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Radiation Detectors for Direct Dark Matter Search

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Dark matter is believed to accont for more than one fourth of the energy density of the universe. Despite many experimental efforts to investigate dark matter, no clear understanding of its nature has been achieved. Direct dark matter searches aim to detect the energy deposited by the elastic scattering between dark and ordinary matters. No "ultimate" direct dark matter detector has been developed to date, thus there is still some room for new technology in this field. In this paper, some requirements for direct dark matter detectors are reviewed.

KEYWORDS: radiation detector, dark matter...

1. Introduction

Cosmological and astrophysical observations indicate that more than one fourth of the energy density of the universe is in the form of unknown particles, dark matter. The first indication of dark matter was reported in the 1930s in the study of galaxy motions in a cluster of galaxies [1]. In the 1970s, dark matter halo on a galaxy-scale was proposed to explain the rotation curves of a galaxy [2]. More recently, cosmic microwave background observations by WMAP and PLANCK satellites have precisely evaluated the amount of the dark matter in the universe [3]. Observations of Galaxy collisions, called Bullet Cluster [4], via weak-lensing, X-rays, and visible light revealed the existence of dark matter on a scale of galaxy clusters.

While dark matter is well understood on the level of gravitational effects, its precise nature is still unclear. One of the best candidates is the weakly interacting massive particles(WIMPs) [5]. Many experimental investigations of WIMPs are in progress throughout the world. Fig 1 shows three typical approaches. They are based on the assumption that WIMPs (DM in the figure) and ordinary matters (q in the figure) interact somehow (the cloud-like shape in the figure).

Main differences between three methods are the directions of their interactions. Collider experiments attempt to create WIMPs through a high-energy state using two ordinary particles. Large Hadron Collider experiments have searched for WIMPs at 13 TeV in RUN-2 and have not obtained any clear evidence thus far [6]. Indirect searches look for annihilation signals such as anti-matters, gamma-rays, and neutrinos from WIMP-WIMP interaction. FERMI [7], PAMELA [9], and AMS-02 [8] experiments have searched for the gamma-rays and anti-particles from the astronomical objects, where dark matters can be gravitationally trapped. These experiments also have not seen any clear evidence. The third type of approach is a direct search. In direct searches, ordinary particle detectors are used to detect WIMP-nucleus interactions. The direct detection mechanism is explained in Section 2, and requirements for the detectors are discussed in Section 3.

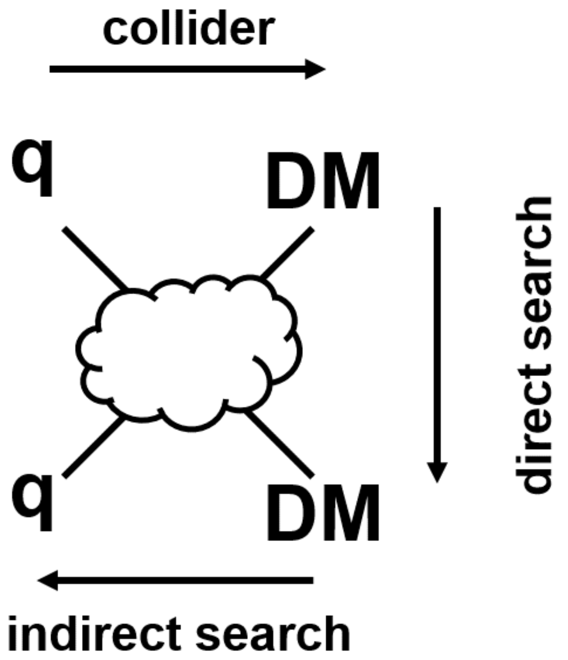

Fig. 1. Schematics of dark matter investigations. DM and q represent dark matter and ordinary matter, respectively. The center "cloud" represents interactions. Arrows indicate the directions of the interactions.

2. Direct Search of Dark Matter

Direct detection uses the WIMP-nucleus elastic (and in some cases inelastic) scattering. The mechanics of direct detection is illustrated in Fig. 2. It is also well-described in a previous study [10]. Dark matter in our galaxy is gravitationally trapped and Maxwellian with the most probable velocity v_0 of 220 kms^{-1} is in most of the cases assumed as its velocity distribution. Considering the velocity (244 kms^{-1}) of the solar system in the galaxy, we can calculate the energy spectrum to be obtained by the detectors on the Earth for a given detector nucleus and assumed WIMP mass. Typical energy spectra are shown in Fig. 3. Here we ignore the minor difference between the two spectra and only look at their global trend. The spectra have exponential like featureless shapes. This leads to two important requirements for dark matter detectors. The first one is a low energy threshold because the lower the threshold, the more events we expect. The second one is a low background because possible background like neutron elastic scattering and gamma-ray Compton scatterings would show similar shape. This requirement can be fulfilled by either a low radioactive detector or a detector capable of particle identification to reject the gamma-ray background. Another important requirement can be deduced from the vertical range of a plot. The vertical axis is often shown as [counts/keV/kg/day]. A 1pb WIMP-proton spin-dependent cross-section is assumed for the spectra. This is three orders of magnitude larger than the world limit. Thus, the third requirement is a large-mass detector.

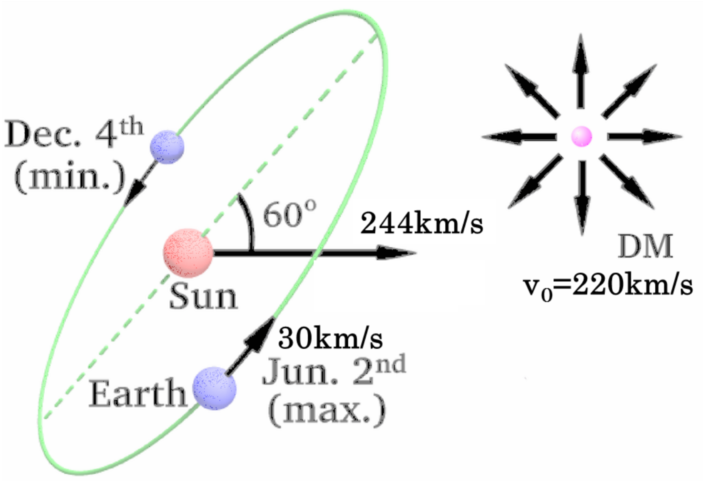

Fig. 2. Schematic of motions of the solar system and dark matter in the galaxy.

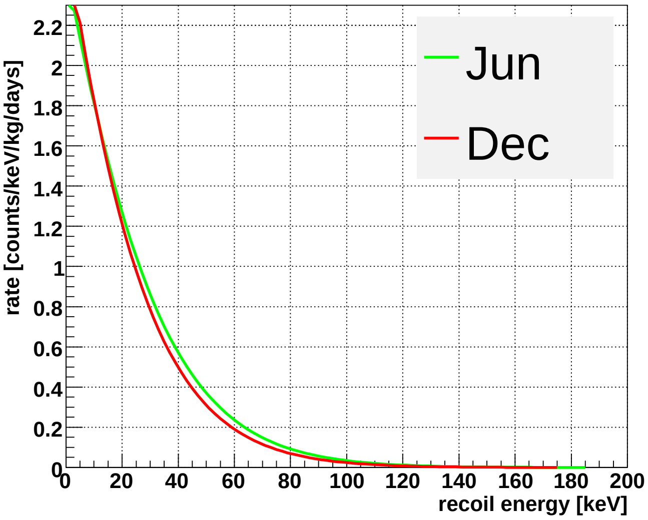

Fig. 3. Examples of the expected energy spectra of dark matter. Jun and Dec indicate the spectra expected in Jun and December, respectively. Fluorine is assumed as a target, and a spin-dependent 1-pb cross-section of WIMP-nucleon (proton) scattering is assumed. The assumed WIMP mass is 100 GeV.

Next, we discuss the detection signal of dark matter. The first signal can be the energy spectrum of detected events. Although the shapes of the energy spectra shown in Fig. 3 are featureless, they still exhibit kinematic-dependent features. Because the type of scattering is non-relativistic elastic scattering, the recoil energy dependence on target nuclei can be easily calculated. The spectra become flat for light targets, and they become steep for heavy ones. Thus, the target-nucleus dependence of the energy spectra can be the first characteristic signal of dark matter detection. There remains a problem of the neutron background which has a similar target mass dependence.

The second signal is an annual modulation signal. Here, we return to Fig. 2. The velocity of the Earth relative to the galaxy is greater in summer than winter. This difference produces a small shift in the energy spectrum: it shifts to the high energy in summer and to the low energy in winter. If we consider a given energy bin, an annual modulation in the event rate is expected. Because the difference is typically a few percent, a large-mass detector is used to observe the annual modulation signal. Although this signal has been believed to be a very clear evidence of dark matter detection, in practice, the answer has not been straightforward. Many ambient background sources were found to show annual modulation. The DAMA/LIBRA experiment has reported annual modulation observations for 14 cycles using large-mass (100 kg for the first half and 250 kg for the second half) NaI(Tl) scintillators [11]. Despite a large, significant modulation signal, the parameter region claimed by the DAMA/LIBRA data has been excluded by many other experiments, and thus, the results are not conclusive [12] [13] [14] [15] [16] [17] [18] [19] [20].

The third signal is a directional signal [22]. Fig. 2 shows that the relative motion of dark matter against the Earth is not isotropic because of the motion of the solar system in the galaxy. In other words, WIMP-wind reaches detectors set in a laboratory. Elastic scatterings of the WIMP nucleon interaction would give a very large asymmetry in the recoil angle and would constitute strong evidence for dark matter detection [21].

3. Radiation Detectors for Direct Dark Matter Search

In this section, radiation detectors for a direct dark matter search are reviewed. In Fig. 4, dark matter detectors are categorized based on detection methods. The energy deposited on the detectors can be measured either as photons, heat, and ionization or a combination of these forms. Direct dark matter search experiments are also indicated in the figure.

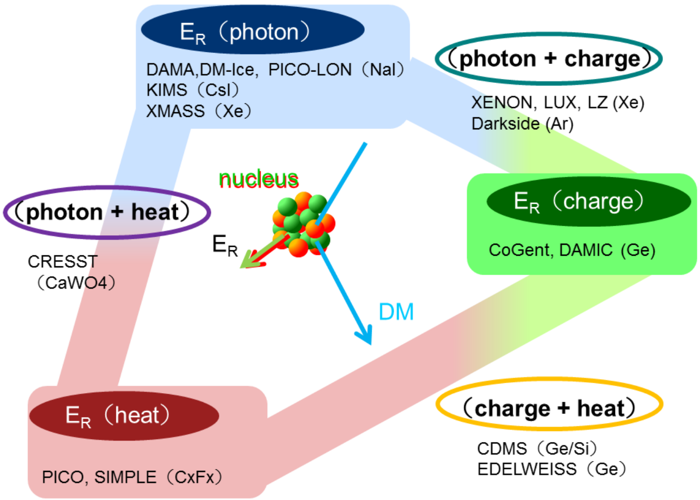

Fig. 4. Conceptual schematics of physical parameters measured by direct dark matter detectors. Three major parameters, photons, charges and heat, are shown at the corners of the triangle. Combinations of these parameters are shown on edges. Direct dark matter search experiments are also indicated.

3.1 Large Mass

As discussed in the previous section, the expected dark matter rate is very low. Thus it is important to have a large mass of typically more than 100 kg. Scintillators (indicated as "photon" in Fig. 4) are easy to scale-up and solid NaI(Tl) and CsI(Tl) scintilators have been used since the early days of direct dark matter search experiments. DAMA/LIBRA experiment employed 250 kg NaI(Tl) scintillators in an underground laboratory for seven years [11]. Liquid noble gas (such as liquid xenon and argon) detectors are becoming increasingly attractive because of the scaling-up and in-situ purification. XMASS experiment uses the largest mass of 800 kg as a direct dark matter detector [23].It has excluded most of the DAMA-allowed parameter regions for the first time using the annual modulation method with a comparable exposure. XENON and LUX experiments use liquid xenon not only for the reason explained above, but also because of the gamma-ray rejection power discussed in the next subsection.

3.2 Low Background

Because the expected rate of dark matter is extremely low, the background should be as low as possible. Most dark matter search experiments are performed in underground laboratories to minimize cosmic background. Detectors are set in in appropriate shieldings against ambient background. In addition, the detectors can also be specially developed to achieve low background. The first important feature is electron-recoil rejection. In contrast to nuclear recoil events by WIMPs, gamma-rays and electrons cause electron-recoil events. The light yield and ionization-collection efficiency depend on the incident particle. Thus, as shown in Fig. 4, electron-recoil rejection can be achieved if two or more carriers are detected. There are experiments using any two of these three carriers. XENON and LUX devices detect not only photons but also ionization charges and thus make electron-recoil rejections possible. The availability of scaling-up and electron rejection allow these two-phase liquid noble gas detectors to improve the sensitivity of direct dark matter searches.

Another important factor is the purity of the detector material. The radioactive contamination such as ^{238}U, ^{232}Th, ^{40}K, and ^{14}C in detectors would often increase the background. NaI(Tl) scintilators used in the DAMA experiment were specially purified ones and are the cleanest detectors made thus far. This is the reason for the lack of the independent validation of DAMA results; no comparable NaI scintillator is available. Recently, DM-ICE and PICO-LON experiments are reaching the DAMA's purity and are going to start the measurements using such radio-pure detectors in a few years [24] [25].

3.3 Low Energy Threshold

The expected dark matter energy spectrum is exponential-like, as shown in Fig 3. This means that the number of expected events will exponentially increase if the threshold is decreased. Direct dark matter detectors need to be optimized for the large mass and low threshold. The main trend is to have a large mass with a reasonably low threshold. An interesting approach reported by the DAMIC group is to use an extremely low threshold of 0.04 keV [26] with a mass of 0.5 g. Using this low threshold, they achieved a sensitivity comparable to that reported for other large-mass detectors.

3.4 Directional Sensitivity

The detection of the WIMP-wind would be a very convincing signal of dark matter detection. This signal can also be used after the detection of dark matter to investigate its motion in the galaxy. Gaseous detectors are most suitable devices for directional detection because the typical track length of recoil nucleus is a few millimeters even in a low pressure gas.

The DRIFT group developed low-background multi-wire proportional chambers and demonstrated a sensitivity comparable with that of other detectors [29]; however, the directional sensitivity has not been confirmed. The NEWAGE experiment has taken a different approach of pursuing the directional sensitivity from the beginning. Using skymaps drawn by nuclear tracks, they set direction-sensitive limits [27] [28]. The directional information is strong and typically requires only a few tens of events to claim the detection of non-isotropy. In contrast, the annual modulation signal generally requires more than several thousand events. One of the most important R&D issues of these detectors that use low pressure gaseous targets is the scaling-up of the devices to have sufficient masses. A nuclear emulsion is a solid detector that can easily be scaled-up. Fine-grain emulsions with a position resolution of less than hundred nanometers have been specially developed for the directional dark matter search, and their performance has been studied [30]. Although an emulsion detector does not have time resolution and needs to be operated on an equatorial telescope, it can be a good detector to improve the directional sensitivity. In future, a combination of gaseous detectors for time-resolved, precise sky mappings and emulsion detectors for large statistical analyses would be profitably used in WIMP astronomy.

4. Conclusion

The direct search of dark matter has been carried out for many years, but no clear evidence has been found. Radiation detectors for direct dark matter searches require some specific features. The most important factors are "large mass", "low background", and "low threshold". New technology detectors with at least one of these characteristics might be good candidates for the direct dark matter search. Obtaining the recoil direction in addition to the recoil energy acquired using conventional detectors would provide additional information, making the detection more significant. Directional detectors could be a strong tool to launch a WIMP astronomy era.

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