Helioscopes: CAST & the IAXO project

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Outline

Axions, ALPs and Helioscopes
CAST: the most sensitive helioscope
IAXO: the future
Conclusions
Axions and ALPs

✓ Axions are the most elegant solution to the Strong CP problem (why QCD does not seem to break the CP symmetry):
  • pseudoscalar particles, neutral, practically stable
  • phenomenology driven by the scale $f_a$, $m_a$ and $g_{ai}$ correlated

✓ Candidates for both cold and hot dark matter

✓ Axion-like particles (ALPs) or WISPs (Weakly Interacting Slim Particles) share the axion phenomenology but $m_{ALP}$ and $g_{ALPi}$ not correlated

✓ Axions and ALPs are predicted by many extensions of the standard model

✓ New theory scenarios: string theory predicts axions/ALPs with detectable parameters

✓ Axions in astrophysics:
  • produced in the core of stars can drain energy from them and alter their lifetime
  • decay to two gammas may produce gamma lines in the emission from places (eg. galactic centre).
  • Hints for axion/ALPs?
    • transparency of the Universe to UHE gammas
    • white dwarf cooling anomaly $\rightarrow$ point to few meV axions
    • ...

Relevant axion/ALPs parameter space at reach of current and near-future experiments
Helioscope technique

Production: Primakoff effect
Thermal photons interacting with solar nuclei produce Axions.

Detection Inverse Primakoff:
Axion interacting with a very strong magnetic field converts to a photon

$$N_{\gamma} = \int \frac{d\Phi_a}{dE_a} \cdot P_{a\to\gamma} \cdot S \cdot t \cdot dE_a$$

Signal: excess of x-rays during alignment over background

Expected number of Photons:

Conversion Probability

- Conversion probability depends on medium, 
- Coherence can be restored: different mass ranges can be covered in different media and densities

Helioscope sensitivity

\[ g_{ay}^4 \sim B^2 L^2 A \epsilon_d b^{-1/2} \epsilon_o \alpha^{-1/2} \epsilon_t^{-1/2} t^{-1/2} \]

- B, L, A: strength, length and section of the magnetic field
- \( \epsilon_d, b \): efficiency and background levels of the x-ray detectors used
- \( \epsilon_o, \alpha \): efficiency and total focusing area of the focusing optics used (if any)
- \( \epsilon_t, t \): fraction of time the magnet follows the Sun and total data-taking time of the experiment

X-ray focusing devices enhance the S/B and increase the identification potential in case of a positive signal
CAST: the CERN Axion Solar Telescope

Decommissioned prototype LHC dipole magnet.
Magnetic field: $B=9\, T$
Length: $L=9.26\, m$

Rotating platform
(Vertical: $\pm 8^\circ$, Horizontal: $\pm 40^\circ$)

2x1.5h solar tracking/day

Sunrise: X-ray Focusing Device/Ingrid + 1 Micromegas
Sunset: 2 Micromegas
CAST Physics program

- **CAST Phase I, Vacuum**
  - $m_a < 0.02\text{eV}$
  - *PRL 94 (2005) 121301*
  - *JCAP04(2007)020*

- **CAST Phase II, $^4\text{He}$**
  - $P < 13.4\text{ mbar (1.8K)}, 160\text{ steps}$
  - $0.02\text{eV} < m_a < 0.39\text{eV}$
  - *JCAP02(2009)008*

- **CAST Phase II, $^3\text{He}$**
  - $P < 120\text{ mbar (1.8K)}$
  - $0.39\text{eV} < m_a < 0.64\text{eV}$
  - *PRL 107 (2011) 261302*

Parallel searches:

- Constraints on the axion-electron coupling $g_{ae}$: *JCAP 1305 (2013) 010*
- High energy axions *JCAP 1003:032, 2010*
- $14.4\text{keV}$ axions from M1 transistions *JCAP 0912:002, 2009*
- Low energy axions
- In preparation: bounds on solar chameleons (data taken with an SDD)
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Latest results:

$^3\text{He}$ phase results for $0.64\text{eV} < m_a < 1.17\text{eV}$ (*mM only*)

Excluded down to $g_{ay} < 0.88 \times 10^{-10}\text{GeV}^{-1}$

*PRL 112 (2014) 091302*

In preparation: paper on the simulations on the gas dynamics inside the magnet
CAST Detectors

X-ray telescope from the ABRIXAS mission coupled to
  a CCD (2002-2013)
  an InGrid (2014...)

S/N increased by a factor ~150 because of the focusing

Typical Rates

<table>
<thead>
<tr>
<th>Detector</th>
<th>Rate (cts/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM (2-10 keV)</td>
<td>~0.5</td>
</tr>
<tr>
<td>CCD (1-7 keV)</td>
<td>~0.2</td>
</tr>
</tbody>
</table>

Also: Barbe (PMT in a parasitic line) for low energy axions in the visible

3 microbulk Micromegas
CAST detectors: microbulk

Low intrinsic radioactivity
  Light mass, radiopure materials

Signal topology, offline analysis
  2D readout pattern, time information

Shielding
  archeological lead, inner Cu, N\textsubscript{2} flushing, muon veto

New electronics
  lowering noise and threshold, analysis in z

New detector design

Active experimental program and simulations
  --Experimental tests with current detectors at CERN, Zaragoza, Saclay
  --Underground setup at Canfranc
  --Simulation works to build a detailed background model

Reduction of $\sim$100x since the beginning!

S. Aune, 2014 JINST 9 P01001

Goal: $<10^{-7}$ c/keV/cm\textsuperscript{2}/s (down to $10^{-8}$ if possible)
Revisiting the vacuum phase:

Three high performance microbulk detectors, increase sensitivity
an InGRID detector substitutes the CCD behind the telescope

But also other exotica:

- *chameleons* (publication in progress with a Silicon Drift Detector (SDD) data),
- *paraphotons*, *low energy axions (visible)*

which require: low background, low threshold

**Current activities at CAST**

preparation of an x-ray optics for the sunrise one, boost discovery potential.
The International AXion Observatory

Letter of Intent already presented to CERN (SPSC-2013-022): SPSC recognised the physics case and recommended to proceed with the TDR.

In roadmaps of Europe & USA (ASPERA/APPEC, ESPP, Snowmass)

IAXO will improve on all the helioscope-relevant parameters more than 4 orders of magnitude in S/N better than CAST

Can be converted in an all-purpose axion observatory:
- non-hadronic axions, WISPs
- non-standard axion production scenarios
- And even relic axions:
  - with long thin cavities, dish antennas

I. G. Irastorza, JCAP 06 (2011) 013
E. Armengaud, 2014 JINST 9 T05002

Towards a new generation axion helioscope

E. Armengaud, 2014 JINST 9 T05002

Conceptual design of the International Axion Observatory (IAXO)
All developments based on known technologies

Magnet structure length: ~25m
Magnet structure diameter: ~5m
Total mass ~ 250ton

8 bores with 60cm diameter
8 focusing devices
8 low-background x-ray detectors

Rotating platform following the Sun for 12h a day
The IAXO magnet

Important change from the previous helioscopes:
- a dedicated magnet with high field and large aperture

Toroidal design (ATLAS-inspired)
- 8 bores

Main characteristics:
- length: 20m
- bore diameter: 60cm
- cross section: 2.3m²
- field peak: 5-6T

IAXO T0 Project
- Preparing to build a test-coil

The optics of IAXO

Using known technology: NuSTAR/HEFT project
Coated thin glass substrates optimized for:
- axion energies
- focusing power efficiency

Main characteristics:
- Focal length: \(~5\,\text{m}\)
- Focusing spot: \(-0.2\,\text{cm}^2\)

IAXO X0 Project

Dummy optics of the final size to be built

| Telescopes | = 8 |
| Layers per telescope | = 123 |
| Mirrors per telescope | \(\approx 2200\) |
| Focal length | = 5 \,\text{m} |
| Coatings | = W/B_4C multilayers |
| Pass band | = 1–10 \,\text{keV} |
| Half-power diameter | = 60 \,\text{arcsec} |
CAST IAXO detectors: microbulk

Low intrinsic radioactivity
Signal topology, offline analysis
Shielding
New electronics
New detector design
Active experimental program and simulations

Goal: \(<10^{-7} \text{ c/keV/cm}^2/\text{s} \) (down to \(10^{-8}\) if possible)

IAXO Pathfinder Project

Building a small optics to couple to the Sunrise
mM of CAST: smaller scale but same techniques
Summary and conclusions

- **Axions** and **ALPs** are of great interest in the rare-event searches field and are continuously called in to solve puzzles of physics.

- The **helioscope technique** is one of the most promising in order to look for them.

- **CAST**
  - **is the most sensitive and most experienced axion helioscope built so far, a reference in axion physics, having restricted a wide \( m_a - g_{\alpha\gamma} \) range**
  - **is currently improving its results in vacuum while being sensitive to other exotica such as solar chameleons**
  - **it also serves as an R&D facility for the development of IAXO**

- The **IAXO** project will push the helioscope technique to its limits:
  - **enhance all relevant aspects: magnet, optics and detectors**
  - **improve CAST results by ~1 order of magnitude**
  - **can become a general axion facility with a good discovery potential**

  CDR already published and base projects are ongoing.
Large parts of the QCD-favoured parameter space could be explored in the coming decade.