Axion emission and detection from a Galactic supernova

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A Galactic supernova (SN) axion signal would be detected in a future neutrino Mton-class water Cherenkov detector, such as the proposed Hyper-Kamiokande in Japan. The main detection channel for axions is absorption on the oxygen nuclei in the water. The subsequent oxygen de-excitation leads to a potentially detectable gamma signal. In this contribution we present a calculation of the SN axion signal and discuss its detectability in Hyper-Kamiokande.

1 Introduction

Low-mass axions can be copiously produced in a core-collapse supernova (SN) affecting the neutrino burst. In fact, bounds on axions have been placed studying the neutrino signal from SN 1987A. In particular, in [1] it was pointed out that a SN axion burst could produce an observable signal in a neutrino water Cherenkov detector by oxygen absorption. The following oxygen de-excitation would produce a photon signal. Currently it has been proposed a future Mton-class neutrino water Cherenkov detector, Hyper-Kamiokande, in Japan. Motivated by this exciting situation, we find it worthwhile to take a fresh look at the possibility of detecting a SN axion burst. In this contribution we present preliminary results of an updated calculation of the SN axion signal in Hyper-Kamiokande. We refer the interested reader to [2, 3] for further details.

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2 SN axion flux

Axions are produced in a SN enviroment via nucleon-bremsstrahlung $NN \to NNa$. The axion-nucleon coupling constant g_{aN} depends on the Peccei-Quinn scale f_a as $g_{aN} = C_N m_N / f_a$, where $N = p, n$, m_N is the nucleon mass and C_N is a model-dependent factor. We computed the axion and neutrino fluxes through a SN simulation developed by the "Wroclaw Supernova Project" based on a spherically symmetric core-collapse SN model, using the AGILE-BOLTZTRAN code [4, 5]. We consider two representative cases:

- Weakly-interacting axions with $g_{ap} = 9 \times 10^{-10}$ and $g_{an} = 0$. In this case, axions are in a free-streaming regime and they drain energy from the SN core, suppressing the neutrino fluxes.
- Strongly interacting axions with $g_{ap} = g_{an} = 10^{-6}$. Axions are in a trapping regime, so they do not reduce the neutrino fluxes. However, they are emitted from a last-scattering surface, the axionsphere. In this case their flux can be larger than the neutrino ones.

3 Axion-^{16}O absorption cross section

Axions can be detected in a water Cherenkov detector via axion-^{16}O absorption, $a^{16}\mathrm{O} \to {}^{16}\mathrm{O}^*$, revealing the oxygen decays in photons. The absorption cross section is evaluated starting from the following axion-nucleon interaction Lagrangian [1]

$$\begin{aligned}\mathcal{L} &= \frac{1}{2f_a} \bar{\Psi}_N \gamma^\mu \gamma^5 (C_0 + C_1 \tau_3) \Psi_N \partial_\mu a \ ; \\ C_0 &= \frac{1}{2}(C_p + C_n) \ ; \\ C_1 &= \frac{1}{2}(C_p - C_n) \ ;\end{aligned}$$

where Ψ_N is the nucleon spinor and τ_3 is a Pauli matrix. The obtained cross section is

$$\sigma = \frac{4\pi^2 E_p}{f_a^2} |\langle J^P || L_{j,0} || 0^+ \rangle|^2 \ ; \tag{1}$$

where

$$\begin{aligned}L_{j,0} &= \frac{i}{p} \int d^3r \, \partial_i (j_j(pr) Y_{j,0}(\Omega)) J^i(\mathbf{r}) \ ; \\ J^i(\mathbf{r}) &= \bar{\Psi}_N(\mathbf{r}) \gamma^i \gamma^5 (C_0 + C_1 \tau_3) \Psi_N(\mathbf{r}) \ .\end{aligned}$$

The reduced matrix element in Eq. (1) is calculated between the ^{16}O ground state, $|0^+\rangle$, and the $^{16}\mathrm{O}^*$ excited state, $|J^P\rangle$. The angular momentum and parity of the excited oxygen are fixed by conservation laws. Therefore J is the axion angular momentum and $P = (-1)^{J+1}$. The cross section in Eq. (1) is explicitly computed with the Random Phase Approximation. Particle- and γ-emissions from the excited ^{16}O were computed using transmission coefficients from the SMARAGD Hauser-Feshbach code [6]. Two-particle emission was included. The obtained total γ-ray and particle spectra were folded with the detector properties to obtain the expected event number.

4 Axion events

As reference detector we consider Hyper-Kamiokande, a next-generation water Cherenkov detector, with $M = 374\,\mathrm{kton}$ of fiducial mass. The detected neutrino (or axion) events in the proposed detector are calculated as

$$N_{\mathrm{ev}} = F \otimes \sigma \otimes \mathcal{R} \otimes \mathcal{E} \ ;$$

where F, the neutrino (or axion) flux, is convoluted with the cross section σ in the detector, the detector energy resolution, $\mathcal{R}$ and the detector efficiency $\mathcal{E}$. We assume $\mathcal{E} = 1$ above the energy threshold ($E_{\mathrm{th}} = 5\,\mathrm{MeV}$) and the energy resolution is the same of the Super-Kamiokande detector.

With the given energy threshold, the majority of the detectable axion signal falls in the range $5 - 10\,\mathrm{MeV}$. Therefore we restrict our attention to this energy window. The neutrino interaction reactions in the detector are a background for the axion detection. In particular, one has to consider the following channels: inverse beta decay (IBD), $\bar{\nu}_e p \to n e^+$; elastic scattering (ES), $\nu e^- \to \nu e^-$; charged and neutral current ν-$^{16}\mathrm{O}$ nuclei interactions (O-CC and O-NC). The number of free-streaming axion and neutrino events in the range $5 - 10\,\mathrm{MeV}$ is shown in Tab. 1. The huge neutrino background dominates the axion signal. However, the axion detectability can be enhanced doping the detector with gadolinium (Gd) to tag the IBD events. This possibility is currently being realized in Super-Kamiokande. We assume that it would occur also for Hyper-Kamiokande. Gd has a large neutron capture cross section and, after a neutron capture, emits a cascade of photons with a total energy of 8 MeV. The coincidence detection of the positron and photon signals tags the IBD events. We will assume 90% tagging efficiency as quoted in [7]. The ES signal can be reduced through a directional cut. Indeed the scattered electrons preserve the incident neutrino direction. Then the majority of ES events (about 95%) is contained in a 40° cone, making possible a reduction of this background by means of a directional cut which eliminates also the 12% of the events in the other channels [8]. The number of events with the background reduction is shown in Tab. 1. We observe that the background reduction makes it possible to detect axions at less than 2σ for a SN at $d = 1\,\mathrm{kpc}$.

Furthermore, a new calculation of the axion bremsstrahlung production in a SN [9], shows that the SN axion flux should be about 20 times lower than the one we used until now. Since the flux in the free-streaming is proportional to g_{ap}^2, to obtain the same luminosity we should use a coupling constant larger by a factor of $\sqrt{20}$. Then the number of axion events is 20 times larger than our previous estimate [Tab. 1]. In this case, the axion signal would emerge at $\sim 28\sigma$ for a SN at 1 kpc and at $\sim 3\sigma$ for a SN at 10 kpc.

We also calculated the events in the trapping regime, obtaining the results in Tab. 2. In this regime the axion signal dominates the neutrino background.

5 Conclusions

We evaluated the Hyper-Kamiokande potential to detect the axion burst associated with a Galactic SN event. We found that axions in the free-streaming regime would be potentially detectable if a careful reduction of the neutrino background is performed. On the other hand, in the trapping regime the axion signal would dominate over the neutrino one, being easily detectable. Therefore a Galactic SN explosion would be a once in a lifetime opportunity for detecting axions.

$g_{ap} = 9 \times 10^{-10}, g_{an} = 0$			
Interaction	Events	BKG RED	NEW FLUX
a-O	270	238	4.76×10^3
IBD	1.99×10^5	1.75×10^4	1.75×10^4
ES	3.53×10^4	1.77×10^3	1.77×10^3
O-CC	1.76×10^3	1.55×10^3	1.55×10^3
O-NC	9.21×10^3	8.10×10^3	8.10×10^3

Table 1: Number of events without background reduction (first column), number of events with background reduction (second column) and number of events with the flux correction factor (third column) in the range $[5; 10]$ MeV for a SN at $d = 1$ kpc and a detector mass $M = 374$ kton.

$g_{ap} = g_{an} = 10^{-6}$	
Interaction	Events
a-O	2.73×10^5
IBD	2.85×10^3
ES	522
O-CC	24
O-NC	116

Table 2: Number of events with background reduction in the range $[5; 10]$ MeV for a SN at $d = 10$ kpc, a detector mass $M = 374$ kton and a coupling constant $g_{ap} = g_{an} = 10^{-6}$.

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References

[1] J. Engel *et al.*, Phys. Rev. Lett. **65** (1990) 960.

[2] P. Carenza, “Axion emission and detection from a galactic supernova,” Master Thesis (2018).

[3] P. Carenza, G. Cò, T. Fischer, M. Giannotti, A. Mirizzi, and T. Rauscher, in preparation.

[4] M. Liebendoerfer *et al.*, Astrophys. J. Suppl. **150** (2004) 263 [astro-ph/0207036].

[5] T. Fischer *et al.*, Phys. Rev. D **94** (2016) no.8, 085012 [arXiv:1605.08780 [astro-ph.HE]].

[6] T. Rauscher, code SMARAGD, version v0.11.0sn (2018).

[7] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93** (2004) 171101 [hep-ph/0309300].

[8] R. Tomas *et al.*, Phys. Rev. D **68** (2003) 093013 [hep-ph/0307050].

[9] J. H. Chang, R. Essig and S. D. McDermott, arXiv:1803.00993 [hep-ph].