Low radioactivity techniques for Large TPCs in rare event searches

- Background components
- Mitigation techniques and tools:
  - Underground facilities and shieldings
  - Material radiopurity
  - Discrimination techniques
  - Simulation and codes

11th Symposium on Large TPCs for low-energy rare event detection

Paris, 13th December 2023

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TCS
Background components

- Cosmic rays
- Muons
- \gamma, neutrons
Background components

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  - Muons → $\gamma$, neutrons

- Radiation and particles from environment
  - Radioactivity in materials (primordial, cosmogenic, anthropogenic): $^{232}$Th, $^{238}$U, $^{40}$K, $^{60}$Co, $^{210}$Pb, ...
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  Muons → $\gamma$, neutrons

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  - **Radon** $^{222}\text{Rn}$ → $\alpha$, $\gamma$ + Outgassing, daughters plate-out on surfaces
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  - Muons
    - $\gamma$, neutrons
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  - **Radioactivity** in materials (primordial, cosmogenic, anthropogenic): $^{232}\text{Th}$, $^{238}\text{U}$, $^{40}\text{K}$, $^{60}\text{Co}$, $^{210}\text{Pb}$, ...
  - **Radon** $^{222}\text{Rn}$
    - $\alpha$, $\gamma$
      - + Outgassing, daughters plate-out on surfaces
  - **Neutrons**: radiogenic: fission, ($\alpha,n$) reactions in rock, cosmogenic: induced by $\mu$

  ![Graph](image)

  - spectrum: up to GeV
  - flux: ~$10^{-9}$ n/cm$^2$/s (~3 km w.e.)

  ![Graph](image)

  - spectrum: up to few MeV
  - flux: ~$10^{-6}$ n/cm$^2$/s

  - ($n,\gamma$) capture; inelastic scattering $\rightarrow \gamma$, …
  - elastic scattering $\rightarrow$ WIMP-like recoils!
Mitigation techniques and tools

- Underground facilities
- Passive shielding
  - $\gamma$: Pb, Cu
  - Neutrons: water, polyethylene, Cd
- Control of radiopurity of materials
  - Measurements
  - Material treatment: bulk, surface
  - Minimizing cosmogenic activation

ANAIS (Annual modulation with NaI Scintillators) at Canfranc

Reducing the flux of background-creating radiation
Mitigation techniques and tools

Reducing the flux of background-creating radiation

Active event tagging

Underground facilities

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Active shielding
-  Anticoincidence
-  Fiducial volumen
-  Vetos

Techniques for background rejection
-  Pulse Shape Discrimination
-  Topology of events
-  Simultaneous measurements of heat and light/ionization signals
-  …

CUORE (Cryogenic Underground Observatory for Rare Events) at Gran Sasso

S. Cebrián, Symposium on Large TPCs, 13\textsuperscript{th} December 2023
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Reducing the flux of background-creating radiation

Active event tagging

Monte Carlo simulations of background

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Underground facilities

- **SNOLAB, Canada**: 2100 m, active nickel mine.
- **Boulby Underground Laboratory, UK**: 1100 m, working potash mine.
- **Laboratoire Souterrain de Modane, France**: 1700 m, roadway tunnel under the Alps.
- **Kamioka Observatory, Japan**: 1000 m, Kamioka mine.
- **Soudan Underground Laboratory, USA**: 710 m, abandoned iron mine, maintained as a State Park.
- **Laboratori Nazionali del Gran Sasso, Italy**: 1400 m, highway tunnel, under the Appennini.
- **Laboratorio Subterráneo de Canfranc, Spain**: 850 m, road tunnel under the Pyrenees.
- **China JinPing Underground Laboratory, China**: 2400 m, tunnel of a hydroelectric power station.
- **Yangyang Underground Laboratory, Korea**: 700 m, tunnel of Yangyang pumped storage power plant.
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Other facilities or projects:
- **Baksan** (Russia)
- **Callio Lab** (Finland)
- **LSBB Rustrel** (France)
- **LABchico** (Mexico)
- **ANDES** (Chile-Argentina)
- **Stawell Laboratory** (Australia)
- **India, South Africa**
Underground facilities

+ Radioassay facilities, Radon abatement systems, clean rooms, specialized services, ...

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- ANDES (Chile-Argentina)
- Stawell Laboratory (Australia)
- India, South Africa
Active shielding: **veto** for neutrons

- In **DarkSide-20k**: TPC walls made of Gd-loaded acrylic between two liquid Ar buffers read by SiPMs

→ neutrons thermalized and captured are tagged by gamma rays
Active shielding: veto for neutrons

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→ neutrons thermalized and captured are tagged by gamma rays

- In XENONnT / LUX-ZEPLIN: tank of Gd-loaded water / liquid scintillator surrounding the Xe TPC
Control of radiopurity: radioassays

**Screening** of materials: radioactivity below mBq/kg (ppb in Th, U; ppm in K)

1. Select materials and components in the design of all the parts of the set-up.
2. Provide inputs for the development of background models based on Monte Carlo simulations.
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→ the testing and certification of materials (different providers, batches) involve precision measurements that consume significant amounts of time, cost and an enormous effort.

“Selecting candidate low-radioactivity materials is as much an art as it is a science”
Control of radiopurity: radioassays

- Glow Discharge Mass Spectrometry (GDMS)
- Inductively Coupled Plasma Mass Spectrometry (ICPMS)
  - Providing concentrations of U, Th and K

😊 Fast: results provided within a few days
😊 Very small samples required
❗ Destructive
❗ GDMS suitable only for metals
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- Non-destructive: components to be actually used can be analyzed
- Sensitive to particular radioactive isotopes
- Large samples, long measurements required

Canfranc Underground Laboratory

SURF
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- Alpha spectroscopy
- Radon emanations

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Attempts of creating single public repositories of radiopurity measurements

**Radiopurity.org:** [https://www.radiopurity.org](https://www.radiopurity.org)

Control of radiopurity: material treatments

- **Purification methods for bulk activity:**
  - **Distillation:** liquid Ar
    - $^{39}$Ar activity in Ar reduced by distillation at the Aria facility
  - **Zone melting:** Ge, NaI
  - **Electroforming:** Cu
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- **Surface cleaning:** to remove a thin layer of material
  - Clean machining
  - Acid etching
  - Electropolishing
  - ...
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  • Applied to Cu, stainless steel, PTFE, … reduction factors of up to 50-100
  • Attention to radiopurity of chemicals, gloves, wipes, …
  • Control of particulate fallout and assembly in clean rooms required to avoid recontamination
Control of radiopurity: cosmogenic activation

Production of long-lived radioactive isotopes in materials due to exposure to cosmic rays (mainly by spallation) can be a hazard for ultra-low background experiments.

- Store materials underground and limit surface residency time
- Avoid flights
- Use shields against cosmic rays
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Recipe for estimates:

1. To know the production rates $R$ of relevant isotopes in the targets, from
   - Scarce experimental data from irradiation/controlled exposure experiments
   - Calculations from production cross sections and cosmic ray spectrum:

   \[
   R = N_t \int \sigma(E) \phi(E) dE
   \]

   - $N_t$ = number of target nuclei
   - $\phi$ = flux of cosmic rays
   - $\sigma$ = production cross section
   - $E$ = particle energy

S. Cebrián, Symposium on Large TPCs, 13th December 2023
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2. To estimate the **induced activity** $A$ knowing the exposure history to cosmic rays

   $$A = R \left[1 - \exp\left(-\lambda t_{exp}\right)\right] \exp\left(-\lambda t_{cool}\right)$$

   - $t_{exp}$ = exposure time
   - $t_{cool}$ = cooling time underground
**BiPo detector** built by the SuperNEMO collaboration and operated in Canfranc, sensitive to levels of μBq/kg of the lower parts of $^{238}\text{U}$, $^{232}\text{Th}$ through BiPo α–β coincidences in very thin samples

A.S. Barabash et al, 2017 JINST 12 P06002
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A.S. Barabash et al, 2017 JINST 12 P06002

Upper limits on Micromegas samples below 0.1 $\mu$Bq/cm$^2$
AlphaCAMM (Alpha CAMera Micromegas) detector being built by the TREX-DM collaboration: a gaseous chamber read with a segmented Micromegas to measure $^{210}\text{Pb}$ surface contamination of flat samples down to $100\ n\text{Bq/cm}^2$

K. Altenmuller et al, 2022 JINST 17 P08035
Control of radiopurity: special detectors

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Micromegas provides topological information to reconstruct origin and end of $\alpha$ tracks from $^{210}\text{Po}$.
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K. Altenmuller et al, 2022 JINST 17 P08035

After proof-of-concept with a non-radiopure prototype, a radiopure detector is being commissioned

Micromegas provides topological information to reconstruct origin and end of $\alpha$ tracks from $^{210}\text{Po}$
Procurement of low-radioactivity Underground Ar for DarkSide-20k

- **Urania**: extraction from CO\textsubscript{2} wells in Colorado (as DarkSide-50)
- **Aria**: purification in a cryogenic distillation column in Sardinia
- **DArT**: quantification of $^{39}$Ar (pure beta emitter) in Canfranc

**Control of radiopurity: special detectors**

S. Cebrián, Symposium on Large TPCs, 13\textsuperscript{th} December 2023
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- 1.35 kg of UAr in Cu vessel, 1 cm$^2$ SiPMs
- Acrylic structure with TPB coating
- Inside ArDM detector in single phase (~1 t Atmospheric Ar buffer as shield and veto, with 13 PMTs)
Control of radiopurity: special detectors

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Techniques for background rejection

• **S1/S2 discrimination for dark matter experiments**

Dual-phase TPCs of liquid scintillators (Xe, Ar): detection of a primary scintillation signal in liquid (S1) and a secondary signal in gas from the drift and extraction of ionization electrons (S2).

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- Electron and nuclear recoils have different ionization

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![Diagram of Dual-phase TPCs](image)


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- Electron and nuclear recoils have different ionization

Combined with very efficient PSD in liquid Ar

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Techniques for background rejection

• Topology of events for double beta decay experiments

Tracks of two electrons from a common vertex can be discriminated from background
Techniques for background rejection

- **Topology of events for double beta decay experiments**

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Plastic scintillators +
Geiger cells
Techniques for background rejection

- **Topology of events for double beta decay experiments**

Tracks of two electrons from a common vertex can be discriminated from background.

Plastic scintillators + Geiger cells

**NEMO3 at Modane**

**NEXT at Canfranc**

High Pressure Xe-Electroluminiscence gas TPC with separate energy / tracking readout.

**NEXT-White real data**

**Double-e**

**Single-e (BG)**
Monte Carlo simulations of the interaction of background radiation in matter are extremely useful to:

• Assessment of effect of background reduction strategies: shieldings, vetoes, discrimination, …

• Evaluation of expected counting rates and sensitivity of future experiments

• Understanding of measured data → background models
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Tools: general-purpose packages

GEANT4 (GEometry ANd Transport), FLUKA, MCNPX

- To define: primary particles + physical processes + set-up + outputs
- Geant4 environments created for particular technologies: MaGe, G4DS, ImpCRESST, …
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- Geant4 environments created for particular technologies: MaGe, G4DS, ImpCRESST, …
- Integration of detector response by specific codes/modules:
  - NEST (Noble Element Simulation Technique) for Xenon detectors
    https://nest.physics.ucdavis.edu/about
  - G4CMP (Condensed Matter Physics with Geant4) for solid-state detectors
    http://geant4-resources.com/G4CMP/G4_CMP.html
  - REST-for-Physics (Rare Event Searches Toolkit for Physics) for gas TPCs
    https://doi.org/10.1016/j.cpc.2021.108281
Simulation and codes

Specific tools (codes, libraries, databases) focused on particular backgrounds

**EXPACS (EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum)**

https://phits.jaea.go.jp/expacs/

To calculate terrestrial cosmic ray fluxes of neutrons, protons, light ions, muons, electrons, positrons, and photons nearly anytime and anywhere in the Earth's atmosphere.
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**MUSUN, MUSIC, MUTE** (MU inTensity codE)
https://github.com/wjwoodley/mute
To obtain **muon intensity** and distributions (E, θ)
**Simulation and codes**

**Yields of radiogenic neutrons**
Allow to set requirements on $\alpha$ activity of materials

**SOURCES$4A(C)$**
$(\alpha, n)$ reaction cross-sections using EMPIRE2.19
V. A. Kudryavtsev et al, NIMA 972 (2020) 164095

**USD calculator**

**NeuCBOT (Neutron Calculator Based On TALYS)**
SRIM code for the stopping power of $\alpha$ particles + TALYS for cross sections

**SaG4n**
Geant4 for $\alpha$ transport + data libraries (JENDL, TENDL) to model $(\alpha,xn)$ reactions
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Experimental data from beam experiments, few data for n EXFOR (Experimental Nuclear Reaction Data) database
http://www-nds.iaea.org/exfor/exfor.htm
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COSMO, YIELDX, ACTIVIA codes
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COSMO, YIELDX, ACTIVIA codes

Monte Carlo simulation: formation and decay of compound nuclei, de-excitation processes
like fission, fragmentation, spallation, or breakup

TENDL (TALYS-based Evaluated Nuclear Data Library)
Using the TALYS code for n and p up to 200 MeV

HEAD-2009 (High Energy Activation Data) library: only for Z≥12
https://doi.org/10.1016/j.nima.2010.08.110
Using a selection of models and codes (CEM, ...)
for p from 150 MeV to 1 GeV

JENDL (Japanese Evaluated Nuclear Data Library)
https://wwwndc.jaea.go.jp/jendl/j40/j40.html
Using GNASH code for n and p up to 200 MeV, from 20 MeV to 3 GeV
Rare event searches demand ultra-low background conditions achieved mitigating all known background sources: cosmic muons, radiogenic, cosmogenic neutrons and radioactivity.

- Deep underground laboratories provide not only shelter but different support facilities.
- Passive and more sophisticated active shieldings are a must.
- Specific background rejection techniques based on different approaches are in continuous development.
- Monte Carlo simulation and codes are valuable tools to study backgrounds.
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https://pdg.lbl.gov/2022/reviews/contents_sports.html
Extra material
Figure 2. Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.
Many dangers for experiments: Radon mobility due to convection and diffusion is a concern. Radon diffuses readily through thin plastic barriers, with different permeability. Due to its intrinsic U content, materials can produce Rn outgassing. Prolonged exposure of materials to air leads to the accumulation of the long-lived radon daughter $^{210}\text{Pb}$ on surfaces (plate-out electrostatically) strongly enhanced on statically charged surfaces such as plastic or glass. Large spread of effective radon daughter collection distances ranging from a few cm to a few m in air → limit the allowable air exposure time. In case raw materials (e.g. in the form of granules) were exposed to air at the production site, the bulk (instead of the surface) of the finished components may be loaded with $^{210}\text{Pb}$ and its daughters.
Radon detectors

Based on alpha spectroscopy (using scintillation, silicon or gas detectors)
Commercial monitors (AlphaGuard): sensitivity of a few Bq/m³

Special systems having efficiency boosted by **electrostatic collection** of radon ions ($^{218}\text{Po}$ and $^{214}\text{Po}$ for $^{222}\text{Rn}$) from a large gas volume onto a small detector
• Electro-polished inside stainless steel vessel shaped to maximize the collection of ions to an alpha counter installed on the upper part.
• Sensitivities of the order of mBq/m³ and even below
Radon emanation measurements: based on the pre-concentration of $^{222}$Rn on a charcoal trap and subsequent counting of alpha decays with miniaturized proportional detectors

- $^{222}$Rn atoms are collected inside an exhalation chamber for several half-lives before adsorption and counting.
- Emanation of large vessels (cryostats, storage tanks, purification columns) can be determined by collecting exhaled radon into transportable charcoal traps.

Extensive study of radon emanations made by XENON1T to achieve 4.5 mBq/kg in the target Xe

Mass spectrometry

Glow Discharge Mass Spectrometry (GDMS)

Consists in creating a low pressure Ar plasma which allows the ionisation of elements by sputtering.

- A 1KV DC Voltage is applied between anode (body cell) and cathode (sample) creating the plasma.
- Ar+ ions thus formed sputters the surface of the sample.
- Particles issued of the sample are ionized forming elemental ions.
Alpha spectroscopy

- Very useful if the decay of some radionuclides is not accompanied by a gamma ray emission of significant intensity
- **Alpha spectrometry** uses very thin samples of low mass, since the range of alpha particles is very short → measurements have to be carried out in a vacuum chamber so that the energy loss of the alpha particles is minimized. The detectors are usually based on **silicon detectors** with a flat and very thin shape.

Due to the very small detector volume the interaction probability of gamma rays is very low; in combination with the relatively high energy of alpha particles of approximately 4 MeV to 9 MeV, very **low background count rates** in the order of few cts/d, depending on the detector size, can be reached.

Alpha spectrometry combined with **radiochemical methods** to extract $^{210}\text{Po}$ offers best sensitivity to quantify the lower part of the $^{238}\text{U}$ chain.
Control of radiopurity: cosmogenic activation

*Example:* many activation studies are available for Cu, a material widely used in experiments.

<table>
<thead>
<tr>
<th></th>
<th>(^{46}\text{Sc})</th>
<th>(^{48}\text{V})</th>
<th>(^{54}\text{Mn})</th>
<th>(^{56}\text{Co})</th>
<th>(^{57}\text{Co})</th>
<th>(^{58}\text{Co})</th>
<th>(^{59}\text{Fe})</th>
<th>(^{60}\text{Co})</th>
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<tr>
<td><strong>Half-life</strong> [27,108]</td>
<td>83.787(16) d</td>
<td>15.9735 d</td>
<td>312.19(3) d</td>
<td>77.236 d</td>
<td>271.81(4) d</td>
<td>70.85(3) d</td>
<td>44.949 d</td>
<td>5.2711(8) y</td>
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<td><strong>Measurement</strong> [202]</td>
<td>2.18 ± 0.74</td>
<td>4.5 ± 1.6</td>
<td>8.85 ± 0.86</td>
<td>9.5 ± 1.2</td>
<td>74 ± 17</td>
<td>67.9 ± 3.7</td>
<td>18.7 ± 4.9</td>
<td>86.4 ± 7.8</td>
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<tr>
<td><strong>Measurement</strong> [184]</td>
<td>2.33±0.95</td>
<td>3.4±1.6</td>
<td>13.3±1.0</td>
<td>9.3±1.4</td>
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<td><strong>ACTIVIA (MENDL-2P)</strong> [36]</td>
<td>3.1</td>
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<td>14.1</td>
<td>36.4</td>
<td>38.1</td>
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<td>9.7</td>
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<tr>
<td><strong>ACTIVIA</strong> [36,184]</td>
<td>3.1</td>
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<td><strong>CONUS</strong> [99]</td>
<td>3</td>
<td>16</td>
<td>9</td>
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<td><strong>GEANT4</strong> [46]</td>
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<td>12.3</td>
<td>10.3</td>
<td>67.2</td>
<td>57.3</td>
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<td><strong>TALYS</strong> [94]</td>
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<td><strong>MENDL+YIELDX</strong> [43]</td>
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</table>

Measured rates from sensitive screening after exposing large samples in controlled conditions at Gran Sasso for long time.

S. Cebrián, Universe 2020, 6, 162
Control of radiopurity: cosmogenic activation

*Example:* specific study of tritium production rates induced in dark matter detectors (Ge, Si, NaI, Ar, Ne)


Production rates in kg⁻¹d⁻¹

<table>
<thead>
<tr>
<th>Target</th>
<th>Ref.</th>
<th>TENDL+HEAD¹</th>
<th>TALYS²⁵⁹</th>
<th>GEANT4³⁷</th>
<th>GEANT4³⁶</th>
<th>ACTIVIA³⁷</th>
<th>ACTIVIA³⁶</th>
<th>ACTIVIA</th>
<th>Others</th>
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<td>natGe</td>
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<td>75 ± 26</td>
<td>27.7</td>
<td>48.3</td>
<td>47.4</td>
<td>52.4</td>
<td>52.4</td>
<td>46/43.5 (Ref. 65)</td>
<td>82 ± 21 (Ref. 65)</td>
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<tr>
<td>enrGe</td>
<td>113/140</td>
<td>94 ± 34</td>
<td>24.0</td>
<td>27.3</td>
<td>47.4</td>
<td>51.3</td>
<td>108.7</td>
<td>140 ± 10 (Ref. 66)</td>
<td>125 (Ref. 52)</td>
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<tr>
<td>Si</td>
<td>83 ± 27</td>
<td>120 ± 23</td>
<td>43.7</td>
<td>27.3</td>
<td>108.7</td>
<td>45.5</td>
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<td>TeO₂</td>
<td>83 ± 27</td>
<td>120 ± 23</td>
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<td>NaI</td>
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</tbody>
</table>

New measurements with LANSCE beam:
- Si: 112 ± 24
- NaI: 80 ± 21
  R. Saldanha et al, Phys Rev. D 107 (2023) 022006