



The influence of reactor neutrino energy spectra for constraints on amplitude of coherent elastic neutrino nucleus scattering

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Content

- 1. Coherent Elastic Neutrino-Nuclear Scattering
- 2. RED-100 detector (technique and design)
- 3. Reactor neutrino enegry spectra
- 4. Calculations of nuclear recoil energy spectra
- 5. Estimations of differential count rate
- 6. The influence of reactor neutrino energy spectra for the constraints of CEvNS amplitude
- 7. Conclusion

Coherent Elastic Neutrino-Nuclear Scattering

• Coherent Elastic v-Nucleus Scattering (CEvNS, CENNS, CNS, CNNS,...)



Detector response for CEvNS

- Neutrino interaction produces a nucleus recoil.
- The detector should be responible at range $< 1 \text{ keV}_{NR}$.
- For two-phase emission detectors this should be a compact (point-like in the XY plane) event!



RED-100 detector design

Russian Emission Detector (RED); [~100 kg of LXe in the fiducial volume]

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«First ground-level laboratory test of the two-phase xenon emission detector RED-100». Collaboration. RED-100 //*Akimov D. et al.* JINST. V. 15 2020. P02020.



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RED-100 detector technique

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- Detector is very sensitive to the single electrons of ionisation!
- The reactor antineutrino CEvNS-like events at RED-100 up to ~10SE.
- The threshold ≥4SE (extracted to the gas phase)
 @~35% transperancy (liquid-gas boundage)

Compact (point like) event just for the S2-signal, S1signal is neglectable (for the reactor neutrino energies).

- S1 scintillation signal (in a liquid phase)
- S2 electroluminiscence signal (in a gas gap)



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Passive shielding for the RED-100 detector



8/21

«Passive shielding of the RED-100 detector in an experiment to study the CENNS process» Lukyashin A.V. @NPhE-2020
«A Passive Shield for the RED-100 Neutrino Detector» Instrum Exp Tech 64, 202–208 (2021).

Reactor antineutrino energy spectrum models

Huber & Muller (H&M) [2011] $2:8 \text{ MeV}$ YES Kopeikin [2012] $0:9 \text{ MeV}$ NO Kurchatov Institute (2012) $0:9 \text{ MeV}$ YES Institute for Nuclear Research (INR) [2024] $2:8 \text{ MeV}$ YES Summation Model 2018 $0.05:+10.75$ YES Daya Bay (DB) [2022] $2:+10.75 \text{ MeV}$ NO RENO (RENO (2021)) $1.8:+8.5 \text{ MeV}$ YES Daya Bay (DB) [2022] $2:+10.75 \text{ MeV}$ NO Daya Bay (DB) [2022] $2:+10.75 \text{ MeV}$ NO Daya Bay (DB) [2022] $2:+10.75 \text{ MeV}$ NO Za ³⁵ U 56.4% 57.1% \sim 7.0% Za ³⁹ U 30.4% 30.0% \sim 7.0% Za ³⁹ Pu 30.4% 30.0% \sim 5.6% \sim 6.0%	Model		E_v rang	ge	Partial SP	MeV)]	A	Reactor neutrino spectra					
Kopeikin [2012] $0 \div 9 \text{ MeV}$ NO Kurchatov Institute (K1) [2023] $2 \div 8 \text{ MeV}$ YES Institute for Nuclear Research (INR) [2024] $0 \div 13 \text{ MeV}$ YES Summation Model 2018 $0.05 \div 10.75$ MeV YES Daya Bay (DB) [2022] $2 \div 10.75 \text{ MeV}$ NO RENO Kopeikin 2012 Daya Bay (DB) [2022] $2 \div 10.75 \text{ MeV}$ NO No Ratio Point by point linear interpolation Daya Bay (DB) [2022] $2 \div 10.75 \text{ MeV}$ NO Z35U 56.4% 57.1% $\sim 57.0\%$ Z38U 7.6% 7.3% $\sim 7.0\%$ Z38U 30.4% 30.0% $\sim 31.0\%$ Z41Pu 5.6% 5.6% $\sim 6.0\%$	Huber & Muller (H&M) [2011]		2÷8 Me	eV	YES					•	DB INR		
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Institute for Nuclear Research (INR) [2024] $0 \div 13 \text{ MeV}$ YES Summation Model 2018 $0.05 \div 10.75$ MeV YES Daya Bay (DB) [2022] $2 \div 10.75 \text{ WeV}$ NO RENU [2021] $1.8 \div 8.5 \text{ WV}$ NO 1.8 \div 8.5 \text{ WV} NO 235U 56.4% 57.1% $\sim 57.0\%$ 238U 7.6% 7.3% $\sim 7.0\%$ 239Pu 30.4% 30.0% $\sim 31.0\%$ 241Pu 5.6% 5.6% $\sim 6.0\%$	Kurchatov Institute (KI) [2023]		2÷8 Me	eV	YES	(fissic					SM 2018 RENO Kopeikin 2012		
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239 Pu 30.4% 30.0% $\sim 31.0\%$ 241 Pu 5.6% 5.6% $\sim 6.0\%$	²³⁸ U	7.6%	7.3%	~	~7.0%	• 0 ,8-					NI		
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	²⁴¹ Pu	5.6%	5.6%	~	~6.0%	(0 2	2	4	6 E	3 10 MeV	12	

Reactor antineutrino energy spectrum data

- T. A. Mueller et al., Improved predictions of reactor antineutrino spectra, Phys. Rev. C 83, 054615 (2011), arXiv:1101.2663 [hep-ex]. (H&M)
- 2) P. Huber, Determination of antineutrino spectra from nuclear reactors, Phys. Rev. C 84, 024617 (2012), arXiv:1106.0687 [hep-ph]. (H&M)
- 3) V. I. Kopeikin, Flux and Spectrum of Reactor Antineutrinos, Physics of Atomic Nuclei 75, 143–152 (2012). (Kopeikin2012)
- 4) V. I. Kopeikin, M. D. Skorokhvatov, and O. A. Titov, Reevaluating reactor antineutrino spectra with new measurements of the ratio between ²³⁵U and ²³⁹Pu β spectra, Phys. Rev. D 104, L071301 (2021), arXiv:2103.01684 [nucl-ex]. (KI)
- 5) D. V. Popov and M. D. Skorokhvatov, Model for the Conversion of Beta Spectra from Fission Products of Uranium and Plutonium Isotopes into Antineutrino Spectra, Physics of Particles and Nuclei Letters 20, 1 (2023). (KI)
- 6) M. Estienne et al., Updated Summation Model: An Improved Agreement with the Daya Bay Antineutrino Fluxes, Phys. Rev. Lett. 123, 022502 (2019), Supplemental Material, arXiv:1904.09358v1 [nucl-ex]. See Supplemental Material for Summation Model 2018 at http://link.aps.org/supplemental/10.1103/PhysRevLett.123.022502, which provides the antineutrino energy spectra for ^{235,238}U and ^{239,241}Pu, Extra Material: Table PDF. (SM 2018)
- 7) S. G. Yoon et al. (RENO Collaboration), Measurement of reactor antineutrino flux and spectrum at RENO, Phys.Rev. D 104, L111301 (2021), arXiv:2010.14989v3 [hepex]. See Supplemental Material for the RENO at http://link.aps.org/supplemental/10.1103/PhysRevD.104.L111301, for RENO 2021 Supplementary Data Release, Extra Material: Table TXT. (RENO)
- 8) F. P. An et al. (Daya Bay Collaboration), Antineutrino energy spectrum unfolding based on the Daya Bay measurement and its applications, Chinese Physics C 45, 073001 (2021), arXiv:2102.04614 [hep-ex]. (DB)
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Calculations of nuclear recoil energy spectra

- Due to a high threshold for the RED-100 detector (>4SE) it is important to take into account the energy reactor neutrinos (E_v above 8 MeV)!
- Also it have a neseesy to use the partial (cumulative ²³⁵U, ²³⁸U, ²³⁹Pu, ²⁴¹Pu) reactor neutrino energy spectra for more precision calculations!
- So, we chooz several models: DB, SM2018, KI, INR.

$$R(T) = \int \frac{d\sigma}{dT} (E_{\nu}, T) \cdot \rho(E_{\nu}) \cdot dE_{\nu}$$

• The nuclear recoil energy spectra could be determined as a convolution the CEvNS differential cross-cection formula with a reactor differential energy spectrum.

Calculations of nuclear recoil energy spectra $T \in [0, T_{max}]$ $\frac{d\sigma}{dT}(E_{\nu},T) = \frac{G_F^2}{4\pi} M Q_W^2 F(q^2) \left[1 - \frac{MT}{2E^2}\right]$ $T_{max} = \frac{2E_{\nu}^2}{2E_{\nu} + M}$ $\frac{d\sigma}{dT}(E_{\nu},T) = \frac{G_F^2}{4\pi} M Q_W^2 F(q^2) \left[1 - \frac{MT}{2E_{\nu}^2}\right] \cdot \left[\theta(T) - \theta(T - T_{max})\right]$ Reactor neutrino spectra $\rho_{\nu}(E_{\nu})$ Also should be take into account quantity Also should be take into account the burn-up fractions of atoms in an of 4 main nuclear fuel isotopes, time period of efffective mass in FV exposition, thermal power of the reactor core, average of the detector energy per fission and average distance betwin the $R(T) = \int_{E}^{E_{max}} \frac{d\sigma}{dT} (E_{\nu}, T) \cdot \rho(E_{\nu}) \cdot dE_{\nu}$ detector and reactor core. E_{min} and E_{max} — boundage values of reactor neutrino energy spectra lukyashin.anton@physics.msu.ru ICPPA-2024 12/21MEPhI Moscow

Calculations of nuclear recoil energy spectra

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Calculations of nuclear recoil energy spectra

$$\frac{d\sigma}{dT}(E_{\nu},T) = \frac{G_F^2}{4\pi} M Q_W^2 F(q^2) \left[1 - \frac{MT}{2E_{\nu}^2} \right] \qquad T_{max} = \frac{2E_{\nu}^2}{2E_{\nu} + M}$$

$$Q_W^2 = [N - Z(1 - 4\cos^2\theta_W)]^2 \qquad M \simeq Z \cdot m_p + N \cdot m_n$$

- The nuclei of xenon have a various number of neutrons (N).
- Several parameters (M, Q_W , T_{max}) at the CEvNS differential cross-cection formula also depends on the number of neutrons (N).
- For the k-th isotop the formula could be writen as:

$$\left[\frac{d\sigma}{dT}(E_{\nu},T)\right]_{k} = \frac{G_{F}^{2}}{4\pi}M_{k}Q_{W_{k}}^{2}F(q^{2})\left[1-\frac{M_{k}T}{2E_{\nu}^{2}}\right]\cdot\left[\theta(T)-\theta(T-T_{max_{k}})\right]$$

Calculations of nuclear recoil energy spectra

The RED-100 xenon isotopic consistans (fractions in [%])

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Estimations of differential count rate

• Noble Element Simulation Technique (NEST package) was used to obtain the partial charge yields (Y_{charge})

$$D(SE) = \sum_{i=1}^{N} \left[Y_{Charge}(SE,T) \right]_{i} \cdot \left[R_{Total}(T) \cdot \Delta T \right]_{i}$$
$$D(SE) = \int_{T_{min}}^{T_{max}} Y_{Charge}(SE,T) \cdot R_{Total}(T) \cdot dT$$

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Estimations of differential count rate

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The influence of reactor antineutrino energy spectra

- Day Bay results predicts best sensitivity, but the calculation for an arbitrary fuel composition is not possible!
- Summation
 Model 2018 has
 been chosen as
 the best fit of
 sensitivity curve!

Conclusion

- Models of reactor neutrino spectra affect the shape of sensitivity curves.
- The high-energy part of the reactor neutrino spectrum has a particularly strong influence.
- This influence is due to the high detector threshold and the barrier (liquid-gas) transmittance of ~35%.
- Models of energy transfer and fluctuations in the number of produced ionization electrons also significantly affect the shape of the sensitivity curves not only for the RED-100 detector, but also for other CEvNS search experiments.

Thank you for your attention!

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Thank you for your attention!

Backup slides

- Quenching models is also of importance!
- CONUS experiment HPGe: arXiv:2401.07684v2 [hep-ex]

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Расположение детектора РЭД-100 на Калининской АЭС

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