4 Cold Dark Matter Search with XENON

M. Auger, P. Barrow, L. Baudis, A. Behrens, G. Kessler, A. Kish, T. Marrodan Undagoitia (until September 2012), D. Mayani, P. Pakarha, F. Piastra, and M. Schumann (until December 2012)

in collaboration with Columbia University, UCLA, INFN, University of Münster, Coimbra University, Subatech, The Weizmann Institute of Science, University of Mainz, SJTU, MPIK Heidelberg, Rice University, University of Bologna, Nikhef, Purdue University, University of Bern

(XENON Collaboration)

XENON100 is a 161 kg double-phase Xe time-projection chamber (TPC) operated at LNGS. It 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 target volume, containing 62 kg of ultra-pure liquid xenon (LXe). The remaining 99 kg of LXe act as an active veto shield against background events. The instrument is described in Ref. [1], and the analysis procedure is detailed in Ref. [2].

Using 13 months of data taken during 2011 and 2012, with a final exposure of 224.6 live days × 34 kg, XENON100 has reached its initial aim to probe spin-independent WIMP-nucleon cross sections down to $2 \times 10^{-45}\,\mathrm{cm}^2$ at a 55 $\mathrm{GeV/c}^2$ WIMP mass [3]. New limits on spin-dependent WIMP-nucleon couplings were derived [4], yielding the world's best sensitivity on WIMP-neutron couplings. After a further distillation run the ^{nat}Kr level was reduced below $\simeq$20 ppt in the latest XENON100 run. A new dark matter search run is to start in spring 2013. Concurrently, several additional analyses are ongoing: a search for solar and dark matter axions, for SuperWIMPs, a search for low-mass WIMPs, and a study of inelastic WIMP-nucleus collisions.

The next phase in the XENON dark matter search program, the XENON1T experiment, has been approved and founded, and will be constructed in Hall B at LNGS. It will use a total of 3 t of LXe operated in 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 3-inch Hamamatsu R11410 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 (top and bottom) arrays, containing 127 and 121 sensors.

4.1 Background studies

The nuclear recoil (NR) background from radiogenic and cosmogenic neutrons has been predicted for the XENON100 experiment based on Monte Carlo studies, using a detailed model of the detector and its shield. The simulation accounts for the energy resolution, veto efficiency, and the efficiency loss introduced by the S2/S1 electronic recoil discrimination cut to define a benchmark WIMP search region [6]. The total NR background predicted for the 224.6 days measurement leading to the WIMP search result of 2012 [3] is $(0.17^{+0.12}_{-0.07})$ events, to be compared to the total electronic recoil (ER) background estimate of (0.8 ± 0.2) events. It can be concluded that neutron background does not limit the sensitivity of the XENON100 detector for WIMP detection.

In order to select materials for the construction of the XENON1T detector and determine their intrinsic radioactivity, the samples are being screened with gamma- and mass-spectrometry methods. The measured activities are used as input information for our GEANT4 simulations [7] aiming at predictions of the electronic and nuclear recoils backgrounds from the detector and shield materials, which are used for the optimization of the TPC design and the detailed background characterization.

Preliminary simulations with a simplified detector model predict a background from the PMTs of 0.2 events/years for NRs, and 0.04 events/year for ERs. The total background from the cryostat is predicted to be 0.23 events/year, where NR and ER events give approximately equal contributions. These studies will be extended using a detailed detector model based on the materials selected in the screening studies.

4.2 XENON1T TPC, cables and connectors

Our group is partially responsible for the design and construction of the XENON1T TPC, together with Bern, Columbia and UCLA. An up-to-date CAD drawing of the TPC is shown in Fig. 4.1. We will design and construct the field cage and the field shaping rings. The design proce-

FIG. 4.1 – A schematic of the XENON1T TPC.

dure involves accurate electric field simulations, based on finite element method software, to determine the uniformity and variations of the electrical field within the detector (see an example in Fig. 4.2). A full-scale model of a section of the full field cage has been produced and successfully subjected to rigorous cryogenic and structural integrity tests in or laboratory; one example is shown in Fig. 4.3.

We are also responsible for the signal transfer from the PMTs to the DAQ. Due to strict background requirements of the experiment, and since the cabling will be located near the active volume of the TPC, ultra-low radioactivity cables and connectors have to be used. We have designed and built a custom-made connector pro prototype that is made of PTFE and copper, shown in Fig. 4.4). The connectors were tested for both the PMT signal transmission and for the high-voltage for the PMTs. Figure 4.5 shows the transmission of a single photoelectron spectrum from one of the PMTs that will be used in XENON1T for three different

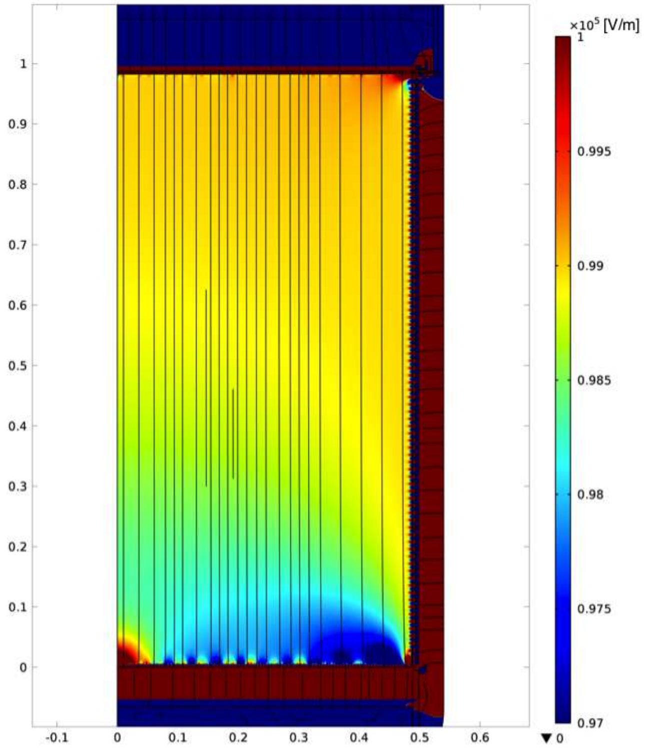

FIG. 4.2 – Electric field simulation of XENON1T after the optimisation, displaying a half cross-section. Electrical field lines are shown for clarity.

FIG. 4.3 – The 1:16 scale mockup using stainless steel field shaping rings during a cryogenic test in LN.

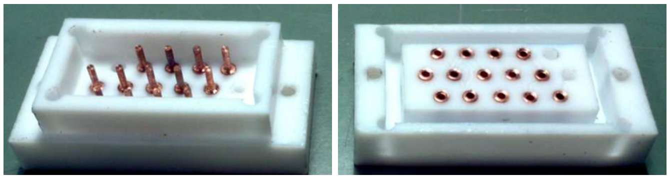

FIG. 4.4 –
The current version of the low-radioactivity connector.

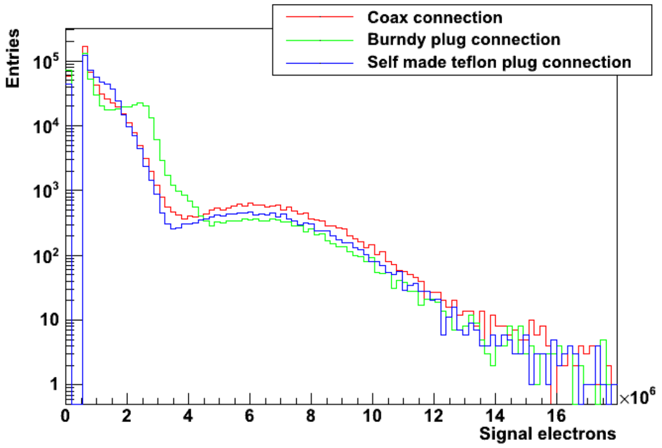

FIG. 4.5 – Single photoelectron spectra of a R11410 PMT taken with the three different connectors mentioned in the legend.

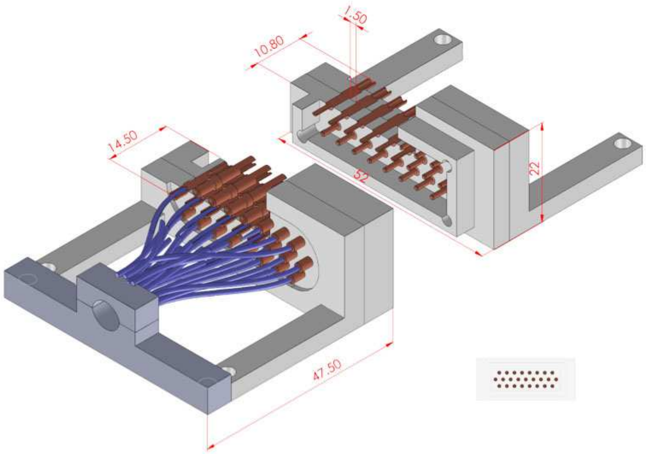

FIG. 4.6 – A CAD drawing of the next generation connector with 25 pins and increased mechanical robustness.

kinds of connections. The prototype connector has superior transmission properties compared to the connector type used in the XENON100 experiment (Burndy).

Based on these preliminary results, an optimization study is ongoing with the goal of reducing the mass, increasing the signal transmission, and improving the mechanical robustness. A schematic of a next-generation connector model is shown in Fig. 4.6.

The Hamamatsu R11410 3-inch PMT has been selected as the light sensor for XENON1T. It was developed to be used at cryogenic temperatures, has a very low intrinsic radioactivity and a quantum efficiency at 178 nm (Xe scintillation wavelength) around 30%. We have carried out several tests aimed at the performance study in environments similar to those in a dark matter detector, examining in particular the long-term behavior and stability in LXe.

Two R11410-MOD and R11410-10 PMTs were characterized at room temperature and in LXe, showing a typical gain of 5×10^6, a peak-to-valley ratio >3 and an afterpulse rate $<10\%$. Long-term stability tests and thermal cycling have demonstrated that these PMTs can be operated stably for several months at cryogenic temperatures with a gain variation of $\pm2\%$. In addition, the PMTs can withstand rapid temperature changes while cooling down and returning back to ambient conditions for several times in periods of a couple of weeks [8].

4.3 Material screening

The Gator facility [9], operated by our group at LNGS, has been extensively used in the XENON100 screening campaign [10], and is currently employed to screen XENON1T components: material samples for the construction of the inner and outer cryostat vessels (copper, titanium and stainless steel), PTFE as support structure and reflector, signal and high-voltage cables, individual parts of R11410 photosensor, etc. We are starting to screen all 300 R11410 PMTs that were purchased for XENON1T. For this purpose, we have designed and fabricated a low-radioactivity PTFE holder, which will house 15 PMTs at a time.

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

[2] E. Aprile *et al.*, *Analysis of the XENON100 Dark Matter Search Data*, (2012) arXiv:1207.3458.

[3] E. Aprile *et al.*, Phys. Rev. Lett. 109, (2012) 181301.

[4] E. Aprile *et al.*, *Limits in Spin-dependent WIMP-nucleon Cross Sections from 225 Live Days of XENON100 Data*, (2013) arXiv:1301.6620.

[5] E. Aprile *et al.* (XENON100 Collaboration), Phys. Rev. Lett. 107, (2011) 131302.

[6] E. Aprile *et al.* (XENON100 Collaboration), in preparation.

[7] GEANT4 Collaboration, NIM A506, (2003) 250.

[8] L. Baudis, A. Behrens, A. Ferella, A. Kish, T.M. Undagoitia, JINST 8 (2013) P04026.

[9] L. Baudis, A. Ferella, A. Askin, J. Angle, E. Aprile *et al.*, JINST 6, (2011) P08010.

[10] E. Aprile *et al.*, Astropart. Phys. 35, (2011) 43-49.