

Physics Opportunities of Large Liquid Scintillator Detectors (II)

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Te Loading for JUNO CD

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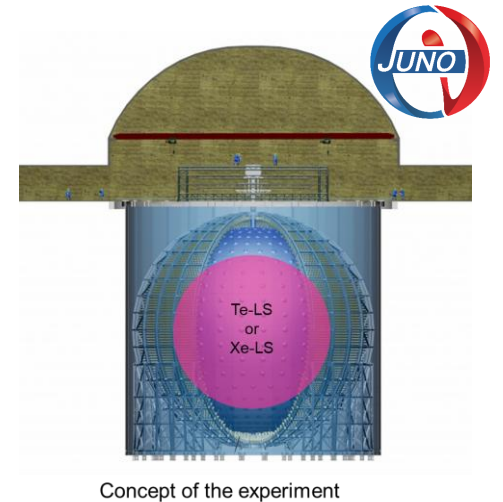
Physics Opportunities of Large Liquid Scintillators Detectors (II), HIM, Oct. 13, 2026

Outline

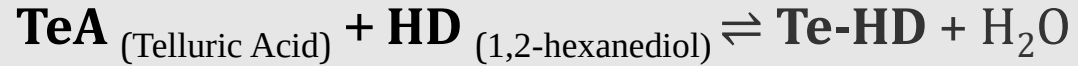
- Motivation for Te-loading in JUNO
- Te-LS research progress at IHEP
- Performance limitations in the development of Te-LS for $0\nu\beta\beta$ search
- Key R&D needs for scaling Te-LS to future detectors

Motivation for Te-loading in JUNO: Searching for $0\nu\beta\beta$

- **JUNO** offers a unique opportunity to search for $0\nu\beta\beta$ after completion of mass ordering measurements (~ 2030)
 - Large target mass: **20 kton LS** $\rightarrow$ 100-ton scale isotope (^{130}Te or ^{136}Xe) loading
 - Ultra-pure LS shielding $\rightarrow$ Low background
 - Energy resolution $\sim 3\%$ @ 1 MeV
- **^{130}Te** is a promising $0\nu\beta\beta$ candidate
 - Moderate Q-value. $Q(\beta\beta) = 2.53$ MeV
 - Highest natural abundance: **34%**. No need for expensive isotopic.
- **Requirements** for Te-LS used in $0\nu\beta\beta$ search: Extremely stringent
 - Exceptionally high Te-doping concentration: 3~5%
 - Minimum impact on LS optical performance
 - Ultra-low radio background
 - High-quality retention >10 years



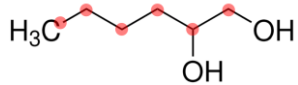
Te-LS research progress at IHEP



One-step synthesis

1,2-Hexanediol was selected through extensive experimental screening.

Six-carbon chain enables Te-HD to be fully miscible with LAB with good stability.



NIM A 1049 (2023 168111); NIM A 1088 (2026) 171531

Two routes

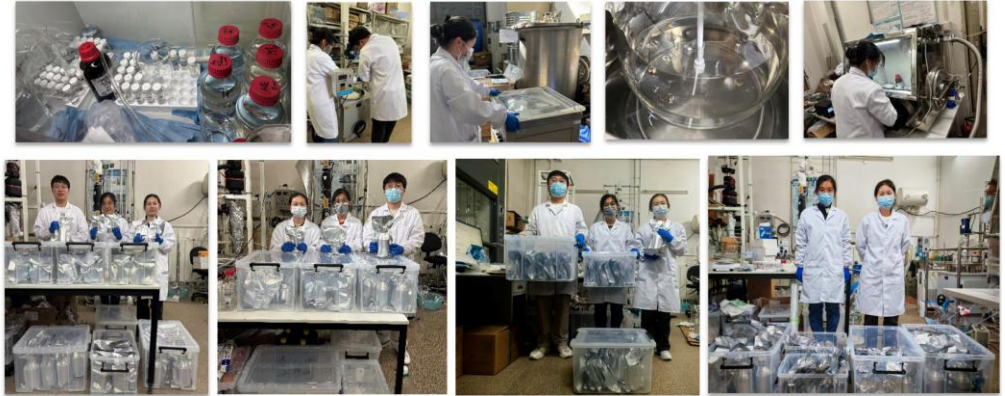
Route1: Azeotropic distillation

- >5% Te, Uniform, Transparent, and Stable

Route2: Room temp. Syn.

- Performance unchanged, safer, low energy consumption & more scalable

Now: 100-kg production with enhanced performance



200 g 1%Te samples each synthesis

>30 kg of 1%Te samples each batch

Favorable optical transparency

- Negligible impact on absorbance (430 nm)
- Attenuation Length of 1% Te-LAB = **20.1** ± 1.1 m

Moderate Relative Light Yield

- **55% ± 2%** at 0.5% Te loading
- **New development: 80% ± 2%** at 0.5% Te loading

Good long-term stability

- Spectral stability confirmed for **> 3 years** (0.6% loading, route 1) and **> 1 year** (1% and 3% loading, route 2) to date

Close to the requirements of JUNO CD

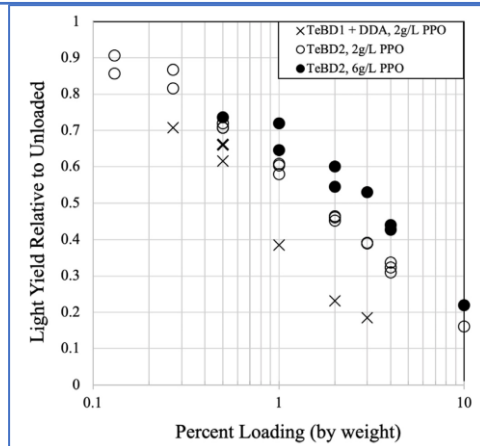
Further improvement needed

Highly promising

Performance limitations in the development of Te-LS for $0\nu\beta\beta$ search

- **Limitation 1:** Light yield decreases with increasing Te loading
 - Best L.Y. to date @IHEP, **Te-HD**, relative to pure LS: 2.5g/L PPO, 3mg/L bis-MSB in LAB
 - **80%** $\pm$ 2% at **0.5%** Te loading; **68%** $\pm$ 2% at **1%** Te loading; **40%** $\pm$ 2% at **3%** Te loading
 - Similar results obtained by other groups loading different Te compounds

SNO+, NIM A 1051(2023)168204, **Te-BD**



Russia, Phys. Part. Nucl. Lett. 20 (2023) 1187,
diphenyltellurium dicarboxylates

Table 1. Light yield and transparency of tellurium-loaded liquid scintillator samples [7]

Te	Composition of the scintillator, wt %			Light yield, relative units	$T_{\lambda} = 430 \text{ nm} \pm 1, \%$
	PPO	POPOP	Naphthalene derivative		
0.5	1	0.04	—	0.55 ± 0.04	88.5
0.5	1	0.04	Diisopropylnaphthalene, 30	0.72 ± 0.04	88.5
1 ¹	2	0.04	—	0.42 ± 0.02	86.2
1 ¹	2	0.04	Diisopropylnaphthalene, 30	0.57 ± 0.03	86.6
1 ¹	2	0.04	2,6-diisopropylnaphthalene, 30	0.57 ± 0.03	81.0
1 ¹	2	0.04	1-methylnaphthalene, 30	0.57 ± 0.03	77.7
1 ²	2	0.04	2,6-diisopropylnaphthalene, 30	0.54 ± 0.03	83.0
1 ³	2	0.04	2,6-diisopropylnaphthalene, 30	0.58 ± 0.03	85.0

¹ In the form of diphenyltellurium di-2-ethylhexanoate.

² In the form of diphenyltellurium diisovalerate.

³ In the form of diphenyltellurium dipivaloate.



- Is there a Te compound that does not affect L.Y. of LS when loaded?
- What is the upper limit of the Te-LS L.Y.? can it be calculated theoretically?

Performance limitations in the development of Te-LS for $0\nu\beta\beta$ search

- **Limitation 2:** radioactive background control, an extremely daunting challenge
 - Tellurium raw material (e.g., TeA) is the main source of Th/U in Te-LS
 - Industrial tellurium is extracted from copper anode slime, so it inevitably carries Th/U impurities from associated minerals
 - Preliminary measurements show Th/U content of commercial TeA is about several hundred ppt
 - Near-term goal: demonstration of 20t Te-LS using JUNO OSIRIS
 - Te loading: 0.5%
 - Minimum Th/U requirement of OSIRIS: $\leq 1\text{E-}15$ g/g
 - Ultimate Goal: Te Loading in JUNO CD
 - Te loading: 3%
 - If Th(U) requirements of JUNO: $\leq 1\text{E-}17$
 - Work need to do
 - Establish a measurement method for Th/U content in TeA with sufficient sensitivity
 - Establish a purification method for radioactive impurities in TeA with sufficient efficiency (can be done in collaboration with manufacturers)
 - Plan to visit the major domestic TeA suppliers soon and establish preliminary cooperation



Th/U in TeA ≤ 0.1 ppt



Th/U in TeA ≤ 0.2 ppq

Key R&D needs for scaling Te-LS to future detectors

- **Improve Te-LS performance through benchtop experiments and 100-kg scale production**
- **Studies required under real detector conditions:**
 - **Radioactive background:** purification and low-background assay of TeA
 - Status: Th/U at several hundred ppt
 - Target: $\leq 1\text{E-}15$ g/g (OSIRIS); $\leq 1\text{E-}17$ g/g (JUNO CD)
 - **Optical performance:** light yield, transparency
 - Status: improved L.Y. at IHEP obtained, further improvement needed
 - Target: meet the sensitivity goal at 3% Te loading
 - **Long-term stability**
 - Status: good stability observed so far
 - Target: stable LY and transparency over the detector operation time
 - **Material compatibility:** JUNO CD/OSIRIS are complex and contain stainless steel; water cannot be fully excluded; long-term contact with acrylic
 - **Stainless steel:** short-term contact shows no visible effect on the Te-LS spectrum

Key R&D needs for scaling Te-LS to future detectors

- **Water:** After stirring 8 mL of 3% Te-LS with 2 mL of water for several hours and letting the mixture settle, the phases separate cleanly and both remain clear; detailed tests planned
- **Acrylic** (JUNO CD material): long-term contact tests planned
- Other materials (tubing, seals): to be evaluated
- **Cosmogenic activation:** control of raw-material storage and transport (to be evaluated)
- **Demonstration of 20 t Te-LS using JUNO OSIRIS is the necessary step before Te loading in JUNO CD**
 - Achieve optical performance and stability at least comparable to the 100-kg scale, with radioactive backgrounds meeting requirements
 - Validate and optimize raw-material purification, especially radio-purification of TeA
 - Optimize the synthesis and verify batch-production scalability, reproducibility and safety

