Water-base Liquid Scintillator

- Description
- Physics Potential
- Status of Development
- Future Plans

Robert Svoboda, J-PARC, August 2015
How Does it Work?

π orbitals merge above and below ring

π orbitals merge above and below ring

Singlet and triplet states of the quantum current ring, with vibrational sub-levels. Add a fluor and Stokes Shift and you have a scintillator.
That's why organic scintillators always are made with solvents that have a benzene ring.

Unlike cryogenic electron drift detectors, there is no fundamental reason that they won't work in water.

Main challenges are then how to dissolve organic liquids in water, and how to keep the solution stable. Sort of like dissolving oil into water...

BNL has solved these basic issues with a proprietary mixture that is tunable for the light output.
Dilution of WbLS in water allows for tuning light yield as desired to match the physics.

WbLS cocktail in water (violet) and cyclohexane (blue)

What can you do with this?
Advanced Scintillator Detector Concept (ASDC): A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator


1. Massachusetts Institute of Technology, Cambridge, MA 02139, USA
2. Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
3. Physics Department, University of California, Davis CA 95616, USA
4. Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
5. Brookhaven National Laboratory, Upton, NY 11973, USA
6. Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA
7. Department of Physics, Princeton University, NJ 08544, USA
8. Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
9. Department of Natural Sciences, Hawaii Pacific University, Honolulu, Hawaii 96814, USA
10. Sandia National Laboratories, Livermore, CA 94550, USA
11. Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822 USA
12. Department of Physics, University of California, Berkeley, CA 94720, USA
13. Department of Geology, University of Maryland, College Park, MD 20742, USA
14. TUM, Physik-Department, James-Franck-Str. 1, 85748 Garching, Germany
15. Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
16. Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
17. Department of Physics, Columbia University, New York, NY 10027, USA
18. Department of Nuclear Engineering, University of California, Berkeley, CA 94720, USA
19. Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
20. Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA 98195, USA
21. Institute for Experimental Physics, University of Hamburg, Germany
22. Institute of Physics & EC PRISMA, Johannes Gutenberg-University Mainz, 55128 Mainz, Germany

arXiv:1409.5864

1% gives ~100 optical photons/MeV
4% WbLS gives approximately four times the light yield of pure water
THEIA:
A realisation of the Advanced Scintillation Detector Concept (ASDC)

- 50-100 kton WbLS target
- High coverage with ultra-fast, high efficiency photon sensors
- 4800 m.w.e. underground (Homestake).
- Is Kamioka a possibility?
- Comprehensive low-energy program: solar neutrinos, supernova, DSNB, proton decay, geo-neutrinos, DBD
- In the LBNF beam: long-baseline program complementary to proposed LAr detector

➡ Broad physics program!

Concept paper - arXiv:1409.5864
Potential Physics Program

1. Long-baseline physics (mass hierarchy, CP violation)
2. Neutrinoless double beta decay
3. Solar neutrinos (solar metallicity, luminosity)
4. Supernova burst neutrinos & DSNB
5. Geo-neutrinos
6. Nucleon decay
7. Source-based sterile searches

Remarkably, the same detector could show that neutrinos and antineutrinos are the same, and that “neutrinos” and “antineutrinos” oscillate differently.
Supernova Burst $\nu$ in Theia

- ~90% events are IBD
- Enhanced neutron tag via low threshold scintillation. Even better if Gd added. Current SK efficiency ~18%. With Gd will be ~60%-70%.
- Enhanced energy resolution of prompt IBD. For 4% loading this would be a factor of two.

<table>
<thead>
<tr>
<th>Neutrino Reaction</th>
<th>Percentage of Total Events</th>
<th>Type of Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>88%</td>
<td>Inverse Beta</td>
</tr>
<tr>
<td>$\nu_e + e^- \rightarrow \nu_e + e^-$</td>
<td>1.5%</td>
<td>Elastic Scattering</td>
</tr>
<tr>
<td>$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$</td>
<td>&lt;1%</td>
<td>Elastic Scattering</td>
</tr>
<tr>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>1%</td>
<td>Elastic Scattering</td>
</tr>
<tr>
<td>$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F$</td>
<td>2.5%</td>
<td>Charged Current</td>
</tr>
<tr>
<td>$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + {}^{16}N$</td>
<td>1.5%</td>
<td>Charged Current</td>
</tr>
<tr>
<td>$\nu_x + {}^{16}O \rightarrow \nu_x + O*/N* + \gamma$</td>
<td>5%</td>
<td>Neutral Current</td>
</tr>
</tbody>
</table>

- Better separation of NC mono-energetic 5-10 MeV gammas from background
- Better efficiency for low energy electrons from the 15 MeV threshold CC interactions. Potential for detection of nuclear breakup.
Diffuse Supernova $\nu$ in Theia

- Muon induced spallation is a major background. Current SK threshold is 13.3 MeV. Scintillation light has the potential to enhance identification of (n,p) events and proton nuclear de-excitation final states.
- A 90% neutron detection efficiency would also reject multiple neutron events (2 of 13 DSNB backgrounds in SK are "double" even with 18% efficiency).
- Low energy "stealth" muon events can be clearly identified. No longer a problem.
- Enhanced energy resolution for signal and background rejection.

<table>
<thead>
<tr>
<th>SRN model</th>
<th>$F_M$</th>
<th>$N_P$</th>
<th>$T_P$</th>
<th>$F_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant SN [1]</td>
<td>52.3</td>
<td>10.8</td>
<td>1.4</td>
<td>147.5</td>
</tr>
<tr>
<td>HBD 6 MeV [10]</td>
<td>21.8</td>
<td>4.4</td>
<td>0.6</td>
<td>150.9</td>
</tr>
<tr>
<td>Chemical evolution [4]</td>
<td>8.5</td>
<td>1.5</td>
<td>0.2</td>
<td>172.6</td>
</tr>
<tr>
<td>Heavy metal [5, 6]</td>
<td>31.3</td>
<td>4.7</td>
<td>0.6</td>
<td>201.5</td>
</tr>
<tr>
<td>LMA [7]</td>
<td>28.8</td>
<td>4.2</td>
<td>0.5</td>
<td>208.8</td>
</tr>
<tr>
<td>Failed SN [9]</td>
<td>12.0</td>
<td>1.7</td>
<td>0.2</td>
<td>214.9</td>
</tr>
<tr>
<td>Cosmic gas [3]</td>
<td>5.3</td>
<td>0.7</td>
<td>0.1</td>
<td>230.6</td>
</tr>
<tr>
<td>Star formation rate [8]</td>
<td>18.7</td>
<td>1.8</td>
<td>0.2</td>
<td>316.3</td>
</tr>
<tr>
<td>Population synthesis [2]</td>
<td>42.1</td>
<td>1.3</td>
<td>0.2</td>
<td>986.1</td>
</tr>
</tbody>
</table>
$p \rightarrow \nu K^+$ Proton Decay in Theia

- SK limited due to the fact that the $K^+$ is below Cherenkov threshold.
- With WbLS this is no longer the case. Kaons identified via time structure.
- Studies by LENA and ASDC group show that expected efficiency is about 70% in detailed MC studies.
- Background depends on effectiveness of n-tagging
- JUNO should do well here

SK: current + 19% efficiency for future
HK: SKII + 3.5% = 16.5%
LBNE: 34 kT Bueno et al. efficiencies
ASDC: LENA efficiencies and pessimistic (0%) and optimistic (90%) n-tagging
Neutrinoless Double Beta Decay

Current limits (EXO-200, KL-Zen, GERDA)
MJD projection
CUORE & SNO+ projection


Slide courtesy of G.D. Orebi Gann
Liquid Scintillator Approach

Projected spectrum in SNO+; 5 years, 0.3% \text{n}_\text{a}t\text{e}Te

Asymmetric ROI (-0.5 - 1.5 $\sigma$):
2.1 $0\nu\beta\beta$ events / yr
7.3 $8B$ solar $\nu$ events / yr

Use of precision timing to separate Chr / scint components allows directional cut to reject dominant $8B$ solar $\nu$ background

Slide courtesy of G.D. Orebi Gann
THEIA Sensitivity

Projected spectrum in SNO+: 5 years, 0.3% $^{nat}$Te

Ultra-low background, scalable
Asymmetric ROI (-0.5-1.5 $\sigma$): 2.1 2$\nu$B$\beta$ & 7.3 $^{8}$B $\nu$ events / yr

Cher / scint separation allows directional cut to reject dominant $^{8}$B solar $\nu$ background

50kt detector
50% reduction of $^{8}$B
Coincidence tags for int r/a $R_{fit} > 5.5$m from PMTs (30kt fid)
0.5% loading ($^{nat}$Te) in 50kt
\[ \Rightarrow 50t \; ^{130}$Te

\[ \Rightarrow 3\sigma \; \text{discovery for } m_{\beta\beta} = 15\text{meV in 10 yrs}

Phys. Rev. Lett. 110 : 062502 (2013);
SNO+ white paper under development;

Slide courtesy of G.D. Orebi Gann
Other Physics (see archive paper)

• Long Baseline Neutrinos: Enhanced NC rejection discussion for Homestake site
• Solar neutrinos: possible addition of 7-Li and enhanced efficiency at low energy
• Geo-neutrinos: neutron tagging
WbLS Development Status

- Light yield studies at BNL and soon at LBNL
- Stability and material compatibility studies at BNL (uncovered one problem so far – butyl rubber adhesive).
- Purification studies at UC Davis using NanoFiltration (NF) to separate organic components from water.
- Scaled up production: 10 liters produced in June with BNL 5 liter reactor. Used for NF and Material studies.
- 100 liter batch under production. Will be used for attenuation length studies (currently have on 1-meter arm). Will use UCI and/or LLNL facility.
- 1-ton BNL prototype approved and under construction.
## Planned Demonstrations

<table>
<thead>
<tr>
<th>Site</th>
<th>Scale</th>
<th>Target</th>
<th>Measurements</th>
<th>Timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>UChicago</td>
<td>bench top</td>
<td>H2O</td>
<td>fast photodetectors</td>
<td>Exists</td>
</tr>
<tr>
<td>CHIPS</td>
<td>10 kton</td>
<td>H2O</td>
<td>electronics, readout, mechanical infrastructure</td>
<td>2019</td>
</tr>
<tr>
<td>EGADS</td>
<td>200 ton</td>
<td>H2O+Gd</td>
<td>isotope loading, fast photodetectors</td>
<td>Exists</td>
</tr>
<tr>
<td>ANNIE</td>
<td>30 ton</td>
<td>H2O+Gd</td>
<td></td>
<td>2016</td>
</tr>
<tr>
<td>WATCHMAN</td>
<td>1 kton</td>
<td></td>
<td></td>
<td>2019</td>
</tr>
<tr>
<td>UCLA/MIT</td>
<td>1 ton</td>
<td>LS</td>
<td>fast photodetectors</td>
<td>2015</td>
</tr>
<tr>
<td>Penn</td>
<td>30 L</td>
<td>(Wb)LS</td>
<td>light yield, timing, loading</td>
<td>Exists</td>
</tr>
<tr>
<td>SNO+</td>
<td>780 ton</td>
<td>(Wb)LS</td>
<td>light yield, timing, loading</td>
<td>2016</td>
</tr>
<tr>
<td>LBNL</td>
<td>bench top</td>
<td>WbLS</td>
<td>light yield, timing, cocktail optimization, loading, attenuation, reconstruction</td>
<td>Early 2015</td>
</tr>
<tr>
<td>BNL</td>
<td>1 ton</td>
<td>WbLS</td>
<td></td>
<td>Summer 2015</td>
</tr>
<tr>
<td>WATCHMAN-II</td>
<td>1 kton</td>
<td></td>
<td></td>
<td>2020</td>
</tr>
</tbody>
</table>
Bad News/Good News

- **Bad News**: 1-kton WATCHMAN proposal rejected by DOE ("too expensive for R&D").
- We were **encouraged** to submit smaller scale R&D proposals. LOI to DOE/HEP last week, proposal due September. Also, discussion with DOE/DNN last week for FY16 went well.
- **Good News**: ANNIE received Stage One approval from Fermilab and is going ahead with a background run starting **THIS YEAR**!
Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions.

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state.

---

SK-IV

PDK MC

Bkgd

ATM $\nu$ MC

---

$\nu$

lepton

hadrons

---

I. Anghel$^{1,4}$, G. Davies$^{4}$, F. Di Lodovico$^{11}$, A. Elagin$^{8}$, H. Frisch$^{9}$, R. Hill$^{9}$, G. Jocher$^{5}$, T. Kalori$^{11}$, J. Learned$^{11}$, R. Northrop$^{9}$, C. Pilcher$^{9}$, E. Ramberg$^{9}$, M.C. Sanchez$^{1,4}$, M. Smy$^{7}$, H. Sobel$^{7}$, R. Svoboda$^{6}$, S. Usman$^{9}$, M. Vagina$^{7}$, G. Varner$^{10}$, R. Wagner$^{1}$, M. Welstein$^{9}$, L. Winslow$^{6}$, and M. Yeh$^{2}$

---

$^1$Argonne National Laboratory  $^2$Brookhaven National Laboratory  $^3$Fermi National Accelerator Laboratory  $^4$Iowa State University  $^5$National Geospatial-Intelligence Agency  $^6$University of California at Davis  $^7$University of California at Irvine  $^8$University of California at Los Angeles  $^9$University of Chicago  $^{10}$University of Hawaii  $^{11}$Queen Mary University of London
### Rates Expected with $1 \times 10^{20}$ POT exposure at SciBooNE pit

<table>
<thead>
<tr>
<th></th>
<th>Total Events [1/1ton/$10^{20}$POT]</th>
<th>Total (per v-type)</th>
<th>Charged Current</th>
<th>Neutral Current</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Booster Beam</strong>&lt;br&gt;(v-mode, Target = CH$_2$)</td>
<td>10419</td>
<td>$\nu_\mu$ 10210</td>
<td>7265</td>
<td>2945</td>
</tr>
<tr>
<td></td>
<td></td>
<td>anti-$\nu_\mu$ 133</td>
<td>88</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_e$ 72</td>
<td>52</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>anti-$\nu_e$ 4.4</td>
<td>3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Booster Beam</strong>&lt;br&gt;(v-mode, Target = H$_2$O)</td>
<td>10612</td>
<td>$\nu_\mu$ 10405</td>
<td>7443</td>
<td>2962</td>
</tr>
<tr>
<td></td>
<td></td>
<td>anti-$\nu_\mu$ 129</td>
<td>85</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_e$ 73</td>
<td>53</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>anti-$\nu_e$ 4.6</td>
<td>3.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>

---

**Diagram:**

- 3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.
- Existing veto on muons produced upstream of the detector (FACC).
- Existing Muon Range Detector (MRD).

**“ANNIE Hall”**

(formerly the SciBooNE pit)
See ANNIE presentation at January 2015 FNAL PAC meeting for details.

First Phase will be neutron background measurement with SciBATH followed by 20 ton water tank with LS (perhaps WbLS) moveable target.

Second Phase will be neutron yield experiment using Booster Neutrino Beam (BNB) and LAPPD fast light sensors

May include internal WbLS target – under discussion
The SciBooNE Hall is now the ANNIE Hall. SciBATH is shown making preliminary neutron measurements.
2015-2016 Run

- Seeking more collaborators, especially those interested in proton decay, DSNB physics and WbLS/LAPPD R&D.
- Seeking readout electronics for Muon Range Detector for Phase 0 (400 channels) and CDF paddle vetos (50 channels) and a group to make it work. **SK electronics?**
- Would also like more PMT's if possible to enhance capture gamma detection.
FroST

Frontiers in Scintillator Technology

March 18-20th 2016

Local Organising Committee
Ed Blucher
Josh Klein
Gabriel Orebi Gann
Bob Svoboda

Scientific Advisory Committee
Steve Biller
Frank Calaprice
Mark Chen
Cristiano Galbiatti
Wick Haxton
Kunio Inoue
Thierry Lasserre
Manfred Lindner
Serguey Petcov
Gioacchino Ranucci
Mayly Sanchez
Yifang Wang
Michael Wurm
Thanks!

Nanofiltration Lab

Future?
1% WbLS-2014 cont’d

- WbLS light-yield as a function of LS% loading
  - Higher light-yield at the cost of optical transmission
- Linear correlation between light-yield and LS% (up to ~15%) 
  - Different behavior with that of pure scintillator
- WbLS-2014 has ~25% more light-yield than WbLS-2012