4 Cold Dark Matter Search with XENON

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(XENON Collaboration)

There is overwhelming indirect evidence that a large fraction of the matter content of the universe is dark [1]. Dark matter may be composed of yet unidentified Weakly Interacting Massive Particles (WIMP), a remnant from the early, hot phase of our universe [2]. The XENON program operates time projection chambers (TPCs) filled with liquid xenon (LXe) as target material to detect nuclear recoils from WIMP elastic scatters off xenon nuclei. Operated as two-phase TPCs, as schematically shown in Fig. 4.1, the detectors observe light and charge signals from scintillation and ionization processes, providing a 3-dimensional interaction vertex reconstruction on an event-by-event basis and efficient discrimination against background signals from γ- or β-interactions. The vertex reconstruction allows to define a central, fiducial region of the detector, avoiding background induced in the walls.

We are involved in XENON100, the current phase in this program, which employs a total mass of 161 kg of LXe and in XENON1T, which will use a total mass of ∼2.4 tons of LXe. The detector is in the design phase, its construction at the *Laboratori Nazionali del Gran Sasso* (LNGS) in Italy will start in late 2012.

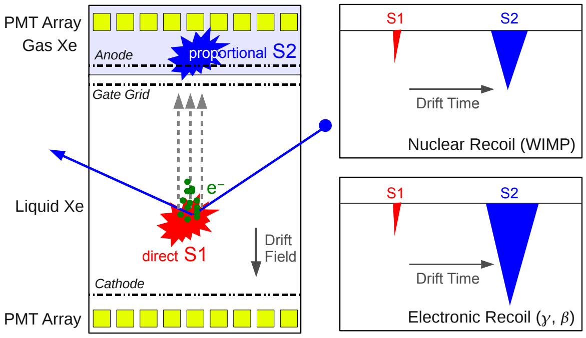

FIG. 4.1 – *Working principle of a two-phase TPC: Particle interactions in the liquid xenon target generate prompt scintillation light (S1) and ionize the target. The electric field across the detector volume drifts the electrons to the top of the TPC, where they are extracted into the gas phase by a strong extraction field. In the gas phase, they produce a localized proportional scintillation signal (S2) which allows to determine the xy-coordinate of the primary interaction. The z-coordinate is derived from the electron drift time, i.e., the time difference between S1 and S2. The S2/S1 amplitude ratio is different for signal (nuclear recoils) and background (electron recoils) [4].*

XENON100

XENON100 is located in the LNGS interferometer tunnel below an average of 3600 m water equivalent rock overburden, which reduces the muon flux by a factor 10^6. It uses the passive lead/polyethylene shield of XENON10, with the addition of an inner 5 cm copper layer as well as an outer, 20 cm thick water neutron shield. With 62 kg of liquid xenon in the TPC, XENON100 has a 4.5 times higher target mass than its predecessor, XENON10.

The gamma background was reduced by two orders of magnitude by means of an optimized detector de sign, as well as screening and selection of radio-pure detector and shield materials [3]. A detail description of the XENON100 instrument is published [4].

In 2011 XENON100 reported results from a 100.9 live days dark matter search [5]. A total of three events were found in the pre-defined signal region, compatible with the background prediction of (1.8 ± 0.6) events. The data was used to constrain the inelastic dark matter model (iDM) [6]. This model overcomes the tension between the annual modulation signal observed by DAMA [8] and the null results of other direct detection experiments. iDM assumes that WIMPs scatter off baryonic matter by simultaneously populating an energy level at δ above the groundstate ($\chi N \rightarrow \chi N^*$). Elastic scattering would be highly suppressed. In contrast to the elastic scattering, where an exponential recoil energy spectrum is expected, the threshold of the inelastic scattering process leads to a peaked recoil spectrum which for xenon ranges from $\approx$10 to $\approx$50 keV$_{nr}$.

Figure 4.3 shows the parameter space allowed by DAMA and other experiments. The result of XENON100 rules out the iDM interpretation of the DAMA modulation at 90% C.L. [7].

The XENON100 detector is continuously taking science data since March 2011. Compared to the last dark matter run, it has achieved a lower trigger threshold, a higher electronegative purity of the xenon, a lower background due to the ^{85}Kr intrinsic contamination, as well as high-statistics calibration runs with external gamma and neutron sources. About 225 live days of dark matter data have been acquired to date. The data is currently being analyzed, results are expected in early summer.

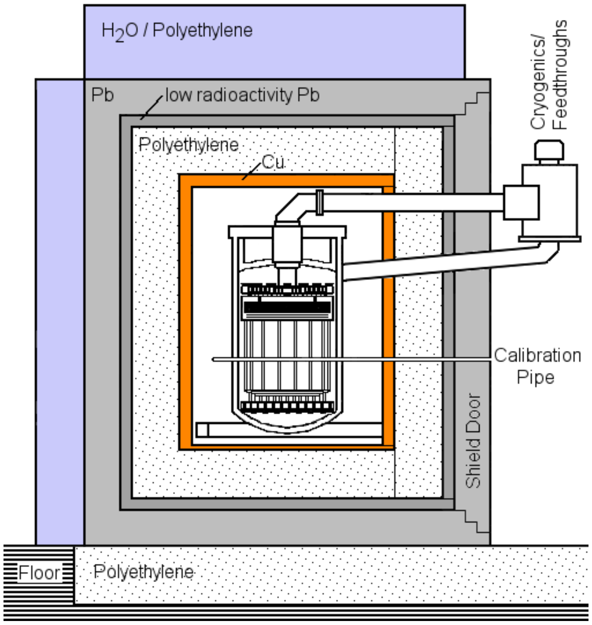

FIG. 4.2 – *XENON100 inside its passive shield made of water, lead, polyethylene, and ultra-pure copper, underground at LNGS [4].*

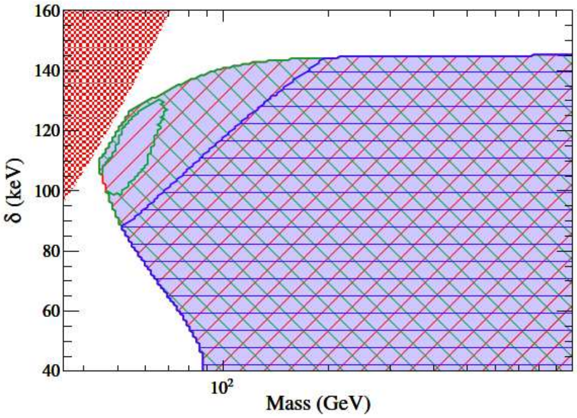

FIG. 4.3 – *Parameter space allowed by the DAMA annual modulation signal [8] in the inelastic dark matter model [6] (light blue area), along with the parameter space excluded by CDMS-II (blue horizontal lines) and ZEPLIN-III (green descending lines). XENON100 (red ascending lines) excludes the entire region allowed by DAMA [7].*

XENON1T

XENON1T will use about 2.4 tons of LXe in total with 1 ton in the fiducial volume. The xenon tank will be surrounded by a cylindrical 9.6 m×10 m water Cherenkov shield to reduce the muon induced neutron background to negligible levels. The raw background rate will be 1×10^{-4} events/(keV kg day), hundred times below the one of XENON100 [9] and the sensitivity to the WIMP-nucleon cross section will be pushed to 10^{-47} cm^2.

The XENON1T technical design report was submitted to LNGS in 2010 and in 2011 the project was approved to be installed in Hall B. The design is presently being finalized and construction is expected to start this year.

Our group is responsible for data acquisition and electronics, material screening, design and manufacturing of the inner detector structure, the photosensor calibration system and the tests of new, low-radioactive photomultiplier tubes (PMTs). We are also conducting Monte Carlo simulations targeted at the optimization of the detector design by minimizing the backgrounds from the intrinsic radioactivity of the components, and by improving the light collection efficiency and the vertex resolution. Together with Hamamatsu, the collaboration has developed a new 3-inch low-radioactivity PMT, R11410. Four units are currently being tested in our laboratory for their performance at room and liquid xenon temperatures. Figure 4.4 shows the stability of the gain for one unit over two months of operation in liquid xenon.

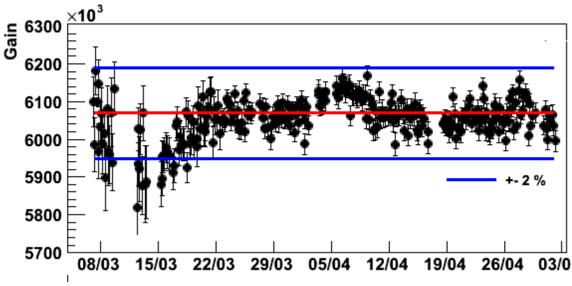

FIG. 4.4 – *The gain of one R11410 PMT at liquid xenon temperature measured during two months. The blue lines represent ±2 % variation.*

Material screening

To screen and select materials for XENON1T, we employ the following techniques:

- Inductively Coupled Plasma Mass Spectrometry (ICP-MS), available at LNGS with a sensitivity down to a few tens of μBq/kg for ^{238}U, ^{232}Th and ^{40}K,

- Neutron Activation Analysis (NAA), available at the Paul Scherrer Institute and at the Johannes Gutenberg University Mainz, with a similar sensitivity as the ICP-MS for the same isotopes,

- High Purity Germanium (HPGe) gamma spectrometers, available both at LNGS (with a sensitivity down to tens of μBq/kg for ^{226}Ra, ^{228}Ra, ^{228}Th and ^{60}Co) and at the Max Plank Institut für Kernphysik (MPIK) (with a sensitivity of $\sim$ 1mBq/kg for ^{226}Ra, ^{228}Ra, ^{228}Th and ^{60}Co),

- ^{222}Rn emanation essaying with ultra-low background proportional counters, available at the MPIK Heidelberg.

Our group operates the Gator facility [10] at LNGS, and has access to the ICP-MS and NAA techniques. These are complementary to gamma-ray spectroscopy as they detect the early parts of the ^{238}U and ^{232}Th chains. Gator contains at its core an ultra-low background, 2.2 kg HPGe detector with a relative efficiency of 100.5%, and a measured energy resolution of $\sim$ 3 keV FWHM at 1332 keV. It was extensively used to screen and select materials for XENON100 [3]. A selection of results for XENON1T materials is shown in Table 4.1. Titanium is considered as a material for the cryostat, while torlon is planned to be used inside the TPC, in a small amount. The R11410-10 PMT, with a quantum efficiency of $>$ 35 % at the 178 nm LXe scintillation light wavelength, will be used for the light sensor arrays.

TAB. 4.1 – Results from the radioactivity screening of the XENON1T samples.

Material	Technique	isotope						Unit
		^{238}U	^{226}Ra	^{228}Ra	^{228}Th	^{40}K	^{60}Co	
Ti grade 1	HPGe	30(10)	1.2(4)	< 1.1	< 0.71	< 2.8	< 0.17	mBq/kg
Ti grade 4	HPGe	< 42	< 1.2	2.1(6)	9(1)	< 4.9	< 0.29	mBq/kg
Ti grade 2	HPGe	40(10)	< 0.81	1.9(6)	3.1(3)	< 2.9	< 0.25	mBq/kg
Ti grade 1	NAA	< 650	–	< 110	–	–	–	mBq/kg
Ti grade 1	ICP-MS	25(4)	–	< 8.1	–	< 1600	–	mBq/kg
R11410-10[a]	HPGe	< 18	< 1.4	< 2.9	< 2.0	17(3)	4.3(4)	mBq/PMT
Torlon	HPGe	< 33	< 2.6	< 5.5	3(1)	< 26	< 11	mBq/kg
Torlon	ICP-MS	4.9(4)	–	0.49(4)	–	11.5(1)	–	mBq/kg

[a] 3" PMT

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