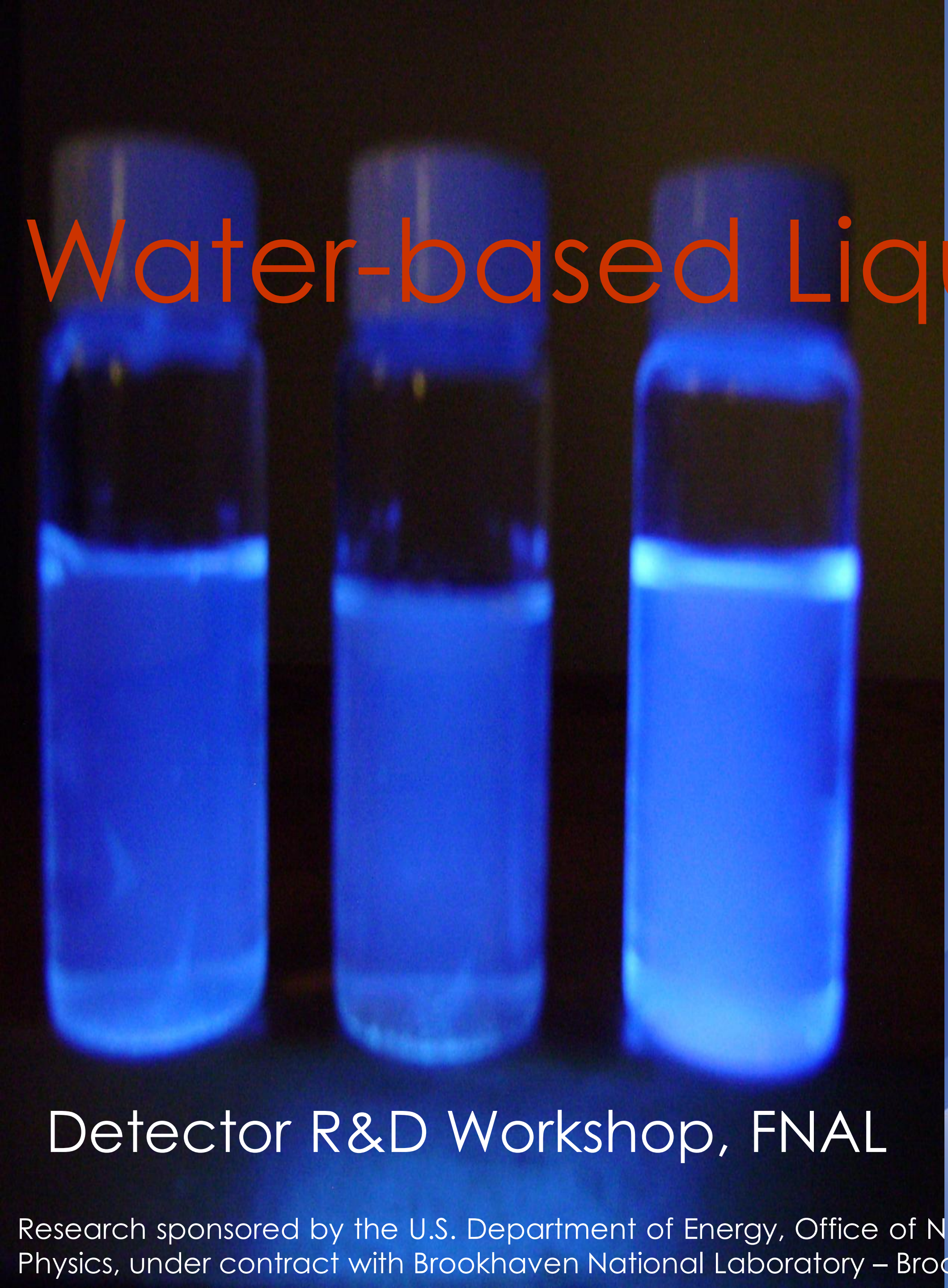
Water-based Liquid Scintillator



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Detector R&D Workshop, FNAL

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Research sponsored by the U.S. Department of Energy, Office of Nuclear Physics and Office of High Energy Physics, under contract with Brookhaven National Laboratory – Brookhaven Science Associates.

First anti-neutrino detector

Large Liquid Scintillation

C. L. Cowan, Jr., F. Reines, F.
E. C. Anderson, and F. N
Los Alamos Scientific Laboratory, Unive
Los Alamos, New Mexi

(Received February 24, 1

THE technique outlined in the preced tion of the free neutrino demands following properties: (1) the provision of a pr... in... re... ti... capture.

sc... design of ... cu... er contain... so... ng 2 cubi... of... ed by the re... d cold-roll ab... rication to fa... ns. The in...

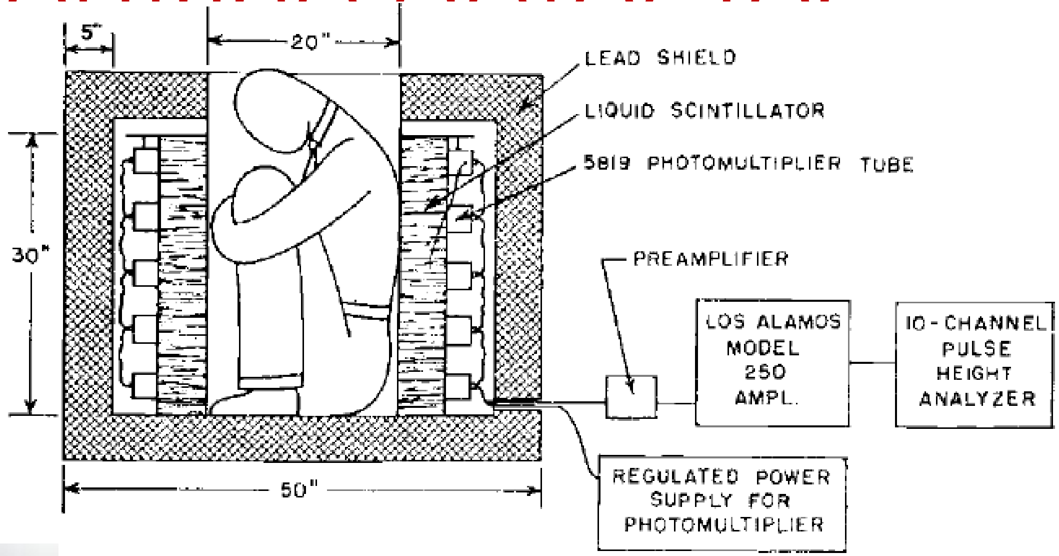


Fig. 8. Schematic view of first human counter (1953).

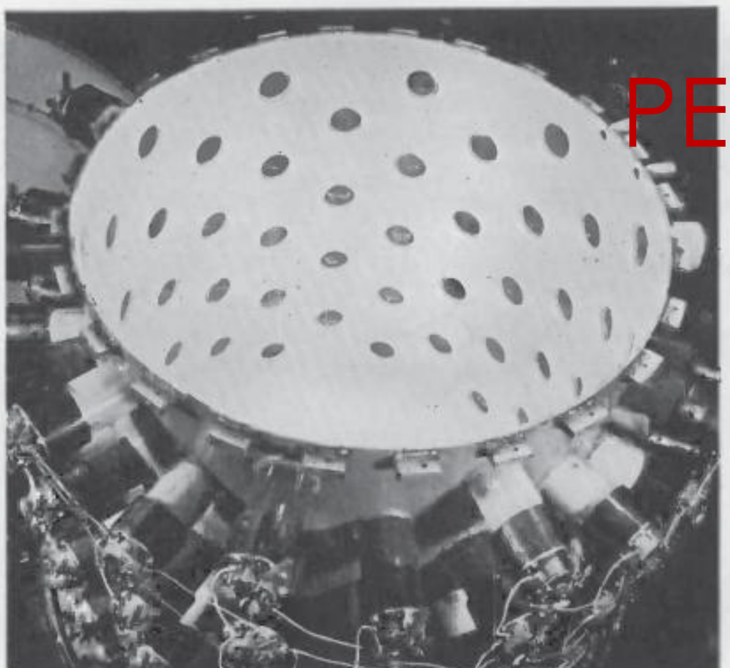


Fig. 2. The Hanford neutrino detector (1953).

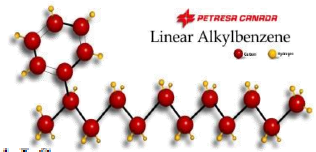
PET or CAT scan?

http://www.strokecenter.org/patients/diagnosis/ct.htm

Liquid Scintillator for Particle Detector

- Physical performance
  - High efficiency of converting kinetic energy of charged particle to detectable light (orders of magnitudes higher than Cherenkov)
  - Good light transparency to the emission wavelength
  - Short decay time for fast signal pulse
  - Mass-producible
- Chemical property and ES&H
  - Index of refraction to minimize scattering loss
  - High flash point, low toxicity, safe to be used in confined space
- Long stability (metal-loaded)
  - i.e., CHOOZ
- Chemical compatibility
- Proton decay and sub-MeV neutrinos

Comparisons of Selected Liquid Scintillators



first identified by SNO+

Table 1
The chemical properties and physical performance of selected LS

	LS[a]						
	PC	PCH	DIN	PXE	LAB	MO	DD
Molecular formula	C_9H_{12}	$C_{12}H_{16}$	$C_{16}H_{20}$	$C_{16}H_{18}$	$C_{18}H_{30}$[b]	C_nH_{2n+2}[c]	$C_{12}H_{26}$
Can Gd be loaded into the LS?	Yes	Yes	Yes	Yes[d]	Yes	No	No
Density (g/ml)	0.89	0.95	0.96	0.99	0.86	0.85	0.75
$abs_{430,\text{before purification}}$	0.008	0.072	0.040	0.044	0.001	0.002	0.001
$abs_{430,\text{after purification}}$	0.002	0.001	0.023	0.022	~0.000	0.001	~0.000
Purification method[e]	v.d.	c.e.	c.e.	c.e.	c.e.	c.e.	c.e.
Index of refraction[f]	1.504	1.526	1.565	1.565	1.482	1.461	1.422
S%[g]	1	0.46	0.87	0.87	0.98	n.a.	n.a.
H-atoms per c.c. ($\times 10^{22}$)	5.35	3.72	5.45	4.34	6.31	8.05	4.77
Flash point (°C)	48	99	>140	145	130	215	71

[a]See the text in Section 3.4 for the chemical names of these organic compounds.
[b]With alkyl side chain containing 12 carbon atoms.
[c]$n \approx 30$ [17].
[d]Only stable for few months.
[e]v.d. = vacuum distillation; c.e. = column extraction with solid Al_2O_3.
[f]Optical index of refraction at 20 °C, except DIN at 25 °C (cited from Material Safety Data Sheets and Ullmann's Encyclopedia of Industrial Chemistry, 5th ed., vol. A, Wiley, November 1991).
[g]Scintillation yield normalized to 100% PC; n.a. = non-aromatic compounds which do not scintillate.

M. Yeh et al. / Nuclear Instruments and Methods in Physics Research A 578 (2007) 329–339

Liquid Scintillator for Neutrino experiments

Experiment	LS	Extractant	Fluors/Shifters
Cowan and Reines	Cd-loaded toluene	carboxylate in methanol	αNPO
Palo Verde	40% PC + 60% Mineral oil	carboxylate	4 g/L PPO + 100 mg/L bis-MSB
CHOOZ	50% Norpar-15 (paraffinic liquid) + 50% IPB (isopropylbiphenyl)	hexanol	1 g/L p-TP + bis-MSB
Eljen	Anthracene + PC	n/a	3 g/L PPO + 0.3 g/L POPOP
Bicron	PC or Mix of PC+MO	EHA	unknown
Borexino	PC	n/a	1.5 g/L PPO or p-TP + bis-MSB
MiniBooNE	MO	n/a	n/a
LENS	LAB	carboxylate	3g/L PPO + 15mg/L MSB
Daya Bay	LAB	carboxylate	3g/L PPO + 15mg/L MSB
SNO+	LAB	carboxylate	2g/L PPO
Reno	LAB	carboxylate	3g/L PPO + 15mg/L MSB
Double-CHOOZ	20%PXE + 80%dodecane	b-diketonate	6g/L PPO + 20mg/L MSB
KamLAND	20% PC + 80% dodecane	n/a	1.52 g/L PPO
NOvA	5% PC + 95% MO	n/a	1.2 g/L PPO + 17 mg/L MSB
LENA	PXE/LAB withdodecane	n/a	PPO/MSB or ?

Metal-loaded liquid scintillators

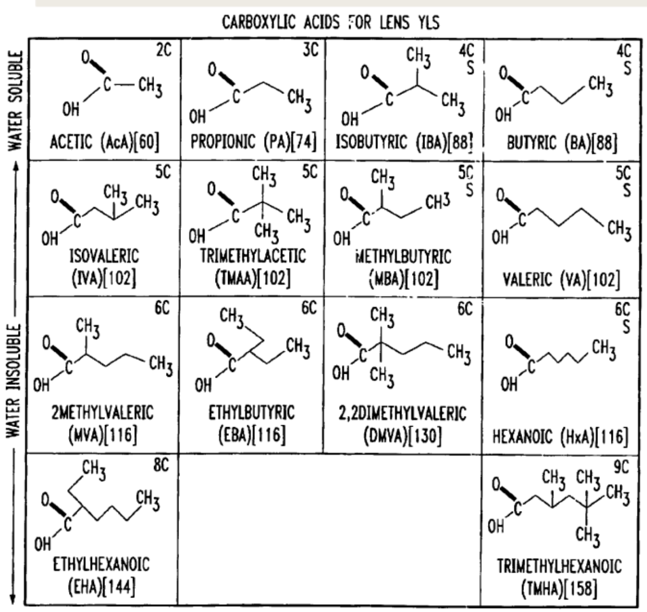
Development and production of Metal-loaded (Yb, In, Nd, Zr, Gd, Li, etc) liquid scintillator (LS) for neutrino experiments

- LENS uses 125 tons of In-loaded LAB or PC
- Daya-Bay uses 200 tons of Gd-loaded LAB
- SNO+ uses 1 KT of Nd-loaded LAB

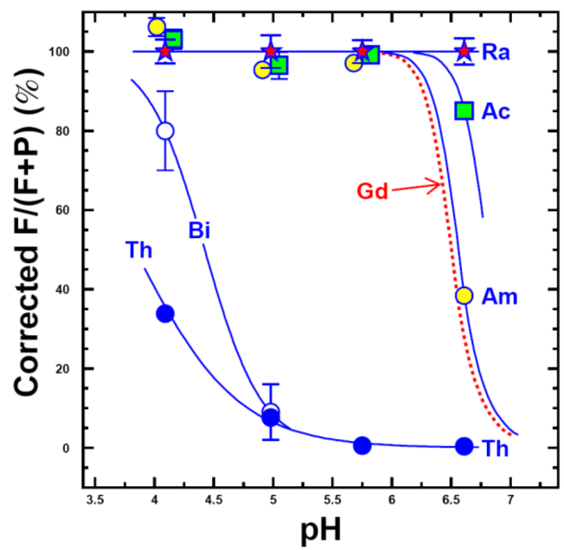
beginning of M-LS in 2000

- M. Yeh et al. Gadolinium-Loaded Liquid Scintillator for High-Precision Measurements of Antineutrino Oscillations and the Mixing Angle, θ13, NIM A 578 (2007) 329-339

Study of optical properties as a function of purity levels and of metal concentration

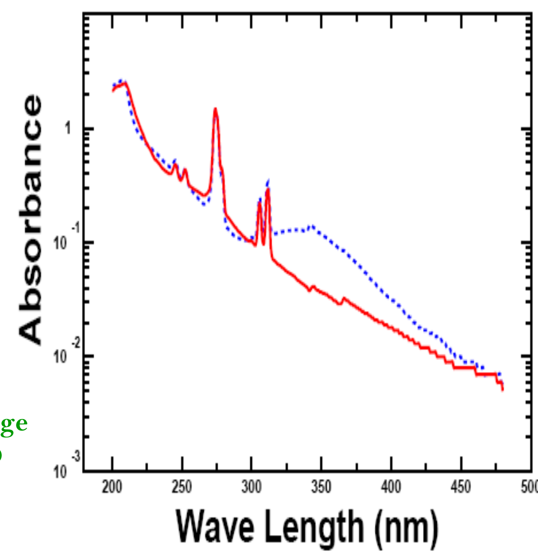


carboxylic acids are the preferred choice

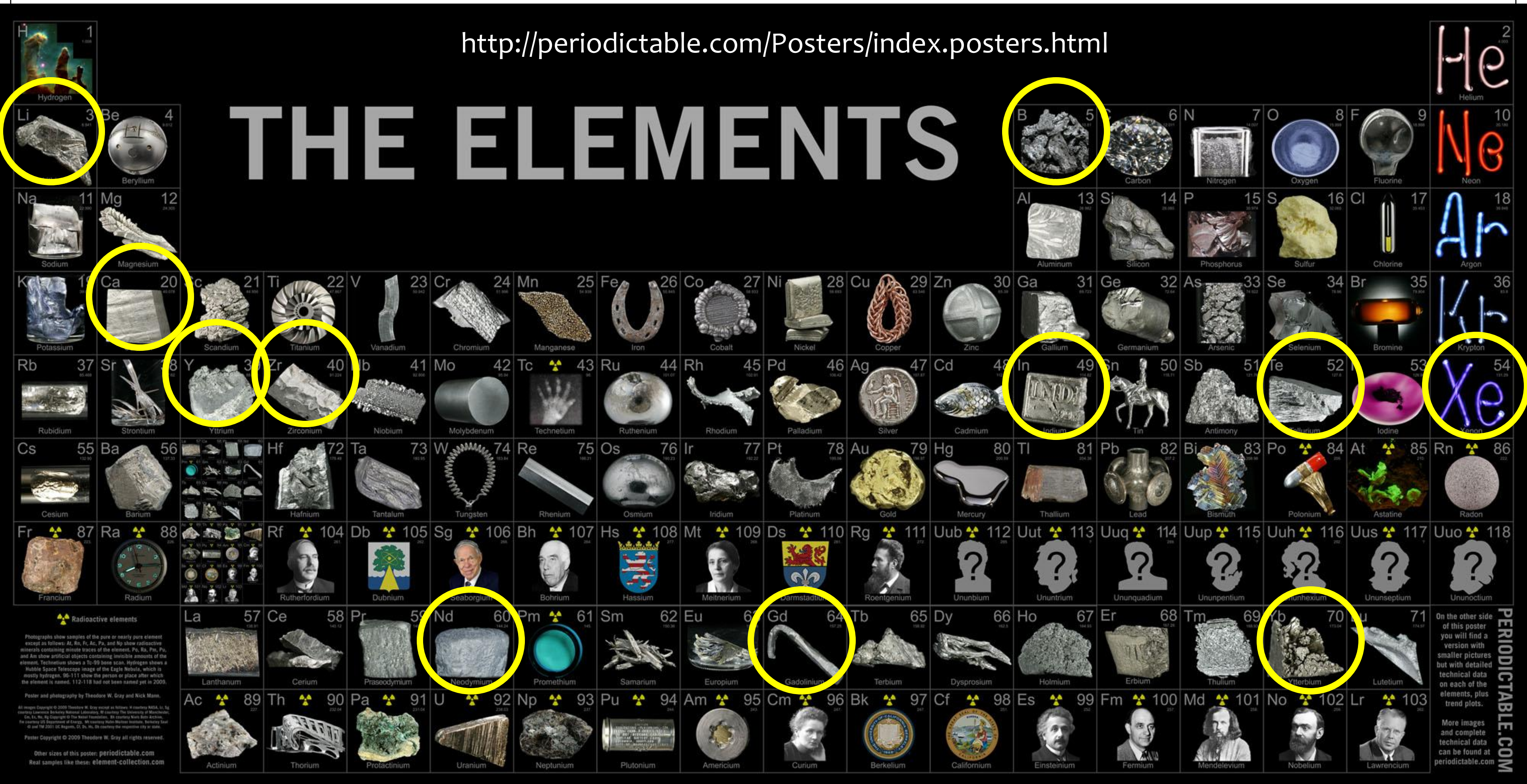


- M. Yeh et al. Purification of lanthanides for large neutrino detectors, NIM A 618 (2010) 124–130

Self-scavenging method to remove Th/U and improve UV



Which one can we load?

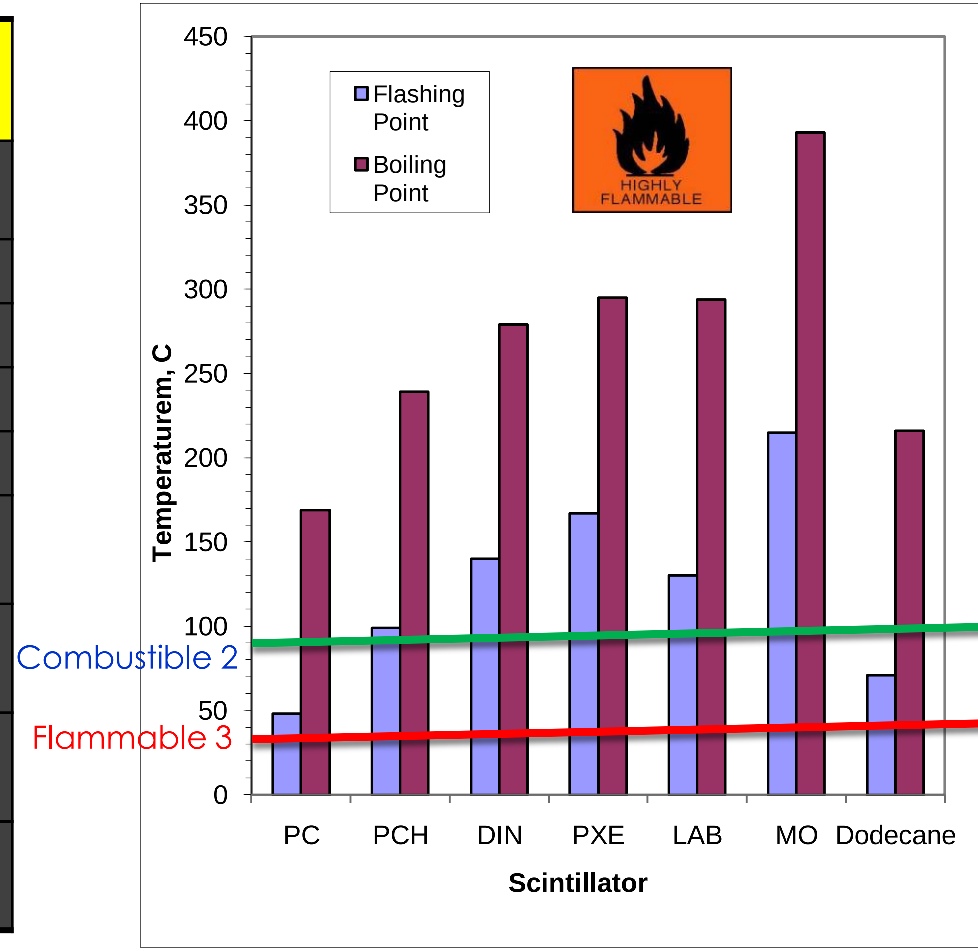


Challenges of Liquid Scintillation

- Safety
  - Chemical and Fire Hazards
- Cost
  - $2k/ton
  - $50-70M for 50-kT or $20M for 15-kT (NOvA)
- Handling and ES&H
  - ex. pesudocumene leakage
- Reactivity
  - Limited compatible materials with organic solvents

NEPA assessment of fire safety for ongoing and newly proposed experiments

Experiment	LS	NEPA Rating
Borexino	PC	**~3**
LENS	LAB/PC	1/3
Daya Bay	LAB	1
SNO+	LAB	1
Reno	LAB	1
Double-CHOOZ	20%PXE + 80%dodecane	2~1
KamLAND	20% PC + 80%dodecane	**3~2**
NOvA	5% PC + 95% MO	1~2
LENA	PXE/LAB/dodecane	1/1/2



Liquid scintillators used in all ongoing or proposed experiments are *combustible* if not *flammable*

A large (>50kT) pure liquid scintillator has challenges of

- cost
- attenuation
- **ES&H**
- Compatibility
- etc

IS THERE AN ALTERNATIVE?

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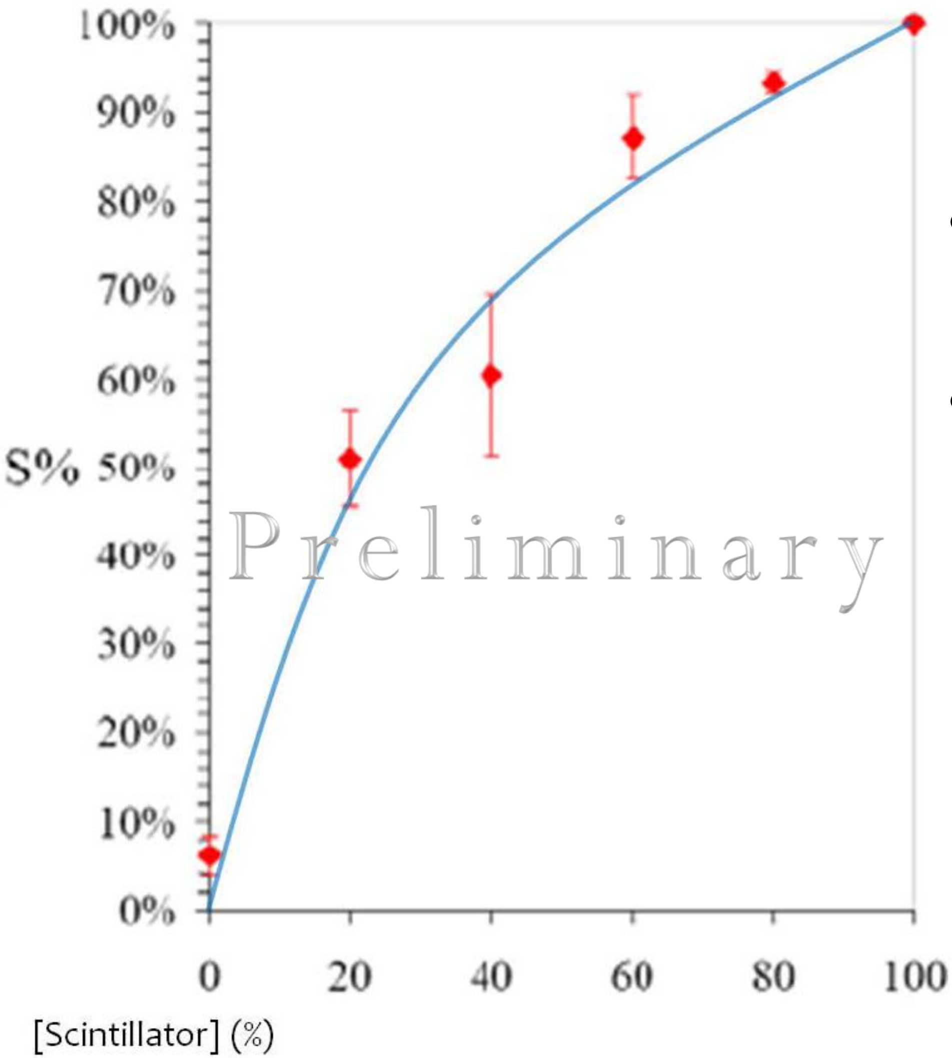
Goal of Water based liquid scintillator

Develop a W-LS to be used as energy spectrometer in large-scale physics experiments or in national-security applications

- Replace the hundreds to many tons of unloaded or metal-loaded organic liquid scintillators to provide:
  - simpler sensitive detection medium
  - fewer compatibility problems
  - cost savings
- Non-linear photon production plus superior water attenuation length makes it possible to detect physics below Cherenkov threshold
  - PDK^+ channel becomes accessible
- R&D initialized in 2009 and 1-FTE RA supported by KA1503 beginning FY10 with a goal of 3-yr R&D
- Dissolving wavelength-shifter in water is not water-based liquid scintillator

Light Yield of PC% in dodecane



- By ^{137}Cs Compton scattering
- Light-yield is a function of percents of liquid scintillator; but is not linear

Goal of Water based liquid scintillator

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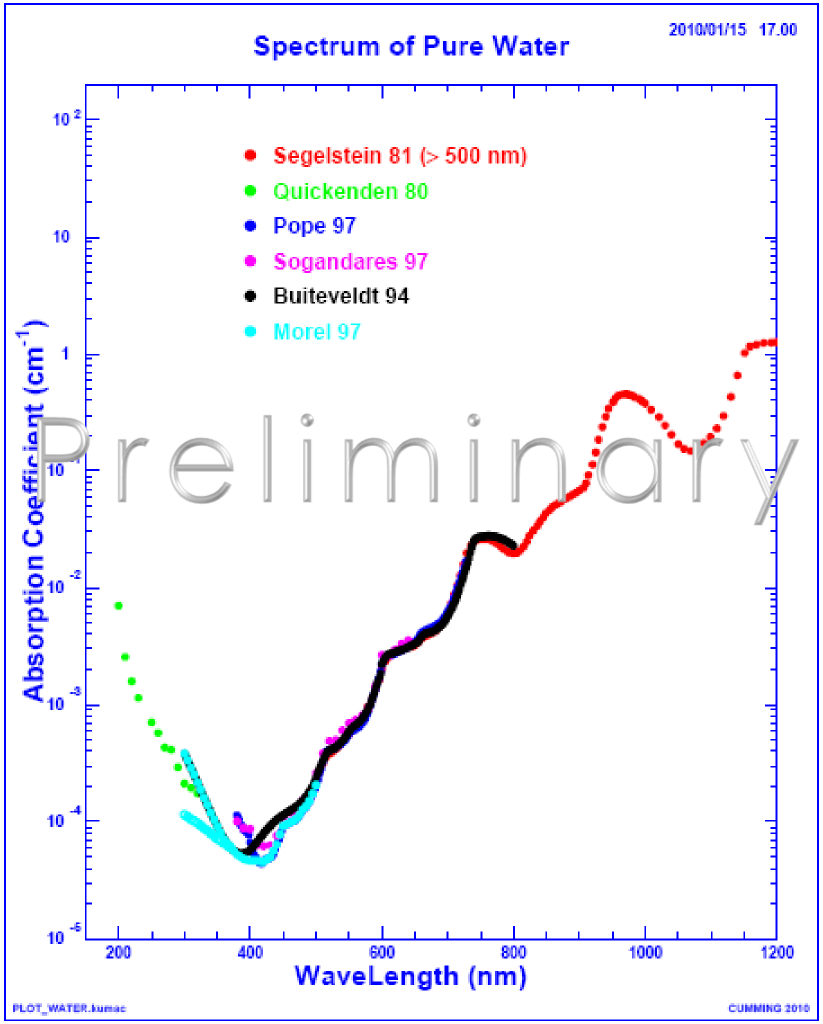
- Dissolving wavelength-shifter in water is not water-based liquid scintillator

Water Optical Transmission



- Superior attenuation length of water could compensate the loss of photon
- High proton density (6.69 atoms per c.c.)

Goal of Water based liquid scintillator

Develop a W-LS to be used as energy spectrometer in large-scale physics experiments or in national-security applications

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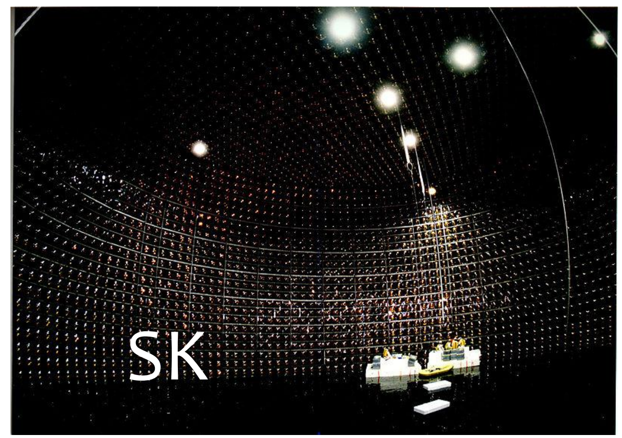
- R&D initialized in 2009 and 1-FTE RA supported by KA1503 beginning FY10 with a goal of 3-yr R&D to assess its feasibility
- Dissolving wavelength-shifter in water is not water-based liquid scintillator

Nucleon Decay

The SUSY SU(5) model predicts the K-decay mode to be dominant with a partial lifetime varying from 10^{29}y to 10^{35} yrs !

$$\tau(p \rightarrow k^{+}\bar{\nu}) > 2.3\times10^{33}\text{yrs}$$



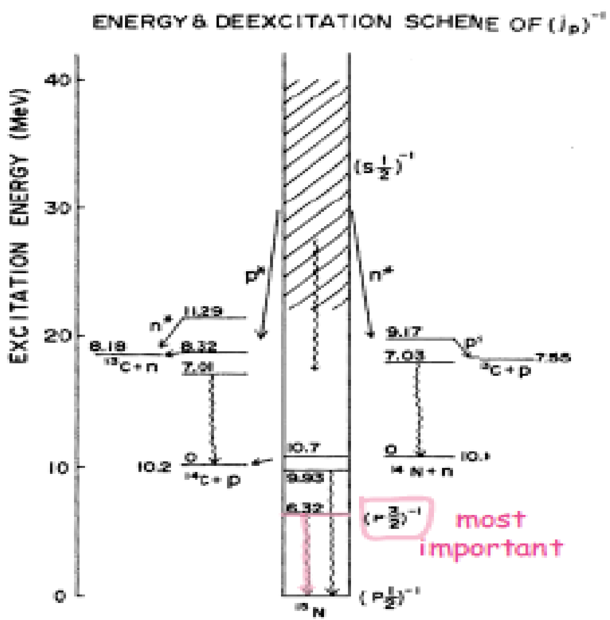


FIG. 2. Level scheme of proton-hole states in ^{15}N and their deexcitation modes. Energies are given in units of MeV. p^* and n^* are the protons and neutrons emitted from the continuum (unbound) region, respectively.

H.Ejiri Phys. Rev. C48 (1993) 1442

- 22.5 kT (7.5 x 10^{33} protons & 6.0 x 10^{33} neutrons) at 40% coverage
- T_{K+} ~340 MeV/c: below Cerenkov threshold
- ^{16}O $(p_{3/2}) \rightarrow {}^{15}$N* + $\gamma_{6.3\ \mathrm{MeV}}$

Water-based LS for PDK^+

- A 50-kt detector would have a sensitivity of t $>4\times10^{34}$ yrs for PDK^+ model after 10 years of run time (LENA)
  - 150 p.e./MeV (30%)
  - $\lambda_{1/e}$~20m
  - >4000m
- 9000 photons/MeV for 100% LAB
- 25% coverage gives 180 p.e. per MeV (DYB)
- Assuming W-LS has 20% of $S_{\gamma,\ LAB}$ at 7-8% LS loading,
  - $\sim 5 = \exp(\lambda/20)$; $\lambda_{1/e} > 32$m
- Need to catch kaon before decay: $t_d < 12.4$ ns
- deep underground

- Polarity Tension
- Like to like

CAN WE LOAD IT?

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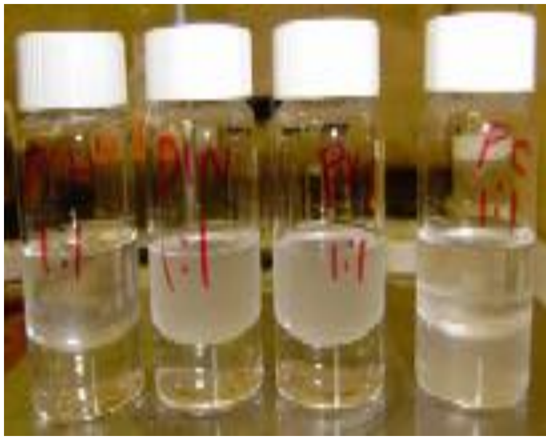
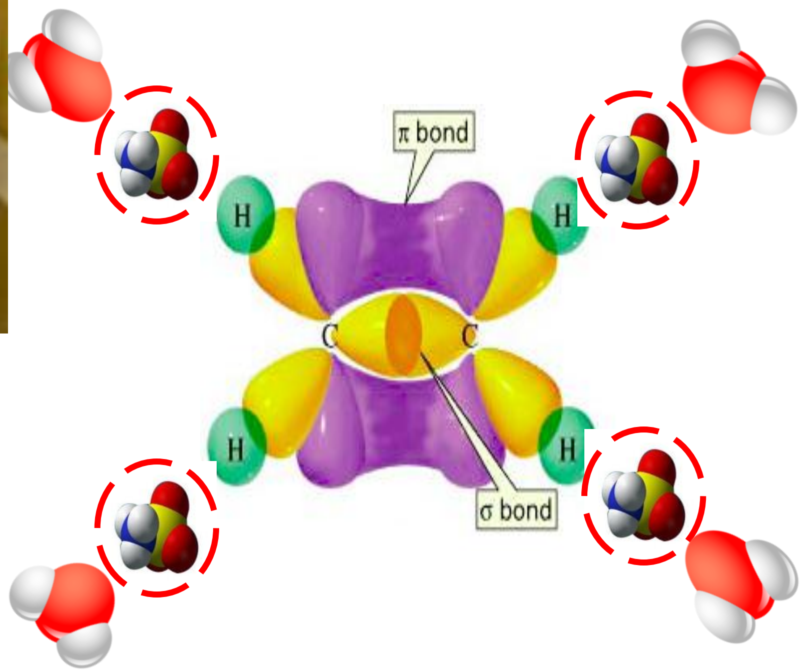
Surfactant reduces the tension; thus balances the “like to like”



Conventional water-miscible cocktails for α/β counting or in medical imaging are not stable in water



A highly stable W-LS with long attenuation length that generates light as particle detector

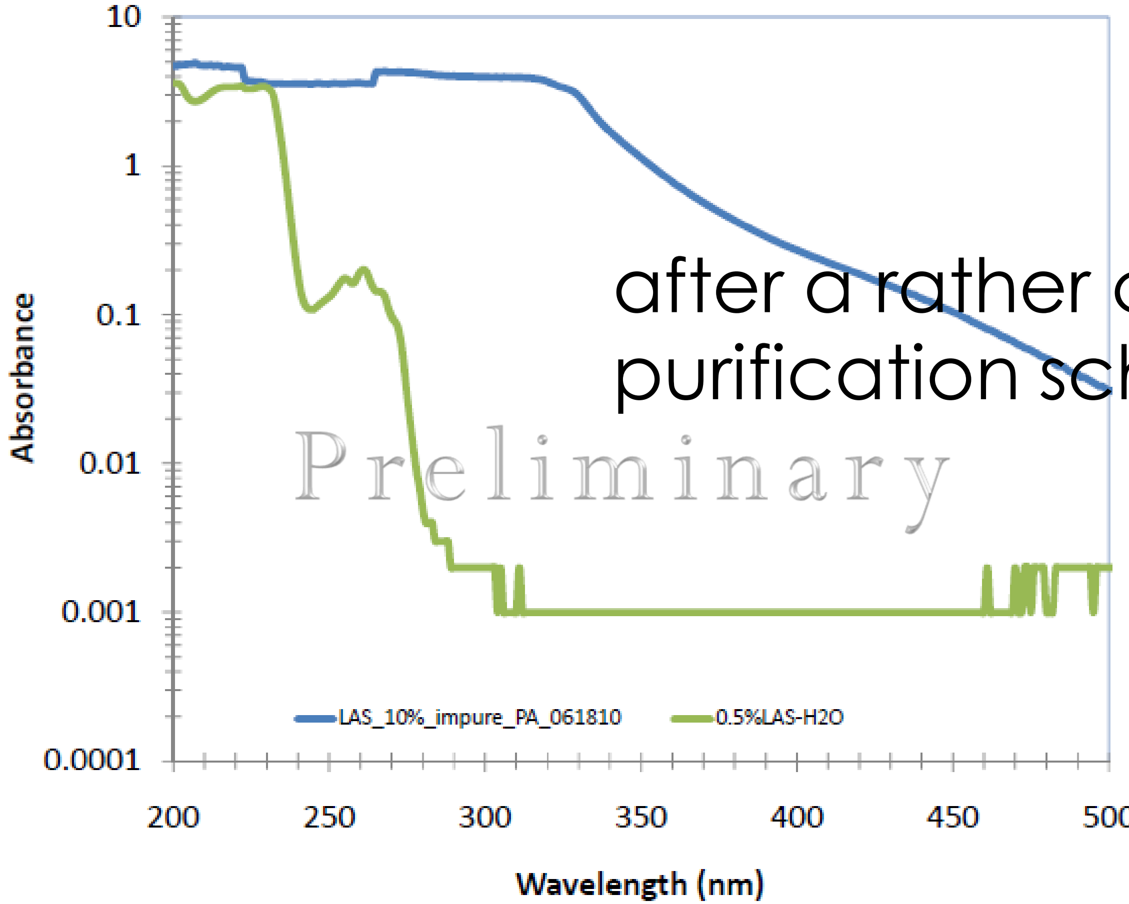
- Purification of raw materials before production
- Online-purification during the data-taking period

LONG ATTENUATION LENGTH IS THE KEY

Purification Scheme and Strategy

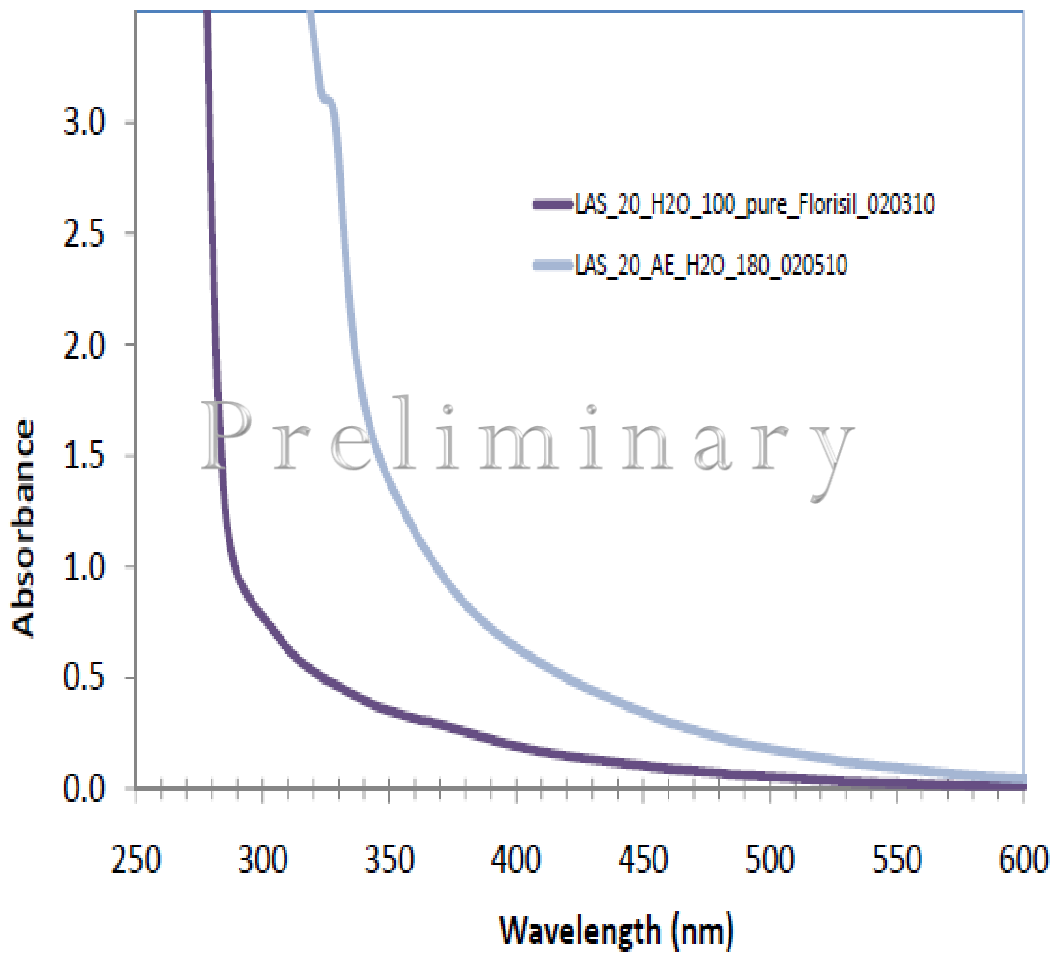
- dry-column extraction
- freezing-isolation
- short-path vacuum distillation
- aqueous/organic solvent-washing
- re-crystallization/dissolution
- **contractors**

0.5% W-LS achieved excellent optical transmission



after a rather complicated purification scheme

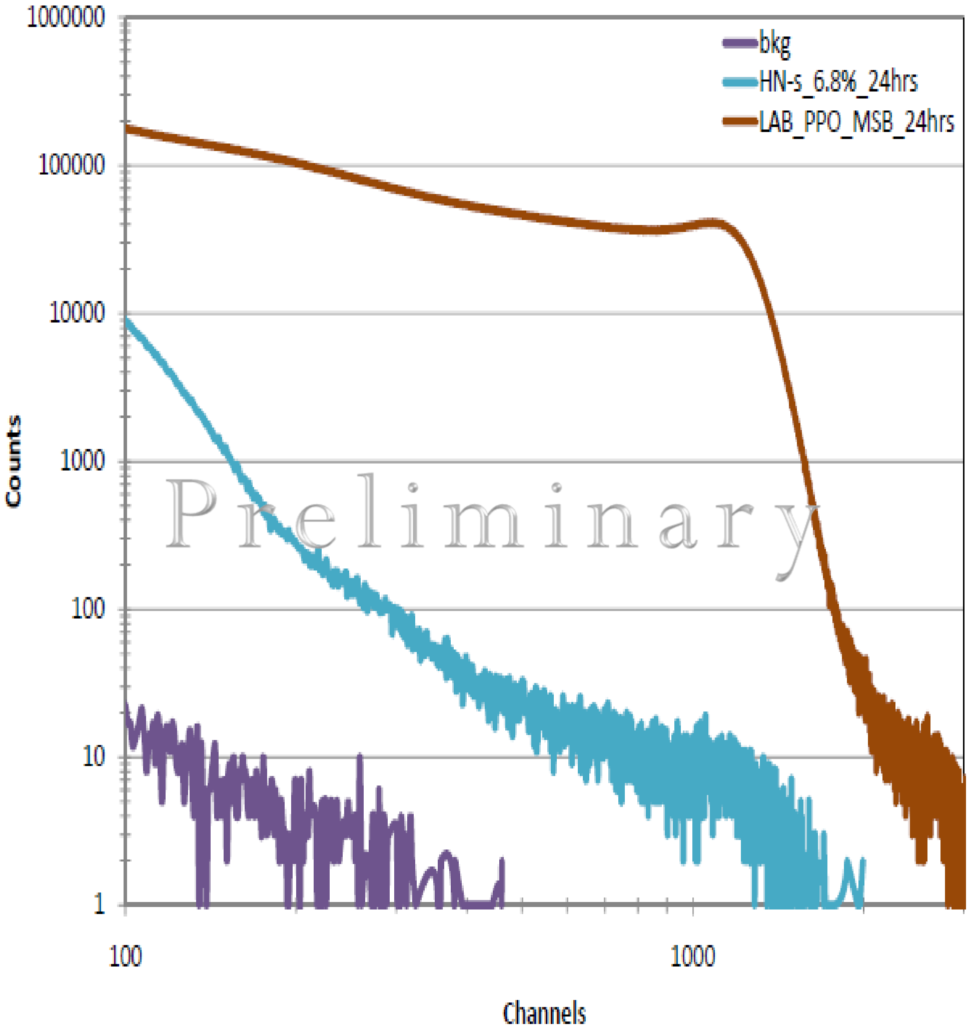
Online purification is achievable; but not easy for large scale

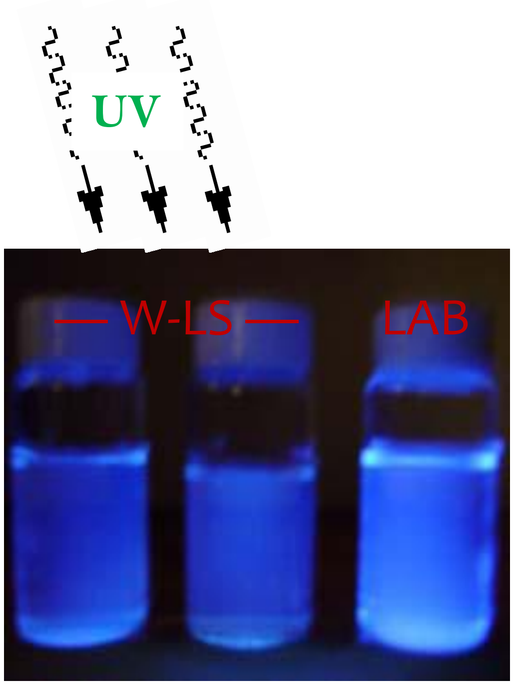


- γ-ray Compton Scattering
- Emission fluorescence spectroscopy

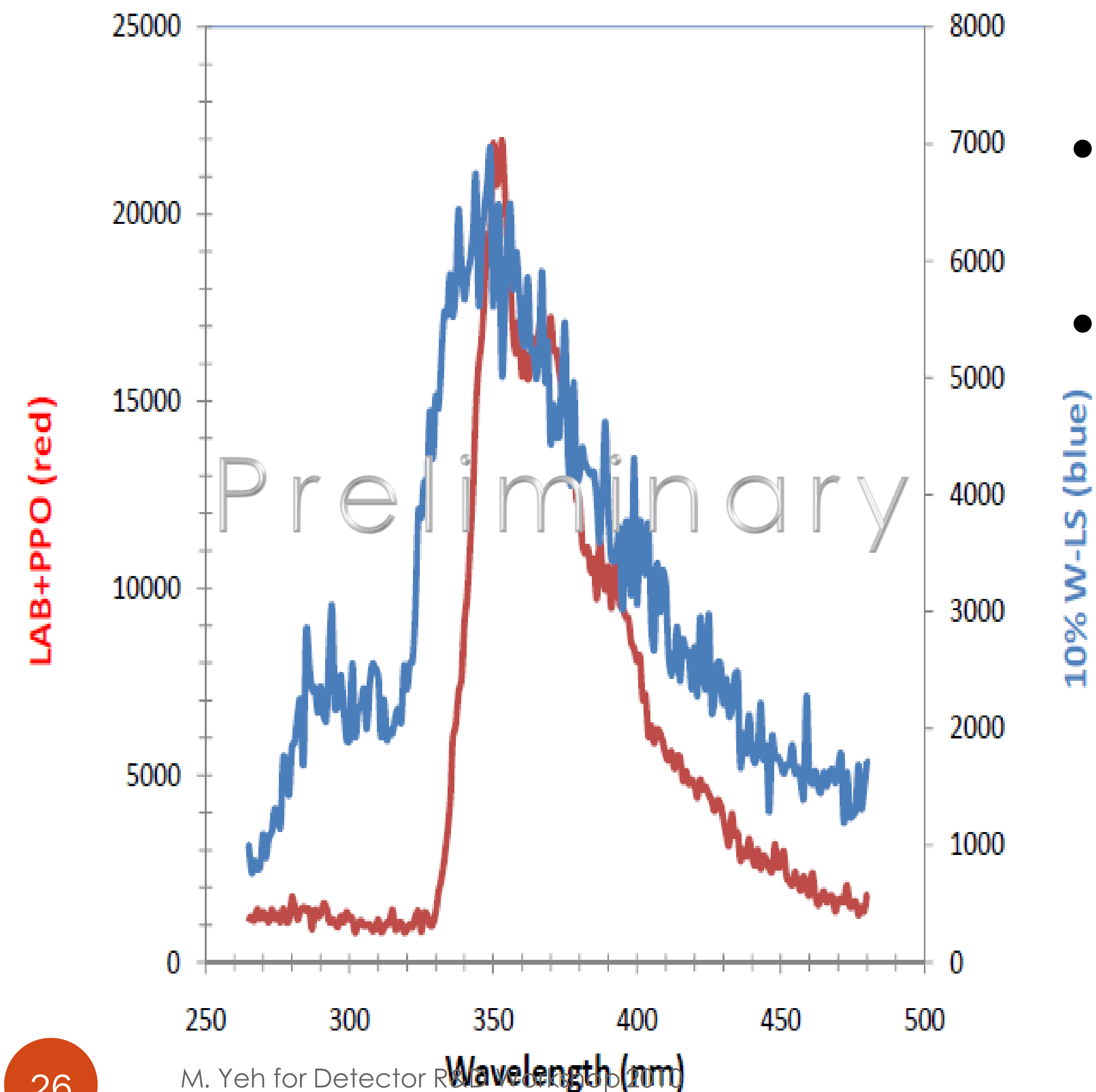
IS THERE A LIGHT?

~7% W-LS has a light-yield of 15~20% of pure LAB (by ^{137}Cs)





Emissions of W-LS and pure LS



- S_γ of 10% W-LS is ~25% of pure LAB
- Non-radiative energy-transfer mechanism is not well-understood yet

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Wavelength shifters for water Cherenkov detectors

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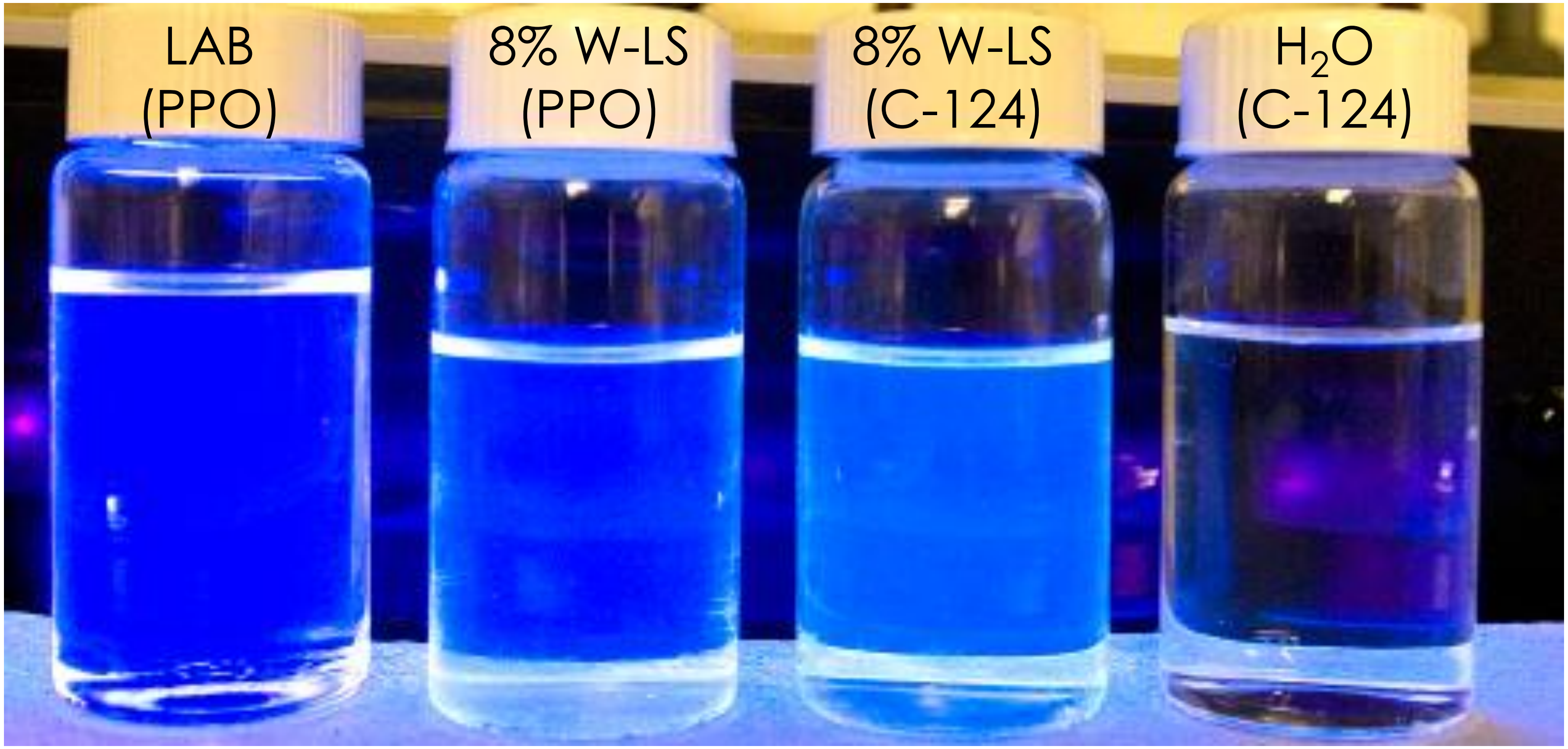
Abstract

The light yield of a water-based Cherenkov detector can be significantly improved by adding a wavelength shifter (WLS). WLS molecules absorb ultraviolet photons and re-emit them at longer wavelengths where typical photomultiplier tubes are more sensitive. In this study, several WLS compounds are tested for possible deployment in the Sudbury Neutrino Observatory (SNO). Test results on optical properties and chemical compatibility for a few WLS candidates are reported; together with timing and gain measurements. A Monte Carlo simulation of the SNO detector response is used to estimate the total light gain with WLS. Finally, a cosmic ray Cherenkov detector was built to investigate the optical properties of WLS.

SNO went through a search of water-soluble wavelength shifters and identified few promising candidates (for Cerenkov)

Blue or Not-Blue



- dissolving a wavelength shifter doesn't generate light
- C-124 needs red shift

- Time-resolved fluorescence spectroscopy
- Single-photon counting

HOW FAST IS THE LIGHT?

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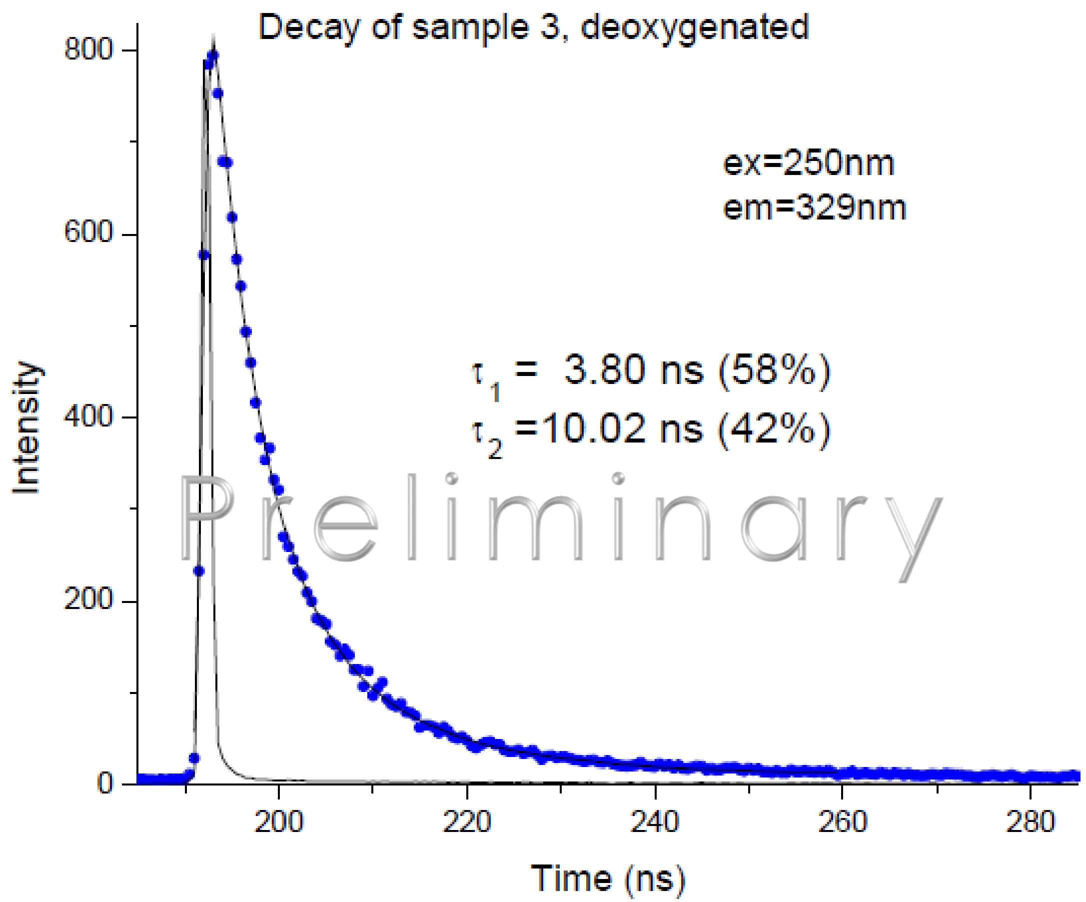
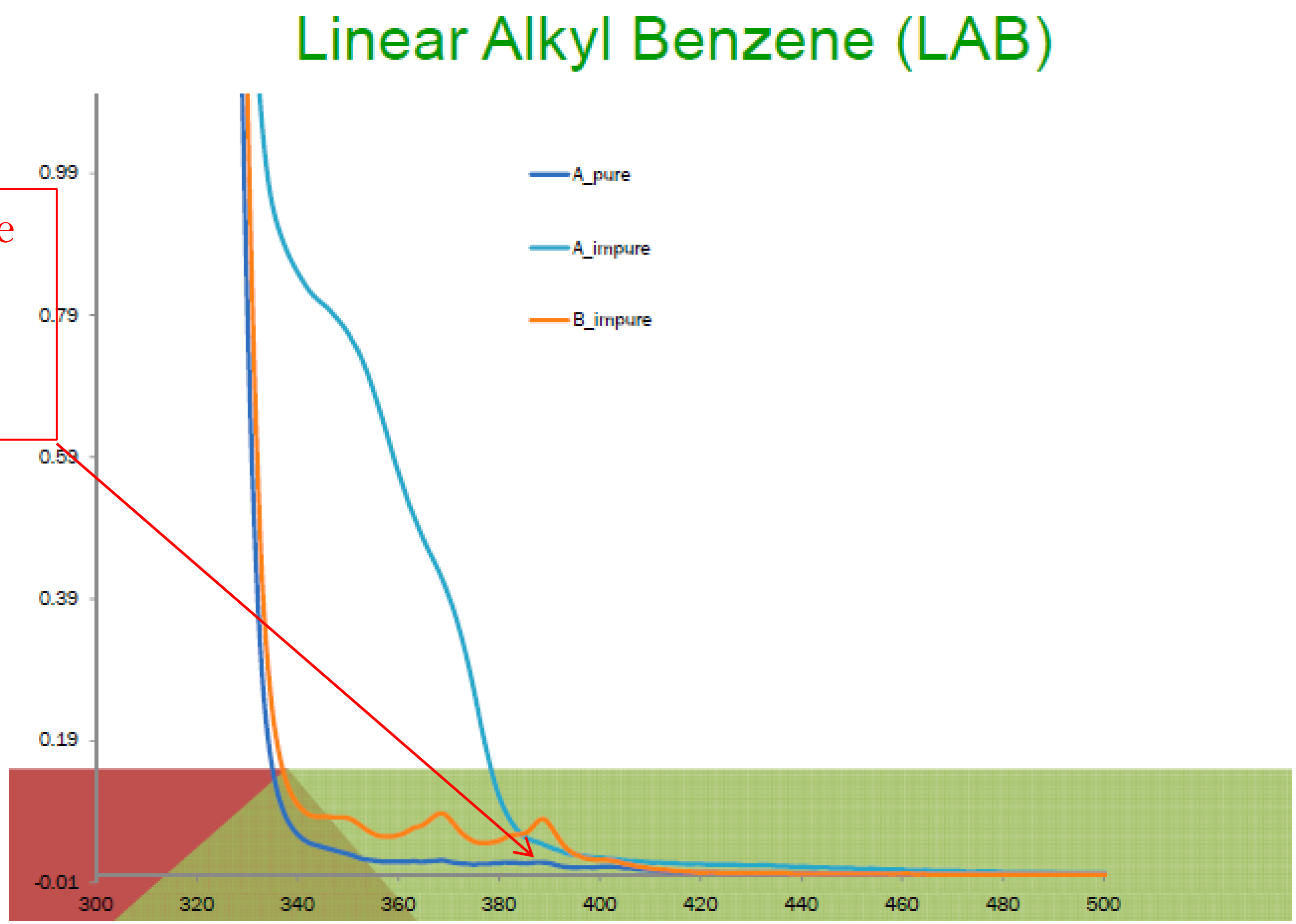
decay time is in the region of interest



- Attenuation measurement of light change at 1% precision
- Use for Daya Bay, SNO+ and LENS (LBNE?)

BNL 2-M DUAL-BEAM SYSTEM

Purification is essential for optical transmission, particularly for large LS detector

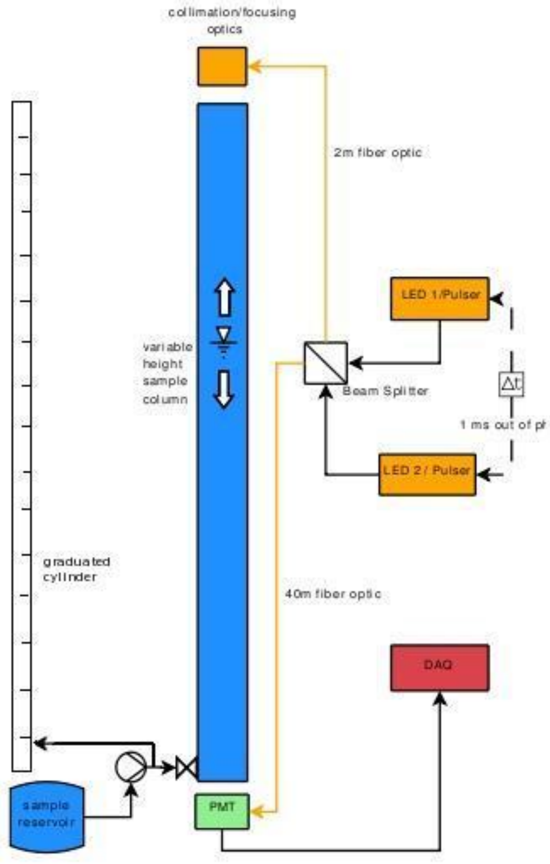


Close to the baseline that a long path-length system is needed!

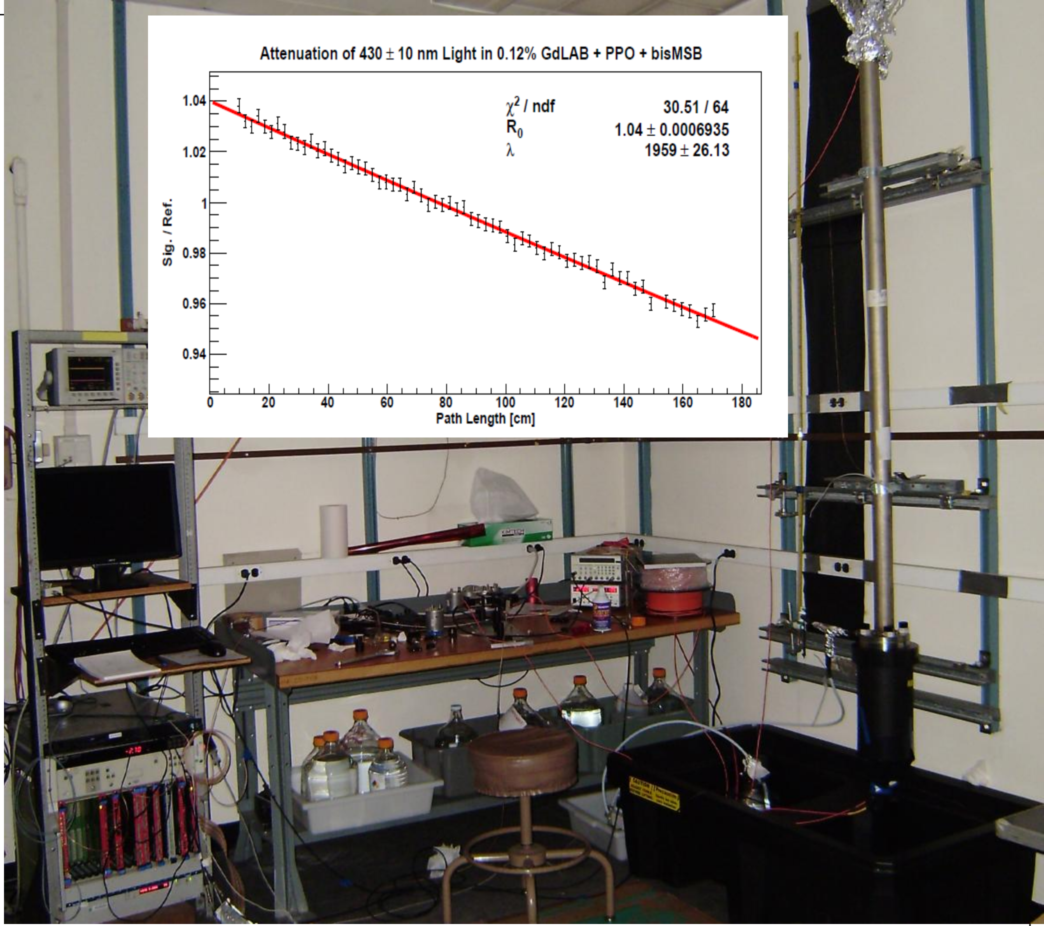
BNL 2-m system

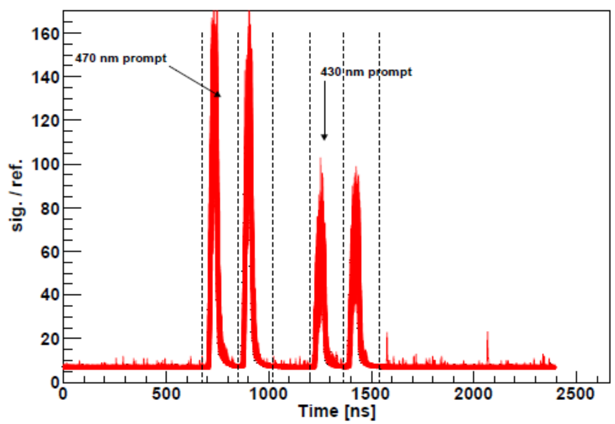
– at 1% precision

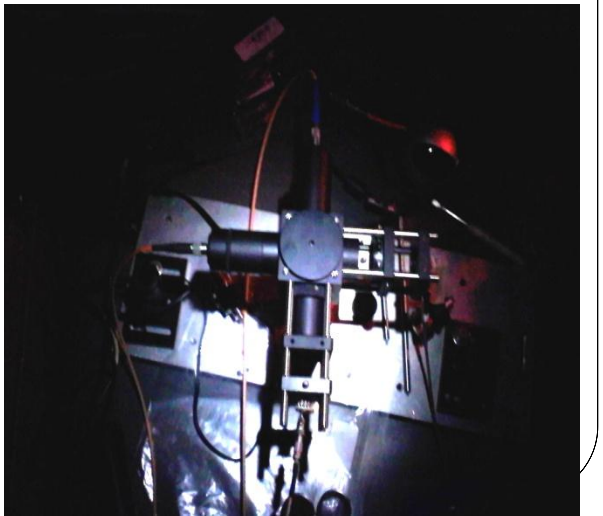
- 2 λs per measurement



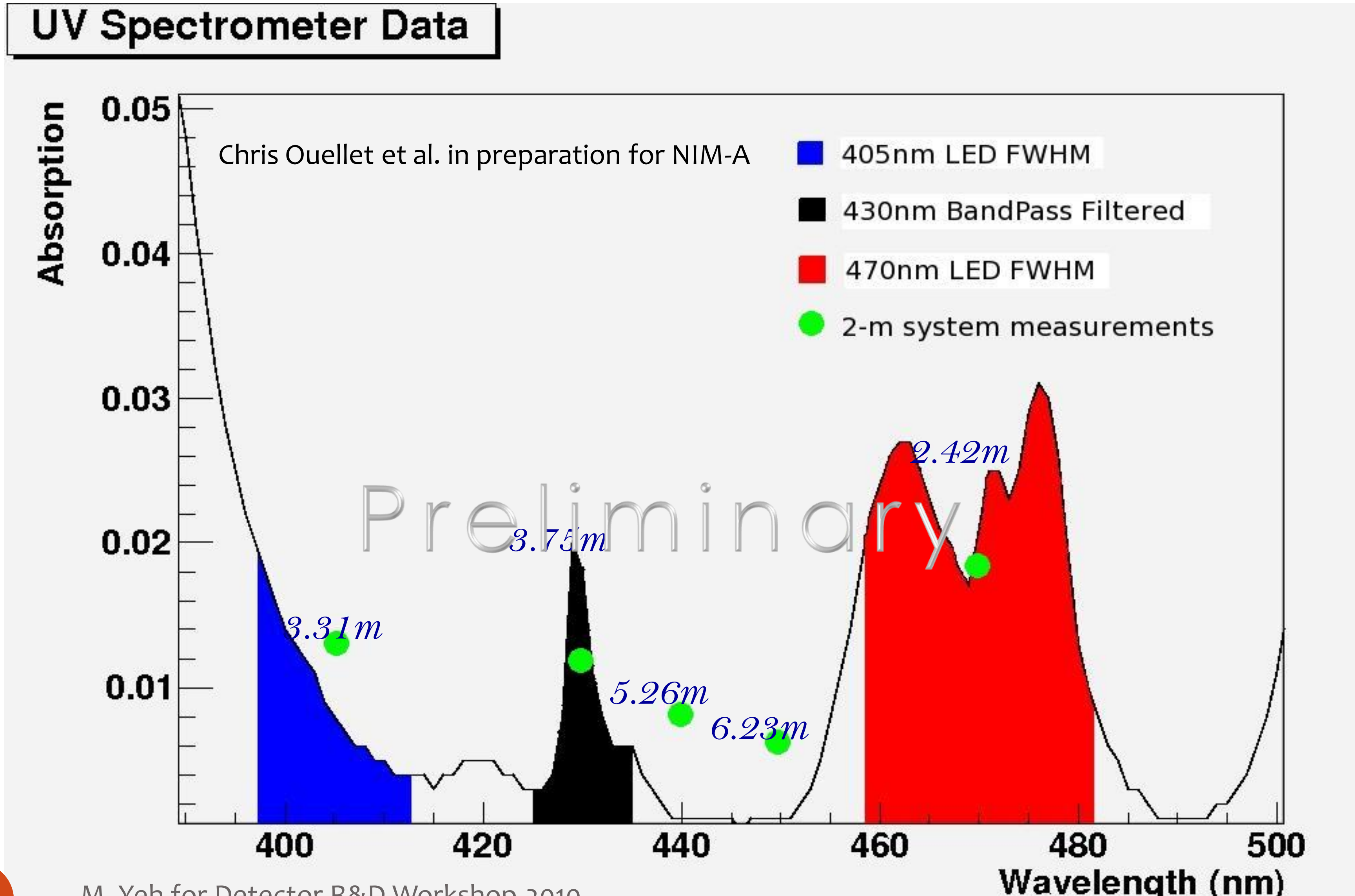
A schematic elevation of the 2-m system.



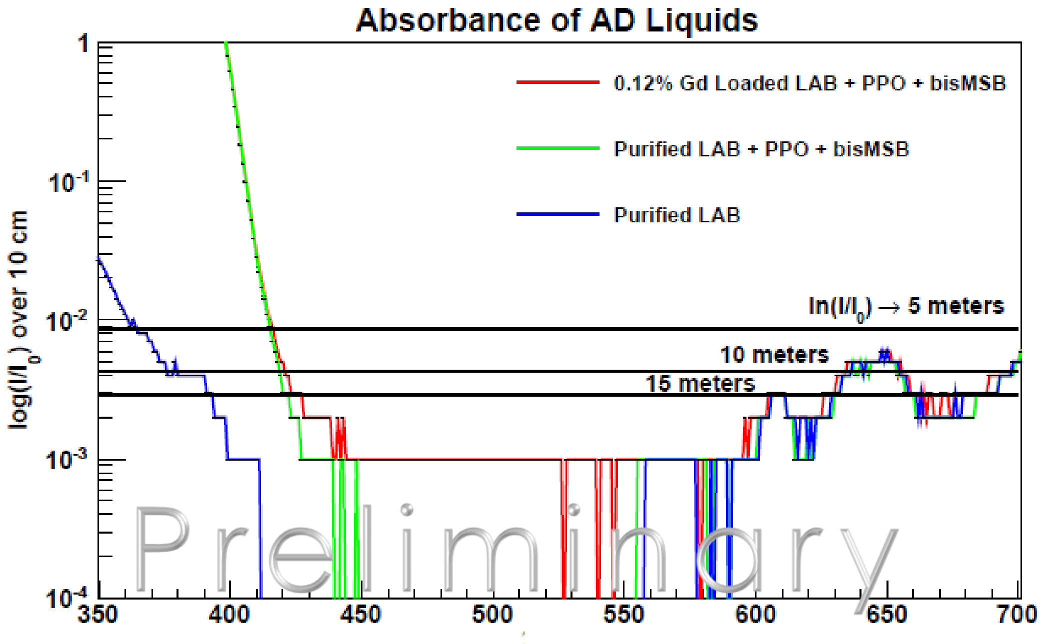


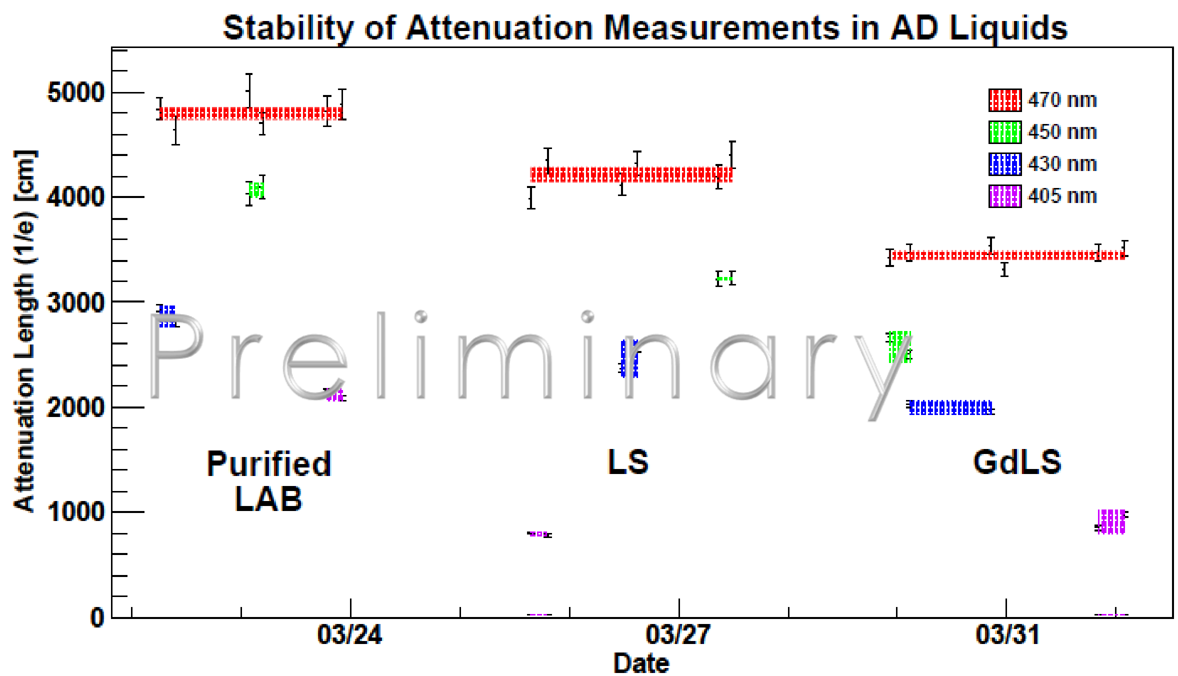


0.1% Nd-LAB by UV 10-cm and 2-m system



Gd-LS Measurement





Johnny Goett et al. in preparation for NIM-A

Summary

- Achieved the first milestone of 3-yr R&D program by developing a W-LS that has
  - Long stability
    - Samples of W-LS have been stable (1.5+ yrs) since preparation
  - Plenty of light
    - but need to optimize fluor selection (organic or aqueous) and understand the quenching effect
  - Fast time pulse
    - decay time at few ~ns
- Large detector for the Physics of PDK^+ in the order of SUSY lifetime becomes affordable

Remaining and Plan to do

- Purify the W-LS in large-scale and on-line during data-taking
  - develop techniques and possibly transfer to contractor
  - can we run it at lower temperature to minimize the microorganisms?
- optimize the light production
  - organic and aqueous fluors and shifters
  - fast
  - stable
- Light production property and quenching effect (*dE/dx)*
  - in response to a proton beam at NSRL (BNL) with kinetic energy of 100 to 1000 MeV.
  - a 250-L prototype for Cf-252 neutron capture.
- Long-term stability test
- Material Compatibility Test (for a 10-yr detector)
  - designated group for LBNE, Daya Bay, SNO+, SNO and LENS
- Detector physics (simulations)
- Other approaches of W-LS
- Can we preserve the scintillation and Cerenkov radiations simultaneously?
  - Little scintillation not to overcome Cerenkov (5 p.e./MeV at 30%)
- Neutron-tagging by adding metal (such as Gd) into the W-LS?
  - IBD followed by Gd-capture sum of 8-MeV

Neutrino at BNL-Chemistry and -Physics

- Richard Hahn
- James Cumming (retiree)

Postdocs

- Sunej Hans
- Liangming Hu
- Pankaj Sinha
- 1~2 openings

Physicists (chemists)

Students/Technicians

- Wanda Beriguete
- Wai Ting Chan
- Johnny Goett (LNGS)
- Richard Rosero

Collaboration between Physics and Chemistry departments

Chemists (Physicists)

Research sponsored by the U.S. Department of Energy, Office of Nuclear Physics and Office of High Energy Physics, under contract with Brookhaven National Laboratory – Brookhaven Science Associates.

BNL 40+ years of neutrino at chemistry

1961

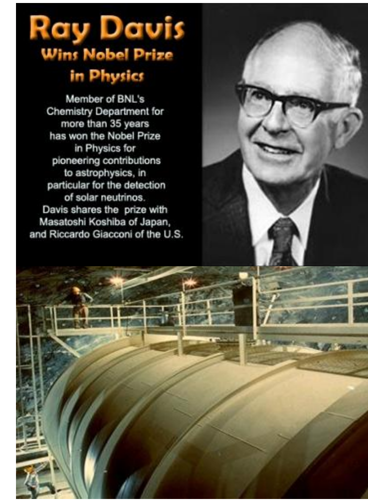
Radio-chemical

Water

Liquid Scintillator

2010

- **HOMESTAKE** Radiochemical Detector
  615 tons of C_2Cl_4; $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$ (~40 years)
- **GALLEX** Radiochemical Detector
  30 tons of Ga; $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$ (1986 - 1998)
- **SNO** Water Čerenkov Detector (SNOLab)
  1-k tons of ultra-pure D_2O (1996 - 2006)



- **LENS** Real-time LS Detector (R&D)
  100 tons of ~8% ^{115}In in Liquid Scintillator (R&D began ~2000)
- **LBNE Long-Baseline Neutrino Experiment**
  V_μ beam to DUSEL (R&D began~2002)
- **Daya Bay High-Precision Reactor θ_{13}** Detector
  200 tons of 0.1% Gd in Liquid Scintillator (R&D ~2003; Project 2007)
- **SNO+ Neutrino-less Double Beta Decay** Real-time Detector
  1-k tons of 0.1% Nd in Liquid Scintillator (R&D ~2004, Project~2009)
- Neutrino Application
  - Nonproliferation and Reactor Monitoring
  - Li/Zr/Ca-loaded Liquid Scintillator (R&D~2008)
- **Water-based Liquid Scintillator (R&D~2009)**