4 Dark Matter Search with XENON and DARWIN

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XENON and DARWIN Collaborations

4.1 Introduction

Overwhelming evidence supports a model of our Universe where dark matter outnumbers baryonic matter by a factor of 5 [1]. One compelling dark matter candidate is a Weakly Interacting Massive Particle (WIMP) with a mass ~1 GeV/c^2-10 TeV/c^2, which arises naturally in various extensions to the Standard Model of particle physics [2]. In the field of direct dark matter detection, dual-phase liquid xenon (LXe) Time Projection Chambers (TPCs) have demonstrated rapid progress during the past decade [3–6], and are among the main technologies to probe the allowed parameter space for WIMPs with masses above a few GeV. LXe is intrinsically radio-pure, is capable of powerful self-shielding, and is sensitive to low-energy nuclear recoils (NRs) with good energy resolution. The simultaneous detection of ionisation signals down to the single electron level, together with prompt scintillation down to a few keV, enables 3D position sensitivity for fiducialisation of the target volume. Particularly attractive is also the scalability of a LXe TPC to contain a homogeneous target of several tons. In such large detectors, neutrons can be distinguished from WIMP-induced NRs due to their multiplicity. This makes LXe TPCs unique in their potential to identify dark matter-induced signals.

XENON is an international collaboration of 164 scientists from 21 institutions with the goal to directly detect dark matter particles in an ultra-sensitive, low-background detector, using the liquified noble gas xenon as target material. The current phase of the project, XENON1T, is a dual-phase TPC with a total mass of LXe of 3.3 t, out of which 2.0 t are in the active target [7]. The detector and its sub-systems are in operation in Hall B of the Laboratori Nazionali del Gran Sasso (LNGS) and the science data taking started in autumn 2016. World-leading results from a first run were published in 2017 [5], and the analysis of the data collected in the subsequent run is in its final stage. The expected sensitivity from this second run is shown in Fig. 4.1.

The upgrade to the XENONnT phase, planned for 2019, will enable XENON to continue leading the direct detection field in the next few years with a sensitivity to dark matter cross sections down to 10^{-48} cm^2 [8]. Figure 4.1 shows the projected sensitivity to spin-independent WIMP-nucleon interactions as a function of WIMP mass, for an exposure of 20 t·y in XENONnT.

[1] P.A.R. Ade et al.,
Astron. Astrophys., 594:A13, (2016).

[2] G. Bertone, Particle Dark Matter (2013).

[3] A. Tan et al. (PandaX Collaboration),
Phys. Rev. Lett. 117(12):121303, (2016).

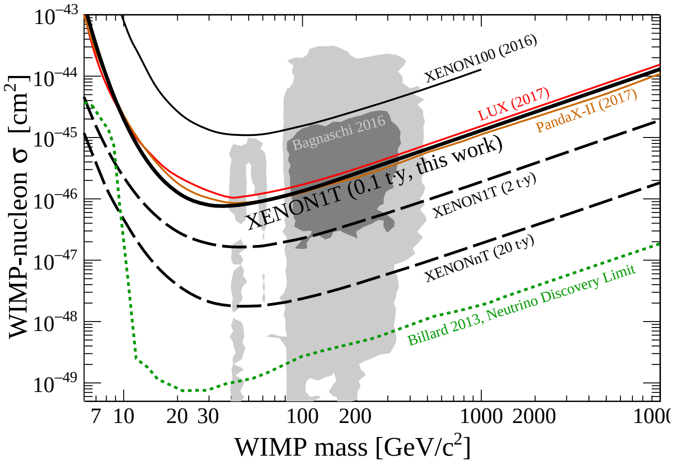

FIG. 4.1 – The projected sensitivity to spin-independent WIMP-nucleon interactions for XENON1T and for XENONnT (dashed black line), assuming an exposure of 20 t·y. Also shown are current results, the sensitivity of XENON1T using 2 t·y of data, and the neutrino discovery limit (dashed orange).

[4] D.S. Akerib et al. (LUX Collaboration), Phys. Rev. Lett. 118, 021303 (2017).

[5] E. Aprile et al., Phys. Rev. Lett. 119, 181301 (2017).

[6] X. Cui et al. (PandaX Collaboration), Phys. Rev. Lett. 119, 181302 (2017).

[7] E. Aprile et al. (XENON Collaboration), Eur. Phys. J. C (2017) 77: 881.

[8] E. Aprile et al., Phys. Rev. D 94 no.12, 122001 (2016).

4.2 Status and First Results from the XENON1T

The XENON1T experiment has collected data with 278.8 days total live time, split into two science runs of 32.1 days (SR0) and 246.7 days (SR1). SR0 was collected between October 2016 and January 18, 2017, when a magnitude 5.7 earthquake caused a two week downtime [9]. SR1 began immediately after and was concluded on February 8, 2018, while the detector continues to run and collect data. The main operational difference between the two science runs is the cathode voltage, which was lowered from −12 kV for SR0 to −8 kV for SR1. All key detector parameters are continuously monitored to ensure operational stability. The LXe level is 2.5 mm above the gate electrode, within sensor reading fluctuations of 2% RMS. The LXe temperature and gaseous xenon pressure were constant at −96.0°C and 1.94 bar, respectively, both <0.02% RMS. 32 PMTs are ignored for the analysis, the majority of which (26 PMTs) due to gas leaks into the tubes, and the remaining due to low single photo-electron (SPE) efficiency.

In November 2017 the first WIMP-search results [10] from the XENON1T experiment were published, based on the SR0 science data. Given the 1042 kg fiducial volume this corresponds to an exposure of 35.6 t day. Six background sources are considered in the search region: electronic recoils due to internal and external radioactive contamination, nuclear recoils due to radiogenic neutrons, coherent neutrino-nucleus scattering, accidental coincidences of unrelated prompt scintillation (*S*1*s*) and ionization (*S*2*s*) signals, inward-reconstructed events which occurred on the PTFE walls of the TPC, and finally a small uniform background component to account for elastic recoil (ER) events with anomalous S2 area. The ER and NR components distributions are calibrated using injected ^{220}Rn and an external ^{241}AmBe source respectively. Both calibrations and the dark matter search data are shown in Fig. 4.2 together with the ER and NR models.

The data in a predefined box were blinded until the event selection and background models had been fixed. 99% of the ER band was left unblinded using this selection. Additionally, a small fraction of the total exposure (four live days, corresponding roughly to the XENON100 exposure) were left unblinded. After unblinding, 63 events remain in the search region: $cS1 \in [3,70]$ and $cS2_b \in [50,800]$, where $cS1$ and $cS2b$ are the corrected $S1s$ signals and the corrected $S2s$ signals from the bottom array, respectively. One event at $cS1 = 68.0$ PE, observed in the initial 4-day unblinded data, is at an extreme $(cS1, cS2_b)$ location for all background and signal models. Another event at $cS1 = 26.7$ PE is at the -2.4σ ER quantile. The background components, together with a mass-dependent signal model are considered independently to produce a limit on the WIMP-nucleon interaction cross-section using an extended unbinned profile likelihood. The resulting limit is shown in Fig. 4.3. The strongest limit is 7.7×10^{-47} cm^2 for 35 GeV/c^2 WIMPs.

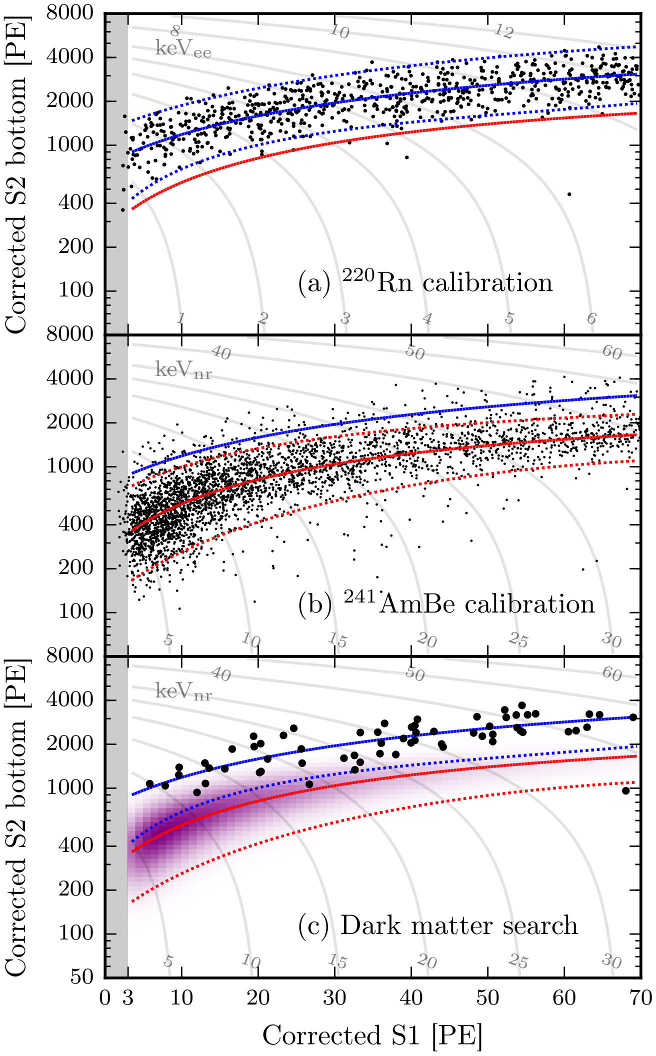

FIG. 4.2 – Observed data in $cS2_b$ vs $cS1$ for (a) ^{220}Rn elastic recoil calibration, (b) ^{241}AmBe calibration, and (c) dark matter search data. Solid and dotted lines are the median and $\pm 2\sigma$ quantiles in $cS2_b$ of the elastic recoil (blue) and nuclear (red) models. The purple shading in (c) shows the signal model for a 50 GeV/c^2 WIMP.

Our research group at the University of Zurich was responsible for significant parts of the analysis for these results, including the development of interaction vertex reconstruction algorithms using a neural network; spatially-dependent signal corrections to compensate for variations in the S2 signal area of up to around 15%; and data-quality selection criteria. In addition we continue to be responsible for ensuring and monitoring the long-term stability of the PMTs and their in-situ calibration using external LEDs. Apart from the standard, SI WIMP analysis, we are leading a few other analysis channels, such as the search for the neutrinoless double beta decay of ^{136}Xe, a search for SuperWIMPs, a search for inelastic WIMP scatters on ^{129}Xe and ^{131}Xe, and detection of solar neutrinos via neutrino-electron scatters.

[9] USGS Database, https://earthquake.usgs.gov

[10] E. Aprile et al., Phys. Rev. Lett. 119, 181301 (2017).

[11] D.S. Akerib et al., Phys. Rev. Lett. 118, 021303 (2017).

[12] A. Tan, et al., Phys. Rev. Lett. 117(12):121303, (2016).

[13] E. Aprile et al., Phys. Rev. D 94 no.12, 122001 (2016).

4.3 The XENONnT Experiment

In parallel to the ongoing operations of the XENON1T detector and analysis of the collected science data, we are working on the upgrade to the XENONnT TPC, which will increase the active LXe target mass to 6 t, improving the sensitivity to WIMP-nucleon interaction by an order of magnitude. Our group is co-responsible for the design and fabrication of the new TPC, for the characterisation measurements and selection of the photosensors, design and production of the PMT voltage-divider circuits, design and production of low-noise, dual-output amplifier boards, cabling on the cold, xenon side, and measurements of the radioactivity levels in the construction materials, including the photosensors.

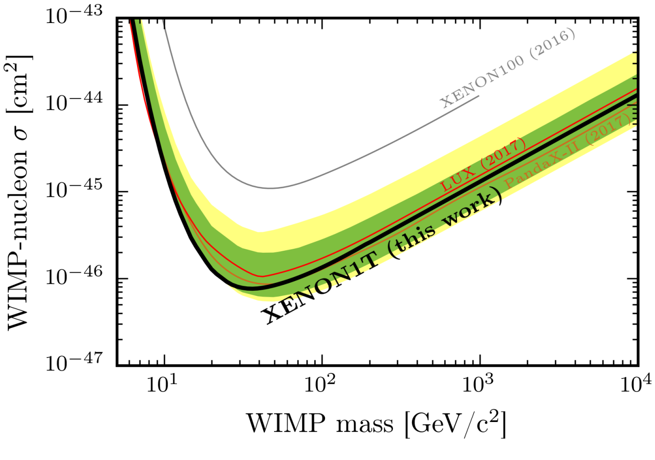

FIG. 4.3 – The limit on the spin-independent WIMP-nucleon cross section at 90% confidence level as a function of WIMP mass for the first result of XENON1T (black line). Green and yellow shading shows the one- and two-sigma sensitivity bands for the same data. Results from LUX [11] (red line), PandaX [12] (brown line) and XENON100 [13] (grey line) are shown for comparison.

Photosensors

As shown in Fig. 4.4, the active volume of LXe in the XENONnT experiment will be equipped with 494 R11410-21 Hamamatsu 3-inch PMTs. These will be assembled in two arrays of 253 (top) and 241 (bottom), to detect both primary and secondary Xe scintillation light with a high collection efficiency and granularity for event vertex reconstruction. Departing from the previous designs for XENON100 and XENON1T, the top PMT array features a pattern of closest hexagonal packing and is more resilient to possible non-functional channels thanks to the increased PMT density. The precision of the xy-position reconstruction is expected to be 10 mm (at 1-σ) at low energies, as in XENON1T.

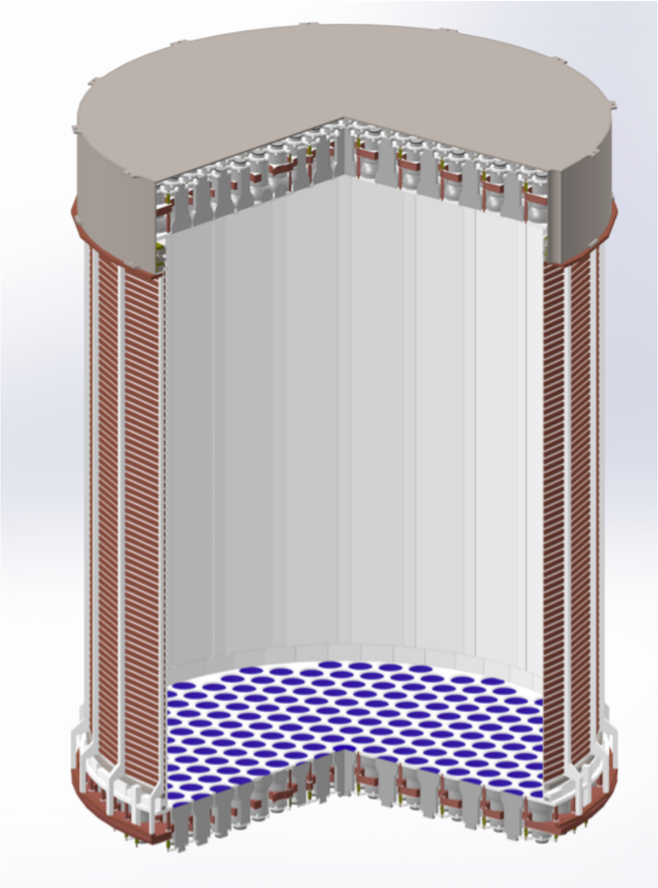

FIG. 4.4 – Technical drawing of the XENONnT time-projection chamber. The scintillation and electroluminescence signals are detected by a total of 494 Hamamatsu R11410-21 PMTs, installed in two arrays above (253 units) and below (241 units) the active LXe target.

Most of the photosensors currently operated in the XENON1T experiment will be re-used for XENONnT, hence about 260 units were newly procured and distributed between the Universities of Stockholm and Zurich for characterisation in LXe. First, the general performance at room temperature is characterised by determining parameters such as amplification gain, dark count and after-pulse rates, HV scan and timing. The measurement of the after-pulse spectra [14] before and after cooling down the PMTs in LXe is of most interest in order to identify potential openings of micro-leaks during the cooling down process.

During cryogenic tests the PMTs are operated in LXe and tested in conditions very similar to the ones of operation in the XENONnT detector, including gaseous xenon. Our MarmotX xenon detector at the University of Zurich can simultaneously test 10 PMTs distributed in two arrays of 5 PMTs each. Typically the photosensors undergo two cool-down cycles, and are operated one week in LXe and one week in gaseous xenon, and the amplification gain and dark count rate are continuously monitored. We also perform light 'stress tests', in which the PMTs are exposed to a relatively large amount of light for a certain period of time, thus emulating the conditions of detector calibrations with radioactive sources.

Over the course of six months, a total of 129 PMTs have been tested in liquid and cold gaseous xenon, out of these 51 in MarmotX. So far, ten units were rejected due to failures and sent to Hamamatsu Photonics to be replaced, including eight with identified xenon ion after-pulses and hence leaks in the vacuum seal. Presently we are measuring several replacement units, combined with the characterisation of a pre-amplified signal read-out circuit, which has been recently developed by our group and may allow to improve the signal quality in future experiments.

We have designed and, after extensive tests, produced new, 16 channel NIM amplifier boards for XENONnT, with dual gain output: a high-gain stage with with non-inverting voltage gain of 20 (gain 10 into 50 Ohm load) and a low- gain stage with non-inverting voltage gain of 1 (gain 0.5 into 50 Ohm load). The high-gain stage operates from DC to 250 MHz, the low-gain stage from DC to 200 MHz. Both stages have a 50 Ohm output impedance and are designed to drive 50 Ohm loads. The aim is to increase the dynamic range of the detector, where the gain-20 signal will be used for the low-energy searches, while the gain-1 signal will be employed for the double beta decay search and for the characterisation of the background up to energies of a few MeV.

The Gator low-background counting facility

Much of the material screening for XENONnT, particularly the PMTs, will be performed using the Gator high-purity germanium spectrometer that is owned by the University of Zurich [15]. Its radiopurity and excellent energy resolution ($\sigma_E < 1$ keV at $E \sim 1$ MeV) allow for low-background material radioassay. The spectrometer is shielded from cosmic radiation by operating it in an ultra-low background facility at LNGS at the same depth as the XENON1T detector.

An upgrade of the enclosure for the Gator spectrometer was performed in 2017, with the primary objective of improving the sealing to the external environment in order to reduce radon diffusion into the cavity. The new shielding includes well-sealed ports and edges, a gate valve to isolate the sample loading box, and hermetic electrical feedthroughs to prevent air leaks. Additionally, a new, top-loading glovebox was designed in order to improve the ergonomics for inserting samples. The new design is shown schematically in Fig. 4.5 (Top).

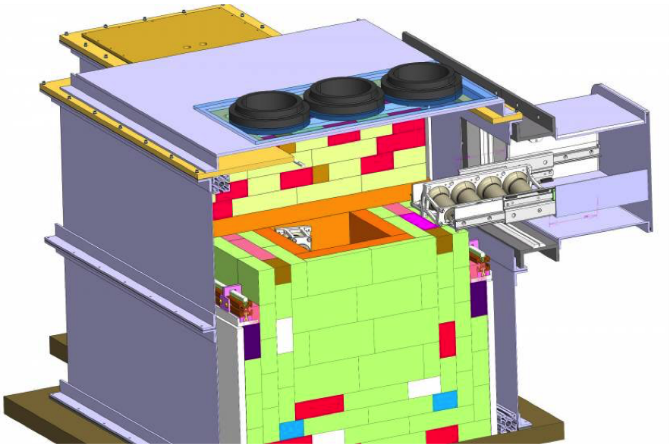

FIG. 4.5 – Top: The design of the new Gator enclosure. It includes well-sealed ports and edges, a gate valve to isolate the screening sample loading box, hermetic electrical feedthroughs to prevent air leaks as well as a new, top-loading glovebox. Bottom: A picture of the new Gator enclosure after assembly was completed in August 2017.

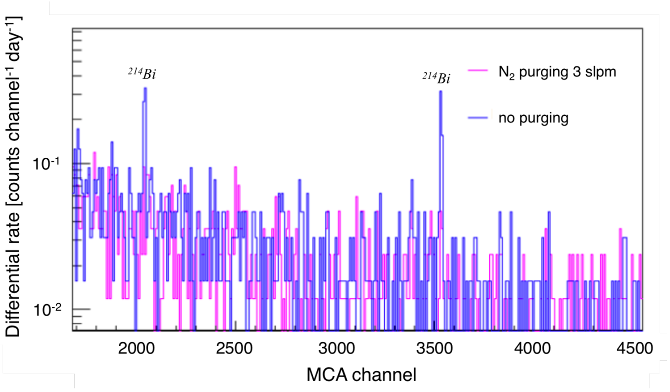

FIG. 4.6 – Disappearance of the ^{214}Bi daughters of radon from a state with no nitrogen flow (blue) and after purging at 3 slpm (pink).

The materials for the housing were procured and tested at UZH, and the construction of the new enclosure, including all of the welded seams, was performed in the UZH machine shop. The new enclosure was shipped to the underground facility at LNGS and installed in August 2017. Prior to installation, the low-background lead and copper shielding was disassembled and cleaned in an ultrasonic bath with ethanol in order to remove any contaminants or dust that accumulated since its initial installation. The shielding was then reassembled and the new closure installed, as shown in Fig. 4.5 (Bottom).

The nitrogen flow rate into the detector cavity was optimised for radon reduction. Initial tests at 3 slpm showed a reduction in radon daughters, as shown by the reduced activity of the ^{214}Bi lines in Fig. 4.6. The upgrade also provided the opportunity to reduce the induced EMI noise: with new electrical feedthroughs and shielding, the noise level was reduced by ∼30%, particularly in the low-energy regime. The detector is now fully operational and acquiring background data specifically to prepare for screening the PMTs for the XENONnT detector.

[14] P. Barrow et al., JINST 12(01):P01024 (2017).

[15] L. Baudis et al., JINST 6, P08010 (2011).

4.4 R&D for the DARWIN Observatory

The new Xurich LXe TPC has been designed and built to investigate the microphysics of particle interactions in LXe at energies below 50 keV, which are relevant for many of the rare event searches using xenon as target material. The instrument and its calibration measurements are described in detail in [16]. The energy calibration is performed with $^{83\mathrm{m}}$Kr, providing low-energy lines at 9.4 keV and 32.1 keV uniformly distributed within the target volume [17]. These are tagged by exploiting their double-S1 and double-S2 topology, given the measured half-life of the first excited state at 9.4 keV of (155±1) ns.

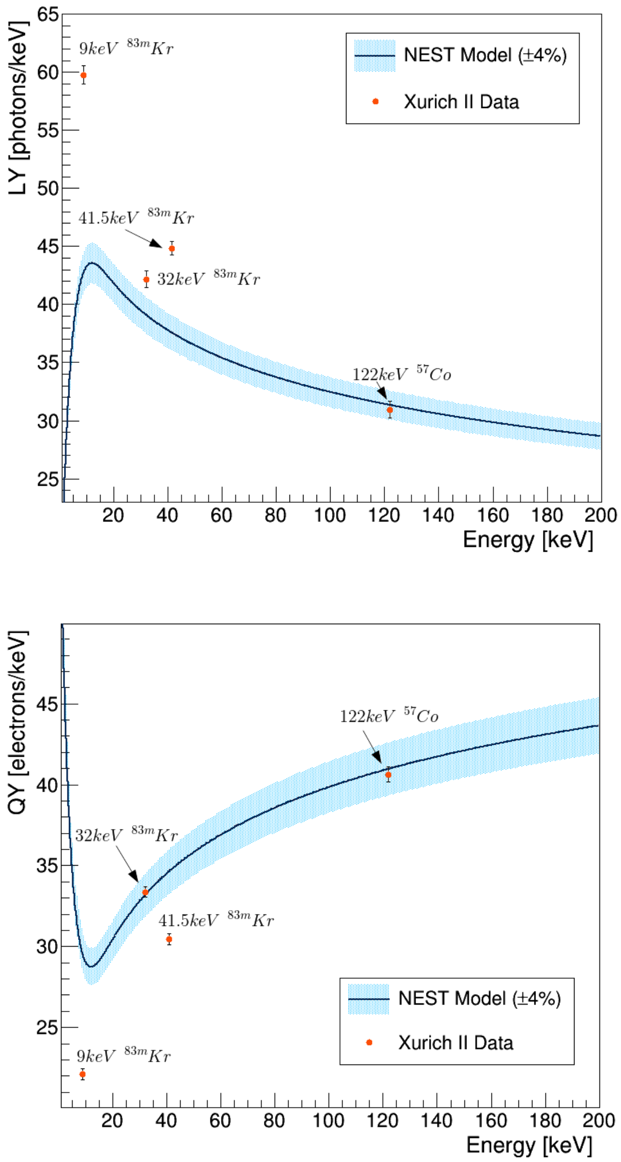

FIG. 4.7 – The scintillation light yield (top) and comparison between the absolute ionisation charge yield (bottom) of liquid xenon for ^{57}Co and $^{83\mathrm{m}}$Kr energy lines measured with the Xurich TPC, and comparison with the prediction by the NEST model [18].

We have performed systematic measurements of the absolute scintillation light and ionisation charge yields of LXe in response to electronic recoils [16], with the results for a drift field of 1050 V/cm shown in Fig. 4.7. A comparison with the empirical NEST model [18] suggests that the light (charge) yield at low energies is higher (lower) than the predictions. These discrepancies are currently under investigation, in particular we will compare the data with a new version of NEST.

The absolute calibration is used to predict the potential of our detector to observe low-energy nuclear recoils, where the energy threshold is estimated based on the predictions of the NEST model [18]. An analysis threshold of 2 PE corresponds to a mean number of 10.5 primary photons, which translates to an energy threshold of (2.3−2.7) keV in nuclear recoil equivalent, depending on the drift field.

The Xenoscope Project

In October 2017, the European Research Council (ERC) funded project Xenoscope has started. The goal of Xenoscope is to conduct research towards the construction of a 50 t LXe observatory, DARWIN [19]. This research is focused on the optimisation of the light collection in a large TPC, on a full-scale TPC demonstrator applied for electric fields, as well as on the mitigation of background radioactivity through an extensive material screening campaign. In addition, new shielding schemes will be studied through geometrical optimisation of the detector design.

In the first part of the project, Multi-Pixel Photon Counters (MPPCs), a new type of light sensors based on a solid-state, silicon photo-multiplier (SiPM) technology, will replace the photomultiplier tubes in the Xurich TPC [16]. The upgrade will happen in two phases. First, the top PMT will be replaced by a MPPC array shown in Fig. 4.8. After a series of calibration runs, the bottom PMT will be replaced by a SiPM array, allowing for a direct comparison of the performance of SiPMs to that of PMTs. The Xurich detector will be calibrated using radioactive sources such as ^{83m}Kr, ^{37}Ar (to be produced at PSI as part of this project), ^{57}Co, AmBe and neutrons from a deuterium fusion generator.

The main project aiming at the optimisation of the light collection is the upgrade of the MarmotX detector [20], which is currently used for qualification tests of the XENONnT PMTs, to a two-phase TPC. This cylindrical detector of 15 cm diameter and 10 cm height will be the first LXe TPC to incorporate a 4π light coverage: a top and bottom arrays of 60 SiPM modules (1.2×1.2 cm^2 from Hamamatsu Photonics) each, and 5 SiPMs rings composed of 28 SiPM modules each, for a total of 140 SiPM modules. The design of the detector will be optimised by Monte Carlo simulations of the light collection efficiency and simulations of the drift field by boundary element methods.

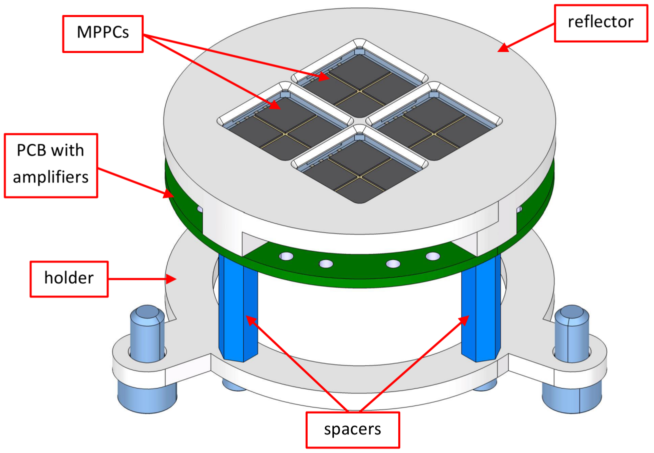

FIG. 4.8 – The top MPPC array which will replace the 2-inch top PMT in the Xurich TPC. It is made out of four 1.2×1.2 cm^2 units from Hamamatsu Photonics, for 16 channels in total.

Finally, the Xenoscope project also aims at the construction of a LXe TPC demonstrator that will be used to investigate the possibility to drift electrons over 2.6 m. This demonstrator will have the full height of the future DARWIN TPC, but will have a diameter of merely 20 cm, incorporating a total of 325 kg of LXe. A LXe filtration system will also be developed to ensure the sufficient electron lifetime (∼1 ms) required to drift and extract electrons in the gas phase.

[16] L. Baudis et al., Eur. Phys. J. C, 78 (2018).

[17] A. Manalaysay et al.,
Rev. Sci. Instrum. 81, 073303 (2010).

[18] M. Szydagis et al., JINST 6, P10002 (2011); M. Szydagis, A. Fyhrie, D. Thorngren and M. Tripathi, JINST 8 C10003 (2013).

[19] J. Aalbers et al. (DARWIN Collaboration), JCAP 1611, 11, 017 (2016).

[20] P. Barrow et al., JINST 12, P01024 (2017).