Compton-like Scattering with Axions or ALPs

Axions or Axion-like particles as dark matter

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Workshop BSM and Astroparticles, 15-16 Mar 2023, IF-UNAM

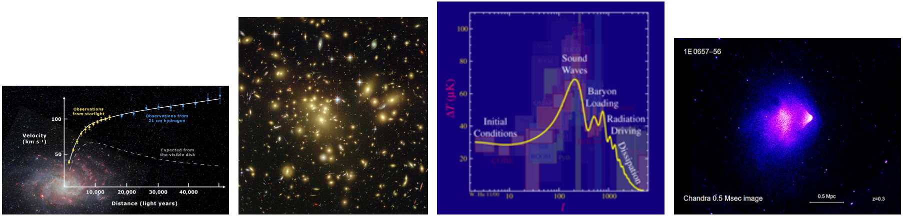
Outline

1. Introduction
2. Axions or ALPs as Dark Matter
3. Inverse Compton Scattering in Astrophysics
4. Compton-like Scattering with axions or ALPs
5. Conclusions and future perspectives

Motivation

1. The Standard Model (SM) are highly successful in the physical description of matter and three of its fundamental interactions.
2. Neutrino oscillations show that the Standard Model is incomplete.
3. It only describes 5% of the matter in the universe.

Evidence for dark matter



(a) (b) (c) (d)

Figure: Some evidence for the existence of dark matter: (a) Galaxy rotation curves(Messier 33), (b) Gravitational lensing, (c) CMB, (d) Bullet Cluster

Axiones and ALPs

Strong CP problem

Why does quantum QCD seem to preserve CP-symmetry?

Solution

The QCD axion is probably the most simple solution: the SM is augmented with an extra pseudo-goldstone boson.

ALPs

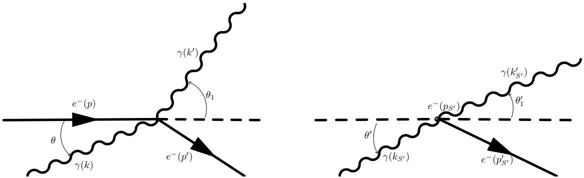
Axion-like particles (ALPs) are pseudo-scalar particles. They are abundant in string theory and are also predicted in many other BSM models.

Electromagnetic interaction

$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g a(x) F_{\mu\nu} \mathcal{F}^{\mu\nu}$. The Feynman rule for the interaction vertex is $\frac{i}{2} g \epsilon^{\mu\nu\rho\sigma} k_{\mu}^{(1)} k_{\rho}^{(2)}$ [1]

Generalized Compton scattering

- A very energetic electron passes through a gas of photons; the electron has energy E and when it passes through the photon gas it experiences Compton scattering and loses energy, this process is known as *inverse Compton scattering* [2].



(a) (b)

Figure: Compton scattering: (a) Reference frame of the laboratory, (b) Reference frame of the electron at rest.

What is the energy distribution of the scattered photons?

- Energy distribution of the scattered photons in the lab frame.

$$\frac{dN_{\gamma,\epsilon}}{dtd\epsilon_1} = \iint_{(\epsilon',\Omega'_1)} \frac{dN_{\gamma,\epsilon'}}{dt'd\epsilon'd\Omega'_1 d\epsilon'_1} \frac{dt'}{dt} \frac{d\epsilon' d\Omega'_1 d\epsilon'_1}{d\epsilon_1} . \tag{1}$$

where $\frac{dN_{\gamma,\epsilon'}}{dt'd\epsilon'd\Omega'_1 d\epsilon'_1} = cdn'(\epsilon';\epsilon)\left(\frac{d\sigma}{d\Omega'_1 d\epsilon'_1}\right)$ is the distribution in energy and angle of the scattered photons per electron per interval of ϵ' in the frame S'. Here $dn'(\epsilon';\epsilon)d\epsilon'$ represents the total differential photon density in the beam in k' (that is, integrated over all the small angles in the beam) within $d\epsilon'$ which are due to photos within $d\epsilon$ in K.

Relativistic kinematics of Compton scattering

- We consider highly relativistic electrons $\gamma \gg 1$
- Additional simplifications can be considered:
  1. (Thomson limit) The energy of the photon before scattering in the reference frame where the electrons are at rest must be $\epsilon' \ll m_e c^2$.
  2. (extreme Klein—Nishina limit) The energy of the photon before it scatters in the reference frame where the electrons are at rest must be $\epsilon' \gg m_e c^2$.

$$\epsilon' = \gamma\epsilon(1 - \beta\cos\theta)$$

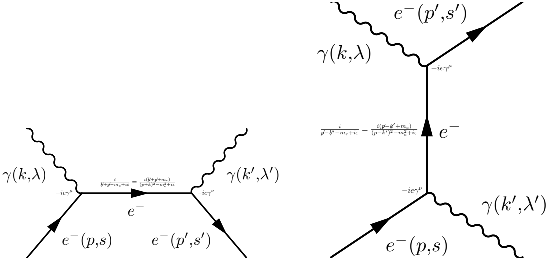
$$\epsilon_1' = \frac{\epsilon'}{\left[1+\left(\frac{\epsilon'}{m_e c^2}\right)(1-\cos(\theta_1'-\theta'))\right]}$$

$$\epsilon_1 = \gamma\epsilon_1'(1 + \beta\cos\theta_1')$$

$$\epsilon_1' \approx m_e c^2 \Rightarrow \epsilon_1 \approx \gamma m_e c^2(1 + \beta\cos\theta_1') \sim \gamma m_e c^2$$

Klein–Nishina formula

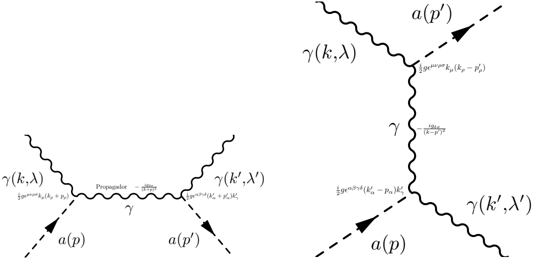
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m_e^2}\left(\frac{\epsilon'}{\epsilon}\right)^2\left[\frac{\epsilon'}{\epsilon} + \frac{\epsilon}{\epsilon'} - \sin^2\theta_1'\right], \tag{2}$$



(a) (b)

Figure: Tree-level contributions in the photon-electron scattering process: (a) Channel s, (b) Channel u.

Feynman diagrams for Compton-like scattering



(a) (b)

Figure: Tree-level contributions in the photon-axion (or ALP) scattering process: (a) Channel s, (b) Channel u.

Cross-Section

- The differential cross-section for a 2 to 2 dispersion process is given by

$$d\sigma = \frac{1}{4\sqrt{(k \cdot p)^2 - m_k^2 m_p^2}} |\mathcal{M}|^2 dLips(s; k', p') \,, \tag{3}$$

  where we have introduced the Lorentz invariant phase space $dLips(s; k', p')$

- If one of the particles involved is a photon with 4-momentum k^μ, then

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{k_0'^2}{(p \cdot k)^2} \overline{|\mathcal{M}|^2} \tag{4}$$

- In the photon-axion (or ALP) scattering we have the following invariant amplitudes

$$i\mathcal{M}_s = \tfrac{i}{2} g \epsilon^{\alpha\beta\gamma\delta} (k'_\alpha + p'_\alpha) \epsilon^*_\beta(\mathbf{k}', \lambda') k'_\gamma \left(-\tfrac{i g_{\delta\sigma}}{(k+p)^2} \right) \tfrac{i}{2} g \epsilon^{\mu\nu\rho\sigma} k_\mu \epsilon_\nu(\mathbf{k}, \lambda)(k_\rho + p_\rho)$$

$$\mathcal{M}_s = \tfrac{1}{4} \tfrac{g^2}{(k+p)^2} (k_\alpha + p_\alpha) \epsilon^*_\beta(\mathbf{k}', \lambda') k'_\gamma \epsilon^{\alpha\beta\gamma\delta} g_{\delta\sigma} \epsilon^{\mu\nu\rho\sigma} k_\mu \epsilon_\nu(\mathbf{k}, \lambda) p_\rho$$

$$\mathcal{M}_s = -\tfrac{3!}{4} \tfrac{g^2}{(k+p)^2} (k_\mu + p_\mu) \epsilon^*_\nu(\mathbf{k}', \lambda') k'_\rho k^{[\mu} \epsilon^{\nu}(\mathbf{k}, \lambda) p^{\rho]}$$

$$\mathcal{M}_s = -\frac{1}{4}\frac{g^2}{(m_a^2+2k\cdot p)}\left\{\left[(k\cdot p)(k'\cdot p)-(m_a^2+k\cdot p)(k'\cdot k)\right]\epsilon^*_\mu(\mathbf{k}',\lambda')\epsilon^\mu(\mathbf{k},\lambda)\ +\left[(m_a^2+k\cdot p)k^\mu k'_\nu-(k'\cdot p)k^\mu p_\nu-(k\cdot p)p^\mu k'_\nu+(k'\cdot k)p^\mu p_\nu\right]\epsilon^*_\mu(\mathbf{k}',\lambda')\epsilon^\nu(\mathbf{k},\lambda)\right\}$$

$$i\mathcal{M}_s = \frac{i}{2}g\epsilon^{\alpha\beta\gamma\delta}(k'_\alpha+p'_\alpha)\epsilon^*_\beta(\mathbf{k}',\lambda')k'_\gamma\left(-\frac{ig_{\delta\sigma}}{(k+p)^2}\right)\frac{i}{2}g\epsilon^{\mu\nu\rho\sigma}k_\mu\epsilon_\nu(\mathbf{k},\lambda)(k_\rho+p_\rho)$$

$$\mathcal{M}_u = \frac{g}{2}\epsilon^{\alpha\beta\gamma\delta}(k_\alpha-p'_\alpha)\epsilon^*_\beta(\mathbf{k}',\lambda')k'_\gamma\frac{g_{\delta\sigma}}{(k-p')^2}\frac{g}{2}\epsilon^{\mu\nu\rho\sigma}k_\mu\epsilon_\nu(\mathbf{k},\lambda)(k_\rho-p'_\rho)$$

$$\mathcal{M}_u = -\frac{1}{4}\frac{g^2}{(m_a^2-2k\cdot p')}\left\{\left[(k\cdot p')(k'\cdot p')-(m_a^2-k\cdot p')(k'\cdot k)\right]\epsilon^*_\mu(\mathbf{k}',\lambda')\epsilon^\mu(\mathbf{k},\lambda)\ +\left[(m_a^2-k\cdot p')k^\mu k'_\nu-(k'\cdot p')k^\mu p'_\nu-(k\cdot p')p'^\mu k'_\nu+(k'\cdot k)p'^\mu p'_\nu\right]\epsilon^*_\mu(\mathbf{k}',\lambda')\epsilon^\nu(\mathbf{k},\lambda)\right\}$$

- The module squared of the invariant amplitude of this process $\gamma + a \to \gamma + a$, $\overline{|\mathcal{M}|^2}$ is

$$\overline{|\mathcal{M}|^2} = \frac{1}{2}\sum_{\lambda,\lambda'}|\mathcal{M}_{a\gamma}|^2 = \frac{1}{2}\sum_{\lambda,\lambda'}\left(|\mathcal{M}_s|^2+|\mathcal{M}_u|^2+2\mathrm{Re}[\mathcal{M}_s\mathcal{M}_u^*]\right)\ ,$$

$$\frac{d\sigma}{d\Omega'_1} \approx \frac{g^4}{(32\pi)^2(\epsilon')^2}\left(m_a^2(\epsilon')^2[2+2\cos\theta'_1+3(1-\cos\theta'_1)^2]-4m_a^3(\epsilon')(1-\cos\theta'_1-(1-\cos\theta'_1)^2)+m_a(\epsilon')^3[2-2(1-\cos\theta'_1)^2]+4m_a^4(1-\cos\theta'_1)+2m_a(\epsilon')^3(1-\cos\theta'_1)^4\right)$$

Conclusions

- Another way of using the coupling of an ALP with two photons to study a phenomenon that may exist in nature is proposed.
- If it is possible to establish general expressions with those that are deduced with electrons, these will have a variety of applications to atrophyphysical phenomena.

Interests

- Astroparticle physics,
- Nature of dark matter (DM),
- Baryogenesis, Leptogenesis.
- Cosmology and understanding astrophysical phenomena

Thank you for your atention! :)

References

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