Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

New Materials and Techniques for Neutrino Detection

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Neutrino and Nuclear Chemistry

@BrookhavenLab

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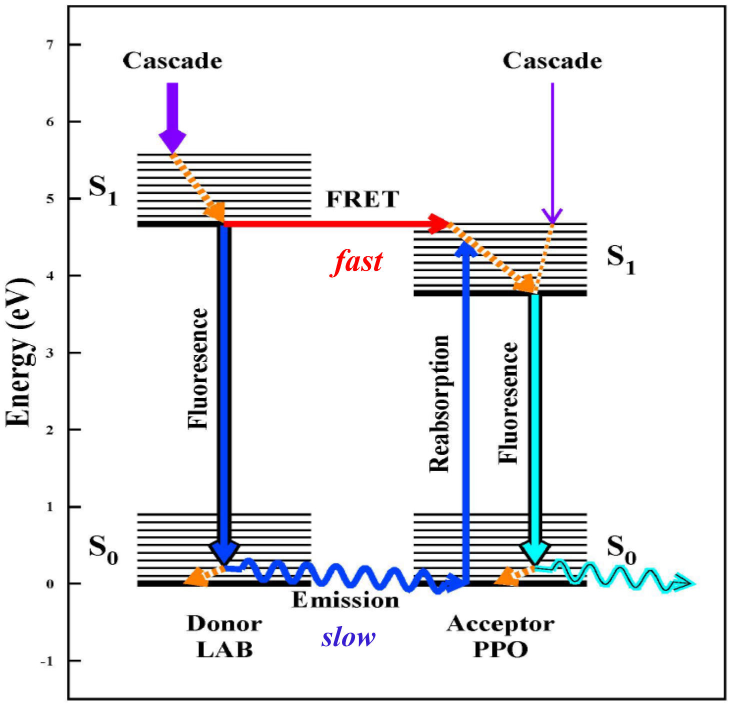
Liquid Scintillator Detectors

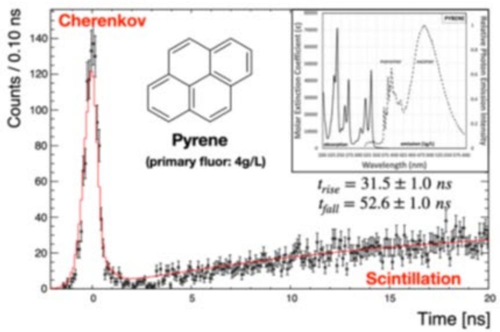
- Serve neutrino community since Reines and Cowan in 1950s
  - Stokes shift, photon-yield, timing structure, and C/H density determine the detector responses
- Next generation LS detector development → directionality
  - **Slow Scintillator**: Timing separation of slow scintillation from fast Cherenkov
  - **LiquidO**: Stochastic light confinement; lossless scattering
  - **Water-based Liquid Scintillator**: Cherenkov and scintillation detection



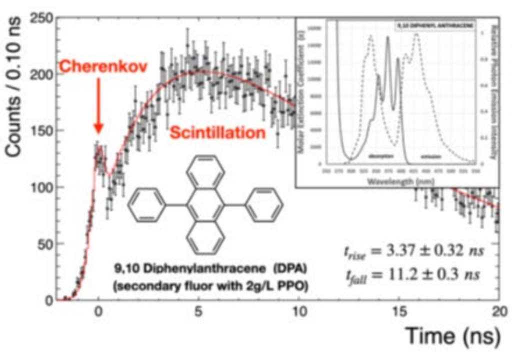
S. Hans, J. Cumming, R. Rosero, S. Gokhale, R. Diaz, C. Camilo, M. Yeh, Light-yield quenching and remediation in liquid scintillator detectors, 2020 *JINST* 15 P12020

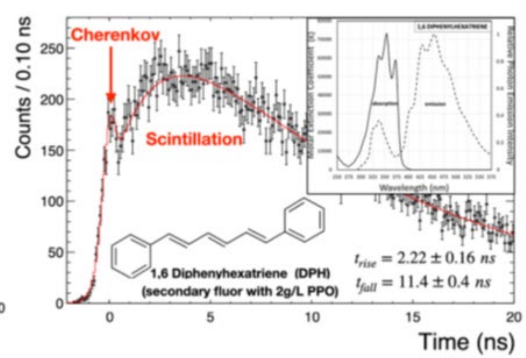
Slow Scintillator

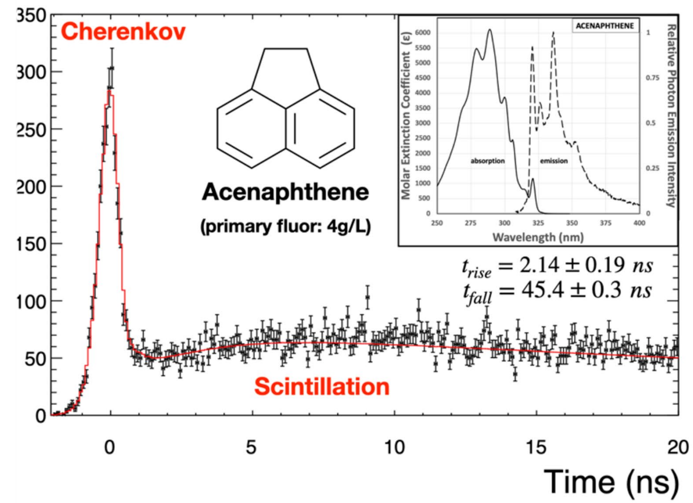
- The properties of slow fluors or wavelength shifters to provide a means to separate Cherenkov light in time from the scintillation signal which allows for directional and particle ID information while also maintaining good energy resolution.
- Readily applied to existing and planned large-scale liquid scintillator instruments without the need of additional hardware development and installation.



Similar spectra are shown for pyrene (left), used as a primary fluor with a concentration of 4g/L in LAB; 9,10-diphenylanthracene (DPA) (lower left) used as a secondary fluor at 30mg/L together with 2g/L of PPO in LAB; and 1,6-diphenylhexatriene (DPH) (lower right) as a secondary fluor at 10mg/L together with 2 g/L of PPO in LAB.

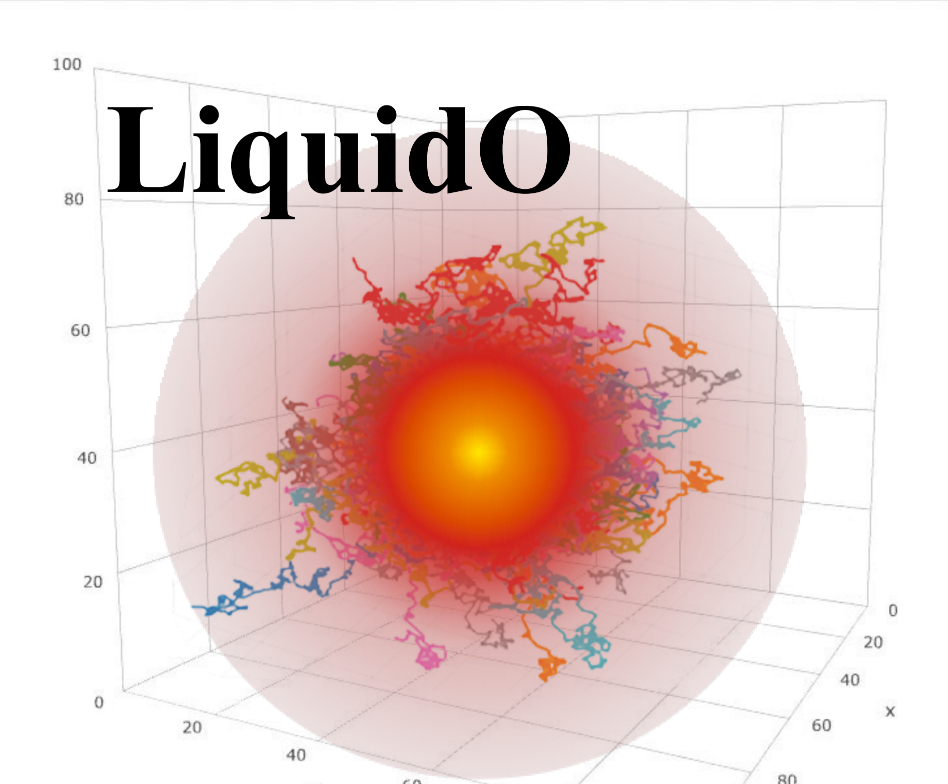




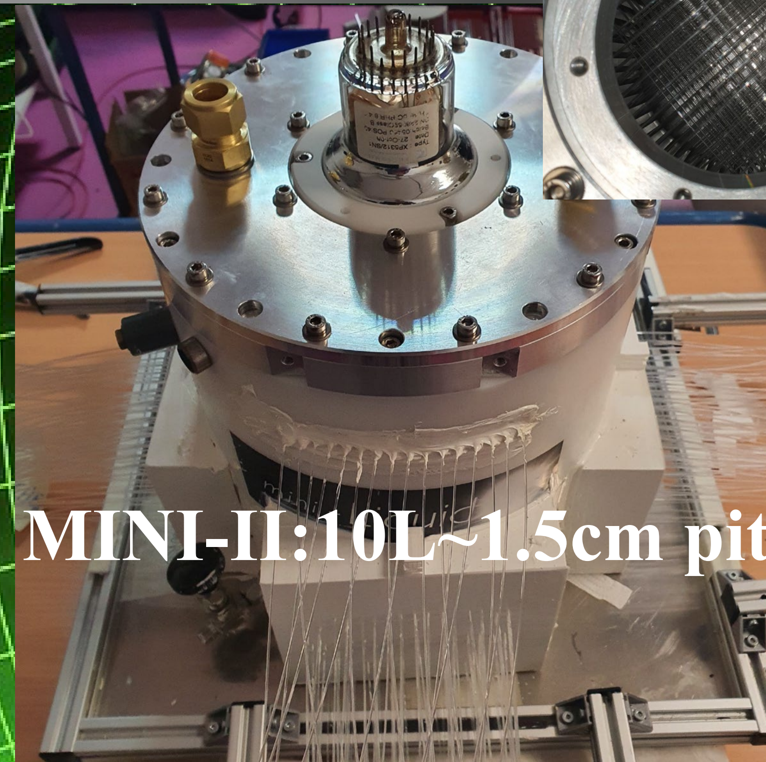


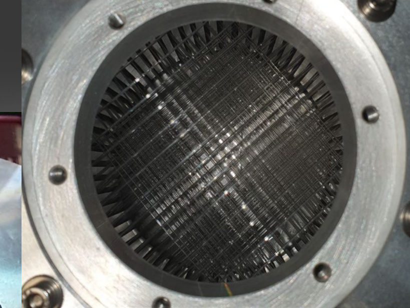
›med in time spectrum for 4 g/L acenapthene in LAB with clear Cherenkov peak.

Nu2022



LiqudiO→ photon's "random walk" (self-confinement)





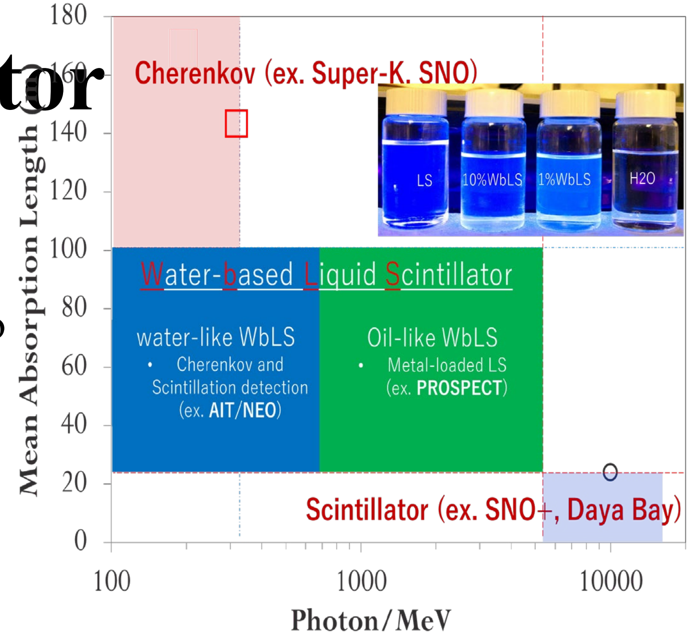
Transparency
λ(scattering)≥10m

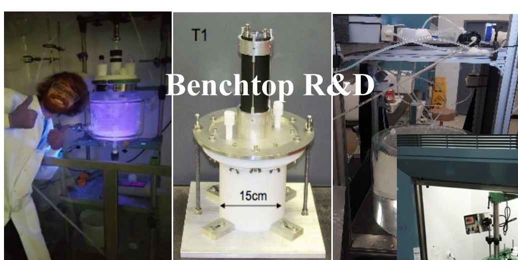
Rayleigh & Mie Scattering
λ(scattering)≤1cm

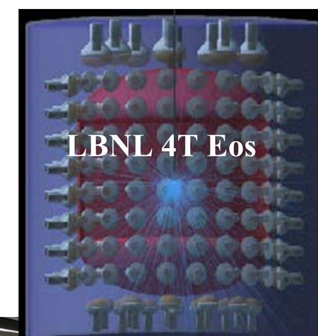
inducing light (lossless) to a point…

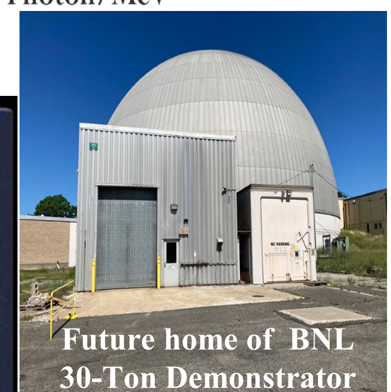
Water-based Liquid Scintillator

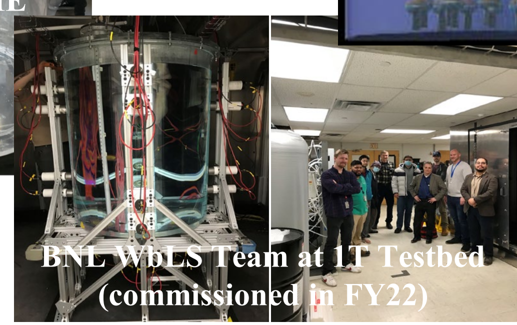
- WbLS, initiated in 2010, is a novel detector liquid (flexible LS%), well characterized: (ORCiD: **0000-0003-2244-0499**)
  - *Scintillation* provides the energy resolution necessary to get above most radioactive backgrounds and the ability to see slow-moving recoils
  - *Cherenkov* enables event direction reconstruction and background discrimination at low energies
- Principle proven and advancing R&Ds at several institutes; in prep for prototyping tests
  - 1-ton Testbed (BNL, FY22), 4-ton Eos (LBNL, FY23) and 30-ton Demonstrator (BNL, FY23)
  - ANNIE (SANDI), WATCHMAN, THEIA
  - (new)T2K/ND, LiquidO











Modern Metal-doped LS Neutrino Map

What has been achieved &
What is new?

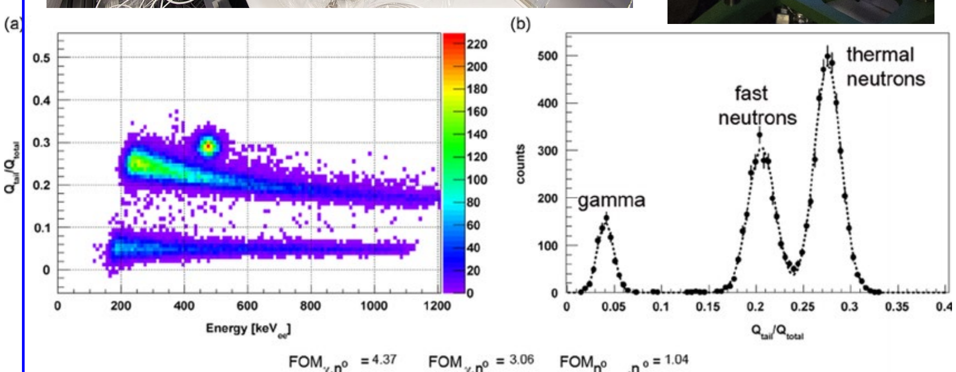
Loading isotopes into LS greatly enhances the physics implication; the challenge is the addition of the inorganic metallic compounds, typically in the form of salt, to the organic scintillator solvents

- **Conventional isotope loading methods**
  - A mediator with high solubility for inorganic salt compounds as alcohols (Chooz)
  - Organometallic complex, which is soluble in the LS.
    - Carboxylates (Savannah River, LENS, Palo Verde, Daya Bay, RENO)
    - Diketone or phosphor-organic ligands (LENS, Double Chooz)
- **New isotope-loading techniques**
  - M-doped WbLS
  - New organocomplex
  - Quantum dot

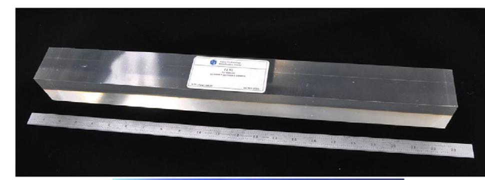
Metal-doped Water-based Liquid Scintillator

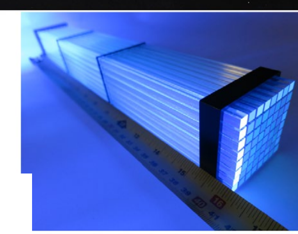
- A simpler approach to add the metal in aqueous solutions directly into liquid scintillators using principle derived from Water-based Liquid Scintillator
- User cases: Li, Gd, Te, K, Fe, W in several frontiers for neutrinos, nonproliferation, $0\nu\beta\beta$, calibration, calorimetry
- A transformative technique for LSC cocktail (environmental and safeguard)

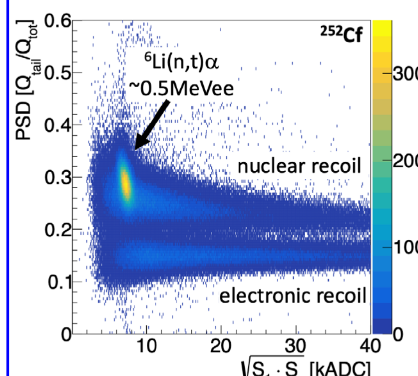
PROSPECT Li-doped LS



Li-doped Plastics



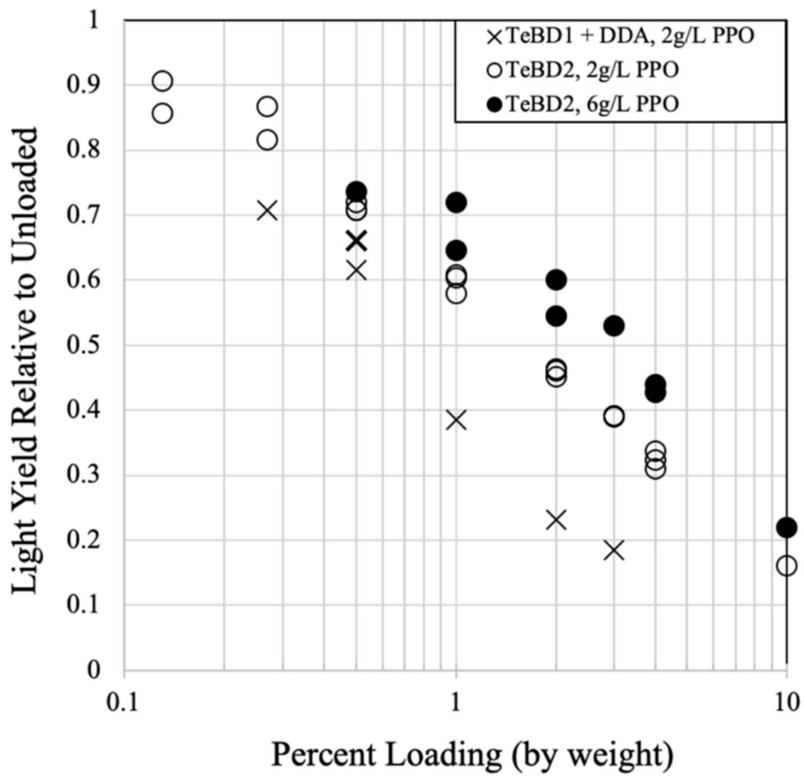




…graphs of ^{6}Li-doped PSD plastic scintillator …p: A 5.5 cm × 5.5 cm × 50 cm bar produced by …ology. *Bottom:* 64 rods of 5.4 mm × 5.4 mm× …ions, as used in the SANDD central module [37].

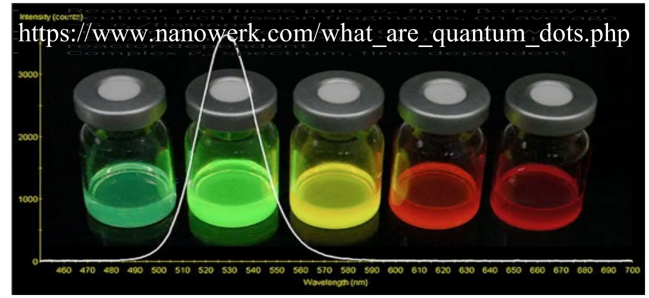
New Organocomplexing Ligands

- A method developed from $0\nu\beta\beta$ (SNO+) for higher loading of tellurium into liquid scintillator.
- An organocomplex using butanediol in conjunction with N,N-dimethyldodecylamine (DDA), which acts as a stabilisation agent.
- Stability of the loading has been demonstrated to be at least on the timescale of years; a highly scalable and economical approach.
- Further advances in purification techniques could provide a practical path to realising sensitivity to the non-degenerate normal mass ordering.



M. Yeh, Snowmass

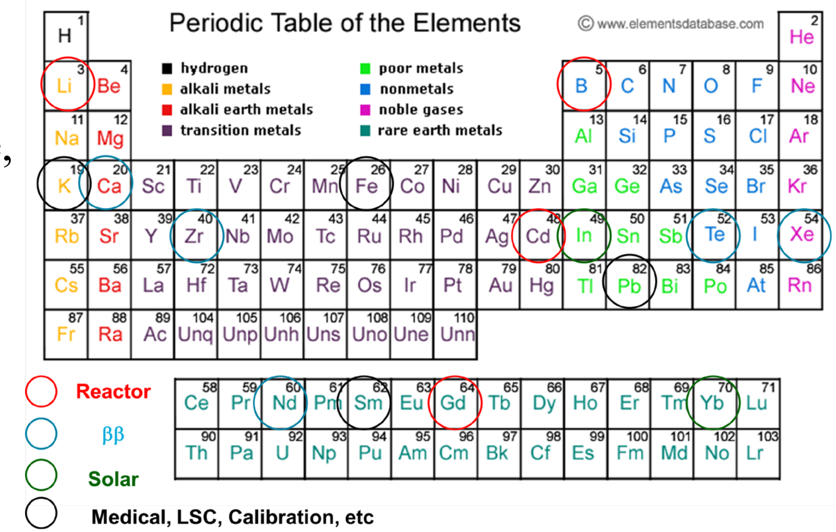
Quantum Dots



- Introduced from semiconducting nanocrystals in which the optical and electrical properties of the quantum dots are directly proportional to their size through resonance process (*tunable emission*).
- The most commonly used quantum dot cores are binary alloys such as CdS, CdSe, CdTe, and ZnS.
  - *neutron-enhanced isotopes (113Cd) and (106,116Cd) and Se, Te, and Zn, which are present in common quantum dot cores, $0\nu\beta\beta$ candidates.*
- Colloidal suspension instead of homogeneous mixing, which could cause aggregation in the concentrated solutions over long time scales.
  - *Mitigated by incorporating with chelating agents or WbLS surface active agents?*
- limitations in use for particle physics detectors are probably cost and availability in large quantity (ton).

Summary

- Liquid scintillator instrumentation has been largely advanced over the past decades
  - New materials with competitive performance, less chemical hazard, and better material compatibility
  - Advanced detector development allowing Cherenkov directionality from scintillation emission
- Advanced metal loading techniques with
  - Improved stability
  - Reduced light-yield quenching introduced from high mass doping
- A 10s kiloton-scale (water-based and/or metal-doped) liquid scintillator detector, sensitive to directionality, enables a broad neutrino program complementary to other detector technologies.



Target	Loading (mass)	Potential Applications
Indium	>8% In	Solar ν
Tellurium	> 6% Te	$0\nu\beta\beta$
Lithium	0.1% ^{6}Li >0.2% ^{6}Li	Reactor $\bar{\nu}$; excellent PSD Reactor $\bar{\nu}$; super PSD with improved optics
Boron	>0.5%	Dark Matter veto, reator $\bar{\nu}$
Potassium	>1%	Calibration for LS detectors
Iron, Strontium	ppm to 1%	Nuclear waste management, enviromental tracers
Gadolinium	0.1% Gd	Dark matter veto Reactor monitoring Reactor $\bar{\nu}$ oscillations
High-Z elements	10-15%Pb	Solar ν Calorimeters Medical QA/AC