Solar axion search by annual modulation with XMASS-I detector

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Introduction of KK axion

- Axions arise from Peccei-Quinn solution to strong CP problem in QCD.
- On the other hand, large extra dimensions are also proposed to solve the gauge hierarchy problem.
  - Extra dimensions are thought to be “compactified ” in a certain radius $R$.
  - Motions of a particle in the extra dimensions can be seen as mass state of Kaluza-Klein (KK) excitations, which are separated in $1/R$.

- In theories with $n$ extra dimensions, axions may be able to propagate and acquire KK excitations.
  - axions acquires an infinite tower of KK modes where the lowest KK state is the normal PQ axions.
- Assumed model
  - $n=2$ extra dimensions
  - $\delta =2$ extra dimensions that axions can propagate in
  - $\rightarrow$ mass spacing of the KK axion $1/R \sim 1$ eV

\[
\begin{align*}
    m_{n+1} &\sim (n+1)/R \\
    m_n &\sim n/R \\
    m_{n-1} &\sim (n-1)/R \\
    m_{a0} &= m_{PQ} \ll 1/R
\end{align*}
\]
Introduction of solar KK axion

- KK axion would be produced in the Sun via the Primakoff effect ($\gamma Z \rightarrow aZ$) and a photon coalescence mechanism ($\gamma \gamma \rightarrow a$)
- A small fraction is trapped by the gravity of the Sun.
- Such solar/stellar KK axion can explain the solar corona problem and so on by massive axion decay
- In APP 19 (2003) 145, they assume KK axion photon coupling $g_{\gamma rr} = 9.2 \times 10^{-14}$ GeV$^{-1}$ by requiring that axion decay is responsible for the X-ray surface brightness of the quiet Sun

Introduction of solar KK axion

- we can predict the present density of trapped solar axion with the following assumptions
  - KK axion photon coupling $g_{a\gamma r} r = 9.2 \times 10^{-14}$ GeV$^{-1}$
  - number of extra dimension $\delta = 2$
  - Compactification radius $R = 10^3$ keV$^{-1}$
  - Mass splitting of KK axion: 1 eV

\[ n_a = 4.36 \times 10^{13} \text{ m}^{-3} \text{ at perihelion } 211.4 \text{ R}_\odot \]
\[ n_a = 3.81 \times 10^{13} \text{ m}^{-3} \text{ at aphelion } 218.6 \text{ R}_\odot \]
Expected energy spectra

- The expected KK axion decay rate $R$:
  \[ R = (2.5 \times 10^{11} \text{ m}^{-3} \text{ day}^{-1}) \left(\frac{g_{\alpha\gamma\gamma}}{\text{GeV}^{-1}}\right)^2 \left(\frac{n_a}{\text{m}^{-3}}\right) \]

  (B. Morgun et al, APP 23 (2005) 287)

- distance between the Sun and the Earth:
  \[ r(t) = a \left(1 - \cos \frac{2\pi(t-t_0)}{T}\right) \]

- KK axion density $n_a$ is a function of $r^{-4}$:
  \[ n_a(t) = \bar{n}_a \left(1 - \cos \frac{2\pi(t-t_0)}{T}\right)^{-4} \]
  \[ \approx \bar{n}_a \left[1 + 4e \left(\cos \frac{2\pi(t-t_0)}{T}\right) + \frac{5}{2} e \cos^2 \frac{2\pi(t-t_0)}{T}\right] \]

- Modulated signal is expected
XMASS-I detector

- Located in the Kamioka mine in Japan (~2700 m.w.e.)
- Single phase liquid xenon detector with 832 kg LXe, 0.288m³ sensitive volume.
- 642 low background 2 inch PMTs: 62% photo-cathodes coverage
- **High light Yield (~15 p.e. / keV) and Low energy threshold**
  - Energy threshold is enough low to search for solar KK axion.
- **High sensitivity for e/γ events as well as nuclear recoil**
  - Able to detect Axion Like Particles (ALP), hidden photon, WIMP-Xe inelastic scattering and so on, as well as “Standard” WIMPs
- **Stable data taking over years gives the modulation analysis method**

Φ10m x 10m ultra pure water shield
70 20-inch PMTs for muon veto

PMT R10789
Data set

- November 2013 - March, 2015
- 504 calendar days with a total live time of 359 days
  - This data set was used for direct DM search by annual modulation. PLB 759 (2016)64
- Data taking is still ongoing.
Event Selection

- **Cut1**: triggered only by Inner detector, \( \geq 4 \) PMT hits
- **Cut2**: Noise events due to afterpulse reduction
  - 10ms veto from previous ID events
  - RMS of hits timing < 100ns
- **Cut3**: Cherenkov events reduction
  - # of hits in the first 20ns is < 40% of total hits, which have < 200 observed p.e.
- **Cut4**: BG events occurring in front of a PMT window reduction
  - Events which have large MaxPE/TotalPE ratio are removed.
**Signal Simulation**

\( g_{\gamma r} = 9.2 \times 10^{-14} \text{ GeV}^{-1} \) is assumed

![Graphs showing event rate and residual event rate against energy at perihelion and aphelion](image)

**Input the decay spectra (sum of 2 photons)**
- not including detector response

\( n_a = 4.36 \times 10^{13} \text{ m}^{-3} \) at perihelion 211.4 R\( \oplus \)
\( n_a = 3.81 \times 10^{13} \text{ m}^{-3} \) at aphelion 218.6 R\( \oplus \)

**Signal simulation in XMASS-I using Geant4 including detector response after each cut**

Assumption:
- Distance = 215.0 R\( \oplus \), semi major axis
\( n_a = 4.07 \times 10^{13} \text{ m}^{-3} \)
\( g_{\gamma r} = 9.2 \times 10^{-14} \text{ GeV}^{-1} \)
Stability Check by Detector calibration

- Inner Calibration sources: $^{55}\text{Fe}$, $^{109}\text{Cd}$, $^{241}\text{Am}$, $^{57}\text{Co}$ and $^{137}\text{Cs}$
- The scintillation light yield response was traced by $^{57}\text{Co}$ 122 keV calibration data taken every (bi-)week, from $Z=-40\text{cm}$ to $+40\text{cm}$
- Intrinsic light yield of the liquid xenon scintillator, absorption and scattering length for the scintillation light extracted from the data/MC comparison

$^{57}\text{Co}$
- ~15PE/keV
- @122keV
Stability Check by Detector calibration

- We take $^{57}$Co calibration data every week and we observed p.e. yield changes:
  1) sudden drop at the power failure
  2) It recovered after purification work in gas phase
  3) we continuously circulate the gas purification
- We can trace observed p.e. yield change as a change in the absorption length.
- Absorption length change: 4m ~ 11m. Uncertainties due to this instability is taken into account.
- Relative intrinsic light yield: stayed within $\pm$1%
Relative cut efficiency

- The change of absorption length affects cut efficiency.
- The relative change of cut efficiency is evaluated using BGMC, and data is corrected by this obtained relative efficiency.
- MC: Dominant BG, summed up corresponds to its amount.
  - U-Chain($^{238}$U-$^{230}$Th, $^{210}$Pb) in the Al seal used for PMT window and body.
  - $^{210}$Pb in the copper plates on the surface of the ID.
- Error band: Al seal shape modeling dependence, $\pm 5\%$.
- Other error, such as non-linearity of scintillation eff are also taken into account.

PMT R10789

[Images of PMT and graphs showing cut efficiency across different energy ranges.]
The data set was divided into 33 time-bin (roughly 15 days each)
- The data in each time-bins were further divided into energy-bin (bin width = 1 keVee)
  - 3-22 keVee, except for 14-17 keVee to avoid systematic effect associated with the end of the range over which the Cherenkov cut is applied
- A least Chi-squares fit all energy/time bins simultaneously to obtain an annual modulation amplitude

\[
\chi^2 = \sum_i \sum_j \frac{(R_{i,j}^{\text{data}} - R_{i,j}^{\text{ex}} - \alpha K_{i,j})^2}{\frac{\sigma^2_{\text{stat};i,j}}{2} + \frac{\sigma^2_{\text{sys};i,j}}{2}} + \alpha^2 + \beta^2
\]

\[R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2} \Delta t_j}^{t_j + \frac{1}{2} \Delta t_j} \left[ C_i + \xi \times (A_i - \beta L_i)(\cos \frac{2\pi(t - t_0)}{T}) + \frac{5}{2}e\cos^2 \frac{2\pi(t - t_0)}{T} \right]
\]

\[C_i : \text{constant term}
\]
\[A_i : \text{expected amplitude}
\]
\[L_i : \text{non-linearity of the scintillation eff.}
\]
\[\xi : \text{the ratio of the expected amplitude between the data and the considered model}
\]
\[\xi = \frac{g_{\alpha\gamma\gamma}^2}{(9.2 \times 10^{-14}\text{GeV}^{-1})^2 \left(4.07 \times 10^{13}\text{m}^{-3}\right)} \left(\bar{n}_a\right)
\]

Free parameter : \(C_i\) and \(\xi\)
Time variation of event rate

- No significant excess in amplitude is found
- Best fit $\xi = 8.2 \times 10^2$ with $\chi^2/\text{ndf} = 522.4/492$
- 90% CL upper limit $\xi = 2.7 \times 10^3$
- $g_{\text{arr}} < 4.8 \times 10^{-12} \text{ GeV}^{-1}$ for $\bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3}$

data
syst.err
(solid): best fit result
(dot): 90% CL upper limit, x20 enhanced
Result

- $g_{\gamma\gamma} < 4.8\times10^{-12}\,\text{GeV}^{-1}$ for $n_a = 4.07\times10^{13}\,\text{m}^{-3}$
- Rate < 234 m$^{-3}$ day$^{-1}$ (90% CL)
- First experimental constraint for KK axions
- Submitted to “Progress of Theoretical and Experimental Physics (PTEP)”

$R = (2.5 \times 10^{11}\,\text{m}^{-3}\,\text{day}^{-1})\left(\frac{g_{\gamma\gamma}}{\text{GeV}^{-1}}\right)^2 \left(\frac{n_a}{\text{m}^{-3}}\right)$

Blue point as a benchmark from L. Di Lella and K.Zioutas APP 19 (2003) 145
To explain X-ray surface brightness of the quiet Sun
Summary

- Solar KK axion would be produced in the Sun and a small fraction is trapped by the gravity of the Sun. Decays into two photons.

- XMASS searched the decay of solar KK axions by annual modulation (832x359 kg · days)

- No significant excess in amplitude is found. and we set 90% CL upper limit:

  \[ g_{\gamma\gamma} < 4.8 \times 10^{-12} \text{ GeV}^{-1} \text{ for } \bar{n}_a = 4.07 \times 10^{13} \text{ m}^{-3} \]

- This is the First experimental constraint for KK axions.

- Submitted to Progress of Theoretical and Experimental Physics (PTEP)
Backup
KK axion lifetime

Axion couples to two photons: \[ g_{\alpha\gamma} = \frac{\alpha_{EM}}{\pi} \frac{C_a}{f_{PQ}} \]

This implies decay to two photons with mean lifetime:

\[ \tau = \frac{64\pi}{g_{\alpha\gamma} m_a^3} \]

However, astrophysical constraints imply \( \tau \) too long to observe:

\[ 10^9 \text{GeV} \leq f_{PQ} \leq 10^{12} \text{GeV}; 10^{30} \leq t \leq 10^{45} \text{days} \]

But propagation in extra dimensions allows shorter, observable, lifetime

\[ m_a = m_{an} \sim \frac{n}{R} \]
Solar KK axion mass spectrum

Basis for an experimental search:

B. Morgan, N. Spooner et al, D. Hoffmann et al., K. Zioutas...


• Leads to differential decay spectrum:

\[ \frac{dR}{dm_a} = \frac{g_{a\gamma}^2}{64\pi} n_0 m_a^3 f(m_a) \]

\[ R = \left(2.5 \times 10^{11} \, m^{-3} \, day^{-1}\right) \left(\frac{g_{a\gamma}}{GeV^{-1}}\right)^2 \left(\frac{n_0}{m^{-3}}\right) \]

Typical rate ~ 1 m^{-3} day^{-1} (~keV events)

Result for trapped axions in orbits around Sun

(local number density depends on \( g_{a\gamma} \))

\( g_{a\gamma} = 9.2 \times 10^{-14} \, GeV^{-1} \)
\( n_0 = 10^{14} \, m^{-3} \)

Mass spectrum for solar axions trapped in orbits around the sun