Astro-physical Signatures Of σ Photon Interaction.

A. K. Ganguly[1*] and M. K. Jaiswal[1]
[1] *MMV Physics, Banaras Hindu University, Varanasi- 221005, INDIA*

Introduction

Sigma meson (σ, alias f_0) is a charge neutral scalar resonance and it has $J^P = 0^+$. This resonance can decay into $\gamma\gamma$ with a width that lies between $\Gamma_{\sigma\to\gamma\gamma}$ =3-5 keV. Although it doesn't have a direct coupling to two photons at the tree level, however, it can couple to the latter via loop effects [1]. However there are differences of opinion about the structure of this resonance and the possible contribution to the loop effects from quark as well as the meson sectors [2]. The structure of the two photon decay vertex for $\sigma\gamma\gamma$ follows from the interaction part of a Lagrangian respecting gauge and Lorentz invariance, and it is given by,

$$\mathcal{L}_I = -\frac{1}{4} g_{\sigma\gamma\gamma}\phi F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where, the coupling constant $g_{\sigma\gamma\gamma}$ is given by $g_{\sigma\gamma\gamma} \sim g_\sigma N_c Q_\sigma I_\sigma \alpha$, with number of colors $N_c = 3$, charge factors $Q_\sigma = \frac{5}{9\sqrt{2}}$, loop factor $I_\sigma \sim \frac{2m_q}{m_\sigma^2}$ (for m_q= current quark mass) and the electromagnetic fine structure constant α. The factor g_σ, is usually considered to be, $g_\sigma = g_\pi = \frac{\sqrt{2}m_q}{f_\pi}$, (Goldberger-Trieman relation) where $f_\pi = 92.4MeV$, is the pion decay constant.

This interaction leads to the possibility of oscillation between the scalar meson and one of the polarized state of the photon in a magnetic field. The other polarized of the photon remains unaffected. The produced σ meson being unstable, would subsequently decay into photons of lower energy. Hence the intensity of the photon beam (with energy ω fixed) of the particular polarization state (that is coupled to the σ) would be degrade. The intensity of the other polarized state of photon, though, would remain the same. We intend to figure out astrophysical implication of this effect.

Pseudo-scalar–meson photon oscillation was originally studied in [3]. Following the same procedure, a similar analysis, when, carried out with the equations of motion given in [4], leads to the probability of a photon with polarization along the magnetic field B– oscillating into a σ meson. It may me noted, that photons with polarization orthogonal to B propagate freely, as mentioned before.

The probability $P(z)$– that a photon of energy ω of mass m_σ, oscillates into a σ meson in a magnetic field of strength B, after travelling a distance z– turns out to be,

$$P(z) = \frac{4\omega^2B^2}{m_\sigma^4 g_{\phi\gamma\gamma}^{-2} + 4\omega^2B^2} sin^2\left[\frac{\sqrt{m_\sigma^4 g_{\phi\gamma\gamma}^{-2} + 4\omega^2B^2}}{4\omega g_{\sigma\gamma\gamma}^{-1}}\right]. \quad (2)$$

Equation [2] agrees with the same obtained in [[5]], when the plasma frequency is neglected therein.

This oscillation probability leads to an oscillation-length, given by,

$$L_O = \frac{4\pi\omega g_{\sigma\gamma\gamma}^{-1}}{\sqrt{m_\sigma^4 g_{\sigma\gamma\gamma}^{-2} + 4\omega^2B^2}} \quad (3)$$

On the other hand the total decay rate for sigma to two photons, is given by

$$\tau_{\sigma\to\gamma\gamma} = \Gamma^{-1}_{\sigma\to\gamma\gamma} = \left[\frac{\pi}{4} g_{\sigma\gamma\gamma}^2 m_\sigma^3\right]^{-1} \quad (4)$$

Assuming, that the particles propagate with velocity close to that of light, oscillation length L_O can be converted to oscillation time by

*Electronic address: avijitk@hotmail.com

dividing the same by c. In natural units ($\hbar = c = 1$), it remains the same. So the ratio of [4] and [2] would provide us with the information about amount of decay of the σ mesons within one oscillation cycle.

Since most of the astrophysical objects come with magnetic field strength $B < 4.3 \times 10^{13} Gauss = .25 \times 10^{-6} GeV^2$., to a first approximation we can neglect terms proportional to B^2 in eqn. [3]. So the ratio $\frac{\tau}{L_O}$ turns out to be,

$$\mathcal{R} = \frac{\tau}{L_O} = \frac{1}{\pi^2 m_\sigma \omega g^2_{\sigma\gamma\gamma}}. \quad (5)$$

For ω close to m_σ, and realistic estimates of the parameters used in eqn. [5], the ratio $\mathcal{R}$ turns out to be greater than unity, implying oscillation time being less than decay time. Therefore only a fractional number of sigma would decay into photons of lower energy.

The magnetized compact objects emit radiation through, curvature radiation, with energy ω extending up to few TeV. The intensity of the electromagnetic beams polarized along $||$ and $\perp$ to the magnetic field has been estimated in terms of modified Bessel function.

$$I_{||}(0) = \left[\sqrt{\frac{8}{3\pi}} \frac{e\omega\rho\beta}{\gamma^2} K_{\frac{2}{3}}(\xi) \right]^2, \quad (6)$$

$$I_{\perp}(0) = \left[\sqrt{\frac{4}{3\pi}} \frac{e\omega\rho\beta}{\gamma^2} K_{\frac{1}{3}}(\xi) \right]^2, \quad (7)$$

$$\text{with} \quad \xi = \frac{\rho\omega}{3\beta}[1/\gamma^2 + \theta^2] \quad (8)$$

In eq. [8], e, ρ, γ are the electric-charge, radius of curvature of the trajectory and instantaneous Lorentz factor of the emitting charged particle and ω along with θ are the energy and opening angle of the emitted radiation.

According to the scenario of our concern $I_\perp$ would not change however $I_{||}$ would attenuate because, they would oscillate into σ that subsequently decays to $\gamma\gamma$. Hence, the oscillation physics can be tested by measuring the intensity of the orthogonally polarized photons coming from distant astrophysical sources.

In terms of the intensities of the radiation beams, the modified intensity, after passing through a distance z in a domain of size one oscillation length $L_O (> z)$ would turn out to be,

$$I_\perp(0) = I_\perp(0),$$
$$I_{||}(0) = I_{||}(0) P(z) \times e^{-\Gamma \frac{m_\sigma}{\omega}(L_o - z)}, \quad (9)$$

where, the factor $\frac{m}{E}$, corresponds to Lorentz boost, for going from the rest frame of sigma to frame of the observer. Rest of the terms have their usual significance.

A strong B field exists in the environment of a compact star, i.e., inside a cylindrical region of radius $R_{LC} = 1/\Omega$ (Ω= rotational velocity of the star); with the axis of the cylinder passing through the center of the star. Therefore one can break up the path of the photons into different domains of size L_O and estimate final $I_{||}$ by summing the contributions due oscillation and decay, from each domain.

Estimation of enhancement in linear polarization due to $\sigma \to \gamma\gamma$ becomes an important exercise, in the light of the fact, that high energy radiation from astrophysical sources show a high degree of linear polarization. Work in this direction is currently under progress and would be reported shortly.

References

[1] F. Giacosa, T. Gutsche and V. E. Lyubovitskij, Phys. Rev. **D77**, 034007 (2008)

[2] E. V. Bereven F. Kleefeld, G. Rupp and M. Scadron, arXiv:0811.2589.

[3] G. Raffelt and L. Stodlsky , Phys. Rev. **D37**, 1237 (1988).

[4] A. K. Ganguly and M. K. Jaiswal, Phys. Rev. **D90**, 026002 (2014). A. K. Ganguly and R. Parthasarathy, Phys. Rev. D79, 2015 (2003).

[5] C. Burrage, Phys. Rev. **D77**, 043009 (2008).
(2009).