Photodetectors for the XENON1T
Dark Matter Experiment

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The XENON1T experiment

The XENON1T dark matter detector is currently under construction below the mountains of Gran Sasso at LNGS in Italy.
The XENON1T experiment

Some highlights of the construction:
The XENON1T experiment
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**XENON1T** is designed to search for dark matter WIMPs by measuring simultaneously the primary scintillation (**S1**) and proportional scintillation from ionization electrons (**S2**) produced by a WIMP interaction within a two phase time projection chamber (**TPC**) filled with liquid xenon (**LXe**).
XENON1T is designed to search for dark matter WIMPs by measuring simultaneously the primary scintillation (S1) and proportional scintillation from ionization electrons (S2) produced by a WIMP interaction within a two phase time projection chamber (TPC) filled with liquid xenon (LXe).

- The top PMTs in GXe detect S2 and give xy position with mm precision.
- The bottom PMTs are fully immersed in LXe to efficiently detect the S1 signal.
The XENON1T experiment

**XENON1T** is designed to search for dark matter WIMPs by measuring simultaneously the primary scintillation (**S1**) and proportional scintillation from ionization electrons (**S2**) produced by a WIMP interaction within a two phase time projection chamber (**TPC**) filled with liquid xenon (**LXe**).
The Photomultiplier Tubes

Hamamatsu R11410-21 low radioactivity **3 inch** PMTs.

**Operating temperature range:**
-110 to 50 deg. C

**Metal casing:**
Cobalt free, low radioactivity

**Quartz window:**
Transparent to VUV photons

**Bialkali photocathode:**
Sensitive to 178 nm wavelength. Typical QE of 32.5%

**Ceramic stem.**

**12 dynode stages:**
Average gain $3.5 \times 10^6$

**Top array:** 127 PMTs.

**Bottom array:** 121 PMTs.

TPC: Talk by Peter Barrow
PMT characterization at MPIK Heidelberg

Upon arrival all PMTs are tested at room temperature:
- DC rate
- HV scan (1320 – 1680) V
- Afterpulses
- Transit time

If all parameters OK → cool down

MPIK setup to cool down and measure 12 PMTs simultaneously:
Nitrogen vapor cooled by LN through a copper coil.
PMT characterization at MPIK Heidelberg

Average QE: **36%**

Average gain **$3.3 \times 10^6$** at -1500 V

P/V and resolution close to maximum at a gain of around: **$2 \times 10^6$** (about -1400 V)

Figures by Meike Danisch
The performance of the R11410 PMTs in LXe is tested at UZH with a dedicated experimental setup.

Double walled vacuum insulated cryostat to maintain the subzero temperatures.

Gas system to purify and circulate the Xe from its storage bottles into the detector chamber.
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Xe liquefaction to \(~170\) K is achieved with a Pulse Tube Refrigerator

Double walled vacuum insulated cryostat to maintain the subzero temperatures.

Gas system to purify and circulate the Xe from its storage bottles into the detector chamber.
Gain evolution during cool down

Effect of the temperature on the PMT gain:

These values include a x10 amplification factor from an external amplifier.
Long term stability tests

**Thermal cycling:** In order to test the stability of the PMTs in LXe, the tubes are submitted to a series of **cool downs** (170 K) and **warm ups** (room temp.) where the gain and dark count rate are monitored constantly.

- At room temperature the gain remains constant within 2%.
- When at LXe temperature, the gain decreased around 5%.
- The DC rate decreased by a factor 10.

**Dark Current:**
Thermal emission from the photocathode produces signals in the PMT.

![Graph showing gain and dark count rate over time](image)

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L. Baudis et al. JINST 8 P04026 (2013)
Study of Afterpulses

Afterpulses are signals that appear after the trigger signal.

It is important to have a low rate of afterpulses (below 10%, as specified by the producer) so that they do not interfere with the identification of S1 and S2 signals.

Three groups of afterpulses are observed:

- **A1**: Pulses of short delay (tens of ns), caused by elastic scattering electrons on the first dynode.
- **A2**: Populated mostly by dark pulses and single photoelectrons.
- **A3**: Pulses produced by positive ions from gas molecules within the PMT.

These afterpulses can be used as a diagnosis of the vacuum quality and identification of contaminants (CH$_4$, CO$_2$, etc.) inside the tube.
PMT field simulations

In order to understand the nature of afterpulses, the PMT field and the tracks of ions and electrons have been simulated with COMSOL.

Simulated photo-electrons have a drift time of around 46 ns, with a collection efficiency of 95%.

The paths of ions produced in the volume of the PMT are also simulated.

Simulations by Peter Barrow.
The simulated drift times are in agreement with the experimental results within 5%.

The afterpulse analysis allows to identify the gas remnants within the PMT and helps identify leaks or impurities.
Outlook

- The construction of XENON1T has started at LNGS.

- MPIK and UZH will continue testing the R11410 PMTs before their final installation in XENON1T.

- Data taking will start in 2015 and over the next few years a sensitivity of $2\times10^{-47}$ cm$^2$ will be achieved.
Direct detection with LXe

Why Xe?
✔ Large atomic mass, high stopping power.
✔ Self shielding.
✔ No long lived radioisotopes.
✔ Efficient scintillator.
✔ Scalable.

Search for **WIMP elastic scattering** off nuclei.

Using large mass detectors with a dense target material.

Nuclear recoil spectrum with exponential shape.

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**WIMP Scattering Rates**

- **Xe** (A=131): 18 events/100-kg/year ($E_{th}=5$ keVr)
- **Ge** (A=73): 8 events/100-kg/year ($E_{th}=15$ keVr)
- **Ar** (A=40)

$M_\chi = 100$ GeV, $\sigma_{\chi-p} = 10^{-45}$ cm$^2$
The photon emission principle

The $S_2/S_1$ ratio allows to distinguish WIMPs (nuclear recoils) from the main backgrounds (electronic recoils).

Some electrons drift to the anode and produce the $S_2$ signal, while others recombine with Xe ions.

The $S_2/S_1$ ratio allows to distinguish WIMPs (nuclear recoils) from the main backgrounds (electronic recoils).
XENON1T PMT map

127 PMTs

121 PMTs
PMT Spectrum and Gain

Example event: Photon signal from LED.

The PMT gain is estimated from the spectrum by identifying the single photo-electron peak, separated from the noise and double photo-electrons.

The gain of each PMT is measured at different voltages.

When operated in LXe, some PMTs show a decrease of around 10%, while in others the change is very small.
Consider the arrival time:

\[ t = \int_{s_0}^{L} \frac{1}{v} ds = \sqrt{\frac{m}{2q}} \int_{s_0}^{L} [V(s_0) - V(s)]^{-1/2} ds, \]

where \( m \) and \( q \) are the mass and charge of the ion, \( s_0 \) is the position of ionization and \( V(s) \) is the electric potential.

The field in a hemispherical PMT can be approximated as quadratic:

\[ V(s) = V_0 \left(1 - \frac{s}{L}\right)^2 \]

So the arrival time calculated from the integral gives:

\[ t = \frac{4}{\pi} \sqrt{\frac{2m}{qV_0}} L, \]

The mass/charge of the ion producing an afterpulse at time \( t \) is:

\[ \frac{M}{Q} = \left(\frac{\pi t}{4L}\right)^2 \frac{V_0}{2} \frac{q_p}{m_p} \]

The mass/charge of the ion is then proportional to \( t^2 \):

\[ \frac{M}{Q} = At^2 \]
PMT radioactivity and XENON1T background

Expected XENON1T background from MC simulations with GEANT4:

**Gamma background:**
Single scatter, 1 ton fiducial volume, [2-12] keVee, 99.75% ER rejection.

*0.05 ev/y*

Mainly from the Cryostat (50%), PMTs (30%) and TPC components (< 10%)

**Neutron background:**
Single scatter, 1 ton fiducial volume, [5-50] keVr, 50% NR acceptance.

*0.2 ev/y*

Mainly from Cryostat (30%), PMT +Bases (30%) and PTFE (20%).

Information from F. Piastra and A. Kish
HV divider base

The base placed at the pins of the PMT provides the voltage difference over the PMT dynodes. It has been developed and optimized at UZH for:

- **Linearity.** Up to 50k PE (approx. 1 MeV particle energy).
- **Low heat dissipation** (total under 10W).
- **Sub-zero** temperature performance
- **Good P/V ratio and high gain**

Screening results with **Gator**:

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<th>Units: mBq</th>
<th>$^{238}$U</th>
<th>$^{226}$Ra</th>
<th>$^{228}$Ra</th>
<th>$^{228}$Th</th>
<th>$^{235}$U</th>
<th>$^{40}$K</th>
<th>$^{60}$Co</th>
<th>$^{137}$Cs</th>
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<td>PMT only</td>
<td>&lt; 13</td>
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<td>0.50</td>
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<td>0.37</td>
<td>13</td>
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<td>PMT + base</td>
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<td>13</td>
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<td>+- 0.06</td>
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