Overview of axions, axion-like particles

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The University of Sheffield
The Strong CP problem

Standard model symmetry group is $SU(3) \times SU(2) \times U(1)$

\[ \mathcal{L}_{\text{CPV}} = \frac{1}{32\pi^2} (\Theta + \text{arg } \det M) E_{QCD} \cdot B_{QCD} \]

Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM $< 10^{-26}$ e-cm.

Even simple dimensional arguments show that this is unexpected. Why do the intricate SU(3) QCD interactions conserve CP when the less intricate SU(2) QED interactions do not? This is the strong CP problem.
The Peccei Quinn Mechanism

Axions and ALPs

\[ \mathcal{L}_{\text{CPV}} = \overline{\Theta} E \cdot B \]

About Minimum: small curvature (hence small mass) with respect to \( \overline{\theta} = \text{arg}(\phi) \) large curvature (hence large mass) with respect to \( \text{Re}(\phi) \)

Axion DOF

ALP DOF
Axion Phenomenology

The axion is a pseudoscalar; has the same quantum numbers as the $\pi^0$, and the same interactions, but with strengths scaled to the axion mass.

$$f_{PQ} \propto \frac{1}{m_a}$$

$$\Omega_{PQ} \propto \frac{1}{m_a^6}$$
Axion Sources for Lab Searches

LAB
- PVLAS
- ALPS/ALPS2*
- OSQAR
- CASCADE*
- ARIADNE*

HALO
- ADMX*
- X3*
- CAPP/CULTASK*
- CASPER
- FUNKY
- MADMAX

SUN
- CAST
- IAXO*
The interaction with fermions $f$ has derivative form and is invariant under a shift $\phi_A \to \phi_A + \phi_0$ as behooves a NG boson,\( L_{\text{Aff}} = C_f^2 \bar{f} \gamma^\mu \gamma^5 f \partial_\mu \phi_A. \)

Here, $\bar{f} f$ is the fermion field, $m_f$ its mass, and $C_f$ a model-dependent coefficient. The dimensionless combination $g_{\text{Aff}} \equiv C_f m_f / f_A$ plays the role of a Yukawa coupling and $\alpha_{\text{Aff}} \equiv g_{\text{Aff}}^2 / 4\pi$ of a "fine-structure constant." The often-used pseudoscalar form $L_{\text{Aff}} = -i (C_f m_f / f_A) \bar{f} \gamma^5 f \phi_A$ need not be equivalent to the appropriate derivative structure, for example when two NG bosons are attached to one fermion line as in axion emission by nucleon bremsstrahlung [22].

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$$C_e = \cos^2 \beta'$$

Resonant Cavity Detectors - ADMX

• Large Scale Experiment running 1995–present.
• Excluded KSVZ axions with mass 1.9–3.6 μeV (460–860 MHz).
• Uses DC SQUID amplifiers.
• Currently commissioning dilution refrigerator upgrade.
• Present search region is 3.6–10 μeV.

\[
P_\gamma = \left( \frac{g_{\alpha\gamma\gamma}^2 \rho_{a} \hbar^2}{m_{a}^2 c} \right) \frac{1}{2\pi c^2 \varepsilon_0 B_0^2 V f_{010} \nu_a Q}
\]

High-resolution channel for non-thermalized axions
• Improved search sensitivity
• “Movie” of galactic formation

Integration: Resolution:
- Maxwellian
- Fine-Structure

\( \Delta E/E \sim 10^{-17} \)

\( \Delta E/E \sim 10^{-6} \)
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FIG. 3. Our exclusion limit at 90% confidence. The light green shaded region is a 1 error band. The large notch around 5.704 GHz is the result of cutting spectra around a previously unidentified TE mode. The narrow notches correspond to frequencies where synthetic axion signals were injected in one of the scans. The inset shows this work (green) together with previous cavity limits from ADMX (magenta, [9]) and early experiments at Brookhaven (RBF, blue, [20]) and the University of Florida (UF, cyan, [21]). The axion model band [14] is shown in yellow.

and subtracting 1 we obtain a set of Gaussian white noise spectra representing excess power which we call the "processed spectra." In the absence of axion conversion each bin in each processed spectrum is a sample drawn from the same Gaussian distribution, with $\mu = 0$ and $\sigma = \frac{1}{\sqrt{p \cdot b \cdot \Delta f}} = 3 \times 10^3$.

In the presence of axion conversion, we expect the mean power to be nonzero (but still $\Delta f$ in 50 consecutive bins in each of the processed spectra in which the frequency corresponding to the axion mass appears. We construct a combined spectrum whose value in each RF frequency bin is given by a sum of the corresponding bins across all processed spectra, weighted according to their different sensitivities. More precisely, the weights are chosen to yield the maximum likelihood estimate for the mean power in each combined spectrum bin, and we normalize each bin to the maximum-likelihood weighted quadrature sum of sample standard deviations from the contributing processed spectra. The probability distribution function (PDF) of the combined spectrum at 100 Hz resolution is Gaussian with $\mu = 0$ and $\sigma = 1$, as we expect.

We then sum non-overlapping 10-bin segments of the combined spectrum to reduce the resolution to 1 kHz, and construct a "grand spectrum" whose $i$th bin is a weighted sum of the $i$th through $(i+4)$th 1 kHz bins. The weights are chosen to yield the maximum likelihood mean power in each grand spectrum bin assuming a Maxwellian axion lineshape with velocity dispersion $\Delta v = 270$ km/s; each bin is normalized to its expected standard deviation as above. Thus, we expect a Gaussian PDF for the grand spectrum with $\mu = 0$ and $\sigma = 1$. The actual distribution is histogrammed in Fig. 2(a): it is Gaussian with the correct mean but $\sigma = 0.93$. We have demonstrated via simulation that the reduction of $\sigma$ is due to the finite stopband attenuation of the SG filter, which leads to small negative correlations between nearby 100 Hz bins. Because we understand the origin of these correlations, we can correct for their effects on the statistics of the grand spectrum.

In each grand spectrum bin the SNR at any constant coupling $|g|$ can be computed as a quadrature sum of terms with the form of Eq. (2), weighted according to the axion lineshape. We must also insert signal attenuation factors that do not appear in Eq. (2). The SG fit will attenuate any real axion signal for the same reason that it reduces on 5 kHz scales; the results of a simulation to quantify this fit-induced power loss are plotted in Fig. 2(b). We also consider loss due to misalignment of the axion signal relative to the grand spectrum binning and loss before the microwave switch, to which the noise calibration is not sensitive: the product of all three loss factors is $\chi = 0.76$. We then adjust the coupling in each bin to obtain a constant target SNR; the resulting frequency-dependent coupling $|g|_x(\Delta f)$ is the final value used to set an exclusion limit.

We chose an SNR target of 5$^{1.1}$, corresponding to a candidate threshold of 3.455 at 95% confidence. There were 28 grand spectrum bins exceeding this threshold, consistent with the candidate yield from simulated Gaussian processes.

X3 - Yale (formerly ADMX-HF)

• Probes the 5-25 GHz (20-100 $\mu$eV) axion mass region.
• Uses a 25 mK dilution refrigerator.
• Uses a highly uniform 9 T magnet.
• Uses Josephson Parametric Amplifiers (JPAs)

[From a talk by Tim Shokair for X3 collaboration, 2015.]
Dish reflector searches

The $E_a$-field excites surface electrons coherently EM radiation from a reflecting surface

$$P \sim |E_a|^2 A_{dish} \sim 10^{-26} \left( \frac{B}{5T} \frac{C_{at}}{2} \right)^2 \frac{A_{dish}}{1m^2} \text{Watt}$$

From talk by Javier Redondo, Bela Majorovits, Warsaw Workshop on Non-Standard Dark Matter, June 2016

Disc reflector idea employed by proposed MADMAX, FUNKY
Nuclear EDM Searches

CASPER is a search for axion to nucleon coupling generating an oscillating EDM in a sample. Sensitive to KSVZ axions, \( m_a \leq 10^{-9} \text{ eV} \)

ARGADNE is a search for short-range axion mediated forces between a source mass and an NMR sample.
IAXO

See Talk by Igor Irastorza TODAY (Tuesday), Elisa Ruiz-Choliz on Thursday

A proposed large scale axion haloscope, with a greatly increased axion conversion volume, new electronics, and a very large high-field magnet. Projected sensitivity to DFSZ/KSVZ axions above 0.01eV.
The interaction with fermions $f$ has derivative form and is invariant under a shift $\phi A \rightarrow \phi A + \phi 0$ as behooves a NG boson, $L_{\text{Aff}} = C_f f^2 f A \bar{\Psi}_f \gamma^\mu \gamma^5 \Psi_f \partial_\mu \phi A$.

Here, $\Psi_f$ is the fermion field, $m_f$ its mass, and $C_f$ a model-dependent coefficient. The dimensionless combination $g_{\text{Aff}} \equiv C_f m_f / f_A$ plays the role of a Yukawa coupling and $\alpha_{\text{Aff}} \equiv g_{\text{Aff}}^2 / 4 \pi$ of a "fine-structure constant." The often-used pseudoscalar form $L_{\text{Aff}} = -i(C_f m_f / f_A) \bar{\Psi}_f \gamma^5 \Psi_f \phi A$ need not be equivalent to the appropriate derivative structure, for example when two NG bosons are attached to one fermion line as in axion emission by nucleon bremsstrahlung [22].

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where $\tan \beta' = v_d / v_u$ is the ratio of the vacuum expectation value $v_d$ of the Higgs field $H_d$ giving masses to the down-type quarks and the vacuum expectation value $v_u$ of the Higgs.
Axion Coupling $|G_{A\gamma\gamma}(1/\text{GeV})|$ (GeV$^{-1}$)

Axion Mass $m_A$ (eV)

- $10^{-16}$
- $10^{-14}$
- $10^{-12}$
- $10^{-10}$
- $10^{-8}$
- $10^{-6}$
- $10^{-4}$
- $10^{-2}$
- $10^0$

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Axion Coupling $|G_{A\gamma\gamma}|$ (GeV$^{-1}$)

Axion Mass $m_A$ (eV)

LSW (OSQAR)

Helioscopes (CAST)

MADMAX (PVLAS)

Telescopes

SN 1987A

HESS

Horizontal Branch Stars

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X3 - 3 years

MADMAX (preliminary proposed)

KSVZ

DFSZ

VMB (PVLAS)
Axion Mass $m_A$ (eV)

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$$C_e = \cos^2 \beta' \frac{3}{2},$$  \hspace{1cm} (8)

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Conclusions

ADMX2 running imminent.

X3 first results available (preliminary).

Other cavity searches ramping up.

‘Mirror’ searches promising.

IAXO greatly increase reach of haloscopes into axion territory.

NMR / spin precession methods developing

Real prospects for axion discovery as rate of coverage of mass range ramps up.