4 Cold Dark Matter Search with XENON

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The XENON project aims at the direct detection of dark matter in the form of Weakly Interacting Massive Particles (WIMPs). Presently, a second generation detector (XENON100 [1]) is in operation at the Laboratory Nazionali del Gran Sasso (LNGS, Italy). A 161 kg double-phase Xe time-projection chamber (TPC) employs two arrays of low-radioactivity, VUV-sensitive photomultipliers (PMTs) to detect the prompt (S1) and proportional (S2) scintillation light signals induced by particles interacting in the active detector region, containing 62 kg of ultra-pure liquid xenon (LXe). The remaining 99 kg of LXe act as an active veto shield against background events.

A data acquisition period with a total lifetime of ∼150 days was recently completed, extending the detector operation to the fifth year and increasing the sensitivity of the search for an annual modulation. The analysis of these data is in an advanced stage and unblinding is expected within a couple of months. A study of the XENON100 response to single electrons has been published recently [2], improving our understanding of the double-phase xenon-based TPC, and enabling searches for low energy events (i.e. WIMP-electron interactions for WIMP masses below 1 GeV/c^2) based on S2 signal alone.

The next phase in the XENON dark matter search program, the XENON1T experiment, is housed in Hall B at LNGS. The detector contains 3 t of LXe surrounded by a 9.6 m diameter water Cerenkov shield. The cryostat will be a double-walled super-insulated pressure vessel, made of stainless steel. The inner vessel will house the liquid xenon, the TPC and two arrays of photomultiplier tubes (PMTs). The TPC will be made of interlocking PTFE panels, and the drift field homogeneity will be achieved with equidistant OFHC field shaping rings connected with high-ohmic HV resistors. The photosensors will be arranged in two arrays, containing 127 PMTs above the target in the gas phase, and 121 PMTs at the bottom of the sensitive liquid xenon volume.

Our group is responsible for constructing the TPC field cage, as well as for the PMT arrays assembly (together with MPIK-Heidelberg). The photodetectors for the XENON1T experiment are 3-inch R11410-21 PMTs with an average quantum efficiency (QE) at the xenon scintillation wavelength (178 nm) of 36%, developed and optimized by Hamamatsu Photonics in close collaboration with our research group at UZH. As the results of the extensive testing and measurements, we provided information on their performance in cryogenic xenon environments and on radioactive contamination.

[1] E. Aprile *et al.*, Astropart. Phys. 35, 573-590 (2012).

[2] E. Aprile *et al.* (XENON Collaboration), J. Phys. G: Nucl. Part. Phys. 41, 035201 (2014).

4.1 Radioactive contamination of the photosensors

All XENON1T tubes are screened with high-purity Ge detectors, in particular Gator [1] operated by the UZH group, and with mass-spectrometry before their installation into the detector in order to verify their low radioactivity values. In order to ensure a safe and consistent handling of all PMTs during the screening process, a low-background PTFE holder was fabricated, shown in Fig. 4.1 with 16 photosensors in the screening chamber which is the largest number of tubes that can be measured at once. For most relevant isotopes a sensitivity below 1 mBq/PMT can be reached after about 18 days of measuring time. As an example the spectrum for batch C is shown in Fig. 4.2 along with the background spectrum of the Ge detector itself.

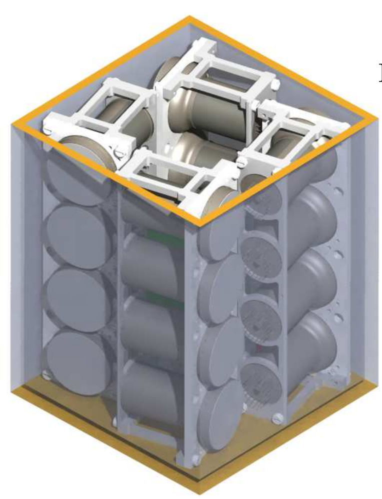

FIG. 4.1 – Sixteen Hamamatsu R11410 PMTs in the Ge detector chamber, fixed by custom-made, low-background PTFE holders.

TAB. 4.1 – Results of the gamma-spectroscopy screening for the various R11410 PMT batches. The number of measured tubes and the measuring time are indicated. Upper limits are given at 90% confidence level, and the quoted errors include statistical and systematic errors. The ^{137}Cs activity is $(0.2 - 0.3)$ mBq/PMT for all batches.

batch	PMTs	days	Activity [mBq/PMT]							
			^{238}U	^{226}Ra	^{235}U	^{232}Th	^{228}Th	^{40}K	^{60}Co	^{110m}Ag
A	10	26	< 18	0.4(1)	0.5(1)	< 1.1	0.4(1)	12(2)	0.7(1)	0.89(1)
B	16	15	< 16	0.5(1)	0.29(9)	< 0.85	< 0.61	13(2)	0.79(8)	1.1(2)
C	15	11	< 20	< 0.82	< 0.52	< 1.1	0.5(2)	13(2)	0.73(9)	0.51(7)
D	15	22	< 13	0.5(1)	0.35(9)	0.4(1)	0.4(1)	12(2)	0.73(9)	0.21(4)
E	15	16	< 17	0.6(1)	< 0.57	< 0.93	< 0.62	14(2)	0.63(7)	0.22(6)
F	11	23	< 15	0.6(1)	< 0.55	< 0.77	0.7(1)	14(2)	0.71(7)	0.23(4)

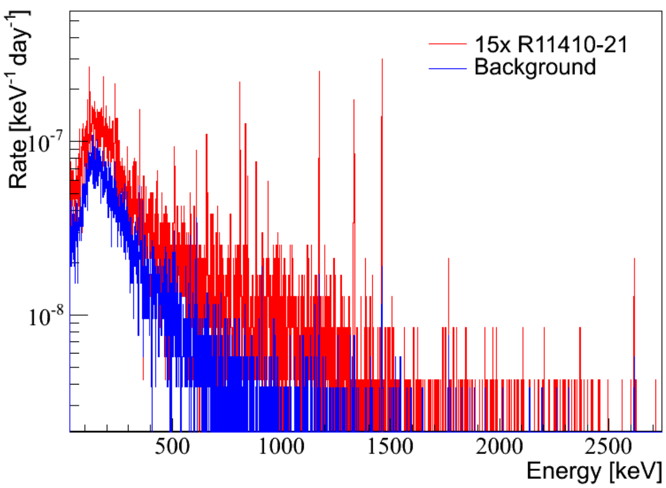

FIG. 4.2 – Energy spectrum of batch C measured in July 2013. The background is obtained by removing the PMTs.

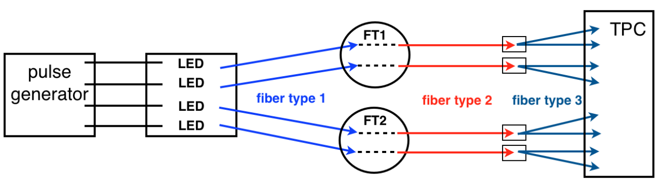

FIG. 4.3 – Schematics of the PMT calibration setup. A 4-channel pulse generator drives four blue LEDs. The LED light is transmitted by standard optical fibers to two dual CF40 optical feedthroughs on the detector flange. From there uncoated 800 μm quartz fibers guide the light into the cryostat. At the TPC end each fiber is split into 2 to 4 branches (180 μm PMMA-PFA fibers).

The screening results for the most relevant radioactive isotopes are shown in Table 4.1. An observed contamination by ^{110m}Ag ($T_{1/2} = 250$ d) was traced back to the silver solder of the ceramic PMT stem.

[1] L. Baudis, A. Ferella *et al.*, JINST 6, P08010 (2011).

4.2 PMT calibration for XENON1T

Long-term operation of the XENON1T detector requires regular calibration of the 248 photosensors. The schematics of our calibration system is shown in Fig. 4.3. Light from external InGaN LEDs ($\lambda = 470$ nm) is uniformly distributed over the sensors through different types of optical fibers. Inside the vacuum quartz fibers with special thermal coating are used, which can be baked up to 200°C. To achieve a uniform illumination of the PMTs, at the TPC end the fibers are split into several branches by means of thin uncoated polymethylmethacrylate (PMMA) fiber bundles with 180 μm core. The system gives a uniform illumination of the PMT arrays and in addition some redundancy in case of failure. PMMA is more flexible than quartz, and hence more suited for the small bending radii inside the cryostat.

The 4-channel pulse generator (BNC-505-4C) is software-controllable via RS-232 interface allowing to remote calibrations. The four LEDs are installed in light-tight enclosures (Fig. 4.4). The initial tests of the calibration system were performed with the UZH test facility for the XENON1T PMTs, the Marmot XL LXe chamber.

FIG. 4.4 – LED modules and matching pulse generator designed by our technician A. James. The picture on the right shows the light-tight enclosure inside an LED module. The light output is provided through an optical SMA connector.