Liquid detectors session

Current trends in organic liquid scintillation and water Cherenkov detectors

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Scintillation

Detection of ionizing radiation through the scintillation light induced in special organic or inorganic materials. The liquid scintillation technique of interest in this context falls in the organic class. Light production is isotropic.

Fundamental properties for a good scintillating material:

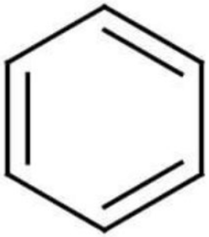
1. High scintillation efficiency
2. Linear dependence between energy deposit and produced light
3. Limited self absorption
4. Short decay time of the scintillation light (fast pulses generation)
5. Suited to be easily shaped in various forms and dimensions
6. Refractive index like the glass (phototube matching)

G. Knoll Radiation detection and measurements
J.B. Birks The theory and practice of scintillation counting

Scintillation mechanism in organic materials

The fluorescence process takes place in transitions between the energetic levels of the single molecule independently from its physical state

In the so called polycyclic aromatic hydrocarbons the molecular levels involved in the process are the so-called electronic levels p which stem from the trigonal hybridization - sp^2 - of the four valence electrons of the carbon atoms at the vertex of the hexagonal planar molecule C_6H_6 - **Benzene ring**



Schematic benzene symbol

Scintillation efficiency

Fraction of the energy of the incoming particle converted into visible light typically 3-4 % (higher in solid inorganic $\mathbf{N_aI}$ 12-13%)

Competing non radiative de-excitation modes limit the energy available for light production – ionization quenching, heat production

The oxygen dissolved in the liquid scintillator is an important additional quenching factor, which must be removed -> nitrogen purging

By exploiting the energy migration process (energy transfer from molecule to molecule of the solvent) typical of the hydrocarbon solvent through the addition of a small quantity of a high efficiency solute the overall efficiency is highly enhanced

$\rightarrow$ **binary liquid scintillators**

Possible addition of a third fluor as wavelength shifter to match the phototube response **ternary scintillator – not essential**

Technological evolution lines in the field

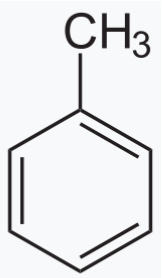
1-Material safety

2-Exploitation of the associated Cherenkov light production for directionality

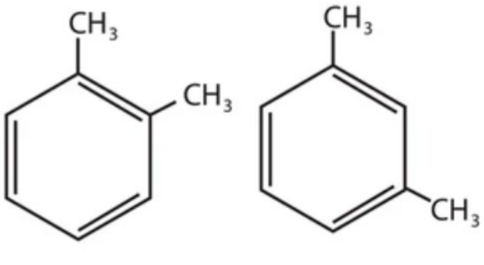
3-Loading with isotopes for neutron capture and special applications-shared with Cherenkov water-based applications

1st line - Commonly used solvents

Toluene
C_7H_8



Xylene
C_8H_{10}



Ortho-xylene

Meta-xylene

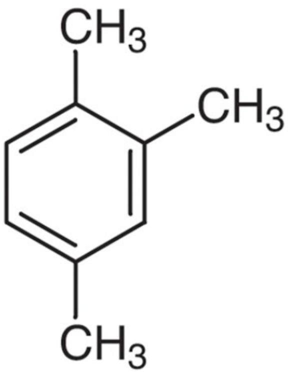
Para-xylene

Mixed isomers

First generation solvents – beginning of '50s

Hazardous flammable and threat to environment though less than benzene

Pseudocumene
(1,2,4-trimethylbenzene)
C_9H_{12}



Second generation solvent – middle of '70s

Less Hazardous and less threat to environment though not with zero harm - flammable

Borexino and its prototype CTF

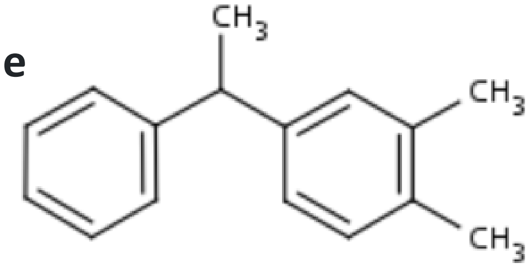
Modern solvents

At the turn of the century introduced a new generation of solvents with the following characteristics:

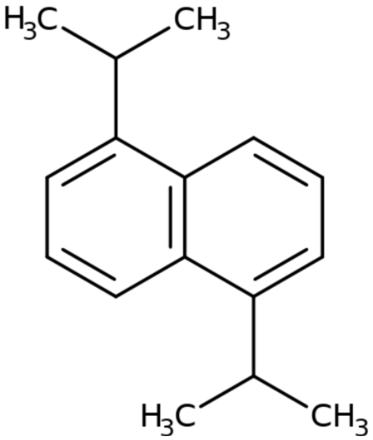
- High Flash point (no flammable)
- Low vapor pressure
- odor lessness
- Low toxicity and irritancy
- Biodegradability

No hazard for operators and environment

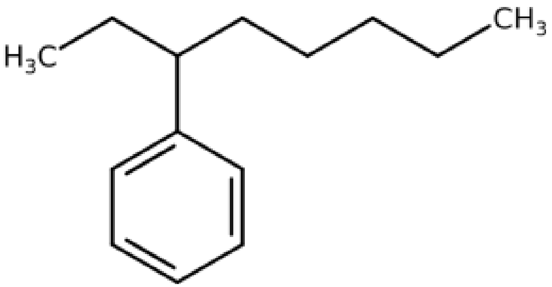
Phenyl xylyl ethane
PXE
$C_{16}H_{18}$



Diisopropylnaphthalene
DIN (mixture of isomers)
$C_{16}H_{20}$



Linear alkylbenzene
LAB
precursor of biodegradable detergents large availability and low cost

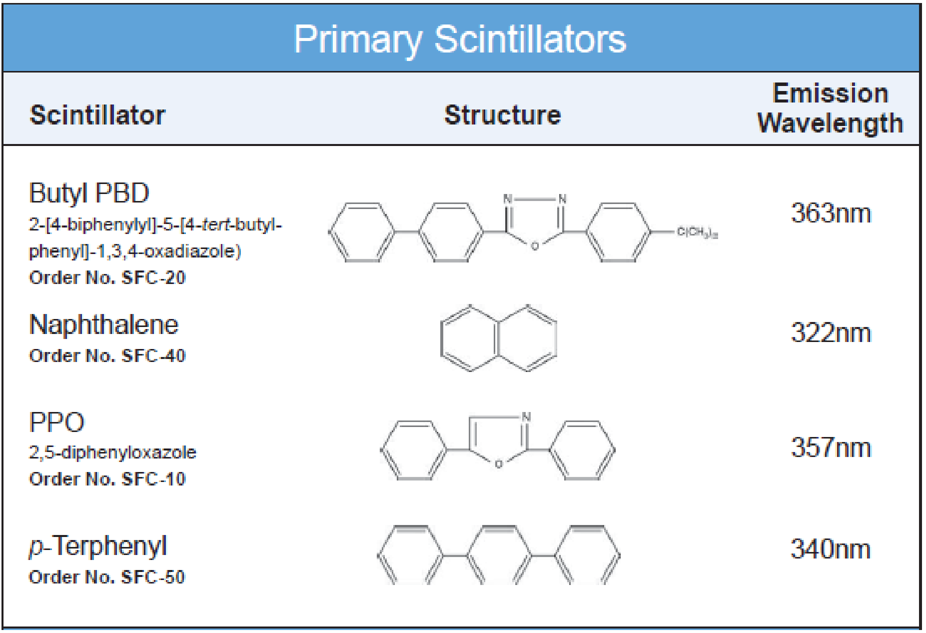


Widespread modern choice

Linear chain of length between 10 and 13
Each vertex CH_2
(mixture of isomers)
$C_6H_5CnH_2n+1$

For a recent review see arXiv:2205.15046

Solutes

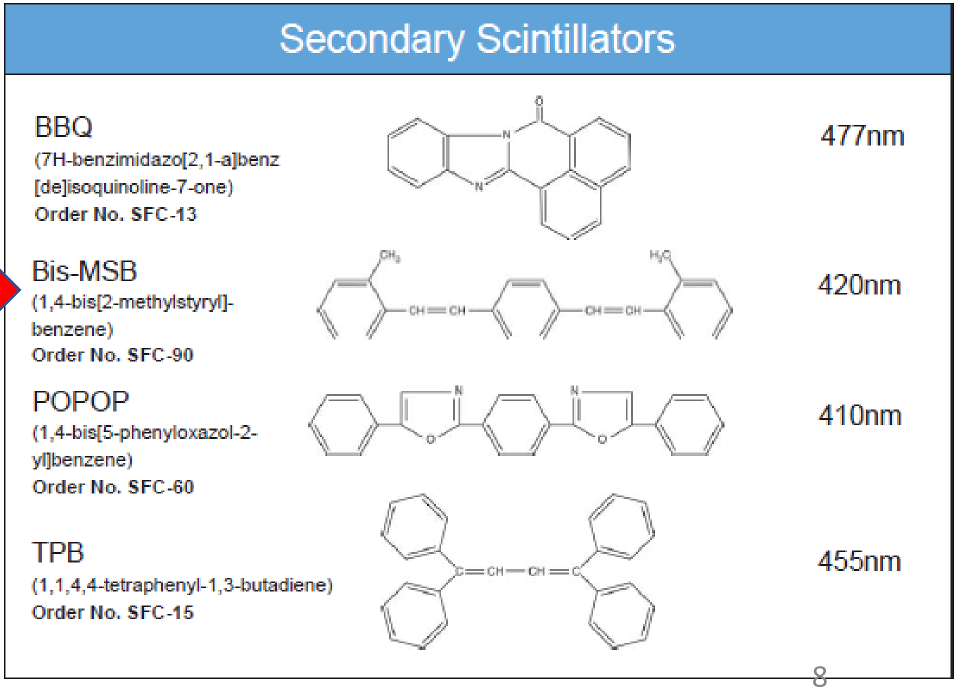


Primary Scintillators

Scintillator	Structure	Emission Wavelength
Butyl PBD 2-[4-biphenylyl]-5-[4-*tert*-butyl-phenyl]-1,3,4-oxadiazole) **Order No. SFC-20**		363nm
Naphthalene **Order No. SFC-40**		322nm
PPO 2,5-diphenyloxazole **Order No. SFC-10**		357nm
p-Terphenyl **Order No. SFC-50**		340nm

Mature elements valid for all solvents - no further research ongoing for them

Among primary solutes PPO is the most used typically few g/l



Secondary Scintillators

BBQ (7H-benzimidazo[2,1-a]benz[de]isoquinoline-7-one) **Order No. SFC-13**		477nm
Bis-MSB (1,4-bis[2-methylstyryl]-benzene) **Order No. SFC-90**		420nm
POPOP (1,4-bis[5-phenyloxazol-2-yl]benzene) **Order No. SFC-60**		410nm
TPB (1,1,4,4-tetraphenyl-1,3-butadiene) **Order No. SFC-15**		455nm

Among secondary solutes bis MSB is the most used typically few mg/l

A close relative: Cherenkov radiation in water

- ✓ In a material with refractive index n a charged particle emits photons if its velocity is greater than the local phase velocity of light → water very convenient material as another widespread incarnation of liquid detectors for particle detection through Cherenkov radiation
- ✓ Advantage
  - ✓ Possibility to amass easily very large quantity of water
  - ✓ Directionality of the Cherenkov light
- ✓ Disadvantage
  - ✓ Low luminosity-much less photon than in the scintillation process
- ✓ Idea
  - ✓ Merge the luminosity of the scintillator and the directionality of the Cherenkov

Intermezzo-neutrino experiments based on liquid scintillation technique

The scintillation technique is suited to build massive experiments devoted to the detection of rare events

In the neutrino field this kind of method has been exploited from the ‘50s for (with different level of overburden)

a) Reactor neutrino experiments

Savannah River (first antineutrino detection), Gosgen, Bugey, Chooz, Palo Verde, KamLAND, Daya Bay, Reno, Doble Chooz etc… (many others not listed here)

b) Accelerator based experiments

LSND, Karmen, Nova

LVD & Borexino @ Gran Sasso

c) Supernova neutrinos

LVD (**Borexino** and KamLAND as ancillary capability)

d) Solar neutrino experiments and detection of other low energy neutrino fluxes like geoneutrinos **Borexino**, SNO+ (also double beta decay exp.) KamLAND

LVD, SNO+, KamLAND - in a version for 0νbb decay - Nova and Reno are those in operation (several small set-ups not listed here)

The baton soon will be taken by **JUNO** (gigantic multipurpose experiment for reactor and other neutrino fluxes of natural origin) with substantial INFN participation

Intermezzo-Class of underground/astroparticle and neutrino detectors based on Cherenkov methodology

From the '80s

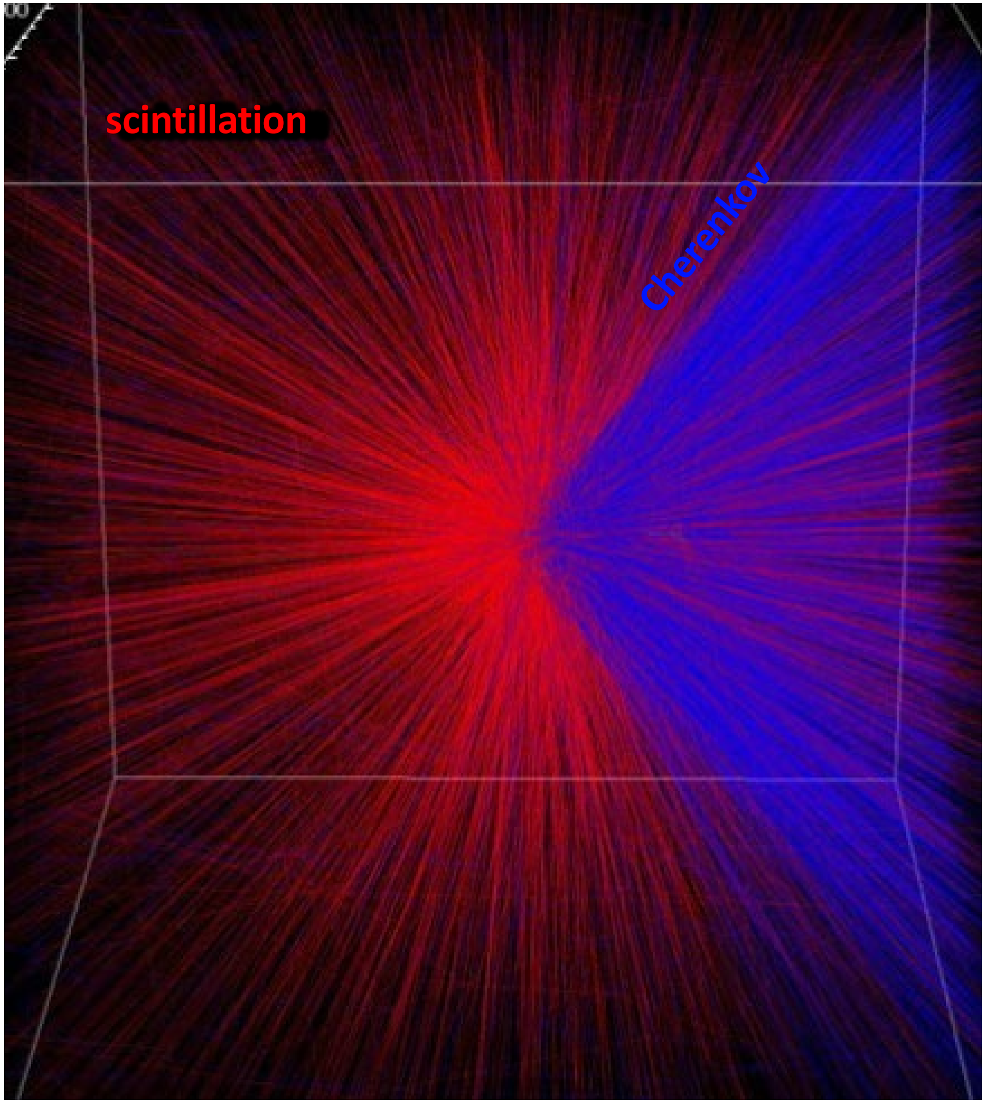
Proton decay
IMB
Kamiokande/Super-Kamiokande
IMB and Kamiokande are the detector of the first and so far only detection of Supernova neutrino → share of the 2002 Nobel prize to Kamiokande

Solar Neutrino
Kamiokande/Super-Kamiokande
SNO (Heavy Water)
Next frontier **Hyper-Kamiokande**

Accelerator Neutrinos
Kamiokande/Super-Kamiokande as far detectors of the K2K/T2K neutrino beams from the KEK Laboratory (Tokyo)

String underwater/under-ice detectors for UHE astrophysical neutrinos
AMANDA
ANTARES
Icecube
Baikal
KM3NET

2nd line - Hybrid Cherenkov-scintillation detection



MeV-GeV neutrino experiments use

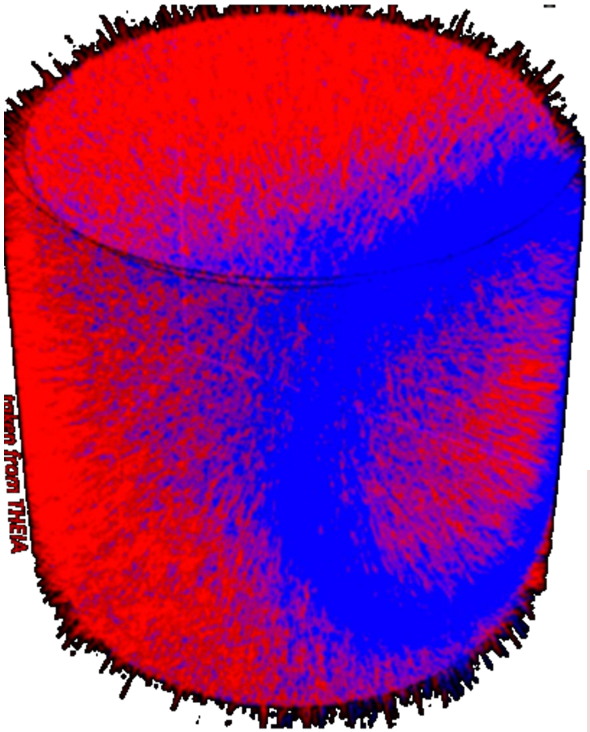
→ **Scintillation:** enables good energy resolution and low thresholds

→ **Cherenkov effect:** particularly useful for reconstruction of direction and (multiple) tracks

→ Cherenkov photons *are* produced in liquid scintillators (~5%), but the majority is scattered or absorbed before reaching PMTs

Idea: merge the characteristics of the two technique to exploit jointly their individual benefits

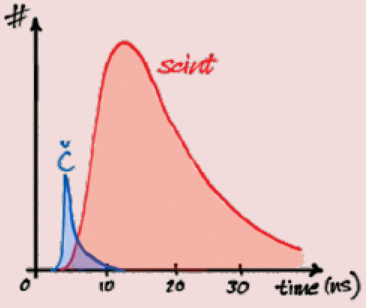
Separating the two components



→ **how to resolve the Cherenkov/scintillation signals?**

Timing

"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better

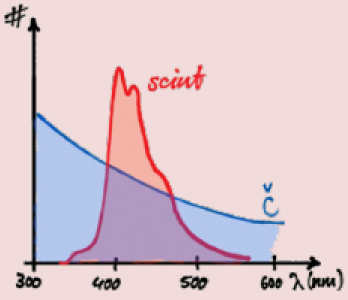


LAPPDs: ~60ps timing

Large Area Picosecond Photon Detectors

Spectrum

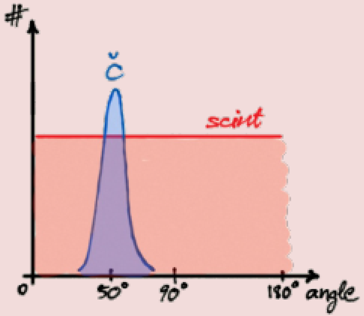
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Dichroic filters

Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Standard PMTs

How to boost the separation of the two components in a liquid scintillator

How to improve/extract the Cherenkov signal? With proper modifications of the scintillator recipes

Two approaches

→ enhance liquid transparency and get more balanced scintillation/Cherenkov production

Water Based Liquid Scintillators WbLS

→ slow down scintillation emission

Slow Scintillators

Both the two major developments for Cherenkov/scintillation (C/S) separation

Water-based liquid scintillators (WbLS)

Composition **WbLS**: water + surfactant + solvent (LAB preferred) + fluor (PPO)

Why the surfactant→mixing water and solvent “Organic solvents are immiscible in water mainly due to the differences in polarities. A surfactant that contains lypophilic and hydrophilic groups is required to emulsify the organic liquid scintillator into the water solvent.”
M. Yeh et al., “A New Water-based Liquid Scintillator and Potential Applications” Nucl. Inst. Meth. A 660 (2011) 51.

Such a development is the core of the ongoing research especially focused to ensure the long-term stability of the resulting scintillator

Proposal for an alternative of a module of the Dune experiment

Theia: Summary of physics program
M. Askins et al. arXiv:2202.12839

Alternative: slow scintillators

General idea

organic scintillators modified for slow(er) scintillation emission to improve the time distinction of the two components

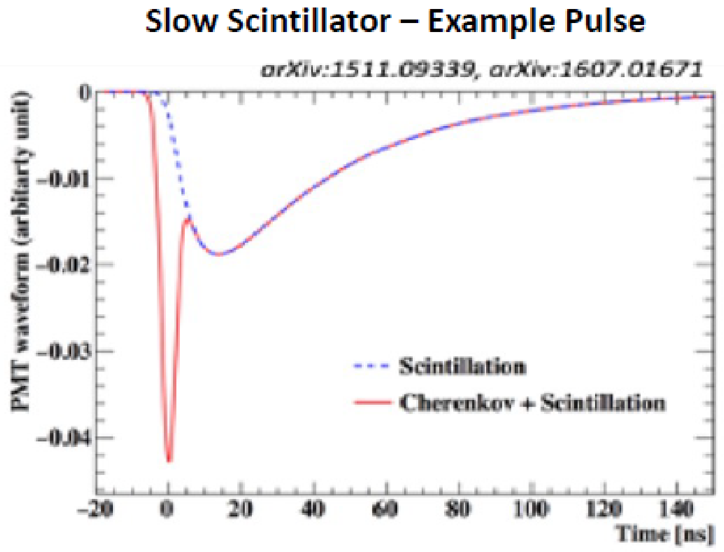
Options

- reduce primary fluor (i.e. PPO) content
  ➔ longer emission but lower light yield [Z. Guo et al., **arXiv:1708.07781**]
- slow fluors selected for long emission times,
  e.g. di-phenyl-antracene/hexatriene [Steve Biller et al., **arXiv:2001.10825**]
- use co-solvent to slow light transfer to fluor [Hans Steiger]

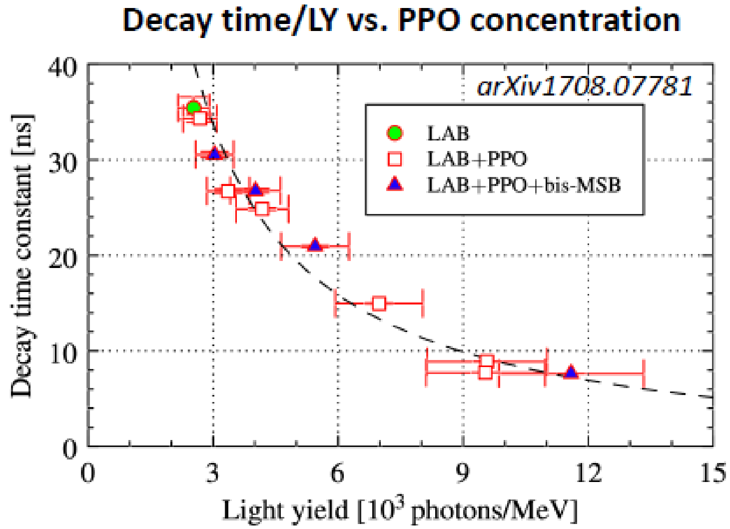
Consequences

- C/S separation can rely on regular PMTs
- high scintillation light yields can be maintained
- quality of vertex reconstruction (and with this indirectly C/S separation) suffers

➔ effects have to be balanced


Slow Scintillator – Example Pulse

arXiv:1511.09339, arXiv:1607.01671


Decay time/LY vs. PPO concentration

arXiv1708.07781

3rd line metal loading

Gadolinium is widespread employed for increased **neutron capture capability**
Dissolving the metal and obtaining a stable scintillator is the challenge → choice of a suitable ligand

- ✓ Wanda Beriguete et al. **arXiv:1402.6694** **“**Production of Gadolinium-loaded Liquid Scintillator for the Daya Bay Reactor Neutrino Experiment”

Isotopes for double beta decays specifically **tellurium: arXiv:2104.11687 “The SNO+ experiment”**

- ✓ **Same task as above dissolution and stability**

A recent Scintillator – Water Cherenkov synergy

→ **Gadolium in water to equip a Cherenkov detector with neutron detection capability**

arXiv:2209.07273 **“**Development of Ultra-pure Gadolinium Sulfate for the **Super-Kamiokande** Gadolinium Project” K. Hosokawa et al.

Suitable for application to the water veto of dark matter experiment

- ✓ **Projected WIMP Sensitivity of the XENONnT Dark Matter Experiment arXiv:2007.08796** E. Aprile et al.

Conclusions

Cherenkov and liquid scintillator techniques since the 50’s proved to be essential tools for the realization of a plurality of powerful, flexible and effective experiments

After several decades of successful application especially for neutrino and astroparticle physics, new technological avenues are being explored to equip the techniques with more feature and make them more performant for the next round of experiments

Aggressive and ambitious researches for safe materials, water-based scintillators, slow scintillators and effective metal loading are the developments expected to define and shape the field in the future

On these premises scintillator and Cerenkov methodologies will continue to play a fundamental role in the next research frontiers based on gigantic detectors (JUNO Hyper-Kamiokande) focused to study multiple neutrino sources of natural and artificial origin