Search for Solar Axions: the CAST experiment at CERN

The XXXIXth Rencontres de Moriond

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for the CAST Collaboration

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Outline:

- Axions
- Principles & Fulfillment
  - CAST: Description
    - Magnet, platform, cryogenics, tracking
    - X-Ray Telescope & X-Ray Detectors
- Preliminary Results
Axions

The STRONG CP PROBLEM

CP-violating term in QCD lagrangian:

\[ \mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \tilde{G} \]

( \[ \tilde{g}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma} \] )

Experimental consequence: prediction of electric dipole moment for the neutron:

\[ |d_n| = A|\theta| \times 10^{-15} e \times cm \]

\[ (A = 0.04 - 2.0) \]

BUT experiment says...

\[ |d_n| < 0.63 \times 10^{-25} e \times cm \]

So,

\[ |\theta| < 10^{-9} \]

Why so small?

Peccei-Quinn (1977) propose an elegant solution to this problem. \( \theta \) not anymore a constant, but a field \( \rightarrow \) the axion \( a(x) \).
Axions

The STRONG CP PROBLEM: Peccei-Quinn solution

- New U(1) symmetry introduced in the SM: Peccei Quinn symmetry of scale $f_a$
- The AXION appears as the Nambu-Goldstone boson of the spontaneous breaking of the PQ symmetry

\[ \mathcal{L}_a = \frac{1}{2} \left( \partial_\mu a \right)^2 - \frac{\alpha_s}{8\pi f_a} a G \tilde{G} \]

- $a \to qq$ transitions
- $a - \pi^0$ mixing
- axion mass $> 0$

PQ Symmetry:

Peccei & Quinn: CP invariance of the strong interactions expected in QCD, for a non-vanishing scalar field that gives mass to a fermion through a Yukawa coupling.

\[ m_a \simeq 0.6 \, \text{eV} \frac{10^7 \text{GeV}}{f_a} \]
Axions

- pseudoscalar
- neutral
- practically stable
- phenomenology driven by the breaking scale $f_a$ and the specific axion model
- Couples to photon

$$L_{a\gamma} = g_{a\gamma}(E \cdot B) a$$

Primakoff (1951) [$\pi^0 \rightarrow \gamma\gamma$]

PRIMAKOFF EFFECT

Any scalar or pseudoscalar particles:

axion-like particles
Axions

PRIMAKOFF EFFECT

Stellar interior → the Sun!! → Solar Axions

Flux at the Earth

\[
\frac{d\Phi}{dE_a} = (g_{(-8)})^2 \frac{\Phi_0}{E_0} \left( \frac{E_a}{E_0} \right)^3 \frac{e^{E_a/E_0} - 1}{E_a/E_0}
\]

\[g_{(-8)} = g_{\alpha\gamma\gamma} \times 10^8 / \text{GeV}^{-1}\]

[K. van Bibber et al., 1989]
Axions

Transverse magnetic field ($B$)

**Signal:** X-rays while tracking (magnet pointing to the Sun) over background

\[ P_{\alpha\gamma} = 1.8 \times 10^{-17} \left( \frac{B}{8.4T} \right)^2 \left( \frac{L}{10m} \right)^2 \left( g_{\alpha\gamma\gamma} \times 10^{10} \text{GeV}^{-1} \right)^2 |M|^2 \]

\[ |M|^2 = 2(1-\cos qL)/(qL)^2 \]

To preserve **Coherence:** $|M|^2 = 1$

\[ m_\alpha < 10^{-2} \text{ eV} \]

Lazarus et al., Brookhaven

Tokyo Helioscope: $B \sim 4T$, $L \sim 2m$

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Axions

Extending the coherence to higher axion masses...

- Coherence for higher masses by using buffer gas.
- Fill magnetic channels with helium
- The photon acquires an effective mass: $m_\gamma > 0$
- Momentum transfer is
  \[ |q| = \frac{m_a^2 - m_\gamma^2}{2E} \] (as opposed to $|q| = \frac{m_a^2}{2E}$)

- Coherence condition ($qL << 1$) is recovered for a narrow mass range around $m_\gamma$
- $m_\gamma$ can be adjusted by changing the gas pressure:
  \[ m_\gamma \approx \sqrt{\frac{4\pi \alpha N_e}{m_e}} = 28.9 \sqrt{\frac{Z}{A}} \rho \text{ eV} \]

- Thus, changing the pressure of the gas will allow to be sensitive to an extended range of higher axion masses
Prospects

Phase II and up (?)

Filling the magnet bores with helium the photon acquires an effective mass: \( m_\gamma > 0 \) and by changing the gas pressure we are sensitive to different masses.

\[ g_{a\gamma\gamma} \leq 1.4 \times 10^{-9} (GeV)^{-1} \frac{b^{1/8}}{t^{3/8} B^{1/2} L^{1/3} A^{1/4}} \]

\( m_\alpha < 1 \text{ eV} \)

To Start in 2005
The Collaboration

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Decommissioned LCH test magnet

Rotating platform

3 X-ray detectors

X-ray Focusing Device
CAST is here:

LEP Point 8
(former DELPHI point)
Building 2875
Magnet, platform, cryogenics

CAST Experimental area

SR8

\[ L = 10 \text{ m} \]
\[ B = 9 \text{ T} \]

\( \Rightarrow 100 \text{ times better} \)
\( \alpha \rightarrow \gamma \) conversion efficiency

than any other!!

4He flexible line

Magnet Feed Box
Moving platform:

alignment with the Sun for
~1200 hours per year

Magnet at
-8°

Magnet at
+8°
Magnet, platform, cryogenics

Tracking system

- Motors
- Encoders
- E. Readout → computer
- Software with astronomical calculations
- Interface to move magnet
- New high precision angle encoders!

- Calibrated and correlated with celestial coordinates → high precision geometer measurement
Twice a year (September & March) we can film the Sun through the window.
Magnet, platform, cryogenics

Slow Control system

- Pressure, load & temperature logging
- Continuous status monitoring (valves, detector gas, various alarms)
- Mail and GSM notification
- On-line plots & history recall utilities.

For:
- Smooth & safe operation
- Data analysis
**X-Ray Telescope & X-Ray Detectors:**

- Detectors
  - CCD
  - TPC
  - Micromegas

- X-Ray Telescope (Focusing Device)

- Big value of $(LB)^2$
- Low background rate detectors

*X-Ray Telescope!!!*
The X-Ray Telescope

Telescope-Magnet Alignment

Space technology:
Spare part of the ABRIXAS Space mission

Telescope on the Magnet with the CCD in place
The X-Ray Telescope

- 27 nested pairs of mirrors
- From 50mmØ (LHC magnet aperture) to ~3mmØ
- ~35% efficiency due to reflections

Efficiency of one sector

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CCD

- Excellent Energy Resolution
  < 0.5 keV

- Excellent Space Resolution
  Pixel size: 150µm x 150µm

Surface: 1x3 cm²
Optimum working temperature: -130°C

Background:
~10⁻⁴ events keV⁻¹ s⁻¹cm⁻²

Efficiency close to 100%
over the full energy range
(works in vacuum without window)

Constrained only by the telescope
CAST Prototype: x-y structure:

192 charge collection strips for x
192 charge collection strips for y
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**Micromegas**

*Calibration $^{55}$Fe*

![Calibration Graph]

- **Background rate:** $<10^{-4}$ events $keV^{-1}s^{-1}cm^{-2}$

- **X-Ray detection threshold:** ~0.6KeV (95%Ar+5%Isobutane)

- **Clean materials**

- **Muon vetos**

![Plot with data from PANTER]
TPC

- **Conventional** therefore robust and stable
- **Position sensitive** (3mm spacing)
  - 48 anode wires (x)
  - 96 cathode wires (y)
  - time (!)

Both windows with data from PANTER

Exploded View
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Clean materials + shielding (polyethylene+copper+ancient lead)

Low Background:

$<10^{-4}$ counts keV$^{-1}$ cm$^{-2}$ s$^{-1}$
Prominent CuK$_a$ and CuK$_b$ fluorescence lines

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**Analysis: CCD**

**PRELIMINARY**

CCD upper Limit $g_{\alpha\gamma\gamma}$ from fit to background subtracted data

Subtracted Spectrum

$g_{\alpha\gamma\gamma} (95\%) < 1.1 \times 10^{-10} \text{ GeV}^{-1}$
**Analysis: CCD**

Number of hits in color code

- CCD area divided into cells of 16×16 Pixels ≈ 7mm² corresponding to image size of axion source of the sun

- CCD position information to be used in refined analysis will reduce efficiently signal to background ratio. On progress.

- Measuring at the same time background and tracking!!!!

*New calibration system for this year run!*
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Entries 1530

Integral 0.00212034

Tracking (red): 20.4h

Background (black): 253h

Using 2-8 keV

\[ g_{\alpha\gamma} (95\% CL) < 1.41 \times 10^{-10} \text{ GeV}^{-1} \]

\[ \chi^2_{\text{min}} / \text{dof} = 14/10 \]

Constrained to the physical region
Micromegas Data: Combined result of 3 Subsets

Analysis: Micromegas

$g_{\alpha\gamma\gamma} \ (95\% CL) < 1.23 \times 10^{-10} \text{GeV}^{-1}$

$\chi^2_{\text{min}} / \text{dof} = 28 / 30$
Analysis: TPC

Tracking & background spectra combined

![Graph showing tracking and background spectra combined for energy in keV with entries 14749.](image)

Spectrum (0.5 keV) with both windows during Tracking - full data set - (P-T-calibrated, in keV) (total E range)
chi2 minimization – 95% C.L. exclusion.

$g_{\alpha\gamma}(95\%) = 1.27 \times 10^{-10}$ GeV$^{-1}$

($\chi^2 = 39.9$)

$\chi^2_{\text{min}}$/dof = 36.0 / 28

Constrained to the physical region
PRELIMINARY ANALYSIS RESULTS

CAST Sensitivity

CAST data from 2002 and 2003

PVLAS
SOLAX + COSME
DAMA
TOKYO Helioscope
CAST 2003
CAST prospects

m_{axion}[eV]

$g_{ax}[GeV^{-1}]$