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MeV-scale event-by-event direction reconstruction with JNE 1-ton slow liquid scintillator prototype

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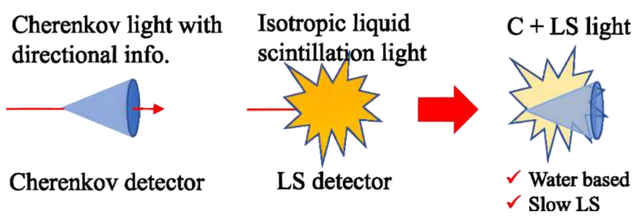
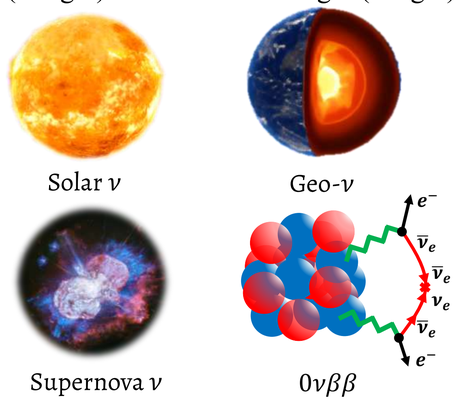
Ⅰ. Introduction

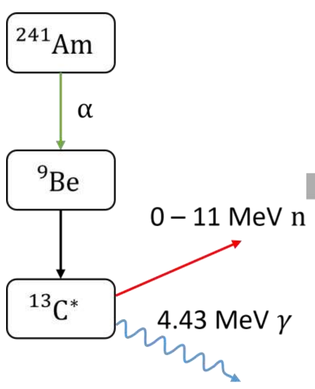
- To advance the exploration of various types of neutrinos, JNE aims to achieve event-by-event MeV-scale neutrino energy and direction reconstruction by Cherenkov light (C-light) and scintillation light (S-light) separation technique.
- This work will present **the first attempt to reconstruct the direction of individual AmBe γ using JNE 1-ton prototype in Slow Liquid Scintillator (SlowLS) phase**.



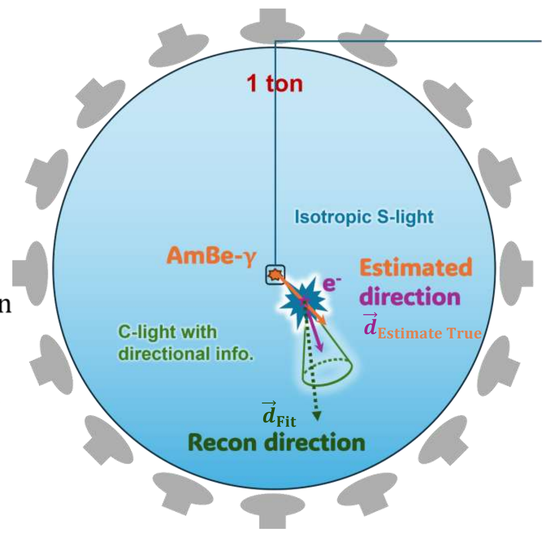


Ⅱ. Physical Process

- AmBe γ deposits energy in SlowLS, with C-light and S-light emitted and received by PhotoMultiplier Tubes (PMTs) successively.



AmBe decay process



SlowLS process

- To validate the directional effectiveness of reconstruction, we can check the **angular correlation** between the two vectors:
  - $\boldsymbol{d}_{\text{Fit}}$: reconstructed particle (e^-) direction.
  - $\boldsymbol{d}_{\text{Estimated True}}$: vector connecting event vertex to the AmBe position.

Appearance of Jinping 1-ton prototype

Structure of Jinping 1-ton prototype

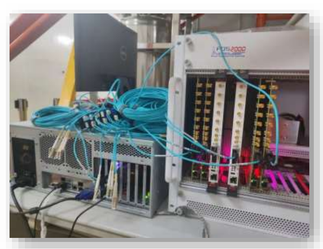
Ⅲ. JNE 1-ton Prototype

- 60 Novel 8-inch MCP-PMTs
  - U, Th: $< 4 \times 10^{-8}$ g/g, K: $< 4 \times 10^{-9}$ g/g
  - High QE: 20% ~ 30%
  - Good TTS: < 1.8 ns
- FADC for PMT waveform readout
  - 350 mW/ch, 12-bit, 1 GSps
  - Readout board: Bandwidth 300 MHz, 40 Gbps
- The subsequent reconstruction is **performed on the data derived from the AmBe source** placed at the center of the prototype, in SlowLS phase.
- SlowLS: oil-based (LAB + PPO + bis-MSB)
  - Light yield: 4245 photons/MeV
  - S-light time spectrum:

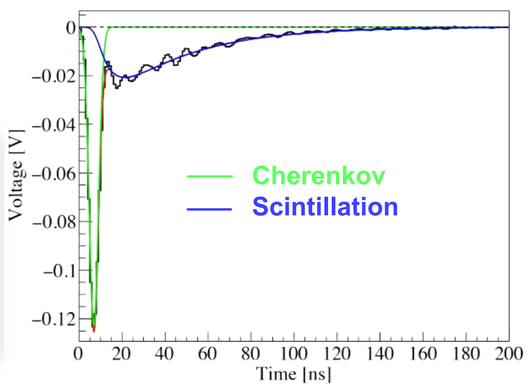
$$n(t) = \frac{\tau_r + \tau_d}{\tau_d^2}\left(1 - e^{t/\tau_r}\right) \cdot e^{t/\tau_d}$$

  - Rising time $\tau_r = 1.67$ ns.
  - Decay time $\tau_d = 26.59$ ns.

8-inch MCP-PMT



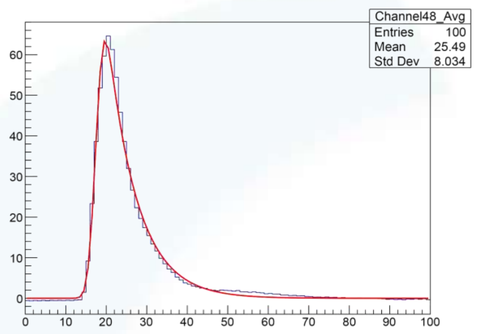
Readout board



Time profile of S-light and C-light in SlowLS

Waveform Analysis

- The output waveform is obtained by convolving the PhotoElectron (PE) with the single PE response of the PMT.



Single PE waveform

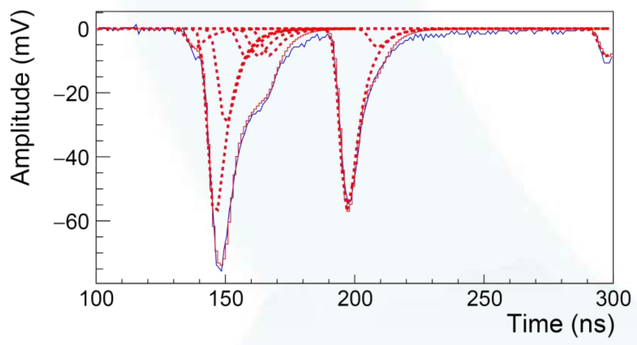
- An empirical formula for single PE response:

$$\mathrm{PE}_{\text{single}}(t) = A_0 \cdot \frac{1}{\tau_{\text{PE}}}\exp\left(-\frac{t}{\tau_{\text{PE}}}\right)\theta(t) \otimes \frac{1}{\sigma_{\text{PE}}\sqrt{2\pi}}\exp\left(-\frac{t^2}{2\sigma_{\text{PE}}^2}\right)$$

- Likelihood to fit multi-PE waveform:

$$\mathcal{L}(n_i^{\text{Obs}}, t_{ij}, R_{ij}) = f_{\text{Poisson}}(n_i^{\text{Obs}}; n_{\text{average}}) \cdot \prod_{k=\text{begin}}^{\text{end}} \text{Gauss}\left([V_{ik} - \sum_{j=1}^{n_i^{\text{Obs}}} R_{ij}\mathrm{PE}_{\text{single}}(k - t_{ij})], \sigma_{\text{base}}\right)$$

  - n_i^{Obs}: the PE number of i-th waveform.
  - t_{ij}: the waveform onset time



Fitted waveform compared with original waveform

PE Number

PE Time

Ⅳ. Waveform Analysis and Reconstruction

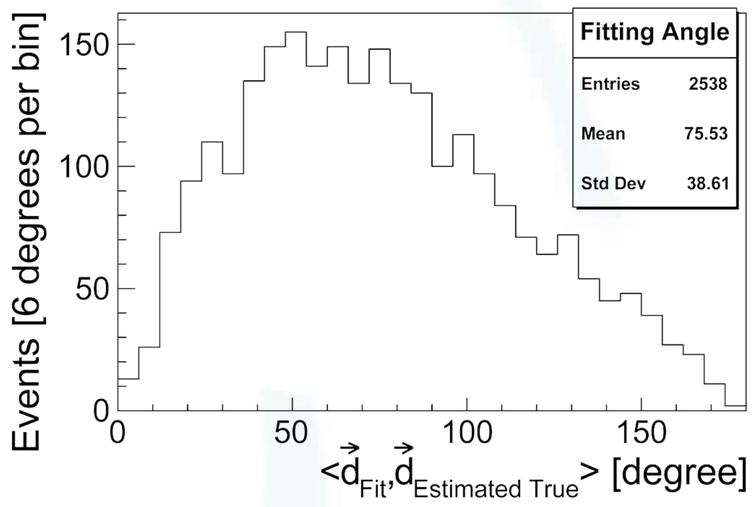
Event Reconstruction

$$\mathcal{L}\left(n_i^{\text{Obs}}, t_{ij} \mid E, x, y, z, t_{\text{event}}, \vec{d}_{\text{Fit}}\right) = \prod_i^{N_{\text{PMT}}} \left[P_i^{\text{C}}\right]_j^{n_i^{\text{Obs}}} P_{ij}^{\text{T}}$$

N_{PMT} Total number of PMT
n_i^{Obs} Number of the observed PE

Known quantities **Fit parameters** **Probability of the Charge and Time**

- C-light and S-light are reconstructed separately (indirect light and dark noise are also taken into account).
- As the right panel, a strong correlation between $\boldsymbol{d}_{\text{Fit}}$ and $\boldsymbol{d}_{\text{Estimated True}}$ was found, **showing the first sign of event-by-event direction reconstruction of MeV scale events in liquid scintillator.**



Correlation between AmBe γ direction and reconstructed particle direction (preliminary results)

Ⅴ. Summary

- JNE 1-ton prototype provides AmBe calibration data in SlowLS phase for reconstruction.
- A simultaneous reconstruction of energy, vertex, direction and time is performed on the calibration data for MeV scale gamma events.
- The effectiveness of MeV-scale event-by-event direction reconstruction is validated, enabling new approaches to neutrino source directionality measurements and improves background discrimination in MeV-scale neutrino experiments.

Reference

1. **Luo, W.; Liu, Q.; Zheng, Y.; Wang, Z.; Chen, S. Reconstruction Algorithm for a Novel Cherenkov Scintillation Detector. J. Inst. 2023, 18 (02), P02004. https://doi.org/10.1088/1748-0221/18/02/P02004.**