PandaX Dark Matter Experiment: from PandaX-I to PandaX-II

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ABSTRACT

PandaX is an experiment searching for dark matter at China Jinping Underground Laboratory. It uses liquid xenon as the target medium to look for signals from the direct interaction of weakly interacting massive particles, which are the hypothetical particles to explain the dark matter problem.

PandaX has a staged program with the first stage 120-kg sensitive target experiment (PandaX-I) completed, fulfilling its goal to confirm/exclude the suspicious signals from light dark matter as reported by several other experiments. Currently PandaX is preparing for the second stage (PandaX-II), with a 500-kg sensitive liquid xenon target, which will search for dark matter at previously unexplored regions of parameter space as predicted by theories beyond the standard model.

INTRODUCTION

Dark matter is proposed to explain the unusual gravitational effects as observed in astrophysics, such as from the galactic rotational curves, the internal motion of galaxy clusters and large scale structures. Although the non-visible, non-baryonic dark matter accounts for more than a quarter of the energy of the Universe [1], the particle nature of dark matter is still unknown. Weakly interacting massive particles (WIMPs) that exist in many models of new physics are natural candidates, in addition to other particles such as axions and sterile neutrinos.

Particle physics experiments are being carried out in many places to search for the WIMPs. They potentially can be produced from high energy colliders and can be observed as some missing energy. They can also be searched for indirectly from their annihilation products from the galactic center or the halo. However, looking for the signals from WIMPs directly interacting in a terrestrial detector will provide the cleanest indication of their existence.

Due to the cosmic ray induced background, direct detections of dark matter are usually carried out in deep underground laboratories. Further shielding and background reduction techniques are required to suppress the background from natural radiations.

Many detector techniques, including low background scintillation crystals, cryogenic bolometers, and superheated bubble chambers were developed to satisfy the low background requirement for WIMPs search. But in the last ten years, detectors using the noble liquid technique, in particular two-phase xenon, have made significant breakthroughs. Experiments such as XENON100 [2] and LUX [3] have been continuously improving the WIMP search sensitivity down to WIMP-nucleon scattering cross sections less than 10^{-45} cm^2.

The PandaX experiment likewise uses the two-phase xenon technique. It was proposed in 2009 as a flagship dark matter search experiment at the yet-to-be-built China Jinping Underground Laboratory (CJPL) [4], together with the CDEX low-mass dark matter search experiment [5] using an ultra-low threshold Germanium detector. CJPL has a rock overburden of 2400 meters, providing the lowest cosmic ray background among all underground laboratories around the world.

With funding support from Shanghai Jiao Tong University, the Ministry of Science and Technology of China (MOST), the National Science Foundation of China (NSFC) and collaboration institutes, the PandaX collaboration has made steady progress toward the construction and operation of the experiment and has joined the worldwide competition for WIMP searches. The first stage of the PandaX (PandaX-I) experiment, with a 120-kg sensitive liquid xenon target mass, started to collect data in March 2014 and by August 2014, the first 17 days of dark matter search data from PandaX-I was released with excellent sensitivity to low-mass dark matter [6]. PandaX-I collected another 63 days of dark matter search data by November 2014. The PandaX-II experiment, with an upgraded detector of 500-kg xenon target mass, is being commissioned and will start to take data later this year.

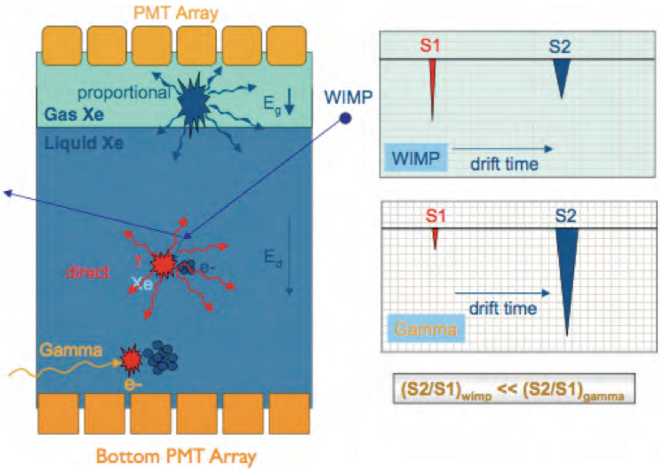

Fig. 1: Operation principle of the two-phase xenon technique for dark matter search.

TWO-PHASE XENON TECHNIQUE

Liquid xenon is a unique target medium for direct detection of WIMPs. Due to the large atomic mass (A) of xenon, the spin-independent interaction rate is enhanced due to coherent scattering and is proportional to A^2. With the large scintillation yield of liquid xenon, the threshold of the xenon detector has been demonstrated to be lower than 3 keV_{nr} (nuclear recoil energy) [3], making xenon detectors sensitive not only to heavy dark matter around 100 GeV/c^2 and above but also to light particles below 10 GeV/c^2

Xenon nuclear recoils are produced when WIMPs are elastically scattered on the target atoms. The nuclear recoils interact with the surrounding xenon atoms, creating excited atoms and electron-ion pairs. The electron-ion pairs will recombine to form additional excited atoms. Scintillation light signals are produced from the decay of the excited states. If an electric field is present, the recombination is partly suppressed and ionization signals can be collected. Due to the different ionization densities for nuclear recoils (NRs) from WIMPs (or neutrons) and for electron recoils (ERs) from background gamma and electrons, the ratios of scintillation and ionization signals are different for these two types of events. This difference can be used to reject ER background, which is the dominant background from various sources. The XENON100[2], LUX[3] and PandaX [6] experiments have reported that more than 99.5% ER background events can be rejected while keeping about 50% NR events in the signal region.

A two-phase xenon technique has been used to enhance the rejection power of xenon detectors. The technique was developed more than ten years ago for the XENON10 [7] and ZEPLIN-II [8] experiments. The operation principle is shown in Fig. 1. The direct scintillation light is read out as a prompt signal (S1) by the photomultiplier tubes (PMTs). The ionization electrons are drifted from the interaction point to the liquid-gas interface, where a stronger field in the gas extracts the electrons, from which proportional scintillation light (electroluminescence) is produced and detected as well by the PMTs as S2.

Using the time delay of the S1 and S2 signals, the event Z position is determined with sub-mm precision. The X and Y positions can be reconstructed from the S2 hit pattern on the top PMT array, with mm position resolutions. The precise three-dimensional event reconstruction allows the rejection of surface background events with fiducialization, as well as the rejection of multiple scattering events, which are not produced by WIMPs.

In addition to the excellent background suppression techniques with ER/NR discrimination and 3D fiducialization, xenon gas can be purified online. The electronegative impurities such as water and oxygen can be removed down to a part-per-billion (ppb) level by passing the gas through a commercial getter in a circulation system. Commercial xenon contains a ppb to a part-per-million (ppm) level of krypton, which has a beta decay emitter ^{85}Kr, generating an important background because the beta decay happens uniformly in the target and cannot be removed by the fiducialization. The distillation column developed by the PandaX experiment [9] has been used to reduce the Kr in Xe down to a part-per-trillion (ppt) level, making krypton a negligible background for the ton scale liquid xenon experiment.

Due to the ultra-low WIMP scattering rate constrained by the current generation experiments, large target masses at the ton or even multi-ton scale are needed for the next generation experiments with discovery potential. Thanks to the relative simple cryogenics at 165K for liquid xenon and the relative inexpensive cost for xenon gas, such multi-ton scale experiments can be realized within the next five to ten years, e.g. see [10].

The PandaX collaboration has successfully demonstrated all the techniques required for the liquid xenon dark matter experiment with the PandaX-I experiment, and is currently preparing for PandaX-II's 500-kg experiment. Both the PandaX-I and PandaX-II experiments are located at the same place at the first phase of CJPL (CJPL-I) with the same passive shielding, cryogenics and gas systems. Given the much larger space provided by the second phase of CJPL (CJPL-II), a PandaX 20-ton liquid xenon experiment could be realized to explore dark matter physics, for 10 (100) GeV/c^2 WIMPs, down to WIMP-nucleon cross sections of 10^{-45} (10^{-49}) cm^2 where the coherent scattering signals from solar, atmospheric and supernovae neutrinos are expected to emerge [11].

Fig. 2: (Top) The cryogenic cooling bus and gas circulation and purification system for both the PandaX-I and PandaX-II experiments. (Bottom) The PandaX experimental area with the gas storage system shown at the near front and the shielding system at the far end.

PANDAX-I

The PandaX-I detector was proposed as the first step of the dark matter experiment using liquid xenon at CJPL. The physics motivation was to search for light dark matter signals at around 10 GeV/c^2 as reported by DAMA/LIBRA [12] and CoGeNT [13], with the additional interesting signals reported by the CRESST-II [14] and CDMS-Si [15] experiments during the preparation of the PandaX-I experiment.

While PandaX-I is a small-scale liquid xenon experiment with a total sensitive target of 120-kg, the infrastructures and associated systems were developed to allow upgrading to a ton-scale experiment. Thus the passive shielding (Fig. 2), with low background lead, polyethylene and oxygen free high conductive copper (OHFC) materials, contains a cavity that is 1.24 meters in diameter and 1.75 meters in height, which can accommodate a detector with two to three tons of a liquid xenon target. The cavity is in a vacuum environment inside an OHFC vessel with 5-cm wall thickness for gamma and Radon shielding. PandaX' s cryogenics system (Fig. 2) [16] utilizes the pulse-tube refrigerator (PTR) with additional liquid nitrogen assisted cooling for both safety and initial high-speed filling. The system has been demonstrated to maintain one-ton of liquid xenon at a stable temperature at around 165 K. A xenon circulation and purification system is demonstrated with a circulation speed of 30 standard liters per minute. A detailed description of the PandaX cryogenics and gas systems can be found at the PandaX technical design report [17]. Such a system thus is able to support the operation of a ton-scale liquid xenon experiment for dark matter.

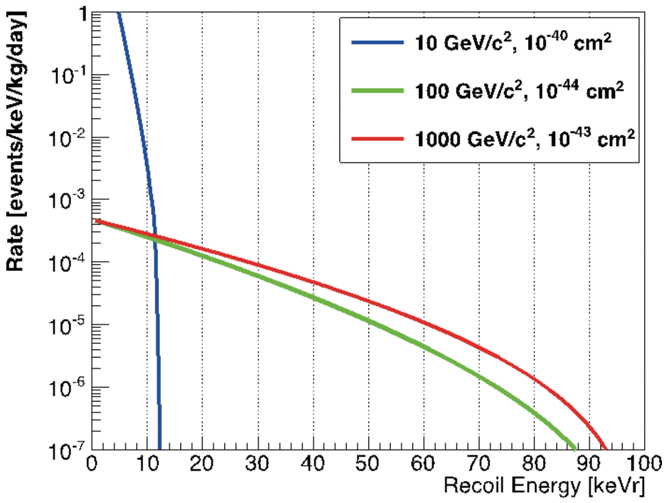

Fig. 3: Event rates as a function of nuclear recoil energy for different WIMP masses in a xenon target. The maximum recoil energy that can be produced from a 10 GeV/c^2 WIMP is less than 10 keV.

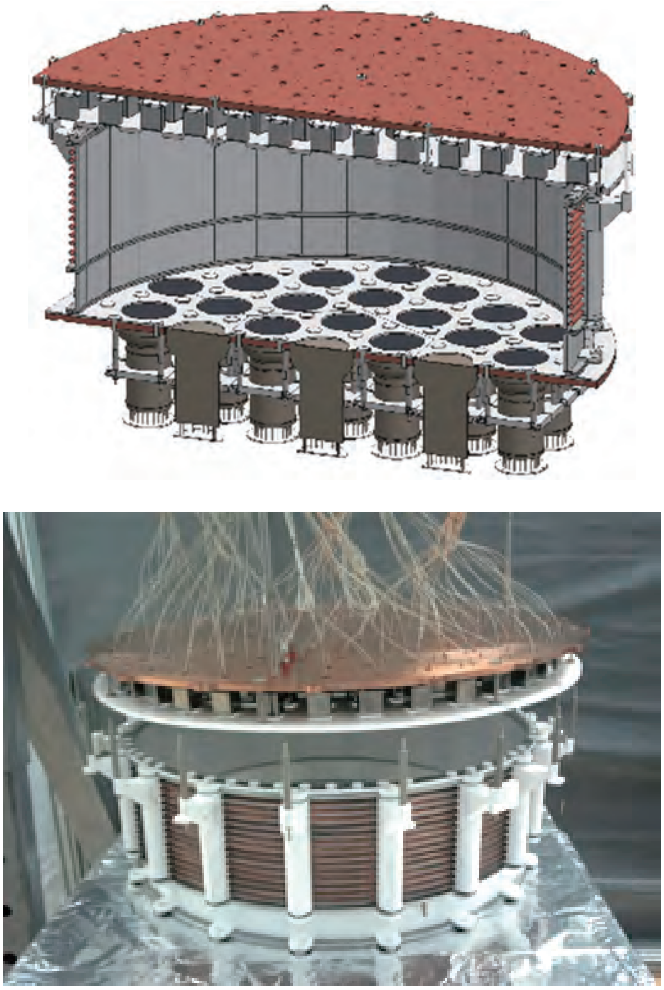

Fig. 4: The cross-section view of the TPC design (upper) and a picture of the completed TPC (lower, the bottom PMT array not shown).

The time projection chamber (TPC) for the PandaX-I detector is designed to have a higher S1 light yield compared to the XENON100 experiment, which was the largest two-phase xenon detector at the time PandaX-I was proposed. S1 Light yield is a key parameter that determines the energy threshold of the detector. A higher light yield provides a lower threshold, thus higher sensitivity for light dark matter due to the sharp exponential increasing of the event rate at lower recoil energy (Fig. 3). In order to produce a high light yield for PandaX-I, we designed the TPC in a pancaked shape with a diameter of 60 cm and a drift length of 15 cm. In addition to that, we chose to use a new type of large photocathode (3-inch), i.e., high quantum efficiency (QE, at least 30%) R11410 PMTs developed by the Hamamatsu Co. In total, the TPC uses 37 R11410 PMTs for the bottom PMT array and 143 R8520 PMTs for the top array. A cross section view of the TPC design and a picture showing the completed TPC are shown in Fig. 4.

The PandaX-I TPC was operated at a drift field of 667 V/cm, with a light yield of 4.2 photoelectrons/keV$_{ee}$ (PE/keV$_{ee}$) [6] for 122 keV gamma rays. For comparison, XENON100 obtained a light yield of 2.2 PE/keV$_{ee}$ [2] at 530 V/cm.

The high light yield of the detector allows us to probe light dark matter with better sensitivity compared to

XENON100. With just 17.4 live-days of exposure in the 37-kg fiducial mass, PandaX-I was able to place an upper limit of 2×10^{-42} cm^2 at a light WIMP mass of 10 GeV/c^2 [6], disfavoring all previously claimed WIMP signals in this region. With the additional 63 live-days (total 80 live-days) of dark matter search data from PandaX-I and more refined analysis, the main conclusion remains the same [18]. The major background for the PandaX-I experiment is the electron recoils by gamma rays from the radioactivity of detector materials, dominated by the stainless steel inner vessel and the PMTs [18]. Thus for PandaX-II, a new inner vessel with much lower radioactive stainless steel is being made. The background from PMTs will also be reduced in the fiducial volume due to a longer drift length (60 cm) compared to the 15 cm of PandaX-I.

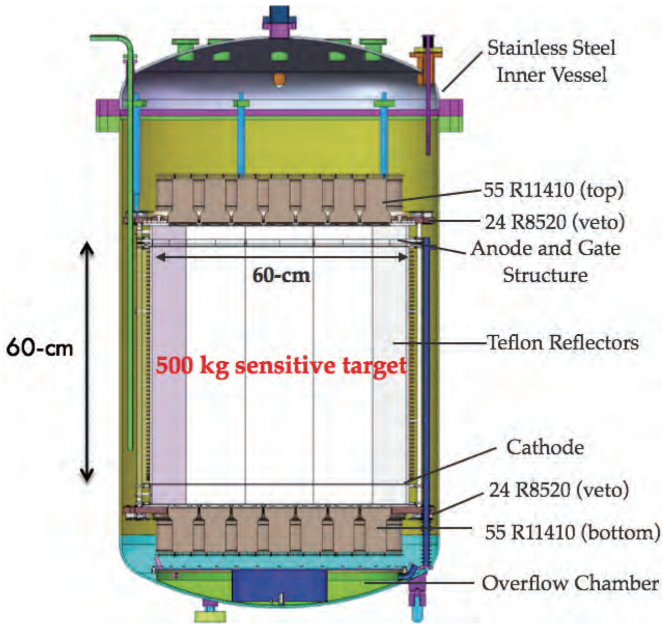

Fig. 5: The cross-section view of the PandaX-II TPC design.

PANDAX-II

PandaX-II is an upgrade from PandaX-I using the existing infrastructure and systems, such as the shielding, cryogenic and purification set-up. The major change is the detector itself, including the stainless steel inner vessel and the TPC inside. The PandaX-II stainless steel is made from fresh ore in a clean oven without the contamination of radioactive elements from old steel. The radioactivity of stainless steel for the PandaX-II vessel is greatly reduced and ^{60}Co activity is reduced by more than one order of magnitude, compared to that of PandaX-I stainless steel. Such low activity stainless steel makes the inner vessel a sub-dominant background source for PandaX-II according to a Geant4 simulation.

A cross-section view of the PandaX-II TPC design is shown in Fig. 5. The stainless steel inner vessel has an inner diameter of 80 cm. The sensitive target of the TPC has an inner diameter of about 60-cm and a drift length of 60-cm, and can contain approximately 500-kg of liquid xenon when filled. The sensitive liquid xenon target is viewed by two identical PMT arrays on the top and bottom. Each array contains 55 R11410 PMTs. There are a few cm of space between the inner vessel and the outer wall of the field cage, allowing the cathode high voltage feed-through, cables for the bottom PMT array and the liquid xenon pipes to pass through. We use two arrays of 24 R8520 PMTs each to view the signals from the region as an active veto. Gamma rays interacting in the active veto and further entering the sensitive target will be vetoed as multiple scattering events.

PandaX-II is currently being prepared at the Jinping Underground Laboratory with the goal to start data taking in 2015 continuously, for at least one year. We expect that PandaX-II will improve the current PandaX-I's limit by more than two orders of magnitude in its 300-kg fiducial mass with one live-year of exposure. Such sensitivity will allow PandaX-II to search for dark matter at WIMP parameter space that was unexplored by other experiments.

CONCLUSION AND PROSPECTS

PandaX is a dark matter direct detection experiment using liquid xenon as the target medium at China's Jinping Underground Laboratory. The experiment has finished its first stage (PandaX-I), placing strong constraints on the suspicious light dark matter signals reported by other experiments. Currently, the project is in its second stage (PandaX-II) with a total 500-kg sensitive target mass. PandaX-II is expected to start data taking within 2015 and to probe previously unexplored WIMP parameter space for both light and heavy dark matter particles.

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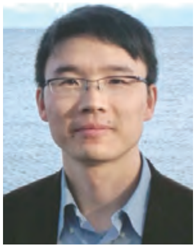

Kaixuan Ni is an associate professor in the Department of Physics and Astronomy at Shanghai Jiao Tong University. He obtained a PhD in 2006 from Columbia University, where he participated in developing the first generation liquid xenon based dark matter detector XENON10. Afterwards, he worked at Yale University and Columbia University as a postdoc and an associate research scientist on the XENON100 experiment, before joining Shanghai Jiao Tong University in 2009. Since then he has continued the experimental search for dark matter in the XENON100 program in Italy and the PandaX dark matter experiment in China. He has led the development of the time projection chambers for the PandaX-I and PandaX-II detectors.