Material screening and selection for XENON100

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Material screening and selection for XENON100

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Abstract

Results of the extensive radioactivity screening campaign to identify materials for the construction of XENON100 are reported. This Dark Matter search experiment is operated underground at Laboratori Nazionali del Gran Sasso (LNGS), Italy. Several ultra sensitive High Purity Germanium detectors (HPGe) have been used for gamma ray spectrometry. Mass spectrometry has been applied for a few low mass plastic samples. Detailed tables with the radioactive contaminations of all screened samples are presented, together with the implications for XENON100.

Keywords: Dark Matter, Material Screening, Low Activity, HPGe

1. Introduction

The indirect evidence of a significant cold dark matter component in the Universe \cite{1,2,3} motivated the start of several experiments aiming to directly detect Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs) \cite{4,5,6}. The possible existence of WIMPs is supported by beyond-Standard Model theories such as supersymmetric theories (SUSY), models with extra dimensions and little Higgs models \cite{7,8,9,10}. Several experiments are aiming to directly detect WIMP dark matter by searching for the elastic scattering of WIMPs on target nuclei. XENON100, which has recently published one of the best limits on spin-independent WIMP-nucleon scattering cross sections \cite{11,12}, is one of the most sensitive experiments of the current generation. It is a double-phase (liquid/gas) time projection chamber (TPC) \cite{13}, which allows fiducialization of the active target and discrimination of the nuclear recoil signal from electronic recoils, induced by background radiation. The former is made possible by a reconstruction of the interaction vertex in three dimensions, whereas the latter is possible because of the different charge to scintillation light ratio for the two types of interaction \cite{14}.

In order to reach its design sensitivity, the experiment is to be built from materials with a very low intrinsic radioactivity. Therefore, the radioactive screening and selection of materials has played an important role in the design and during the construction phase of XENON100, as well as in the background simulation of the experiment \cite{15}. The XENON collaboration used the High Purity Germanium (HPGe) detector Gator \cite{16}, operated by the University of Zurich, to perform gamma ray spectrometry in order to determine the intrinsic radioactivity of materials considered for the construction of XENON100. Moreover, HPGe detectors of the low-level counting facility at Laboratori Nazionali del Gran Sasso (LNGS), Italy, \cite{17} were also used. This facility includes the GeMPI-I and GeMPI-II detectors, which are the most sensitive low-radioactivity HPGe detectors in the world \cite{18}. The radioactivity of a few low-mass samples has been determined by mass spectroscopy.

This paper is organized as follows: First the radiopurity requirements of experiments searching for Dark Matter are reviewed, followed by a short description of the methods used for the sample screening in Sections \cite{3} and \cite{4} The results are presented and discussed in Section \cite{5}.
2. Radiopurity Requirements for direct Dark Matter Searches and XENON100

Experiments searching for Dark Matter are often limited by background radiation from the detector materials and surroundings, including a possible radiation shield, and by interactions induced by cosmic rays, especially muons.

Generally, particles can interact either with the atomic electrons of the detector material (electronic recoils) or with the target nuclei (nuclear recoils). Since the electrically neutral WIMPs and neutrons are both expected to produce nuclear recoils, neutrons are the most dangerous background for Dark Matter experiments, as they can potentially mimic a WIMP signal. In most cases, however, the dominating background is from electronic recoils. For this reason, most experiments employ at least one technique to discriminate between nuclear and electronic recoils.

The dominant electronic recoil background usually comes from γ-rays from radioactive isotopes in the shield and in the detector itself. β-decays only contribute when they occur in the target or at the target’s surface. Depending on the energy of the electrons, they can generate Bremsstrahlung in the vicinity of the sensitive volume, which might add an additional source of background. α-decays do not directly contribute to the background at low energies, given the typical α energies of > 3 MeV. However, they might indirectly contribute to the nuclear recoil background, as they can produce neutrons in (α, n) reactions and cause nuclear recoils from daughter nuclei. Another source of neutrons is from spontaneous fission of 238U.

The most relevant sources of radioactive contamination in the XENON100 experiment are primordial radionuclides (238U, 232Th and 80Kr), anthropogenic radionuclides (137Cs, 85Kr), cosmogenic radionuclides (mainly 60Co) and environmental radioactive noble gases, such as 222Rn and 220Rn which are daughters of the 238U and 232Th decay chains.

The goal of the XENON100 experiment is to probe spin-independent WIMP-nucleon scattering cross sections down to the level of ∼2 × 10^{-45} cm². In order to reach this sensitivity, one of the key requirements on the experiment design is the suppression of background and a total electronic recoil background of < 10^{-2} events keV^{-1} kg^{-1} day^{-1} is required. This is achieved by shielding the detector from environmental radioactivity with a passive shield, by the detector design using an active LXe veto scintillator, fiducial volume cuts, and by constructing the detector from materials with a low intrinsic radioactivity [15].

3. Gamma Ray Spectrometry with HPGe Detectors

When measuring the intrinsic radioactivity of a sample material with high purity germanium (HPGe) detectors, one exploits the excellent energy resolution of these detectors, together with the very low background spectrum of dedicated counting setups. This allows to identify radioactive contaminations by identification of the γ-lines from their decay [19]. The spectrometers used for the measurements presented here are installed underground at LNGS, at a depth of 3100 meters water equivalent relative to a flat overburden, where the muon flux is reduced by a factor ~ 10^6 with respect to above ground. This also reduces the neutron flux by several orders of magnitude since the hadronic showers from cosmic rays are completely blocked and muon induced neutrons are strongly suppressed. The remaining neutron flux is mainly due to fission and (α, n) reactions. A ventilation system constantly brings fresh air from the outside to the laboratory, leading to a rather constant 222Rn concentration of ∼30 Bq/m³ at the location of the HPGe spectrometers.

In this section we briefly describe the facilities used for this study and how the measurements were analyzed.

**Gator Facility.** Gator [16] is a High Purity p-type coaxial germanium detector of 2.2 kg sensitive mass, a relative efficiency of 100.5%[4] and a measured resolution of ∼3 keV FWHM at 1332 keV. In order to ensure high detection sensitivities, the detector and its shield have been constructed using materials selected for their extremely low intrinsic radioactive contaminations. The shield of Gator fulfills the crucial requirements of having sufficient sample capacity and low intrinsic background, and uses nitrogen purging against radon and its progenies. The inner dimensions of the sample cavity are 25 × 25 × 33 cm³, with the detector reaching into the cavity. The total available volume is ∼19 liters. An example measurement, showing the different gamma lines for the spectrum of a sample measured with Gator, is shown in Fig. 1.

![Figure 1: Example of a measurement with Gator: 7 Hamamatsu R8520 PMTs were screened (entry 34 in Table 1). The lines from their intrinsic radioactive contaminations (solid black) are clearly visible above the Gator background spectrum (blue).](image)

**LNGS Counting Facility.** The low background germanium counting facility of LNGS [17] is equipped with several high-purity coaxial germanium detectors with large sensitive volumes, low intrinsic background and high energy resolution (< 2.6 keV FWHM at 1332 keV). They include GeMPI-I and GeMPI-II [18], the most sensitive screening facilities worldwide. For all detectors and shields, only selected materials with lowest intrinsic radioactivity have been used. The sample cavities have volumes which range from one liter up to 15 liters (GeMPI-I/II).

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1The efficiency is defined relative to a 7.62 cm × 7.62 cm NaI(Tl) crystal, for the 1.33MeV 60Co photopeak, at a source-detector distance of 25 cm [21].
Measurement. In order to increase the sensitivity of a γ-counting measurement, it is beneficial to use massive samples. Since placing the samples very close to the detector also increases the efficiency, the best configuration is to place the samples on top of the germanium crystal. For large or heavy samples, however, this requirement cannot always be fulfilled and the sample has to be placed around the detector.

Before the measurement, the samples are properly cleaned from surface contaminations in an ultrasonic bath of pure ethanol (> 98%). Afterwards they have been stored in an environment purged with pure boil-off N₂ for several days in order to let ²²²Rn and its progenies decay or diffuse out. Once the samples are inserted into the spectrometers, the γ-ray spectra are acquired automatically using standard multi-channel analyzers. The measurement time varied according to the sample. Typically it was in the range of days to several weeks. Data analysis has been performed off-line after the measurement.

As the geometrical arrangement of every sample is unique, the detection efficiency has been calculated for every measurement using Monte Carlo simulations. For Gator, the GEANT4 toolkit [20] is used, while the LNGS facility detectors employ simulations based on GEANT4, GEANT3.21 and EGS4 (Electrons Gamma Showers). In all cases, the whole sample and detector geometry is coded. Standard sources of known activity are regularly used to test the reliability of this method of efficiency estimation, giving excellent agreement [16].

Analysis. To determine the concentration of a specific radioactive decay chain, the characteristic γ-lines of the chains are considered:
- ²³²Th chain: ²²⁸Ac, ²¹²Pb, ²¹²Bi and ²⁰⁸Tl.
- ²³⁸U chain: ²³⁴Pa, ²³⁴Th, ²¹⁴Pb and ²¹⁴Bi.
- ²³⁵U chain: ²³⁵U.

In some cases the activity of ²³⁵U is deduced from that of ²³⁸U by taking into account their relative abundance in natural uranium (0.70% of ²³⁵U and 99.27% of ²³⁸U). The activities of the different decay chains are calculated taking into account the mass of the sample, the measurement time, the efficiency from the Monte Carlo simulation and the number of counts in the characteristic γ-line. The background spectrum, which is measured regularly and the Compton continuum from other lines are subtracted. More details on the analysis can be found in [16]. Upper limits are calculated using the method introduced in [22] for Gator and in [23] for the LNGS screening facility.

Secular equilibrium can be verified for ²³²Th because of the relatively high branching ratios of the γ-lines emitted in the initial part of the chain. For most of the screened samples this is not possible for ²³⁸U. However, upper limits obtained from the γ-lines of the daughters ²³⁴⁰Pa and ²³⁴Th do not exclude the secular equilibrium hypothesis. The only samples for which a break in the secular equilibrium of ²³⁸U has been detected are the field shaping resistors and the ceramic feedthrough (entries 44 and 46 in Table 1): the radioactivity of the different parts of the decay chain are given explicitly there.

All other relevant radioactive nuclides contributing to the γ-ray spectra (such as ⁴⁰K, ⁶⁰Co, ¹³⁷Cs, etc.) are analyzed using their most prominent γ-lines at specific energies and branching ratios.

4. Inductively Coupled Plasma Mass Spectrometry

For a few plastic samples, with a total mass too small to yield reasonable sensitivity with the HPGe detectors, inductively coupled Plasma-Mass Spectrometry (ICP-MS) has been used to determine the intrinsic radioactivity. The ICP-MS 7500a from Agilent Technologies employed here is a quadrupolar mass spectrometer using an argon plasma torch (ICP-torch) to ionize the sample.

Before the procedure, the samples are cleaned and prepared as described in Section 3. They are then ashed at 600°C, using the dry ashing procedure described in [24] and dissolved in a 10% ultra pure nitric acid solution, which is nebulized in a spray chamber where it forms an aerosol. The aerosol is atomized and ionized by the ICP-torch, producing a cloud of positively charged ions. The ions are extracted from the plasma into an ultra high vacuum system containing a quadrupole analyzer, where they are separated according to their mass-to-charge ratio q. The count rate obtained for a particular q is compared with a calibration curve to determine the concentration of the elements in the sample.

For the samples screened with the ICP-MS secular equilibrium is assumed.

5. Results and Discussion

The main results from the screening campaign are presented in Table 1. It lists the material, the supplier and its use in the XENON100 experiment (see also Section 5.5). It provides details on the measurement (detector, measurement time and sample mass) and gives the measured radioactive contaminations or, where no spectral lines have been observed, upper limits at 95% confidence level. In this Section, the most relevant results are discussed.

5.1. Metal Samples

Lead is used for the XENON100 passive shield. Material from two different suppliers was screened (entries 1-4 in Table 1). The lead from Plombum FL is a standard lead while the one from Fonderies de Gentilly has a low contamination of ²¹⁰Pb. This was confirmed in both HPGe facilities, however, measured with different sample masses. When evident lines are detected, the results are in agreement, when only upper limits can be given, the limits from the measurement with more mass are considerably lower. The ²¹⁰Pb activities are (530±70) Bq/kg and (26 ± 6) Bq/kg for lead with high and low ²¹⁰Pb contamination, respectively.
| Material                  | Supplier         | Use                      | Detector | Time [d] | Amount | Unit | $^{226}$Ra | $^{228}$Th | $^{238}$U | $^{235}$U | $^{40}$K | $^{137}$Cs | $^{60}$Co |
|---------------------------|------------------|--------------------------|----------|----------|--------|------|------------|------------|-----------|----------|--------|-----------|----------|
| Metal                     |                  |                          |          |          |        |      |            |            |           |          |        |           |          |
| 1. Lead                   | Pbolum           | Outer Pb shield          | Gator    | 18.4     | 2.27 kg| mBq/kg| < 6.9     | < 0.52     | < 260     | < 4.2    | < 12    | 14(3)    | < 0.81  |
| 2. Lead                   | Pbolum           | Outer Pb shield          | LNGS     | 14.5     | 44 kg  | mBq/kg| < 6.6     | < 1.6      | < 130     | < 5.7    | < 51     | 14(6)    | < 2.1   |
| 3. Lead                   | Foundaries de Gentiilly | Inner Pb shield     | Gator    | 17.8     | 2.27 kg| mBq/kg| < 0.66    | < 0.42     | < 24      | < 0.71   | < 1.8   | < 1.46   | 0.63(6) |
| 4. Lead                   | Foundaries de Gentiilly | Inner Pb Shield       | LNGS     | 18.7     | 44 kg  | mBq/kg| < 3.9     | < 4.3      | < 33      | < 6.8    | < 20    | < 28     | < 0.85  |
| 5. Copper                 | Norddeutsche      | Shield                  | Gator    | 51.4     | 512 kg  | µBq/kg| 21(7)     | 21(7)      | 70(20)   | 70(20)   | 3.4     | 23(6)    | 2(1)    |
| 6. Copper                 | Norddeutsche      | TPC                     | Gator    | 20.3     | 18.1 kg| mBq/kg| < 0.37    | < 0.33     | < 11      | < 0.37   | < 0.47  | < 1.3    | 0.14    |
| 7. Stainless Steel        | NIRONIT          | Cryostat wall           | LNGS     | 6.87     | 1.2 kg | mBq/kg| < 2.4     | < 1.0      | < 130     | < 1.9    | < 2.0   | 10(4)    | < 0.9   |
| 8. Stainless Steel        | NIRONIT          | Cryostat bottom         | LNGS     | 20.6     | 1.97 kg| mBq/kg| < 3.1     | < 1.5      | < 42      | < 2.7    | < 1.4   | < 12     | < 0.88  |
| 9. Stainless Steel        | NIRONIT          | Grid frame              | Gator    | 6.76     | 6.6 kg | mBq/kg| < 4.1     | < 1.8      | < 130     | 3.6(8)   | < 5.8   | < 5.7    | 1.1     |
| 10. Stainless Steel       | NIRONIT          | Top flange/Support bars | LNGS     | 5.58     | 1.52 kg| mBq/kg| < 0.92    | 2.9(7)     | < 20      | < 1.3    | < 7.1   | < 0.82   | 1.4(3)  |
| 11. Screws 2-56 7/16"    | McMaster         | Standard screw          | Gator    | 12.1     | 0.27 kg| mBq/kg| 26(5)     | < 21       | < 550     | < 13     | < 25     | < 47     | < 5.1   |
| Plastic                   |                  |                          |          |          |        |      |            |            |           |          |        |           |          |
| 12. Polyethylene          | in2plastic       | Shield wall             | Gator    | 5.85     | 2.76 kg| mBq/kg| < 5.4     | < 3.7      | < 170     | < 5.1    | < 7.6   | < 14     | < 1.7   |
| 13. Polyethylene          | in2plastic       | Shield door             | Gator    | 3.12     | 3.1 kg | mBq/kg| < 4.3     | < 5.8      | < 220     | < 6.5    | < 9.9   | < 13     | < 2.1   |
| 14. Polyethylene          | in2plastic       | Shield                  | LNGS     | 28.9     | 8.44 kg| mBq/kg| < 0.094   | < 0.14     | < 3.8     | 0.29(5)  | < 0.37  | 0.7(4)   | 0.06(3) |
| 15. PTFE                  | Maagtechnic      | TPC                     | Gator    | 14.35    | 13.5 kg| mBq/kg| < 0.39    | < 0.16     | < 6.2     | < 0.31   | < 0.28  | < 2.25   | < 0.13  |
| 16. PTFE                  | Maagtechnic      | TPC                     | Gator    | 47.4     | 23.5 kg| mBq/kg| < 0.16    | < 0.10     | < 3.0     | < 0.06   | < 0.13  | < 0.75   | < 0.07  |
| 17. PTFE                  | McMaster         | Veto reflector          | ICP-MS   | 5.1 g    | mBq/kg| 0.5(1)  | 0.5(1)    | 0.25(5)   | 0.25(5)  | 0.011(2) | < 3.1   |
| 18. PTFE                  | McMaster         | XENON10                 | LNGS     | 10.1     | 0.23 kg| mBq/kg| < 1.8     | < 2.3      | < 36      | < 1.1    | < 1.4   | < 7.6    | 0.44    |
| 19. PTFE                  | APT              | Not used                | LNGS     | 23.5     | 6.54 kg| mBq/kg| < 0.15    | < 0.13     | < 12      | < 0.16   | < 0.59  | 3(1)     | < 0.11  |

Table 1: Screening Results. See text for discussion.
Table 1: Screening Results (continued).

| Material        | Supplier            | Use                  | Detector | Unit | Time [d] | Amount |
|-----------------|---------------------|----------------------|----------|------|----------|--------|
| Light Sensors   |                     |                      |          |      |          |        |
| 20. R8520 - Batch 1 | Hamamatsu          | Top array, veto      | LNGS     | 11.6 | 7 pc     | mBq/PMT | 0.32   |
| 21. R8520 - Batch 2 | Hamamatsu          | Bottom array         | LNGS     | 21.6 | 7 pc     | mBq/PMT | 0.22   |
| 22. R8520 - Batch 3 | Hamamatsu          | Not used             | LNGS     | 6.65 | 1 pc     | mBq/PMT | 2.1    |
| 23. R8520 - Batch 4 | Hamamatsu          | Top array            | LNGS     | 18.4 | 7 pc     | mBq/PMT | 0.23   |
| 24. R8520 - Batch 5 | Hamamatsu          | Not used             | LNGS     | 12.8 | 4 pc     | mBq/PMT | 0.49   |
| 25. R8520 - Batch 6 | Hamamatsu          | Not used             | LNGS     | 10.4 | 5 pc     | mBq/PMT | 0.42   |
| 26. R8520 - Batch 7 | Hamamatsu          | Top/bottom array, veto | LNGS     | 24.4 | 39 pc    | mBq/PMT | 0.087  |
| 27. R8520 - Batch 8 | Hamamatsu          | Top array, veto      | LNGS     | 11.9 | 48 pc    | mBq/PMT | 0.11   |
| 28. R8520 - Batch 9 | Hamamatsu          | Bottom array         | LNGS     | 4.7  | 23 pc    | mBq/PMT | 0.5(2) |
| 29. R8520 - Batch 10 | Hamamatsu         | Bottom array         | Gator    | 5.5  | 22 pc    | mBq/PMT | 0.59   |
| 30. R8520 - Batch 11 | Hamamatsu          | Veto                 | LNGS     | 17.1 | 15 pc    | mBq/PMT | 0.19(3)|
| 31. R8520 - Batch 12 | Hamamatsu          | Bottom array         | Gator    | 9.34 | 12 pc    | mBq/PMT | 0.70   |
| 32. R8520 - Batch 13 | Hamamatsu          | Top array            | LNGS     | 11.9 | 10 pc    | mBq/PMT | 0.13   |
| 33. R8520 - Batch 14 | Hamamatsu          | Bottom array         | LNGS     | 5.12 | 4 pc     | mBq/PMT | 0.33   |
| 34. R8520 - Batch 15 | Hamamatsu          | Bottom array         | Gator    | 9.51 | 7 pc     | mBq/PMT | 0.97   |
| 35. R8520 - Batch 16 | Hamamatsu          | Top/bottom array, veto | Gator    | 5.6  | 11 pc    | mBq/PMT | 1.1    |
| 36. R8520 - Batch 17 | Hamamatsu          | Top/bottom array     | LNGS     | 10.4 | 5 pc     | mBq/PMT | 0.32   |
| 37. QUPIDs       | Hamamatsu/ UCLA    | R&D for XENON        | Gator    | 60.0 | 5 pc     | mBq/QUPID | 0.4 |
| 38. R11410-MOD   | Hamamatsu          | R&D for XENON        | Gator    | 20.4 | 1 pc     | mBq/PMT | 3.8    |
| 39. R11410       | Hamamatsu          | R&D for XENON        | LNGS     | 11.9 | 1 pc     | mBq/PMT | 2.7    |

Connections, Cables, etc.

| Material        | Supplier          | Use                  | Detector | Unit | Amount |
|-----------------|-------------------|----------------------|----------|------|--------|
| 40. R8520 PMT base | Custom Luceat     | PMT base calibration | LNGS     | 6.0  | 48 pc  |
| 41. PMMA-PFA optical fiber |                | PMT calibration    | ICP-MS   | 6.0  | 48 pc  |
| 42. Coaxial cable (RG174) | Cabarn-MDC      | PMT Signal          | LNGS     | 5.0  | 100 m  |
| 43. Kapton cable (1-CC-0712) | Cabarn-MDC     | PMT High Voltage    | LNGS     | 14.0 | 79.6 g |
| 44. Surface mount precision plate, SMD, 700MΩ resistors | Finechem | TPC, drift field shaping | LNGS    | 20.8 | 30 pc  |

Vacuum Parts

| Material        | Supplier          | Use                  | Detector | Unit | Amount |
|-----------------|-------------------|----------------------|----------|------|--------|
| 45. Ceramic RO430B prepg feedthrough | Rogers Corporation | Not used             | Gator    | 4.9  | 0.014 kg |
| 46. Ceramic Feedthrough | Cabarn-MDC       | Electrical feedthrough | LNGS    | 12.8 | 0.586 kg |
| 47. Stainless Steel Flange | Cabarn-MDC | Feedthrough-flange | LNGS    | 22.3 | 0.495 kg |

Environment

| Material        | Supplier          | Use                  | Detector | Unit | Amount |
|-----------------|-------------------|----------------------|----------|------|--------|
| 48. Concrete    | LNGS              | LNGS wall             | Gator    | 0.71 | 0.035 kg |
| 49. Concrete    | LNGS              | LNGS floor            | Gator    | 0.23 | 0.033 kg |
One of the most radiopure metals which is commonly available is oxygen-free high-conductivity (OFHC) copper. This makes it a very interesting candidate to be used for the innermost structural parts of low background detectors and it is a very pure material for shielding. Large samples of copper typically give null results, even in the most sensitive spectrometers available [15]. The copper used in the XENON100 shield (entry 5 in Table 1) is the same as used in the shield of the Gator spectrometer. From the detailed background model of this facility, copper activities of (75 ± 14) µBq/kg for 226Ra and (21 ± 7) µBq/kg for 232Th have been determined [16]. Of all samples presented in this paper, where a detection can be claimed, these are the ones with the lowest radioactivity contaminations.

The second copper sample in the Table (entry 6) is from the same provider (Norddeutsche Affinerie AG) and its radioactive contamination with 226Ra and 232Th is below the sensitivity of the spectrometer. At the time of the screening, it had, however, a non negligible concentration of 60Co since it had been stored at the Earth’s surface for several months where it was activated by cosmic rays.

Several samples of austenitic stainless steel type 1.4571 (316Ti), all supplied by NIRONIT Edelstahlhandel GmbH & Co. KG, were screened and confirm the results published in [25] (entries 7–10). The sample sheets had a different thickness. The content of 226Ra and 232Th in all samples is below 4 mBq/kg. Lines were detected only in the 3 mm and 25 mm thick samples (entries 9 and 10, respectively) which had the largest sample mass. This is in agreement with [25]. The contamination of 60Co is even lower than the measurements presented there.

Radioactivity generated by cosmic ray activation during surface exposure was detected in all the samples, with the longest lived isotope being 54Mn (\(t_{1/2} = 312\) days) which was found with activities ranging from (1.7 ± 0.4) mBq/kg in the 25 mm sample to (0.5 ± 0.2) mBq/kg in the 2.5 mm sample.

### 5.2. Plastic Samples

In direct Dark Matter detection experiments, polyethylene (entries 12–14) is commonly used as neutron moderator in radiation shields surrounding the experiments. The polyethylene from the XENON100 shield was measured in different quantities and for different measurement times. All measurements are compatible with each other. 226Ra, 40K and 137Cs are detected when a large sample (8.44 kg) is measured for a relatively long time (28.9 days), but the respective contaminations are all below 0.7 mBq/kg. However, following these results it was decided to add a 5 cm layer of OFHC copper to the XENON100 shield, inside the Polyethylene, in order to suppress this y-background.

Polytetrafluoroethylene (PTFE, Teflon) is a material widely used in liquid xenon applications because of its physical, mechanical, dielectric and optical properties. It withstands liquid xenon (LXe) temperatures (−95°C) and is a good insulator with a dielectric constant very similar to LXe (\(\epsilon_r = 2\)). It also is an excellent reflector for VUV light at the xenon scintillation wavelength \(\lambda = 178\) nm [26].

A possible drawback of using PTFE in Dark Matter experiments is that fluorine 19F, the main component of the PTFE, has a high cross section for \((a, n)\) reactions (∼200 mb for \(E_a = 5.5\) MeV [29]). The \(a\)-particles for these reactions would come from the 226Ra and 232Th chains from intrinsic contaminations. Therefore, a number of measurements were performed with the PTFE used for the construction of the XENON100 TPC (entries 15–16 in Table 1). No evidence for radioactive contaminations in the PTFE has been found within the sensitivity of the used spectrometer and only upper limits could be derived. In particular the contamination with \(a\)-emitters is found to be <0.1 mBq/kg for 232Th and <0.06 mBq/kg for 226Ra. Other samples of PTFE from different suppliers were measured (with a lower sensitivity) and found to have radioactive contaminations below 2 mBq/kg (entries 17–19 in Table 1).

Because of their small mass, two plastic samples were screened using the ICP-MS technique described in Sect. 4, a polymethyl methacrylate (PMMA) optical fiber to guide blue light from a LED into XENON100 for photosensor calibration (entry 41) and a thin PTFE sheet used as a light reflector (entry 17). The PTFE sheet has a radioactive contamination well within the XENON100 radioactivity requirements. Although the optical fiber exhibits a higher radioactivity than other plastic samples its contribution to the XENON100 background is negligible with respect to other samples, given its very small mass (10 g total).

#### 5.3. R8520-06 Hamamatsu PMTs

Among the most important samples presented in this paper are the R8520-06-Al square 1″ × 1″ photomultiplier tubes (PMTs) from Hamamatsu. They are the light sensors chosen for XENON100 and therefore a central part of the detector. Given their proximity to the target volume and their nature of being a composite, fully assembled object, they are one of the dominating background sources. In order to determine the contribution of the PMTs to the overall background, and to reject possible “hot” tubes, a large fraction of the PMTs installed in the detector has been screened (entries 20–36 in Table 1) in the various facilities.

In order to fulfill the design requirements of XENON100, the manufacturer of the PMTs has assured that the components used for the production of the various PMT batches always have the same controlled origin. Nevertheless, some of the processes or working conditions in the production of the components might differ. Therefore, the PMTs have been subdivided in groups of typically 10-20 PMTs with tubes from the same production batch. The different groups have been screened independently to cross check their intrinsic radioactive contamination. Some batches have been discarded because of their increased level of radioactivity (entries 22, 24 and 25), which does not fulfill the design requirement. The PMTs in batch 25 were a subsample of devices used in XENON10. They have not been re-used in XENON100 because of their high 60Co and

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2X10CrNiMoTi18-1.
of the measured activities of the individual parts of the Hamamatsu R8520-06 PMT. The last row gives the expected values for a single PMT based on the measurements (1-6) taking into account the mass model, given in the second column of the Table.

| PMT Component                        | Mass g | $^{238}$U mBq/kg | $^{232}$Th mBq/kg | $^{40}$K mBq/kg | $^{60}$Co mBq/kg | $^{137}$Cs mBq/kg |
|--------------------------------------|--------|------------------|------------------|--------------|----------------|-----------------|
| 1. Kovar Metal: main metal package   | 13     | 19(7)            | <13              | <13          | 90(10)         | 1.2(1)          |
| 2. Borosilicate glass: used in stem  | 1      | 970(20)          | 340(20)          | 3.4(2)       | 2300(200)      | 2.3(2)          |
| 3. Ceramic: spacer between electrodes| 0.04   | 780(20)          | 260(20)          | 0.010(1)    | 800(100)       | 0.032(4)        |
| 4. Aluminum: sealing between quartz window and metal package | 0.1 | 17(8)            | 370(200)         | 0.37(2)     | 5(2)           | 0.0005(2)       |
| 5. Stainless Steel: electrodes       | 7      | 19(7)            | 18(8)            | 0.13(6)     | 0.15(2)        | 1.1(1)          |
| 6. Glass (synthetic silica): window  | 2      | <0.5             | <0.001           | <0.0036     | 18(3)          | 0.036(6)        |

| R8520-06-AL (total)                  | 23.14  | 1.4(2)           | 0.85(7)          | 4.6(2)      | 0.6(3)         |

All other screened PMT batches met the radioactivity requirements and were installed in the detector.

In order to have a detailed characterization of this PMT model and the possibility to improve the radioactivity in collaboration with Hamamatsu, all components of the R8520 PMT type used in XENON10 have been screened individually. The results are given in Table 2.

According to the PMT mass model provided by Hamamatsu, the main components responsible for the overall PMT radioactivity have been identified: these are the metal package and the stem pins (made of Kovar metal which has a small thermal expansion coefficient), the borosilicate glass in the stem and the stainless steel electrodes. The table shows the contributions of the single components to the overall PMT radioactivity. Knowing the constituents dominating the overall radioactivity allows to select other materials, or materials processed in a different way, to use them in the development of new photosensors. This is important for the next generation of rare event search experiments where the background requirements are even more demanding.

The predicted activities for a single PMT, based on these measurements of the individual components, are given in the last row of Table 2. The numbers have to be compared with entries 20–36. For $^{238}$U and $^{232}$Th the predictions are higher than the average of the PMTs used in XENON100, but somewhat lower in $^{40}$Co and $^{40}$K. However, since the individual parts were not from the batches used in XENON100, and the disagreement is only a little larger than the uncertainties, this is an acceptable result.

### 5.4. Other samples

New photosensors with a larger active area (entries 37–39 in Table 1) have also been examined as they are interesting for the next generation LXe detectors such as XENON1T.

Special effort went into the design of the voltage divider circuit (bases) for the R8520-06 PMTs used in XENON100. The components (surface mount resistors and capacitors on a Cirlex substrate) have been reduced in mass and number and have been selected for lowest possible radioactive contaminations (entry 40 in Table 1). However, the contribution of the bases to the total background at low energies is still 10% of that from the PMTs.

Two samples were taken from the wall and from the floor surrounding the XENON100 installation. The precise knowledge of the concrete’s radioactive contaminations allows to calculate the expected neutron flux from $(\alpha, n)$ and spontaneous fission reactions in the material. The results measured with the Gator facility (entries 48, 49) agree with measurements of the background $\gamma$-flux at the same location.

### 5.5. Location of the screened components in XENON100

This section summarizes the location of the screened materials, as listed in Table 1 in XENON100. The detector is a position-sensitive TPC using liquid xenon (LXe) as target material. The light signals are detected by two arrays on top and bottom of the detector. Two samples were taken from the wall and from the floor surrounding the XENON100 installation. The precise knowledge of the concrete’s radioactive contaminations allows to calculate the expected neutron flux from $(\alpha, n)$ and spontaneous fission reactions in the material. The results measured with the Gator facility (entries 48, 49) agree with measurements of the background $\gamma$-flux at the same location.

In order to suppress the $\gamma$-background from the laboratory environment (mainly from concrete, entries 48 and 49), the detector is placed inside a passive shield. It is made from lead (15 cm “normal” lead, entries 1 and 2, followed by 5 cm lead low in $^{210}$Pb, entries 3 and 4), 20 cm polyethylene (entries 12–14) and 5 cm OFHC copper (entry 5). The whole shield sits...
on a 25 cm slab of polyethylene and is additionally shielded against neutrons with 20 cm water on 3 sides and on the top.

The detector is installed in a double-walled cryostat made from low radioactivity stainless steel (entries 7-10). The LXe target volume is enclosed by a PTFE cylinder (entry 16) of ~15 cm radius and ~30 cm height. Copper wires, wound around the TPC and connected with resistors (entry 44), ensure electric field homogeneity. The PTFE panels are stabilized using rings of OFHC copper (entry 6). The same copper supports the PMTs on the bottom of the detector and all PMTs in the active LXe veto. The PMTs above the target are resting in a PTFE structure (entry 16) and fixed by smaller copper rings (entry 6). Everything is held together with stainless steel screws (entry 11). In order to improve the light collection in the active LXe veto volume the cryostat wall is covered by a thin PTFE sheet (entry 17).

A complete study of the XENON100 background has been published in [15]. It uses the screening results reported here as input values.

6. Summary

The materials used to construct experiments for rare event searches have to be selected in order to achieve the lowest possible radioactive background. This paper presents the results from the radioactivity screening campaign for XENON100, which aims to directly detect WIMP Dark Matter.

More than 20 different materials have been examined, mostly using low background HPGe detectors, but also applying mass spectrometry. In many cases, several batches of samples have been screened to check systematics or because the material properties were slightly different (different production batches, thickness, etc.). All results are given in Table 1 which might be very useful for other experiments searching for rare events. For this reason, we also provide the supplier for all samples.

These results have been used in a study to predict the electromagnetic background of XENON100 [15]. By comparing the measured energy spectrum between threshold and 2700 keV to a detailed Monte Carlo analysis, it is verified that the background design goal of < 10⁻² events keV⁻¹ kg⁻¹ day⁻¹ has indeed been reached. Of all running direct Dark Matter detection experiments, XENON100 has the lowest electromagnetic background. This has already allowed to set a competitive limit on spin-independent WIMP-nucleon interactions with only a few days of measuring time [11, 12].

A detailed study of the intrinsic radioactive contamination of the Hamamatsu R8520-06 PMT, the light sensor used in XENON, has also been presented. The screening of individual PMT components provides information about which parts have to be modified in order to further decrease the radioactivity level. Almost equally important are the results obtained for the PTFE used for the XENON100 TPC, which is one of the purest PTFE samples ever reported in the literature.

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