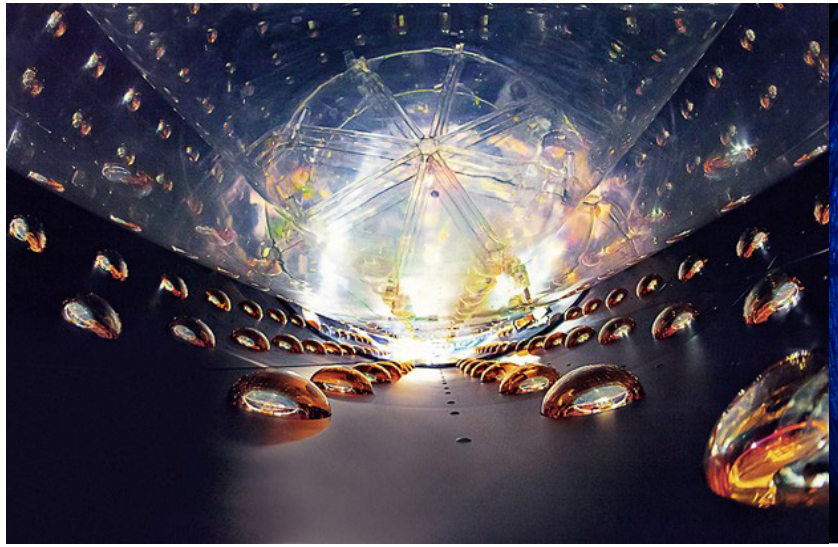
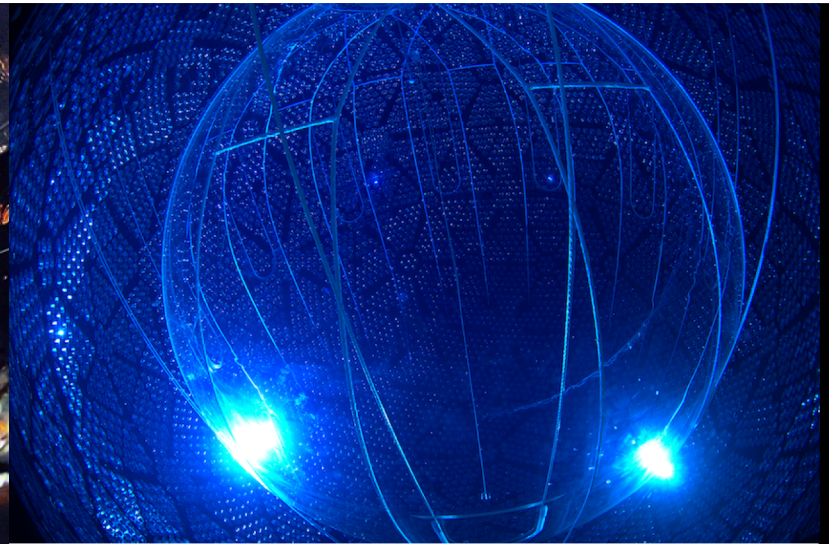
Development of Novel Methods for Isotope-doped Liquid Scintillators for 0νββ-Decay Searches

Hans Th. J. Steiger[1], Manuel Böhles[2], Marco Beretta[3] & Kilian Porth[1],

Lorenzo V. D'Auria[4], Alberto Garfagnini[4], Arsenii Gavrikov[4], Moritz Kolb[1], Johannes Kowalewicz[1], Paolo Lombardi[3], Kai Loo[5], Adil W. Muggo[1], Elena Pasini[4], Benedetta Rasera[4], Andrea Serafini[4], Konstantin Walter[1], and Michael Wurm[2]

[1]Technical University of Munich (TUM) Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany
[2]Institute for Physics, Johannes Gutenberg University Mainz, Mainz, Germany
[3]INFN, Sezione di Milano e Università degli Studi di Milano, Dipartimento di Fisica, Italy
[4]Dipartimento di Fisica e Astronomia dell'Universita di Padova and INFN Sezione di Padova, Padova, Italy
[5]University of Jyväskylä, Department of Physics, Jyväskylä, Finland

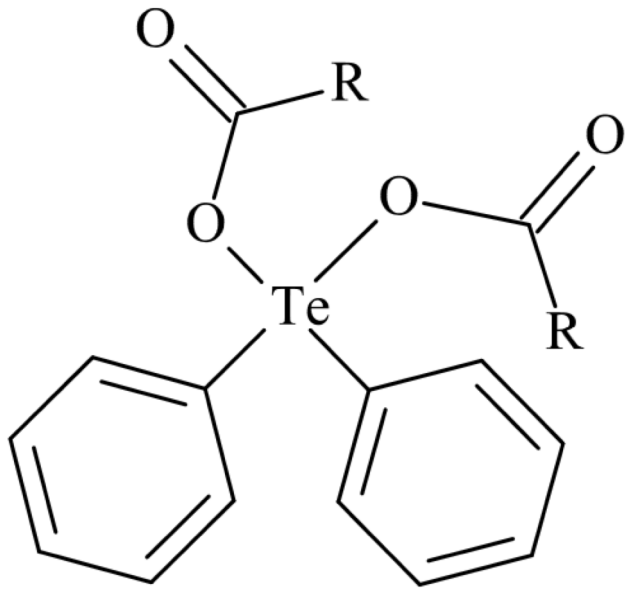




Tellurium Doping of Slow LS Cocktails using Diphenyltellurium Dicarboxylates

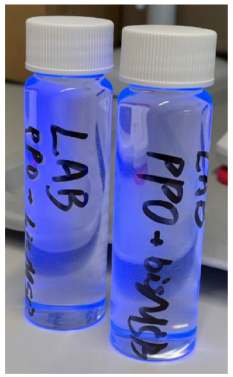
Ideal Dopant:

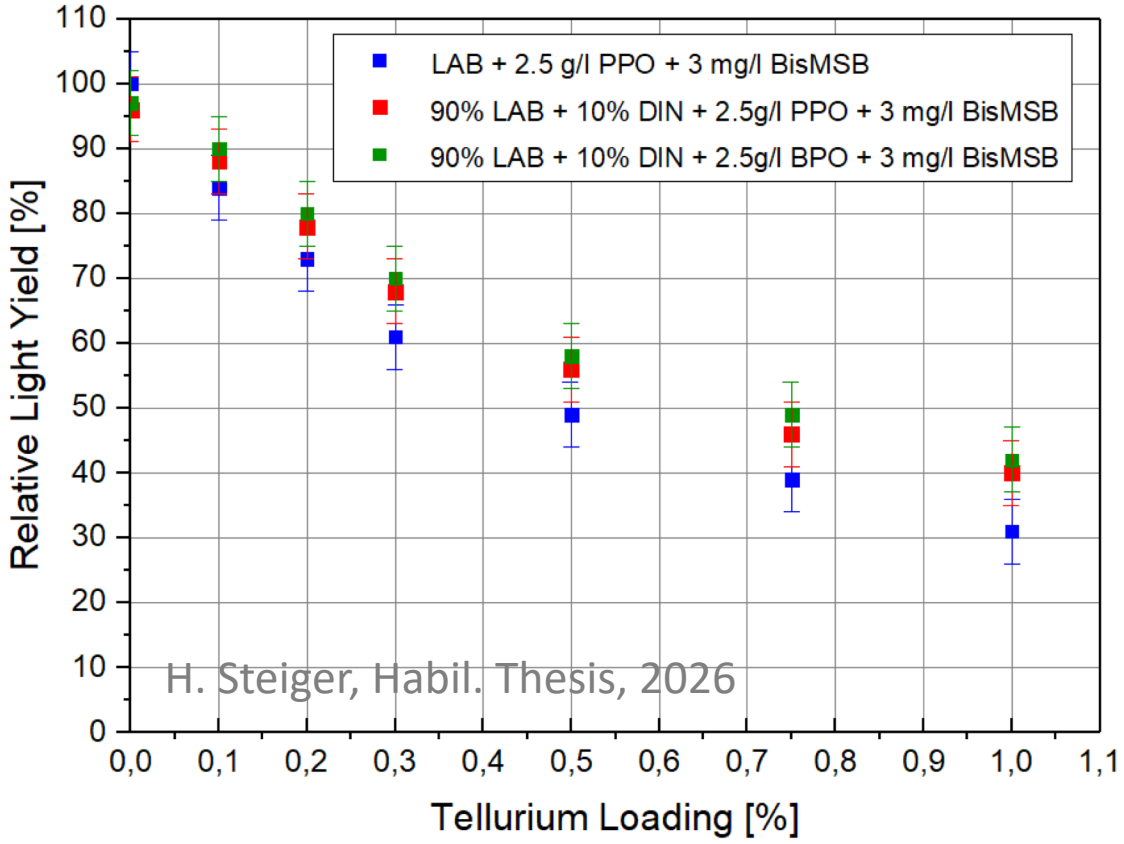
- **high solubility in LAB**
- individual compound
- solid material (powder)
- **no absorption bands in the emission region of the LS**
- **chemical stability** against humidity, oxygen + material compatibility
- low toxicity
- high flashpoint

Loading via the method of **I.A. Suslov et al., NIM-A, 1040 (2022) 167131**



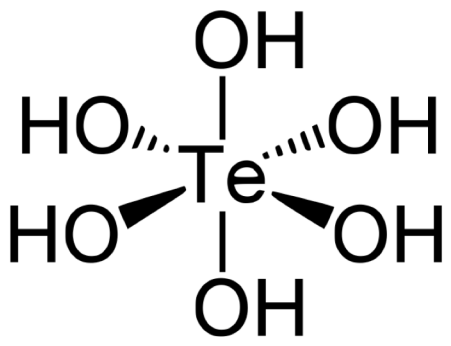
Diphenyltellurium dicarboxylates:
(a) dipivalate
(b) diisovalerate
(c) di-2-ethylhexanoate



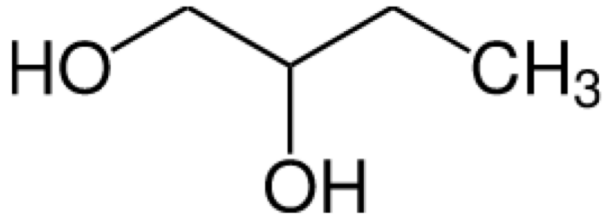


- Loading up to 0.2% by mass Tellurium do not harm the LY too much
- Nearly no visible influence on LS transparency (in UV/Vis measurement)
- Admixtures of DIN: reduce light-loss by Te-dopant a lot!
- BPO instead of PPO: better LY (better energy transfer from DIN)
- Excellent stability over 1 year (see also Suslov et al., 2023)

Tellurium Doping of Slow LS Cocktails – A bit closer to SNO+

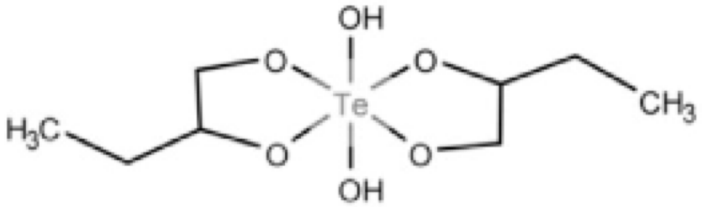


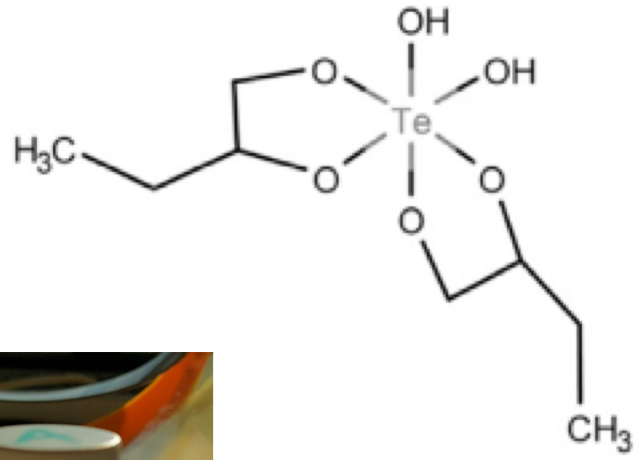
Telluric Acid (TeA)



1,2-Butanediol

Azeotropic Distillation
(Toluene, Benzene etc.)



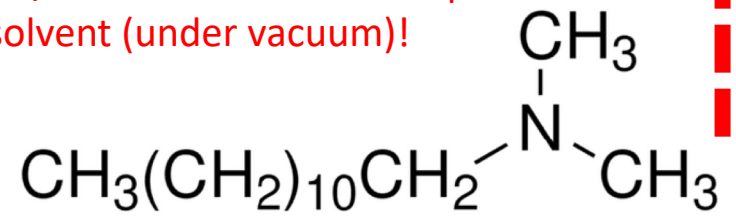


N_2 bubbling and mixing with toluene/benzene as an azeotropic solvent (under vacuum)!

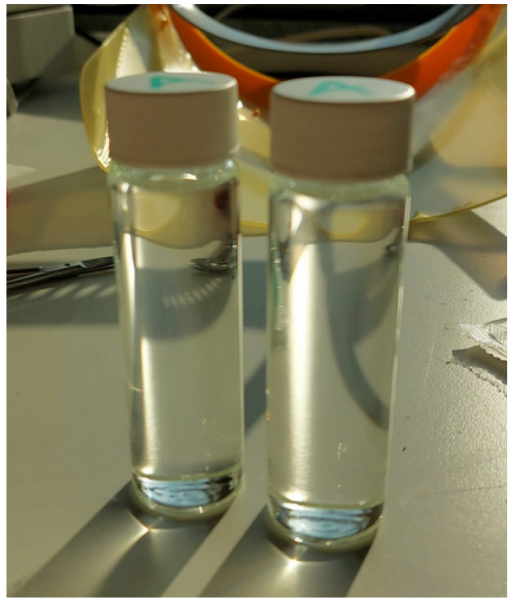
Neutralization of TeA



Weak acid – but solid at 20°C



N,N-Dimethyldodecylamin



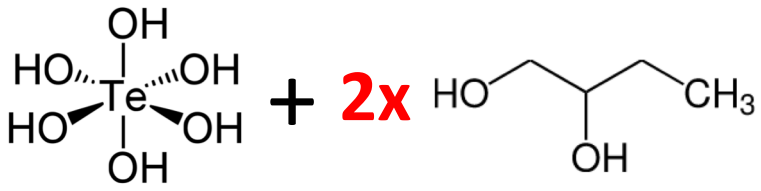
First samples: 1%$_m$ and 20%$_m$ Te-loading in LAB!

Two ways:

- Hot synthesis in aqeous solution
  → Oligomerization (SNO^+) + DDA
- Cold way via neutralization with amine (no water!)

Tellurium Doping: R&D (2024-2026)

A closer look to the chemistry:



Telluric Acid (TeA) 1,2-Butanediol

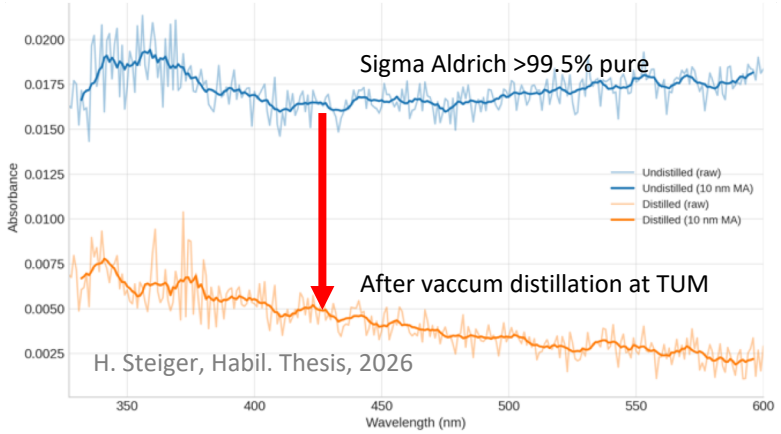
Catalysts: Amines (DDA)

Azeotropic Distillation at room-temperature!

→ Select solvents and pressure in a closed distillation facility accordingly!

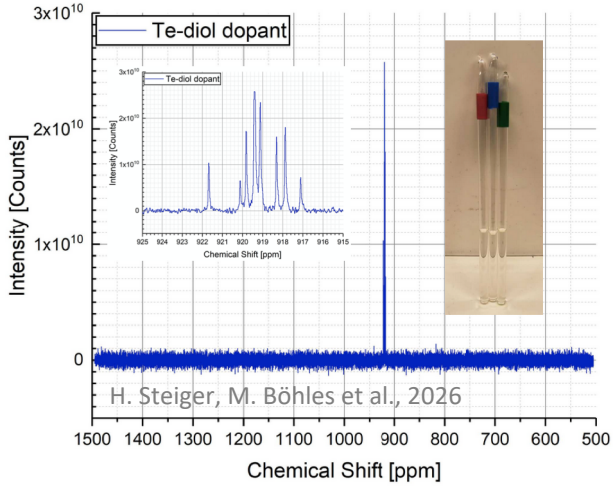
→ best solvents: MeOH, CHX, Benzene, Toluene

Purification of 1,2-Butanediol:



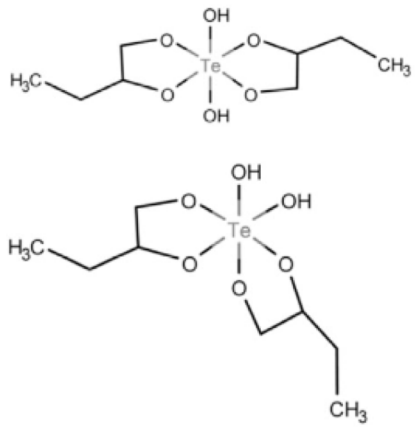
Slowest possible vacuum distillation at lowest possible temperature

NMR of the product (Te-Diols):



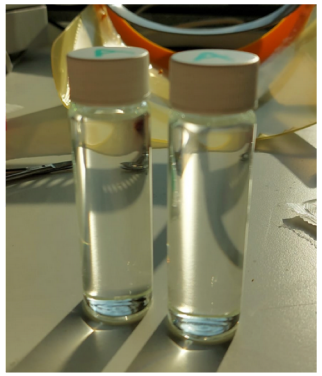
No lines of oligomers visible at all!

Product:



Publications:

1) H. Steiger et al., JINST 19 P09015 (2024).
2) H. Steiger et al., JINST 21 P09001(2026).

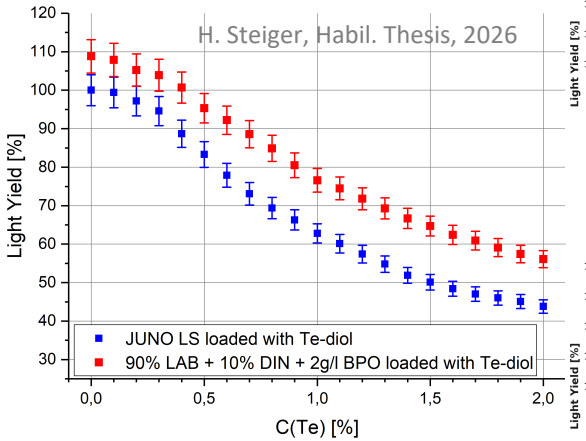


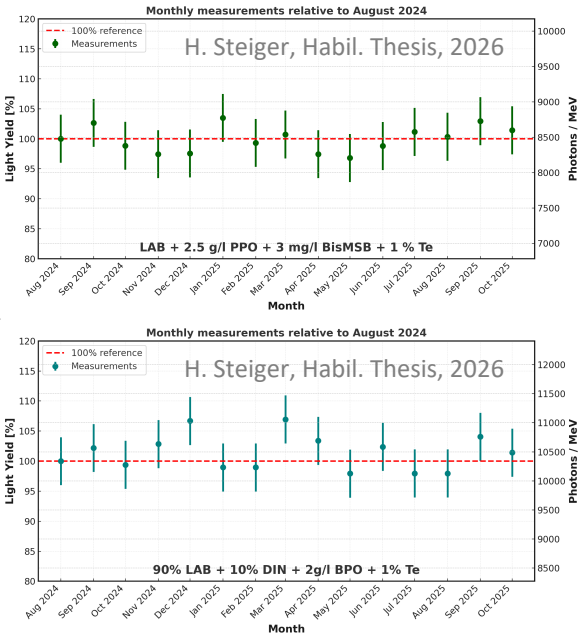
Those two molecules are the reaction product!

Rection >99.95% efficient!

Completely free of oligomer production (see NMR and MS)

Light Yield of doped JUNO-LS and a slower alternative:

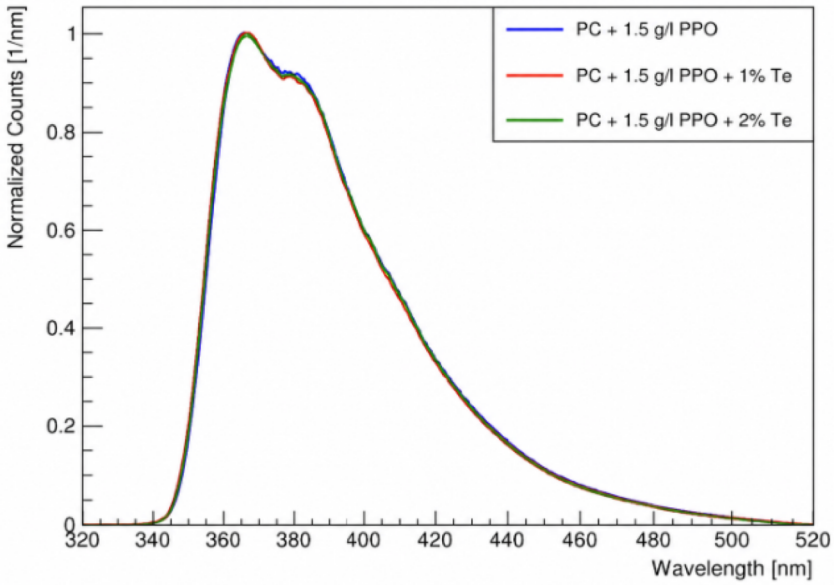




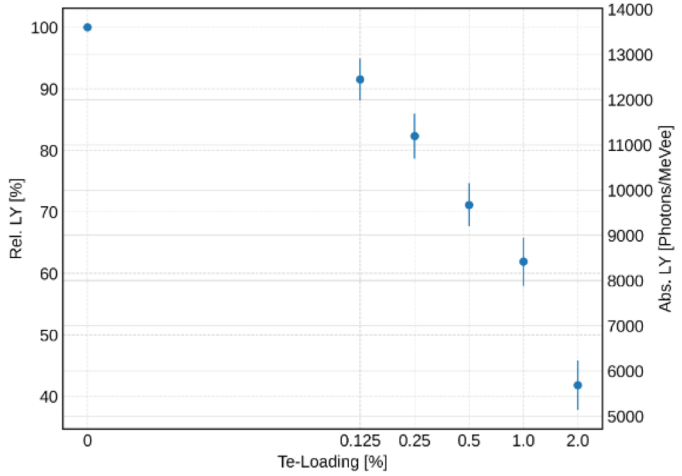
Samples: 1%$_m$ and 20%$_m$

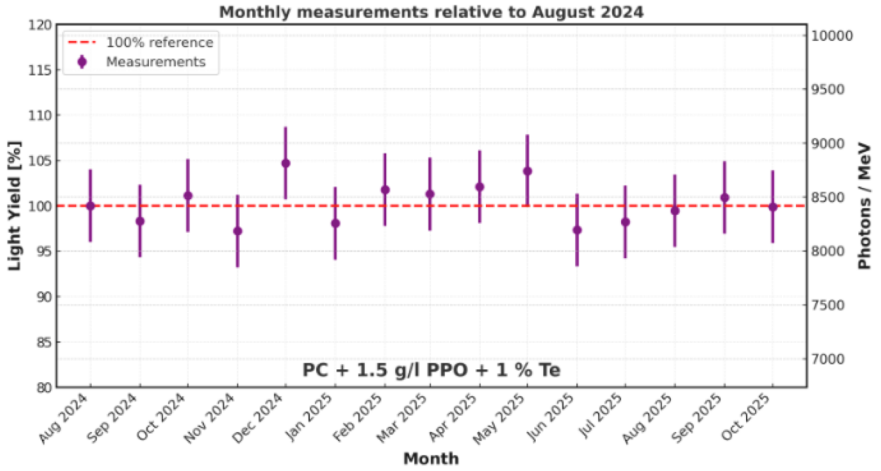
Te-loading in LAB!

Tellurium Doping of the Borexino Detector Liquid (2025/2026)

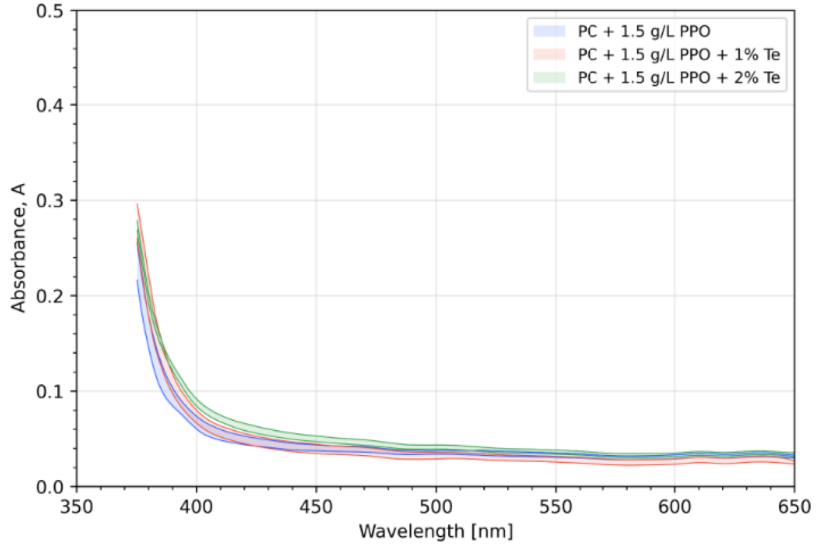


Emission Spectrum unchanged up to 2% Te!

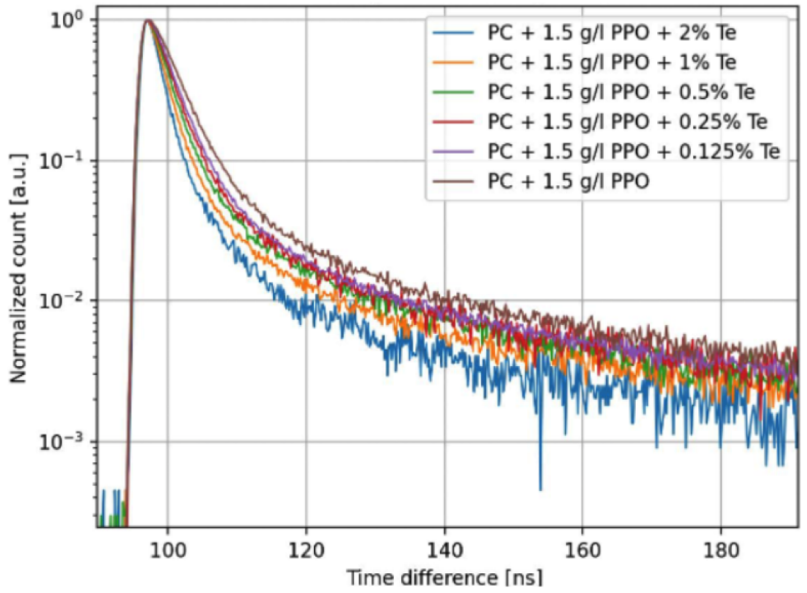




Te-Loading	0%	0.125%	0.25%	0.5%	1.0%	2.0%
Rel. LY [%]	100	91.5 ± 3.42	82.3 ± 3.63	71.1 ± 3.50	61.9 ± 3.95	41.8 ± 4.01
Estimated Abs. LY [Photons/MeV$_{ee}$]	13600	12444 ± 466	11193 ± 494	9670 ± 476	8418 ± 538	5685 ± 546



Nearly no transparency loss!



Successful Synthesis:
Water-free, room-temperature method for loading Te-diols into a pseudocumene-based LS.

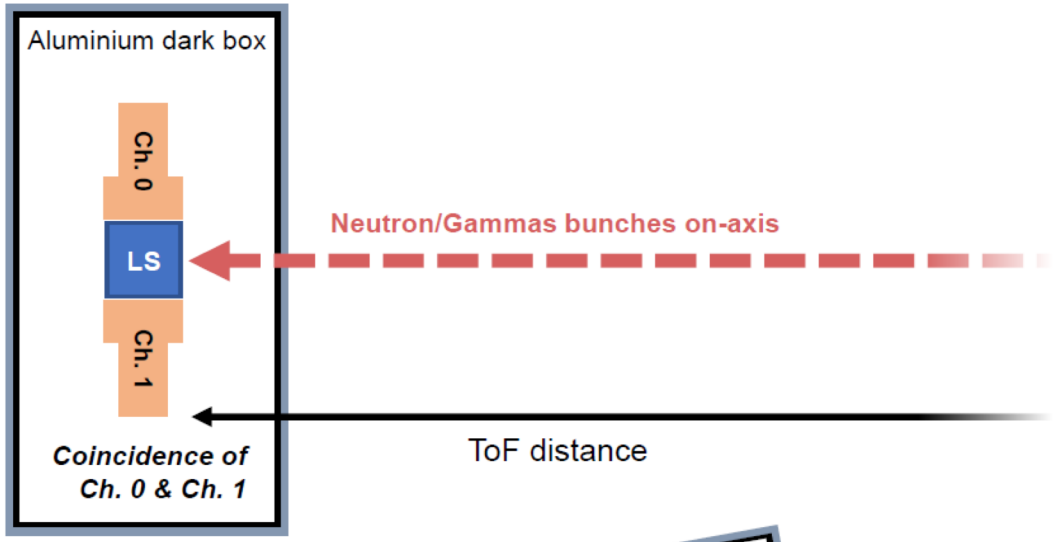
Performance:
The PC/PPO system retains high optical transparency and a stable PPO-dominated emission spectrum.

Detector Readiness:
Despite expected quenching, the system retains a robust light yield (~8400 photons/MeV$_{ee}$ at 1%) and excellent long-term stability, highly suitable for future $0\nu\beta\beta$ searches.

Publication: H. Steiger et al., JINST 21 P09001(2026).

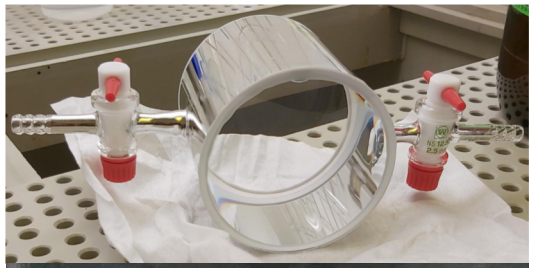
Pulse Shape Discrimination and p-QF Study at the INFN-LNL

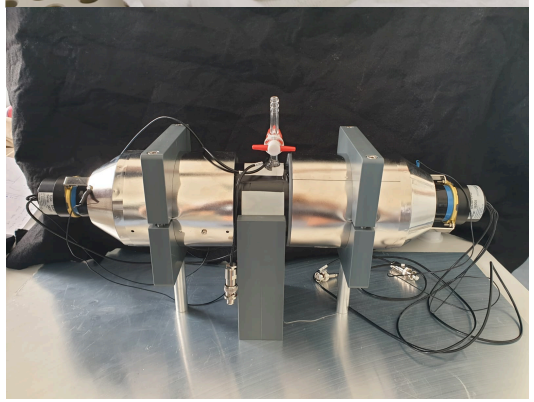
We simultaneously operate two experiments.

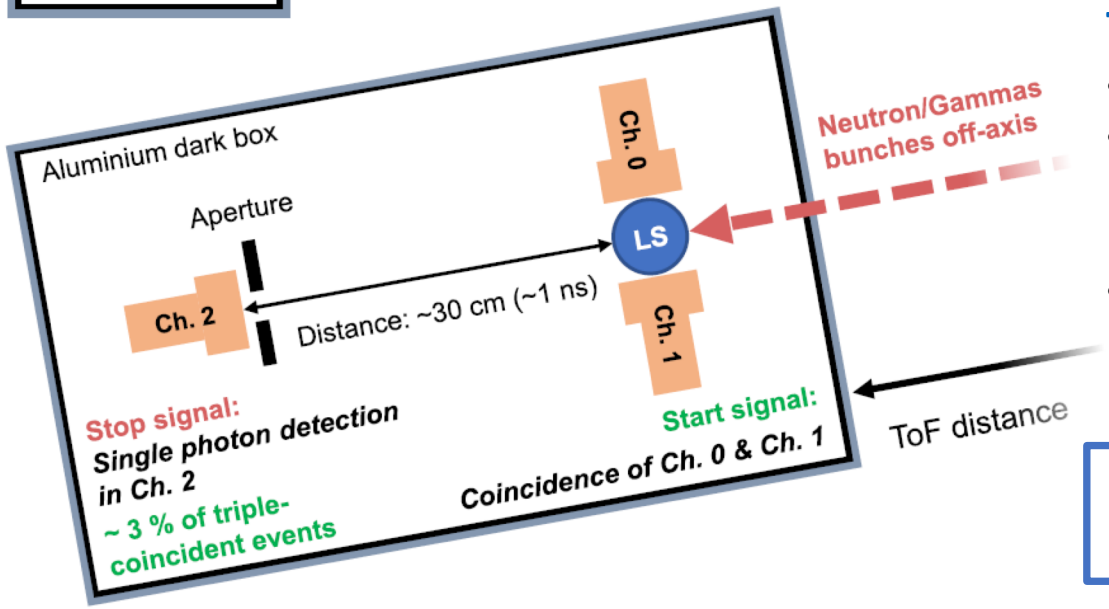


Quenching Factor (QF) experiment

- positioned directly on the beam axis
- detector placed in its own dark box
- target vessel contains ~400 cm^3 of LS
- optimized for low energy threshold with an efficient noise suppression:
  - coincidence of 2 PMTs with the beam trigger
  - vessel walls with highly reflective aluminum mirrors (BX-CTF)

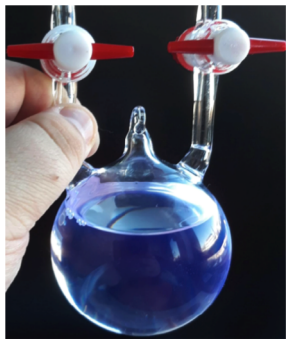






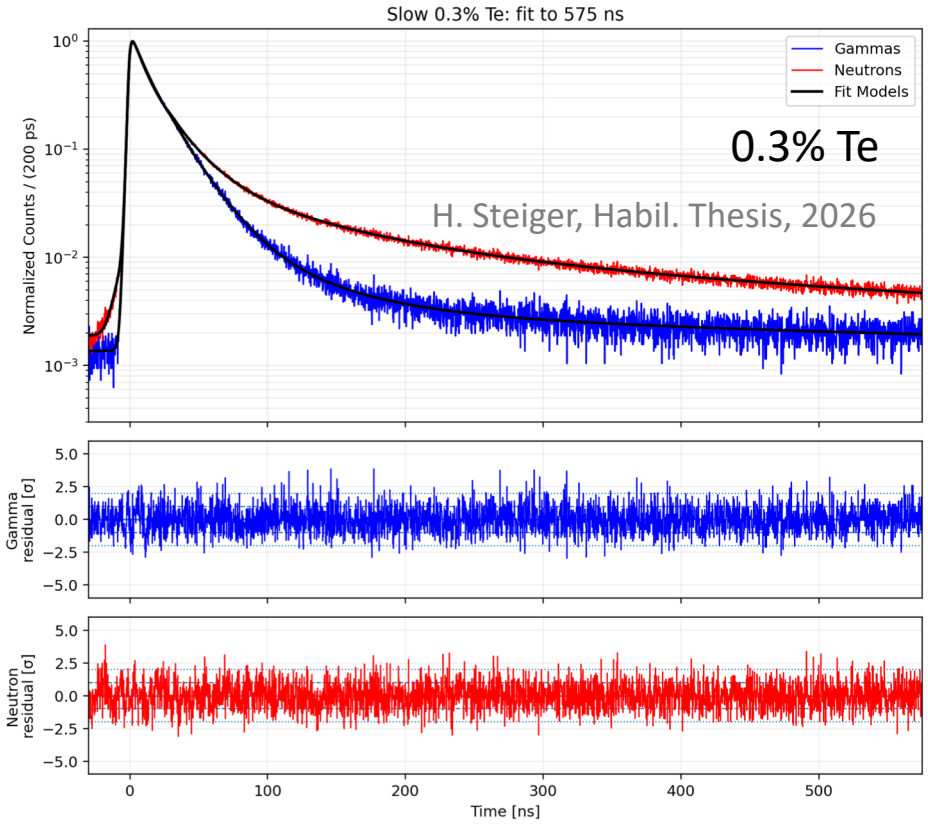
Time Profile Experiment

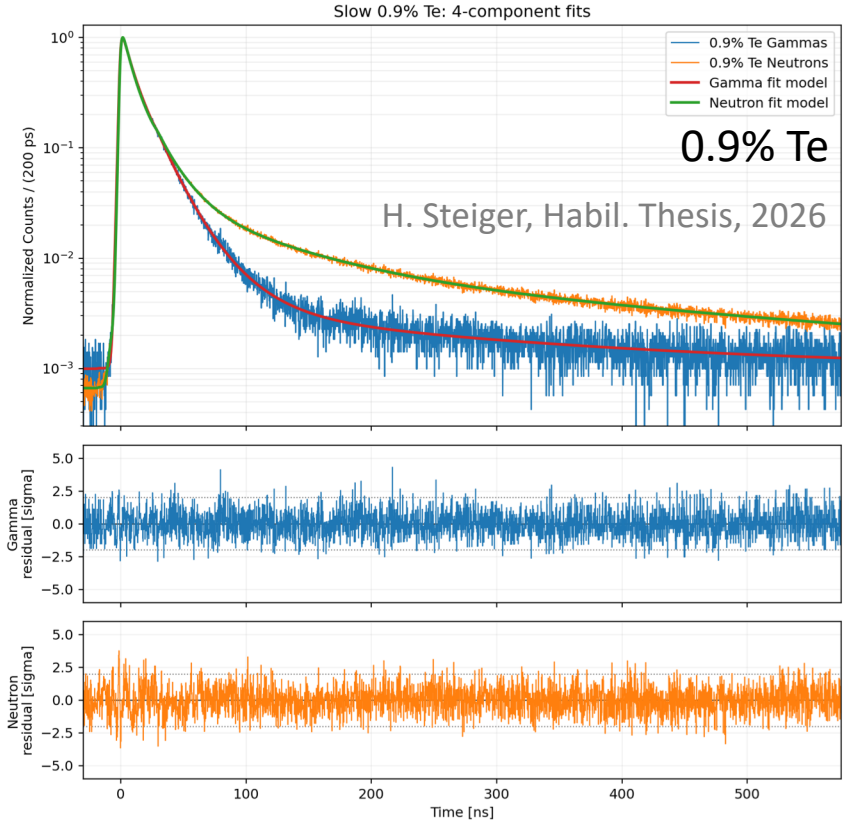
- Setup is placed in its own dark box.
- The vessel containing ~180 cm^3 LS is placed between two photomultiplier tubes (PMTs)
  - provide the start signal of the time measurement.
- third PMT is placed in a certain distance to ensure the detection of only a single photon from each event!
  - provides the stop signal.

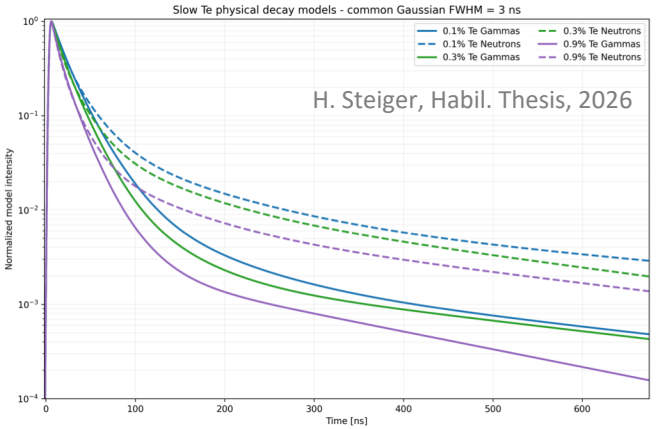


In both experiments we distinguish neutron interactions from beam correlated gammas by time-of-flight (ToF) measurements!

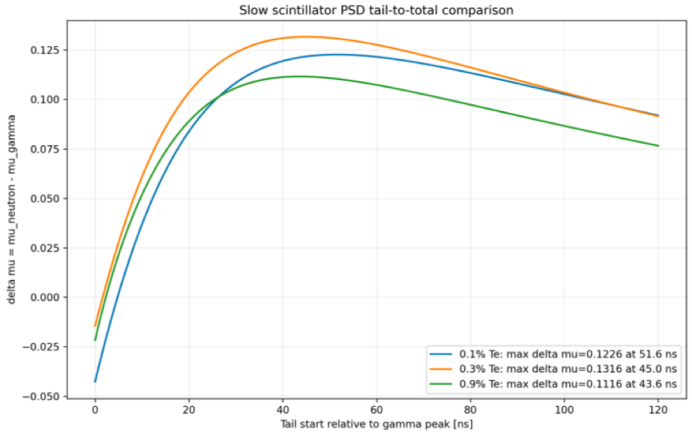
Pulse Shape Discrimination in Slow TeLS



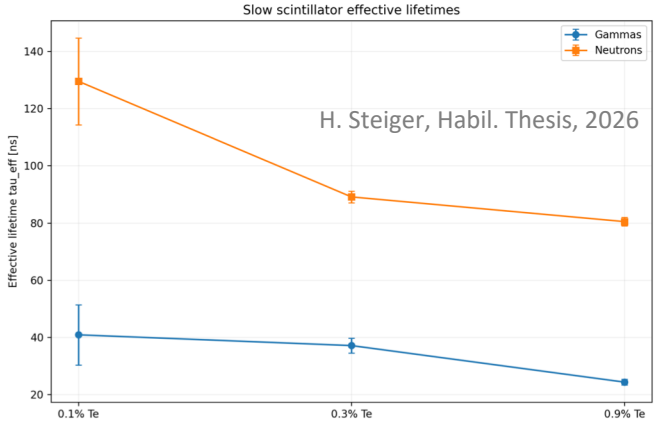




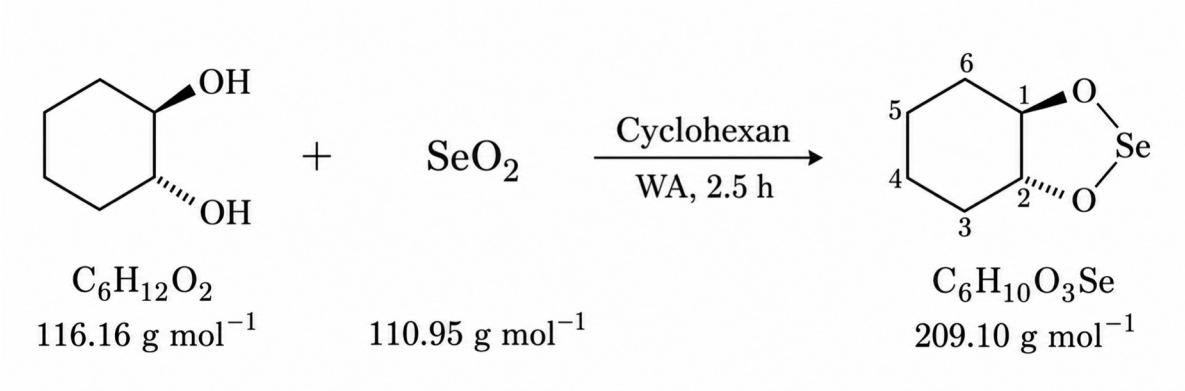
Note:
While conventional scintillators like JUNO or Borexino LS are getting much faster with high-loading, the speed increase in Bi-Solvent Slow LS is drastically weaker!



PSD: stays supperior to conventional LAB-based scintillators (like the undoped JUNO-mixture) despite doping a slow cocktail up to 0.9% Te!

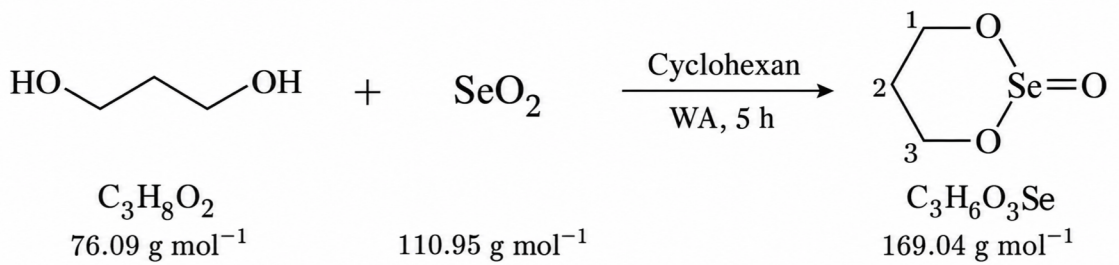


Selenum – An Alternative Element – Chemistry R&D



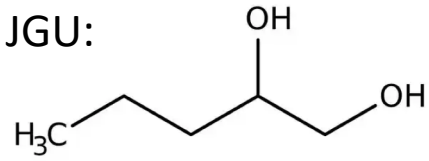
H. Steiger, Habil. Thesis, 2026

Alternative compounds under investigation @ TUM & JGU



Propane-1,3-diol

Alternative diols under investigation @ JGU:
1,2-Pentanediol





- First Sample: 1:1 Mixture of Selenum in CHX
- Current work: Building a small reactor in the lab
- NMR + ESI @ Bavarian NMR Center (BNMRZ)

Master Thesis @ Chair for Inorganic Chemistry (LMU) synthesized most of the compounds back in 2008:
Reichvilser, M. M. Cyclische Selenite von Kohlenhydraten. Master's Thesis, Ludwig Maximilian University of Munich, Munich, Germany, 2008.

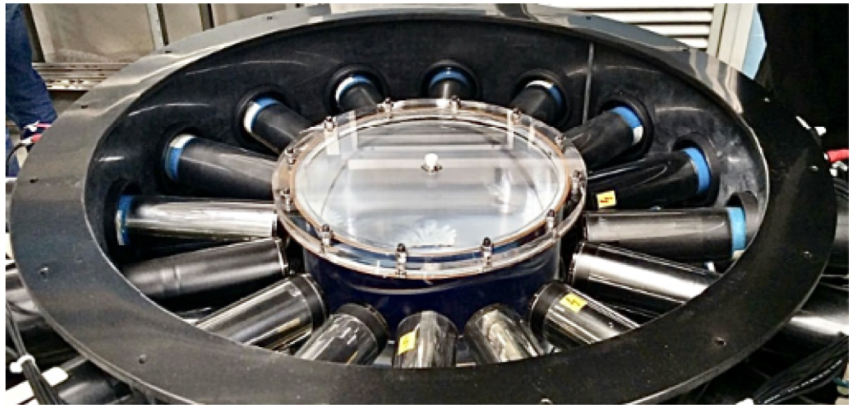


Collaboration Established:
Prof. Dr. Peter Klüfers
Chair for Inorganic Chemistry
Bioinorganic Chemistry and Coordination Chemistry
Ludwig Maximilians Universität München

Some Impressions: A strong R&D Collaboration was established!



Testbeam Team at the INFN-LNL
(TUM, Uni Padova, JGU Mainz)



Larger Detector of the Uni Padova:
A lot of beamtime is provided by the INFN-LNL CN and Tandem XTU + ALPI



Isotope Loading Team:
TUM, INFN-Milano & JGU Mainz
(Sept. 2026)

Close Collaboration with the
Bavarian NMR Center (BNMRZ)!





Bayerisches NMR Zentrum

Dr. Mihail Mondshki:
Chemist at JGU Mainz
→ Performs chemical analysis!
→ Mass Spectrometry, NMR Spectroscopy



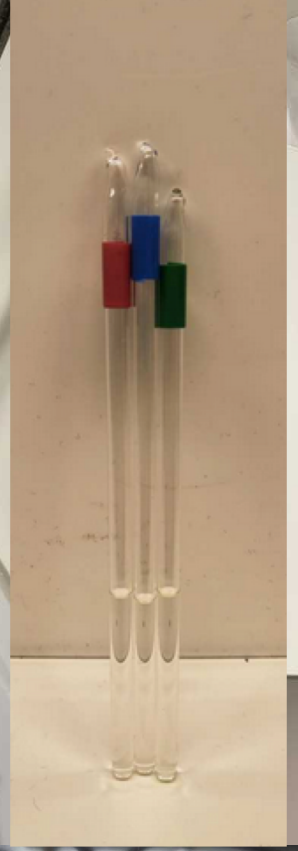
The TUM Hybrid Detector Team

Thank you for your attention

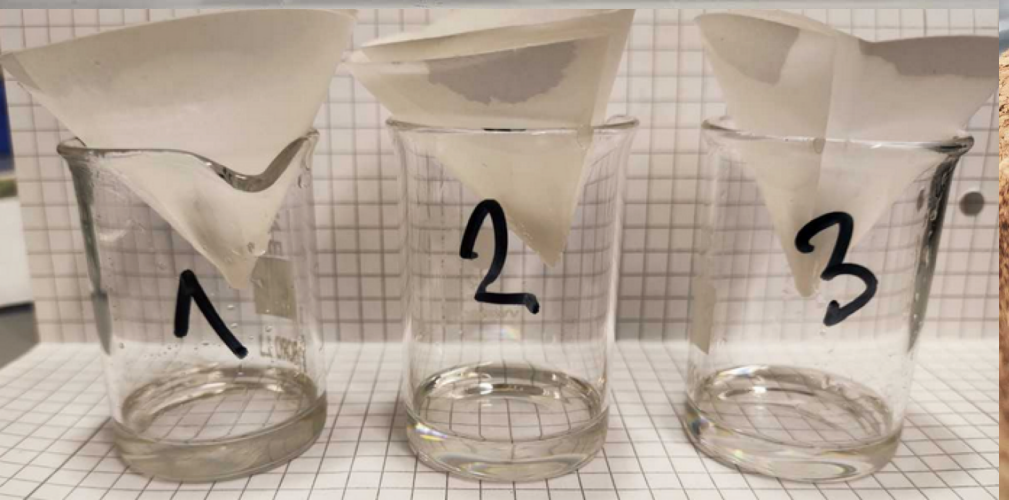
R&D on Advanced Liquid Scintillators at Mainz, TUM, Padova, Perugia and INFN Milano

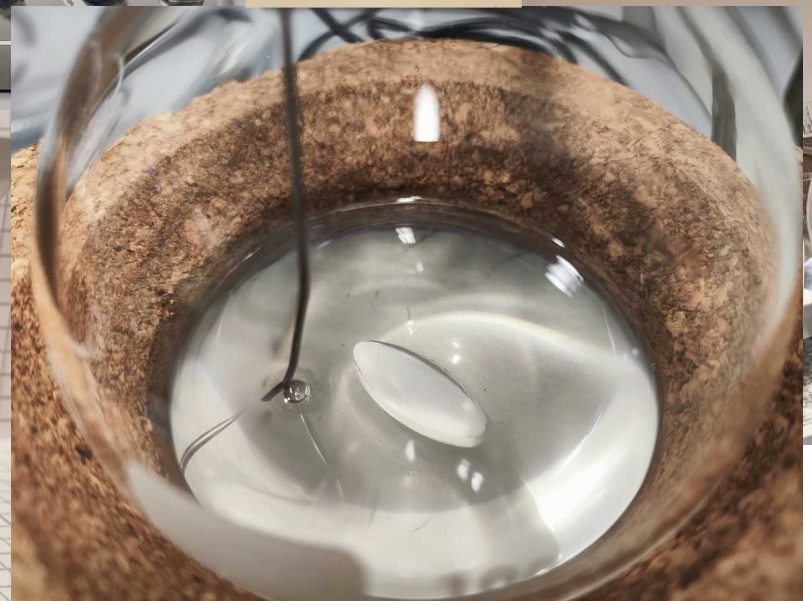












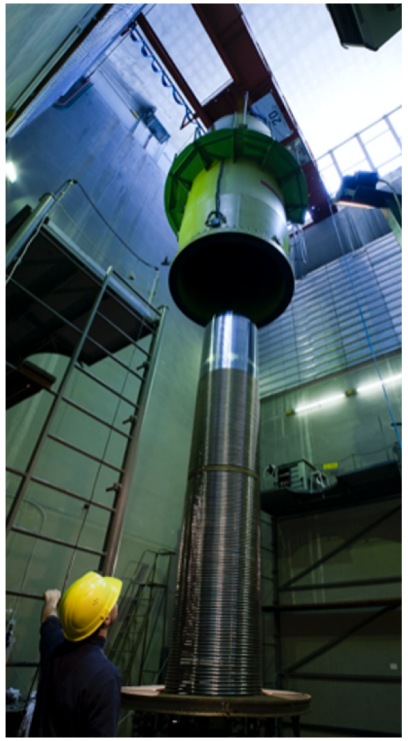
QUESTIONS?

The CN Van de Graaff Particle Accelerator of the INFN-LNL as source of quasi-monoenergetic neutrons

INFN Istituto Nazionale di Fisica Nucleare — Laboratori Nazionali di Legnaro



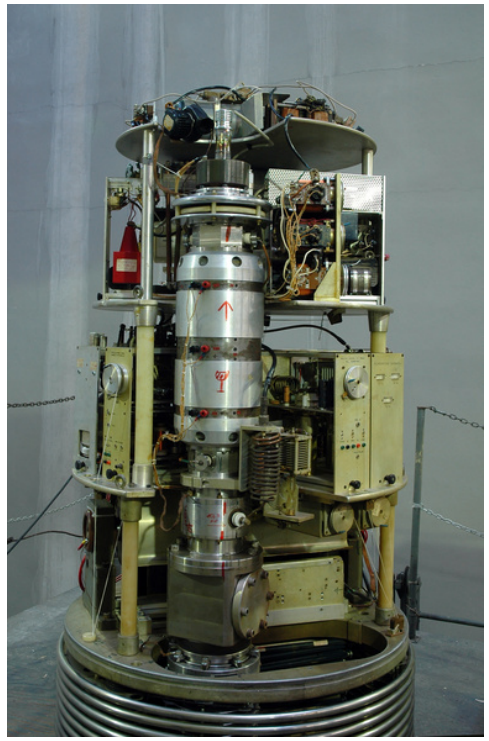
Aerial view of the LNL with the tower of the CN accelerator



The CN HV Column



CN in operation
(closed pressure vessel)



Ion source and buncher

Proton beam with energies from 3.5 - 5.5 MeV.
(0.8-3 MV requires shorting parts of the accelerating column)

Energy stability: 2-3 keV

Currents: continous up to 3 uA, pulsed: 1 uA at 3 MHz

Pulse width: < 1ns

$$^{7}Li + p \rightarrow {}^{7}Be + n$$

Nuclear reaction for quasi-monoenergetic neutron production
(Reaction Threshold: 1877 keV)