First dark matter search results from the PandaX-I experiment

XIAO MengJiao1, XIAO Xiang1, ZHAO Li1, CAO XiGuang4, CHEN Xun1, CHEN YunHua8, CUI XiangYi1, FANG DeQing4, FU ChangBo1, GIBONI Karl L.1, GONG HaoWei1, GUO GuoDong1, HU Jie1, HUANG XingTao3, JI XiangDong1,6,71, JU YongLin2, LEI SiAo1, LI ShaoLi1, LIN Qing1, LIU HuaXuan2, LIU JiangLai16, LIU Xiang1, LORENZON Wolfgang5, MA YuGang4, MAO YaJunn6, NI KaiXuan1*, PUSHKIN Kirill1.5, REN XiangXiang3, SCHUBNELL Michael5, SHEN ManBing8, STEPHENSON Scott5, TAN AnDi7, TARLÉ Greg5, WANG HongWei4, WANG JiMin8, WANG Meng3, WANG XuMing1, WANG Zhou2, WEI YueHuan18, WU ShiYong8, XIE PengWei1, YOU YingHui8, ZENG XiongHui8, ZHANG Hua2, ZHANG Tao1 & ZHU ZhongHua8
(The PandaX Collaboration)

1The Institute of Nuclear and Particle Physics, Astronomy and Cosmology (INPAC) and Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China;
2School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China;
3School of Physics and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Jinan 250100, China;
4Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China;
5Department of Physics, University of Michigan, Ann Arbor, MI, 48109, USA;
6School of Physics, Peking University, Beijing 100800, China;
7Department of Physics, University of Maryland, College Park, MD, 20742, USA;
8Yalong River Hydropower Development Company, Ltd., 288 Shuanglin Road, Chengdu 610051, China

Received August 22, 2014; accepted August 23, 2014; published online September 5, 2014

We report on the first dark-matter (DM) search results from PandaX-I, a low threshold dual-phase xenon experiment operating at the China Jinping Underground Laboratory. In the 37-kg liquid xenon target with 17.4 live-days of exposure, no DM particle candidate event was found. This result sets a stringent limit for low-mass DM particles and disfavors the interpretation of previously-reported positive experimental results. The minimum upper limit, 3.7 × 10⁻⁴⁴ cm², for the spin-independent isoscalar DM-particle-nucleon scattering cross section is obtained at a DM-particle mass of 49 GeV/c² at 90% confidence level.

dark matter, direct detection, xenon

PACS number(s): 95.35.+d, 29.40.-n, 95.55.Vj

Citation: Xiao M J, Xiao X, Zhao L, et al. First dark matter search results from the PandaX-I experiment. Sci China-Phys Mech Astron, 2014, 57: 2024–2030, doi: 10.1007/s11433-014-5598-7

†Spokesperson (email: xdj@sjtu.edu.cn; xji@umd.edu)
*Corresponding author (LIU JiangLai, email: jianglai.liu@sjtu.edu.cn; NI KaiXuan, email: nikx@sjtu.edu.cn)
§Current institution: Physics Institute, University of Zürich

The dark matter is a leading candidate to explain gravitational effects observed in galactic rotational curves, galaxy clusters, and large scale structure formation, etc. [1]. Weakly interacting massive particles (WIMPs), a particular class of dark-
matter (DM) candidates, are interesting in particle physics and can be studied in colliders, indirect and direct detection experiments [2]. These particles can naturally arise from models beyond the Standard Model of particle physics, such as supersymmetry and extra dimensions [3]. Direct positive detection of WIMPs using ultra-low background detectors in deep underground laboratories would provide convincing evidence of DM in our solar system and allow the probing of fundamental properties of WIMPs.

Direct detection experiments using different technologies have produced many interesting results. The first reported positive observation was from the DAMA/LIBRA experiment which used NaI(Tl) crystal as targets [4]. The results can be explained by WIMPs with masses around 10 or 50 GeV/c² [5]. More recently, experiments using ultra-low threshold detectors with a germanium target (CoGeNT [6]) and a silicon target (CDMS II-Si [7]) reported signals above background, pointing to a low-mass WIMP particle near 10 GeV/c². In addition, the CRESST-II experiment using the CaWO₄ crystal also reported signals indicating 10 or 30 GeV/c² WIMPs, but not confirmed by the upgraded detector [8, 9]. These results have produced much excitement in the community [10] and call for further examinations of the low-mass WIMP signals through other experiments [11–14].

In recent years, new techniques using noble liquids (xenon, argon) have shown exceptional potential due to the capability of background suppression and discrimination, and scalability to large target masses. The XENON10/100 [15–19] and LUX [20] experiments using the dual-phase technique have improved WIMP detection sensitivity by more than two orders of magnitude in a wide mass range.

The PandaX experiment, operated at the China Jinping Underground Laboratory (CJPL) [21], uses the dual-phase xenon technique to search for both low and high mass WIMP dark matter. The first stage of PandaX (PandaX-I) employs a pancake-shaped time projection chamber (TPC) with about 120-kg active xenon target mass. This TPC, designed with a high light-yield thus low-energy threshold, is dedicated to searching for low-mass DM particles. A detailed description of the PandaX-I experiment and CJPL is given in ref. [22].

The PandaX TPC, with a diameter of 60 cm and drift length of 15 cm is mounted in a stainless steel inner vessel, 75 cm in diameter and 103 cm in height, containing a total mass of 450 kg of liquid xenon (LXe). The inner vessel is over-dimensioned to accommodate the future upgrade to PandaX-II. It is contained in a vacuum cryostat constructed from 5-cm thick high-purity oxygen-free copper, and enclosed by a passive shield made of copper, polyethylene, lead, and polyethylene, from inner to outer layers. The gap between the copper cryostat and inner copper shield is continuously flushed with dry nitrogen gas to reduce radon to below 10 Bq/m³. The cryogenics and gas handling systems are installed outside the shield and maintain the LXe at a working temperature of 179.5 K and an absolute pressure of about 2.0 atm. During data taking the cryogenics system provided a thermal and pressure stability of better than 1%. Xenon is continuously recirculated through a getter purification system at a rate around 30 SLPM, resulting in a stable electron lifetime of approximately 260 µs.

The dual-phase xenon TPC technique enables the detection of both the primary scintillation signal (S1) in the liquid and the ionization signal through proportional scintillation (S2) in the gas. This allows discrimination of nuclear recoils (NR) from electron recoils (ER) via the S2 to S1 ratio [23]. Further background reduction is achieved through fiducialization of the target volume using 3D event position reconstruction. The PandaX-I TPC is operated with cathode, gate, and anode potentials setting to −15 kV, −5 kV, and ground, respectively. This generates an expected drift field of 667 V/cm, which agrees within 3% with the average simulated from the actual geometry. The electron drift velocity is 1.7 mm/µs according to ref. [24], in excellent agreement with drift time distribution in our data. The liquid level is centered between the gate and anode, which are separated by 8 mm. The level can be adjusted to a precision of 0.1 mm with an externally-controlled overflow mechanism.

The scintillation light is collected by two opposing horizontal arrays of photomultiplier tubes (PMTs). The bottom array, consisting of 37 3-inch Hamamatsu R14110-MOD PMTs, is immersed in LXe 5 cm below the cathode. The top array consists of 143 1-inch Hamamatsu R8520-406 PMTs and is mounted in the gaseous xenon above the anode. The horizontal position of an event is reconstructed using the S2 signal captured by the top array, while the vertical position is determined using the time difference between S1 and S2 signals. During operation, three top PMTs and two bottom PMTs were disabled due to malfunction.

The PMT gains are adjusted to $2 \times 10^6$, calibrated weekly using low-intensity LED light, and are stable within 10% over time. Random hits are used to monitor the PMT dark rates and gains. During the DM search run, dark rates of the top and bottom PMTs are approximately 50 Hz and 1 kHz, respectively. These rates have correlation with detector parameters such as cryogenic conditions, TPC high voltage, as well as ambient temperature. The data with spurious dark rates are removed from this analysis.

The raw signals from the PMTs get amplified by a factor of 10 through Phillips 779 amplifiers, then fed into CAEN V1724 14-bit 100 M$/$s digitizers. The event trigger is constructed by summing, integrating, and discriminating the time-over-threshold ("Majority") outputs from the digitizers for the bottom PMTs. For events triggered by S2 signals relevant for DM search, the trigger threshold corresponds to 89 photoelectrons (PEs). Waveforms from the PMTs are recorded 100 µs before and after the trigger, with zero length encoding for signals below 1/3 PE on each channel.

We analyzed waveforms for each PMT channel to define physical events. Hits are identified from each PMT waveform with a threshold corresponding to about 40% single PE amplitude. These hits are clustered in time to form physical
signals. Consistent selection results were obtained by alternatively implementing signal finding on the summed waveform. The S1 and S2 signals are identified primarily using their widths. An event relevant for DM search contains a single S1 signal before the S2 signal.

Data quality filters are applied to separate physical signals from noise. The 200 kHz noise originating from the PMT high-voltage supplies is filtered based on its ringing signature. Events with large baseline variations as well as abnormal S2 signal ratios of the bottom to top PMTs are rejected. A good S1 signal requires at least two PMTs fired and an appropriate pulse height-to-area ratio.

The horizontal position of an event is reconstructed by both a center-of-gravity (CoG) and neural network (NN) algorithm using the S2 pattern observed with the top PMT array. The average difference of the positions for the two methods is about 1 cm, and events with large difference due to abnormal S2 hit patterns are rejected. In our analysis, we use the CoG approach, and have confirmed that the conclusions do not change when the latter approach is used.

Calibration runs with $^{137}$Cs and $^{60}$Co gamma sources and a $^{252}$Cf neutron source, deployed between the outer and inner vessels, were taken to characterize the detector response. The neutron source produces both elastic NR events as well as inelastic events with gamma energies of 40 ($^{129}$Xe) and 80 keV ($^{131}$Xe). The 40 keV inelastic events are utilized in the uniformity corrections to the S1 and S2 signals. After subtracting the NR contribution, the ER light yield is 5.1 (4.7) PE/keV$_{ee}$ (electron-equivalent) at 40 (80) keV. Extrapolating these light yields using the NEST model [25], we obtain a light yield at 122 keV of (4.2±0.2) PE/keV$_{ee}$ at a drift field of 667 V/cm and (7.3±0.3) PE/keV$_{ee}$ at zero field ($L_{ee}^{x}$) [25].

The S1–S2 combined energy scale for ERs is defined as $E_{ee}^{S} = W \cdot (S1/\alpha + S2/\beta)$. The work function $W = 13.7$ eV [25] is the average energy needed to produce a quantum (photon or electron) in liquid xenon, $\alpha$ is the photon detection efficiency (PDE), and $\beta$ is the product of the single-electron gas gain and the electron extraction efficiency (EEE). The single-electron gas gain is determined to be 22.1 PE/e with a 45% resolution by fitting single-electron S2 signals. The PDE and EEE are found to be $(10.5±0.4)\%$ and $(79.8±7.0)\%$, respectively, by fitting the anti-correlation between S1 and S2 for 40 and 80 keV inelastic events (Figure 1). The uncertainties in these values are estimated from the difference between the values extracted from the two gamma peaks. The scintillation and ionization yields at 40, 80, and 662 keV ($^{137}$Cs) obtained from our data are consistent with the NEST predictions within 10%–20%.

The detector response to ER and NR events is studied with $^{60}$Co and $^{252}$Cf calibration data. Single scattering events are selected and a fiducial cut of 20 cm radius and 20–80 µs drift time is applied to the reconstructed vertices. We select low-energy calibration events with S1 between 2 and 30 PE, and S2 from the bottom PMT array greater than 300 PE. The NR purity from the $^{252}$Cf data within this energy range is expected to be approximately 98% based on a Monte Carlo (MC) simulation. The bands from ER and NR calibration data are shown in Figure 2. For the ER calibration band, a total of 278 events are found during 135.4 live-hours of $^{60}$Co calibration data. The mean of the ER band is computed for every 1-PE slice of S1, and fitted with a double exponential form. The width of the band was assumed independent in S1, due to limited statistics. An average ER Gaussian leakage fraction of 0.32% below the mean of the NR band (or 99.7% ER rejection efficiency) is obtained based on the width of the ER band. We have performed alternative fittings of the ER

![Figure 1](image1.png) S2 versus S1 distribution from $^{252}$Cf calibration data. The horizontal and vertical lines close to the axes indicate the average NR contribution that is subtracted from the inelastic peaks when performing the anti-correlation fit, and the off-diagonal lines are the fit results.

![Figure 2](image2.png) The log$_{10}$(S2/S1) versus S1 for (a) ER and (b) NR calibration data with means (solid blue and red lines, respectively) and ±2σ ER contours (dashed blue lines). The dashed magenta curve represents the 300 PE bottom S2 cut. The gray dashed lines are the constant energy contours using the combined energy scale based on NEST and the measured PDE and EEE.
band, which generate about 0.1% change in the leakage fraction.

The overall event detection efficiency is the combination of cut efficiency $\epsilon_{\text{cut}}$ and signal acceptance $A$ of the NR signal window. The cut efficiency $\epsilon_{\text{cut}}$ includes the identification and quality cut efficiencies on both S1 and S2, and the trigger efficiency on S2 signals. The S1 identification and quality cut efficiencies are evaluated using the low-intensity LED data. The S2 identification efficiency is determined by regrouping closely-packed multiple S1 signals as mis-identified small S2 signals, and is close to 97%. The S2 quality cut efficiency due to bottom-to-top-charge-ratio cut is evaluated by selecting events well located on the NR band and taking the ratio due to bottom-to-top-charge-ratio cut is evaluated by selecting events well located on the NR band and taking the ratio of events with and without the cut. Finally, the S2 trigger efficiency is obtained by fitting the measured S2 NR spectrum assuming an exponential form of the true energy spectrum. Combining these, $\epsilon_{\text{cut}}$ is found as a rising function of S1 with a maximum of about 70% at 25 PE, and then falls gradually due to the pulse height to area ratio quality cut on the S1 waveform. Consistent cut efficiency, depicted in Figure 3, is obtained by taking the ratio of the measured NR spectrum to the expected spectrum from the MC. This cut efficiency includes the contribution due to the 300 PE bottom S2 cut. The corresponding signal acceptance $A$ is defined as the ratio of the number of NR events below the mean (i.e., average) of the NR band to the total, also shown in Figure 3 together with the overall efficiency. The change of the acceptance as a function of S1 indicates the variation of the log$_{10}$($S2/S1$) distribution in different S1 slices. The events on the NR band with suppressed S2 could be due to multiple-scattered neutrons that deposit partial energy below the cathode. Using double-scatter neutrons with the second scatter in the very bottom layer of the TPC as a proxy, we estimate that those below-cathode events could lead to a maximum fractional reduction of 25% to the overall NR detection efficiency. A detailed study of this will appear in a separate publication.

The analysis results reported here are from 17.4 live-days of DM search data, taken from May 26 to July 5, 2014. Event rates are summarized in Table 1 for various cut levels. The reduction of background due to single S2 cut is consistent with the MC expectation. Dark matter candidates are selected by employing identical selection cuts used in the calibration data. The signal window for S1 between 2 and 30 PE corresponds to a mean energy range of 0.5–5.5 keV$_{ee}$ or 4.1–31.6 keV$_{nr}$ (nuclear recoil) based on the NEST model.

The signal vertex distribution before fiducial and ER rejection cuts is displayed in Figure 4. The fiducial cut indicated by the dashed box is asymmetric in the vertical direction to provide balanced shielding from radiation originating in the top and bottom PMT arrays. The cut in $r^2$ was optimized to reduce residual background near the detector walls. The LXe contained in the fiducial volume is $(37.0 \pm 2.2)$ kg, where the uncertainty is estimated from the difference between the CoG and NN reconstructions for 40 keV inelastic events in the neutron calibration data.

The measured energy distribution for events in the fiducial volume, after correcting for the detection efficiency, is in agreement with a GEANT4-based MC prediction [26], taking into account known background from detector material radioactivities. The average background rate of $(32 \pm 5) \text{ mDRU} (\text{DRU} = \text{events/keVee/kg/day})$ is consistent with the $(43 \pm 11) \text{ mDRU} \text{ MC expectation} \ (\text{Table 2}). The K_r level is estimated.

**Table 1** The event rate of the dark matter data for different cut levels

| Cut               | # Events | Rate (Hz) |
|-------------------|----------|-----------|
| All triggers      | 4062609  | 2.70      |
| Quality cuts      | 1877707  | 1.25      |
| Single-site cut   | 1195119  | 0.80      |
| S1 range (2–30 PE)| 10268    | 6.8X10^{-3} |
| S2bottom range (300–20000 PE)| 7638 | 5.08X10^{-3} |
| Fiducial volume   | 46       | 3.06X10^{-2} |

**Figure 3** Nuclear recoil detection efficiency as a function of S1 (the corresponding mean nuclear recoil energy are indicated as the ticks on the top). The red, blue, and black curves are the cut efficiency $\epsilon_{\text{cut}}$, nuclear recoil acceptance $A$, and the overall NR detection efficiency, respectively.

**Figure 4** Vertex distribution of all events before the fiducial and ER rejection cuts during 17.4 live-days of dark matter search data. The 37-kg fiducial volume is contained within the blue dashed box. The location of the detector wall, the gate grid, and the cathode are also indicated in red.
The 90% C.L. upper limit for spin-independent isoscalar WIMP-nucleon cross section for the PandaX-I experiment (red curves): PandaX-I using $E_{\text{eff}}$ and $S_1$ mapping from NEST [25] (red solid) and using $L_{\text{eff}}$ from ref. [17] (red dashed). Recent world results are plotted for comparison: XENON100 first results [17] (black dashed), XENON100 225 d results [19] (black solid), LUX first results [20] (blue), CDEX 2014 results [12] (magenta), SuperCDMS results [14] (orange solid), DAMA/LIBRA results [4] (green), CoGENT results [6] (cyan), CDMS II-Si results [7] (orange dashed), and CRESST-II 2012 results [8] (brown).

In Figure 6 our results are presented together with recent

![Figure 5](image-url)  
Figure 5. The log\(_{10}(S2/S1)\) versus $S_1$ distribution of events in the fiducial volume from DM search data. No event lies in the signal region. The curves are the same as those defined in Figure 2.

| Source                        | Background level (mDRU) |
|-------------------------------|-------------------------|
| Top PMT array                 | 10.9±1.8                |
| Bottom PMT array              | 4.0±0.6                 |
| Inner vessel components       | 18.5±10.1               |
| TPC components                | 2.3±0.8                 |
| 85Kr                          | <3.3                    |
| 222Rn and 220Rn               | 2.7±2.0                 |
| Outer vessel                  | 1.3±0.9                 |
| Total expected                | 43±11                   |
| Total observed                | 32±5                    |

from the delayed coincidence signals from 85Kr and 85mRb decays in the 120-kg target mass to be less than 83 ppt mol/mol (90% C.L.), assuming an abundance of 85Kr of $2 \times 10^{-11}$ in Kr. This is consistent with a direct measurement of the xenon sample using a specialized residual gas analysis system with a cold trap [27]. 222Rn and 220Rn in the detector are identified by their characteristic $\beta$-$\alpha$ delayed coincidences. The total decay rate in the FV, dominated by 222Rn, is measured to be (0.83±0.59) mBq, where the uncertainty is dominated by that in the efficiency of the $\beta$-$\alpha$ selection cuts. This results in a background of (2.7 ± 2.0) mDRU based on a MC simulation. Gamma events which multiple-scatter in the detector with a large fraction energy deposition in the LXe below the cathode can fake NR events because their ionization energy is only partially captured in the S2 signal. These events, known as the “gamma-X” events [15], contribute 0.2 events in the 17 d of dark matter data, as estimated by a MC simulation.

The $\log_{10}(S2/S1)$ versus $S_1$ band from the DM data is shown in Figure 5. No candidate event survives the ER rejection cut. To determine the spin-independent isoscalar WIMP-nucleon scattering cross section as a function of WIMP mass, the WIMP event rate is calculated based on the standard isothermal halo model [28, 29] with a DM density of 0.3 GeV/cm$^3$, a local circular velocity of 220 km/s, a galactic escape velocity of 544 km/s, and an average earth velocity of 245 km/s. After modeling detection efficiencies, Poisson fluctuation in the S1 signal is applied to smear the S1 acceptance. The 90% C.L. upper limit of the DM signal is calculated from the Feldman-Cousins statistical model [30] with no observed event and an expected ER Gaussian leakage background of 0.15 event. For a more conservative DM limit, we did not add the gamma-X estimate into our expected background. The lowest cross section obtained is $3.7 \times 10^{-44}$ cm$^2$ at a WIMP mass of 49 GeV/c$^2$.

Figure 2. The log\(_{10}(S2/S1)\) versus $S_1$ corrected (PE) distribution of events in the fiducial volume from DM search data. No event lies in the signal region. The curves are the same as those defined in Figure 2.
world direct detection data [4, 6–8, 12, 14, 17, 19, 20]. To quantify the impact of uncertainties in the energy scale on the experimental limit, the calculation is performed using two different $L_{\text{eff}}$ ([17]) scalings between $S_1$ and $E_{\text{nr}}$. The first $L_{\text{eff}}$ is taken from the NEST model using the measured PDE of 10.5%. The second is the conservative $L_{\text{eff}}$ used by XENON100 [17] with our measured $L_{\text{eff}}^{12,22}$. Below 10 GeV/$c^2$, the latter gives a more conservative limit. Note that our results show a nominally better limit below 6 GeV/$c^2$ than that from LUX due to that LUX used an energy scale with zero light yield below 3 keV/$nr$, which is very conservative compared to NEST or other phenomenological models (e.g., ref. [31]). Our result is comparable in the high WIMP mass region to that of ref. [17] with similar exposure, and is significantly more constraining in the low-mass region, demonstrating the advantage of the low-energy threshold of the PandaX-I detector. At the 90% C.L., our results are incompatible with the spin-independent isoscalar WIMP interpretation of previously reported observed signals from DAMA, CoGeNT, CRESST and CDMS II-Si [4, 6–8]. In the high WIMP mass region, our result confirms the power of the LXe dual-phase technique as one of the leading technologies to probe the theoretically-favored DM particles, e.g., predicted by supersymmetric models.

In summary, we report the first results using 17.4 live-days of data in the 37-kg fiducial mass from the PandaX-I dark matter experiment at CJPL. They place strong constraints in the low WIMP mass region which are being actively studied by many other experiments. PandaX-I continues to take data and explore low-mass WIMPs. PandaX-II, with about ten times larger fiducial mass and improved background properties, is being constructed to reach a sensitivity beyond the current best limits in a wide WIMP mass range.

This work was supported by the 985-III grant from Shanghai Jiao Tong University, the National Basic Research Program of China from Ministry of Science and Technology of China (Grant No. 2010CB833005), the National Natural Science Foundation of China (Grant No. 11055003) and the Office of Science and Technology in Shanghai Municipal Government (Grant No. 11DZ2260700). CHEN Xuan acknowledged support from China Postdoctoral Science Foundation (Grant No. 2014M551395). The project was also sponsored by Shandong University, Peking University, the University of Maryland, and the University of Michigan. We would like to thank many people including APRILE Elena, CHEN XianFeng, HALL Carter, LEE T.D., LIN ZhongQin, LIU Chuan, LV Lv, PENG YingHong, TONG Weilian, WANG HanGuo, WHITE James, WU YueLiang, YE QingHao, YUE Qian, and ZHAO HaiYing for help and discussion at various level. We are particularly indebted to Prof. ZHANG Jie for his strong support and crucial help during many stages of this project. Finally, we thank the following organizations and personnel for indispensable logistics and other supports: the CJPL administration including directors CHENG JianPing and KANG KeJun and manager LI JianMin, YangLong River Hydropower Development Company, Ltd. including the chairman of the board WANG Huisheng, and manager CHEN XianTao and his JinPing tunnel management team from the 21st Bureau of the China Railway Construction Co.

1 See for example, Bertone G, Hooper D, Silk J. Particle dark matter: Evidence, candidates and constraints. Phys Rept, 2005, 405: 279–390
2 Akimov D. Techniques and results for the direct detection of dark matter (review). Nucl Instrum Meth A, 2011, 628: 50–58; Gaiskell R. Direct detection of dark matter. Ann Rev Nucl Part Sci, 2004, 54: 315–359; for more recent experiments, see talks at 2014 Dark Matter Conference at UCLA, https://hepgconf.physics.ucla.edu/dm14/agenda.html
3 Jungman G, Kamionkowski M, Griest K. Supersymmetric dark matter. Phys Rept, 1996, 267: 195–375
4 Bernabei R, Belli P, Cappella F, et al. (DAMA Collaboration). First results from DAMA/LIBRA and the combined results with DAMA/Nal. Eur Phys J C, 2008, 56: 333–355; Bernabei R, Belli P, Cappella F, et al. (DAMA Collaboration). New results from DAMA/LIBRA. Eur Phys J C, 2010, 67: 39–49; Bernabei R, Belli P, Cappella F, et al. (DAMA Collaboration). Final model independent result of DAMA/LIBRA-phase1. Eur Phys J C, 2013, 73: 2468
5 Savage C, Gelmini G, Gondolo P, et al. Compatibility of DAMA/ LIBRA dark matter detection with other searches. J Cosmol Astropart Phys, 2009, 0904: 010
6 Aalseth C E, Barbeau P S, Colaresi J, et al. (CoGeNT Collaboration). Results from a search for light-dark matter with a p-type point contact germanium detector. Phys Rev Lett, 2011, 106: 131301; Aalseth C E, Barbeau P S, Colaresi J, et al. (CoGeNT Collaboration). CoGeNT: A search for low-mass dark matter using p-type point contact germanium detectors. Phys Rev D, 2013, 88(1): 012002; and latest analysis using maximum likelihood method in arXiv:1401.6234
7 Agnese R, Ahmed Z, Anderson A J, et al. (CDMS Collaboration). Silicon detector dark matter results from the final exposure of CDMS II. Phys Rev Lett, 2013, 111: 251301
8 Angloher G, Bauer M, Bavykina I, et al. (CRESST Collaboration). Results from 730 kg days of the CRESST-II dark matter search. Eur Phys J C, 2012, 72: 1791
9 Angloher G, Bento A, Bucci C, et al. (CRESST Collaboration). Results on low mass WIMPs using an upgraded CRESST-II detector. arXiv:1407.3146
10 See for example, Volkas R R, Petraki K. Review of asymmetric dark matter. Int J Mod Phys A, 2013, 28: 13S0028; Zurek K M. Asymmetric dark matter: Theories, signatures, and constraints. Phys Rept, 2014, 537: 91–121, and the references there-in
11 Zhao W, Yue Q, Kang K J, et al. (CDEX Collaboration). First results on light-mass WIMPs from the CDEX-1 experiment at the China Jinping underground laboratory. Phys Rev D, 2013, 88: 052004
12 Yue Q, Zhao W, Kang K J, et al. (CDEX Collaboration). Limits on light WIMPs from the CDEX-1 experiment with a p-type point contact germanium detector at the China Jinping underground laboratory. arXiv:1404.4946
13 Agnese R, Anderson A J, Asai M, et al. (SuperCDMS Collaboration). Search for low-mass weakly interacting massive particles with superCDMS. Phys Rev Lett, 2014, 112: 241302
14 Agnese R, Anderson A J, Asai M, et al. (SuperCDMS Collaboration). Search for low-mass weakly interacting massive particles using voltage-assisted calorimetric ionization detection in the SuperCDMS experiment. Phys Rev Lett, 2014, 112: 041302
15 Angle J, Aprile E, Arneodo F, et al. (XENON10 Collaboration). First results from the XENON10 dark matter experiment at the Gran Sasso National Laboratory. Phys Rev Lett, 2008, 100: 021303
16 Angle J, Aprile E, Arneodo F, et al. (XENON10 Collaboration). Search for light dark matter in XENON10 data. Phys Rev Lett, 2011, 107: 051301; Erratum-ibid, 2013, 110: 249901
17 Aprile E, Arisaka K, Arneodo F, et al. (XENON100 Collaboration). First dark matter results from the XENON100 experiment. Phys Rev. 2029
Lett, 2010, 105: 131302
18 Aprile E, Arisaka K, Arneodo F, et al. (XENON100 Collaboration). Dark matter results from 100 live days of XENON100 data. Phys Rev Lett, 2011, 107: 131302
19 Aprile E, Alfonsi M, Arisaka K, et al. (XENON100 Collaboration). Dark matter results from 225 live days of XENON100 data. Phys Rev Lett, 2012, 109: 181301
20 Akerib D S, Araujo H M, Bai X, et al. (LUX Collaboration). First results from the LUX dark matter experiment at the Sanford underground research facility. Phys Rev Lett, 2014, 112: 091303
21 Kang K J, Cheng J P, Chen Y H, et al. Status and prospects of a deep underground laboratory in China. J Phys Conf Ser, 2010, 203: 012028; Wong H T, Dark matter search with sub-keV germanium detectors at the China Jinping underground laboratory. J Phys Conf Ser, 2012, 375: 042061; Li J, B X, Haxton W, et al. The second-phase development of the China JinPing underground laboratory. arXiv:1404.2651[physics.ins-det]
22 Cao X G, Chen X, Chen Y H, et al. (PandaX Collaboration). PandaX: A liquid xenon dark matter experiment at CJPL. Sci China-Phys Mech Astron, 2014, 57(8): 1476–1494
23 Aprile E, Doke T. Liquid xenon detectors for particle physics and astrophysics. Rev Mod Phys, 2010, 82: 2053–2097
24 Yoshino K, Sowada U, Schmidt W F. Effect of molecular solutes on electron-drift velocity in liquid Ar, Kr, and Xe. Phys Rev A, 1976, 14: 438–444
25 Szydagis M, Barry N, Kazkaz K, et al. NEST: A comprehensive model for scintillation yield in liquid xenon. J Instrum, 2011, 6: P10002; Szydagis M, Fyhrie A, Thonggren D, et al. Enhancement of NEST capabilities for simulating low-energy recoils in liquid xenon. J Instrum, 2013, 8: C10003
26 Agostinelli S, Allison J, Amako K, et al. GEANT4—a simulation toolkit. Nucl Instrum Methods Phys Res Sect A-Accel Spectrum Defect Assoc Equip, 2003, 506(3): 250–303; Allison J, Amako K, Apostolakis J, et al. Geant4 developments and applications. IEEE Trans Nucl Sci, 2006, 53(1): 270–278
27 Dobi A, Davis C, Hall C, et al. Detection of krypton in xenon for dark matter applications. Nucl Instrum Methods Phys Res Sect A-Accel Spectrum Defect Assoc Equip, 2011, 665: 1–6
28 Smith M C, Ruchti G R, Helmi A, et al. The RAVE survey: Constraining the local Galactic escape speed. Mon Not R Astron Soc, 2007, 379: 755–772
29 Savage C, Freese K, Gondolo P. Annual modulation of dark matter in the presence of streams. Phys Rev D, 2006, 74: 043531
30 Feldman G J, Cousins R D. Unified approach to the classical statistical analysis of small signals. Phys Rev D, 1998, 57: 3873–3889
31 Mu W, Xiong X N, Ji X D. Scintillation efficiency for low energy nuclear recoils in liquid xenon dark matter detectors. Astropart Phys, 2014, 61: 56–61