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# Direct Detection of Dark Matter

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**Abstract.** The principles and some important features of the direct detection of dark matter are introduced, and recent experimental progress is reported. In particular, the XMASS experiment, which is a large-scale dark-matter experiment in Japan, is explained in detail.

## 1. Introduction

At present, the existence of dark matter is widely recognized and accepted. One of the most important subjects in astrophysics and elementary particle physics is the identification of dark matter properties. According to the recent cosmological observations, more than 80 % of dark matter is not ordinary matter such as baryons [Komatsu et al. (2011)]. Direct dark-matter experiments aim to detect dark-matter particles directly in a laboratory. Positive evidence would prove that the dark matter is composed of particles and allow us to study their properties in detail. Such detailed studies are important for the elementary particles physics because they will stimulate the rise of a new field beyond the standard model of particle physics.

## 2. Principles of Direct Detection

### 2.1. Expected Interaction

Direct dark-matter experiments expect the dark-matter particles to interact with ordinary matter such as nucleons. This is a reasonable assumption if we assume that dark-matter particles were thermally produced in the early universe, decreased through annihilations into ordinary matter, and were frozen in number density in a comoving volume. Figure 1 shows schematically how interactions lead to annihilation into ordinary matter such as quarks. This interaction implies the existence of the scattering of dark matter with the ordinary matter as shown by the vertical arrow in the figure. Since the interaction is expected to be weak, these particles are called weakly interacting massive particles (WIMPs). They must be massive because any massless particles cannot behave as matter does.

### 2.2. Amount of Dark Matter Around Us

The frequency of interaction depends on how many WIMPs exist and on how fast they are moving. From the observed rotational curve of the galaxy, the local mass density

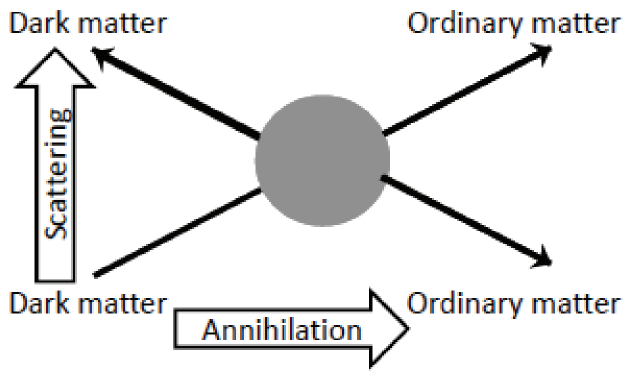


Figure 1. Dark-matter particles thermally generated in the early universe are considered to annihilate into ordinary matter. This assumption implies the existence of an interaction between dark-matter particles and ordinary matter, as shown in the figure.

and their mean velocity can be derived. The former is expected to be 0.3 GeV/cc to within a factor of two to three [Nakamura et al. (2010)] and the latter is expected to be around 230 km/s [Lewin & Smith (1996)]. From these numbers, the expected number density and flux, which are inversely proportional to the mass of WIMPs, can be calculated.

### 2.3. Signals After Interaction

The interaction between WIMPs and ordinary matter causes energy transfer. The typical kinetic energy after the energy transfer is $1/2m\beta^2$, where $m$ is the mass of the ordinary matter and $\beta = v/c \sim 10^{-3}$ . Because of this, we usually look for nuclear-recoil signals instead of electron-recoil signals. Thus, nuclei of mass similar to that of the WIMPs are the best choice from the point of view of kinematics.

Once the energy transfer occurs, various signal channels can be expected, such as scintillation light, phonon signals, ionization signals, and bubble generation. Multiple signals are useful for reducing various types of common background, such as background caused by gamma rays. By utilizing these signals, each experimental group strives to minimize background and maximize signal.

### 2.4. Expected Energy Spectrum

If one makes assumptions such as the Maxwell distribution for the velocity of WIMPs in the rest frame of the galaxy, the recoil energy spectrum can be calculated. One important aspect to consider in calculations is the coherence of the interaction. Since the interaction amplitude can be calculated by summing the wave function of the mediating particle at each nucleon, a small momentum transfer (long wavelength) causes an amplitude proportional to the number of nucleons. Since the interaction cross section is proportional to the square of the amplitude, a large enhancement can be expected for spin-independent interactions. A more detailed treatment can be found elsewhere [Lewin & Smith (1996)].

### 2.5. Annual Modulation and Directional Distribution of Recoil Nuclei

Although we assumed a Maxwell distribution for the WIMP velocity, our targets in laboratories are moving in the galaxy with the sun and the earth. Since the sun is moving at 230 km/s in the galaxy and the earth is moving at 30 km/s around the sun, the velocity of the target in the galaxy changes as a function of time over a sidereal year. This is expected to cause a variation in the event rate as well in the nuclear-recoil spectrum. Such an effect would not be large but would be considered an important finding in support of the interpretation of positive signals.

Another important expectation is the directionality of nuclear recoils. Since we usually assume isotropic scattering in the center-of-mass frame, nuclear recoils in forward angles are expected. If the detector is sensitive to the nuclear-recoil direction, it can give "smoking gun" evidence. Since this requires a very fine track readout (as short as $0.1\,\mu$m in LXe and longer in gas targets), development of better detectors is necessary.

## 3. Direct-Detection Experiments

Over 30 experiments are ongoing around the world– collecting data, or preparing their detectors to search for positive signals from dark-matter particles. Here, I categorize the positive signals into three types: (1) a significant excess over known background, (2) an annual modulation, and (3) an observed of directionality. To date, no positive evidence of a type-3 signal has been observed because it requires reading out nuclear-recoil tracks under very low background. However, results are available for type-1 signals from CRESST-II [Angloher et al. (2011)] and type-2 signals from DAMA/LIBRA [Savage et al. (2009)] and CoGeNT [Aalseth et al. (2011)]. Conversely, XENON10/XENON100 [Aprile et al. (2011)], CDMS [Ahmed et al. (2010)], and EDELWEISS [Armengaud & collaboration (2011)] report negative results. Many efforts are ongoing to check the consistency between these experiments [Censier (2011)] but, for now, further experimental studies remain indispensable.

## 4. XMASS Experiment

The XMASS experiment aims to construct multipurpose, low-background detectors for astroparticle physics and to detect signals from low-energy solar neutrinos, neutrinoless double beta decay, and dark matter in the universe [Suzuki (2000)]. In the first phase of the experiment, a detector was constructed in the Kamioka mine, Japan, which required 800 kg of liquid xenon (fiducial volume 100 kg) for dark-matter searching. As shown in Fig. 2 (left), the central part (liquid xenon) is surrounded by 642 hexagonal photomultiplier tubes (PMTs) arranged spherically. Photocathodes cover 62% of the inner surface of this sphere. Figure 2 (right) depicts the interaction of gamma rays and WIMPs. A dominant background due to gamma rays from the PMTs are absorbed at the surface of the liquid xenon. However, WIMPs would interact uniformly inside the detector. If we could extract only the inner events, the dark-matter search could be done in a low-background environment. To locate a given interaction the events must be reconstructed, which can be done based on the observed photoelectron pattern. By comparing the observed pattern with expected results at various positions in the detector, we can determine the interaction vertex.

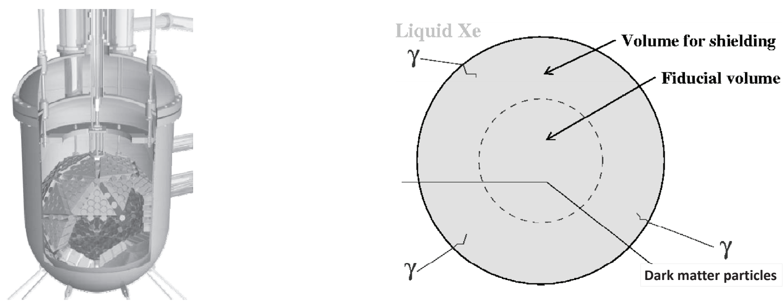


Figure 2. Structure of the 800-kg detector (left). Liquid xenon fills the central part and is surrounded by 642 photomultiplier tubes. Since the dominant background is caused by gamma rays from the PMTs, which can be absorbed by the exterior layer of the liquid xenon, a low-background experiment would be possible if the inner radioactivity was shown to be low (right).

For this reason, it is important to demonstrate event reconstruction, and we have prepared gamma-ray sources that can be inserted into the detector for such a purpose. Figure 3 shows the reconstructed energy spectrum of a $^{57}$Co source as well as the one from our simulation. The energy resolution and the vertex resolution for the 122-keV gamma ray were found to be 4% and 1 cm, respectively, which is a satisfactory result.

The 800-kg detector was successfully constructed and is currently in the commissioning phase. All the parameters related to the reconstruction are being tuned, the detector performance is being confirmed, and an investigation of background properties is underway. We expect the dark-matter searches to begin very soon. Figure 4 shows the expected sensitivity for the dark-matter search, which constitutes an order of magnitude improvement in sensitivity.

## 5. Summary

Direct detection of dark matter is expected to reveal the nature of this material. Numerous experiments around the world are currently dedicated to the search, and these represent significant improvements in the sensitivity of detecting dark matter. Although some groups have claimed positive evidence of dark matter, the results are still controversial and so must be clarified by new experimental data. The XMASS experiment

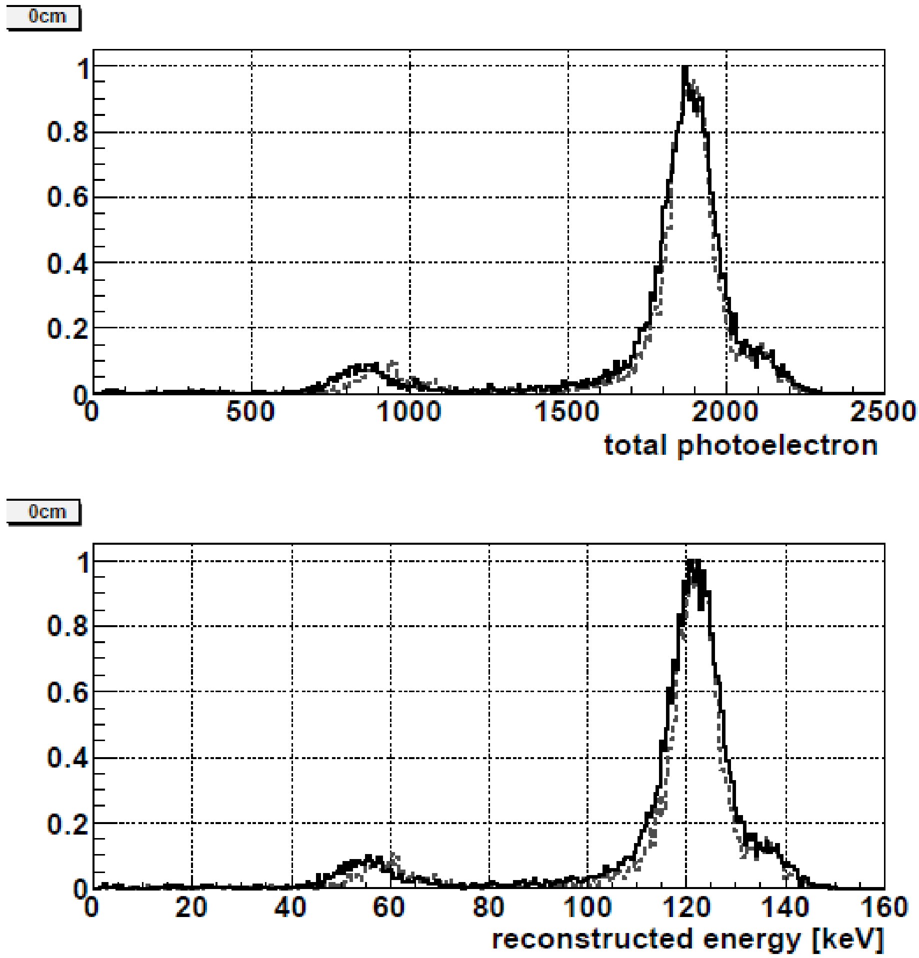


Figure 3. Observed total photoelectron distribution and reconstructed energy spectrum for $^{57}$Co source (122 keV and 136 keV from $^{57}$Co and 60 keV from X-rays from tungsten inside the source) at center of detector. The solid histogram is for the data and the dashed histogram is for the Monte Carlo simulation, and the two agree reasonably well. The photoelectron yield is ~15 p.e./keV which is larger than expected.

utilizes a very massive 800-kg detector and has entered its commissioning phase, so it will soon begin contributing to the search for dark matter.

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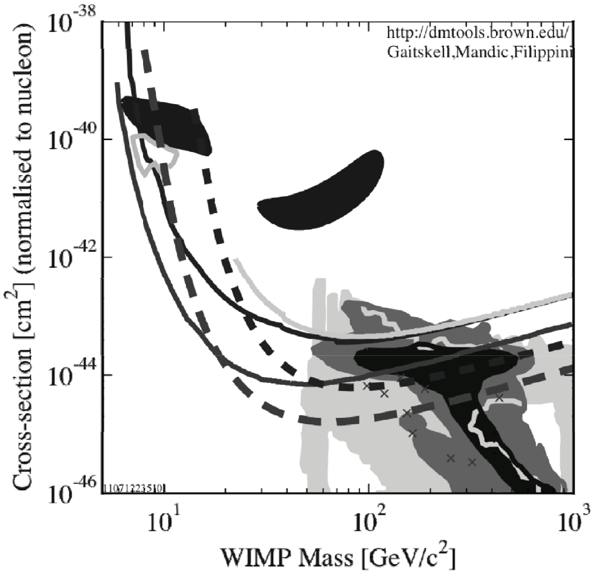


Figure 4. Sensitivity of XMASS experiment. The two dashed lines represent the 100 days data for our sensitivity, with 5- and 2-keV electron-equivalent-energy thresholds. Solid lines give results of other experiments. We can expect a large improvement in the sensitivity of detecting dark matter. The two shaded areas above show DAMA results. The area around 10 GeV and $10^{-40}$ cm$^2$ shows CoGeNT results. The areas at the bottom right are predictions from supersymmetry models. Except for the dashed lines, the plots are generated by Gaitskell & Mandic (2004)

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