

The Principle and Detection Progress of Axion Dark Matter

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Abstract. Detection of the axion is a significant yet challenging discovery for particle physics and astrophysics. Based on information retrieval and interpretation of results, a summary of state-of-art detection methods could be achieved, and future progress and be predicted. Although the axion suffices for its properties of hidden nature and impact on gravity, which leads to the difficulty of detection. There are currently several candidates for the detection of axions: cavity microwave experiments, solar axion searches, and radio telescope searches. With progress on all of these detection methods, analysis can be performed to establish a foundation for further development in these detection methods. If current methods continue to become more efficient and new methods are continuously proposed, the axion's detection can be hastened and proof or counter-proof would be established quicker. Overall, these results offer a guideline for further axion search and newer questions based on the axion in the near future.

Keywords: Dark Matter, Axion, Quantum Chromodynamics, Cavity Microwave Experiment, Helioscope, Radio Telescope Search.

1. Introduction

Dark matter is a concept that humans typically fail to realize the true nature of a complex phenomenon. The event in question is the force of attraction within galaxies demonstrated through their faster spin. However, the galaxy's force of attraction is greater than its estimated mass, which is true for all galaxies observed. There is currently no explanation for such a phenomenon, thus one could assume that the creation of such strong observable forces of gravitational attraction must be able to evade detection in some way, i.e., naming the overall term for the factor "dark matter". Dark matter could be in a variety of forms: unobservable stars, supersymmetry concepts, and particles (mostly proposed are axions and WIMPs) [1]. Axions came from a discussion of a different topic, the quantum chromodynamics [2].

It was only after its undetectability and predicted abundance surfaces that this became a potential dark matter candidate, as it shares qualities with observable traits in dark matter that is mathematically proven. The topic of Axions is so compelling that discovery could happen at any time, as it is one of the most researched and discussed disciplines, which has been mathematically verified. Yet it is evident that there is still much more progress needed to detect the axion.

This paper will introduce the history of the axion, detection methods and results as well as the future progress of it. The rest part of the paper is organized as follows. The Sec. 2 will explain the history of the axion and theories that it originates from. Subsequently, the Sec. 3 will introduce several detection principles of the axion. Afterwards, the Sec. 4 will establish some recent detection results based on advanced approaches. Eventually, a brief summary is given in Sec. 5.

2. Basic descriptions of the axion

The axion is a hypothetical particle used to solve the strong-CP problem and theorized to be a candidate for dark matter. The Strong-CP problem surfaces from quantum chromodynamics, where the QCD Lagrangian contains:

$$L_{QCD} \supset \bar{\theta} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{a\mu\nu} \quad (1)$$

If Θ is assumed to be around the value of 1, the electric dipole of the neutron would be calculated to be around 10^{10} times larger than the experimental value. Therefore, the value of $\bar{\theta}$ must be smaller than 10^{-10} , but there is no explanation for this phenomenon, and therefore it is generally believed that a new theory could establish why $\bar{\theta}$ is this incredibly small value. A possible solution to this is a new $U(1)$ symmetry that is spontaneously broken that could lead $\bar{\theta}$ to be reduced to near-zero values, as published by Peccei and Quinn [1, 3],

$$V(\Phi_{PQ}) = \frac{\lambda}{4} (|\Phi|^2 - f_{PQ}^2)^2 \quad (2)$$

This leads to Wilczek and Weinberg's prediction [4] that this could lead to a new Nambu-Goldstone boson called the axion. The axion has a small mass since larger masses could lead to rapid meson decays and larger scales could lead to the cooling of stars. The small scale of the axion, as well as its predicted stability, would mean that sufficient quantities of axions could contribute to dark matter. Its density relative to the critical density of the universe is given by this term:

$$\Omega_a \approx \left(\frac{6\mu eV}{m_a} \right)^{\frac{7}{6}} \quad (3)$$

Thus, an axion would only need to be around $20\mu eV$ to sufficiently account for all of the dark matter observed.

However, to obtain sufficient quantities, one must propose a method that axions formed. Firstly, axions could be produced through pure energy (thermal axions) [5], however, such few would have been produced that it would've made only a small impact on dark matter. Another more plausible solution [6-8] is that $\bar{\theta}$ had a higher value previously when the universe was warmer, and as the universe cooled $\bar{\theta}$ reached its small scale. When it is driven towards this small scale, the energy stored in the Peccei-Quinn field transfers into axion production, and the amount estimated to be produced through this method is comparable to the amount of dark matter observed. It has also been proposed that $\bar{\theta}$ being different values in different regions of the universe could lead to axionic strings or domain walls, which the decay of these unequal areas of space could lead to similar axion production to the unequal $\bar{\theta}$ through time theory [9]. Cosmological inflation occurring before the symmetry breaks is required as inflation would erase the axion-forming strings and domain walls. However, to prove that the $U(1)_{QP}$ (and subsequently axionic dark matter) even exists, there must be empirical proof that such a particle can be found.

3. The detection principle of the axion

Current experiments fall into one of two broad categories in attempting to detect the axion. The first is to detect relic axions, a current example is the ADMX experiment. This kind of experiments often use the principle of RF-cavity. This works through detecting axions by monitoring axions' resonant conversion to photons, and a high-Q cavity with a magnetic field inside is needed to achieve detection. The transverse magnetic field of a solenoid is swept in a near 0K cavity and excess power output is monitored for axion conversions.

Thus, a strong magnetic field could allow energy to be released from the axion field to the cavity, creating a spike in radio frequency, thus hinting at the possibility of axions. The first generation of experiments to achieve this is The Rochester-Fermilab-Brookhaven experiment and the University of Florida Experiment [10]. To be specific, a tuning sapphire rod was inserted into a high-purity copper cavity, and an electromagnet with a peak field of 8.5 T was used. The operating temperature lowered was 4.2K. Axions were found through a peak in cavity output of power, above standard average power. Each frequency range was swept twice and both had to issue a peak for axions to be considered. However, no peaks were axion candidates after re-examination.

The University of Florida experiment was another noteworthy first-generation experiment at a small scale. This used an 8.6T electromagnet, along with the copper cavity, and was operated at 2.2K.

A dielectric rod was responsible for the large part of the tuning and finer tuning was done through a smaller tuning rod. This was using a 32-bin power spectrum at 1kHz resolution generated for subspectra. Peaks above the mean of 2σ are rescanned up to 4 times, but none ended up being suspected axions.

The Axion Dark matter experiment (ADMX) is placed on a larger scale than the previous experiments and searched for axions at a $1.3\mu\text{eV} - 13\mu\text{eV}$ range. This involved a stainless-steel cavity along with two aluminum oxide or copper tuning rods moving between the edge and the center of the cavity to tune the experiment in the range of 300-900MHz. A signal from an electric field is amplified, then filtered down to a 35kHz signal 50kHz in bandwidth at audio frequency. A Fourier transform tool calculates 400 channels each with a width of 125Hz. A fast Fourier transform then reads and calculates data 0.02Hz in channel width, and peaks resulting from axions are observed. The experiment has previously measured no axions in the $2.1\text{--}3.3\mu\text{eV}$, excluding axions of that mass [11]. More recently, axions of mass $3.3\text{--}4.2\mu\text{eV}$ have also been excluded [12].

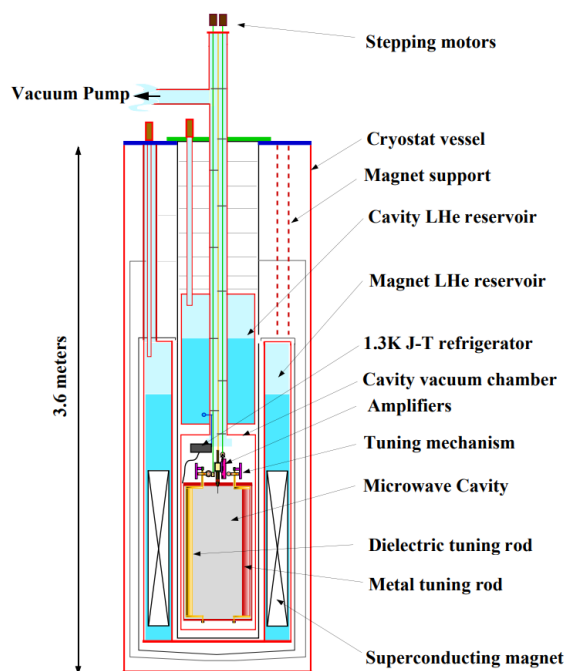


Figure 1. Diagram of the ADMX search apparatus [13].

Creating an artificial cavity for axion search may not guarantee a strong enough magnetic field or enough axions present in order to fully observe axion-photon conversion and measure its results. Thus, searches have begun around cosmological areas with extremely strong magnetic fields. The Green Bank and Effelsberg Radio Telescope Search attempts to determine a spectral peak from hypothetical sources of axion-photon conversion, being the center of the Milky Way and around two nearby neutron stars [14]. These experiments have the benefit of observing a magnetic strength of around 100T, ten times stronger than that of cavity laboratory experiments. Preliminary studies have detected no axions within the $5\text{--}11\mu\text{eV}$ (1GHz) range, yet the team theorize that further observations could be applied to detect and verify axions of different mass ranges.

Solar axions present yet another option for axion detection. One famous example is CAST, similar to cavity experiments, uses 9T magnets operated at cryogenic temperatures. Detectors on the ends of the magnet detect axion photon transformations and the instrument itself aligns with the sun to look for the transformations. Through CAST, axions have been set an upper bound of $2.17 \times 10^{-10} \text{ GeV}^{-1}$ in the range $0.02 < m_a < 0.26 \text{ eV}$ [15].

4. Current results

Up to now, the axion has not yet had any evident proof that it had been discovered, but humans are very close to finding actual evidence on whether this particle exists. Just near the end of 2021, the ADMX collaboration published a paper eliminating axions from the entire 3.3-4.2 μeV range [16], a follow-up from the 2018 search of masses between 2.66 and 2.81 μeV [17], and the 2020 results of exclusion from the 2.81-3.31 μeV range.

On the other hand, the CAST helioscope provided direct results for 14.4 keV solar axions from Iron-57 [18] and MeV-range axions from transitions of Lithium-7 and Helium-3 [19]. It has also been the basis of experience of further hypothetical improvement, e.g., helioscopes benefitting from a much larger magnet aperture, and requiring focusing optics to accomplish that, reducing the signal-noise ratio and thus making the helioscope more sensitive to potential axion signals.

On the radio telescope search, along with the recent demonstration results from neutron stars [14], a new cosmological axion search has been proposed, stating the dwarf spheroidal galaxies may release signals that indicate axion coupling [20]. This method may increase detection sensitivity by 2-3 times compared to current searches. The potential future of cosmological axions is yet to be seen.

5. Conclusions

In summary, this article has summarized key methods of discovering axions, as well as explaining some of the discoveries made through these methods. Currently, magnet searches (cavity and helioscope) remain the dominant type of search that is running, yet new methods, e.g., cosmological radio detection, have just been verified and are being developed. As third-generation detectors are continuing work and fourth-generation detectors are being proposed and developed, the axion mass and frequency range continually decrease.

The future of axion detection remains to be attributed to searching a variety of frequencies until an example is found or a counter-proof is stated. However, axion search is still in its early stages that there cannot be a conclusion formed from the current results. Yet, as the axion's parameters become increasingly restricted, the simplicity of finding either of those options increases significantly. Nevertheless, reaching more frequencies with the available methods is increasingly gaining difficulty, and the largest limiting factor on axions is the extensive number of frequencies and each frequency range has different masses to search. Thus, finding consistent proof is extensively difficult. A larger magnetic field could be significantly important to more efficient searches in both cavity and helioscope developments, and radio searches would need more experience, instrument sensitivity, and detection check reliability to be effective. In the end, axion detection development shifts between improving current methods and searching for new methods of detection. A significant development is a shift from CAST to IAXO, a designed telescope that is prototyped and about to be tested as babyIAXO, a new helioscope originating from experience with CAST. Radio telescope searches have been proposed to work with dwarf galaxies, yet that has remained untested but proven to be significantly more effective.

Overall, these results and future prospects offer guidelines for a conclusion of whether axions exist. After this conclusion has been reached, more questions would appear that need further and further verification. These relate to the concept of dark matter, symmetry-breaking particles, and the standard model itself. It is these developments that build to answer the question of the true nature of incomprehensible events in the universe.

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