The Search for Dark Matter with XENON

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The XENON100 experiment aims at detecting cold dark matter particles via their collisions with xenon nuclei in a two-phase time projection chamber filled with a total of 165 kg of ultra pure liquid xenon. The detector sensitive target mass is about 65 kg, surrounded by about 100 kg of active veto. The detector has been installed underground at the Gran Sasso National Laboratory (LNGS) since 2008 and after a successful calibration, dark matter data taking has started. The current status of the XENON100 as well as future plans for the upgrade are presented.

1 Introduction

There is an increasing number of astrophysical and astronomical observations pointing to the existence of a non-luminous, non-baryonic and cold (i.e. non-relativistic) matter component in the universe, called Cold Dark Matter (CDM) [1, 2]. The most appealing candidates for CDM are Weakly Interactive Massive Particles (WIMPs) predicted by supersymmetric theories (SUSY), models with extra dimensions and little Higgs models [3, 4, 5].

The XENON project is currently one the most promising experiments for the direct detection of dark matter. After the successful results of the first 10 kg scale detector XENON10 [6, 7], the collaboration has designed and built a second-generation experiment exploiting the two-phase time projection chamber (TPC) technique based on liquid xenon (LXe). The XENON100 detector features an increase in mass by a factor of 10 and a reduction of the radioactive background level by a factor of 100, as shown by the first measured scientific data [8]. XENON100 sensitivity reach is a factor of 50 better than that of XENON10.

2 Detector Operation

Liquid xenon is appealing as a target material for dark matter direct detection. It is a heavy (A = 131) and dense ($\rho \sim 3$ g/cm^3) medium and an efficient scintillator (80% of NaI). The high mass number provides excellent detection capabilities for the spin-independent WIMP-nucleon scattering ($\sigma \propto A^2$). The abundance of odd isotopes (about 50%) allows the detection of spin-dependent interactions ($\sigma \propto$ J(J+1)). The high density and high Z provide self shielding against external gamma radiation. Xenon has no long lived isotopes and purification of krypton

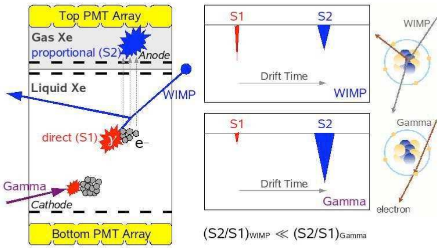

Figure 1: Principle of a two-phase liquid xenon TPC. A particle generates primary scintillation light (S1) and ionization electrons. These are drifted upwards with the field and detected via secondary scintillation light in the gas phase (S2). The S2 hit pattern (xy) and the drift time (z) give complete information for the position of events. Additionally, the ratio S2/S1 allows event discrimination between nuclear recoils (WIMPs, neutrons) and electron recoils (γ, β).

in xenon has been shown down to the level of a few ppt, which is an important advantage in the search for rare dark matter induced events.

The XENON100 detector is a two-phase (liquid-gas) time projection chamber (TPC). A particle interacting with the target generates electron ion pairs and excited xenon atoms, which produce scintillation light and free electrons in the medium (Figure 1). The primary light (S1) is detected immediately by the two photomultiplier (PMT) arrays above and below the target. An electric field (~ 0.53 kV/cm) across the TPC drifts the free ionization electrons upwards, where they are extracted into the gas phase by an even stronger extraction field. In the gas phase, the electrons generate very localized proportional scintillation light (S2). The PMT hit pattern of the S2 signal can be used to determine the xy-position of the interaction point and since the z-position is known from the drift time, the event positions can be reconstructed in three dimensions. This allows to select an inner fiducial volume in our target which together with the self shielding capability of liquid xenon drastically reduces the radioactive background from external sources.

The high ionization density of nuclear recoils in liquid xenon leads to a smaller S2/S1 ratio compared to electron recoils. The simultaneous measurement of charge and light provides a powerful discrimination between signal (nuclear recoils) and background events (electron recoils) via the ratio S2/S1. A discrimination of 99.5-99.9% has been achieved, for 50% nuclear recoil acceptance, in both XENON10 and XENON100.

3 Detector Setup

The XENON100 detector consists of 165 kg of liquid xenon divided in two concentric cylinders. The inner sensitive volume contains 65 kg of Xenon and is separated from the outer volume by a PTFE cage on the sides, a diving bell on the top and a PMT array in the bottom. Two electric field regions are created in this volume with one mesh in the bottom and three in the top, near the liquid gas interface. These electric fields allow electrons produced in interactions to drift in the main volume and be extracted to the gas where they produce proportional scintillation light. The PTFE cage acts as a reflector for the UV light from the liquid xenon and also accommodates a set of 40 field shaping rings and their resistive divider chain to improve the homogeneity of the field. The outer volume acts as an active veto reducing the amount of interactions in the inner volume and allowing to identify multiple scatter events. This in fact reduces the DAQ rate and the amount of data collected and improves our ability to reject gamma events as WIMP candidates.

The light readout is based on 1" × 1" Hamamatsu R8520-06-Al low-radioactive PMTs with quantum efficiencies up to $\sim 35\%$. 98 PMTs in the top array above the anode mesh are arranged in a circular pattern to improve position reconstruction, while 80 PMTs on the bottom are arranged in a compact grid to optimize the light collection. 64 PMTs in the active veto allow to detect energy depositions as low as 100 keVee reducing the overall background by a factor 4.

The detector is surrounded by a passive shield consisting, from the inside to the outside of 5 cm copper, 20 cm polyethylene and 20 cm lead (which has a low concentration of ^{210}Pb) and 20 cm of water. All the systems associated with the cooling and the purification of the xenon are placed outside this shield in order to minimize the background level.

The cryostat and detector production was completed in early 2008 and the detector was installed underground at LNGS. An extensive calibration of the detector systems has been performed in 2009 and blind dark matter data taking started in January 2010.

4 Detector Calibration

The XENON100 detector has been installed underground in LNGS since the middle of 2008, and has been tested in a series of successful calibrations during this period. Monitoring of the detector performance has been done on a regular basis using ^{137}Cs and blue LEDs to study the PMT gain, the light collection efficiency and the electron absorption. For dark matter detection one of the most important features of a two-phase liquid xenon TPC is the ability to distinguish between electronic and nuclear recoils. In order to characterize the electron recoil regions several calibrations with a ^{60}Co source have been performed. A high energy veto has been used to acquire only the lower part of the spectrum $\leq$150 keV.

To study the response to nuclear recoils, during December 2009 and for three days a calibration was performed with an AmBe neutron source. This allowed us to collect a large sample of elastic nuclear recoils, but also a rather homogeneous sample of 40 keV and 80 keV gamma-rays from inelastic scatterings which have been used to measure the energy resolution of the detector down to this energy.

5 XENON100 First Results

During the detector calibration period in 2009 some data were taken when no source was present and in ideal detector conditions. While this data were not originally blinded, we decided to perform a blind analysis on them by defining selection cuts only on the calibration data [8]. 11.2 days of data were analysed with a fiducial volume of 40 kg. Only very basic cuts were defined, aiming to remove noisy events, events interacting in the gas or events with multiple interactions in the detector. After applying these cuts a total of 22 events were observed in the fiducial volume and the energy region preselected for the signal, corresponding to a background level of $\sim$7 mdru, which is the lowest measured in a dark matter search up to date. None of the measured events lies in the nuclear recoil band, showing for the first time the successful background free operation of a liquefied noble gas TPC. Figure 2 shows the limit for spin

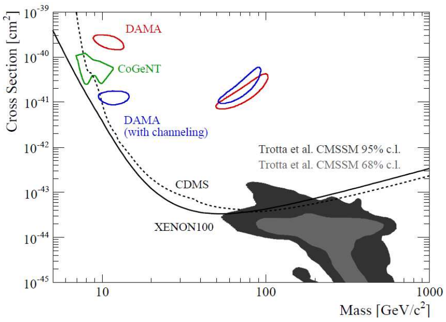

Figure 2: Exclusion plots for spin independent WIMP-nucleon interactions. The current limits are the curves around 10^{-43} cm^2, given by XENON100 (solid,[8]) and CDMS II (dashed,[9]). The projected sensitivity for XENON100 is one order of magnitude lower. The shaded regions are theoretical expectations of CMSSM.

independent dark matter parameter space established from this result, which already at this early stage of operation is comparable to the best exclusion limit to date.

Blind data acquisition started at the beginning of 2010 and to date more than 10 times the exposure used for this analysis has been completed and analysed [10]. Currently (2011) we are taking new set of blind data.

6 XENON1T

The XENON100 gamma background is dominated by the PMTs and the PMT bases, followed by the polyethylene of the shield and the stainless steel of the cryostat. The next step in the XENON dark matter project will be XENON1t, with a fiducial mass of ~1.1 ton. In order to achieve reduced background , PMT arrays will be replaced by QUPIDs [11], novel photo-sensors with an extremely low intrinsic radioactivity, developed by UCLA and Hamamatsu for this experiment. Additionally, a copper cryostat and 10 meter diameter water shield acting also as an active muon veto will be implemented. This detector will bring an improvement in the spin-independent WIMP-nucleon sensitivity of 2 orders of magnitude by 2015.

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