Argon Cross-Sections and Supernovae Neutrinos at the DUNE Experiment

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Research Question

The proposed study examines the impact of different ν_e + Ar^{40} cross-section models on the interpretation of supernova neutrino measurements at the DUNE detector. This research will explore how theoretical uncertainties in the cross-section models can limit experimental precision, and will include an analysis of the effects of neutrino oscillations under both normal and inverted hierarchies.

Neutrino Fluxes

1. Neutrino Production in Supernovae

- Neutrinos are generated in the core-collapse of supernovae, a key stage in the death of massive stars.
- These high-energy particles escape directly from the neutrinosphere, the dense shell where neutrinos are last scattered.

2. Neutrino Flux Model

- The un-oscillated neutrino flux, $F^0_{\nu_\alpha}$, is a measure of the intensity of neutrino emission for a specific neutrino flavor α, before any flavor transformations occur.
- This flux is crucial for understanding the initial quantity and energy distribution of neutrinos as they are emitted from the supernova.

$$F^0_{\nu_\alpha} = \frac{L_{\nu_\alpha}}{4\pi d^2 \langle E_{\nu_\alpha} \rangle}$$

Basic equation for un-oscillated neutrino flux as a function of luminosity, distance, and mean energy.

Parameter	Description
L_{ν_α}	Luminosity of neutrino type α
d	Distance to supernova (typically 10 kpc)
$\langle E_{\nu_\alpha} \rangle$	Mean energy of neutrinos (often < 100 MeV)

Table 1. Key parameters defining neutrino flux.

- The standard distance used for calculations is 10 kiloparsecs (kpc)
- The mean energy of neutrinos is typically below 100 MeV, relevant for the energy ranges of neutrinos produced in supernovae.

3. Distribution of Neutrinos

$$f_{\nu_\alpha}(E_\nu, t) = \mathcal{N} \left(\frac{E_\nu}{\langle E_{\nu_\alpha}(t) \rangle} \right)^{\beta_{\nu_\alpha}(t)} \exp\left[-(\beta_{\nu_\alpha}(t) + 1) \frac{E_\nu}{\langle E_{\nu_\alpha}(t) \rangle} \right] \qquad (1)$$

- $\mathcal{N}$ is the normalization constant, ensuring the distribution integrates to unity.
- β_{ν_α}, the pinching parameter, adjusts the width of the energy spectrum, influencing how peaked or broad it is.

Equation describing the normalized energy distribution of neutrinos, showing dependency on energy, mean energy, and pinching parameter.

Expected Signal in Underground Detector

$$\frac{dN(t)}{dt} = N_{\text{tar}} \int_{E_{\text{thr}}}^{E_{\text{max}}} dE \int_{E_{\text{thr}}}^{\infty} dE_\nu \int_0^{\infty} dE' \, \epsilon(E') \frac{dF_\nu}{dE_\nu}(E_\nu, t) \frac{d\sigma}{dE'}(E_\nu, E') G(E, E', \delta)$$

1. Detector Info. Thresholds, Fiducial Vols., efficiency, smearing, resolution, quenching, etc.

   Assuming a "perfect" detector, the efficiency is 1.
2. Neutrino Fluxes. Neutrino oscillation, different flavors for different reaction
3. Cross Sections. Charged-Current (CC) and Neutral-Current (NC) cross-sections

Neutrino Fluences

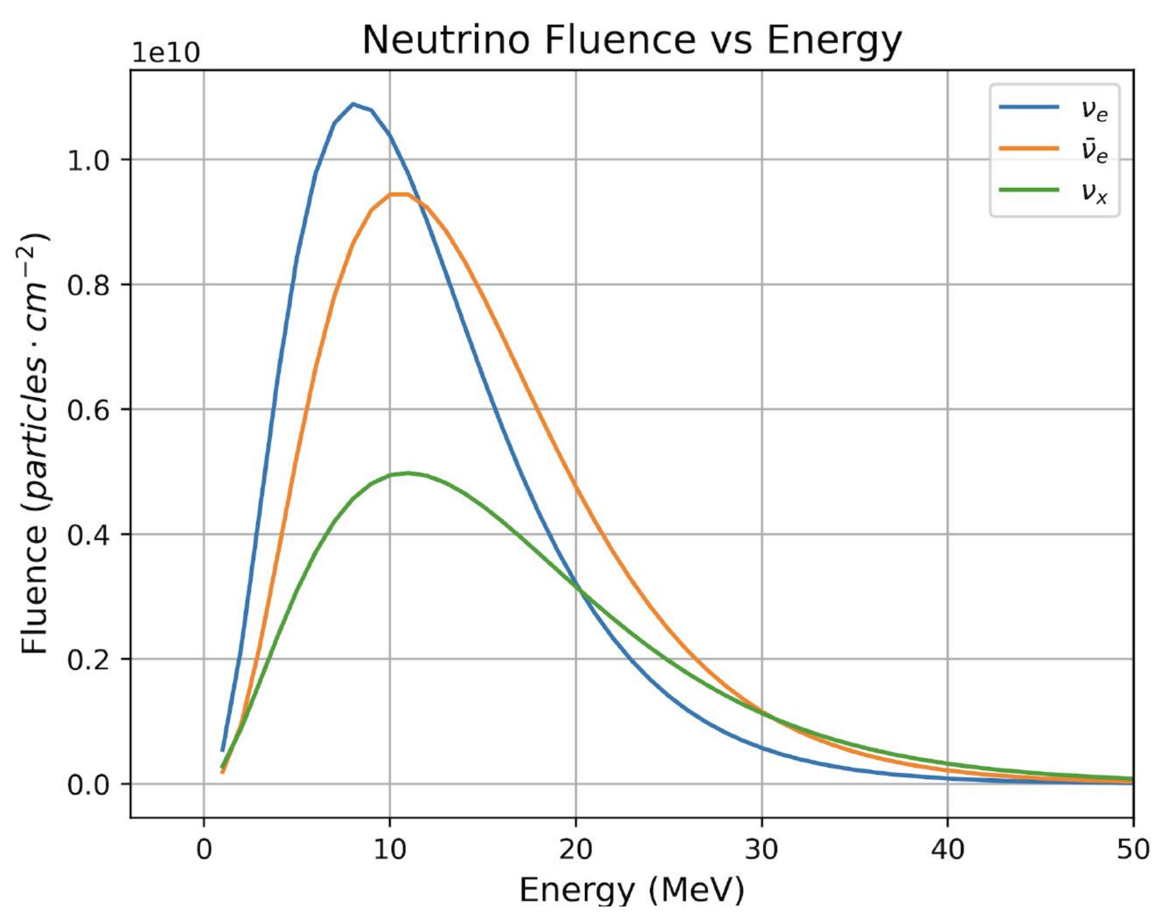
Neutrino Fluences: A quantification of the total number of neutrinos passing through a given area, integrated over the duration of a supernova event.

Data Source: The presented fluences are based on data from high-fidelity 3D supernova simulations with 25 solar masses provided by Vartanyan et al.

Methodology: Detailed computational approach for estimating neutrino fluences.

- Integration of neutrino flux over time captures the complete supernova event.
- Spectral parameters derived from simulations feed into the flux model.

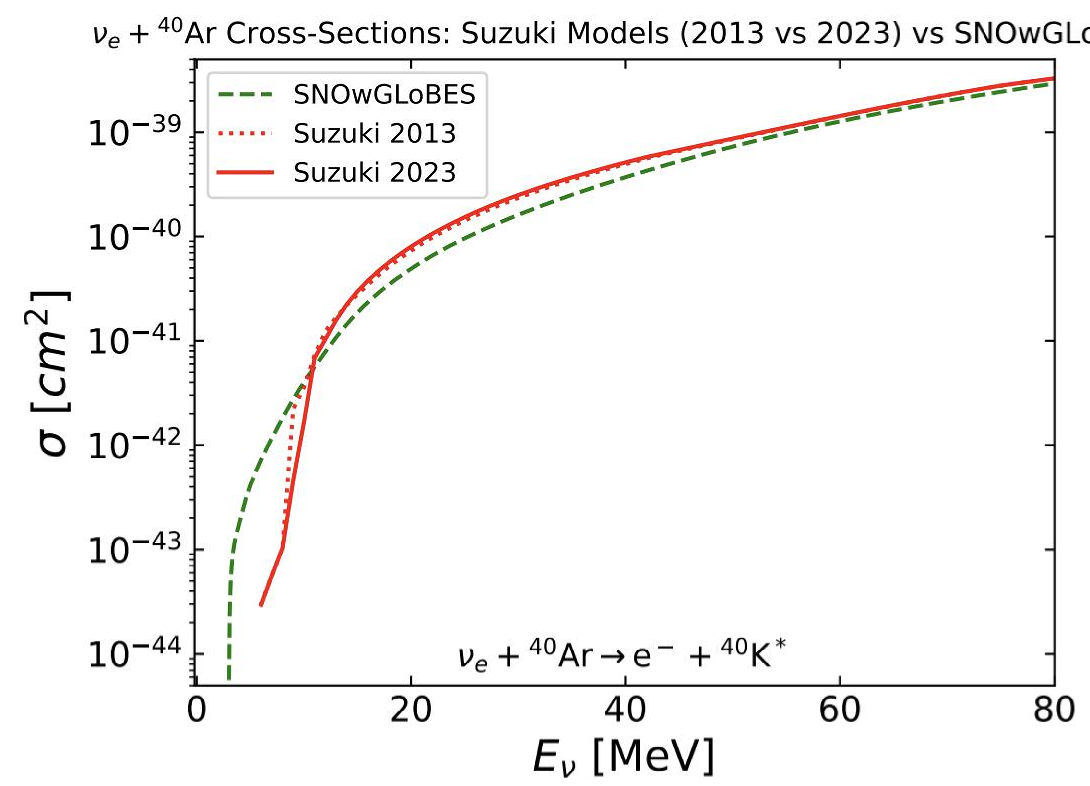
Graph Analysis



Observations and Conclusions

- Graph Analysis: The plot illustrates the energy spectra of different neutrino types from the supernova.
  - Each line represents the fluence for a specific neutrino flavor.
  - Energy range spans from the threshold of detection to the peak supernova neutrino energies.
- Conclusions: Interpretation of the fluence spectra yields several important conclusions.
  - Variations in fluence between neutrino types suggest differences in production mechanisms.
  - Observations help constrain the properties of neutrinos and the nature of the supernova progenitor.

SNOwGLoBES vs Suzuki Models 2023



SNOwGLoBES Uses predetermined cross sections and response functions to simulate neutrino detection scenarios, particularly for supernova neutrinos [1].

Suzuki 2023 Use the nuclear shell model for Gamow-Teller transitions and RPA for forbidden transitions from (2013) but updates the interaction model using the extended Kuo-Krenciglowa (EKK) method derived from chiral interactions for 1+ multipole [2].

- DUNE's program primarily focuses on GeV-scale neutrino beams, highlighting the importance of neutrino-nucleus scattering comprehension in this energy range [3, 4]
- However, sparse attention has been given to the MeV regime for SN neutrino detection.
- Theoretical calculations for CC neutrino-argon cross sections below 100 MeV show significant discrepancies, with no available measurements.

Calculating the Expected Signal at DUNE

- Neutrino Data:
  - Utilize fluence data from 3D supernova models to understand the initial neutrino spectrum.
- Cross Section Data:
  - Incorporate SNOwGLoBES for simulating signal rates based on supernova neutrino interactions.
  - Leverage cross section data from Suzuki 2013 and recent updates from 2023 to encompass a comprehensive range of neutrino interactions.
- DUNE Settings:
  - Apply DUNE's expected operational parameters, including energy resolution and detector volume, to simulate realistic signals.
- Methodological Approach:
  - Combine fluences/flux data with cross sections in a computational model tailored to DUNE's specifications.
  - Validate the approach using known supernova neutrino data or theoretical models as benchmarks.
- Anticipated Outcomes:
  - Quantify the expected neutrino signal at DUNE for typical supernova events.
  - Assess the impact and sensitivity of σ modeling and its uncertainties on DUNE's expected signals.

References

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