UPDATE ON ANTINEUTRINO-BASED SAFEGUARD APPROACHES FOR SPENT NUCLEAR FUEL

Yan-Jie Schnellbach
schnellbach@nvd.rwth-aachen.de

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Nuclear Verification and Disarmament
III. Physikalisches Institut B
RWTH AACHEN UNIVERSITY

*Nuclear Technology Review 2021, GC(65)/INF/2, IAEA Report, https://www.iaea.org/sites/default/files/gc/gc65-inf2.pdf

INTRODUCTION: SPENT NUCLEAR FUEL

- Spent Nuclear Fuel (SNF) produced in every reactor
  - Total stored SNF estimated to be ~300,000 t HM*
  - Yearly accumulation of SNF: ~7,000 t*
  - This does not include SNF going to reprocessing
- SNF is discharged from current reactor types regularly (12-24 months between refuellings)
- SNF is then transferred into spent fuel ponds for several years before going to intermediate storage in casks or reprocessing

Spent nuclear fuel stored underwater and uncapped at the Hanford site
https://www.hanford.gov/c.cfm/photogallery/gal.cfm/SNF/2#

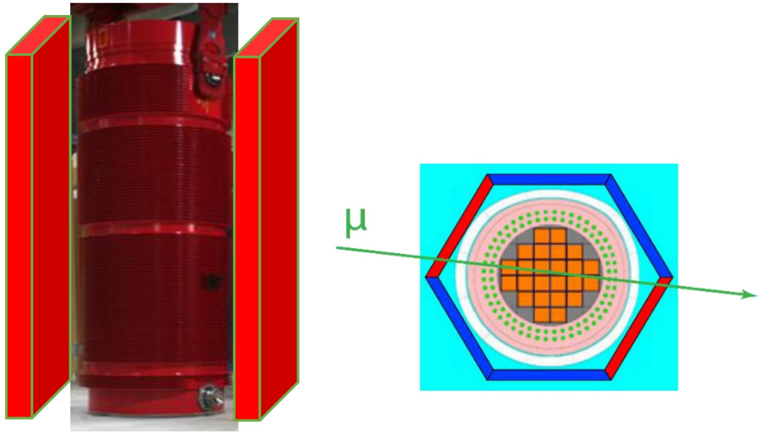
COMPOSITION OF SNF

- Typically consists of
  - Uranium (93-96%, mostly 238U, but also <0.8% 235U)
  - Fission products (3-5%, e.g. 90Sr, 137I etc)
  - Pu (~1% 239Pu, 240Pu)
  - Minor actinides (<1%)
- Small proportion, but significant given total amount of SNF
  - Definition of "significant material" 8 kg of 239Pu
  - Some of it returns to fuel cycle via reprocessing
  - Majority ends up in SNF storage – also relevant to safeguards

TOOLS FOR SAFEGUARDING SNF REPOSITORIES

- Surveillance and monitoring
  - Video surveillance
  - Inspection and seals
- Under development
  - Muon tomography
  - Improved surveillance ("laser curtains")
- All of these are valuable tools but are used complementary
  - Direct monitoring or verification difficult due to heavy shielding of casks

ZWILAG Zwischenlager Würenlingen AG



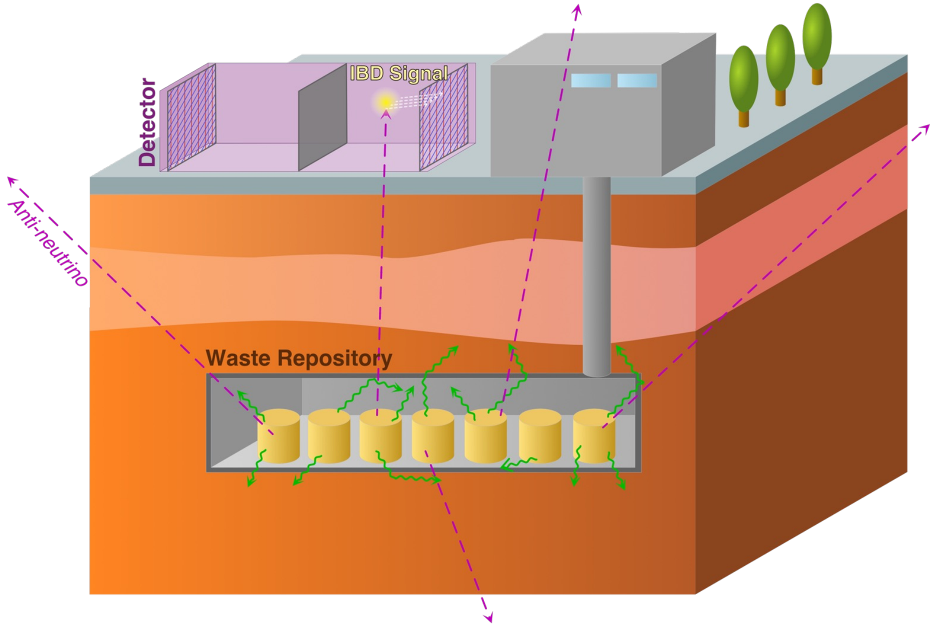
D. Ancius et al., Muon tomography for dual purpose casks (MUTOMCA) project. Proceedings of the INMM & ESARDA Meeting 2021.

ANTINEUTRINOS AS SAFEGUARDS

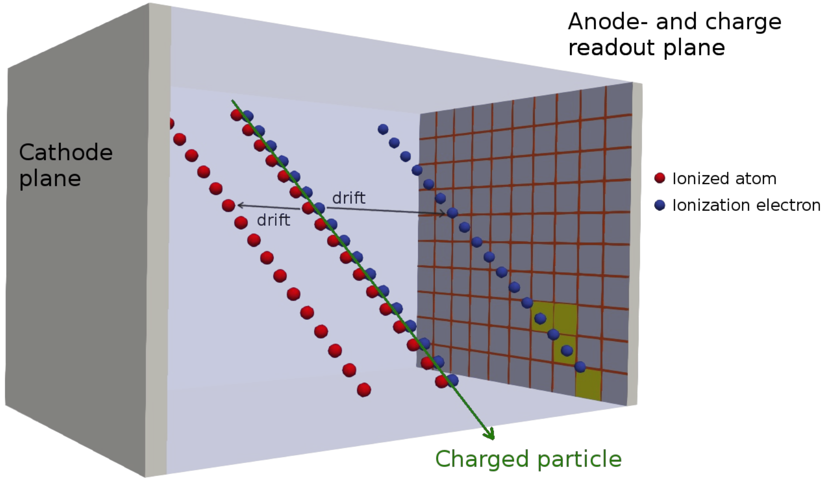
- Natural extension of reactor safeguards
  - Active reactors produce large amounts of antineutrinos
  - Fission products beta-decay in lower but still significant numbers for decades to centuries

- Antineutrinos cannot be shielded – especially important for repositories (safety for large quantities requires very good shielding)

- Potential complementary safeguards channel to expand the “toolkit”

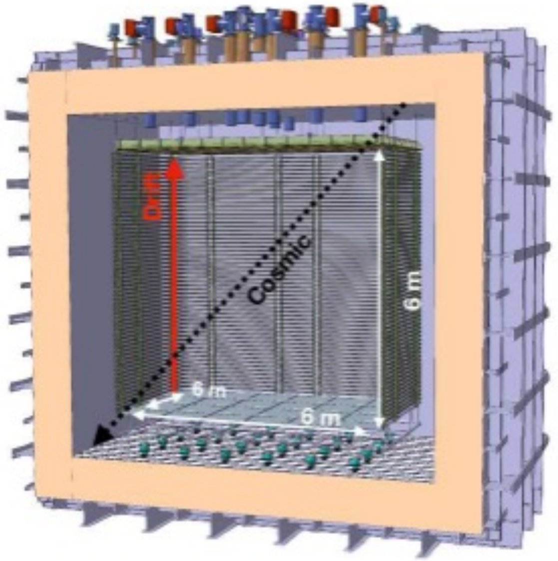


PREVIOUS STUDY AT RWTH AACHEN UNIVERSITY: LIQUID ARGON TPC



- Using Liquid Argon Time Projection Chamber (TPC) for antineutrino detection
  - Understood technology (proposed ‘77, used in several experiments)
  - Scalability core feature (10s of tons of target material possible)
  - High resolution read-out of events – detection of all final state particles

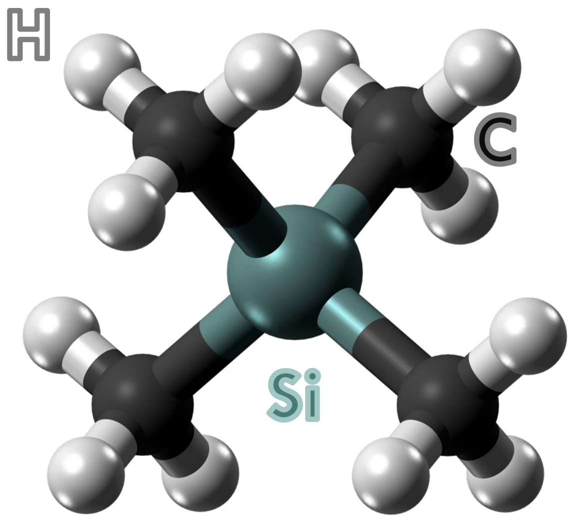
- Main downside
  - High energy threshold (multiple MeV) for many useful interaction channels, low cross-section for low-energy interactions (e.g. elastic scattering)



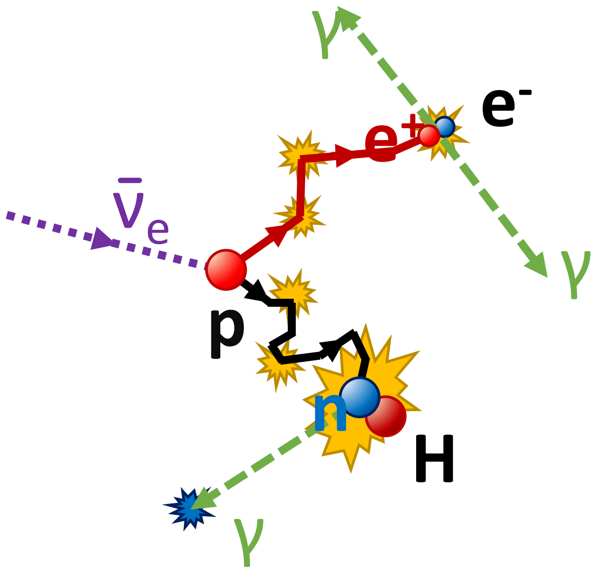
ProtoDune Module

DUNE Collaboration, „Status of ProtoDUNE Dual Phase“. IOP Conf. Series: Jour. Of Phys.: Conf Series 1312 (2019).

NEW CONCEPT: LIQUID ORGANIC TPC

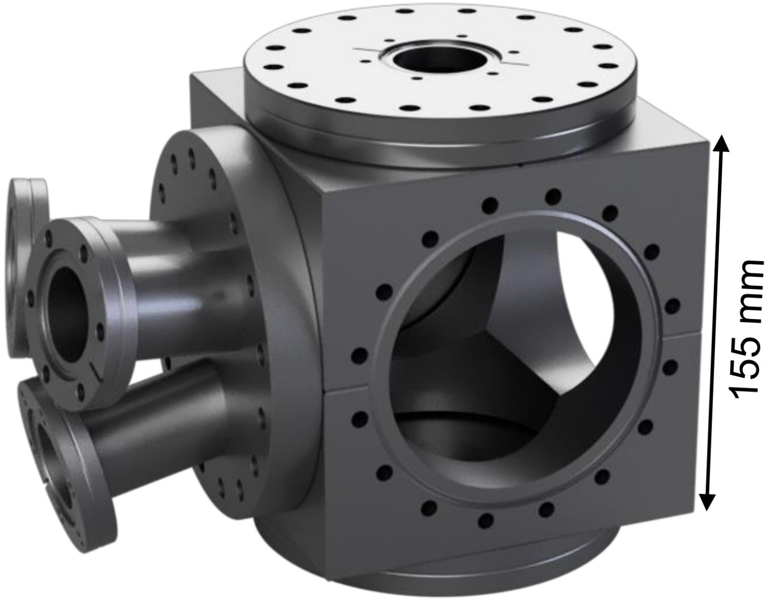


- LAr-TPC concept evolved into LOr-TPC concept
  - Replace liquid argon with an organic liquid
  - Same principle of operation, same advantages (scalability, reconstruction)
  - Organic liquids are generally hydrocarbons: contain semi-free hydrogen as interaction target
- This enables "classic" inverse beta-decay (IBD) detection
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Double coincidence signal for background rejection
  - Positron carries energy information, neutron direction information
- Medium under investigation
  - Tetramethylsilane (TMS): $Si(CH_3)_4$
  - Basic feasibility investigated by S. Wu *et al.* at Stanford https://arxiv.org/abs/1911.12887

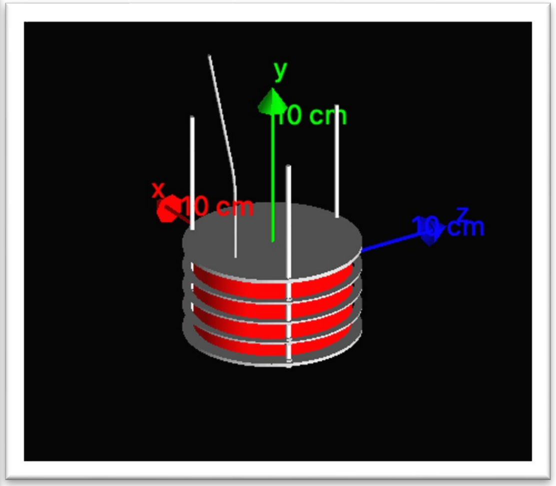


CURRENT TMS PROTOTYPE EFFORTS

- Construction of a small scale prototype for testing TMS properties is underway
  - Test of purification system
  - Test of drift properties with sources (gamma & neutron sources)
- Simulation studies done in parallel
  - Prototype studies will inform simulation to better model TMS behaviour
  - Improve prediction for a large scale system capable of observing antineutrinos



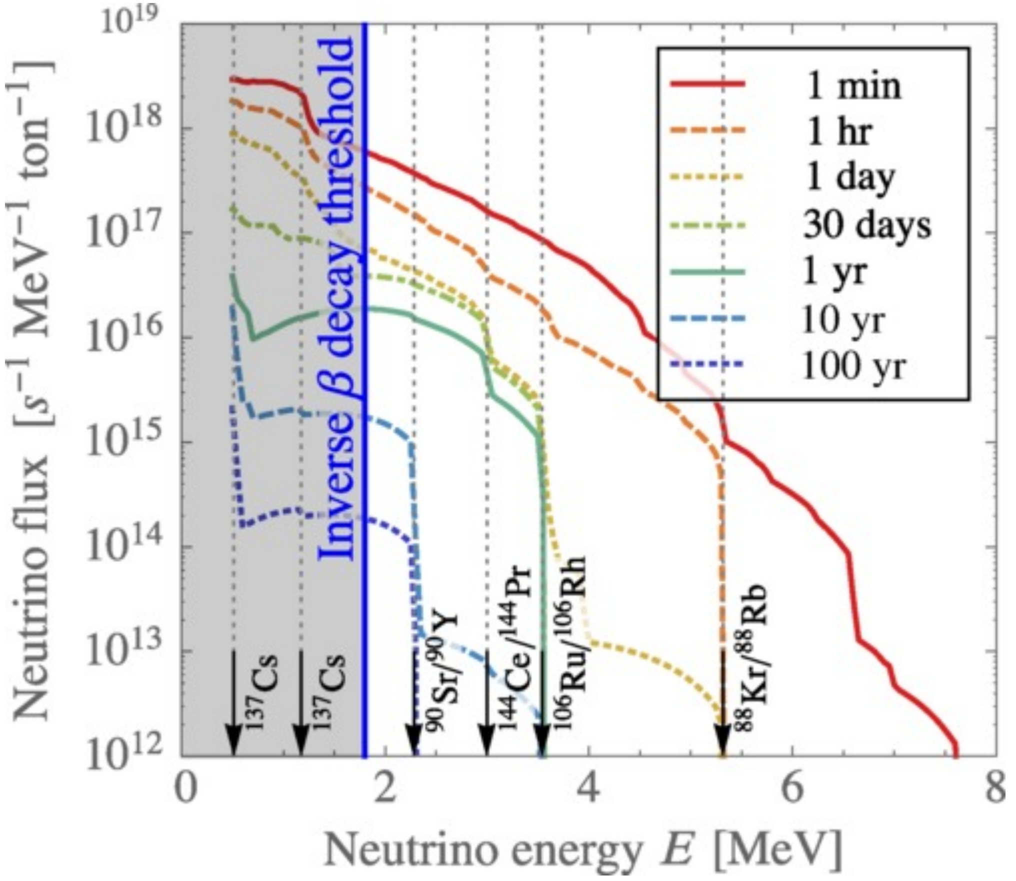
DN100CF Cube



Brdar, V. and Huber, P. and Kopp, J., "Antineutrino Monitoring of Spent Nuclear Fuel",
Phys. Rev. Applied, vol. 8, issue 5, pg 054050 (2017).
DOI: https://doi.org/10.1103/PhysRevApplied.8.054050

SPECTRA FROM ANTINEUTRINOS IN SNF

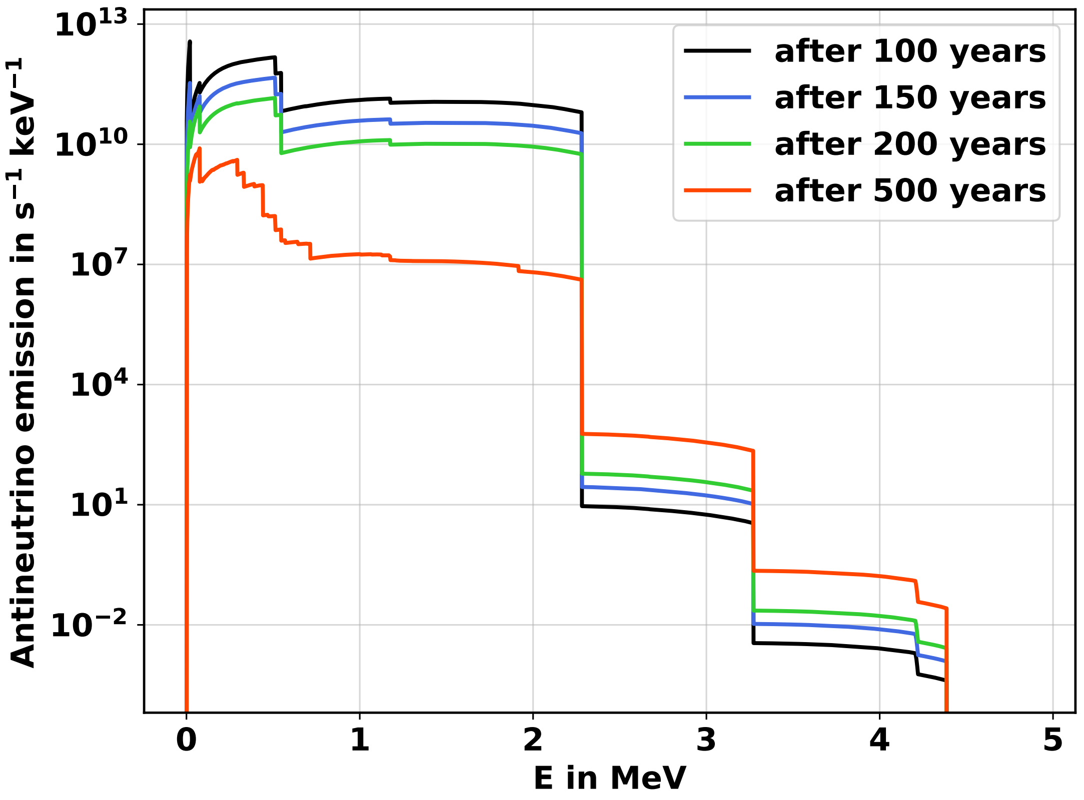
- Short-lived fission fragments produce higher energy antineutrinos
  - But decay quickly…
- Isotopes of interest are short-lived beta decays from isotopes in secular equilibrium with long-lived parent isotope
  - High energy antineutrino
  - Longer presence of isotope
- Case study by Brdar, Huber & Kopp in 2017



T. Radermacher, M. Göttsche, I. Niemeyer and S. Roth, "Antineutrino Monitoring for Safeguarding Spent Nuclear Fuel". Submitted Paper for IAEA Symposium on International Safeguards 2022.

ANTINEUTRINO SPECTRUM SIMULATIONS

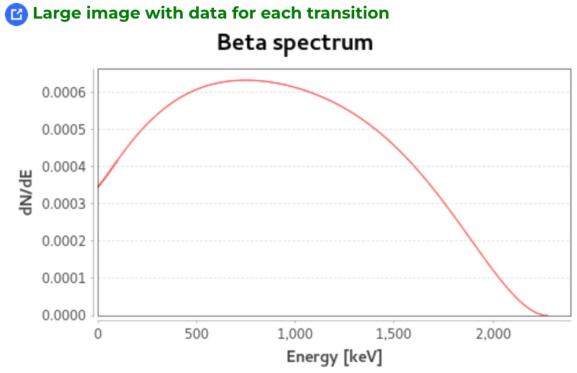
- Simulation with SERPENT 2
  - PWR simulation
  - Burn-up: 55 MWd/kg, 4% enrichment
- Spectrum based on converted beta spectra of beta-decaying nuclides
- Key isotopes:
  - ^{90}Sr (Q = 0.55 MeV)
  - **^{90}Y (Q = 2.28 MeV)**
  - ^{137}Cs (Q = 0.51 MeV)
- Endpoint of ^{90}Sr/^{90}Y above 1.8 MeV threshold for IBD on hydrogen

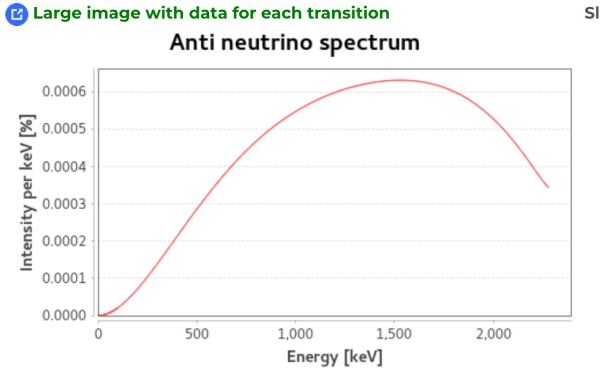


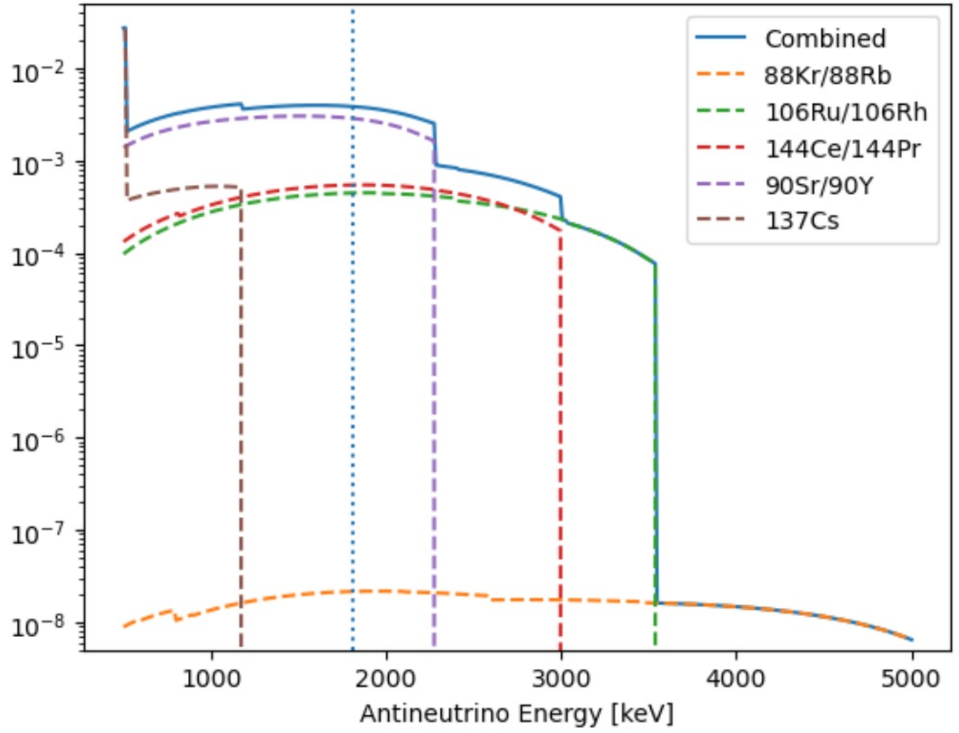
Nuclear Verification and Disarmament III. Physikalisches Institut B RWTH AACHEN UNIVERSITY https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html#&showtype=2&lastnuc=90Y&tabid=NR

ONGOING SIMULATIONS

- Now using ONIX* as simulation code
  - Adopted by several members of the NVD group – example: GKNII fuel assembly at 54 MWd/kg (3.3% enrichment)
  - Simulation output interfaced with beta spectrum shapes from NDS ENSDF database
  - Faster & easier than direct use of Betashape
- Used from here on to produce further spectra for different reactor scenarios
- Note: database output produces very useful graphs, but tables need more post-processing (only given for betas, not antineutrinos!)







*J. Lanversin, M. Kütt, A. Glaser, "ONIX: An open-source depletion code". Ann Nucl. Energy, **151**, (2021)

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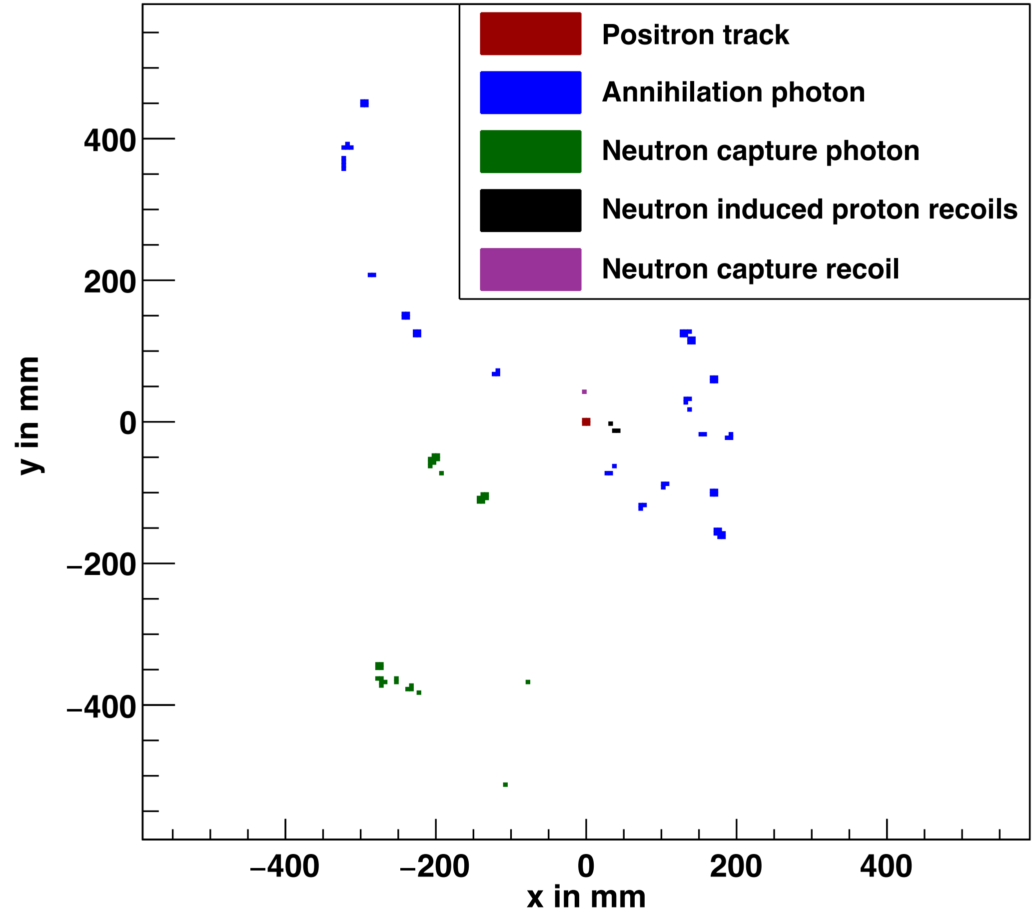
T. Radermacher, M. Göttsche, I. Niemeyer and S. Roth, “Antineutrino Monitoring for Safeguarding Spent Nuclear Fuel”. Poster at IAEA Symposium on International Safeguards 2022.

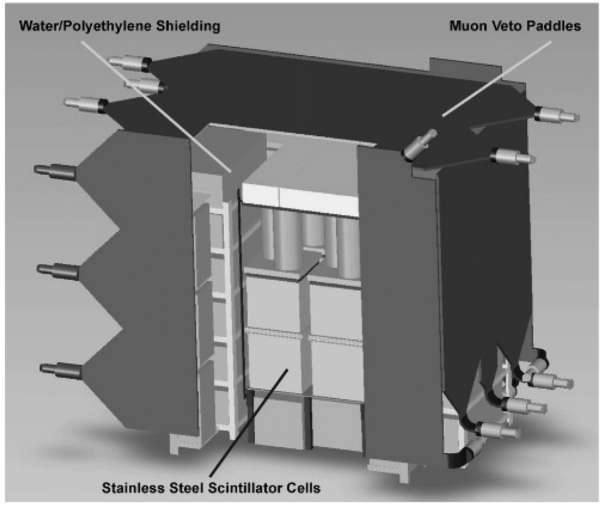
DETECTOR SIMULATION FOR 80 M³ DETECTOR

	Detector configuration 1
maximum drift length l	1 m
electric field E	5.0 kV/cm
drift velocity v_d	5.5 µm/ns
diffusion coefficient $d_{L,T}$	$60\,\mu\text{m}/\sqrt{\text{cm}}$
electron yield G_{if}	$7\,e^-/\text{keV}$

- Geant4 simulations of IBD events in TMS, combined with electron drift calculation
- Different types of hits are spatially separated
  - Allows reconstructing interaction vertex (positron track) and neutron direction
  - Infer original antineutrino direction
- This adds additional information for background rejection and directionality

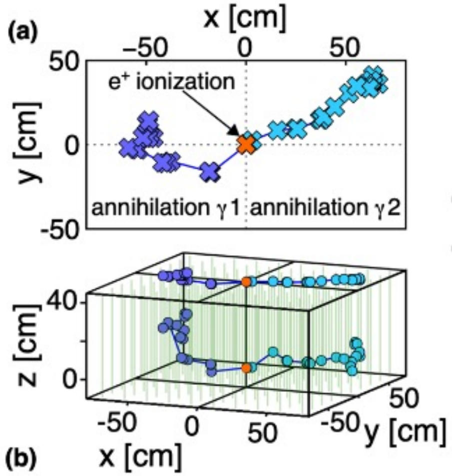


GENERAL FEASIBILITY & COMPARISON STUDIES



SONGS1 Experiment
Bowden, N.S. et al, „Experimental results from an antineutrino detector
For cooperative monitoring of nuclear reactors".
NIM A, vol. 572, iss. 2, pg. 985.

MiniCHANDLER Test: North Anna Nuclear Power Plant
http://cnp.phys.vt.edu/chandler/



LiquidO Consortium, "Neutrino physics with an opaque detector", Commun Phys, vol. 4, pg 273 (2021).
DOI: https://doi.org/10.1038/s42005-021-00763-5

- Benchmarking LOr-TPC versus other antineutrino safeguards approaches
- Understand strengths/weaknesses of different technologies
  - Especially w.r.t. scintillator-based approaches

SUMMARY AND OUTLOOK

- Continued programme investigating antineutrino-based safeguards for SNF
- Investigating use of LOr-TPC detectors for antineutrinos
  - Potential to resolve events in high detail
  - Can improve energy resolution and reconstruct directional information
- Now working on in-depth simulation to expand work into specific case studies

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FREIGEIST
FELLOWSHIP DER VOLKSWAGENSTIFTUNG

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BACKUP SLIDES

DETECTOR SIMULATION

Work in Progress