Analysis of Dark Matter Candidates and Detection Scenarios

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Abstract. In recent years, the observations collected by the state-of-art detectors have shown that there is considerable amount of invisible matter in our universe, which is named as dark matter. The study of dark matter has become one of the main research directions nowadays. Contemporarily, there are many particle models are considered as candidate of dark matter, including the models of axion, sterile neutrino, and Weakly Interacting Massive Particle (WIMP) e.g., inert Higgs boson, lightest Kaluza-Klein particle and neutralino in supersymmetry. Furthermore, there are also many experiments and measurements of axions and WIMPs, including axion haloscope ADMX, axion helioscope CAST, and WIMP nuclear recoil detection experiments, such as LUX-ZEPLIN and DarkSide-50. In this paper, the basic model of above candidates will be introduced. In addition, discussion about the additional parity-like symmetry for WIMP model building, shortage of the experiments and the future upgraded dark matter experiments will also be presented. Overall, these results shed light on guiding further exploration of dark matter detection and searching.

Keywords: Dark matter; axion; WIMP.

1. Introduction

Dark matter was first discovered by studying the rotation curve of the spiral galaxy, which implied there should be more matter than one can see in the universe, and the gravitational lensing effect of the light from distant galaxies can also show that there is a considerable amount of matter that are invisible, i.e., inactive to the electromagnetic force. It implies that 86% of the mass of the universe is made by this invisible matter, and it also makes up 27% of the total mass-energy. Due to such a large amount of matter that we still have no good theory to explain, it becomes a crucial point in modern particle physics. There are many particle theories trying to describe the its properties and existence, such as axions [1], sterile neutrinos [2], inert Higgs bosons [3], the lightest Kaluza-Klein particle [4], supersymmetry [5] etc., where the last 3 candidates are considered to be the WIMPs. The models predict the dark matter particles with mass from μeV to TeV, and the ways to extend the Standard Model (SM) are also different among these models.

The detection for the dark matter candidates also becomes a significant direction of the modern physics, and the detection of axions and WIMPs could be the most popular directions of the dark matter searching. For the axion detection, there is axion haloscope experiment ADMX [6], and axion helioscope experiment CAST [7]. For the WIMP detection, there are nuclear recoil detectors such as LUX-ZEPLIN [8], DarkSide-50 [9], PandaX-4T and XENON1T.

In this paper, the dark matter models and the corresponding detection experiments will be discussed. The Sec. 2 will introduce some of the dark matter particle models, including the models introduced above. In the Sec. 3, the detection mechanism and experiments for axions and WIMPs will be discussed, including the axion haloscope, axion helioscope and WIMP elastic scattering detection experiments. The Sec. 4 will contain some extra discussion, including the additional parity-like symmetry among WIMP models, the problems facing for current experiments and the future experiments for axion and WIMP detection. Eventually, a brief summary will be given in Sec. 5.

2. The Candidates

2.1. Axions

Axions was predicted to exist by the work of Peccei and Quinn for the strong CP problem [10], which is that the strong interaction could theoretically violate the CP symmetry, but there is no experimental evidence showing that the strong CP violation was found. More specifically, the problem is caused by the quantum chromodynamics theta term

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{\mu\nu a} \quad (1)$$

where θ is the phase angle, g_s is the coupling constant, $G_{\mu\nu}^a$ is the SM $SU(3)$ gauge field strength tensor, and $\tilde{G}^{\mu\nu a}$is the dual of the strength tensor, i.e. $\tilde{G}^{\mu\nu a} = 1/2\,\epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}^a$, and the theta term should theoretically violate the CP symmetry with a non-zero θ [1], but the experiment showed that the neutron's electric dipole moment was extremely small and in the order of 10^{-26}e cm and it will constrain the angle θ in the theta term to the order of 10^{-11}. To solve this problem, a scalar field was introduced with an anomalous global symmetry $U(1)_{\mathrm{PQ}}$ (called Peccei–Quinn symmetry) which would spontaneously break, and the corresponding Goldstone boson with nonzero mass is called axion [11]. Therefore, the phase angle θ in the theta term becomes $\theta + Na/F_a$, where a is the introduced new scalar field, F_a is the PQ scale, the scale where the symmetry breaks and N is the axion color anomaly.

The interaction of the axions depends on the models, and there are two main models for axion dark matter, which are the hadronic Kim–Shifman–Vainshtein–Zakharov (KSVZ) model and the Dine–Fischler–Srednicki–Zhitnitsky (DFSZ) model [11]. In the KSVZ model, the axions directly couple to at least one additional type of very massive quarks, and the rest of the fields have no PQ charge, which makes the axion color anomaly $N = 1$, and it also means that other fields need to interact with axions through a loop of the new quarks, and it makes the axions very inactive with the SM particles. In the DFSZ model, the SM particles and the extra Higgs bosons have appropriate charges, which makes the color anomaly $N = 3$, as all 3 generations of quarks can interact with the axions. The mass of the axion is caused by the QCD instanton effect, and apart from some SM parameters, the mass also depends on the PQ scale F_a and the axion color anomaly N [11]. As the scale of PQ symmetry breaking should be very large, it would make the mass of the axions very small, and the mass of axions would be in the range of μeV∼eV.

2.2. Extended Theories for Neutrinos and Higgs Bosons

As right-handed neutrinos do not interact under the SM gauge symmetry, the theory considered neutrinos should be massless, which violates the experimental observation. Therefore, one can add a gauge-invariant Majorana mass term in which only right-handed neutrinos get involved [2]. Besides, it leads right-handed neutrinos to become sterile neutrinos, which means they are very weakly interacting, i.e., they only interact with gravity, and the left-handed neutrinos in SM are then called the active neutrinos. Apart from the extended theory for neutrino, there is also a theory with two Higgs doublets under a Z_2 discrete symmetry, called Inert Doublet Models (IDM). The symmetry would make one Higgs doublet odd charged and the rest of the fields in the SM even charged. Then the lightest component of the odd charged Higgs doublet becomes stable, which is called inert Higgs bosons, and it has a similar order of mass as the SM Higgs bosons [3]. Apart from the IDM, there are also some other models extending the Higgs theory, which would also provide the Higgs WIMP candidate, such as the little Higgs mechanism, and the twin Higgs mechanism, and these models also predicted stable lightest Higgs bosons with masses in several GeV.

2.3. Lightest Kaluza-Klein Particle

The models which introduce additional spatial dimensions can also provide dark matter candidates and the lightest Kaluza-Klein particles (LKP) are one of them. The theory behind it introduced the universal extra dimensions (UED) to the 3+1-dimensional spacetime. The idea of introducing extra dimensions (Kaluza-Klein theory) was first proposed by physicists Theodor Kaluza and Oskar Klein in 1926 [12], but it was considered untenable, and the idea of UED was a modern modification to the KK theory [13]. In the simplest case of UED, the extra dimension is compactified in an orbifold S^1/Z_2 with radius $R\sim\text{TeV}^{-1}$. The momentum in the extra dimension will behave like the extra mass of the particle in the 4-dimensional Minkowski view, and the extra mass is quantized in the unit of $1/R$. Therefore, every SM particle has infinite KK partners under the KK excitation which is called the KK tower, and the first excitation state of the SM $U(1)$ hyper-charge gauge boson, $B^{(1)}$, is considered as the LKP. Due to the Z_2 quotient of the compactified orbifold, the conservation of the momentum in the 5th dimension would break into a Z_2 discrete symmetry called the KK parity, which is a parity flip of the extra dimension. If one considers the KK parity is conserved, it would imply that the LKP should be stable [4]. The mass of the LKP is in the order of TeV which is based on the size of the compact manifold.

2.4. Supersymmetry

Supersymmetry (SUSY) can be one of the most popular theories in particle physics, and it proposed there should be a symmetry relation between all fundamental fermions and bosons, which implies there should be a corresponding super partner for every SM particle. There is also a Z_2 parity in SUSY called R-parity. The R-parity defines the SM particles have $+1$ parity and SUSY particles have -1 parity. If one considers R-parity should conserve, there should be equal number of SUSY particles coming in and out at each interaction vertex on the Feynman diagram. As the SUSY particles will eventually decay the lightest particle, to preserve the odd R-parity, the lightest SUSY particle (LSP) wiil be stable [5]. The LSP would be more likely to be the neutralinos $\tilde{\chi}^0$ [14],

$$\tilde{\chi}^0 = \alpha\tilde{B} + \beta\widetilde{W}^3 + \gamma\widetilde{H}_1^0 + \delta\widetilde{H}_2^0 \tag{2}$$

where α, β, γ and δ are the normalized free parameters, and $\tilde{B}$, $\widetilde{W}^3$, $\widetilde{H}_1^0$and $\widetilde{H}_2^0$ are the superpartners of gauge bosons and neutral higgs bosons, i.e., B-ino, neutral W-ino, and two neutral Higgsinos. Then the lightest neutralino $\tilde{\chi}_1^0$ can be considered as the most probable candidate in SUSY. As the model of neutralino largely depends on the SUSY parameters, the particle $\tilde{\chi}_1^0$ can be bino-like, wino-like or higgsino-like, which makes the theory flexible to adjust to fit the astrophysical observations for dark matter. The neutralino is the most popular dark matter candidate in SUSY, and apart from neutralinos, the super-partners of gravitons, neutrinos and axions, i.e., gravitinos, sneutrinos and axinos, are also considered to be the dark matter candidates.

2.5. Candidates Summary

The models above all predicted the candidate dark matter particle should be non-baryonic, electric neutral, color neutral and have a long lifetime, which are the properties that are constrained by the cosmological observations. However, the masses of them may vary from μeV to TeV. The masses of axions and sterile neutrinos are relatively small, and the small masses is also one of the reasons that the particles remain stable. The mass of inert Higgs boson, LKP and LSP have the masses from GeV to TeV, and they are the WIMPs. Table 1. shows the candidates with their masses and spins.

Table 1. Dark matter candidates with their masses and spins.

Model	Axion	Sterile neutrino	Inert Higgs Boson	LKP	Neutralino
Mass	μeV~eV	keV	50GeV	10GeV~10TeV	TeV
Spin	0	1/2	0	1/2	1

3. The Detection

3.1. Detection for Axions

There are several ways to detect the existence of axions, the most of detection is mainly based on the very weak interaction between axions and photons, the axion-photon interaction or the Primakoff effect, and the interaction is caused by the Lagrangian term:

$$\mathcal{L}_{\alpha\gamma\gamma} = -\frac{g_{\alpha\gamma\gamma}}{4} aF_{\mu\nu}\tilde{F}^{\mu\nu} = g_{\alpha\gamma\gamma} a\boldsymbol{E}\cdot\boldsymbol{B} \tag{3}$$

Where $g_{\alpha\gamma\gamma}$ is the coupling constant which depends on the axion color anomaly and axion electromagnetic anomaly of the models and some SM parameters, a is the scale field of axion as mentioned before, $F_{\mu\nu}$ is the $U(1)$ EM gauge field tensor, $\tilde{F}^{\mu\nu}$ is the dual of the EM tensor (similar to the dual of strong field tensor in Eq. (1)), and $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electric and magnetic vector fields. Under this interaction, the axions can convert into photons under a strong electric field or a strong magnetic field, which makes detection of the axions possible.

One of the detections is called the axion haloscope, which is first proposed by Sikivie [15]. Considering axions are dark matter, there should be a sufficient amount of axions in the halo of the Milky Way, which would pass through the earth at every moment. The detection experiment may need a large microwave cavity with a strong magnetic field passing through, and the halo axions will be converted into a microwave signal with a certain frequency resonantly in the cavity. The conversion power is:

$$P = g_{\alpha\gamma\gamma}^2 \frac{\rho_a B^2 V Q}{m_a} \tag{4}$$

where $g_{\alpha\gamma\gamma}$ is the coupling constant as before, ρ_a is the axion density in the halo, m_a is the axion mass, B is the B-field in the cavity, V and Q are the volume and quality factor of the cavity. The resonant conversion will need the detection frequency equal to the mass of the particles to reach the maximum power. However, even under the resonant power, the signal is very tiny, i.e., in the order of 10^{-23}W. To have a high resolution, the signal-to-noise proportion needs to reduce to a sufficient level, and the ratio is:

$$\frac{S}{N} = \frac{P}{k_B T}\sqrt{\frac{t}{\Delta\upsilon}} \tag{5}$$

Where k_B is the Boltzmann constant, T is the system temperature, t is the time taken, and $\Delta\upsilon$ is the frequency range of the axion signal. One of the most recent detection experiments for axion haloscope is the Axion Dark Matter Experiment (ADMX). The experiment has successfully excluded the signals with frequencies between 460 and 890 MHz, which implies under the KSVZ models, the axions cannot have mass in the range of $1.9\sim3.7\mu$eV [16].

Another way to detect the axions is called the axion helioscope, and it is also first proposed by Sikivie in the same essay shown in the last paragraph [15]. As the sun naturally produces a very large magnetic field, it can be considered as a large axion source. Under the strong magnetic field on the earth, the solar axions will convert into X-ray and become detectable. In the KSVZ model, the solar axion flux at the earth is in the order of $10^{11}\text{cm}^{-2}\text{s}^{-1}$ with axion energy distribution in $1\sim10$keV. The probability conversion of relativistic axions into photons related to the magnetic field and its length, so to detect the solar axion, one may need a long and strong magnetic field. One of the axion helioscope experiment is the CERN Axion Solar Telescope (CAST), and the experiment uses the LHC magnet with a 9T B-field and 9.3m length. For the recent data in 2017, the CAST has shown the axion-photon coupling constant should be less than $0.66 \times 10^{-10}\text{GeV}^{-1}$ at 95% C.L. for axion mass $m_a < 0.02$eV [7]. The experiment has also obtained the data of the coupling constant such that $g_{a\gamma\gamma} \lesssim 2.3 \times 10^{-10}\text{GeV}^{-1}$ for axion mass $0.02\text{eV} < m_a < 0.64\text{eV}$ at 95% C.L., and $g_{a\gamma\gamma} \lesssim 3.3 \times 10^{-10}\text{GeV}^{-1}$ for axion mass $0.64\text{eV} < m_a < 1.17\text{eV}$ at 95% C.L. [16].

3.2. Detection for WIMPs

The WIMPs have mass in the order of GeV, and interaction rate to the normal matter is very low. The first detection method for WIMP dark matter was discussed by Goodmann and Witten [17], which indicated that one can detect the WIMPs directly by measuring the recoil of the nucleus elastically scattered off by the particles. The expected rate of the scattering-off is calculated as [18]:

$$\frac{dR}{dE} = \frac{\rho M}{m_N m_\chi} \int_{v_{min}}^{v_{nax}} v f(v) \frac{d\sigma}{dE} dv^3 \tag{6}$$

Where R is the scattering rate, E is the recoil energy of the nuclei, ρ is the local density of the WIMPs, M is the mass of the detection target, m_N and m_χ are the masses of the nuclei and the WIMPs, v is the speed between the WIMPs and the detector, $f(v)$ is the speed distribution of the particles, and σ is the cross-section. The expected recoil is in the range of $1 \sim 100\text{keV}$, and the mass of the detected WIMPs is related to the recoil energy (large particle makes high recoil). To measure such tiny recoil energy, the experiment needs a very high sensitivity to the weak signal and needs to reduce the background noise as much as possible. Therefore, the experiments may need a massive amount of very pure inactive nuclei (as the equation (6) showed), e.g., noble liquid, with high-sensitivity detectors (photomultiplier tubes), and operate deep underground to minimize the noise from the environment, the detector, and the cosmic particles. Nevertheless, there is still some noise that cannot be blocked completely, which is caused by the solar and cosmic neutrinos, and it naturally makes ultimate hinder for the WIMP nuclear recoil detection.

There are many experiments for nuclear recoil detection for the WIMPs operating nowadays. The limit for the WIMP cross-section with the nuclei needs to be minimized as much as possible until maybe one day the WIMP is detected. For the spin-independent measurements, the detection for WIMPs with mass greater than 5GeV mostly uses liquid xenon to be the detection target, and there are several such experiments operating simultaneously. The leading experiments are the LUX-ZEPLIN, PandaX-4T, and TPCs XENON1T. One of the latest measurements for the mass range shown above is obtained by LUX-ZEPLIN (LZ), the successor of experiment LUX. The experiment uses 5.5t liquid xenon as the detection target with 60-day exposure, and it limited the nuclear cross-section to the order of around 10^{-46}GeV^{-1}, and the lowest value was found for WIMP with maas at 30GeV, which is $5.9 \times 10^{-48}\text{GeV}^{-1}$ with 90% C.L. [8]. The LZ is largely approaching the neutrino background noise (or the neutrino floor) discussed in the last paragraph, and the measurements at masses around 9GeV start to touch this natural restriction. For the WIMPs with masses less than 5GeV, one liquid argon detector measured the one of lowest limits of the cross-section, which is the experiment DarkSide-50. The measurement was taken for the WIMP mass range $1.8\text{GeV} \sim 6\text{GeV}$, and it showed that the nuclear cross section for this mass range should be less than the order of around 10^{-42}GeV^{-1} [9]. The Fig. 1 show the measurements obtained by LZ and DarkSide-50.

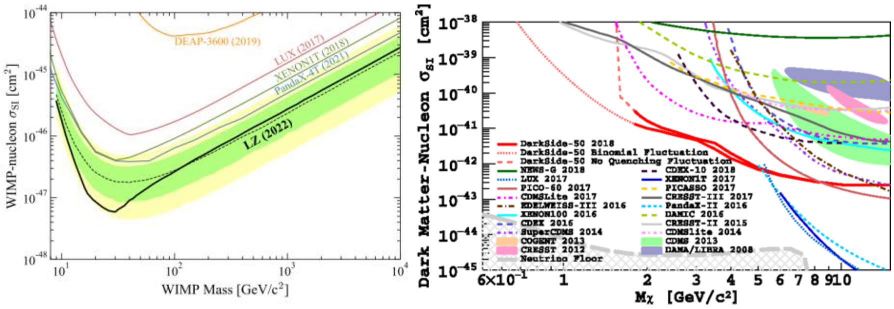

Fig. 1 Left panel: The data (black line) obtained by the LZ group in 2022 for the spin-independent WIMP nuclear cross-section against masses, the green and yellow regions showed the 1 and 2 sigma values of sensitivity, and the line with other colors showed the date obtained by other experiments. Right panel: The data (red line) obtained by the DarkSide-50 group in 2018 for the spin-independent WIMP nuclear cross-section against masses, and the line with other colors showed the date obtained by other experiments.

4. Discussion

4.1. Parity-like Symmetries for WIMP Models

In Sec. 2, the candidate model part, for the massive candidate particles which are also the WIMP, including inert Higgs bosons, lightest KK particles and neutralinos, the particles become stable owing to each parity-like symmetry conservation (i.e., the Z_2 symmetry for the two Higgs doublets makes inert Higgs stable, KK parity makes LKP stable, and R-parity makes neutralino stable). As such conservation law would make the interaction for each dark matter candidate produce an odd number of its own kind of particles, like baryon and lepton numbers conservation laws in the SM. The Z_2 parity-like symmetries are crucial to the WIMP dark matter models, as it reasonably makes the massive dark matter particle stable.

4.2. New Axion Helioscope Experiment

For the axion helioscope experiment, the production mechanism would be a bit different from the halo axion production. In the non-hadronic model like DFSZ model, the production channel for the axion-electron reaction can dominate the axion creation. The additional flux could be a couple of hundred times greater than the axion-photon one, but with a much lower axion total energy peak. To detect the axion produced in the non-hadronic model, an experiment which is sensitive to low energy axion flux is needed. There is a next-generation experiment, International Axion Observatory (IAXO), would allow the more sensitive detectors than the CAST experiment, which will reduce the range of axion-photon coupling to the order of $10^{-12}\mathrm{GeV}^{-1}$. Besides, it can also detect the additional axion flux predicted in the non-hadronic models. It will also have around 5 orders of magnitude more sensitive than the CAST experiment [19]. The IAXO experiment will start its operation in 2028.

4.3. New WIMP Detection Experiments

The direct detection of WIMPs is updating frequently in recent years, and the race of nuclear recoil detection for heavy WIMPs with mass greater than $5\mathrm{GeV}$ is still ongoing. The latest limits were just updated by the LZ in 2022 as mentioned in Sec. 3.2, and its upgrade from LUZ to LZ was just finished in 2020. The experiments XENON1T and PandaX-4T will also upgrade their own sensitivities in the future: The XENONnT experiment, the successor of XENON1T, will hold 6.5t of liquid xenon as the detection target, and the Panda-30T experiment, the successor of Panda-4T, is going to use 30t of liquid xenon as its name showed, and there is also another future experiment called DARWIN, an experiment planning to use 40t of liquid xenon as the detection target. The future experiments will push the limits to the order of around $10^{-49}\mathrm{GeV}^{-1}$, which will be very close to the neutrino floor over the major mass range of $10\sim10^{3}\mathrm{GeV}$ [20]. Considering the neutrino floor will be reached soon detection, the solar neutrinos and the atmospheric neutrinos will make the deep underground no longer a good place to isolate this irreducible noise. Therefore, alternative methods should be utilized for future heavy WIMP measurements.

5. Conclusion

In conclusion, the paper discussed some dark matter particle models and the corresponding detection experiments. In particular, it introduced the theoretical models of axions, sterile neutrinos, inert Higgs bosons, LKP and neutralinos, where the last 3 models are considered to be the WIMPs. The masses, interactions, creations and origination of the models were briefly discussed, and the additional parity-like symmetries for the WIMP models were also mentioned, which was considered to be crucial for the massive stable particle model building. Furthermore, the detection mechanism and the detection experiments of the axion haloscope, axion helioscope and WIMP spin-independent nuclear recoil detection were also introduced. Some shortages of the current experiments were discussed, such as the non-hadronic model axions may not be detected in the CAST experiment and the neutrino floor in the WIMP nuclear recoil detection may make the irreducible high noise for future high-sensitivity detection experiments. Finally, future experiments including IAXO, XENONnT, Panda-30T and DARWIN were also mentioned. Overall, these results offer a guideline of dark matter searching based on the state-of-art facilities.

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