Exp. Methods in Astroparticle Physics (SS 2020) - Problem sheet 6

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Deadline for this sheet: Thu, 04.06.2020

Axions: thermal production, solar axions, light-shining through a wall

6.1 Thermal production of axions and cold dark matter *4 Points*

As mentioned in the lecture, the axion mass m_{a} and coupling constant f_{a} closely depend on each other via:

$$m_{\mathrm{a}} = 57 \times \left(\frac{10^{11}\,\mathrm{GeV}}{f_{\mathrm{a}}} \right) \mathrm{\mu eV}. \tag{1}$$

We will try to calculate a limit on m_{a} given that axions should be stable with respect to the age of the universe, $13.8 \times 10^9\,\mathrm{y}$. We consider the decay of an axion into a pair of photons. The decay width $\Gamma_{a\to\gamma\gamma}$ of this process can be computed and is given by:

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_{\mathrm{a}}^3}{64\pi}, \tag{2}$$

where $g_{a\gamma\gamma}$ describes the coupling strength. In a simplified KSVZ model, it can be calculated via:

$$g_{a\gamma\gamma} = -\frac{\alpha}{2\pi f_{\mathrm{a}}} \left(\frac{2\,(4+z)}{3\,(1+z)} \right). \tag{3}$$

Here, $z = m_{\mathrm{u}}/m_{\mathrm{d}}$ describes the mass ratio between up and down quark, and $\alpha = 1/137$ is Sommerfeld's fine-structure constant.

a) Assuming that $z = 0.56$, compute an upper limit on m_{a}.

b) The thermal decoupling of axions could happen after the QCD transition at a temperature $T \simeq m_\pi$, when the reaction $\pi + \pi \to a + \pi$ is no longer in equilibrium. With this, we can calculate the corresponding energy density fraction of axionic dark matter to be

$$\Omega_{\mathrm{a,th}} \sim \frac{m_{\mathrm{a}}}{130\,\mathrm{eV}}. \tag{4}$$

Argue why or why not thermally produced axions could represent the full dark matter content of the Universe.

6.2 Solar axions *4 Points*

Read the paper at https://arxiv.org/pdf/1705.02290.pdf by the CAST collaboration and answer the following questions:
(For convenience: The magnet length $L = 9.26\,\mathrm{m}$*, the magnetic field* $B = 9\,\mathrm{T}$*, and the cross section* $A = 14.5\,\mathrm{cm}^2$*.)*

a) Briefly describe the setup that is used for the CAST experiment.

b) By which process can axions be detected with this instrument? Write down the probability of axion-to-photon conversion for a magnet with length L and magnetic field B. What is the coherence condition? Write down the probabilty of axion-to-photon conversion in the coherent case. Calculate the maximum mass that can be investigated in CAST.

c) How can the sensitivity to detect axions with $m_\mathrm{a} = 1\,\mathrm{eV}$ be increased in the CAST experiment?

d) During parts of the day, the helioscope is used to track the sun while recording data. What kind of measurements are taken while the sun is not being tracked? Why is this data important? What kind of background processes can disturb the measurement, and how are they suppressed?

6.3 Light-shining-through a wall *2 Points*

In the ALPS I experiment, two of the HERA magnets with a length of $8.8\,\mathrm{m}$ and a magnetic field of $5.3\,\mathrm{T}$ were used for the axion production region and reconversion region, respectively. The production region was equipped with a Fabry-Pérot (FP) cavity with a power build-up factor $\beta_\mathrm{PC} \sim 5000$, while the reconversion region had a FP cavity with $\beta_\mathrm{RC} \sim 40000$. The probabilty $P\left(\gamma \to \mathrm{a} \to \gamma\right)$ can be written:

$$P\left(\gamma \to \mathrm{a} \to \gamma\right) = \frac{1}{16}\beta_\mathrm{PC}\beta_\mathrm{RC}\left(g_{a\gamma\gamma}BL\right)^4 . \tag{5}$$

Knowing that a $30\,\mathrm{W}$ laser at $1064\,\mathrm{nm}$ is used, how many photons per second would be expected for a coupling strength of $g_{a\gamma\gamma} = 0.2 \times 10^{-10}\,\mathrm{GeV}^{-1}$?