Axion Hunting at the Turn of the Millenium

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The status of several current and proposed experiments to search for galactic dark-matter and solar axions is reviewed in the light of astrophysical and cosmological limits on the Peccei-Quinn scale.

1. INTRODUCTION

Twenty years after their inception [1], axions [2] remain a popular solution to the strong CP problem as well as a candidate for the cold dark matter of the universe. As a research topic, axions and related issues seem to have retained much of their appeal (Fig. 1), and indeed 1998 could yet become the year with the largest number of axion research papers ever. All that is missing in this flurry of activities is the appearance of the main character, the axion itself, which thus far has eluded all attempts at a discovery.

In the framework of “invisible axion” models where the scale \( f_a \) at which the Peccei-Quinn symmetry is spontaneously broken could be arbitrarily large, and where axions therefore could be arbitrarily weakly interacting, previous experiments really did not stand a plausible chance of finding these particles. Therefore, the most exciting recent development is that there are now two full-scale search experiments for galactic dark-matter axions in operation which do have a realistic discovery potential. Also, there is a surprising amount of activity around the search for solar axions which is beginning to become competitive with astrophysical limits. The chance of an actual discovery, however, appears more remote than in the search for galactic axions.

2. ASTROPHYSICAL LIMITS

Axion models are characterized by the Peccei-Quinn scale \( f_a \), or equivalently by the axion mass \( m_a = 0.60 \text{ eV} \left( 10^7 \text{ GeV}/f_a \right) \). Several astrophysical lower limits on \( f_a \) (Fig. 2) are based on the requirement that the axionic energy loss of stars, notably globular-cluster stars or the core of supernova (SN) 1987A, is not in conflict with certain observed properties of these objects [4,5]. These limits imply \( m_a \lesssim 10^{-2} \text{ eV} \) or \( f_a \gtrsim 10^9 \text{ GeV} \), indicating that axions, if they exist, are both extremely light and very weakly interacting.

These limits on the axion mass are indirectly derived from limits on the coupling strength to photons (globular cluster stars) and nucleons (SN 1987A). The axionic two-photon interaction is \( \mathcal{L}_{\text{int}} = g_{\alpha \gamma} E \cdot B a \), where

\[
g_{\alpha \gamma} = \frac{3\alpha}{8\pi f_a} \frac{m_a/\text{eV}}{0.69 \times 10^{10} \text{ GeV}} \xi
\]
\[ \xi \equiv \frac{4}{3} \left( \frac{E}{N} - 1.92 \pm 0.08 \right). \quad (2) \]

\( E/N \) is a model-dependent ratio of small integers. In the DFSZ model or GUT models one has \( E/N = 8/3 \), corresponding to \( \xi \approx 1 \), and it is this case for which the globular-cluster limit

\[ g_{a\gamma} \lesssim 0.6 \times 10^{-10} \text{ GeV}^{-1} \quad (3) \]

is shown in Fig. 2 as a limit on the axion mass, \( m_a \lesssim 0.4 \text{ eV} \). The axion-photon coupling for a variety of models has recently been compiled [6]; often-discussed cases are \( E/N = 8/3 \) (DFSZ) or \( E/N = 0 \) (KSVZ).

However, models with \( E/N = 2 \) can be constructed, allowing for a near or complete cancellation of \( g_{a\gamma} \). In this case there is no globular-cluster limit on \( m_a \) or \( f_a \) so that there is a small window for \( m_a \) near 10 eV. It was recently shown [7] that in this range axions could be a cosmological hot dark matter component which certain structure-formation arguments suggest in addition to the main cold dark matter.

In the early universe, axions are thermalized if \( f_a < \sim 10^8 \text{ GeV} \) [8], a region excluded by the stellar-evolution limits except for the special case \( E/N = 2 \). If inflation occurred after the Peccei-Quinn symmetry breaking or if \( T_{\text{reheat}} < f_a \), the “misalignment mechanism” [9] leads to a contribution to the cosmic critical density of \( \Omega_a h^2 \approx 1.9 \times 3^{\pm 1} \left( 1 \text{ m eV}/m_a \right)^{1.175} \Theta_i^2 F(\Theta_i) \) where \( h \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\).

The function \( F(\Theta) \) with \( F(0) = 1 \) and \( F(\pi) = \infty \) accounts for anharmonic corrections to the axion potential. Because the initial misalignment angle \( \Theta_i \) can be very small or very close to \( \pi \), there is no real prediction for the mass of dark-matter axions even though one would expect \( \Theta_i^2 F(\Theta_i) \sim 1 \).

A possible fine-tuning of \( \Theta_i \) is limited by inflation-induced quantum fluctuations which in turn lead to temperature fluctuations of the cosmic microwave background [10,11]. In a broad class of inflationary models one thus finds an upper limit to \( m_a \) where axions could be the dark matter. According to the most recent discussion [11] it is about \( 10^{-3} \text{ eV} \) (Fig. 2).

If inflation did not occur at all or if it occurred before the Peccei-Quinn symmetry breaking with \( T_{\text{reheat}} > f_a \), cosmic axion strings form by the Kibble mechanism [12]. Their motion is damped.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Astrophysical and cosmological exclusion regions (hatched) for the axion mass \( m_a \) or equivalently, the Peccei-Quinn scale \( f_a \). An “open end” of an exclusion bar means that it represents a rough estimate; its exact location has not been established or it depends on detailed model assumptions. The globular cluster limit depends on the axion-photon coupling; it was assumed that \( E/N = 8/3 \) as in GUT models or the DFSZ model. The SN 1987A limits depend on the axion-nucleon couplings; the shown case corresponds to the KSVZ model and approximately to the DFSZ model. The dotted “inclusion regions” indicate where axions could plausibly be the cosmic dark matter. Most of the allowed range in the inflation scenario requires fine-tuned initial conditions. In the string scenario the plausible dark-matter range is controversial as indicated by the step in the low-mass end of the “inclusion bar.”}
\end{figure}
primarily by axion emission rather than gravitational waves. After axions acquire a mass at the QCD phase transition they quickly become nonrelativistic and thus form a cold dark matter component. The axion density such produced is similar to that from the misalignment mechanism for $\Theta_i = \mathcal{O}(1)$, but in detail the calculations are difficult and somewhat controversial between two groups of authors [13,14]. Taking into account the uncertainty in various cosmological parameters one arrives at a plausible range for dark-matter axions as indicated in Fig. 2.

3. DARK MATTER SEARCH

If axions are the galactic dark matter one can search for them in the laboratory. The detection principle is analogous to the Primakoff process for neutral pions, i.e. the two-photon vertex allows for axion transitions into photons in the presence of an external electromagnetic field (Fig. 3). Dark matter axions would have a mass in the $\mu$eV to meV range. As they are bound to the galaxy their velocity dispersion is of order the galactic virial velocity of around $10^{-3}c$ so that their kinetic energy is extremely small relative to their rest mass. Noting that a frequency of 1 GHz corresponds to 4 $\mu$eV, the Primakoff conversion produces microwaves. Galactic axions are nonrelativistic while the resulting photons are massless so that the conversion involves a huge momentum mismatch which can be overcome by looking for the appearance of excitations of a microwave cavity rather than for free photons.

An axion search experiment thus consists of a high-$Q$ microwave resonator placed in a strong external magnetic field ("axion haloscope" [15]).

The microwave power output of such a detector on resonance is [15,16]

\[
P \approx 0.4 \times 10^{-22} \text{ Watts} \left( \frac{V}{0.2 \text{ m}^3} \right) \times \left( \frac{B}{7.7 \text{ Tesla}} \right)^2 \left( \frac{C}{0.65} \right) \left( \frac{Q}{10^5} \right) \times \left( \frac{\rho_a}{300 \text{ MeV cm}^{-3}} \right) \left( \frac{m_a}{1 \mu\text{eV}} \right),
\]

where $V$ is the cavity volume, $B$ the applied magnetic field, $C$ a mode-dependent form factor which is largest for the fundamental $T_{010}$ mode, $Q$ the loaded quality factor, and $\rho_a$ the local galactic axion density. If $m_a$ were known it would be easy to detect galactic axions with this method—one may verify or reject a tentative signal by varying, for example, the applied magnetic field strength. Therefore, it would be hard to mistake a background signal for dark-matter axions. The problem is, of course, that $m_a$ is not known so that one needs a tunable cavity, stepping its resonance through as large a frequency range as possible and to look for the appearance of microwave power beyond thermal and amplifier noise.

Two pilot experiments of this sort [17,18] have excluded the range of axion masses and coupling strengths indicated in Fig. 4. For a standard local halo density of about 300 MeV cm$^{-3}$ they were not sensitive enough to reach realistic axion models. Two current experiments with larger cavities, however, have the requisite sensitivity.

The U.S. Axion Search [19] uses conventional microwave amplifiers (HEMTs) which limit the useful cavity temperature to about 1.4 K. A first exclusion slice has been reported [19]—see Fig. 4 where the ultimate search goal is also shown. In a next-generation experiment one would use SQUID amplifiers, increasing the sensitivity to encompass more weakly coupled axion models.

The Kyoto experiment CARRACK [20], on the other hand, uses a completely novel detection technique, based on the excitation of a beam of Rydberg atoms which passes through the cavity. This is essentially a counting method for microwaves which does not require a (noisy) amplifier so that one can go to much lower physical cavity temperatures. This enhances the sensitiv-
ity and also allows one to use smaller cavity volumes and thus to search for larger axion masses. With the current setup a narrow slice of axion masses is to be searched (Fig. 4), while a new apparatus currently under construction will allow for the coverage of a much broader mass range.

The search goals of these second-generation experiments covers the lower range of plausible axion masses in the framework of the cosmological string-scenario of primordial axion production, and a significant portion of the plausible mass range in the inflation scenario if one does not wish to appeal to fine-tuned initial conditions of the axion field (Fig. 2). If these experiments fail to turn up axions, it would be extremely important to extend the experimental search into a regime of larger masses toward the meV scale. This would require new detection methods.

Figure 4. Limits on galactic dark matter axions from the University of Florida (UF) [17] and the Rochester-Brookhaven-Fermilab (RBF) [18] pilot experiments and the recent limit from the U.S. Axion Search [19]. Also shown are the search goals for the U.S. experiment employing HEMTs for microwave detection, for a next generation experiment using SQUIDs, the 1998 search goal for CARRACK I (Kyoto) and for CARRACK II, both using Rydberg atoms.

4. SOLAR AXIONS

4.1. Helioscope Method

Another classic way to search for axions is to use the Sun as a source and to attempt an experimental detection of this flux. Unfortunately, the experimental sensitivity typically lies in an $f_a$ range which is already excluded by the stellar-evolution limits of Fig. 2 so that one needs to appeal to large systematic uncertainties of the astrophysical bounds in order to hope for a positive detection. On the other hand, such experiments can provide independent limits on the parameters of axions and similar particles even if the chances for a positive detection seem slim.

In the so-called “helioscope” method [15,21] one again uses the Primakoff effect (Fig. 3) by pointing a long and strong dipole magnet toward the Sun. The axions produced in the hot interior of the Sun would have typical energies of a few keV and would thus convert into x-rays which can then be picked up by a detector at the downstream end of the magnet. A pioneering experiment was conducted several years ago [22], but detecting axions would have required a flux larger than what is compatible with the solar age.

Recently, first results were reported from the Tokyo axion helioscope where a dipole magnet was gimballed like a telescope so that it could follow the Sun and thus reach a much larger exposure time [23]. The limit on the axion-photon coupling of $g_{a\gamma} < 6 \times 10^{-10} \text{ GeV}^{-1}$ is less restrictive than the globular-cluster limit of Eq. (3), but more restrictive than the solar-age limit of $25 \times 10^{-10} \text{ GeV}^{-1}$ [24], and also more restrictive than a recent solar limit of about $10 \times 10^{-10} \text{ GeV}^{-1}$ which is based on helioseismological sound-speed profiles of the Sun [25].

Another helioscope project with a gimballed dipole magnet was begun in Novosibirsk several years ago [26], but its current status has not been reported for some time. A very intriguing project at CERN would use a decommissioned LHC test magnet that could be mounted on a turning platform to achieve reasonably long times of alignment with the Sun [27]. With this setup one would begin to compete with the globular cluster limit of Eq. (3).
The helioscope approach is bedevilled by the same problem which requires the use of a resonant cavity in the galactic axion search, viz. the momentum mismatch between (massive) axions and (massless) photons in the Primakoff process. For example, the above limit of the Tokyo helioscope applies only for \( m_a < \sim 0.03 \text{ eV} \), implying that the “axion-line”—the relationship between \( g_{a\gamma} \) and \( m_a \) of Eq. (1)—is not even touched, i.e. the limit applies only to particles which for a given \( g_{a\gamma} \) have a smaller mass than true axions.

In a next step one will fill the transition region with a pressurized gas, giving the photon a dispersive mass in order to overcome the momentum mismatch [21]. As in the cavity experiments, this is a resonant method (the match is only good for a small range of axion masses) so that one needs to take many runs with varying gas pressure to cover a broad \( m_a \) range. In this way it is hoped to eventually cut across the axion line. The same approach would have to be used for the proposed CERN helioscope.

4.2. Bragg Diffraction

An alternative method to overcome the momentum-mismatch problem in the Primakoff process is to use an inhomogeneous external electromagnetic field which has strong Fourier components for the required momentum transfer. It has been suggested to use the strong electric fields of a crystal lattice for this purpose [28]. In practice one can use germanium detectors which were originally built to search for neutrinoless double-beta decay and for WIMP dark matter. The Ge crystal serves simultaneously as a “transition agent” between solar axions and x-rays and as an x-ray detector. The beauty of this method is that one can piggy-back on the existing Ge experiments, provided one determines the absolute orientations of the crystal axes relative to the Sun because the expected conversion rate depends on the lattice orientation in analogy to Bragg diffraction.

A first limit produced by the SOLAX Collaboration [29] of \( g_{a\gamma} < 30 \times 10^{-10} \text{ GeV}^{-1} \) is not yet self-consistent as the properties of the Sun already require \( g_{a\gamma} > 10 \times 10^{-10} \text{ GeV}^{-1} \). However, the limit easily cuts across the axion line (it applies for \( m_a < \sim 1 \text{ keV} \)), and no doubt it can be significantly improved as \( \beta\beta \) and WIMP search experiments grow in size and exposure time.

4.3. Mössbauer Absorption

If axions essentially decouple from photons for \( E/N = 2 \) models, and if they also do not couple to electrons at tree level, there is a small window of allowed axion masses in the neighborhood of 10 eV (Fig. 2). One can search for axions in this range by appealing only to their coupling to nucleons. The Sun would emit a nearly monochromatic 14.4 keV axion line from thermal transitions between the first excited and ground state of \( ^{57}\text{Fe} \) which is quite abundant in the Sun. In the laboratory one can then search for the axion absorption process which would give rise to x-rays as \( ^{57}\text{Fe} \) de-excites [30]. Of course, the Doppler broadening of the line in the Sun of about 5 eV is much larger than the natural line width of order 10 neV so that the Mössbauer absorber in the laboratory picks up only a small fraction of the total flux. Even so it may be possible to detect or significantly constrain solar axions in an experiment which is now in preparation in Tokyo [31]. A recent pilot experiment by another group did not have enough sensitivity to find axions in the above window [32].

5. SUMMARY

A surprisingly large number of experiments to search for solar and galactic dark-matter axions have recently emerged. The U.S. Axion Search as well as the Kyoto experiment CARRACK have now reached a sensitivity where they could realistically detect galactic dark matter axions, surely an important step because the role of axions as an alternative to supersymmetric particles as a cold dark matter candidate is perhaps the most important aspect of the continuing interest in axion physics. As it stands, axion dark matter could well show up before the millenium ends!

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