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Analysis of the Latest Research Progress on Dark matter in the Universe

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Abstract: Dark matter research has become the most challenging fundamental research topic in the current physics field. The existence of dark matter has been confirmed, and its characteristics are far beyond that of traditional particle physics. However, its mass, rotation, and interactions with other particles are still not fully revealed. Over the past few decades, theoretical and experimental studies on dark matter have made great strides. We have gained more insights and made significant progress on dark matter from previous studies, from various dark matter models to direct or indirect detections. In this paper, we will investigate the latest development of dark matter experimental research in the past few years, including detection methodology, current status, and some important experimental results, aiming to provide valuable references for future dark matter research.

Keywords: Dark matter; Cosmology; Experimental progress.

1. Introduction

Over the past few decades, dark matter detection experiments have become an important spot in the field of particle physics research. Researchers are trying to develop more techniques to explore dark matter, aiming to discover more unknown physical phenomena. At present, some progress has been made in detection techniques. For example, dark matter detection experiments could be divided into three kinds, namely, direct detection, indirect detection, and collider detection. Currently, more than 20 dark matter experiments utilizing various advanced technologies are being conducted around the world.

2. Progress on Direct Detection

Analyzing the scattering of dark matter particles and nuclei has now become the most commonly used means of detecting dark matter. WIMP has been widely recognized as the most promising dark matter research object today. In 1985, Goodman and Witten [1] proposed a new method to detect dark matter by using the scattering of WIMP and detector target nucleus, a discovery that has dramatically changed most of the directions of dark matter detection, making it the most important research object. By measuring the elastic collision between the WIMP and the target nucleus, the energy of the recoiling nucleus could be obtained, thus setting certain parametric limitations for the mass and cross-section of the WIMP. It is an effective way for direct detection experiments. In the dark matter halo theory, the interaction of WIMP with the Earth's surface is affected by the Earth's rotation and spin, and this effect may show periodic changes. Therefore, studying the modulation effect of the orientation of WIMP and the scattering ratio of WIMP to the target nucleus would help us to better understand the essence of the universe. The scattering cross-section of WIMP could be divided into two categories. One is spin-dependent and the other is spin-independent. The spin of the target nucleus is the main factor affecting its correlation cross-section. As the mass number of the target nucleus increases, the discovery of the spin-independent cross section is almost negligible, and its discovery probability is much higher than that of spin correlation. Therefore, the spin-independent WIMP-nucleon interaction has become the most important way to detect dark matter today.

3. Current Technologies for Direct Detection of Dark Matter in the Universe

3.1. Liquid Inert Gas Detectors

Currently, liquid xenon and liquid argon have become the most commonly used liquid inert gases for dark matter detection. The melting points of both xenon and argon are between -108◦C, so they could be easily dissolved. Over the years, the purification technology of liquid xenon and liquid argon has been greatly advanced and their purity has been greatly improved. Both are excellent scintillation materials, and the number of scintillation photons and electron ions produced per unit energy of deposition is quite impressive.

Currently, three experimental groups are using the gas-liquid two-phase xenon time-projection chamber technique, namely the XENON lab in Italy, the CJPL lab in China, and the SURF lab in America. All of these experiments are exploring the application of this technique. XMASS [2] used single-phase liquid xenon technology in an experiment conducted in Kamioka, Japan.

The XENON experiment is believed to be the world's first attempt to use liquid xenon as a reflector for dark matter detection in a two-phase time-projection chamber. In 2005, the first experimental equipment in the LNGS, XENON10[3], was successfully completed and would provide important support for technology research. In 2008, the XENON-100[4] detector underwent a complete overhaul and upgrade. In 2016, the successful operation of XENON1t[5] marked the entry of dark matter detection technology into a new, larger-scale experimental phase. After careful debugging and testing, the XENONnT[6] experimental set containing 5.9 t of liquid xenon has reached its optimal condition. The PandaX experiment is considered to be an important part of two of China's most important dark matter detection programs. The CJPL-I laboratory carried out the first two phases of the experiments, PandaX-I[7] and CJPL-I[8]. Currently, the third phase of the experiment, containing 3.7 t of liquid xenon, has been completed at the CJPL-II laboratory[9].

Both the DarkSide and DEAP-3600 experiments conducted at LNGS and SNOLAB in Canada used liquid argon as a detection medium for dark matter and achieved satisfactory results. Compared with liquid xenon, liquid argon is cheaper and its detection ability of electron reflections is better. However, the presence of 39Ar cosmogenic nuclides in argon could severely reduce the sensitivity of detection. The DarkSide-50 experiment[12] utilized an advanced biphasic argon time-projection chamber technique as well as argon collected from the subsurface and greatly reduced the interference of 39Ar. DarkSide-20k[13] is an important research project that aims to use 20t of liquid argon for in-depth studies. The DEAP-3600[14] experiment uses about 3.2t of liquid argon, which is a single-phase liquid argon scintillation detector that detects scintillation light signals emitted from within the liquid argon.

3.2. Extremely Low-Temperature Calorimeter

When the temperature drops below mK, the activity of molecules is severely limited and even the smallest change in energy could yield important information. By using a solid and extremely low-temperature calorimeter, thermal phonon signals could be measured at extremely low-temperature changes, with the threshold as low as 100 Ev. In combination with measurements of scintillating light or ionization signals, nuclear and electronic recoils can be accurately distinguished. The experimental scheme shows excellent performance in the GeV and sub-GeV energy regions.

Currently, research teams using extremely low-temperature calorimetry have covered several projects such as superCDMS[15], EDELWEISS[16], and CRESST[17]. By using SuperCDMS, we could detect both ionization and phonon signals at low temperatures of about 50 mK and could detect noise up to 56 eVee.

3.3. Semiconductor Detectors

High-purity germanium detectors are widely used in dark matter detection, which could detect ionization signals generated by nuclear reactions and provide scientists with effective research methods. With the advancement of area melting technology, current high-purity germanium crystals have reached an accuracy level of 139. As a semiconductor detector, high-purity germanium has excellent energy resolution for a variety of applications. High-purity germanium detectors using point-electrode structures have the advantages of small capacitance size, low electronic noise, and low energy thresholds, making them ideal for light-mass WIMP detection.

Internationally, experiments using this technology include TEXONO[18], CoGeNT[19], CDEX, etc. TEXONO was the first experiment on germanium with an extremely low energy threshold of 20 g conducted in Taiwan. After that, TEXONO applied this technology to the CJPL in 2011. CoGeNT used advanced germanium detection technology to conduct precise experiments. The CJPL experiment is one of China's most important direct detection projects of dark matter, aiming to study the existence of specific elements underground in the Liangshan Yi Autonomous Prefecture in Sichuan Province through observation and analysis. Using a special point-electrode technique with liquid nitrogen as the medium, we could accurately detect the lightweight WIMP. In the first phase of CDEX[20], the two detectors were 1 kg and CDEX-1B[21], which reached the thresholds of 475 and 160 eVee[22], respectively. Meanwhile, the second phase of the experiment is currently underway to explore more possibilities.

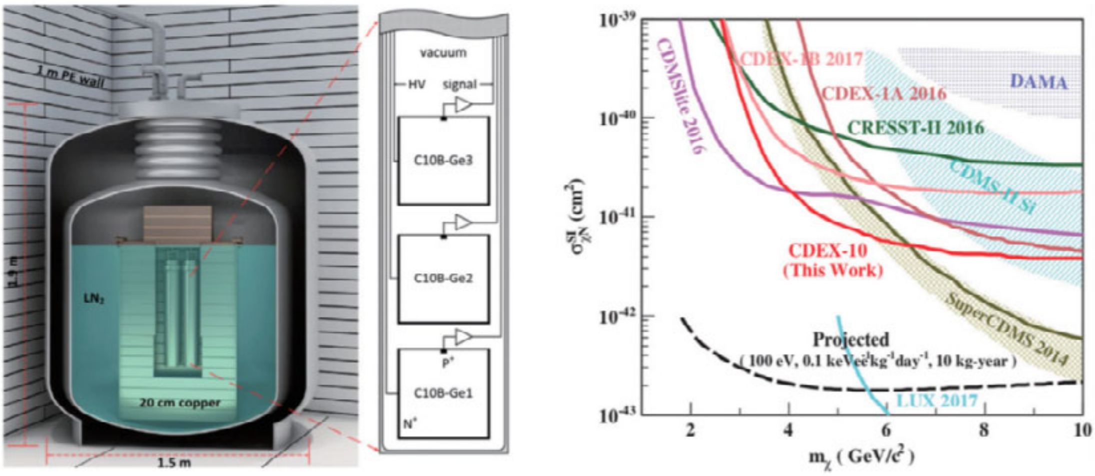

Figure 1. (a) Sections of CDEX-10 detection system profile; (b) Spin-independent physical results of CDEX-10 WIMP particle

In recent years, many advanced semiconductor technologies have been applied to detect dark matter, as well as other potential matter. By using silicon charge-coupled device (i.e., CCD) technology, the DAMIC experiment allows for three-dimensional positional reconstruction and efficient identification of the background [23-24].

3.4. Superheated Liquid Detector

The detector consists of two parts, namely a high-temperature droplet detector and a bubble chamber. As the particles travel through the liquid medium, they release energy and cause the temperature to rise, forming a series of bubbles that can be captured by the camera so as to retain them permanently. Since electron recoils consume very little energy, it is difficult for them to form bubbles. However, we can increase the likelihood of bubbles by changing the energy loss rate of the particles. Since superheated liquid detectors could not accurately measure the energy of each recoil, any recoil that exceeds a particular energy will result in the creation of bubbles. With a unique property, this threshold detector is able to adjust the threshold according to changes in the temperature and pressure of the liquid. It could be more flexible in choosing the experimental medium. Besides, F is included in most of the experiments because its nucleus possesses a different proton that could provide higher sensitivity. Therefore, dark matter independent of its own magnetic field[25] could be better detected.

3.5. Annual modulation

With the rotation of the Earth, the trajectories of dark matter have changed significantly and the relative velocities between them are increasing. Therefore, direct detectors of dark matter could not capture them in underground laboratories. We need to rely on other technical means to obtain more information. Measurements of annual modulation effects are currently carried out by using simple NaI(Tl) scintillator detector arrays that are stable and capable of long-term operation. DAMA/LIBRA [29] was the first experiment to demonstrate the existence of annual modulation effects in dark matter. The detectors used in the experiment consist of NaI(Tl) scintillator crystals weighing about 250 kg. After many years of continuous operation in the LNGS laboratory, a strong annual modulation signal was discovered, a discovery that has been confirmed for more than 20 years. However, experiments using other dark matter such as germanium and xenon have failed to prove this conclusion. COSINE-100[30] and ANAIS-112 [31] experiments have employed an identical technical scheme to verify its reliability and validity.

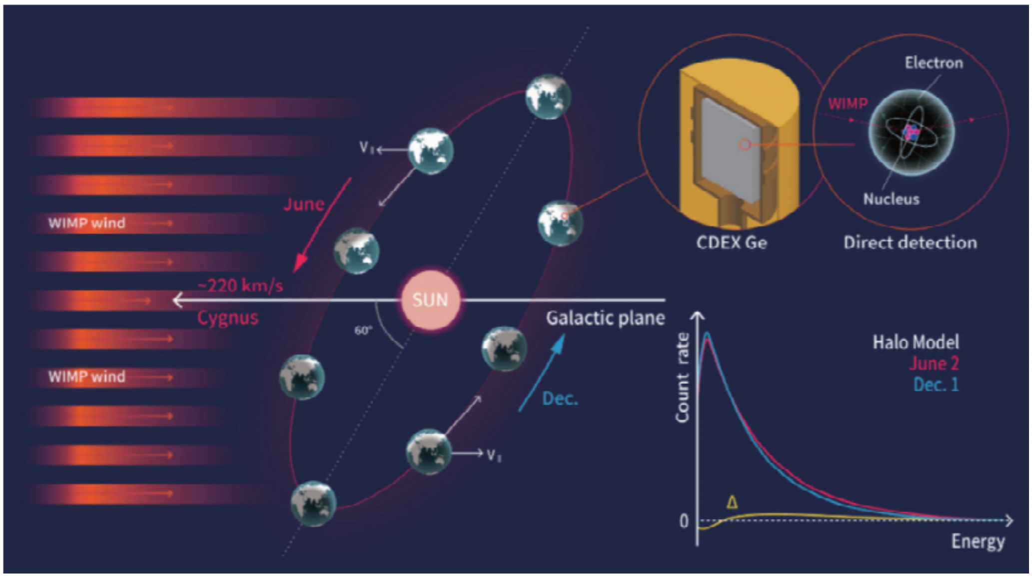

Figure 2. Schematic diagram of dark matter annual modulation effect

In addition to the above three experiments, some other experiments targeting annual modulation are also being gradually carried out. For example, the SABRE [32] experiment at LNGS and the PICOLON [33] experiment at Kamioka, Japan, both plan to develop ultra-high purity NaI(Tl) crystals and further reduce the existing background level by using passive shielding and liquid flashback conformity technology. COSINUS [34] experiment at LNGS plans to develop an extremely low-temperature quantum heater for NaI based on the technology of the CRESST experiment. The results of the DAMA/LIBRA experiment would be examined more accurately with the help of the screening of nuclear versus electronic recoil.

3.6. Directionality Measurement

According to the dark matter halo theory, the motion trajectory of dark matter is affected by the rotation and spin of the Earth. The motion trajectory of its background may be indeterminate, and it may be moving in a specific direction. By using detectors with high precision, the energy of a nuclear reaction could be accurately measured and its trajectory could also be recorded. As a result, the signal of dark matter could be effectively compared with other base information to determine its direction. Depending on the energy transferred and the density of the target material, the trace length of the recoil nucleus would vary. For example, when the energy is a few tens of keV, its trace length is only about a few hundred nanometers. At the same time, when the energy is lower, its trace length could reach a few millimeters. For solid media, only nuclear latex detectors could meet such precision currently. With the development of technologies, current dark matter experiments have begun to use higher-precision and low-pressure gases for directional measurements and used smaller time-projection chambers for detection. CF4 is a common gaseous medium that is very sensitive to spin-coupling effects. Electron recoils have longer trails and lower ionization densities compared with nuclear recoils, so this method could distinguish them more accurately.

4. Conclusion

Existing observations support the idea that the universe is composed of baryonic matter, dark matter, and dark energy. In order to reveal the essence of dark matter, scholars have proposed a variety of models and candidates. Each model or theory coincides with the observational data to some extent. All of them have made theoretical predictions on the possible candidates of dark matter. The continuous improvement and development of the theory and the increasing precision of the experiments all could help to solve some core problems in particle physics. In a word, dark matter research is of great significance to the development of astrophysics and particle physics.

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