Physics implications of Dresden-II reactor data

Magnificent CEνNS Conference, 2023

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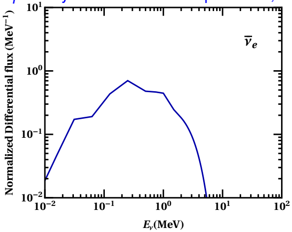
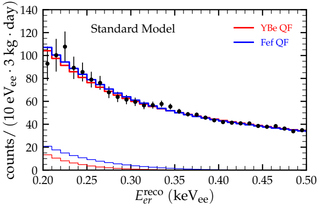
Recent First Observation of CEνNS by Reactor $\bar{\nu}_e$ at Dresden-II Facility

Produced through the β decay of the fissible isotopes $^{235}\mathrm{U}$, $^{238}\mathrm{U}$, $^{239}\mathrm{Pu}$, $^{241}\mathrm{Pu}$.



- Low energy, yet yielding very high fluxes possible.
- Require very low threshold (typically sub-keV nuclear recoil threshold) to observe CEνNS.
- Very low signal rate expected: Robust background rejection essential.



- Dresden-II uses a 3 kg germanium detector, namely NCC-1701.
- The experiment collected beam-on data for 96.4 days, located 10.39 meters from the Dresden-II reactor, with a low detection threshold of 0.2 keV$_{ee}$.

CEνNS

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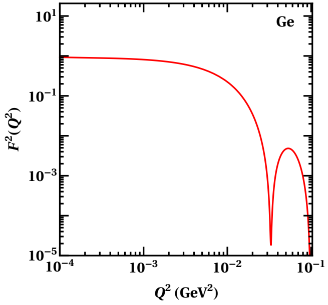
CEvNS is a fascinating process where low-energy neutrinos interact coherently with atomic nuclei, allowing us to study neutrinos and nuclei properties as well as to search for new physics beyond the Standard Model.

Freedman, 1974

$$\left.\frac{d\sigma}{dE_{nr}}\right|_{\rm SM} = \frac{G_F^2 m_N}{\pi} Q_{\rm SM}^2 \left(1 - \frac{m_N E_{nr}}{2E_\nu^2} - \frac{E_{nr}}{E_\nu}\right) F^2(E_{nr})$$



Simulation of the Dresden-II signal

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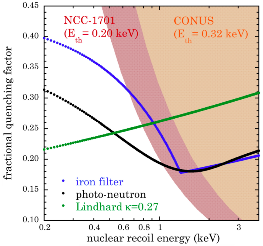
- Depending upon the various CEνNS interaction chanels, efficiency corrected events have been computed with incorporating the resolution effects by smearing the "electron equivalent" ionization energy, E_{er}^{true} into measured (or "reconstructed") ionization energy, E_{er}^{reco} throuh a truncated Gaussian function.
- The nuclear recoil energy, E_{nr} is converted into E_{er}^{true} using the Quenching factor: $E_{er}^{\text{true}} = \mathcal{Q}_f(E_{nr})E_{nr}$
- Dresden-II collaboration reported 2 different Quenching Factor models:

1. Fef: iron filtered neutron beam
2. YBe: photo-neutron $^{88}\mathrm{Y/Be}$ source

Colaresi et al. 2022

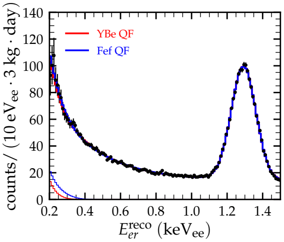


Background Fitting

In the ROI of Dresden-II, the background model is reported by the collaboration. It depends on four individual components, coming from epithermal neutrons and three electron capture (EC) peaks.

$$R_{\text{bkg}} = N_{\text{epith}} + A_{\text{epith}}\, e^{-\left(\frac{E_{er}^{\text{reco}} - E_{\text{epith}}}{\tau_{\text{epith}}}\right)} + \sum_{i=L_1,L_2,M} A_i\, e^{-\left(\frac{E_{er}^{\text{reco}} - E_i}{\sqrt{2}\sigma_i}\right)^2}$$

For a proper analysis the background must be fitted with signal using the prescription given in the ancillary file of PRL 129 no. 21, (2022) 211802.



Standard Model and Beyond

Weak Mixing Angle

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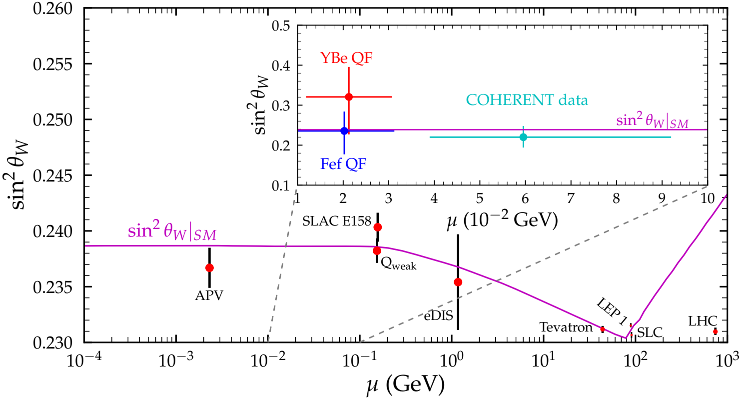
The CEνNS interaction rate is proportional to $Q^2_{\rm SM} = \left[\left(\frac{1}{2} - 2\sin^2\theta_w\right) Z - \frac{1}{2}N\right]^2$.

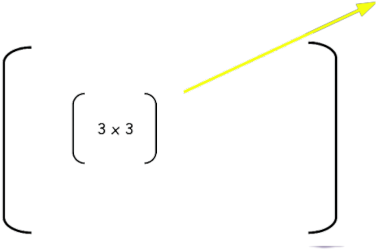
$$\left.\begin{array}{ll} \text{YBe:} & \sin^2\theta_W = 0.321^{+0.075}_{-0.094} \\ \text{Fef :} & \sin^2\theta_W = 0.236^{+0.048}_{-0.058} \end{array}\right\}$$

[Majumdar, Papoulias, Srivastava, Valle, PRD 106 (2022) 9, 093010]



Violation of lepton unitarity

- Flavour conversion happens when neutrinos travel from their source to the detector.
- Two factors are required for this phenomenon to occur:
  1. Mixing between flavour and mass eigenstates.
  2. Non-zero neutrino masses: $\Delta m^2 \neq 0$.
- In the typical analysis of neutrino oscillation data, the mixing matrix U is assumed to be unitary (i.e., $UU^\dagger = 1$) where $\nu_\alpha = U_{\alpha i}\nu_i$.
- However, the unitarity of the neutrino mixing matrix is yet to be proven, hence we can consider a typical scenario where the (Effective) mixing matrix of light neutrinos is a subset of a larger unitary mixing matrix involving mixing with additional heavy particles, making $\mathbf{U}_{\rm PMNS}$ non-unitary.



$$N = N^{\rm NP} U^{3\times 3} \qquad N^{\rm NP} \equiv \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{12} & \alpha_{22} & 0 \\ \alpha_{13} & \alpha_{23} & \alpha_{33} \end{pmatrix}$$

[Escrihuela, Forero, Miranda, Tortola, Valle, PRD 92 5, 053009]

Violation of lepton unitarity

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- The simplest example where Non-Unitarity can be generated: The Standard Model augmented with heavy singlet fermions, N_i. By 'heavy', we mean:
  - Masses that are much larger than the energies of neutrino oscillation experiments.
  - This is a 'minimal' realization of Non-Unitarity in the sense that: it only introduces new physics in the neutrino sector, and it only involves the 3 light neutrinos.
- The oscillation probabilities in the presence of NU are expressed as

$$
\begin{aligned}
P_{ee} &= \alpha_{11}^4 P_{ee}^{3\times 3} , \\
P_{e\mu} &= (\alpha_{11}\alpha_{22})^2 P_{e\mu}^{3\times 3} + \alpha_{11}^2 \alpha_{22} |\alpha_{21}| P_{e\mu}^{I} + \alpha_{11}^2 |\alpha_{12}|^2 , \\
P_{e\tau} &= (\alpha_{11}\alpha_{33})^2 P_{e\tau}^{3\times 3} + \alpha_{11}^2 \alpha_{33} |\alpha_{31}| P_{e\tau}^{I} + \alpha_{11}^2 |\alpha_{13}|^2
\end{aligned}
$$

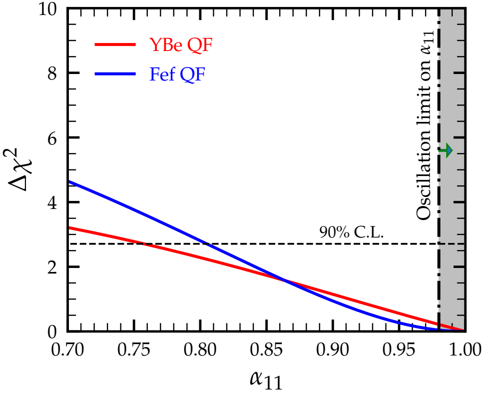
- For very short baseline experiments, such as Dresden-II

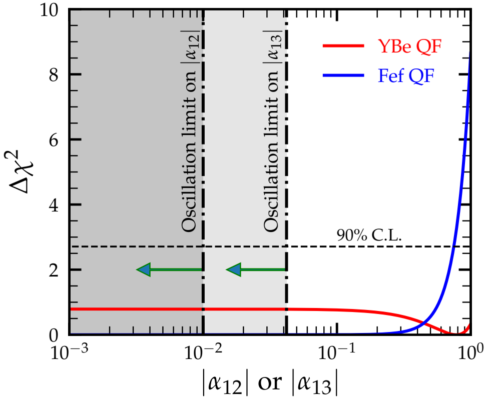
$$
\boxed{R_{\rm NU} = \alpha_{11}^2 \left(\alpha_{11}^2 + |\alpha_{12}|^2 + |\alpha_{13}|^2\right) R_{\rm SM} ,}
$$

Violation of lepton unitarity

[Majumdar, Papoulias, Srivastava, Valle, PRD 106 (2022) 9, 093010]

NU parameter	Oscillations	YBe QF	Fef QF
α_{11}	> 0.98	> 0.758	> 0.805
$\lvert\alpha_{12}\rvert$	$< 10^{-2}$	—	< 0.747
$\lvert\alpha_{13}\rvert$	$< 4.2 \times 10^{-2}$	—	< 0.747





NSI and NGI

NSI: Phenomenology of NSIs are discussed with a model independent parametrization.

Wolfenstein, 1978

$$\mathscr{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\, G_F\, \varepsilon_{\alpha\beta}^{qC} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{q}\gamma_\mu P_C q\right)$$

NGI: The convensional NSIs can be extended by incorporating all possible Lorentz-invariant interactions up to dimension 6 between neutrinos and other SM fermions—i.e., scalar, pseudoscalar, vector, axial vector, and tensor.

$$\boxed{\mathscr{L}_{\text{eff}}^{\text{NGI}} = \frac{G_F}{\sqrt{2}} \sum_{X=S,P,V,A,T} \left[\bar{\nu}\Gamma^X \nu\right] \left[\bar{q}\Gamma_X \left(C_X^q + i\gamma_5 D_X^q\right) q\right] \qquad \Gamma_X = \{\mathbb{I}, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}}$$

NSI and NGI

The NGI cross section is parameterized by nuclear currents - Scalar, Vector, and Tensor. Pseudoscalar and Axial vector interactions are ignored as they suppressed by nuclear spin, and also choose $D_X^q = 0$.

$$\left.\frac{d\sigma}{dE_{nr}}\right|_{\mathrm{NGI}} = \frac{G_F^2 m_N}{\pi}\left\{ C_S^2 \frac{m_N E_{nr}}{8E_\nu^2} + \left(\frac{C_V}{2} + Q_{\mathrm{SM}}\right)^2 \left(1 - \frac{m_N E_{nr}}{2E_\nu^2} - \frac{E_{nr}}{E_\nu}\right) + 2C_T^2 \left(1 - \frac{m_N E_{nr}}{4E_\nu^2} - \frac{E_{nr}}{E_\nu}\right) \pm \mathcal{R}\frac{E_{nr}}{E_\nu} \right\}$$

In this study we have explored the different scenarios:

- **The Single parameter case**, where only one nuclear current is present at a time.
- **The Two parameter case**, where two nuclear currents coexist and interact simultaneously.

NSI and NGI

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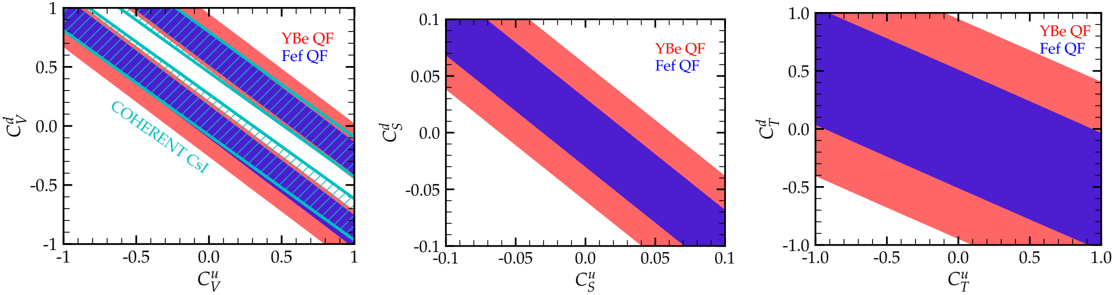
The Single parameter case:



[Majumdar, Papoulias, Srivastava, Valle, PRD 106 (2022) 9, 093010]

NSI and NGI

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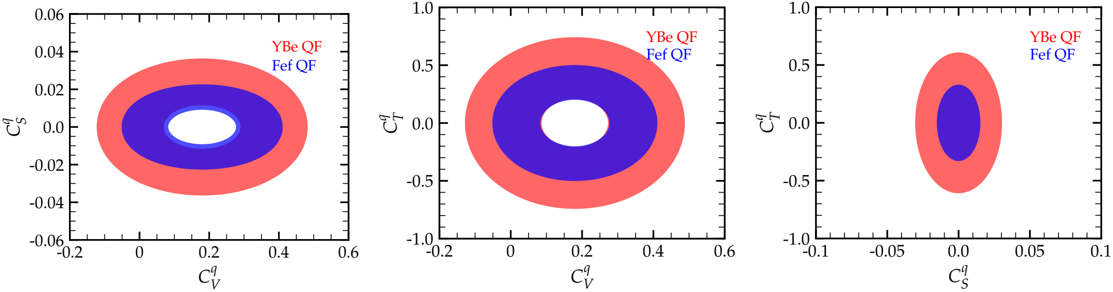
The Two parameter case:



[Majumdar, Papoulias, Srivastava, Valle, PRD 106 (2022) 9, 093010]

Conclusions

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- Phenomenological analyses of the latest Dresden-II data have uncovered new insights into the Standard Model and beyond, placing complementary constraints on a wide range of parameters.
- Although our Dresden-II determination of the weak mixing angle in the low-energy regime is not as competitive as the existing one from the COHERENT data, the best-fit value is in better agreement with the theoretical prediction from RGE extrapolations. However, one should note that the best-fit value differs dramatically for the two QF models we have adopted.
- Current Dresden-II data do not have sufficient statistics to place a competitive constraint on unitarity violation parameters. However, short baseline reactor CEνNS experiments may provide a promising unitarity violation probe in the long run.
- Dresden-II data place competitive constraints on NGI parameters with respect to COHERENT experiment.

Extras

χ^2 function

The statistical analysis in our present work is based on the Gaussian χ^2 function:

$$\chi^2(\vec{S}, a, \beta) = \sum_{i=1}^{130} \left[\frac{(1+a)R^i_{\text{CE}\nu\text{NS}}(\vec{S}) + R^i_{\text{bkg}}(\beta) - R^i_{\text{exp}}}{\sigma^i_{\text{exp}}} \right]^2 + \left(\frac{a}{\sigma_a} \right)^2 + \left(\frac{\beta_{M/L_1} - 0.16}{\sigma_{\beta_{M/L_1}}} \right)^2$$

where $R^i_{\text{CE}\nu\text{NS}}$ stands for the theoretically estimated CEνNS events in the ith bin, and $\vec{S}$ denotes the set of new physics parameters, while R^i_{exp} and σ^i_{exp} are the experimental number of events and the corresponding uncertainty in the ith bin, all taken from data release. The neutrino flux normalization uncertainty is taken into consideration through the nuisance parameter a with $\sigma_a = 2\%$. The uncertainty of β_{M/L_1} is taken to be $\sigma_{\beta_{M/L_1}} = 0.03$, and the prior 0.16 is assigned. In what follows, for a given parameter of interest from the set $\vec{S}$, our analysis involves minimization of the χ^2 function over each component of β and a.

Details on Background fitting

Background Parameters (β)	Allowed range	YBe QF	Fef QF
N_{epith}	$[0,\ 25]$	14.082	13.779
A_{epith}	$[0,\ 150]$	66.505	62.947
τ_{epith} (keV)	$[0,\ 2]$	0.249	0.262
A_{L_1}	$[70,\ 250]$	84.577	84.63
E_{L_1} (keV)	$[1.2,\ 1.4]$	1.29228	1.29237
σ_{L_1} (keV)	$[0.04,\ 0.1]$	0.0694	0.06963
β_{M/L_1}	$[0,\ 0.3]$	0.17	0.158
Fitted events (SM + Background)		5080.29	5103.4
χ^2_{min}		105.95/d.o.f.	102.66/d.o.f.