锦屏中微子实验百吨探测器建设与掺钕液闪研发

Jinping Neutrino Experiment: Hundred-ton Detector Construction and Neodymium-Doped Liquid Scintillator R&D

续本达
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On behalf of JNE collaboration

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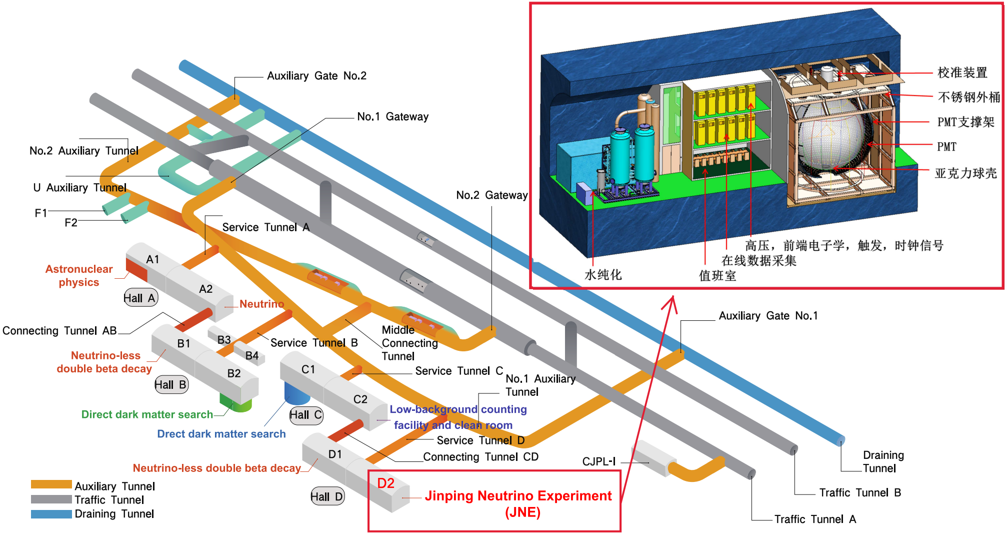
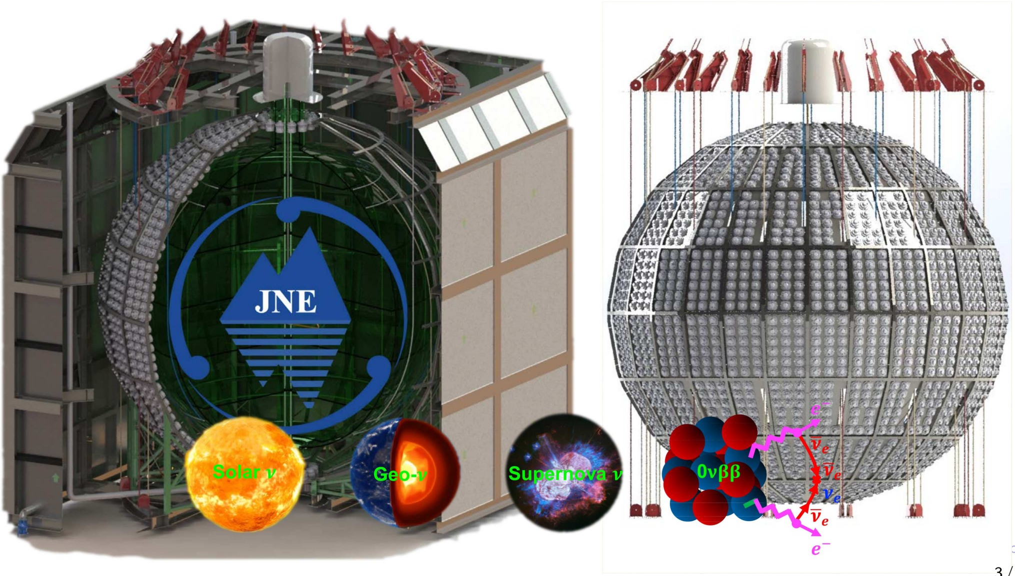
高能物理研究中心
工程物理系

ν NN 兰州 2025-07-23

D2 Hall of CJPL



Design of the Jinping Neutrino Hundred-Ton Experiment



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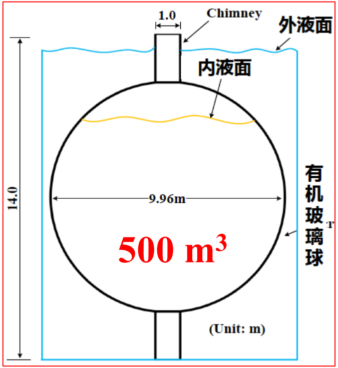
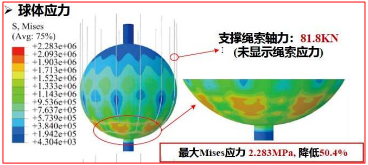
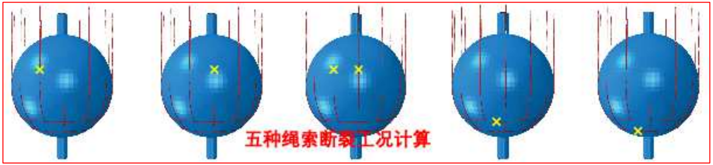
Construction Progress

Design of acrylic vessel

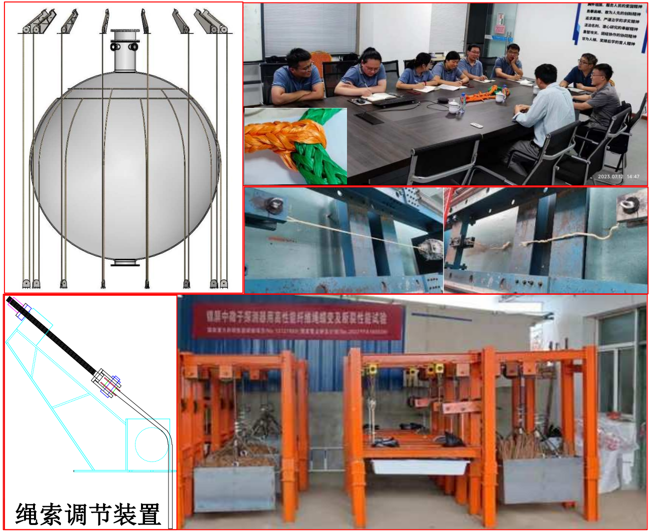






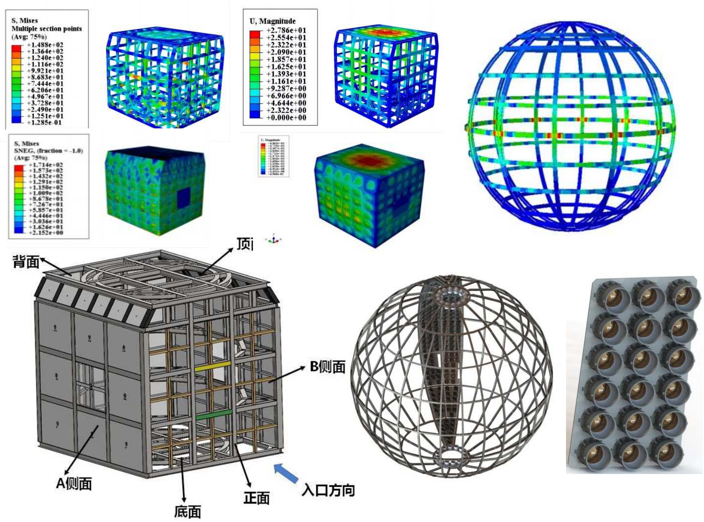
- acrylic vessel isolation for liquid scintillator, meeting environmental requirements.
- A rope-based securing design to counteract the notable density disparity $\pm 20\,\%$ between the internal and external liquids during the experiment.

Study on rope selection



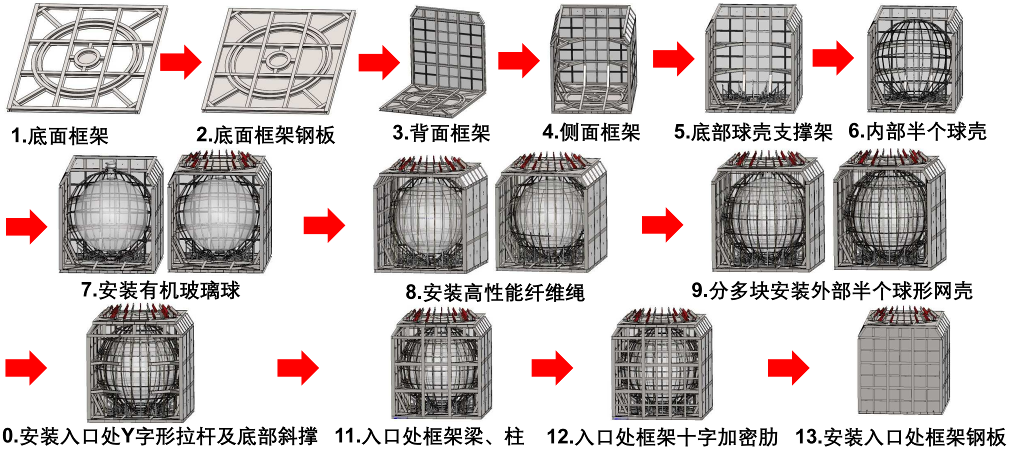
- Selection of rope, weaving, knotting, and installation scheme;
- Design of a rope tensioning mechanism;
- Radioactive background measurement and water solubility test;
- Long-term creep testing in aqueous and oil-based liquids.

Stainless steel water tank and PMT support structure

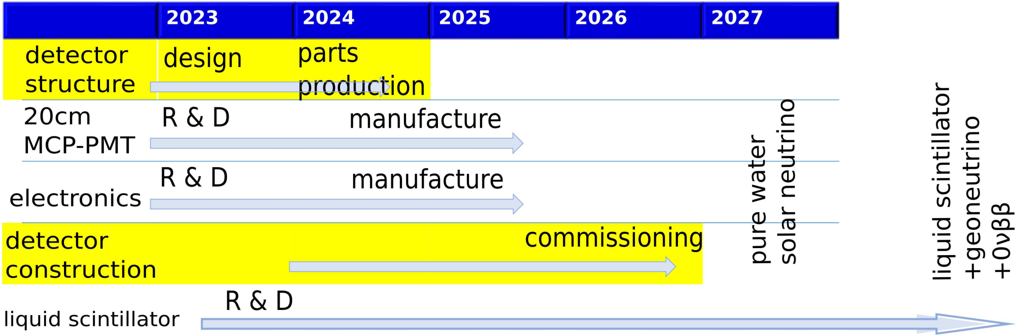


- Water tank design and its stress and displacement analysis from no-load to full-load states.
- Design of the PMT support structure, arrangement and installation modules.

Detector construction process



Time line



Phase 1 (2027–)

Ultra low cosmogenic background (6700 mwe vertically) to measure solar $^{8}\mathrm{B}$ neutrino flux and spectrum.

Neodymium-Doped Liquid Scintillator Project Plan

Trade-offs among PID, resolution, target mass

$$\frac{m_e^2}{G_{0\nu}\langle m_{\beta\beta}\rangle^2 M_{0\nu}^2} = T_{1/2}^{0\nu\beta\beta} = \frac{\epsilon}{\sqrt{b}}\sqrt{\frac{Mt}{\Delta E}}$$

实验测量目标

靶质量

相因子
高Q值

中微子质量
世界前沿
<100meV

信噪比:
低放射性
高Q值
双电子识别

能量分辨率:
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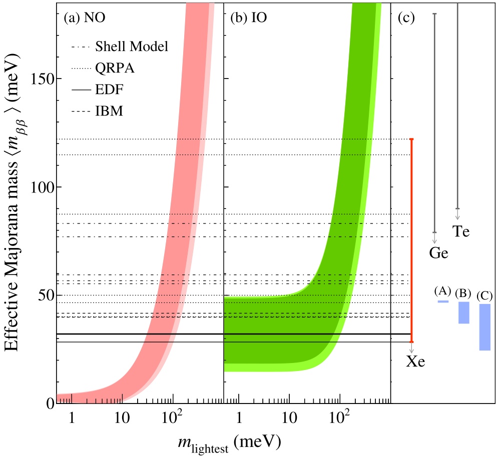
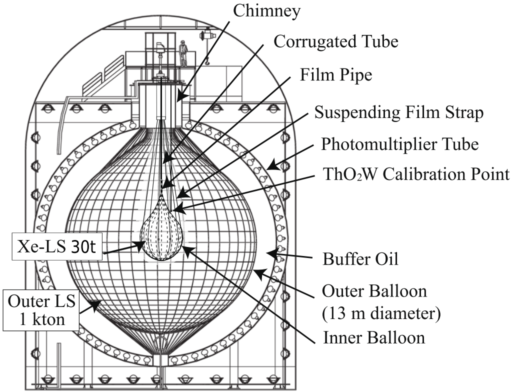
type	large mass	energy resolution	particle identification	Experiments
liquid scintillator	oo			KamLAND-Zen、SNO+、JUNO-$0\nu\beta\beta$
time projection	o(liquid)		o(gas)	EXO、PandaX、NνDEX、NEXT
Ge semiconductor		oo		LEGEND、CDEX
bolometer		o	o(light readout)	CUORE、CUPID
tracker			oo	NEMO

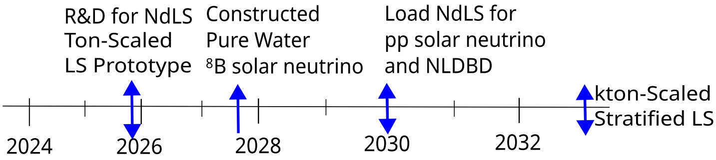
liquid scintillator $0\nu\beta\beta$: focusing on large target mass





- KamLAND-Zen gave best limits of $\langle m_{\beta\beta} \rangle$ in 2013, 2016, 2023.
- 2024, 3.8×10^{26} yr, $\langle m_{\beta\beta} \rangle = 28$ meV to 122 meV, (arXiv:2406.11438)

Jinping neutrino experiment “清心计划”



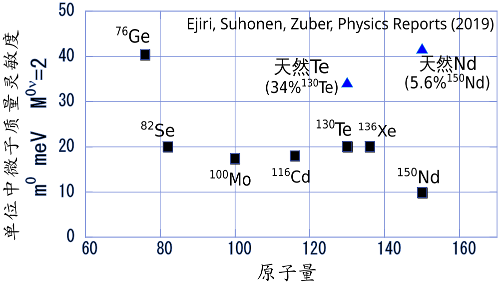
Covering the parameter space of inverted mass ordering

KamLAND2-Zen	JNE NdLS
Kamioka 1 km depth, cosmogenics dominate	Jinping 2.4 km depth
High light yield ^{136}Xe-LS	High light yield ^{150}Nd slow LS
Winston cone light concentrator	3D-optimized PMT light concentrator
HyperK high-QE PMT	NNVT fast $\varnothing 20$ cm MCP-PMT
down to 18 meV	Touching 20–30meV at 1% loading

arXiv:1703.07527 , arXiv:2303.05373, arXiv:2402.13266, arXiv:2502.20712

Advantage of Nd

- $0\nu\beta\beta$ multiple isotopes
  - Constrain nuclear matrix elements
  - Precise $\langle m_{\beta\beta}\rangle$ convertion
- $Q_{\beta\beta} > 3\,\mathrm{MeV}$
  - Predicted faster decay of $0\nu\beta\beta$.
  - Suppress natural radioactivity, higher energy resolution.



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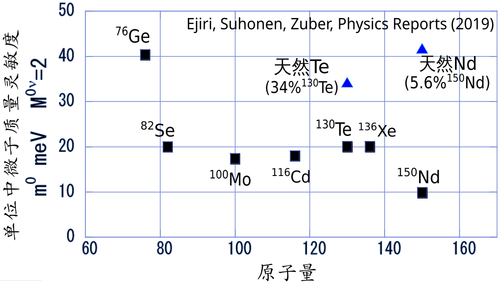
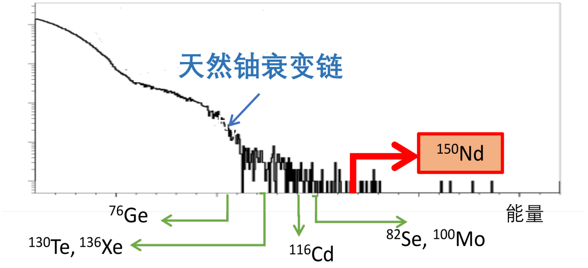
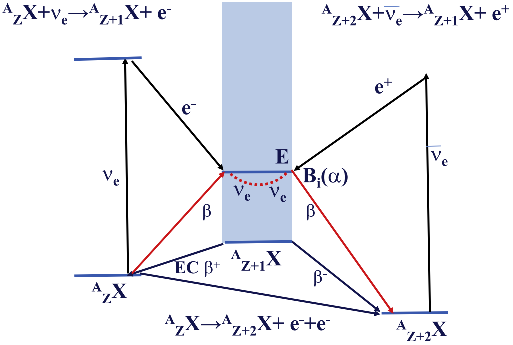




	$Q_{\beta\beta}$ MeV	abundance %
^{150}Nd	3.37	5.6
^{100}Mo	3.04	9.7
^{96}Zr	3.35	2.8
^{48}Ca	4.27	0.19

$2\nu\beta\beta$ induced by solar ν

delayed coincidence



- no e-ν elastic scattering smearing;
- e^- carries all the ν energy via charged-current on the nucleus;
- It is either a seriuos background or a solar ν machine.

Ejiri et. al., Physics Reports, 797 (March 23, 2019): 1–102.

Zero-background solar neutrino spectrometer

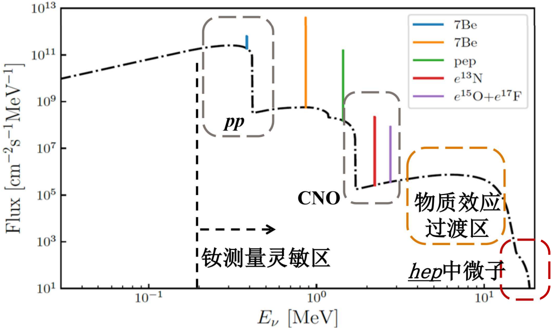
- 利用钕中微子–原子核散射直接能量测量

$$\nu_e + {}^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Pm}^* + e^- - 0.197\,\mathrm{MeV}$$

钕

$\xrightarrow{\sim 10\,\mathrm{ns}}$ ${}^{150}\mathrm{Pm} + \gamma + 0.11\,\mathrm{MeV}$

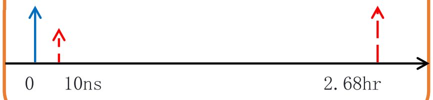
钷 $\xrightarrow{2.68\,\mathrm{hr}}$ ${}^{150}\mathrm{Sm} + e^- + \bar{\nu}_e + 3.45\,\mathrm{MeV}$



- 电子中微子物质效应显著

与液氙核相干散射（三类中微子等同）联合观测

^{150}Nd原子核散射：电子中微子标记

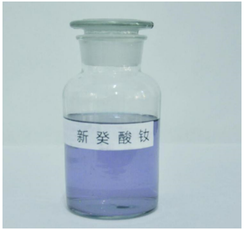


依托我国稀土全产业链优势，实现鉴别电子中微子的能谱探测方案，从中微子测量原理上突破。

Zuber 2012

Technical Challenges

Nd Availability

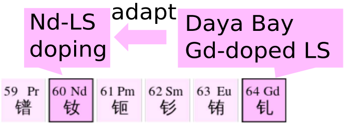


Neodymium

- Industry: laser, magnets, engine, dynamo, rubber catalyst
- From phosphate ore, $\mathrm{NdCl_3}$ and Nd neodecanoate available on market.

Stable Nd organic solution

- SNO+ early R&D
- start from the Daya Bay's Gd-LS technology



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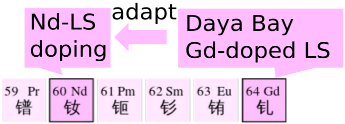
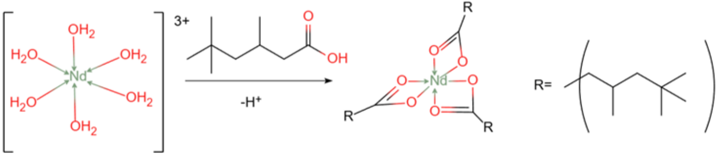




Exploring alternative ligands.

Absorption bands of the Nd complex

- Select and design more ligands, explore more fluors for transperancy.
  - Needs for systematic computation and search.

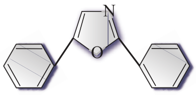


图: PPO

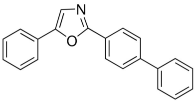
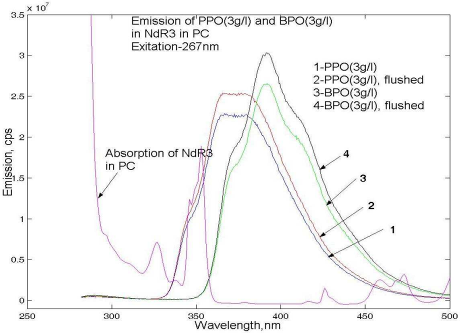
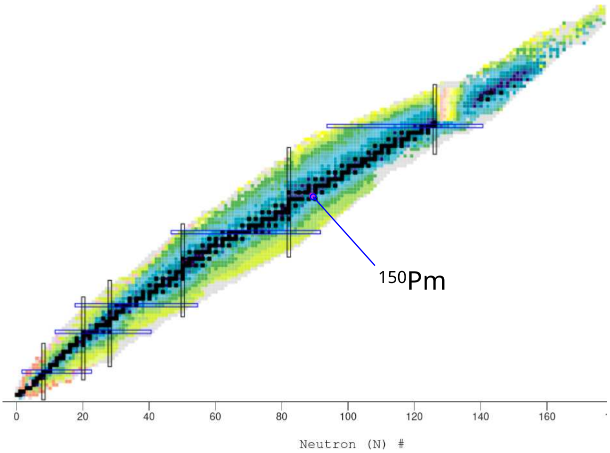


图: BPO



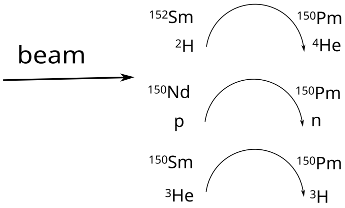
Barabanov et al. arXiv:0909.2152

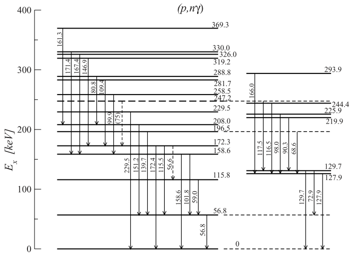
Lifetime of excited states



- No available data despite the proximity to stable isotopes.
- How well can we calculate it, or measure it? (PRL 131 052501 & 052502 (2023))

Possible measurement of the lifetimes





LaBr$_3$ array spectrometer

- Apply for beam time and prepare for 1 ns level measurement.
- A $^{51}\mathrm{Cr}$ source to calibrate ν_e response.

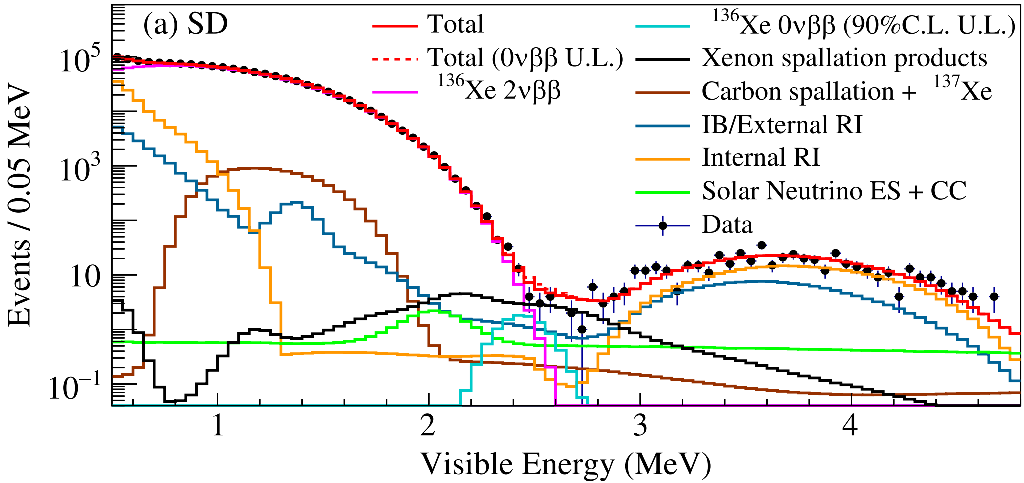
Bucurescu et al. 2012

Landscape of LS $0\nu\beta\beta$

Experiment	target element mass	Isotope
KamLAND-Zen	1ton	enriched $^{136}\mathrm{Xe}$
SNO+	$>$ 3ton	natural Te (34% $^{130}\mathrm{Te}$)
JUNO-$0\nu\beta\beta$	100ton	$^{136}\mathrm{Xe}$ or $^{130}\mathrm{Te}$
JNE NdLS	10ton	natural Nd (5.6% $^{150}\mathrm{Nd}$)
ZICOS	30ton	natural Zr (2.8% $^{96}\mathrm{Zr}$)

Common challenge: push for energy resolution and signal/background tagging.

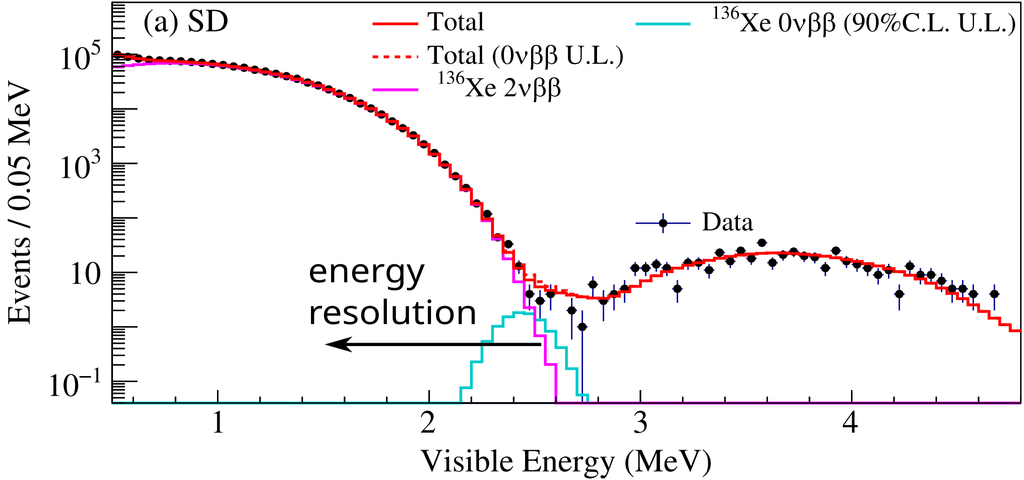
KamLAND-Zen energy spectra



- State-of-the-art for liquid scintillator $0\nu\beta\beta$.

arXiv:2406.11438

Energy resolution for $2\nu\beta\beta$



- $2\nu\beta\beta$ is irreducible background
  - unless for different angular distributions of $0\nu\beta\beta$.

KamLAND2-Zen: $4\,\% \rightarrow 2\,\%$

	KamLAND	JUNO	KamLAND2
PE yield per MeV	250	>1300	1200
Photocoverage/%	34	78	61
Light yield (relative)	1	1.5	1.4
PMT QE $\times$ CE/%	12	30	23

Hyper-Kamiokande PMT specs

- PMT TTS: $2.6\,$ns.
- Charge resolution: $31\,\%$.

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Hyper-Kamiokande PMT specs

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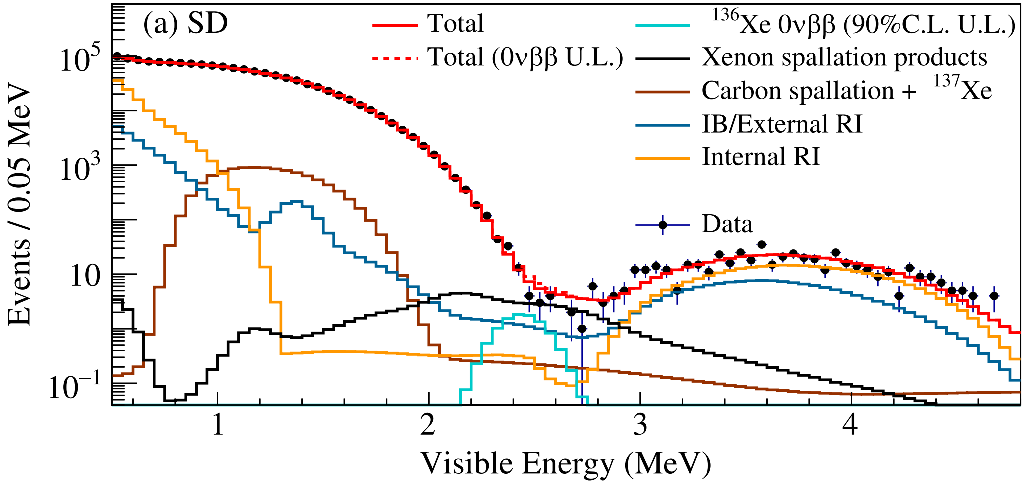
Rooms for improvement

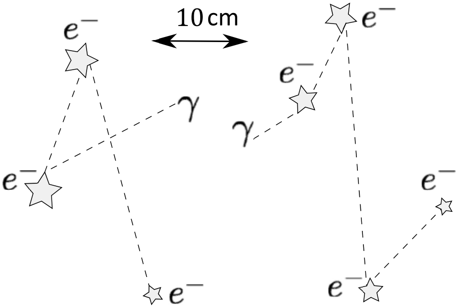
- $\frac{1}{\sqrt{1200\times2.5}} = 1.8\,\%$. vs. design goal: $2\,\%$.
- Major challenges: photon counting, detector response, dark noise modeling.

γ from β decays



- γ imaging with camera.

γ spread compared to vertex resolution



Possible to model individual electrons.

Remark

PMT TTS is negligible compared to scintillation time.

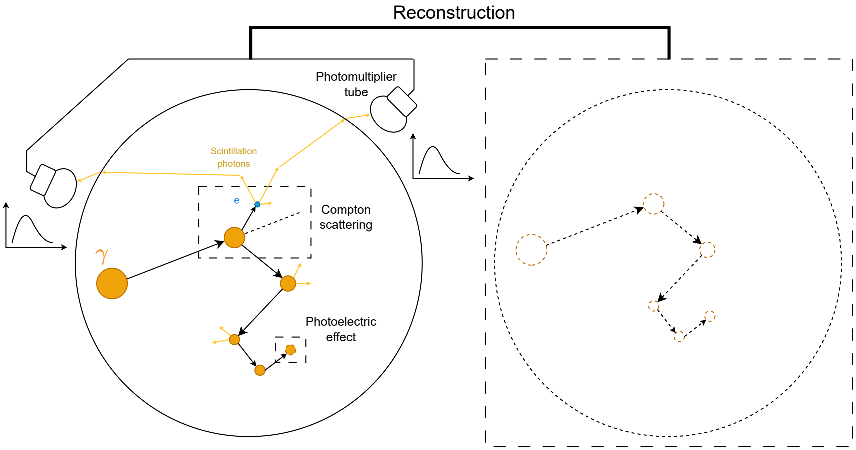
NIM A 568, 2 700 (2006)

KamLAND2 vertex resolution for 1 MeV e^-

$$\sqrt{\frac{3}{1200}} \times 20\,\mathrm{cm/ns} \times 10\,\mathrm{ns} = 10\,\mathrm{cm}$$

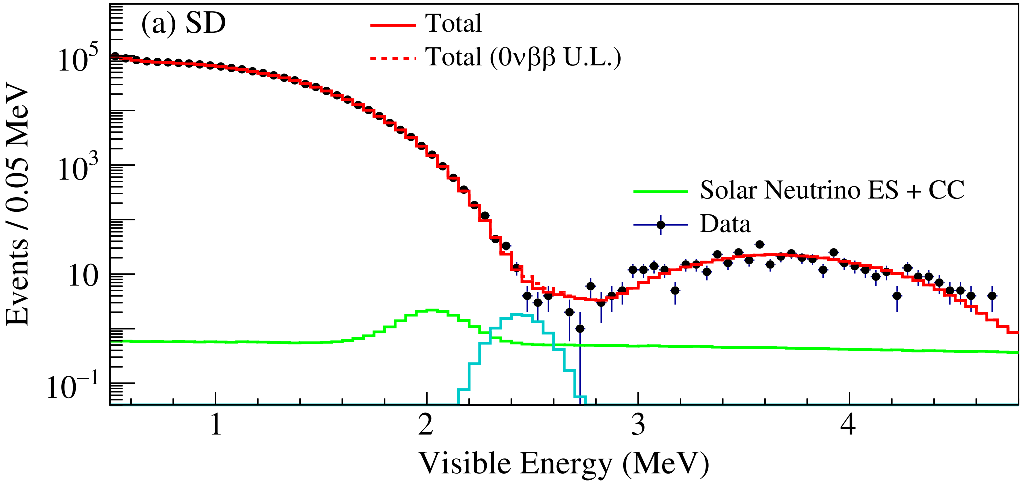
light speed (20 cm/ns); number of PEs (1200); scintillation time (10 ns)

Computed imaging with PMTs



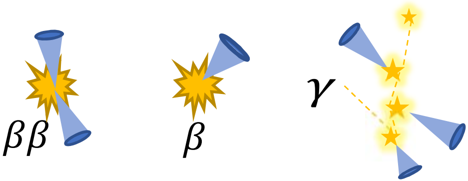
- My group is developing omni-directional optical time-projection (OγTPC)
- Challenges: photon timing, detector response

How many β for solar ν

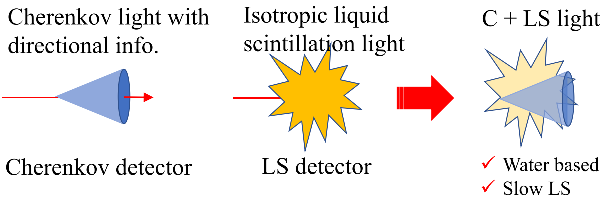


- A solar ν always gives 1β.

β multiplicity: $1\gamma = n \times \beta$



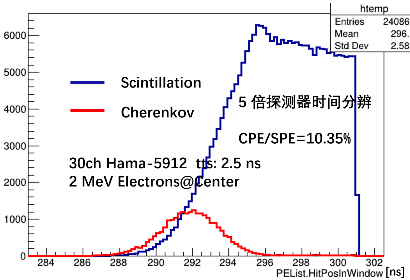
Cherenkov light in LS

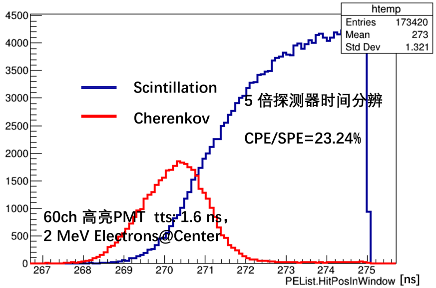


- Separation of Cherenkov photons to measure the angular correlation of two electrons.

Separation of Cherenkov and Scintillation lights with timing

- Cherenkov time scale: 0.1 ns, scintillation: 10 ns.
  - TTS of PMT from 2.5 ns to 1.6 ns gives $2\times$ difference.





- Challenges: photon timing, fast PMTs, slow liquid scintillator

Remark

Fast Cherenkov photons helps vertex resolution.

Key technologies

target	PE counting PE timing	detector response dark noise	Cherenkov separation
energy resolution	o	o	o
γ tagging	o	o	o
β multiplicity	$\rightarrow$	$\rightarrow$	o

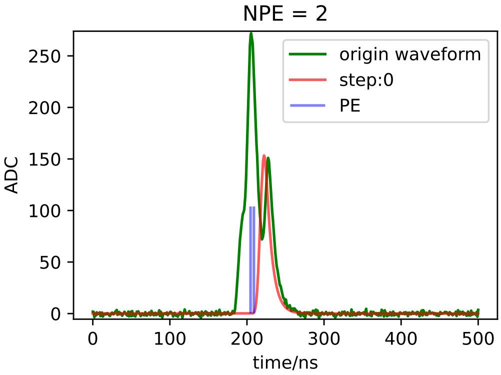
Achieved milestones.

- Cherenkov separation with slow liquid scintillator and fast PMT NIM A 1055(2023)168506, NIM A 1066(2024)169626;
- PE counting and timing with fast stochastic matching pursuit JINST 17 P06040, arXiv:2403.03156;
- Detector response with time-dependent Poisson point process NIM A 1057(2023)168692, EPJC 85, 4, 438.

Solution with Reversible jump Markov Chain Monte Carlo

$$p(\vec{w}|t_0,\mu) = \underbrace{p(\vec{w}|\emptyset)p(\emptyset|t_0,\mu)}_{\text{no integral}} + \underbrace{\int_{\vec{z}\in T} p(\vec{w}|\vec{z})p(\vec{z}|t_0,\mu)\mathrm{d}\vec{z}}_{\text{single integral}} + \underbrace{\iint_{\vec{z}\in T^2} p(\vec{w}|\vec{z})p(\vec{z}|t_0,\mu)\mathrm{d}\vec{z}}_{\text{double integral}} + \underbrace{\iiint_{\vec{z}\in T^3} p(\vec{w}|\vec{z})p(\vec{z}|t_0,\mu)\mathrm{d}\vec{z}}_{\text{triple integral}} \cdots.$$

NPE is the uncertain count of elements in $\vec{z}$.



- Use Markov chain, having $\vec{z}$ jumping over different terms, solved.

(JINST 17 P06040, arXiv:2403.03156)

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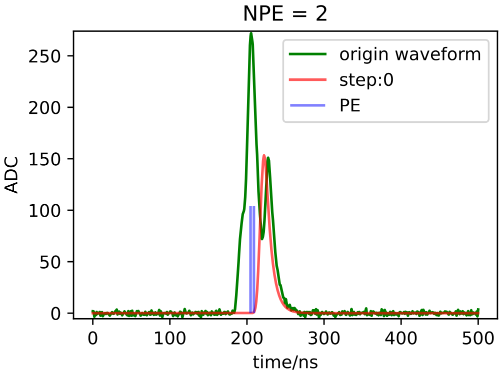

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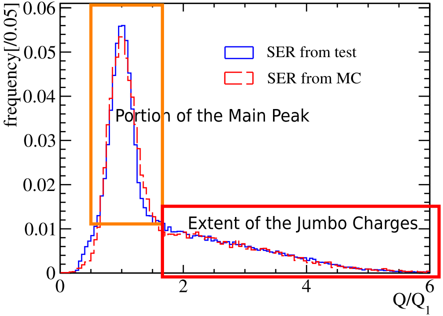
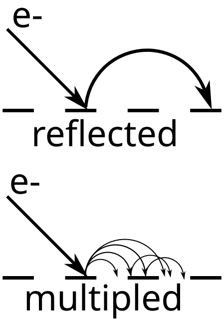
(JINST 17 P06040, arXiv:2403.03156)

Physics of high-collection-efficiency MCP-PMT

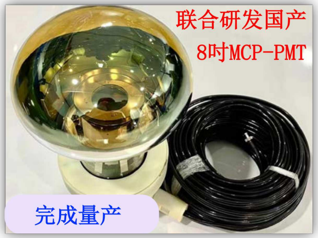




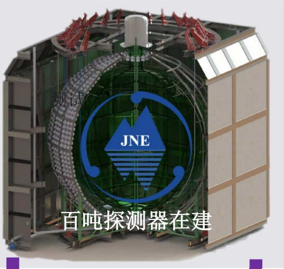
- Portion of the main peak p_0 is affected by open-area ratio.
- Extent of the jumbo charges is determined by the true secondary yield δ'_{ts}.
- They are both affected by the probability of multiplication (true secondary process).

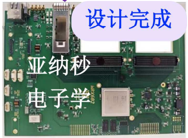
NIM A 1055(2023)168506, NIM A 1066(2024)169626

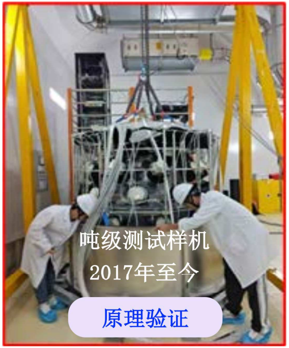
Technological achievements in research and development



亚纳秒级时间分辨提升5倍
光子检出效率提升1.7倍
NIM A 1055(2023) 168506
NIM A 1066(2024) 169626







太阳中微子事例率
已有方案：1个/天
掺5%钕后：2个/天

Summary

Highlights of JNENd-doped liquid scintillator for $0\nu\beta\beta$

1. Large target mass: $500\,\mathrm{kg}$ $^{150}\mathrm{Nd}$ is 2% natural Nd;
2. High Q value, expected faster $0\nu\beta\beta$ decay;
3. Unique zero-background solar ν spectrometer;
4. 中国独有：依托成熟稀土工业，应用高纯度钕研究基础物理，参与国家稀土高技术含量、高附加值产业升级的稀土强国战略布局。

Established technical foundation

Fast PMT and electronics, PE counting, Cherenkov-scintillation dual readout.

particle identification β/γ, Cherenkov readout

energy resolution high light-yield transparency LS, photon counting

10ns coincidence precise photo-electron time measurement

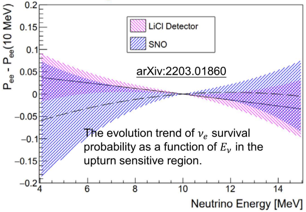
Ongoing efforts

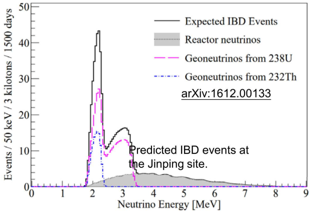
- High light-yield transparency Nd-doped LS.
- $^{150}\mathrm{Pm}\ 1^{+}$ in-beam spectroscopy measurements, calibration of ν_e response.

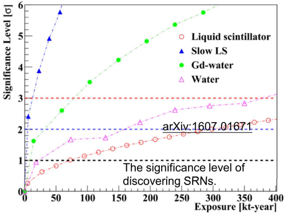
备用

太阳地球与超新星遗迹

- Charged current on Li-7 has an advantage than ν_e ES in measuring solar neutrino **upturn effect**
- JNE is very sensitive to **Qinghai-Tibet plateau crust neutrinos**
- Have the capability for **PID to suppress atmospheric neutrino neutral current background**



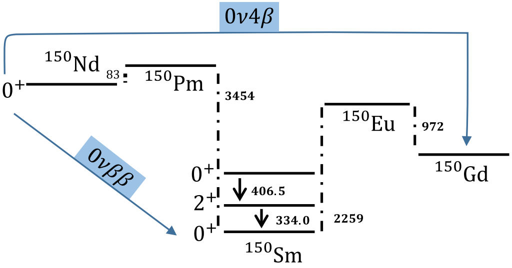


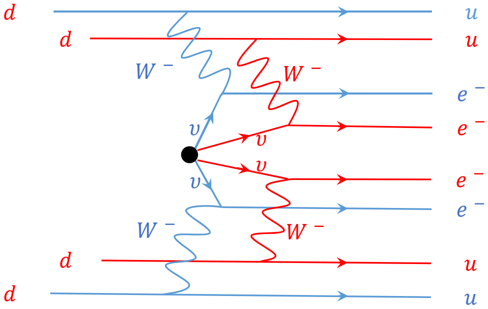


中微子是 Dirac 型吗？

- 倘或 10 年后，JUNO 测出中微子质量为逆序，我们把实验灵敏度推进到了 $\langle m_{\beta\beta}\rangle \sim 10\,\mathrm{meV}$ 仍然没有观察到 $0\nu\beta\beta$，如之奈何？
- 反之，倘或 20 年后，我们把实验灵敏度推进到了 $\langle m_{\beta\beta}\rangle = 1\,\mathrm{meV}$，仍然没有观察到 $0\nu\beta\beta$ ，如之奈何？

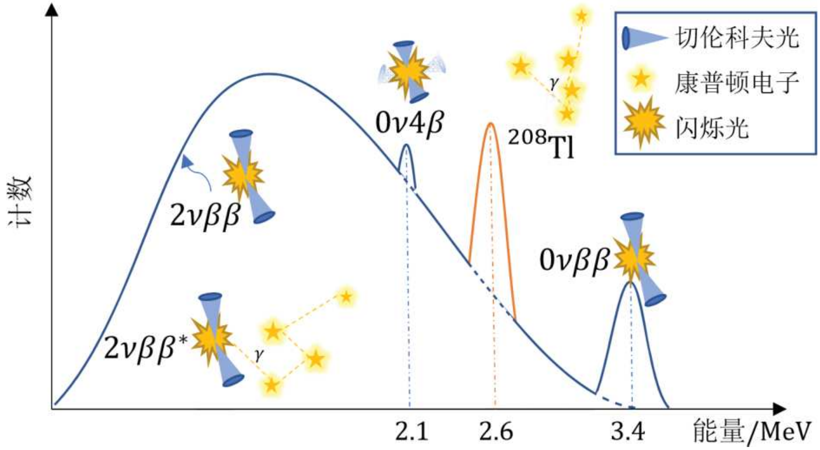
无中微子四贝塔衰变 $0\nu4\beta$ Heeck and Rodejohann 2013





- 同一实验交叉验证中微子的费米子属性 $T_{1/2}^{0\nu4\beta} \sim 1 \times 10^{46}\,\mathrm{y}$

本底与待寻找的目标信号

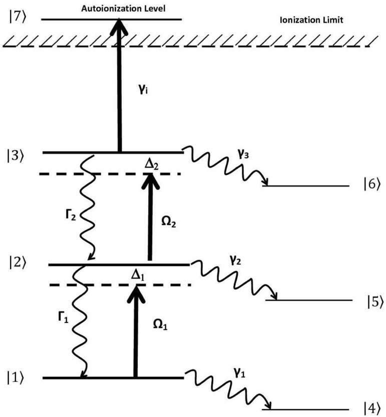


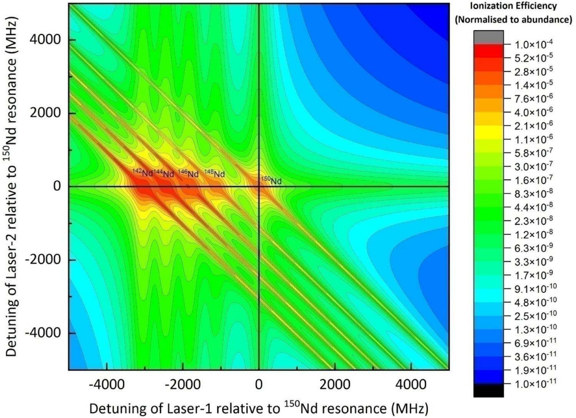
- $0\nu4\beta$ 主要的本底是 $2\nu2\beta$，应竭力提升能量分辨率
- 若识别切伦科夫光，有可能测量产生的电子数目，区分本底和电子动量等

^{150}Nd 的丰度尚有 20 倍提升空间

- 作为稀土元素，Nd 没有气态物料，无法使用离心机组

原子蒸气激光同位素分离 (atomic vapor laser isotope separation, AVLIS)



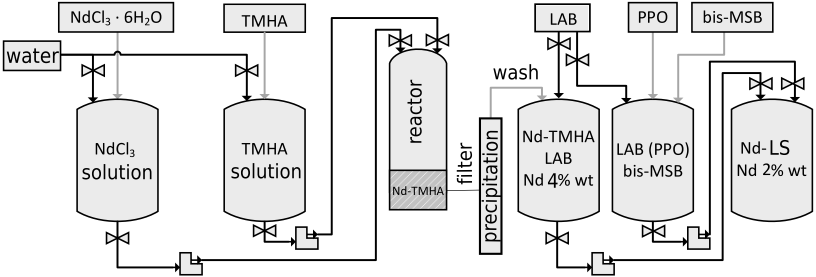


Suryanarayana 2022

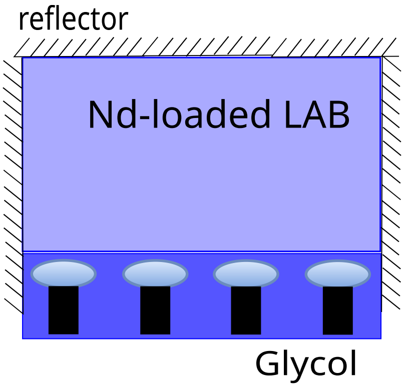
β-二酮 同位素分离

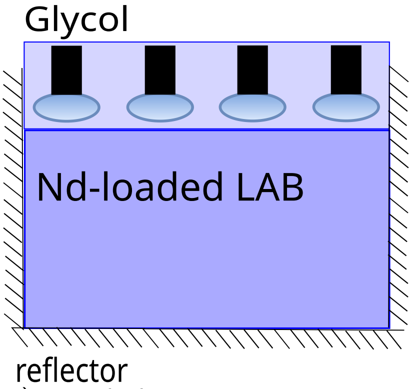
- Li-7 分离有。

NdLS production plant



Stratified liquid scintillator





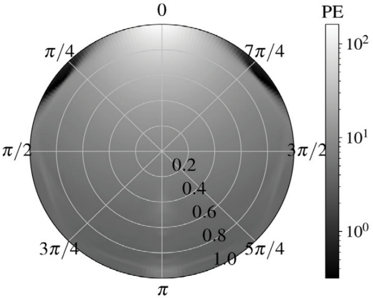
- inspired by SNO+ long-standing (7month+) mixed phase.
- possible to do away with nylon baloon or acrylic vessel.
- test a 1ton prototype in Beijing and in CJPL.

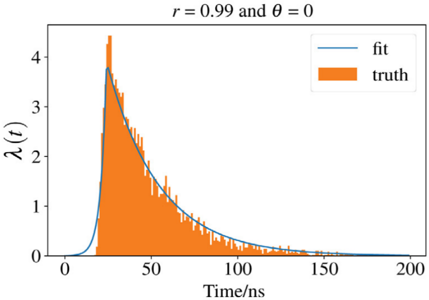
Mortan-Blake, NIM A, 2022

Why SNO+ switched from Nd to Te

- Nd absorption lines
- Nd enrichment
- Robertson(2013) implies the higher Q value of Nd is offset by some unknown empirical law.

Reconstruction optical model





- Inhomogeneous poisson process as the basis of optical transport.
- DayaBay flash-ADC anti-neutrino detector for a test of reconstruction feasibility.

NIM A: Liangjian Wen 2011, Wei Dou 2023

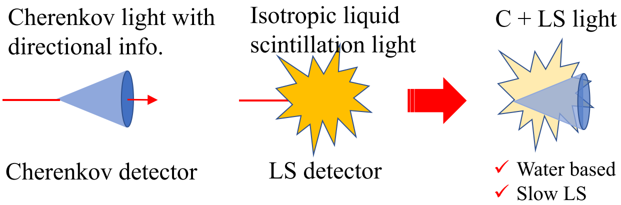
Road to particle identification

- Scintillation
  - Poisson point process for isotropic light emission.

$$E = \frac{N_{\mathrm{PE}}}{\sum_j \lambda_j}$$

j is the index of PMT and λ is the expected number of photoelectrons.

- Cherenkov-Scintillation



- Tracking-Cherenkov-Scintillation
  - Tracking is inevitible to correctly get Cherenkov
  - ν_e MeV need imaging: embed dynamic laws into reconstruction.