Axion Searches

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Bethe Forum:
Axions and the Low Energy Frontier
Bonn, 7–18 March, 2016
the cavity haloscope
the axion helioscope
shining light through walls
telescope searches
NMR methods
axion mediated long-range forces
LC circuit
atomic transitions
Axion dark matter is detectable

\[ \mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E} \cdot \vec{B} \]

\[ \vec{E}_{TM\ 001} \]

\[ \vec{B}_0 \]
\[ h\nu = m_a c^2 \left(1 + \frac{1}{2} \beta^2 \right) \]

\[ \beta = \frac{v}{c} \quad 10^{-3} \]

\[ Q_a \quad 10^6 \]
Axion Dark Matter eXperiment

see talk by G. Carosi

Magnet with Insert (side view)

- Stepping motors
- Liquid helium
- Amplifier, refrigerator
- Tuner
- Tuning rods
- Superconducting magnet
  8T, 6 tons

Pumped LHe → T ~ 1.5 k

Magnet

8 T, 1 m × 60 cm Ø
ADMX enters its second generation

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ADMX-HF at Yale

- Multi-post system that consists of 3 rotors connected on common axis and 3 stators.
- 4” ID cavity: Six 0.5” diameter rods
- Freq. span 4.7-5.6 GHz
Gen 2 ADMX sensitivity

Will scan the lower-mass decade at or below DFSZ sensitivity
Cavity limits, present and anticipated
Dish antenna

\[ P \sim |E|^2 A_{\text{dish}} \sim 10^{-26} \left( \frac{B}{5T} \frac{c\gamma}{2} \right)^2 \frac{A_{\text{dish}}}{1 \text{ m}^2} \text{ Watt} \]

D. Homs, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo & A. Ringwald, 2013

B. Doebrich et al. ,2014
Axion to photon conversion in a magnetic field

\[ p(a \leftrightarrow \gamma) = \left( \frac{\alpha g_{\gamma}}{\pi f_a} \right)^2 B_0^2 \left( \sin \frac{q_z L}{2q_z} \right) \]

with \[ q_z = \frac{m_a^2 - \omega_{pl}^2}{2E_a} \]

Theory
- P. S. '83
- L. Maiani, R. Petronzio and E. Zavattini '86
- K. van Bibber et al. '87
- G. Raffelt and L. Stodolsky, '88
- K. van Bibber et al. '89

Experiment
- D. Lazarus et al. '92
- R. Cameron et al. '93
- S. Moriyama et al. '98, Y. Inoue et al. '02
- K. Zioutas et al. 04
- E. Zavattini et al. 05
Tokyo Axion Helioscope

- refrigerators
- superconducting magnet
- PIN photodiodes
- vacuum vessel
- turntable
- gas container
- solar axions
Primakoff conversion of solar axions in crystals on Earth

\[ E_a = \text{few keV} \]

Bragg scattering on crystal lattice

Solax, Cosme '98
Ge

DAMA '01
Nal (100 kg)
Changes every day
Detecting solar axions using Earth’s magnetic field

by H. Davoudiasl and P. Huber

hep-ph/0509293

For axion masses \( m_a \leq 10^{-4} \text{ eV} \), a low-Earth-orbit x-ray detector with an effective area of \( 10^4 \text{ cm}^2 \), pointed at the solar core, can probe down to \( M_a \leq 10^{11} \text{ GeV} \), in one year.

\[
(L_{a\gamma\gamma} = \frac{1}{M_a} a \vec{E} \cdot \vec{B})
\]
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services
Linearly polarized light in a constant magnetic field

\[ \overrightarrow{B}_0 \]

\[ \overrightarrow{A} \]
\[
A'_{\parallel} = A_{\parallel} \left(1 - \frac{1}{2} p - i\psi\right)
\]
\[
A'_{\perp} = A_{\perp}
\]
\[
p = 4 \frac{B_0^2 \omega^2}{M_a^2 m_a^4} \sin^2 \left(\frac{m_a^2 L}{4\omega}\right)
\]
\[
\alpha = -\frac{1}{4} p \sin(2\theta)
\]
\[
\frac{\alpha g_{\gamma}}{\pi f_a} = g_{\alpha\gamma} = \frac{1}{M_a}
\]

Rotation
Rotation and Ellipticity

Maiani, Petronzio and Zavattini, 1986

\[ A'_{\parallel} = A_{\parallel} (1 - \frac{1}{2} p - i\psi) \]

\[ A'_{\perp} = A_{\perp} \]

\[ p = 4 \frac{B_0^2 \omega^2}{M_a^2 m_a^4} \sin^2 \left( \frac{m_a^2 L}{4\omega} \right) \]

\[ \psi = 2 \frac{B_0^2 \omega^2}{M_a^2 m_a^4} \left[ \frac{m_a^2 L}{2\omega} - \sin \left( \frac{m_a^2 L}{2\omega} \right) \right] \]
Shining light through walls

\[ \text{rate} \propto \frac{1}{f_a^4} \]

K. van Bibber et al. '87
A. Ringwald '03
R. Rabadan,
A. Ringwald and
C. Sigurdson '05
P. Pugnat et al. '05
C. Robilliard et al. '07
A. Afanasev et al. '08
A. Chou et al. '08
K. Ehret et al. '10
Limits from "light through wall" axion searches
Resonantly Enhanced Axion-Photon Regeneration

F. Hoogeveen (1996); P.S., D. Tanner and K. van Bibber (2007)
ALPS II at DESY

A. Lindner et al.

Expected sensitivity: \( 2 \cdot 10^{-11} \text{ GeV}^{-1} \)
PVLAS Laser experiments
Solar search HB Stars
Resonantly enhanced photon regeneration

$m_a$ (eV)

g_{a\gamma\gamma}$ (GeV$^{-1}$)

Microwave cavity dark matter searches
Axion models

PVLAS

Microwave cavity dark matter searches
Axion models

Resonantly enhanced photon regeneration

Solar search HB Stars

Laser experiments
Macroscopic forces mediated by axions

\[ L_{a\bar{f}f} = g_f \frac{m_f}{f_a} \bar{a} f (i\gamma_5 + \theta_f) f \]

forces coupled to the \( f \) spin density

forces coupled to the \( f \) number density

background of magnetic forces

\[ \mathcal{O}_f \equiv 10^{-17} \]

Theory:
J. Moody and F. Wilczek '84

Experiment:
A. Youdin et al. '96
W.-T. Ni et al. '96
NMR with long range axion field

A. Arvanitaki and A. Geraci, 2014

\[ H_{\text{int}} = \frac{g_f m_f \theta_f}{f_a} a(x) \]

the rotating mass on the left produces an oscillating axion field

\[ H_{\text{int}} = \frac{g_f m_f}{f_a} \nabla a(x) \cdot \vec{\sigma} \]

the oscillating axion field is an effective magnetic field in an NMR experiment

\[ \omega = \gamma_N B_0 \]
Macroscopic forces mediated by axions

\[ L_{a f f} = g_f \frac{m_f}{f_a} a \bar{f} (i\gamma_5 + \theta_f) f \]

forces coupled to the \( f \) spin density

forces coupled to the \( f \) number density

background of magnetic forces

Theory:
J. Moody and F. Wilczek '84

Experiment:
A. Youdin et al. '96
W.-T. Ni et al. '96

\( \mathcal{G}_f \cong 10^{-17} \)
Wire array detector

- pass currents through superconducting wires
- produce \( \vec{B} = \hat{x}B_0 \cos(qz) \)
- enhance the quality factor by placing the array in a confocal resonator
- tune to \( q = m_a \)

see J. Redondo’s talk

PS, D. Tanner and Y. Wang, 1992
G. Rybka, A. Wagner et al. 2004
Recent proposals for axion dark matter detection

• Using NMR techniques
  P. Graham & S. Rajendran '13
  D. Budker et al. '13

• Using LC circuit in a strong magnetic field
  PS, N. Sullivan & D. Tanner '13

• Using atomic transitions
  PS, '14
NMR techniques

P. Graham, S. Rajendran; D. Budker, M. Ledbetter, A. Sushkov

\[ g_{aNN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N \quad \implies \quad H_N \supset g_{aNN} \nabla a \cdot \vec{S}_N \]
the axion field induces an oscillating nuclear
electric dipole moment

\[ d_e \sim 10^{-16} \ e \ cm \ \frac{a(x)}{f_a} \]
FIG. 2: Estimated constraints in the ALP parameter space in the EDM coupling $g_A$ (where the nucleon EDM is $d_n = g_A a$ and $a$ is the local value of the ALP field) vs. the ALP mass [17]. The green region is excluded by the constraints on excess cooling of supernova 1987A [17]. The blue region is excluded by existing, static nuclear EDM searches [17]. The QCD axion is in the purple region, whose width shows the theoretical uncertainty [17]. The solid red and orange regions show sensitivity estimates for our phase 1 and 2 proposals, set by magnetometer noise. The red dashed line shows the limit from magnetization noise of the sample for phase 2. The ADMX region shows what region of the QCD axion has been covered (darker blue) [34] or will be covered (lighter blue) [59, 60]. Phase 1 is a modification of current solid state static EDM techniques that is optimized to search for a time varying signal and can immediately begin probing the allowed region of ALP dark matter. To calculate limits from previous (static) EDM searches as well as our sensitivity curves, we assume the ALP is all of the dark matter.
Axion dark matter detection using an LC circuit

PS, D. Tanner and N. Sullivan, 2013

\[ \mathbf{\nabla} \times \mathbf{B}_a = \mathbf{j}_a \equiv g_{a\gamma\gamma} \mathbf{B}_0(\mathbf{x}) \partial_t a(\mathbf{x}, t) \]

circuit should be cooled to milli-Kelvin temperatures
Axion dark matter detection using atomic transitions

\[ L_{a\bar{f}f} = -\frac{g_f}{2f_a} \partial_\mu a(x) \bar{f}(x) \gamma^\mu \gamma_5 f(x) \]

\[ H_{a\bar{f}f} = +\frac{g_f}{2f_a} \vec{\sigma}_f \cdot \vec{\nabla}a \]

- tune using the Zeeman effect
- use laser techniques to count axion induced transitions
- must cool to milli-Kelvin temperatures
cavities

atomic transitions
Conclusions

• Axion dark matter is well motivated

• Axion dark matter can be detected over most of the plausible mass range