Chapter 1

Radiopurity and background model

For a ton–year of ^{136}Xe, and an effective mass of the neutrino of 50 meV, we are expecting a few counts per year at the $Q_{\beta\beta}$ energy of 2.457 MeV. To be sensitive to such a low number of counts, we need a background of the order of 10^{-4} counts/keV/kg/year in a region of interest (ROI) of 1% around the $Q_{\beta\beta}$ energy (a few ten counts per year –around 10^{-3} counts/keV/kg/year – for an effective neutrino mass of 100 meV). This implies the use of clean materials and a shielding to protect the experiments against the laboratory walls contamination, mainly the 2.615 Mev photons coming from the ^{208}Tl isotope of the radioactive chains with a flux around 0.13 γ/cm^2/s [1] and ^{214}Bi photons of 2.448 MeV, much less abundant but dangerous since are very close to the $Q_{\beta\beta}$ energy.

First studies presented in the LOI showed that using a 6.5 cm–thick lead shielding around 1 cm thick copper vessel, the number of counts, after analysis software cuts, coming from walls were around 2 counts/keV/kg/year. It also added almost 10^{-2} counts/keV/kg/year by itself due to their ^{208}Tl and ^{214}Bi contaminants (a contamination of 1 mBq/kg in ^{238}U and ^{232}Th for the lead was assumed). Therefore a thicker and cleaner shielding was needed. Further simulations indicate that the thickness of the shielding should be around 25 cm in the case of lead. Moreover materials should be clean enough with contaminations less than 100 μBq/kg for the first cm's of the lead shielding.

Radon in air, water and from material emanation will affect the experiment and the shielding project must study how to eliminate this contribution. With this aim, an estimate of the relevance of the airborne ^{222}Rn ($T_{1/2}$=3.8 days) has been done in the case of a lead castle structure. Assuming a radon contamination of 100 Bq/m^3 and 2.55 m^3 of air volume (around 20 cm of distance between vessel and shielding), 400 counts would be registered after cuts in our detector. This has to be avoided surrounding the whole setup with a plastic bag containing nitrogen or working in a radon free room (airborne radon around 10 mBq/m^3.

Another worrisome radon source are materials: vessel, inner part of the shielding, cabling, gaskets ... Here, the ^{222}Rn contribution from vessel and shielding has been estimated assuming 10 μBq/kg for ^{238}U contamination in copper and 1 mBq/kg in lead and a radon diffusion distance of 0.1 mm in both lead and copper (which means a total emanation of around 2 Bq). This value implies a contribution of a few 10^{-4} counts/keV/kg/year. To reduce 1 order of magnitude it is needed to renew the whole volume, 2.5 m^3, every 13.4 hours while two orders implies a renewal every 1.3 hours (5 l of liquid N_2 are enough to fill up this volume). The higher the nitrogen flux, the lower the radon contribution. The case of ^{220}Rn has not been considered since if decays in less than 1 min into polonium which it is not a gaseous isotope and the emanation is expected to be much lower.

Other possible external sources of background are neutrons, whether produced by natural radioactivity in the walls or shielding or as secondary products of cosmic muons. Preliminary estimations seem to point that these contributions are very much below the level of concern for NEXT. High energy gammas can be produced in muon-induced electromagnetic cascades. Although they too seem to be of no importance for NEXT, they could be partially tagged by using active muon veto in the shielding.

Therefore, we assume that the shielding fulfils the following specifications, which allow us to neglect in our background model all external gamma contributions, all radioactive emission from shielding materials (other that the innermost cm´s of vessel and first layer of shielding) and contribution from radon and its progeny

- The shielding should be thick enough to decrease the number of external background counts below a few counts per ton and year ($\approx 10^{-4}$ counts/kg/keV/year). The chosen option is a lead castle (around 25 cm–width) in which a first layer of copper (around 5 cm) have to be included since the screened lead is not clean enough.
- The radiopurity of the different layers of the shielding must be such that each of the layer's contribution to the background, after attenuation of the material inside that layer, does not amount in total to more than the stated 10^{-4} counts/kg/keV/year. The radiopurity of the innermost layer, in particular, has the strongest radiopurity constraint, at the level of the detector components themselves. This is achieved by the lead castle option by using an inner lining of about ~ 5 cm high purity copper ($\sim 10\,\mu$Bq/kg)
- The shielding is built with anti-radon measures mentioned above (radon-tight tent, radon-free gas flushing system), so that it efficiently fights against radon emanation from materials or radon diffusion from the laboratory air, and bring the radon concentration down to negligible levels for NEXT.

This assumptions justify the exclusion from our background model of all external sources of background as well as radioactivity from the shielding materials, other than the innermost 3 cm of copper of the shielding or vessel. We will focus in the following in the identification of all possible internal sources of background and therefore on the radiopurity of the inner materials.

1.1 Control of material radiopurity

Information on radiopurity of the materials expected to be used in the construction of NEXT100 has been compiled, performing specific measurements and also taking data from the literature for materials not screened yet. Relevant materials for shielding, vessel, High Voltage and Electroluminiscence components, detector components at the energy and tracking planes and others (Xe gas, gas system,. . .) have been taken into consideration. This collection is intended to be helpful for:

- The selection of radiopure materials, identifying if possible, the provider or a model of the component giving the lowest activities. Information on previous measurements helps to establish fair priorities in the use of Ge detectors.
- The construction on the NEXT100 background model, providing reference activities to normalize simulations.

The techniques employed up to now for the radiopurity measurements performed for NEXT are GDMS (Glow-Discharge Mass Spectrometry) and germanium spectroscopy. GDMS measurements have been made by Shiva Technologies (Evans Analytical Group) in France; this method (very suitable for metals) is fast and requires only a small sample of the material, but as the output is only the concentration of elements, particular isotopes are not identified and broken secular equilibrium in the chains cannot be detected. Ge spectroscopy measurements have been made at the Canfranc Underground Laboratory, using a ∼1 kg detector operated by the University of Zaragoza and the ∼2 kg detectors from the Canfranc Underground Laboratory. The possibility of using ICPMS (Inductively-Coupled Plasma Mass

Spectrometry) was explored in collaboration with CIEMAT but achievable sensitivity has not been fixed yet.

Results of all radiopurity measurements performed for NEXT are compiled at a database available for the collaboration by means of a web application [2], including all the available, relevant information.

1.1.1 Shielding

Lead: samples from different providers (Mifer, Tecnibusa and COMETA) have been screened by GDMS. Results are shown at rows #1-5 in Table 1.1. Specifications on radiopurity of COMETA lead (row #2) agree with the measured activities and offer <100 mBq/kg of ^{210}Pb. A half-brick sample of Tecnibusa lead has been measured at the Canfranc Underground Laboratory using a Ge detector (GeAnayet); results are presented at row #6 in Table 1.1.

Copper: samples from different origins (Luvata company with both hot and cold rolling, Sanmetal company and electroformed copper at University of Zaragoza) have been screen by GDMS. Results are shown at rows #7-11 in Table 1.1.

More measurements performed on these materials in the framework of different experiments are compiled at the documentation page of the website [2]. Water containers and polyethylene have not been taken into consideration since, in principle, they are not going to to be used.

1.1.2 Vessel

Titanium: Ti grade 2 (or grade 3) was expected to be used for cylindrical shell, flanges, heads, nozzles and supports in the vessel.

- A sample from Nironit, grade 1, type A35, Titanium was measured for the XENON experiment using the GATOR detector at Gran Sasso Laboratory [7]. Results are shown at row #12 in Table 1.1.

- One Ti sample coming from the batch used in the LUX cryostat (type CP1) was screened using different techniques and after undergoing different treatments. Qualitative information on this sample was obtained also from PIXE (Particle Induced X-ray Emission) and RBS (Rutherford Back Scattering) analysis at the Centro Nacional de Aceleradores in Sevilla. Results are shown at rows #14-16 in Table 1.1. An important surface contamination was produced at some step when handling the sample; after polishing it, removing a thin layer of ∼0.5 mm, the high activity levels were dramatically reduced (compare results at rows #15 and #16 in Table 1.1) but results coming from different techniques are not fully compatible. The LUX collaboration has recently presented the results of an exhaustive analysis of Ti samples [8]; best activities, corresponding to a 8-kg sample measured using Ge detector MAEVE (ORO), are also shown at row #13 in Table 1.1.

- A sample of grade 2 Titanium coming from a Spanish provider, Titanio SMP[1], has been screened with two of the 2-kg Ge detectors (GeOroel,GeTobazo) of the Canfranc Underground Laboratory. It consisted of 8 1-mm-thick cylinders having a total mass of 121 g. A standard cleaning protocol was including:

  1. Diamond cut.
  2. Diamond-sanding to remove the titanium oxide surface.
  3. Cleaning with acetone (alcohol was avoided because it can affect the mechanical properties).
  4. Acid-detergent.

[1] http://www.titaniosmp.com/

5. Nitric acid-bat, to remove iron that may be on the surface without affecting the titanium).
6. Back to clean with acetone.
7. Saving in an hermetic plastic bag.

Preliminary results are shown at rows #17-18 in Table 1.1. The cross-check exercise of screening a sample using two different Ge detectors was satisfactory.

- A sample of grade 2 Titanium from Titanium Metal Supply[2], as the one used by the LUX Collaboration, has been screened at the Canfranc Underground Laboratory with detector GeOroel. It consisted of three cubes ($50\times50\times50$ mm^3 corresponding to a mass of 0.57 kg each) and underwent the standard cleaning protocol fixed and described before. Preliminary results are shown at row #19 in Table 1.1.

Stainless steel: vessel could also be made of this material.

- One sample of type **304L** from Pfeiffer has been screened using the Ge detector from University of Zaragoza at Canfranc. Results are shown at row #20 in Table 1.1. Type AISI304L was also analyzed by Borexino [3].
- Type **316L** was studied using GDMS for the DRIFT experiment by UKDMC and results are reported at [16] and summarized at rows #21-22 in Table 1.1. Many samples of this type of steel were analyzed also at SNOLab [6] and results for one of the cleanest sample are quoted at row #23 in Table 1.1, but values up to one order of magnitude higher were also found.
- Material referenced as **austenitic 1.4571** (also 316L) has been extensively studied by GERDA and by XENON. Best values reported in Table 1 at [4] (measurement #7) are for stainless steel 316Ti supplied by Nironit, 1.5-mm-thick and used for the XENON cryostat wall; they are presented at row #24 in Table 1.1. Best results obtained by GERDA (sample #2) [5] are also quoted at row #25 in Table 1.1. According to these measurements, values or upper limits on activity at the level of even tenths of mBq/kg can be found for isotopes from the natural chains at the best case.
- Samples of different types and suppliers have been analyzed by several experiments, like for instance at SNOlab (NA Stainless, Nironit, Swagelok, 316L) [6].

Screening of stainless steel samples from Nironit company, having different thicknesses suitable for different parts of NEXT100 vessel, has started at Canfranc Underground Laboratory.
Inconel: bolts will be made of this material. Samples of Inconel 718 (diameter: 32 mm, height: 50 mm) and Inconel 625 ($80\times70\times10$ mm^3) from the Spanish company Mecanizados Kanter[3] have received the standard cleaning protocol and have been screened with one of the 2-kg Ge detectors (GeOroel) of the Canfranc Underground Laboratory. Preliminary results are shown at rows #27-28 in Table 1.1.

Concerning the joints and gaskets, Helicoflex seals from Garlock (Al jacket) could be used, although materials like peek, PCTFE or viton could be also relevant.
PCTFE: EXO has screened a PCTFE sample, reported as "Saint Gobain supplied Daikin Neoflon PCTFE (Kel-F), M-400H, raw material" at measurement #50 at [9]. Results are shown at row #29 in Table 1.1.
Viton: a sample for O-ring seal was screened by EXO (measurement #154 at [9]). Results are shown at row #30 in Table 1.1.

Electron beam, TIG or MIG are possibilities for the welding. A sample referenced as "Stainless steel TIG" from Harris Product Group has been screened at SNOlab and results are quoted at row #26 in

[2]http://www.titaniummetalsupply.com
[3]http://www.mecanizados-kanter.es/

Table 1.1. EXO has reported (measurement #6 at [9]) the concentrations of Th and U after TIG welding on a copper sample: <9.8 pg/cm of Th, 10.2±3.4 pg/cm of U. A filler for TIG soldering, made of Ti grade 2 (diameter: 2 mm) supplied by ETM company is being screened at Canfranc Underground Laboratory.

1.1.3 High Voltage and Electroluminiscence components

The main components of the *field cage* will be copper rings, resistors and peek. High density polyethylene could also be used.
Peek: a sample (18 bars) from Sanmetal company has been screened using the Ge detector from University of Zaragoza at Canfranc. Values obtained are shown at row #31 in Table 1.1. Results from another measurement on peek presented at [10] are quoted at row #32 in Table 1.1.
Resistors: surface mount precision plate resistors supplied by Finechem were screened by XENON (measurement #44 at Table 1 in [4]). Results are shown at row #33 in Table 1.1. SMD resistors from both Finechem and Farnell have been also measured at Canfranc with the Ge detector from University of Zaragoza and results are presented at rows #34-35 in Table 1.1.
Polyethylene: samples of material to be used as neutron moderator in shieldings have been screened for different dark matter experiments; best results from EDELWEISS (supplier Plastiques du Rhone) presented at [16] and from XENON (supplier in2plastic, measurement #14 in Table 1 at [4]) are shown at rows #36-37 in Table 1.1. More results are available at [16]. Polyethylene insulator from cables has been analyzed by EXO and values from measurement #199 at [9] are quoted at row #38 in Table 1.1.

The *High Voltage feedthroughs* will consist of a metal rod pressed into a plastic tube (Tefzel or FEP). Copper shields could be used.

For the *Electroluminiscence grids*, the mesh will be made of stainless steel.

The *light tube* will be made of Tetratex fixed over a 3M substrate, coated with TPB. ArDM has screened specifically PTFE Tetratex from Donaldson Membranes by ICPMS [11]. Results are summarized at row #39 in Table 1.1. TPB from two different manufacturers have been measured at SNOlab [6] and results are presented at rows #40-41 in Table 1.1.
Teflon: samples from many different origins have been screened in the context of several experiments (a compilation is available at the documentation page of the website [2]).

- The cleanest one we are aware of is DuPont Teflon TE-6472, for which raw material has been measured by EXO using Neutron Activation Analysis (NAA) (measurement #43 in Table 3 at [9]); these results are summarized at row #42 in Table 1.1.
- GERDA has also reported results for a clean Teflon sample (Dyneon TF 1620) [12], quoted at row #43 in Table 1.1; at [13], where slightly different activities are reported for this PTFE, it is said that it was sintered on special request in a clean way by ElringKlinger Kunstofftechnik GmbH.

1.1.4 Detector components

Energy plane

Different models of *photomultipliers* have been under consideration.

- **Hamamatsu R8520-406**: many different batches of model R8520 have been screened in the context of the XENON100 experiment; an average of measured activities has been made using results in Table 1 at [4] (considering batches from 1 to 17 excluding 3, 5 and 6) and is shown at row #44 in Table 1.1. Activities on a custom base for this PMT model are also reported at measurement #40 in Table 1 at [4] and summarized at row #45 in Table 1.1.
- **Hamamatsu R7378A:** activity is ∼50 mBq/PMT of ^{238}U and ^{232}Th [14].

- **Hamamatsu R11410MOD:** XENON (measurement #38 in Table 1 at [4]) and LUX [15] have measured activities for this photomultiplier, quoted at rows #46-47 in Table 1.1. Specifications provided by Hamamatsu for this model are also shown at row #48 in Table 1.1. This photomultiplier could be placed in copper cans.

The photomultiplier *tubes* could be made of titanium and their cables could be collected in a copper tube. A photomultiplier *feedthrough* made of steel and glass ceramic, having 41 pins Au plated supplied by Ceramtec company has been screened at Canfranc Underground Laboratory using GeTobazo detector. Results are in progress.

Sapphire and quartz have been proposed as possible materials for the *windows* coupling PMTs to the vessel.

Sapphire: sapphire crystals from different origin have been screened within the ROSEBUD experiment; best results from [16] are summarized at rows #49-50 in Table 1.1. Sapphire windows have been measured by EXO (from Swiss Jewel Company, substrate for EXO high voltage resistors). Results obtained using NAA (measurement #155 in [9]) are quoted at row #51 in Table 1.1.

Quartz (or fused silica): different kinds of quartz have been screened by EXO (measurements #61 to #67 at [9]) using NAA. One of the cleanest sample is Heraeus 2, having activities reported at row #52 in Table 1.1.

Tracking plane

The *daughter boards* for *SiPM* will be made of cuflon coated with TPB. Silicon, as germanium, is a very radiopure material with intrinsic activities of ^{238}U and ^{232}Th at the level of some μBq/kg [17]. Information on TPB from [6] was presented at rows #40-41 in Table 1.1.

Cuflon: a circuit board made of cuflon was screened for the EDELWEISS experiment and the results taken from [16] are shown at row #53 in Table 1.1. GERDA has reported more stringent results for cuflon at [12], shown at row #54 in Table 1.1. A cuflon sample was analyzed by ICPMS and Ge gamma spectroscopy at [18], and results are shown at rows #55-56 in Table 1.1; even independent results for Cu and Teflon have been reported from ICPMS.

For the *mother boards* or other *electronic boards*, many different types of circuit boards from several providers have been screened for different experiments, like EDELWEISS. Results taken from [16] are shown at rows #57-65 in Table 1.1. PCBs of fr4 have been proposed to be used in the in-vessel electronics, being necessary, for 107 front-end boards, 5.6 kg of fr4 together with 2.9 of copper; measurements of a fr4 PCB performed using the Ge detector of University of Zaragoza are reported at row #66 in Table 1.1. Glass fiber-reinforced materials at base plates of circuit boards can be a source of radioactive contamination [17]. In addition to quite high activity levels, an unacceptable rate of outgassing has been observed for this material. Components made of just kapton (like cirlex) and copper offer very good radiopurity, as shown in the measurements of kapton-copper foils published at [19] and reported at row #67 in Table 1.1 and in the screening of a monolayer PCB made of kapton and copper supplied by LabCircuits using the Ge detector of the University of Zaragoza, presented at row #68 in Table 1.1.

Concerning *soldering*, no specific information has been found for the radiopurity of the Sn/Pb wire usually used for electronics; some data are available for metal soldering using Sn/Ag or silver at [16]. Screening to select the best wire seems to be consequently mandatory. The involved mass per SiPM soldering has been measured as 0.045 mg (2.88 g per board having 8×8 SiPMs). An alternative proposed to SiPM soldering would be the use of epoxies. Results of a radiopurity measurement for EPO-TEK 301-2 adhesive are available at [20] and shown at row #69 in Table 1.1. Concerning silver epoxy, information taken from [16] (EPO-TEK H20E, Epoxy Technologies) and from [20] (EPO-TEK 417F, Epoxy Technologies, thick silver paste) is presented at rows #70-71 in Table 1.1; a specially radiopure silver epoxy (Tra-Con Tra-Duct 2902, from Ellsworth[4]) has been identified by American colleagues and the measured

[4] http://www.ellsworth.com/tracon.html

activities are reported at row #72 in Table 1.1 [21]. More results on epoxies, adhesives or glues can be found at [16] (for ''glues"), [20] and [6].

Connectors FFC/FCP (Flexible Printed Circuit & Flexible Flat Cable) are necessary for SiPM daughter bards. Information on this kind of connector supplied by Molex company is available from the EDELWEISS experiment at [16] and reported at row #73 in Table 1.1. Data on other kind of electric connectors (supplied by ITT Canon, Glenair, Omnetics, Fischer) can also be found at [16]. Jupiter connectors were screened by Borexino [3] and High Voltage connectors (from Kings) at SNOlab [6].

Regarding *resistors*, measurement results on SMD resistors supplied by Finechem and Farnell has been presented at rows #33-35 in Table 1.1, being those of the first company more radiopure. More information on carbon resistors or from other suppliers is available at [16].

No information has been found for SMD or electrolytic *capacitors*. Screening results for tantalum capacitors (150 μF, supplied by AVX) are reported at [16] and shown at row #74 in Table 1.1. According to measurements available also at [16], ceramic capacitors seem to be far more radioactive than the screened tantalum ones.

Different kinds of wires and cables have been screened; for example, coaxial cables from Axon [16], by EXO [9], from Caburn-MDC by XENON [4], from Habia (Cu/PTFE) by GERDA [12]. Information on High Voltage cables is also available at [16], [9] or [4] (silver coated, kapton insulated cables supplied by Caburn-MDC for XENON). Copper wires were screened by EXO [9]. Information on optical fibers from Luceat has been also presented by XENON [4]. A collection of some measurements of radiopurity of connectors, resistors, capacitors, wires,... was made and is available at the documentation page of the website [2].

No information has been found for specific components like ADCs, amplifiers, voltage regulators or transceivers to be used in the front-end boards making part of the in-vessel electronics; therefore, screening of these components is required.

1.1.5 Others

Xe gas: activities of ^{238}U and ^{232}Th chains were estimated by means of $\beta\alpha$ (BiPo sequences) and $\alpha\alpha$ coincidences at the Gotthard experiment [22], being of 0.11 mBq/kg of ^{238}U and 0.02 mBq/kg of ^{232}Th. Information on activities of ^{85}Kr and ^{39}Ar could be deduced from the purity measurements performed for both natural and enriched xenon by EXO200 [23].

Regarding the *gas system*, pipes and valves as well as temperature, pressure or flux sensors located inside the shielding and moreover inside the vessel must be controlled. Just as an example, the HF4000 CARTEN valve ($\sim$47.7 kg), used for turbomolecular pump and mostly made of 316L stainless steel, would be close to the vessel requiring possibly to be inside a radiopure cap.

Materials for other elements of the experimental set-up still to be defined, like the calibration or the slow control systems, should be also considered.

After collecting available information and in order to efficiently perform new radiopurity measurements, the following conclusions can be drawn:

- As it can be deduced from Table 1.1, no information on radiopurity has been found at the literature for inconel, Helicoflex gaskets, SiPM or materials for HV feedthroughs; specific measurements for these components are therefore mandatory and must be completed or undertaken in the next future. Construction of new daughter boards with SiPMs for the tracking plane will be undertaken in the following months taking care of radiopurity of components and measurements at different steps are necessary.

- Concerning photosensors, although there is available information on photomultipliers, boards and other relevant materials, as soon as final components to be used in NEXT100 are chosen, a campaign to screen them should start. Screening of the recently purchased Hamamatsu R11410MOD photomultiplier will be made soon.

- There is a great deal of information and also measurements made on purpose for NEXT regarding vessel and shielding materials, but specific measurements on stainless steel are now of high priority to fix the vessel design.

Table 1.1: Activities of ^{238}U , ^{232}Th and ^{40}K measured in relevant materials and following different techniques.

#	Material	Technique	Unit	^{238}U	^{232}Th	^{40}K	Ref.
	Shielding						
1	Pb, Cometa	GDMS	mBq/kg	0.37	0.073	<0.31	NEXT
2	Pb, Cometa		mBq/kg	<0.5	<0.5	<1	Cometa
3	Pb, Mifer	GDMS	mBq/kg	1.24	0.32		NEXT
4	Pb, Mifer, new provider	GDMS	mBq/kg	0.33	0.10	1.21	NEXT
5	Pb, Tecnibusa	GDMS	mBq/kg	0.73	0.14	0.91	NEXT
6	Pb, Tecnibusa	Ge (by LSC)	mBq/kg	<1.3 (e)	<0.9 (f)	<1.8	NEXT (+)
7	Cu, Luvata C10100	Ge (by UZ)	mBq/kg	<11.0*	<9.7*	<17.7*	NEXT
8	Cu, Luvata C10100 hot rolled	GDMS	mBq/kg	<0.012	<0.004	0.061	NEXT
9	Cu, Luvata C10100 cold rolled	GDMS	mBq/kg	<0.012	<0.004	0.091	NEXT
10	Cu, Electroformed	GDMS	mBq/kg	<0.062	<0.020		NEXT
11	Cu, ETP Sanmetal	GDMS	mBq/kg	<0.062	<0.020		NEXT
	Vessel						
12	Ti, Nironit, XENON	Ge	mBq/kg	0.93±0.24 (b)	0.22±0.10	0.90±0.30	[7]
13	Ti, LUX	Ge	mBq/kg	6.2±1.2, <0.19	<0.25	<0.9	[8]
14	Ti, LUX	GDMS	mBq/kg	52	2.5	<1.5	NEXT
15	Ti, LUX	Ge (by UZ)	mBq/kg	238±28	417±54	49±11	NEXT
16	Ti, LUX, after polishing	Ge (by UZ)	mBq/kg	<15*	4.2±1.4	<22*	NEXT
17	Ti, SMP	Ge (by LSC, GeOroel)	mBq/kg	<9.4 (e)	<9.4 (f)	<19	NEXT (+)
18	Ti, SMP	Ge (by LSC, GeTobazo)	mBq/kg	<6.3 (e)	<7.7 (f)	<9.3	NEXT (+)
19	Ti, Ti Metal Supply	Ge (by LSC)	mBq/kg	<0.30 (e)	3.2±0.3 (f)	<0.52	NEXT (+)
20	Stainless Steel, Pfeiffer 304L	Ge by UZ	mBq/kg	14.8±2.8 (a)	10.4±2.0 (a)	<16.6	NEXT
21	Stainless steel 316L, Elantic, UK, DRIFT	GDMS	mBq/kg	17.4±1.2	3.3±0.4	<9.3	[16]
22	Stainless steel 316L, block, Italy, DRIFT	GDMS	mBq/kg	<6.2	8.2±0.8	<9.9	[16]
23	Stainless steel 316L, SNOlab	Ge	mBq/kg	0.63±0.15 (b)	0.62±0.15	<0.97	[6]
24	Stainless steel 316Ti, Nironit, XENON	Ge	mBq/kg	<1.9 (b)	<1.0 (d)	10±4	[4]
25	Stainless steel Austenitic 1.4571, GERDA	Ge	mBq/kg	<0.24 (b)	<0.11 (d)	<0.93	[5]
26	Stainless steel TIG, SNOlab	Ge	mBq/kg	1.01±0.71 (b)	2.8±0.8	<1.45	[6]
27	Inconel 718	Ge (by LSC)	mBq/kg	<5.6 (e)	<4.6 (f)	<11	NEXT (+)
28	Inconel 625	Ge (by LSC)	mBq/kg	<1.8 (e)	<2.0 (f)	<2.6	NEXT (+)

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#	Material	Technique	Unit	^{238}U	^{232}Th	^{40}K	Ref.
29	PCTFE, Daikin Neoflon, EXO	Ge	mBq/kg	5.6±1.2	<2.3	<30	[9]
30	Viton, O-ring seal, Johannsen AG, EXO	Ge	mBq/kg	868±87	130	2170±226	[9]
	HV and EL components						
31	Peek, Sanmetal	Ge (by UZ)	mBq/kg	36.3±4.3	11.7±2.2	8.3±3.0	NEXT
32	Peek	Ge	mBq/kg	<70 (b)	<50 (d)	<260	[10]
33	SM5D, 700MΩ resistors, Finechem, XENON	Ge	mBq/pc	0.027±0.003 (b)	0.014±0.003 (d)	0.19±0.03	[4]
34	SMD resistors, Finechem	Ge (by UZ)	mBq/pc	0.022±0.007 (e)	<0.016* (f)	0.17±0.07	NEXT
35	SMD resistors, Farnell	Ge (by UZ)	mBq/pc	0.15±0.04 (e)	0.28±0.06 (f)	0.19±0.08	NEXT
36	Polyethylene, EDELWEISS	Ge	mBq/kg	16±10 (e)	<6 (f)	70±50	[16]
37	Polyethylene, XENON	Ge	mBq/kg	0.23±0.05 (b)	<0.14 (d)	0.7±0.4	[4]
38	Polyethylene insulator, EXO	NAA	mBq/kg	<2.9	<0.57	1.46±0.22	[9]
39	Tetratex, ArDM	ICPMS	mBq/kg	12.4±3.7	<1.6	<16	[11]
40	TPB, Sigma-Aldrich, SNOlab	Ge	mBq/kg	1.63±1.01 (b)	0.47±1.11	8.22±12.03	[6]
41	TPB, American Chemicals, SNOlab	Ge	mBq/kg	<4.33 (b)	<1.69	<36.29	[6]
42	Teflon, Du Pont TE-6472, EXO	NAA	mBq/kg	<0.0096	<0.0011	0.0558±0.0062	[9]
43	PTFE, Dyneon TF 1620, GERDA	Ge	mBq/kg	0.025±0.009 (b)	0.031±0.014 (d)	0.60±0.11	[12]
	Detector components: energy plane						
44	PMT, Hamamatsu R8520, XENON	Ge	mBq/PMT	0.19±0.01 (b)	0.20±0.02(d)	9.9±0.4	[4]
45	PMT base, Hamamatsu R8520, XENON	Ge	mBq/base	0.16±0.02 (b)	0.07±0.02 (d)	<0.16	[4]
46	PMT, Hamamatsu R11410MOD, XENON	Ge	mBq/PMT	<2.4 (b)	<2.6 (d)	13±4	[4]
47	PMT, Hamamatsu R11410MOD, LUX		mBq/PMT	<0.4	<0.3	<8.3	[15]
48	PMT, Hamamatsu R11410MOD		mBq/PMT	3.3	2.3	5.7	Hamamatsu
49	Sapphire, Czochralsky Type, ROSEBUD	Ge	mBq/kg	<5 (e)	<5(f)	<30	[16]
50	Sapphire, Verneuil Type, ROSEBUD	Ge	mBq/kg	<3 (e)	<3(f)	<12	[16]
51	Sapphire window, EXO	NAA	mBq/kg	<0.31	0.123±0.029	<0.20	[9]
52	Quartz, Heraeus 2, EXO	NAA	mBq/kg	0.068±0.027	0.027±0.005	0.062±0.016	[9]
	Detector components: tracking plane						
53	Cuflon, circuit board, EDELWEISS	Ge	mBq/kg	<23 (e)	<30 (f)	400±200	[16]
54	Cuflon, Crane Polyflon, GERDA	Ge	mBq/kg	<0.85 (b)	<1.9 (d)	±15	[12]
55	Cuflon	Ge	mBq/kg	<0.84 (b)	<1.9	48±15	[18]
56	Cuflon	ICPMS	mBq/kg	$0.36^{+0.07}_{-0.04}$	$0.28^{+0.04}_{-0.03}$	6^{+9}_{-2}	[18]
57	ARJOPROX, ARLON	Ge	Bq/kg	<0.044 (e)	<0.065 (f)	0.3±0.2	[16]
58	ARAMID paper, CIMULEC	Ge	Bq/kg	<0.06 (e)	0.04±0.03 (f)	0.15±0.14	[16]
59	Kapton, AXON	Ge	Bq/kg	0.07±0.03 (e)		0.3±0.2	[16]
60	Kapton+Cu, KAPPA Industrie	Ge	Bq/kg	0.014±0.012 (e)	0.013±0.012 (f)	<0.09	[16]
	(Follows at next page)						

(Continuation)

#	Material	Technique	Unit	^{238}U	^{232}Th	^{40}K	Ref.
61	Kapton+Cu, SOGGEG (g)	Ge	Bq/kg	<0.08 (e)	0.05±0.04 (f)	<0.9	[16]
62	Kapton+Cu, CIRE (g)	Ge	Bq/kg	0.09±0.05 (e)	<0.08 (f)	0.7±0.4	[16]
63	Kapton+Cu, CIRE (g)	Ge	Bq/kg	0.28±0.26 (e)	0.3±0.2 (f)	<2.1	[16]
64	Kapton+Cu ATLANTEK (g)	Ge	Bq/kg	<0.06 (e)	<0.02 (f)	0.4±0.2	[16]
65	Polyamide+Cu VISHAY	Ge	Bq/kg	9.1±0.2 (e)	3.3±0.2 (f)	7.0±0.7	[16]
66	FR4 PCB	Ge (by UZ)	Bq/kg	0.4	0.24	1.5	
67	Kapton-copper foil	Ge (by UZ)	mBq/cm^2	<0.011	<0.0046*	<0.0077*	[19]
68	Kapton-copper PCB, LabCircuits	Ge (by UZ)	mBq/cm^2	<0.014* (e)	<0.003* (f)	<0.040*	
69	EPO-TEK 301-2FL, Epoxy Tech.	Ge	mBq/kg	9±3 (b)	<60 (d)	<25	[20]
70	EPO-TEK H20E, silver, Epoxy Tech.	Ge	mBq/kg	<25 (e)	<40 (f)	600±400	[16]
71	EPO-TEK 417F, silver, Epoxy Tech.	Ge	mBq/kg	68±11 (b)	<131 (d)	<65	[20]
72	Tra-Con Tra-Duct 2902 silver epoxy, Ellsworth	ICPMS	mBq/kg	0.98±0.05	0.045±0.004		[21]
73	FFC/FCP connector, Molex	Ge	mBq/unit	3.0±0.2 (e)	1.8±0.1 (f)	3.5±0.5	[16]
74	Tantalum capacitor, AVX	Ge	Bq/kg	0.32±0.05 (e)	0.41±0.05 (f)	0.3±0.2	[16]

(a) Average on different isotopes
(b) Activity of ^{226}Ra
(c) Two values for early/late part of chain
(d) Activity of ^{228}Th
(e) Activity from ^{214}Bi
(f) Activity from ^{208}Tl
(g) Special fabrication
(*) Level obtained from the minimum detectable activity of the detector (MDA)
(+) Preliminary result.

1.2 Radon emanation and background contribution

1.2.1 Emanation in gas system and radon activity in detector

Let us consider a source of radon emanation anywhere in the gas system adding Rn222 atoms in gas with a rate of λ_e. Then, these atoms decay with a period of $T_{1/2}$=3.82 days, implying a decay constant of λ_d=ln(2)/(3.83 × 24 × 60)=1.26 × 10^{-4} min^{-1}.

The number of Rn220 atoms at time t in the system will follow the equation

$$\frac{dN}{dt} = \lambda_e - \lambda_d N, \tag{1.1}$$

whose solution accounts for the total number of ^{222}Rn nuclei

$$N(t) = \frac{\lambda_e}{\lambda_d}(1 - e^{-\lambda_d t}). \tag{1.2}$$

In the case of a large time we get an maximum and stable number of atoms, which depends on the rapport between production and decaying $N(t)=\lambda_e/\lambda_d$, and an activity of $A(t)=\lambda_d N(t)=\lambda_e$. Therefore, the emanation rate can be directly translated into activity. ^{222}Rn decays (99.98%) into ^{218}Po (positively charged Po ions in 80% of the cases) which will be deposited on the cathode and accumulated there as an extra . Assuming that only 80% of the Xe is inside the fiducial volume, and that the cathode has a diameter of around 115 cm, the 214Bi contamination of the cathode due to the radon dissolved in gas will be

$$R_e \times 0.8 \times 0.8/10387 \sim 62 \times R_e \qquad (\mu\,\mathrm{Bq/cm^2}), \tag{1.3}$$

R_e being the emanation rate in ^{222}Rn nuclei/s. As radioactive contamination in cathode and readout is one of our main concerns due to the proximity of these components to the fiducial volumen, we should requiere very low Bi214 contaminations, at least of the order of that of the readout (it has been measured 26 μ Bq/cm^2 for MM's).

Some emanation data

Emanation data contributing to the Xe gas radon contents have been collected in literature. The Bi214 deposition on cathode has been estimated considering that 80% of the circulating volume is inside the fiducial volume; also another 0.8 factor take into account the neutral ^{218}Po ions.

Another contribution to the radon contents of the xenon gas may be tubing and piping for recirculation. Assuming 8 m of stainless steel piping (0.5 inch diameter), the emanation surface would be around 0.31 m^2. SNO collaboration gives a limit for steel emanation around $80\times10^{-6}\,\mathrm{s^{-1}/m^2}$, which translated into ^{214}Bi on the cathode gives a contamination of the order of nBq/cm^2, totally negligible.

More emanation rates can be looked for in the bibliography, but it is worthy to make some remarks:

- The most worrisome materials are those in close contact with the gas in its way to the vessel, since any emanation rate here is equivalent to radon activity inside the chamber.
- Once emanation stops, radon activity decreases with radon decay half life.
- All radon emanation measurements have been performed in vacuum. Emanation depends on pressure difference and, for a high pressure vessel, emanation rate due to inner material should be negligible. This is not the case inside the circulation system and filters.
- In all references, electronic cables present an important radon emanation due to the high number of cables and, therefore, the large exposed surface (for coax cables the estimated exposed area is 2500 m^2 in SNO). An N_2 overpressure between vessel and shielding would minimize the emanation of the closest cables to the detector.

Type	Description	weight (kg)	emanation (mBq)	Temp. (°C)	^{214}Bi (μBq/cm^2)	source
cold getter	Fe/Mn Zeolite	0.360	1640 (4)	20	102	Internal comm.
cold getter	Ni Zeolit	0.360	620 (4)	20	38	Internal comm.
hot getter	Zr	0.360	<LDL	20		Internal comm.
Sieve	CarbonsieveTM SIII	0.01	67E-4(17)	20	4E-4	GERDA
			1.5 (3)	150	9E-4	GERDA
			8.0(6)	330	5E-3	GERDA
	Molecular sieve 13X	1280	0.627(63)	20	4E-2	SNO
Filter	Trigon	0.093	46.3 (2.2)	150	3	GERDA
			46.1 (3.9)	20	3	GERDA
	Oxisorb	0.100	1.9	20	0.12	GERDA

Table 1.2: Vacuum emanation data for different filters. The ^{214}Bi deposition on cathode has been roughly estimated (see text for explanation).

More ^{222}Rn emanation data can be extracted from ^{238}U radiopurity data, assuming a few microns for emanation length in metals and almost a cm in plastics (emanation length in porous materials is much larger), but screws, gaskets, internal tubes ... increase the exposed surface and, therefore, radon emanation. Most of the double beta or dark matter experiments have carried out radon emanation measurements, though they usually stay as internal reports. Some of the published data can b found in references [24]-[26].

1.3 Background model

The background of the experiment can be affected by all components of the detector close enough to the active volume, through their radiopurity, and, in particular, also the readout radiopurity. To build a **background model** for an experiment like NEXT several factors have to be taken into account: the tracking performance (the topological information provided by the readout is used to perform cuts on the data and reduce the background), effects of the diffusion, pixel threshold or energy resolution. The last two factors depend strongly on the readout while diffusion goes with the use of a gas and depends mainly on the pressure and on the length of the vessel; the tracking performance has a dependence on the readout pixelization and also on diffusion.

Diffusion effects

The high diffusion coefficient in pure Xenon implies a wider ionization electron cloud. The spreading of the charge makes the tracking more complicated since more pixels are hit and the charge per pixel is lower. It strongly depends, moreover, on the distance to the readout and at high z it more difficult identify events as *one track* instead of two depositions (which could be caused by background events). One of the consequences of diffusion is that tracks produced by different electrons (as for example, those caused by multicompton interactions) merge and fake two electron tracks. To eliminate them, analysis parameters have to be adjusted to *clean* the connection; however, this will also affect signal events and imply an efficiency lost, more pronounced at larger distances to the readout. Then, in the case of high diffusion media, analysis procedure to look for one track events should include a certain z dependence. Another consequence of diffusion is that the energy deposition at the end of the track (*blobs*) spreads over a large radius making it more difficult to distinguish this deposition from the energy deposited at other points of the track. This effect is more difficult to solve through analysis since events at high z are too *rounded*. The use of quenchers would decrease diffusion and make easier separate events at any position.

Tracking performance

In gas TPCs the ionization track of the particle along the medium can be registered with relative precision. This topological information can be used to identify and reject background events.

For the purpose of the present document, the discrimination algorithms used rely only on 3 conservative categories of topological information of the event tracks. These algorithms are an extension of those initially developed in [27], where also the basic concepts are introduced and studied. The three categories are:

- **Fiducial cut**: the outermost cm of the active volume is treated as a veto, i.e. events depositing energy close to the edges of the field cage are rejected. This discrimination criterion rejects electron events associated with surface contamination (β emission) or with interactions in the wall materials.
- **Single "connection" cut**: this method aims at singling out only events with just one track or connection. The raw background at $\sim$2.5 MeV energies is largely composed by gammas interacting

several times via Compton scattering in the gas. They are composed by more than one connection, and so they are easily rejected by this criterion. Unfortunately, $\beta\beta$ events may also yield multi-connection topologies (due to bremsstrahlung emission), and therefore this provokes an efficiency loss. Due to the wiggling nature of electron tracks of these energies (due to multiple scattering) the algorithm makes use of Graph Theory concepts developed in [27] to identify and number the connections of the event. Diffusion tends to merge connections that otherwise would appear disconnected. In order to reach some immunity against this, the algorithm plays with energy thresholds of neighboring pixels.

- **Two-blobs cut**: once events with just one connection are selected, those with 2 identifiable large energy deposits at the ends (blobs) are singled out. These blobs are the expected feature of an electron slowing down in the gas due to the increase of the dE/dx of electrons at lower energies. Two such blobs are expected in signal two-electron $\beta\beta 0\nu$ events, while only one in average single-electron background events. The algorithm developed always assigns blob candidates to the events, then main track between two of these candidates is drawn using the segments obtained in the connection method. Finally the charge of the blobs found at both ends is compared, since signal-events are expected to have similar energy depositions at the end of both electron tracks. Features of the background events (δ-rays, random accumulation of charge, bremsstrahlung photons interaction close to the main track) may be misidentified as blobs.

As background events have different sources, the rejection factor for each cut depends on the origin of the contamination. Then, surface events will show a higher fiducial veto rejection factor since for these events charged particles emitted at the same time than photons reach the sensitive detector volume; the one connection cut will be more effective for ^{208}Tl events since they have a higher probability to suffer multicomptom interactions (more than one connection) in ROI than ^{214}Bi events; while the capability to identify one or two electrons in selected tracks does not depend on the origin of the track. In table 1.3 we show the effect in contributions coming from parts far from target and from parts around it.

Origin	Rejection Factor (F)			
		Fiducial Cut	Single Connection	Two Blosb Cut
Far from target	Tl-208	1.3	45	6
	Bi-214	1.1	15	6
Readout	Tl-208	5	45	6
	Bi-214	50	15	6

Table 1.3: Effect of each discrimination cuts sequentially applied on elements near target (as readout) and and far from the xenon volume. Values shown here are mean values obtained from different simulations and analysis. Rejection factors of a cut are expressed in relation to the previous cut surviving events.

All the analysis parameters have been chosen to get high rejection factors avoiding a significant loss of efficiency. Table 1.4 shows the signal reduction due to the analysis. Signal events might be produced near detector walls and therefore be affected by the fiducial cut; but, what its more relevant in the efficiency reduction: Bremsstrahlung emission produces more than one track, loss of charge if the photon left the chamber, or a faked blob if interacts near the chamber.

	Efficiency			
	RoI	**Fiducial Cut**	**One track**	**Topological Cut**
$\beta\beta0\nu$	0.92	0.79	0.37	0.27

Table 1.4: Effect of the different cuts on the signal efficiency (surviving events versus total events), for our region of interest (RoI). Cuts have been sequentially applied.

As already said, pattern recognition is the main advantage gas offers versus liquid and we are conscious that in our way to be sensitive to lower neutrino masses, this point is crucial. However very high pressure an diffusion make more confuse the distinction between signal and background. The higher the pressure, the shorter and twisted the track; the higher the diffusion the more difficult to distinguish two track and to identify "blobs". Though some studies have been done to quantify these effects, some lines can be drawn to continue:

1. Study the effect of quenchers lowering the diffusion. Preliminary studies show also that the clearer the track the better the pattern recognition.
2. Improve the identification of events interacting near the readout or the cathode. Analysis of real data will be very helpful in this direction.
3. Continue the study on the way the charge is deposited along the track at different pressure conditions, in order to try to extract further topological information from dE/dx. Study pressure effects on real data.
4. Use these algorithms to analysis data from an electron source as cesium.
5. Continue the research for a better identification of bremsstrahlung photons interacting near the main track.

Background model

An appropriate background model for NEXT should include as many background sources as possible, together with a description of the geometry of the detector and a simulation of its response as faithful as possible.

All external sources beyond the detector vessel are excluded from our background model. This is justified only if the specifications expressed in that section for the shielding are met, namely: 1) that the shielding is thick enough to stop all relevant external gamma radiation down to negligible levels for NEXT, 2) that the "clean" innermost part of the shielding is thick enough to stop any radioactivity from the outer part of the shielding, and that it is as clean, at least, as the vessel material itself. Moreover, we identify this innermost material (high purity copper) with the vessel material(it could be also and inner lining) and therefore only the innermost 3 cm of shielding/vessel are representative and are included in the background model.

Moreover, we have made an effort to identify as many elements as possible of the inner components of the detector, their material, quantity, and potential radiopurity, as they will be unavoidable sources of background. Only decays capable of populating the $Q_{\beta\beta}$ area have been considered, namely ^{208}Tl, from the ^{232}Th natural chain, and ^{214}Bi from the ^{238}U chain. The simulated geometry includes only the main media of geometrical relevance: the vessel parts (body, encaps and flanges) and lining, the field cage teflon support and copper rings, the readout (simplified into a single plane of contamination), cathode, and a plane representing the PMT contamination. Simulated data from some prototype geometrical locations has been generically generated (vessel, field cage, cathode, readout). The contribution of smaller elements not included in the geometry (e.g the field cage resistors or the flat cables) are estimated by taking the data simulated from the prototype location that matched most the geometry of that element, and properly renormalizing it using its mass and radiopurity. For example for the resistors, the simulation from the field cage was used. We took care that in these procedures the approximations performed went always in the conservative direction. For example, for the flat cables estimation we used the data simulated from the readout plane, although the flat cable geometry

is however partially obscured by copper from the endcap. In this way, the following list of elements have been identified to estimate their contribution:

- The body of the vessel (0.5 cm–thick Titanium or 1 cm–thick Steel): cylindrical body plus flanges and the 2 endcaps.
- A possible copper inner lining of 5–6 cm thick.
- The cylindrical field cage composed by copper strips imprinted in teflon.
- A possible cylindrical teflon piece supporting the drift cage and isolating the high voltage from the vessel (2 cm thick).
- A 90% transparent copper cathode mesh.
- A possible cylindrical cover made by teflon and situated between drift and vessel walls to avoid sparks in these region. Thickness 2cm.
- 3 bars made by teflon to support the drift.
- The readout plane, its support and cables and electronics to extract the signals form the pixels to the feedthroughs.
- The PMT plane to measure t_0 (including sapphire windows).
- A copper bar covering the high voltage wire that give voltage to the cathode.
- Silver to do the connections between resistors and field cage.
- Extra protective teflon pieces above the cathode and composing the HV feedthrough.

The contribution of each of these elements, both by their ^{208}Tl and ^{214}Bi contaminations, have to be singled out. First estimates tell us that the main contribution will come from the vessel (steel or titanium), copper lining, readout and PMT planes, with contributions each higher than 10^{-4} counts/keV/kg/year while elements like PTFE electrical protections, cathode or field cage show contributions below this level.

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