High-Energy Axion Detection: Probing hadronic axions with the CAST calorimeter

I. Origin of hadronic axion models and constraints
II. Axion emission by nuclear de-excitation
III. The CAST $\gamma$-calorimeter & results

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Origin of hadronic axions

- The PQ / Weinberg & Wilczek axion was pinned to the weak scale, resulting in $m_a \sim 0.1-1$ MeV
  - Quickly ruled out experimentally (e.g. quarkonium and kaon decays)

- New models developed to evade such constraints:
  - Adjustment of the PQ scale ($f_a \rightarrow >10^6$ GeV)
  - Modification of couplings

**DSFZ**
Axion couples to Fermions and photons
  $\rightarrow$ Less experimentally favored

**KSVZ**
Tree-level couplings to quarks suppressed
$\rightarrow$ Evades constraints of DFSZ model
  $\rightarrow$ Nucleon coupling still possible
Hadronic axion window

• SN1987A hadronic axion constraints (via $g_{aNN}$)
  – For $10^{-2} < m_a < 2-5$ eV, axions would have carried away too much energy from SN1987a
• The so-called “hadronic axion window” is $2-5 < m_a < 20$ eV

“Experiments probing distinct properties of axions, even if redundant in the context of a particular model, provide independent constraints on theories incorporating the PQ symmetry.” [1]

Axion-nucleon coupling: $g_{aNN}$

- $g_{aNN}$ derives from axion-light meson mixing
  - independent of the U(1)$_{PQ}$ charges that are implicit in KSVZ (i.e. hadronic) axion models

- As a pseudoscalar object, carries $J^P = 0^-, 1^+, 2^-, \ldots$
  - M1 nuclear transitions could (should?!) emit axions

- Axion-nucleon coupling explicitly as

$$L_{aNN} = -i \bar{\psi}_N \gamma_5 g_{aNN} \psi_N a$$

$$= -i \bar{\psi}_N \gamma_5 (g_0 + g_3 \tau_3) \psi_N a$$

Where $g_0$ and $g_3$ are the isoscalar and isovector axial-current contributions, respectively
Nuclear de-excitation via axions

• For any (e.g. thermally) excited M1 nuclear transition

\[
\frac{d\Phi_a}{dE_a} = \frac{1}{4\pi r_E^2} \int_0^{R_{\text{sun}}} D \cdot N_a \cdot \rho(r) 4\pi r^2 \, dr
\]

\(D\) = Gaussian Doppler Broadening term

\(N_N\) = # density of the isotope

\(B\) = the Boltzmann factor for thermally excited nuclear state

\(\tau_\gamma\) = lifetime of excited nuclear state

Axion emission per gram solar mass, per sec

\[
N_a = N_N \cdot \frac{\Gamma_a}{\Gamma_\gamma} \cdot B \cdot \frac{1}{\tau_\gamma} \left[ \text{g}^{-1} \text{s}^{-1} \right]
\]

Axion-photon branching ratio

\[
\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha} \left( \frac{k_a}{k_\gamma} \right)^3 \left[ \frac{g_0 \beta + g_1}{(\mu_0 - 1/2)\beta + (\mu_1 - \eta)} \right]^2
\]

ALL of the decay channel-specific axion physics is contained in \(\beta\) and \(\eta\) \(\rightarrow\) nuclear structure dependent terms
Decay channels and signal

- A few M1 transition decays available from solar core:
  - $p + d \rightarrow ^3\text{He} + a$ (5.5 MeV)
  - $^7\text{Li}^* \rightarrow ^7\text{Li} + a$ (0.48 MeV)
  - $^{23}\text{Na}^* \rightarrow ^{23}\text{Na} + a$ (0.44 MeV)

- Give mono-energetic axions at the decay energy
  - Detector signal will of course include effects such as escape peaks (for $E_a > 1.2$ MeV)

- $\gamma$-ray energy axions have improved probability of conversion for a helioscope

\[ P_{a \rightarrow \gamma} = g_{a\gamma}^2 \frac{(B/2)^2}{q^2} \left[1 - 2 \cos(qL)\right] \propto E_a^2 \]
The CAST high-energy calorimeter

Detector design goals

- Maximize sensitivity to γ-ray conversion photons
  - A dense crystal works well
- Maintain minimalist design due to CAST constraints
  - Minimal lead shielding + muon veto
- Search for several decay channels and other possible new pseudoscalar bosons
  - So maintain good photon efficiency & dynamic range for $E > 100$ MeV
The CAST high-energy calorimeter

- Large scintillating crystal (CdWO₄)
- Very pure & high γ efficiency
- Low-background PMT
- Offline particle identification
- Env. radon displacement
- Plastic muon veto
- Thermal neutron absorber
- Low 0.2 MeV energy threshold
- ~100 MeV dynamic range
- Compact XIA Polaris - Digital Gamma Spectrometer
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Front View

~4π Plastic Muon Veto

Muon veto PMT

Pb shielding

Gammas (from magnet bore)

Ultra-low bckg Pb

Characteristic pulse ~16μs rate~4 Hz

Large CWO (good particle ID, radiopure, efficient)

Radon displ. & borated thermal absorber

Shielded electronics

Brass support tube

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Particle identification

We actually expect very few $\alpha$ events since CWO so pure.
Calorimeter data and operation

A. Data acquisition
   - Digital waveform acquisition @ 40 MHz
   - Muon veto coincidence rejection (95% of $\mu$ events)

B. Offline processing
   - Livetime calculation via LED pulser
   - Particle identification cuts
   - Correction for detector systematics (temp, position)
   - BCKG: $2 \cdot 10^{-6}$ cm$^{-2}$ s$^{-1}$ kev$^{-1}$

C. Background subtraction

D. Limits on possible anomalous events
   - Look for Gaussian signals at low energies
   - Look for complex signal shape (including photon escape peaks) at higher energies

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Looking for evidence in the data

- Signal: Gaussian peaks $E < 10$ MeV
  - $E > 10$ MeV the functional changes due to photonuclear reactions
- Obtain 95% CL ($2\sigma$) for allowed anomalous events at each energy
- Any signal after subtraction could be a hint towards new physics…
Limits on axion physics

• This is tricky…
  – Production mechanism (generally) relies on nuclear coupling
  – Detection mechanism relies on photon coupling

• It is possible but unlikely that there are cancellations in the PQ symmetry that cause $g_{a\gamma\gamma} \sim 0$ but $g_{aNN} \neq 0$ ...in which case we can stop talking now [2]

\[
\Phi_\gamma \geq P_{a\rightarrow\gamma}(m_a) \Phi_a g_{a\gamma\gamma}^2
\]

\[g_{a\gamma\gamma} \leq \sqrt{\frac{\Phi_\gamma}{P_{a\rightarrow\gamma}(m_a) \Phi_a}}
\]

To derive this limit we must: (a) calculate the expected axion flux or (b) make an assumption about what it is.

(a) In order to calculate $\Phi_a$:

\[
\Phi_a = \frac{1}{4\pi r_E^2} \frac{1}{\tau_\gamma} \left( \frac{\Gamma_{M1}}{\Gamma_{\text{total}}} \right) \left( \frac{\Gamma_a}{\Gamma_\gamma} \right)
\]

- $\Gamma_a / \Gamma_\gamma$ most difficult
  - $p + d \rightarrow ^3\text{He} + a$: we have concentrated most on this reaction...assumption (b) used, now direct calc.
  - $^7\text{Li}^* \rightarrow ^7\text{Li} + a$
  - $^{23}\text{Na}^* \rightarrow ^{23}\text{Na} + a$

Calcs in progress

Results from the calorimeter: 5.5 MeV

(a) Of course, we want an expression for $\Phi_a$:

- $\eta$, $\beta$ almost impossible to calculate (3-body nuclear decay)
- Perhaps we can simplify the expression?? Not sure yet.

(b) Assume $\Phi_{a,\text{MAX}}$:

\[ g_{a\gamma} \leq \sqrt{\frac{\Phi_{\gamma}}{P_{a\rightarrow\gamma}(m_a)\Phi_a}} \]

Self-consistent improved limits possible for several energies of interest, e.g. 5.5 MeV, by using $\Phi_{a,\text{MAX}}$… but we are in the process of calculating $\Phi_a$ for several channels.
Conclusions

• *Axion-nucleon coupling will give rise to axion-emission through M1 transitions*

• *We have built a gamma-ray detector that is sensitive to several axion decay channels*

• *In a generic search in the range 0.3 – 60 MeV, no statistically significant signal has been seen*

• *To correctly set limits on the axion parameters ($f_{PQ}$) more careful calculations of nuclear structure dependent parameters are necessary...IN PROGRESS!*
Backup slides
Details for this data set

<table>
<thead>
<tr>
<th>Description</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data taking period (2004)</td>
<td>15/09 – 08/11</td>
</tr>
<tr>
<td><strong>Total Running Time</strong></td>
<td>1257 hrs (53 days)</td>
</tr>
<tr>
<td><strong>Tracking Time</strong></td>
<td>60.3 hrs (2.5 days)</td>
</tr>
<tr>
<td>Total Background Time</td>
<td>898 hrs (37 days)</td>
</tr>
<tr>
<td><strong>Normalized Background Time</strong></td>
<td>117.3 hrs (5 days)</td>
</tr>
<tr>
<td>Systematics Time (valves open, quenches…)</td>
<td>299 hrs (12 days)</td>
</tr>
<tr>
<td>Ratio Norm BCKG to Total BCKG</td>
<td>0.13</td>
</tr>
</tbody>
</table>
## Data processing and results

<table>
<thead>
<tr>
<th>Data treatment</th>
<th>% data kept</th>
<th>BCKG Count rate (Hz)</th>
<th>Integ. Φ 0.3-50 MeV (cm² sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw data</td>
<td>100</td>
<td>3.82</td>
<td>0.263</td>
</tr>
<tr>
<td>Anti-coincidence with muon veto</td>
<td>63.4</td>
<td>2.42</td>
<td>0.167</td>
</tr>
<tr>
<td>Recursive $^{40}$K peak gain shifting (temperature correlated)</td>
<td>63.4</td>
<td>2.42</td>
<td>0.167</td>
</tr>
<tr>
<td>PSD analysis and cuts</td>
<td>37.4</td>
<td>1.43</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>FULL DATA TREATMENT</strong></td>
<td><strong>37.4</strong></td>
<td><strong>1.43</strong></td>
<td><strong>0.1</strong></td>
</tr>
</tbody>
</table>
Crystal selection and Monte Carlo

- **Tested:** CWO, BGO, BaF₂
- **MC:** CWO, BGO, BaF₂, PWO, YAG, LSO, NaI, ...

**Crystal Selection and Monte Carlo**

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**Graphs:**
- Full-energy (peak) efficiency for different crystals
- MCNP calculated full-energy (peak) efficiency for collimated axion-induced gammas
- CWO crystal (l=7.5cm) in Pb shielding (R=4.75cm) response to 1 MeV isotropic bckg and collimated axion beam signal (MCNP MonteCarlo)
Detector Parameters

Resolution versus energy

Efficiency for full energy deposition

$\chi^2/\text{ndf} = 2.44/3$

$p_0 = 14.1 \pm 0.5517$

$p_1 = -0.5401 \pm 0.08073$
Energy Spectrum

- **Without** position normalized background data
  - Apparent agreement, **but** systematic effect due to the pointing position of the magnet, as in TPC

- **With** position normalization
  - Error bars increase by factor \( x^2 \)
  - Systematic effect of position is removed
Software cuts

• Use $\gamma$ calibrations to determine software cuts
  – Keep 99.7%!!!!!!
    • Of the events above 300 keV...threshold set due to noise events + BCKG

• Set cuts for:
  – Energy
  – Shape of Pulse
    • PID = pulse identification parameter
  – Pulse rise time
Look for evidence buried in data

- **Signal**: mono-energetic peaks below 10 MeV
  - Width determined by measured detector resolution
- **Obtain** 95% CL (2σ) for allowed anomalous events at each energy
- **Above** 10 MeV the functional form used becomes more complex (effect of photonuclear reactions)
- **Dedicated search** for specific energy, including escape peaks in fit, yields better sensitivity than simple gaussian and full-E efficiency (a first-order approach).

Example illustrated here is emission at 5.5 MeV

\[(p + d \rightarrow \text{He} + a \ldots a \rightarrow \gamma\gamma)\]


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Residual spectra
Difference between signal (solar tracking) and background

Low energy 0.3 – 3 MeV
Mid energy 3 – 10 MeV
High energy 10 – 50 MeV

3 energy regions to allow for different binning based on detector resolution
From counts to photons

- Use the 95% CL allowed counts at each energy and convolve with
  - Detector efficiency ($\varepsilon$)
  - livetime ($t$)

$$\frac{\Phi_{\text{counts}}}{t \text{ livetime } \varepsilon_{\text{det}}} = \Phi_{\gamma}$$