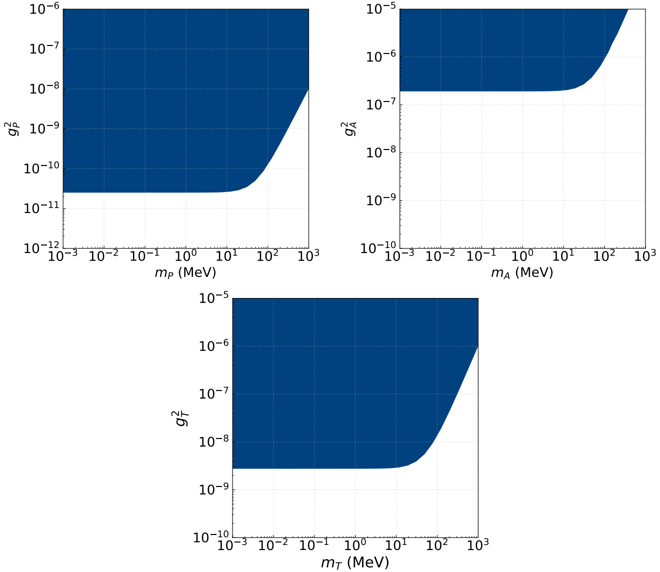
$$\chi^2 = \sum_{i=4}^{15} \left(\frac{N^i_{obs} - N^i_{theo}(1+\alpha) - N^i_{bkg}(1+\beta)}{\sqrt{N^i_{obs} + N^i_{bkg} + 2N^i_{ss}}} \right) + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 \quad (26)$$

- Scalar and Vectorial (90% C.L.)



- Suitable with [D. K. Papoulias, PRD 102 (2020)].

- Pseudoscalar, Axial, and Tensorial (90% C.L.)



Summary

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- We have shown the general case of the occurrence of new interactions in the CEνNS process.
- Reactor neutrino provides most probable environment for searching the light new mediators effect on CEνNS framework.
- Advancement from future observations will improve bound of the model.
- Trigger other branches: nuclear, quantum, material physics.

Thank You!