Water-based Liquid Scintillator

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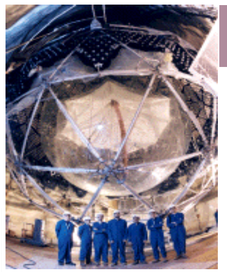
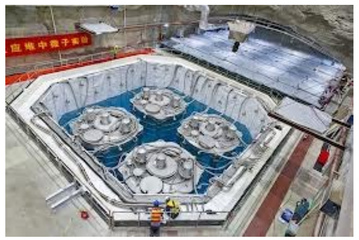
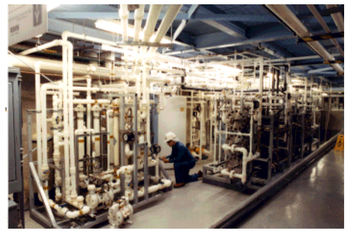
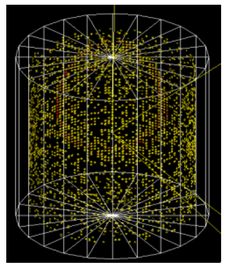
Snowmass Community Summer Study, UW-Seattle, 07/17-26/2022

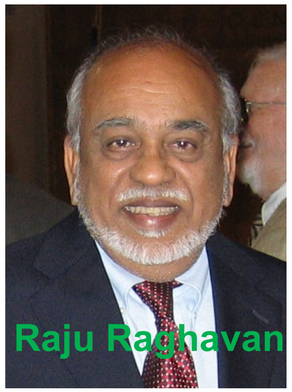
BNL Neutrino and Nuclear Chemistry Since 1960 (*career in chemistry & physics*)

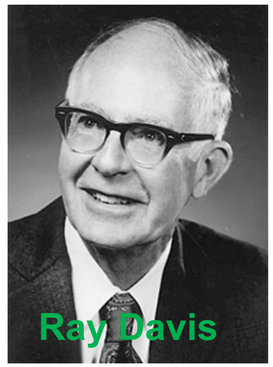












HOMESTAKE — 615t $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

Gallex — 30-t $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

780t D_2O CC/NC — SNO

200-kt H_2O or 37-kt LAr — LBNF (DUNE)

120-t 8% In-LS — LENS

200-t 0.1% Gd-LS — Daya Bay

780t 0.3% Nd/Te-LS — SNO+

^6Li, ^{10}B or Gd doped LS — PROSPECT/LZ

(Metal-doped) WbLS — 0νββ, dark-matter, medical, nonproliferation

Water-based LS

Scintillator

Radiochemical — Cherenkov

1960 1970 1980 1990 2000 2010 2020

Liquid Scintillator ν Map (Yeh)

Periodic Table of the Elements

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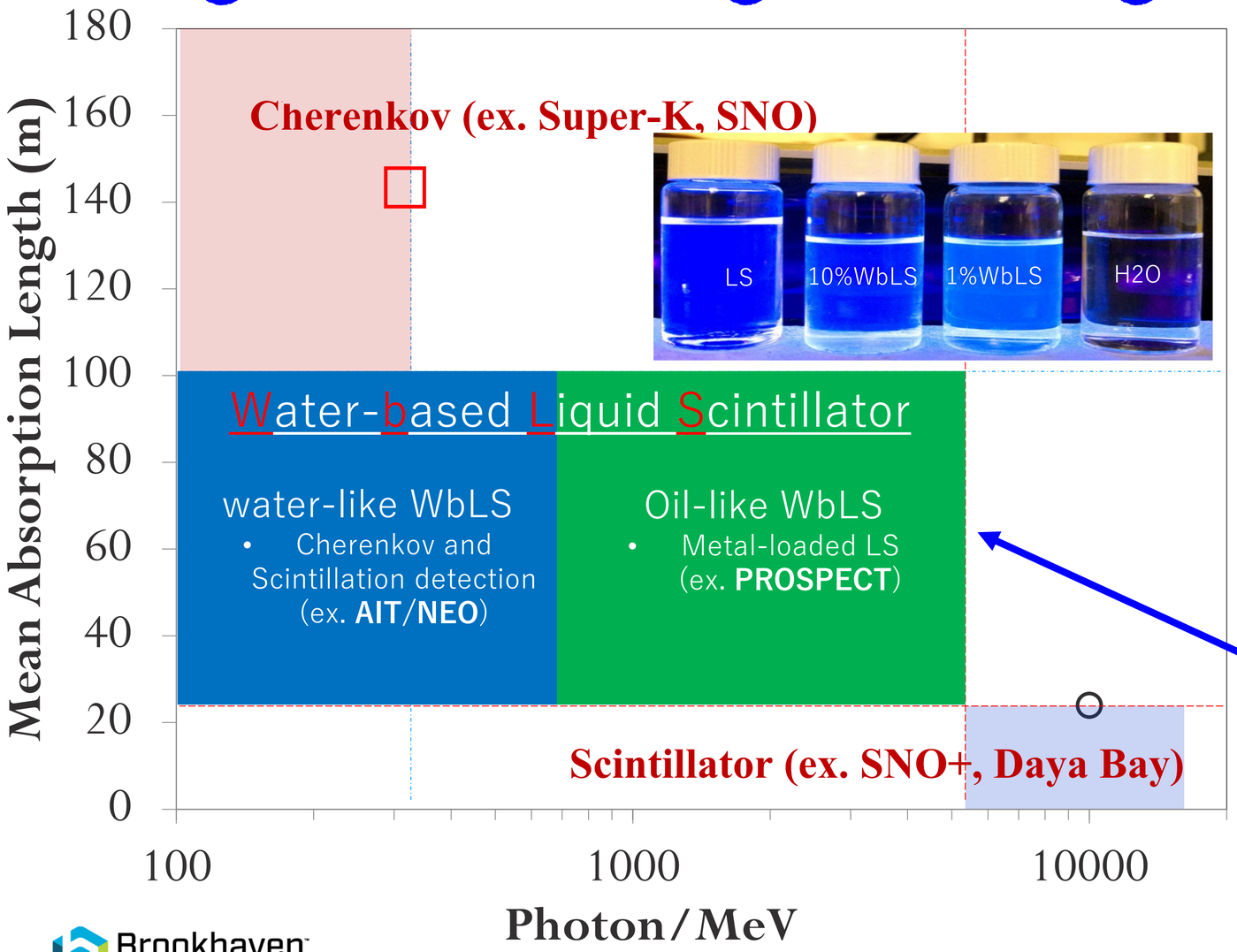
hydrogen
alkali metals
alkali earth metals
transition metals
poor metals
nonmetals
noble gases
rare earth metals

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Unq 104	Unp 105	Unh 106	Uns 107	Uno 108	Une 109	Unn 110								

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

- Reactor
- ββ
- Solar
- Medical, LSC, Calibration, etc

If you always do what you always did, you will always get what you always got. -Albert Einstein



Next liquid scintillator detector development → *directionality*

- Slow Scintillator: timing separation of slow(er) scintillation from fast Cherenkov
- LiquidO: stochastic light confinement; lossless scattering
- Water-based Liquid Scintillator: Cherenkov and scintillation detection

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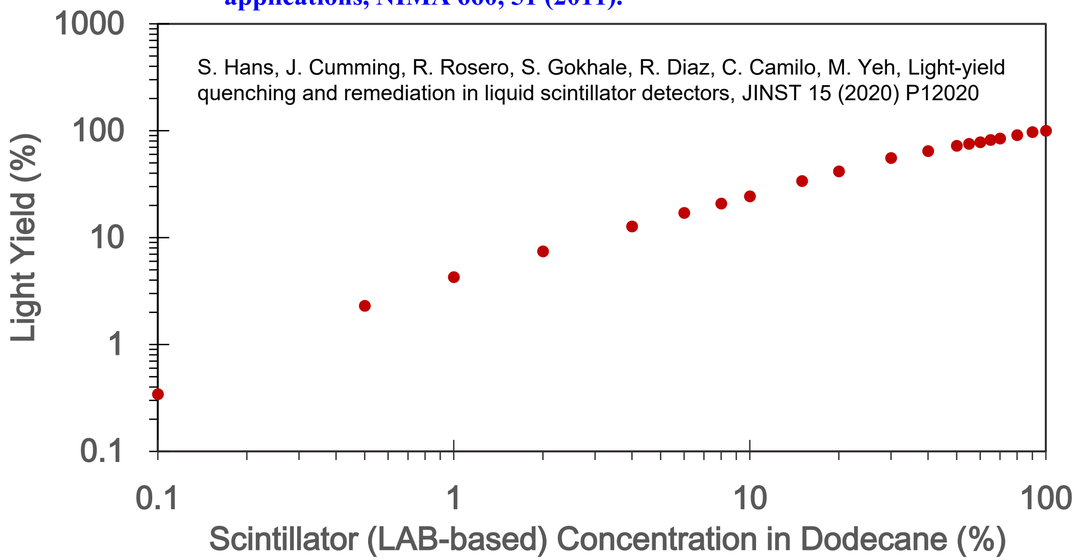
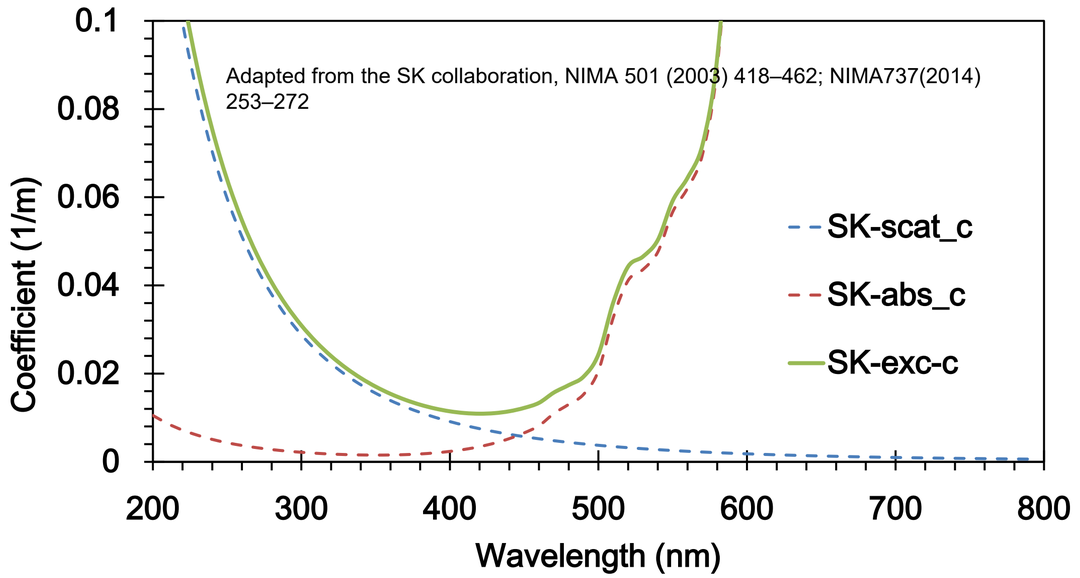
Water-based Liquid Scintillator

- a novel low-energy detection medium, bridging scintillator and water, to explore physics below Cherenkov threshold
- tunable scintillation light from ~pure water to ~organic.
- environmentally friendly and non-combustible for underground physics.
- a directional scintillator detector capable of high-energy (Cherenkov) and low-energy (scintillation) detections
- viable to load a variety of metallic isotopes for varied physics applications
- ANNIE, WATCHMAN, THEIA25/100

M. Yeh et. al., A new water-based liquid scintillator and potential applications, NIMA 660, 51 (2011).





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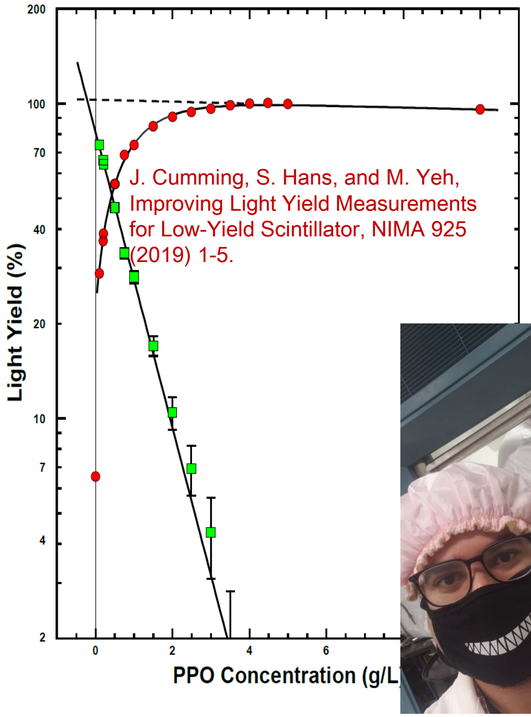
Principle proven with characterizations

Scintillator Yield, *Č/S* Separation, Timing Structure, optical (absorption and scattering),…,etc.

- *Principal demonstrated in laboratory environment; characterization and analysis tools, developed over the past years*
- *WbLS-rhttps://orcid.org/**0000-0003-2244-0499**elated pubs:*



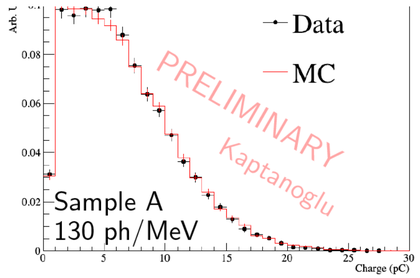
LS Samples	τ_{rise} [ns]	τ_1 [ns]	f_1 [%]	τ_2 [ns]	f_2 [%]	τ_3 [ns]	f_3 [%]
0.5 g/L PPO	0.98 ± 0.04	7.0 ± 0.6	61	$16. \pm 1.$	34	80 ± 5	4.4
1 g/L PPO	0.92 ± 0.07	5.5 ± 0.3	72	13.7 ± 0.9	25	84 ± 2	3.7
2 g/L PPO	0.88 ± 0.05	4.3 ± 0.2	82	13.4 ± 0.8	15	86 ± 1	3.7
3 g/L PPO	0.83 ± 0.06	3.6 ± 0.1	84	13.4 ± 0.9	12	83 ± 2	4.0
5 g/L PPO	0.69 ± 0.03	2.81 ± 0.07	84	13.0 ± 0.8	12	80 ± 2	4.4
10 g/L PPO	0.49 ± 0.03	2.06 ± 0.04	77	11.2 ± 0.4	18	72 ± 2	5.1
30 g/L PPO	0.33 ± 0.12	1.15 ± 0.02	55	9.9 ± 0.5	38	64 ± 4	7.0
70 g/L PPO	0.26 ± 0.03	0.58 ± 0.02	38	10.5 ± 0.4	55	69 ± 4	7.1
90 g/L PPO	0.24 ± 0.02	0.48 ± 0.01	35	11.1 ± 0.1	58	72 ± 3	7.4

Table 1 Rise times (τ_{rise} in ns), decay times (τ_i in ns), and decay component fractions (f_i in %) are displayed for each pure LS sample, varying PPO concentration in LAB, from excitation with a pulsed X-ray excitation source, as shown in Figures 3 and 5. The error bounds listed are 95% confidence intervals measured by repeating this experiment; thus they account for any random error of sample positioning, data acquisition, and component fitting.

WbLS Samples	τ_{rise} [ns]	τ_1 [ns]	f_1 [%]	τ_2 [ns]	f_2 [%]	τ_3 [ns]	f_3 [%]
1% LAB/PPO	0.23 ± 0.06	2.00 ± 0.03	87	12 ± 1	6.8	110 ± 10	6.2
5% LAB/PPO	0.23 ± 0.04	2.00 ± 0.02	88	10.0 ± 0.6	6.6	106 ± 6	5.7
10% LAB/PPO	0.29 ± 0.03	2.22 ± 0.03	89	10.7 ± 0.9	6.0	102 ± 9	5.5

imes (τ_{rise} in ns), decay times (τ_i in ns), and decay component fractions (f_i in %) are displayed for each WbLS sample, from excitation X-ray excitation source, as shown in Figure 4.

D.R. Onken, F. Moretti, J. Caravaca, M. Yeh, G.D. Orebi Gann, E. Bourret, Time Response of Water-based Liquid Scintillator from X-ray Excitation, accepted by Materials Advances (2020).



	Preferred LY [ph/ MeV]
0.1% GdWbLS	60
Sample A	130
Sample B	140
Sample C	160
Sample 4	140
Sample 5	160
Sample 6	130
Sample 7	$\sim$ 100

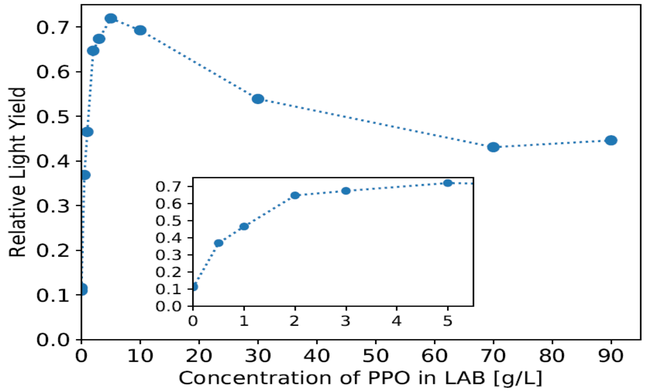


Fig. 6 Relative light yield for the pure LS samples, varying as a function of PPO concentration in LAB. Light yield values are presented as a fraction of the EJ-301 light yield. The inset focuses on concentrations $\leq$5 g/L PPO.

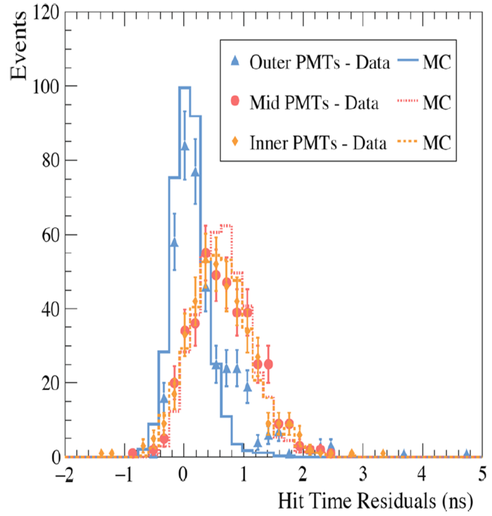


Fig. 10 Hit-time residual distributions in LAB/PPO for data and MC
J. Caravaca, F.B. Descamps, B.J. Land, M. Yeh, G.D. Orebi Gann, Cherenkov and scintillation light separation in organic liquid scintillators, Eur. Phys. J. C (2017) 77:811.

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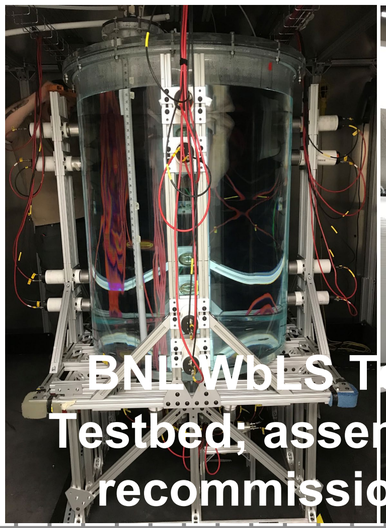
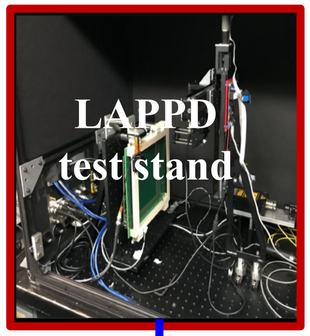
BNL Scintillator Research

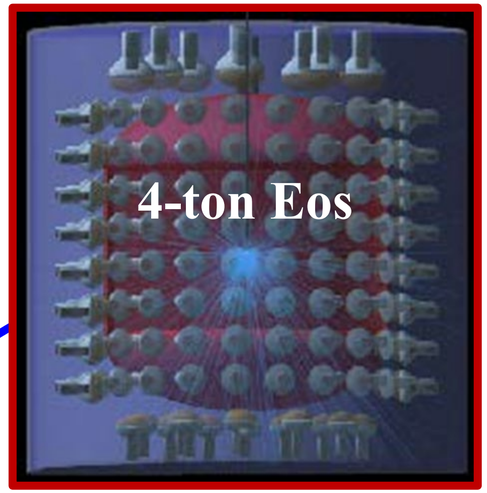
- LS research laboratories with state-or-art equipment
  - Bench top R&Ds and mid-scale (10-100 liter) study
  - **Host students and collaborators >5 per year**
- Ton-scale liquid scintillator production facility (commissioned in FY19; user cases → PROSPECT and LZ)
- 1-ton Testbed (1TBNL, commissioned in FY22)
- 30-ton Demonstrator (30TBNL, renovation ongoing, plan to commission in FY23)

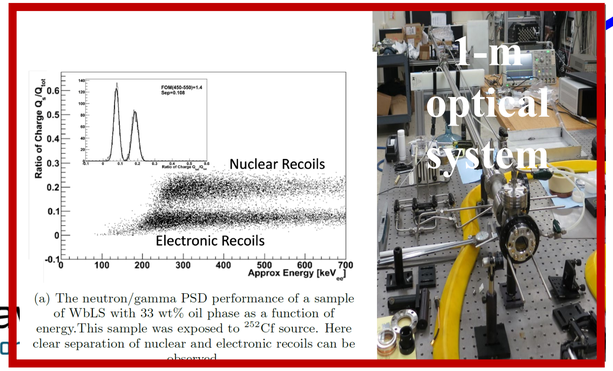


2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

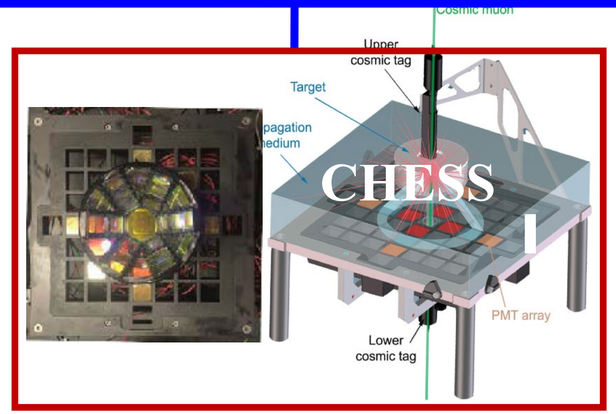
Advancing WbLS/THEIA-related R&Ds…





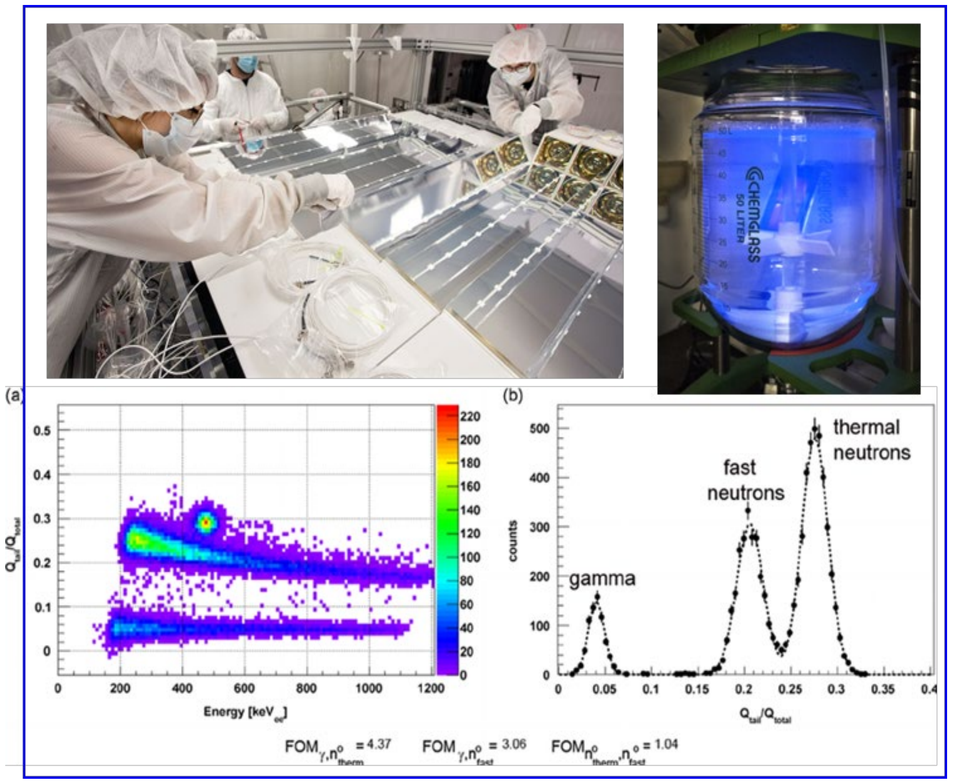


(a) The neutron/gamma PSD performance of a sample of WbLS with 33 wt% oil phase as a function of energy.This sample was exposed to ^{252}Cf source. Here clear separation of nuclear and electronic recoils can be observed.



Research, Operation, and Progress

- Complete WbLS mixing and deployment in ONE step within the detector vessel
  - In-situ sequential mixing scheme
    - *Direct injection of scintillator materials into water*
    - *Remove on-site complications to save labor & space*
  - Proven at 100-liter scale; ready for prototyping tests
- In-situ circulation/purification system
  - Nanofiltration system separates oil from water and sends each to purification
  - Benchtop test successfully demonstrates >95% (~ppm) efficacy; ready for prototyping tests
- Li, Gd doping in WbLS successfully developed
  - PROSPECT, WATCHMAN
  - 30%W for calorimetry?
- Low material cost; affordable for 10s kton detectors:
  - 10-ton materials ($4k per ton) for a 1000-ton detector (99% water)



PROSPECT (ORNL) Li-doped LS

Summary

- WbLS is a new scintillation material along with advanced detector instrumentation, such as dichroicon, nanofiltration, LAPPD…, etc., building for next-generation experiments (flexible doping allowing a phased program, i.e. THEIA)
  - *Scintillation* provides the energy resolution necessary to get above most radioactive backgrounds and the ability to see slow-moving recoils
  - *Cherenkov* enables event direction reconstruction and background discrimination at low energies
  - Capable of metal doping or enrichment to enhance interaction rate
- WbLS R&D is advancing with several ton-scale deployments
  - principle and stability (>years) proven at benchtop; well characterized
  - 1TBNL, ANNIE in 2022
  - 4TEos, 30TBNL in 2023/24
  - Production facility readiness for large-scale manufacture in 2023
- Snowmass: WbLS-related whitepapers and presentations to different frontiers
- Planning new initials in T2K/ND:SuperFGD, LiquidO, dark matter veto (G3), medical physics