The analytical description and detection of two types of dark matter: the WIMPs and axion

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Abstract. Contemporarily, the dark matter is considered as the jewel of the modern physics and whether it is existence or not still puzzling scholars. With the development of the detection techniques, the searching range and detection accuracy have been updated dramatically. In this paper, the basic principle and analytical descriptions for dark matter is introduced. Subsequently, the state-of-art detection approaches for the two well-known dark matter types (i.e., WIMPs and axion) are demonstrated. These results shed light on the further development of dark matter searching.

Keywords: dark matter, modern physics, axion.

1. Introduction

Dark matter, a hypothesised type of matter, is thought to make up about 85% of all matter in the cosmos, which is not detectable by any known method yet [1]. In retrospect, the idea that the universe is made up of a mysterious substance called dark matter was first proposed by Fritz Zwicky in 1933. According to his comments, galaxies seemed to be moving too fast for their mass to be accounted for by visible stars and gas. To explain the phenomenon, researchers proposed the existence of unseen, non-luminous matter named 'dark matter' [2, 3]. On this basis, the problem is led to that the standard models of cosmology to date are not able to account for dark matter, dark energy, and inflationary expansion in a consistent way. In this case, one needs new physics beyond what already known [4].

Lord Kelvin calculated the number of dark bodies in the Milky Way based on measured velocity dispersion of stars revolving around the galaxy's centre in a discussion given in 1884 [5]. He calculated the mass of the galaxy using these data, which he found to be different from the mass of visible stars. Therefore, Lord Kelvin concluded that most of the stars, especially the vast majority of them, could be black bodies [6, 7].

In 1929, Swiss astrophysicist Fritz Zwicky proposed what is now known as Zwicky's hypothesis that there are many invisible stars within our own galaxy that cannot be seen because they are too faint to be detected with present technology. However, this hypothesis never gained much support from other astronomers and scientists [2, 3]. Until 1992 when two independent teams independently published research papers suggesting models involving new forms of particles called WIMPs (weakly interacting massive particles). Since then, most theoretical physicists believe these WIMP-based models provide a good explanation for why galaxies do not fly apart under their own weight even though they contain hundreds of times more mass than all the stars in our galaxy combined [4].

Nowadays, among all the proposed types of dark matter, the WIMPs and axions are the most two widely investigated types, which is believed as the most possible candidate dark matter. Thus, this paper will focus on the two types and introduce the detection approach as well as the theoretical description for the two. The rest part of the paper is organized as follows. The Sec. 2 will introduce the basic description of the dark matter. Subsequently, the Sec. 3 and 4 will demonstrate the analytical model as well as detection scenarios accordingly for WIMPs and axion, respectively. Eventually, a brief summary is given in Sec. 5.

2. Basic descriptions of dark matter

Since its discovery, dark matter has been detected in many different types of astronomical objects, including galaxies and clusters of galaxies. It is thought to account for about 80% of the mass-energy

content in the universe. The remaining 20% consists mostly of ordinary matter, mainly atoms and molecules (e.g., hydrogen, helium, carbon and oxygen), that makes up stars, planets and other celestial bodies [4].

There are mainly two types of dark matter: weakly interacting massive particles (WIMPs) and axions. WIMPs are believed to be the most abundant type of particle in the universe, while axions may be even more common. Both types of dark matter have been proposed as candidates for explaining the missing mass in galaxies. They can also explain why galaxies rotate so quickly, since they would not need to exert much gravitational pull on each other if they were made up mostly of WIMPs or axions. Whereas, neither theory has yet been confirmed by experiment.

The detection of dark matter is based on the gravitational effects that it has on ordinary matter. The most common method for detecting dark matter is through its gravitational effect on ordinary matter, which is also known as direct detection. In other words, if one knows where and how much a certain amount of dark matter exists in space, then it is feasible to calculate the mass of all the stars and galaxies in that area. This calculation will tell you how many times more massive each galaxy is than what it should be given its distance from us (its luminosity). If this value is too high or too low, then there must be some additional mass present which accounts for these discrepancies. On the other hand, indirect detection approaches are also designed. These methods do not involve direct observation of dark matter itself but instead rely on indirect observations about the properties of ordinary visible light or other types of radiation emitted by objects within our own galaxy or beyond it (e.g., neutrinos).

3. WIMPs progress

The WIMP model is a theory of how the universe works that was developed by physicists in the 1980s. It suggests that there are three fundamental forces: gravity, electromagnetism and weak nuclear force. These forces interact with each other to form particles like protons and neutrons, which then combine to make atoms. Atoms combine together to form molecules, which then combine together into larger structures like stars and planets. The WIMP model also explains how these larger structures can be broken down into smaller ones through collisions between subatomic particles called quarks or gluons.

The thermal decoupling paradigm, which is based on statistical mechanics and particle and nuclear physics applications to cosmology, is extremely successful at making specific predictions for observables in the early Universe, e.g., light element abundances and the CMB [8]. It's only reasonable to use a similar approach to deduce the quantity of DM as a thermal relic from the early Uuiverse just from the features of the underlying DM particles.

Assuming there are interactions between a cosmologically stable particle – the (generic) DM and Standard Model (SM) particles that are large enough for the DM to be in thermal equilibrium with 2 the primordial thermal bath for a high enough temperature T, the cosmological evolution of the DM particle can be traced based on the Boltzmann equation [9]:

$$\frac{dn_\chi}{dt} + 3H(T)n_{chi} = -<\sigma v>\left(n_\chi^2 - n_{\chi,eq}^2\right) \tag{1}$$

Where the number density of the DM can be defined as:

$$n_\chi(T) = g_\chi \int \frac{d^3p}{(2\pi)^3} f_\chi(p,T) \tag{2}$$

The DM distribution function is denoted by f_χ, while the number of internal degrees of freedom of the DM particle is denoted by the term g_χ [9].

All visible structures, e.g., galaxies and clusters of galaxies, are surrounded by DM halos, according to astrophysical and gravitational evidence. The halos are generated by DM particles with a velocity distribution that changes over time. The goal of DD experiments is to discover DM by

scattering off nuclei from the halo that surrounds our galaxy and flows through the Earth. The goal of direct DM detection is to quantify the nuclear recoil caused by a WIMP particle's dispersion. The differential scattering rate of WIMP-nuclei can be represented as:

$$\frac{dR(E,t)}{dE} = \frac{N_T \rho_\chi}{m_\chi m_A} \int_{v_{min}}^{v_{esc}} v f_E(\boldsymbol{v}, t)\, d^3\boldsymbol{v} \tag{3}$$

Where E is the recoil energy associated with the scattering events, N_T is the number of target nuclei per kilogramme of the detector, m is the DM mass, ρ_χ is the local DM density (= 0.3GeV/cm^3) [10-14], $\boldsymbol{v}$ is the DM particle velocity relative to the Earth, $f_E(\boldsymbol{v}, t)$ is the distribution of WIMP velocities in the Earth's frame, and v_{min} is the minimum WIMP speed required to produce E. The escape velocity (V_{esc}) is the speed at which the WIMPs are no longer gravitationally bound to the Milky Way. The WIMP-nucleus reduced mass μ (mN is the nucleus mass) is equal to $m_\chi m_N/(m_\chi+m_N)$, and the differential cross-section as follows for WIMP-nucleus scattering is equal to $d\sigma/dE(v, E)$,

$$\frac{d\sigma}{dE} = \frac{m_N}{2\mu^2 v^2} \left(\sigma^{SI} F^2(q) + \sigma^{SD} S(q)\right) \tag{4}$$

The momentum transfer is represented by q. The Spin-Independent (SI) and Spin-Dependent (SD) form factors, as described in Refs. [15-19], are F^2(q) and S(q), respectively. Following the measurement of the scattering rate, the next and most important duty is to separate the signal from the background. This is accomplished by utilising the detector response to electron and nuclear scattering, which varies from experiment to experiment. The combination of energy threshold, background and exposure control, and target affects an experiment's sensitivity to a WIMP signal.

4. Axion Model

The Axion model is a dark matter candidate, which has been proposed in the early 2000s by two physicists. Its name is derived from its resemblance to an axion, a hypothetical elementary particle that does not interact with other particles and whose mass is so small that it can pass through ordinary matter without being detected. The Axion model predicts the existence of several types of dark matter candidates: weakly interacting massive particles (WIMPs), sterile neutrinos and axions. WIMPs are predicted to be stable, while sterile neutrinos have no interaction with ordinary matter at all. An axion should exist only if it decays into WIMP-like particles or into lighter ones within 10^{60} years as well as if there are enough of them around for their gravitational effects to be detectable on Earth. Initially, the axion was proposed as a solution to the strong CP problem [20-27]. The Strong CP issue arises from the fact that the phrase

$$L \supset \frac{g_s^2}{32\pi^2}\, \theta_{QCD}\, tr\, G\tilde{G} \tag{5}$$

All symmetries in the Lagrangian of the Standard Model (SM) allow for G, the QCD field strength, and $\tilde{G}$, the QCD gauge coupling, however experimental data limit θ_{QCD}. The neutron acquires a dipole moment d_n of [28] due to the term in following equation:

$$d_n = 1.2 \times 10^{-16} \theta_{QCD}\, e \cdot cm \tag{6}$$

The current bound on QCD is derived from experimental bounds on the neutron's dipole moment [28]. The Strong CP problem is used as incentive for physics beyond the SM because there is no reason for QCD to be so small in the SM. By converting the parameter θ_{QCD} into a dynamical field, the axion a, the Peccei-Quinn mechanism [20,21] elegantly addresses this difficulty (x). The axion has a potential that is commonly expressed as

$$L \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} tr\, G\tilde{G} + m_a^2 a^2 \tag{7}$$

The axion decay constant is fa, and the mass of an axion is given by

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \tag{8}$$

The QCD confinement scale is Λ_{QCD} ~200 MeV in this case. The axion appears as a pseudo-Goldstone boson when a global UPQ symmetry is broken, and it has a mixed anomaly with QCD [20-23]. This symmetry is disrupted at the scale f_a, which suppresses all of the axion's couplings to the SM and dictates the axion's phenomenology [20-27]. A suitably light axion is a great dark matter candidate 29, as its density is related to the Universe's critical density is given by

$$\Omega_a \approx \left(\frac{6\mu eV}{m_a}\right)^{\frac{7}{6}} \tag{9}$$

The total dark matter density of the Universe, $m \approx 0.27$, would be accounted for by an axion of ma ≈ 20 eV (within a factor of nearly two). Much lighter axions might overclose the Universe if the initial misalignment angle was not tuned; thus, m_a 1 eV may be considered a strong bottom limit on the axion mass m_a. However, the current agreement is that the sum of all contributions to a could result in a two-order-of-magnitude increase in the axion mass corresponding to DM. Since human beings are primarily interested in setting conservative ranges for tests right now, searches should aim towards the eV scale. The Fig. 1 presented a typical sketch of the detection facility.

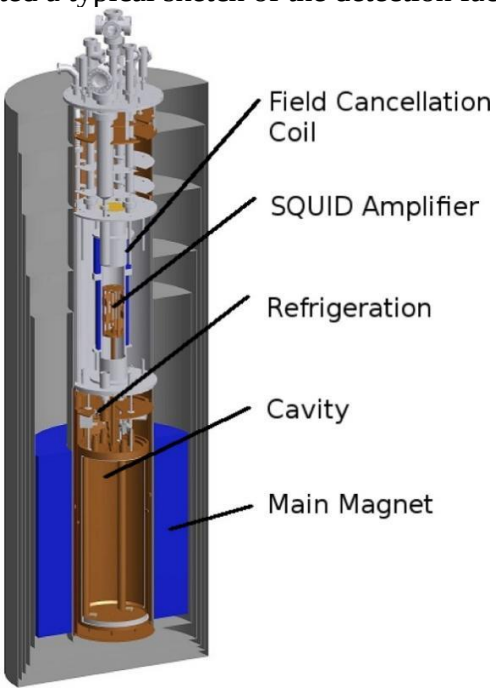

Figure 1. A sketch of the typical detector for axion [30]

The axion could solve the issue "what is dark matter comprised of?" in addition to solving the strong CP problem. The axion is a neutral particle with extremely weak interactions that could be created in sufficient quantities to form dark matter. ADMX is one of just a few experiments capable of detecting axions, the dark matter that accounts for the majority of matter in our universe. The axion haloscope approach is implemented in the ADMX experiment. It is made out of a right circular cylinder microwave cavity with a copper coating that is about a metre tall and 30 cm in diameter that is positioned inside an 8 Tesla superconducting magnet [30]. The cavity's resonant frequency is adjusted by moving two copper or dielectric rods from the cavity's edge to the centre. Dark matter axions transform to photons in the cavity's resonant TM modes if the cavity is adjusted to the correct frequency. A small antenna at the top of the cavity picks up these photons, as well as black body radiation photons, and sends them to microwave amplifiers.

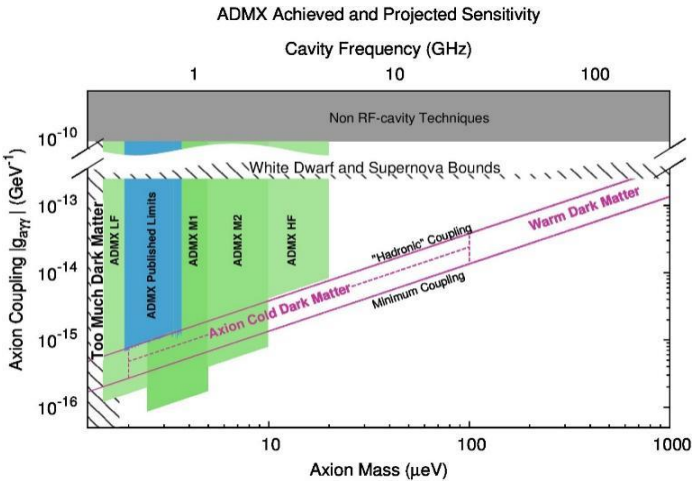

Figure 2. The detection range of ADMX [30].

The ADMX experiment should be able to study a wide range of axion masses with the installation of the dilution refrigerator, and dark matter axions with the more pessimistic DFSZ coupling should be observable even if axions make up only a fraction of the local dark matter density. The Fig. 2 illustrate the detection range of ADMX. After one year of operation at dilute refrigerator temperatures, the ADMX experiment's target search range, as well as the range targeted by R&D efforts. The current plan is to investigate this search range in 2015, then move on to higher frequencies in 2016. This is a major portion of the possible axion dark matter mass range, i.e., has a high chance of being discovered.

5. Conclusion and Future outlook

In summary, the basic descriptions of dark matter and the analytical as well as experimental progress of detecting WIMPs and axions are demonstrated. Based on the analysis, the significance of dark matter research is that it may provide a way to test the Standard Model of particle physics. The model, which has been tested by experiments, e.g., the Large Hadron Collider at CERN in Switzerland and Fermilab near Chicago, is widely believed to be correct. Nevertheless, some scholars are sceptical about its validity because it does not explain dark matter. They believe there must be more fundamental particles than those known so far. If these exist, they would have had a profound effect on our history and could help determine how we ended up with life on Earth rather than elsewhere in the universe. With new technologies being developed at CERN's accelerator complex near Geneva, Switzerland, scientists are optimistic that they will one day be able to detect dark matter directly using high-energy collisions between protons and antiprotons without any need for a detector (e.g., LHC.) On the theoretical side though, the next decade will be critical. Most models of WIMPs with masses below 1 TeV are expected to be fully probed by the next generation of direct detection experiments. Hence, if the clear signals can be obtained, one should arguably push for directional direct detection experiments. Overall, these results offer a guideline for dark matter searching based on the state-of-art facilities.

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