Technologies for obtaining radio-pure materials; methods of low radioactivity detection

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Outline

• Physics beyond the Standard Model
  – Double-beta decay – The GERDA Experiment
    • Surprising $^{42}\text{K}$
    • Ions in cryogenic liquids
  – Cold Dark Matter – The DarkSide Experiment
    • Ubiquitous $^{222}\text{Rn}$
    • Electrostatic chamber for on-line gas monitoring

• Summary
Double beta decay

\[2\nu\beta\beta \quad (Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e\]

Allowed in SM and observed for several isotopes with forbidden single beta decay. Conserves lepton number. Long half-lifetimes \((10^{19} \div 10^{21} \text{ y})\).

\[0\nu\beta\beta \quad (Z, A) \rightarrow (Z+2, A) + 2e^-\]

Does not conserve lepton number \((\Delta L = 2)\). Possible if neutrinos are Majorana particles. Expected lifetimes > \(10^{24} \text{ y}\).
Energy spectrum of double-beta decays

E.g. \( ^{76}\text{Ge} \) \( Q_{ee} = 2039 \text{ keV} \)
$2\beta^{0}\nu$ limit on $T^{0\nu}_{1/2}$ depends on the background index $B_E$

Without background

\[ T^{0\nu}_{1/2} > A\epsilon \ln(2) T \frac{m}{m_{mol}} N_A \]

In the presence of background $B_E$

\[ T^{0\nu}_{1/2} > A\epsilon \frac{\ln(2)}{m_{mol}} \sqrt{\frac{mT}{B_E \delta_E}} N_A \]

- $A$: isotope abundance
- $\epsilon$: registration efficiency
- $T$: time of measurement [y]
- $N_A$: Avogadro constant
- $m$: detector mass [kg]
- $m_{mol}$: molar mass of Ge [kg/mol]
- $B_E$: background in $Q_{ee}$ region [y^{-1}keV^{-1}kg^{-1}]
- $\delta_E$: energy resolution [keV]
The GERDA Experiment @ LNGS

Steel cryostat with internal Cu shield

Clean room
Lock system

Array of bare Ge-diodes

Water: γ,n shield Cherenkov medium for μ veto

High-purity liquid argon (LAr) shield & coolant
Optional: active veto
Surprising $^{42}$K

- $^{42}$K $\beta^-$ decay with $Q = 3525$ keV above $Q_{ee}$ of $^{76}$Ge (2039 keV)
- Half life-time of $^{42}$Ar is 32.9 y
- $^{42}$K half life-time is 12.36 h
- If $^{42}$K decays on the surface of detectors then background for $0\nu\beta\beta$
- $^{42}$K signature – 1525 keV $\gamma$ line
- GERDA proposal: $^{42}$Ar / $^{nat}$Ar < $3 \times 10^{-21}$ g/g
  (43 $\mu$Bq/kg) homogenously distributed in the cryostat volume
Surprising $^{42}$K

$^{42}$Ar $\beta^-$ decays to $^{42}$K$^+$
Charged $^{42}$K drifts towards the detector
$^{42}$K $\beta^-$ decays ($Q = 3525$ keV, above $Q_{\beta\beta}$)
possibly nearby the detector
GERDA espectrum before the unblinding (June 2013)

\[ T_{1/2} = 269 \text{ y} \]
\[ Q = 565 \text{ keV} \]

\[ ^{39}\text{Ar} \quad \beta^- \]

\[ 2
\nu\beta\beta \]

- enriched coaxials, 13.65 kg x yr
- natural coaxials, 4.69 kg x yr

Scaled to exposure of enr. coaxial
Cold Dark Matter

- Astronomical evidences (large-scale galaxy surveys and microwave background measurements) indicate that the majority of matter in the Universe is non-baryonic
- The “dark matter” is typically a factor of 10 times greater in total mass
- The nature of this non-baryonic component is unknown, but of fundamental importance to cosmology, astrophysics, and elementary particle physics

- One of the candidates are WIMPs – Weakly Interacting Massive Particles, possibly detectable through their collisions with ordinary nuclei, giving observable low-energy (<100 keV) nuclear recoils
Cold Dark Matter – The DarkSide Experiment

- WIMP

Two-phase Liquid Argon TPC
Ubiquitous $^{222}$Rn

- $^{226}$Ra present in most of the construction materials;
- Gaseous $^{222}$Rn emanation dissolves into the cryoliquids;
- Ionized decay products are subject to electric field, induced in the cryoliquid (e.g. drift chambers);
- Energy released in alpha, beta and gamma decays in $^{226}$Ra decay chain are high;
- Natural intrinsic source of background in majority of the low background experiments.

$^{226}$Ra $^{1602}$y $\alpha$ $^{222}$Rn $^{3.8}$d $\alpha$ $^{218}$Po $^{3.1}$m $\alpha$ $^{214}$Bi $^{19.8}$m $\beta^-$ $^{214}$Po $^{164.3}$us $\alpha$ $^{210}$Pb $^{22.3}$y $\beta^-$ $^{214}$Po $^{164.3}$us $\alpha$ $^{210}$Pb $^{22.3}$y $\beta^-$
DarkSide – Electrostatic Rn monitor

- Simulations of $^{222}$Rn daughters drift in electric field to optimize efficiency for different carrier gases

- Design allowing for operation up to 20 kV
DarkSide – Electrostatic Rn monitor

- On-line monitoring of the $^{222}$Rn content in the DarkSide clean-rooms (Rn-reduced air);
- Recently completed;
- Sensitivity $\sim 0.5$ mBq/m$^3$ (250 atoms of Rn/m$^3$).
Summary

• Ultra-low background experiments demand supreme purities of the construction materials and online monitoring;
• Technologies for obtaining highly radiopure materials rely on:
  – careful material selection;
  – understanding properties of the radio-impurities;
  – dedicated experiments focused only on the impurities;
• Material selection and online monitoring depend on the limitations of the activity detection techniques (minimum detectable activity), e.g.:
  – direct measurements of $^{42}$K in cryoliquids;
  – online monitoring of gases in drifting chambers ($^{222}$Rn);
• Physical and chemical properties of radio-impurities need to be studied in sophisticated experiments due to their... low activities. We need to know:
  – diffusion coefficients;
  – chemical reactions;
  – neutralization time;
  – mobility etc.
Backup slides & References

- ZDFK UJ: http://bryza.if.uj.edu.pl/
- The GERDA Experiment: http://www.mpi-hd.mpg.de/gerda/
- The DarkSide Experiment: http://darkside.lngs.infn.it/
Neutrinoless double beta decay

Energetically forbidden $\beta$ decay

Allowed double-$\beta$ decay
Neutrinoless double beta decay

In theory:

\[
\frac{1}{T_{1/2}^{0\nu}} = G(Q) |M|^2 \langle m_{ee} \rangle^2 \quad \langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|
\]

- \( G(Q) \) – Kinematic coefficient
- \( |M|^2 \) – Nuclear matrix element
- \( \langle m_{ee} \rangle \) – effective Majorana neutrino mass

\( T_{0\nu}^{1/2} \) will be determined experimentally
The GERDA Experiment @ LNGS

LNGS Assergi

1400 m ~ 3.500 m.w.e. shielding against muons