14. Background in underground experiments

General

- Radioactivity and radiation exists everywhere and it is (as natural or induced) common in rock and soil, oceans, lakes and rivers, and in construction materials
  - mostly harmless for humans, animals and plants, and life
  - usually extremely harmfull for a sensitive physics experiment
- From experimental point of view, the progress in astroparticle and underground physics (neutrinos, proton decay, dark matter, double beta decay) is largely related on the better reduction of background radiation
- The radioactive isotopes found in the nature (or in detector materials) are generally divided into three groups
  - primordial isotopes (∴ natural radioactivity (radon))
  - cosmogenic isotopes
  - artificial isotopes,

or it is induced directly (”on-line”) by cosmic rays
14. Background in underground experiments

Primordial isotopes

- Life time $\sim 10^9$ years or longer
- The same ancient stuff that formed the Earth
- The most important primordial isotopes are $^{40}$K and members of the natural $^{238}$U and $^{232}$Th decay series
- $^{40}$K
  - the main source of background gamma radiation
  - the abundance of $^{40}$K in natural potassium is $\delta \approx 0.012\%$
  - $\tau \sim 1.3 \times 10^9$ years, $E_\gamma \approx 1.46$ MeV, 0.04–1.1 Bq/g at soil
  - potassium normally occurs in rock and concrete as $\text{K}_2\text{O}$ and $\text{K}_2\text{CO}_3$ (present at the $\sim 1\%$ level)
- $^{235,238}$U and $^{232}$Th
  - $^{232}$Th $1.41 \times 10^{10}$ yr thorium serie at the soil
  - $^{238}$U $4.47 \times 10^9$ yr uranium serie $\delta=99.2745\%$, at the soil
  - $^{235}$U $7.04 \times 10^8$ yr actinium serie $\delta=0.72\%$
  - occurs widely in surrounding environment and contribute to large variety of background types; mainly by high-energy gammas and neutrons $\implies$ radioactive decay chains
14. Background in underground experiments

Primordial elements

<table>
<thead>
<tr>
<th>1</th>
<th>H</th>
<th>2</th>
<th>He</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>90</td>
<td>Th</td>
<td>91</td>
<td>Pa</td>
</tr>
</tbody>
</table>
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

**Uranium Series**

\[ A = 4n + 2 \]

- \(^{238}\text{U} \) (4.5 × 10^9 y)
- \(^{234}\text{Pa} \) (1.16 min)
- \(^{234}\text{U} \) (1.54 × 10^9 y)
- \(^{230}\text{Th} \) (1.35 × 10^9 y)
- \(^{226}\text{Ra} \) (1.67 × 10^7 y)
- \(^{222}\text{Rn} \) (3.84 d)
- \(^{218}\text{Po} \) (3.03 min)
- \(^{214}\text{Pb} \) (26.5 min)

**Thorium Series**

\[ A = 4n \]

- \(^{232}\text{Th} \) (1.4 × 10^10 y)
- \(^{228}\text{Ac} \) (6.13 h)
- \(^{228}\text{Th} \) (1.91 a)
- \(^{224}\text{Ra} \) (3.64 d)
- \(^{230}\text{Rn} \) (3.3 × 10^6 y)
- \(^{216}\text{Po} \) (0.145 sec)
- \(^{212}\text{Bi} \) (60.5 min)
- \(^{208}\text{Pb} \) (stable)

**Actinium Series**

\[ A = 4n + 3 \]

- \(^{235}\text{U} \) (7.04 × 10^8 y)
- \(^{231}\text{Pa} \) (1.27 × 10^9 y)
- \(^{231}\text{Th} \) (25.5 h)
- \(^{227}\text{Ac} \) (18.7 d)
- \(^{227}\text{Th} \) (11.4 d)
- \(^{223}\text{Ra} \) (11.4 d)
- \(^{213}\text{Rn} \) (3.9 sec)
- \(^{210}\text{Po} \) (1.35 d)
- \(^{212}\text{Bi} \) (60.5 min)
- \(^{208}\text{Pb} \) (stable)
- \(^{210}\text{Po} \) (1.35 d)
- \(^{211}\text{Bi} \) (2.16 min)
- \(^{211}\text{Po} \) (0.36 y)
- \(^{207}\text{Pb} \) (stable)
- \(^{207}\text{Pb} \) (stable)
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

- As the final results of the four decay chains (thorium, uranium, actinium and neptunium) the heaviest stable isotopes are formed: $^{206}\text{Pb}$, $^{207}\text{Pb}$, $^{208}\text{Pb}$, $^{209}\text{Bi}$

- Estimation of the soil activity
  - a one square-mile area and one-foot thick piece of soil, having the total volume of approximately $8 \times 10^5 \text{ m}^3$.
  - typical values have been used, local variations exist

<table>
<thead>
<tr>
<th>Element</th>
<th>Activity</th>
<th>Mass</th>
<th>Total activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>25 Bq/kg</td>
<td>2200 kg</td>
<td>31 GBq</td>
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<tr>
<td>Thorium</td>
<td>40 Bq/kg</td>
<td>12000 kg</td>
<td>52 GBq</td>
</tr>
<tr>
<td>Potassium ($^{40}\text{K}$)</td>
<td>400 Bq/kg</td>
<td>2000 kg</td>
<td>500 GBq</td>
</tr>
<tr>
<td>Radium</td>
<td>48 Bq/kg</td>
<td>1.7 g</td>
<td>63 GBq</td>
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<tr>
<td>Radon</td>
<td>10 kBq/m$^3$</td>
<td>11 $\mu$g</td>
<td>7 GBq</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>$&gt;653$ GBq</td>
</tr>
</tbody>
</table>
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

Radioactivity in the rock
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

- The oceanic activity
- Amounts of water (volumes) [Ref. 1990 World Almanac]
  - Pacific Ocean = $6.6 \times 10^{17}$ m$^3$
  - Atlantic ocean = $3.1 \times 10^{17}$ m$^3$
  - All oceans = $1.3 \times 10^{18}$ m$^3$

<table>
<thead>
<tr>
<th>Element/Isotope</th>
<th>Activity</th>
<th>Pacific</th>
<th>Atlantic</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>33 mBq/l</td>
<td>22 EBq</td>
<td>11 EBq</td>
<td>41 EBq</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>11 Bq/l</td>
<td>7400 EBq</td>
<td>3300 EBq</td>
<td>14000 EBq</td>
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<tr>
<td>Tritium</td>
<td>0.6 mBq/l</td>
<td>370 PBq</td>
<td>190 PBq</td>
<td>740 PBq</td>
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<tr>
<td>$^{14}$C</td>
<td>5 mBq/l</td>
<td>3 EBq</td>
<td>1.5 EBq</td>
<td>6.7 EBq</td>
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<tr>
<td>$^{87}$Rb</td>
<td>1.1 Bq/l</td>
<td>700 EBq</td>
<td>330 EBq</td>
<td>1300 EBq</td>
</tr>
</tbody>
</table>
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

- Radioactivity in construction materials
  - figures are typical values

<table>
<thead>
<tr>
<th>Material</th>
<th>Uranium ppm [mBq/g]</th>
<th>Uranium ppm [mBq/g]</th>
<th>Thorium ppm [mBq/g]</th>
<th>Potassium ppm [mBq/g]</th>
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<td>46</td>
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<td>3</td>
<td>0.3</td>
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</tbody>
</table>
14. Background in underground experiments

Primordial isotopes & Radioactive series (natural radioactivity)

- U and Th isotopes and their daughter activities (like Rn) exist as impurities in all materials found in the nature
  - the problem comes usually from $\gamma$-rays of $^{208}\text{Tl}$ and $^{214}\text{Bi}$
  - $E_\gamma \approx 2.6$ MeV ($^{208}\text{Tl}$)
  - $E_\gamma \approx 2.2$ MeV and $E_\gamma \approx 2.4$ MeV ($^{214}\text{Bi}$)
  - the spectrum (of natural gamma activity) ends up to $\approx 3$ MeV

- Protection by liquid purification or clean way of material production, various methods
  - electrolytically manufactured copper, CVD (Chemical Vapor Deposited) nickel, ...

- Radon ($^{220}\text{Rn}$ ja $^{222}\text{Rn}$)
  - $T_{1/2}^{(220}\text{Rn}) \approx 1$ min
  - $T_{1/2}^{(222}\text{Rn}) \approx 4$ days ("nasty")
  - gaseous material $\longrightarrow$ travels easily in all places
    $\longrightarrow$ diffuses easily through materials
  - daughter activities stack easily on dust or electrostatic surfaces
  - protection $\longrightarrow$ tight structure, overpressure, efficient air condition, ...
14. Background in underground experiments

Cosmogenic isotopes

- Radioactive isotopes produced by cosmic-ray-induced interactions
  - in the atmosphere
  - at the ground

- Number of nuclear interactions $\sim 2000 \text{ kg}^{-1} \cdot \text{d}^{-1}$

- Cosmic-ray radiation can be divided into two classes: primary and secondary cosmic rays
  - at upper atmosphere interaction with primary (and high-energy) particles
  - closer to the surface interactions with secondary (and lower-energy) particles (electrons, muons, protons, neutrons, photons, ...)

- Typically lighter and much shorter-living that primordial isotopes

- For example
  - $^{14}\text{C}$ 5730 yr  $^{14}\text{N}(n,p)^{14}\text{C}$ 0.22 Bq/g in organic materials
  - $^{3}\text{H}$ 12.3 yr  CR: N,O; spall: $^6\text{Li}(n,\alpha)^3\text{H}$
  - $^7\text{Be}$ 53.3 d  CR: N,O
  - Others: $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{37,39}\text{Ar}$, ..., $^{38}\text{Mg}$, $^{80}\text{Kr}$
14. Background in underground experiments

Cosmogenic isotopes

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<td>91</td>
<td>Pa</td>
<td>92</td>
<td>U</td>
<td></td>
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</tbody>
</table>
14. Background in underground experiments

Cosmogenic isotopes

- There are several various cosmic-ray induced reactions that may produce long-lived radioactive isotopes
  - muons, neutrons, protons, electrons, ... 
  - decay energy ($Q$-value) varies from low to high energies
    - high-energy part may cause problems, for example, for double $\beta$-decay or high-energy solar neutrino experiments
    - low-energy part may cause problems, for example, for dark matter searches and low-energy solar neutrino experiments
- Cosmogenics can be produced in the detector material or in the detector shielding material
  - for example, $^{68}\text{Ge}$ ($T_{1/2} = 271$ d) is created in interactions of fast neutrons ($E > 100$ MeV) and $^{76}\text{Ge}$ (stable)
  - fast neutrons (and other particles, as electrons) are produced by high-energy muons
    - anti-coincidence with arriving muon helps to reduce fast-neutron induced events but it does not help to reduce cosmogenics of being created in the detector
14. Background in underground experiments

Cosmogenic isotopes

- Cosmogenic background can be reduced by storing the material and running the experiment deep underground
- Cosmic-ray induced muons
  - the muon flux at the Earth surface $\Phi_\mu \sim 100–150 \text{ m}^{-2}\text{s}^{-1}$
- Protection
  - cosmic-ray induced muon flux attenuates at the rock (or in any material)
  - $\sim 1400$ metres of rock is equivalent with $\sim 4000$ metres of water
- Muon flux measured at the Pyhä-salmi mine as a function of the depth
14. Background in underground experiments

Cosmogenic isotopes – in germanium, an example

- Radioactive isotopes created in a Ge crystall during 10 days by cosmic-ray induced reactions. Then taken underground (Gran Sasso) for one year and measured.
14. Background in underground experiments

Cosmogenic isotopes – in germanium, an example

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Mode</th>
<th>$T_{1/2}$</th>
<th>Energy into crystal [keV]</th>
<th>Activity [µBq/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$H</td>
<td>$\beta^-$</td>
<td>12.33 yr</td>
<td>$E_{\beta^-}=18.6$</td>
<td>3.6</td>
</tr>
<tr>
<td>$^{49}$V</td>
<td>EC</td>
<td>330 d</td>
<td>$E_K(Ti)=5$, no $\gamma$</td>
<td>0.79</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>EC+$\beta^+$</td>
<td>312.3 d</td>
<td>$E_\gamma=840.8$, $E_K(Cr)=5.5$</td>
<td>10.3</td>
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<tr>
<td>$^{55}$Fe</td>
<td>EC</td>
<td>2.73 yr</td>
<td>$E_K(Mn)=6$, no $\gamma$</td>
<td>0.52</td>
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<tr>
<td>$^{57}$Co</td>
<td>EC</td>
<td>271.8 d</td>
<td>$E_\gamma=20.81$, $E_K(Fe)=6.4$</td>
<td>1.17</td>
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<tr>
<td>$^{58}$Co</td>
<td>EC+$\beta^+$</td>
<td>70.9 d</td>
<td>$E_\gamma=817.2$, $E_K(Fe)=6.4$</td>
<td>0.49</td>
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<tr>
<td>$^{60}$Co</td>
<td>$\beta^-$</td>
<td>5.27 yr</td>
<td>$E_{\beta^-}=318$, $E_\gamma=1173,1133$</td>
<td>0.24</td>
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<tr>
<td>$^{63}$Ni</td>
<td>$\beta^-$</td>
<td>100.1 yr</td>
<td>$E_{\beta^-}=66.95$, no $\gamma$</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{65}$Zn</td>
<td>EC+$\beta^+$</td>
<td>244.3 d</td>
<td>$E_\gamma=1124.4$, $E_K(Cu)=8-9$</td>
<td>9.08</td>
</tr>
<tr>
<td>$^{68}$Ge</td>
<td>EC</td>
<td>270.8 d</td>
<td>$E_K(Ga)=10.37$</td>
<td>676</td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>EC+$\beta^+$</td>
<td>67.6 m</td>
<td>$Q$-value=2921.1</td>
<td>676</td>
</tr>
</tbody>
</table>
14. Background in underground experiments

Artificially produced isotopes

- Artificial production of radioactive isotopes started in 1930’s and 1940’s and is since then cumulated in the nature mainly by nuclear weapon test and partly by operation of nuclear power plants
  - significant quantities of $^3\text{H}$ and $^{14}\text{C}$, as well as $^{85}\text{Kr}$, $^{90}\text{Sr}$ $^{137}\text{Cs}$
  - lifetimes are usually smaller compared to primordial isotopes
- Due to nuclear weapon tests
  - the amount of $^{14}\text{C}$ was nearly doubled (between 1952 and 1962),
  - the amounts of $^{39,42}\text{Ar}$ was increased (effect on Argon-detectors)
  - $10^5$ Bq of $^{239,240}\text{Pu}$ spread at the Earth surface
- Accidents in nuclear power plants
  - long-lived isotopes $^{90}\text{Sr}$, $^{137}\text{Cs}$, Pu spread in the environment
  - radioactive noble-gas isotopes $^{42}\text{Ar}$ and $^{85}\text{Kr}$ in the atmosphere
14. Background in underground experiments

Artificially produced isotopes

- The Chernobyl accident also produced atmospheric releases large enough to be detected in sensitive experiments
- Increase in the production of $^{85}$Kr has also been an issue for low-energy solar-$\nu$ experiments
  - $^{85}$Kr emits $E_\gamma \approx 514$ keV gamma ray
  - $\Rightarrow$ exclusion or filtering of atmospheric air is usually practised to eliminate this route of contamination
- HDMS ($\beta\beta$-experiment, Ge)
  - reported no observable $^{137}$Cs activity in 17.7 kg·year of counting in isotope-separated $^{76}$Ge detector
    - $\Rightarrow$ limit of $\sim 10^{-6}$ femtogram of $^{137}$Cs per gram of Ge
  - The radionuclide $^{60}$Co was observed (probably cosmogenic origin)
  - In the inner copper shielding $^{137}$Cs activities were measured (30–100 times larger than the limit for Ge)
    - $\Rightarrow$ emphasis the background level dependency on the chemistry of the material and its history
14. Background in underground experiments

Artificially produced isotopes

- **Examples**
  - $^3$H  12.3 yr  weapon tests and production, reactors
  - $^{14}$C  5730 yr  weapon tests and production, reactors
  - $^{131}$I  8.04 d  weapon test and reactors, medical applications
  - $^{129}$I  $1.57 \times 10^7$ yr  weapon tests and production, reactors
  - $^{137}$Cs  30.17 yr  weapon tests and production, reactors
  - $^{90}$Sr  28.78 yr  weapon tests and production, reactors
  - $^{99}$Te  $2.11 \times 10^5$ yr  decay product of $^{99}$Mo used for med.applics.
  - $^{239}$Pu  $2.41 \times 10^4$ yr  $^{238}$U + n $\rightarrow ^{239}$Np ($\beta^-$) $\rightarrow ^{239}$Pu

- Artificial radioactivity is not usually a serious problem for sensitive physics experiments
14. Background in underground experiments

Common background in experiments

- Astroparticle or underground experiments vary in the physics questions, detection techniques, materials included in the detectors, and physical processes they are sensitive to.
- Despite the differences, they are exposed to a common background radiation environment, including:
  - Direct interactions of particles produced by radioactivity outside the experiment itself (primarily the rock walls), such as $\gamma$-rays from $^{40}$K and ($\alpha$,n) reactions from U and Th in the rock.
  - Radioactive impurities incorporated into the detector material, or any of the surrounding materials, usually long-lived isotopes of the specific material itself.
  - Radioactivities produced in the 'pure' materials, by cosmic-ray (muon produced) neutrons or photodisintegration by $\gamma$-rays.
  - Direct interactions of cosmic rays (muons or neutrinos deep underground) with the detector materials.
14. Background in underground experiments

Proton decay experiments

- Background requirements relatively modest compared with other APP experiments
  - large energy release of several 100s of MeV
  - quite small number of particles involved

- The main background comes from atmospheric-νs
  - gives similar signal
  - can not be reduced by the depth or detector shielding → appropriate event selection criteria (e.g. coincidence)

- Background may arise also from fast neutrons produced by high-energy cosmic rays (muons)
  - the neutron spectrum may extend up to several GeV
  - (still) thicker shielding is not a solution, but may produce even more neutrons
  - the most effective way to reduce fast neutrons is to operate deeper underground
14. Background in underground experiments

Solar neutrino experiments

- Background requirements differ (substantially) depending on the technique, sensitivity and neutrino energy.

- In SNO (or any other with D\(_2\)O), the \(\nu\)-flavour-independent sensitivity comes from the NC reaction \(\nu_x + D \rightarrow n + p + \nu'_x\)
  - \(\gamma\)-background above 2.2 MeV produced in U and Th decay chains could disintegrate the D, resulting nearly similar signal.

- In Borexino, the main background comes from the radioactive decays of cosmogenic isotopes, as \(^3\)H and \(^{14}\)C, as well as \(^{39}\)Ar and \(^{85}\)Kr, and radon produced in the air.

- All solar experiments require very clean instrumentation, low natural background radioactivity, and sufficient overburden to reduce cosmic-ray activity.
14. Background in underground experiments

Supernova neutrino experiments

- Detecting supernova neutrino burst does not produce any specific problems for detectors looking for proton decay or studying solar neutrinos
  - the pulse is quite short ($\sim$10 sec) and have large number of neutrinos

- Diffuse supernova neutrino background is more difficult due to low flux
  - measurement limited by nuclear reactor neutrinos in the low-energy part and atmospheric neutrinos in the high-energy part
  - the nuclear reactor background can be influenced by the location, but the reduction of the background in the high-energy part is difficult
14. Background in underground experiments

Borexino

▶ In Gran Sasso lab. with 3500 mwe of shielding
  ▶ gives $\sim 10^{-6}$ reduction in muon rate: $R_\mu \sim 1.1 \text{ m}^{-2}\cdot\text{h}^{-1}$
    (compare: in Pyhäsalmi $R_\mu \sim 0.5 \text{ m}^{-2}\cdot\text{h}^{-1}$ with 4000 mwe)

▶ Currently the most sensitive detector in neutrino physics
  ▶ 278 tons of liquid scintillator and 889 tons of buffer shielding

▶ Main aim to measure the 862-keV $^7\text{Be}$ $\nu$-flux from the Sun
  ▶ the flux, according to the standard solar model, at the Earth surface is $\sim 4.3\times 10^9 \text{ cm}^{-2}\cdot\text{s}^{-1}$

▶ That flux produces 0.1–0.5 event·ton$^{-1}$.d$^{-1}$ of scintillation material from $\nu - e$ scattering

▶ The liquid scintillator is a solution of 1.5 g/ℓ of PPO (2,5-di-phenyloxazole) in pseudocumene (1,2,4-trimethylbenzene, PC)
  ▶ chosen due to relatively simple purification process and appropriate scintillation properties

▶ In order to detect the flux of this order requires radiopurity levels that have not been obtained earlier; see the table next page
## 14. Background in underground experiments

### Borexino

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Source</th>
<th>Typical level in scintillator without purification</th>
<th>Removal strategy</th>
<th>Design level (&lt; 1 cpd/100 ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C</td>
<td>Cosmic ray activation of $^{14}$N</td>
<td>$^{14}$C/$^{12}$C$\sim 10^{-12}$. Corresponds to equilibrium from cosmic radiation at earth’s surface</td>
<td>Petroleum derivative (old carbon)</td>
<td>$^{14}$C/$^{12}$C$\sim 10^{18}$</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>Cosmic ray activation of $^{12}$C</td>
<td>$2.7 \times 10^7$ cpd/ton. Corresponds to equilibrium for cosmic ray activation of $^{12}$C to $^{7}$Be at earth’s surface</td>
<td>Distillation and underground storage of scintillator</td>
<td>&lt;0.01 cpd/ton</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Air and emanation from materials</td>
<td>$1.3 \times 10^7$ cpd/ton. Corresponds to equilibrium Rn absorption into PC for air with $^{222}$Rn = 10–100 Bq/m$^3$ air</td>
<td>Nitrogen stripping</td>
<td>&lt;0.01 cpd/ton</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>$^{210}$Pb decay</td>
<td>$2 \times 10^4$ cpd/ton. Corresponds to $^{210}$Pb decay after exposing surface of the containment vessel to air with 10 Bq/m$^3$ $^{222}$Rn for 1 year.</td>
<td>Surface cleaning</td>
<td>-</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>$^{210}$Pb decay</td>
<td>$2 \times 10^4$ cpd/ton. Corresponds to $^{210}$Pb decay after exposing surface of the containment vessel to air with 10 Bq/m$^3$ $^{222}$Rn for 1 year</td>
<td>Surface cleaning</td>
<td>-</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>Suspended dust, organometallics</td>
<td>$10^4$ cpd/ton (includes the $^{238}$U$\rightarrow^{206}$Pb decay chain)$&lt;10^{-12}$ g-U/g-scintillator Corresponds to 1 g-dust suspended in 1 ton of scintillator. Dust has U content equal to average of earth’s crust, $10^{-6}$ g-U/g-dust</td>
<td>Distillation, filtration</td>
<td>$&lt;10^{-17}$ g-U/g-scintillator</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Suspended dust, organometallics</td>
<td>$10^4$ cpd/ton $&lt;10^{-12}$ g-Th/g-scintillator. Corresponds to 1 g-dust suspended in 1 ton of scintillator. Dust has Th content equal to average of earth’s crust, $10^{-5}$ g-Th/g-dust</td>
<td>Distillation, filtration</td>
<td>$&lt;10^{-17}$ g-Th/g-scintillator</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>Contaminant found in fluor</td>
<td>$2700$ cpd/ton $\sim 10^{-9}$ g-K/g-scintillator Corresponds to scintillator with 1.5 g-PPO/L and PPO has $10^{-6}$ g-K/g-PPO.</td>
<td>Water extraction, filtration and distillation of fluor solution</td>
<td>$&lt;10^{-14}$ g-K/g-scintillator</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>Air</td>
<td>$200$ cpd/ton. Corresponds to equilibrium Ar absorption into PC for air with $^{39}$Ar = 13 mBq/m$^3$ air</td>
<td>Nitrogen stripping, leak-tight system</td>
<td>&lt;500 nBq/m$^3$-N$_2$</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>Air</td>
<td>$4.3 \times 10^4$ cpd/ton. Corresponds to equilibrium Kr absorption into PC for air with $^{85}$Kr = Bq/m$^3$ air</td>
<td>Nitrogen stripping, leak-tight system</td>
<td>&lt;100 nBq/m$^3$-N$_2$</td>
</tr>
</tbody>
</table>
14. Background in underground experiments

Borexino

Scintillator
270 t PC+PPO (1.5 g/l)
contained in the
Inner Nylon Vessel
R = 4.25 m, 150 mm thick

Buffer Region
PC+DMP (5 g/l)
4.25 m < R < 6.75 m

Outer Nylon Vessel
R = 5.50 m
(\(^{222}\)Rn barrier)

Steel Sphere
R = 6.75 m
2212 PMTs
1350 m\(^3\)

Water Tank
\(\gamma\) and n shield
208 PMTs serve as Cherenkov
Muon Veto
2100 m\(^3\)

Carbon Steel Plates

20 steel legs
14. Background in underground experiments

Borexino

![Borexino Experiment Diagram](image-url)
14. Background in underground experiments

Borexino

- The detection of the electron recoil signal from solar $^7$Be (0.86 MeV) $\nu$-flux in Borexino takes place in the energy window of 0.0–0.66 MeV
  - the estimated rate is 0.1–0.5 events·ton$^{-1}$·d$^{-1}$
  - for pp-$\nu$'s it is $\sim$2 event·ton$^{-1}$·d$^{-1}$
- Such a rare and low-energy neutrinos events has not been measured earlier
  - too large background of the detector material itself, due to natural radioactive contaminants such as $^{232}$Th and $^{238}$U
    $\implies$ cannot be shielded
- (Commercial) high-purity materials certified to ppt level (parts per trillion) in U/Th content
  - background radiation rate much above 0.5 events·ton$^{-1}$·d$^{-1}$ between 0–5 MeV
- Requirement for $^{238}$U level is $10^{-16}$ gU·g$^{-1}$
  - had never been demonstrated
14. Background in underground experiments

Borexino – $^{14}$C level in pseudocumene (PC)

- The spectrum of $^{14}$C ($E_{\text{max}} \approx 0.16$ MeV)
  - overlaps with the pp-\(\nu\) energies (0.0–0.25 MeV)
  - overlaps with the low-energy tail of $^7$Be-\(\nu\)'s

- At the start of Borexino, the most sensitive limit (in any material) of $^{14}$C was $^{14}$C/$^{12}$C $< 10^{-15}$
  - $^{14}$C rate $\sim 2 \times 10^7$ ton$^{-1}\cdot$d$^{-1}$ in an organic liquid
    $\implies$ ruling out of pp- and $^7$Be-measurements

- Organic material naturally free of $^{14}$C only option
  - petrochemical organics (based on natural gas, oil)
  - the underground residence of such materials for millions of years removes the original $^{14}$C
    $\implies$ 'old carbon'

- Isotopically enriched natural gases were tested and ratios of $^{14}$C/$^{12}$C $< 10^{-18}$ were obtained
14. Background in underground experiments

Borexino – Purification

- **Distillation**
  - the most effective process to improve the optical clarity of the scintillator
  - highly effective of reducing several of the radioactive impurities in the scintillator – does not remove noble-gas impurities Ar, Kr and Rn

- **Nitrogen stripping**
  - Ar, Kr and Rn could also be removed using a second line of distillation column
  - in Borexino noble-gases are removed using a separate gas-stripping operation (nitrogen)

- **PPO**
  - commercial product, with too high contamination level of K (level of ppm)
  - purified by modified distillation process
14. Background in underground experiments

Borexino – The detector and purification system
14. Background in underground experiments

Borexino – Measured $^7$Be $\nu$-spectrum

![Graph showing the measured $^7$Be $\nu$-spectrum with various decay curves for different isotopes and a fit with $\chi^2/\text{NDF} = 185/174$.](image-url)
14. Background in underground experiments

Double $\beta$-decay

- Detector: Gd$_2$SiO$_5$:Ce (GSO) (Cerium-doped gadolinium silicate scintillation detector)
- Solotvina Underground Laboratory, salt mine 430 metres underground (1000 mwe)
- Measurement time: 13950 h
- The size of GSO crystal: 95 cm$^3$
- Muons: $1.7 \times 10^{-6}$ cm$^{-2}$·s$^{-1}$
- Neutrons: $2.7 \times 10^{-6}$ cm$^{-2}$·s$^{-1}$
- Radon in air: $< 30$ Bq/m$^3$
14. Background in underground experiments

Double $\beta$-decay – 2
14. Background in underground experiments

EMMA

- Two types of detectors
  - drift chambers (0.73 m², Ar(92%):CO₂(8%) 1 bar)
  - SC16 scintillation detectors (thickness 3 cm)
  - Limited Streamer Tube detectors

- Cosmic-ray secondaries counting rate
  - at the ground \( R \approx 150 \text{ Hz} \cdot \text{m}^{-2} \) (muons and electrons)
  - 75 m underground \( R \approx 1 \text{ Hz} \cdot \text{m}^{-2} \) (muons)

- Counting rate of one drift chamber (\( A \sim 1 \text{ m}^2 \))
  - at the ground \( R \approx 200 \text{ Hz} \) (expected \( R \approx 100 \text{ Hz} \))
  - 75 m underground \( R \approx 100 \text{ Hz} \) (expected \( R \approx 1 \text{ Hz} \))

\[ \implies \] Where does the extra \( R \approx 100 \text{ Hz} \) comes from?

- The 100 Hz background in a drift chamber has been identified to consists of gamma radiation
  - drift chambers are extremely unefficient detectors for \( \gamma \)-rays
  - how to get rid of it?
14. Background in underground experiments

EMMA – drift chambers

- How to reduce the gamma background in EMMA?
  - drift chamber is just a counter (no energy-loss information)
  - trigger logic ('detecting only interesting events')

Background trigger rate

5 x

300 Hz
400 Hz

5 x

300 Hz
400 Hz

5 x 700 Hz
3500 Hz

(3 μs) AND

\( R_{BG} ? \)
14. Background in underground experiments

EMMA – drift chambers

- Background trigger rate is number of trials $\times$ trigger gate width

$$R_{BG} \approx 3500 \text{ Hz} \times 3500 \text{ Hz} \times 3 \, \mu\text{s} \sim 40 \text{ Hz}$$

- With three detector layers: $R_{BG} \sim 4 \text{ Hz}$

- Number of triggering muons ($\sim 1 \text{ Hz} \cdot \text{m}^{-2}$): $R_{\mu} \sim 6 \text{ Hz}$
  - the total trigger rate is $R \sim 10 \text{ Hz}$

- The gamma-ray background in EMMA can be handled by tight enough (but not too tight) trigger condition
  - gamma-ray background do not influence on the operation or on the muon showers, but would increase the amount of data substantially (and fill the hard disk)
14. Background in underground experiments

EMMA – SC16 scintillation detectors

- The thickness of the SC16 scintillation detectors in EMMA is 3 cm
  - there is a reason for that

- Natural (or primordial) radioactivity produces $\gamma$-rays of
  - $E_\gamma \approx 1.4$ MeV ($^{40}$K)
  - $E_\gamma \approx 2.6$ MeV ($^{208}$Tl)
  - $E_\gamma \approx 2.2$ MeV and $E_\gamma \approx 2.4$ MeV ($^{214}$Bi)
  - the spectrum (of natural gamma activity) ends up to $\approx 3$ MeV

- Muons (at high energy; minimum ionising particles, MIPs) release
  $\sim 2$ MeV/cm in plastic scintillator ($\approx$ water)
  - in SC16 $\Delta E \approx 6$ MeV
  - energy loss above the 3 MeV background limit
14. Background in underground experiments

EMMA – Gamma-ray background

Measured at the depth of 75 m in Station B, with germanium detector