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Analysis of the Searching Scenarios for WIMPs and Axion

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Abstract:

As a matter of fact, since dark matter was proposed in 1922, the beginning of the 20th century, the research on what dark matter is has been carried out continuously implemented until now. In the course of the study, different scholars put forward different theories and hypotheses. Since the nature of dark matter has not been explored. With this in mind, this paper summarizes the development of dark matter based on the existing research conclusions and expounds the confirmed nature of dark matter and the research methods of its two candidates, i.e., WIMPs and Axion. To be specific, the model configurations of the two candidates are evaluated. In the meantime, the searching facilities have been discussed. At the same time, the current detection results are demonstrated though no determination signs have been recorded for the existence of the dark matter candidates. According to the analysis, the current limitations and prospects for further searching are also provided, shedding light on guiding further exploration of dark matter searching.

Keywords: Dark matter; WIMPs; axion.

1. Introduction

At the beginning of the 20th century, Jacobus Cornelius Kapteyn first mentioned that the possible existence of invisible matter in the universe revolving elliptically around the Sun as the center could be deduced indirectly from the configuration and motion of the sidereal system, thus proposing the concept of dark matter in 1922. And he concluded that "it appears at once that this (dark) mass cannot be excessive" [1]. After a decade, Jan Hendrik Oort deduced that dark matter's total mass near the Sun is very small from the analysis of matter density near the Sun [2]. After Oort announced the existence of the dark matter, there's no difference between local and global dark matter. However, Fritz Zwicky announced that the dark matter not only exist in individual galaxies but also in clusters, groups and galaxies which means the larger scale the dark matter owned [3]. Generally, there are two types of dark matter hypotheses. One of it is thought to be a particle. Some kinds of new particles are considered to be dark matter in this group, for example, sterile neutrinos which goes beyond the standard model as it only interacts with gravitational field. The other group hold the view that particle dark matter does not exist. In this group, the dark matter effects are attempts to be explained by various modifications to the known physical laws so far without inventing new particles [4].

In the process of investigating what the dark matter

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it is, a variety of hypotheses have been taken while some of it went beyond the Standard Model. For example, the dibaryon hypothesis put forward by Adlarson et al in 2014 is the closest one to verify by experiment analysis. However, Bugg pointed out the logical flaw in dibaryon hypothesis, while providing another explanation to the experiment results taken by the Adlarson et al. To Bugg's explanation which belongs to baryonic dark matter, the Standard Mode does not include the dark matterl, meanwhile it is based on the Dirac equation which belongs to the standard quantum mechanics [7]. In addition, it explains the observations of Bowman J.D. et al in 2018 and Jeffrey et al. in 2021. According to the analysis of McGaugh in 2018, Bowman et al and Barkana proposed that the dark matter is baryonic which means the hypotheses about non-baryonic can be excluded among the variety of hypotheses.

As an unsolved mystery in physics, dark matter has aroused the interest of thousands of scientists so that continuous research work is still carried out yet even today. There's no doubt that the research into dark matter taken by scientists is driving the advances in physics, especially in cosmology and quantum mechanics. Dark matter is an important part of the universe, and its existence can explain many unsolved phenomena in astronomical observations. In the meantime, the detection and investigation of it has great and profound significance for the origin and evolution of the universe. In the search for it, scientists may be able to learn more about the nature of the universe. To get to know what dark matter is, this article aims to give a brief explanation of the features of the dark matter and the main methods to explore it. In the following pages, this article will give the main category of the dark matter according to various theories, as well as, the searching of dark matter including searching for WIMPs and searching for Axion as well as the limitations and prospects of the research on dark matter.

2. Descriptions for Dark Matter

Most objects can be observed due to the light it emitted. Some other objects which cannot be observed will form a dark region as it absorbed light. So, almost all the information one can known about the universe are based on the photons. Thus, both the emission and absorption of light can help to trace the matter in the universe. However, not all the astronomical bodies either emitting light or absorbing light. Astronomers usually infer the mass of astronomical bodies through the light emission. On the other hand, the mass of these bodies can be directly inferred through the motion of other bodies around or within the body under study. In these cases, a different result where the estimated mass of body is much larger than the luminous mass of known astronomical bodies is considered as the dark matter [2]. Therefore, dark matter can only be identified by its gravitational pull-on visible matter, it does not emit or absorb light because it does not interact with electromagnetic fields. Furthermore, the matter made up of all the stars and galaxies only makes up a small amount of the universe, about 5%, whereas dark matter, which has about five times the mass of visible matter, makes up around 27% in the entire universe [8].

Generally, the classification of dark matter can be divided into two types. The first classification contains baryonic dark matter and non-baryonic dark matter. It can be considered as the substance which interacts with gravitational field with visible matter. Hence, it does not need to be the composed of new fundamental particles as it can make up with standard baryonic matter. However, Numerous pieces of evidence suggest that most dark matter is not baryonic. Primordial black holes and speculative particles like axions or weakly interacting massive particles (WIMPs) are the two main contenders [2]. Warm dark matter (WDM), hot dark matter (HDM), and cold dark matter (CDM) are all included in the second classification [6]. These categories according to the corresponding velocity. All of these matters do not interact with electromagnetic radiation which made them hard to detect through conventional instruments, and that is the reason why they are named as dark matter. CDM contains particles that move very slowly. The possible candidates for CDM contain WIMPs, primordial black holes and axions. WDM contains particles that move fast enough to produce relativistic effects. The general candidates for WDM are sterile neutrinos and gravitinos. HDM contains particles that travel with ultra-relativistic velocity. Neutrino is an example of HDM.

3. Searching for Dark Matter

3.1 WIMPs

WIMP is a particle that remains in the theoretical stage from now on, also it is a promising candidate for the cold dark matter in the universe as they do not interact with ordinary matter since they are not a member of the strong nuclear force and the electromagnetic force, which prevents them from being directly observed, and also, due to their large mass, they move much slowly and are able to cluster together. However, the latest research indicates that its mass is smaller than that of WIMPs. According to theory, these particles ought to possess the subsequent two attributes: First, the interaction cross section between the particles is smaller than that of the weak nuclear force, or the particles only interact through gravity. Secondly, it is more massive than ordinary particles in the standard model of particles.

WIMPs can be directly searched for through their elastic scattering with a target material since they can be thermally created with the necessary abundance to account for the known dark matter density. Several experiments are currently underway or planned with this goal in mind [8]. The amount of WIMP dark matter is dictated by the freeze-out mechanism. Dark matter abundance can be anticipated if the properties of dark matter are understood. Nevertheless, the estimate of the WIMP dark matter abundance is not without some uncertainty [9]. The energy of nuclei struck by dark matter particles as they pass over (large) detectors buried deep below is measured by standard dark matter direct searches [10]. Based on galaxy dynamics and ideal GS-models, one can therefore conclude that the average velocity of dark matter in the Milky Way's dark matter halo is about 220 km/s, or $\beta = v/c = 7.34\times10^{-4}$, either at or away from the galactic center. Furthermore, since dark matter particles are non-relativistic, all terms are proportional to velocity and momentum transfer. Assume that a particle of dark matter has a mass of 100 GeV/c^2. Then the nuclear binding energy can be concluded that

$$K = \frac{1}{2}mv^2 = \frac{1}{2}m\beta^2c^2 = 27keV \quad (1)$$

While the normal binding energy in heavier nuclei is about 6–8 MeV, the typical recoil energy is at the keV energy scale, seen from Fig. 1, which means there is no enough energy to fission nuclei. Therefore, it can be deduced that the interactions with nucleus will be elastic [11], as shown in Fig. 2. Generally, there are three kinds of tracking detectors' models which have different sensitive materials have been put into experiments. The initial model, the NEWSdm nuclear emulsion detector, ranging from 20 to 80 nm and has a density of $\rho = 3.1 g/cm^3$. This is a significant improvement over a conventional nuclear emulsion, whose grain size was roughly 200 nm, as utilized, for instance, in the OPERA $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation search experiment. The second model functions as a bubble chamber detector and is a 500 L liquid propane C_3H_8 with a density of $\rho = 0.495\ g/cm^3$. For the third one, one took into consideration of the anticipated PICO experiment detector, which is a 500 L bubble chamber filled with 1.601 g/cm^3 of octafluoropropane C_3F_8 [12].

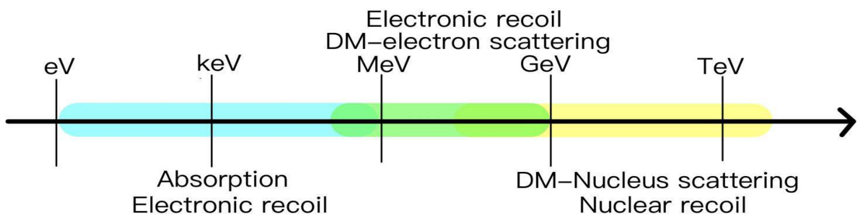

Fig. 1 The possible masses of dark matter particle with its experiments to detect [11].

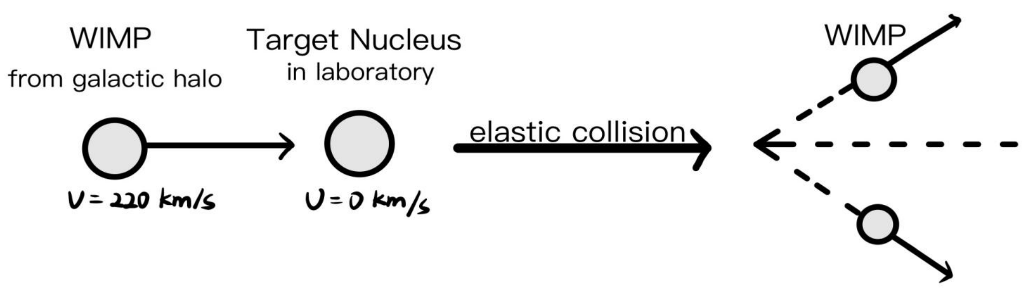

Fig. 2 The process of elastic interaction between dark matter scattering off the target nucleus [11].

Through this deduction in the laboratory frame, one can move to the center-of-mass frame to get more details about the kinematics of this scattering. To sum up, the detection equations of dark matter are

$$E_R = \left(\frac{m_X m_N}{m_X + m_N}\right)^2 . \frac{v^2}{m_N} (1\text{-}\cos\theta_R) \quad (2)$$

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_X m_N}\int_{v_{min}}^{\infty} vf(v)\frac{d\sigma_X N}{dE_R}\,\mathrm{dv} \quad (3)$$

In 30 kg nuclear emulsion, 500L C_3H_8 and C_3F_8 liquid, the yearly signal of WIMP (m=10 GeV) has been detected. It was discovered that in the emulsion's deemed sensitive volume, one occurrence is anticipated to occur annually. C_3H_8 and C_3F_8, two of the less dense targets,

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have extended nuclear orbitals, are made up only of light nuclei, and experience 24 and 194 wimp events annually. It is reasonable to use lighter and less dense targets as sensitive elements of the detector system in direct detection scenarios, given the current experimental restrictions on the interaction cross section of the WIMP-nucleus interaction. These findings, in addition to calculations of the quantity of solar neutrino recoil incidents, are shown in the Table 1.

Table 1. Detector substance for detection results.

detector substance	element	N of WIMP per day in 1 kg of this element	N of WIMP per year in 1ky of substance	N of WIMP
emulsion, 30 kg	H 1.6%	$7.03 * 10^{-7}$	$3.14 * 10^{-2}$	0.94
emulsion, 30 kg	C 10.1%	$3.23 * 10^{-4}$	$3.14 * 10^{-2}$	0.94
C3H8, 500 L	H 18.2%	$7.03 * 10^{-7}$	$4.82 * 10^{-2}$	23.75
C3H8, 500 L	C 81.8%	$3.23 * 10^{-4}$	$4.82 * 10^{-2}$	23.75
C3H8, 500 L	C 19.1%	$3.23 * 10^{-4}$	$2.42 * 10^{-1}$	194.0

3.2 Axion

An axion is a subatomic particle in hypothesis that was deduced in the 1970s to solve the CP conservation problem, and was first mentioned in the 1977 Peccei-Quinn theory. Theory predicts that axions have an extremely small mass of 10^{-6} to 10^{-2}eV (one part in 500 billion to one part in 50 million of an electron), and have zero charge and spin. Axions were once thought to be one of candidates of dark matter, but some scholars have ruled out axions as candidates for dark matter particles. Before talking about the axion, there is a brief explanation about the CP problem which shows the lack of CP violation observed in strong interactions can be taken as the simple conclusion of the strong CP problem [13]. Furthermore, one variable that defies CP symmetry is the neutron electric dipole moment. Thus, Peccei and Quinn introduced a new symmetry. When this kind of symmetry is broken at high energy, pesudo-Nambu-Goldstone boson is produced, also called axion. The axion is the most popular solution for the PC problem. However, its mass cannot be predicted. A more general class of Axion-Like Particles has also been created to expand the concept of the axion as illustrated in Fig. 3. The mass and coupling constant in this instance are unrelated to one another [14].

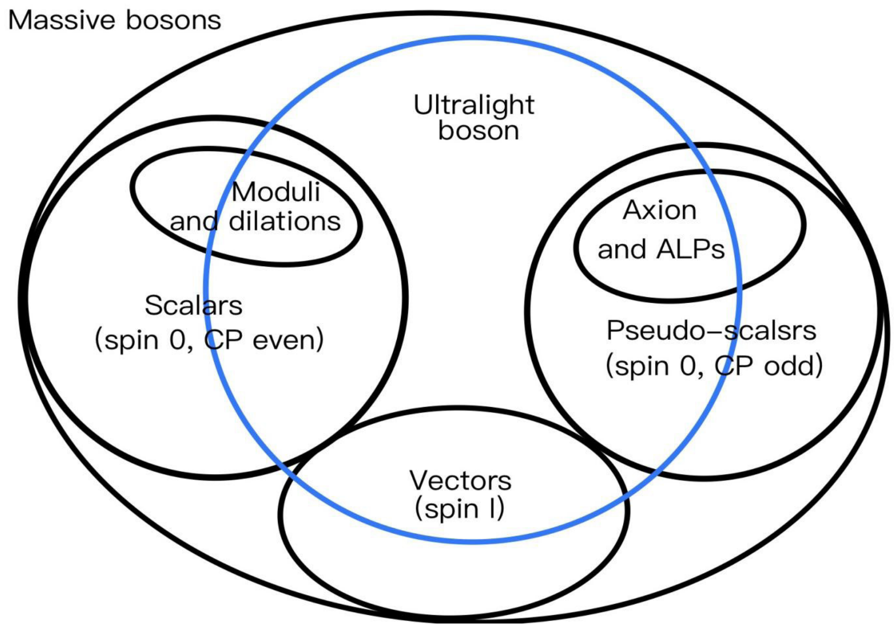

Fig. 3 Extensions of the Standard Model [14].

At present, there are two methods of probing axions. One is to use Italy's PVLAS detector, which works by shining a linearly polarized laser into a vacuum with a strong magnetic field, and then observing the polarization of laser as it passes through the field. A 10-12 rad change has been detected, but it may be the instrument itself. Another method is that whenever the quasar 3C 279 aligns with the Sun and the Earth around October, the photons emitted by 3C 279 pass through the Sun, and these photons may be converted into axions by the Sun's magnetic field, and then back into photons, and detecting these photons can help us understand whether the existence of axions.

After years of improvement, cavity techniques have reached sufficient sensitivity to detect dark matter that can be valued even by weak electromagnetic coupling DFSZ. The type of large superconducting solenoid magnet most commonly used in experiments. The type of large superconducting solenoid magnet that is most commonly experimented with first, the requisite hole solenoid-type magnet is filled with a cylindrical resonant cavity. To reach higher frequencies, one can fill the available volume inside the magnet hole with many of the same cavities and combine their output power. A properly constructed multi-cavity array has an effective form factor of order 1 and allows for an upward expansion of the frequency range within which a galaxy's halons can be searched with a given magnet, at the cost of engineering complexity.

4. Limitations and Prospects

The limitations of dark matter research are mainly due to the complexity of its observations and the design of experiments. Dark matter cannot be directly observed, and only the gravitational effects of dark matter may be used by physicists to infer its existence. Galaxies and clusters of galaxies have much more mass than can be observed, which shows that there are a great number of dark matters in the presence, taking up 80% of the total mass of the universe. However, designing experiments to detect dark matter directly is very difficult because the interaction with dark matter is very weak. Secondly, research about dark matter is limited due to the diversity of hypothesis under its theoretical models. From now on, there are a variety of dark matter models, but the specific properties and interaction mechanisms of these models have not been fully determined. And experiments about dark matter can only be tested under the specific model hypotheses, rather than irrelevant hypotheses under the other model, which greatly limits the universality of the experimental results. For example, despite being one of the most promising dark matter hypotheses, WIMPs, it cannot completely explain all the characteristics of dark matter which have been observed. In the last, experimental techniques is one of the limitations for the research of dark matter. Although dark matter detectors can reduce background noise and improve the efficiency of signal detection, they still cannot completely eliminate other interference factors, like Cosmic rays and other particles, which may produce a similar signal compared to dark matter, making it difficult to distinguish the different signals.

There's no doubt that the research about dark matter has unlimited prospects, and more and more scientific and professional research teams will join the research in this field in the future, providing more possibilities for unsolved mysteries of the universe. With the development of science and technology, the methods for searching dark matter are increasingly diversified and comprehensive. In addition, with the application of high-precision detection instruments and equipment, superconducting experiments, quantum computer technology and other high-tech means, researchers can more effectively detect the dark matter particles directly to get the direct evidence of the presence of it. At the same time, the development of data simulation also played a significant role in theoretical prediction, leading to higher calculation accuracy which promotes the refinement and validation of dark matter. Future dark matter research will focus on improving sensitivity in detection and covering a wider range of dark matter candidate particles. Underground experiments such as XENONnT and LUX-ZEPLIN tend to improve detector sensitivity continually to detect the interaction with dark matter particles. The Large Hadron Collider (LHC) will conduct higher energy particle collision experiments, looking for possible signals of dark matter particle production. Theoretical research will also continue to explore high-energy physics models such as supersymmetry and string theory to explain the nature and origin of dark matter.

5. Conclusion

To sum up, dark matter research has a long way to go. Based on the results have discovered, dark matter can be divided into two main categories. Various studies have been carried out under different hypothetical models, such as WIMPs, among the most auspicious possibilities for dark matter, and Axion, which has been ruled out almost. With the development of science and technology, scientists will continue to deepen the study of dark matter until they find direct evidence to prove the nature of dark matter. On this kind of basis, to find out more about the characteristics of dark energy, and even the universe's creation and assessment.

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