# Effect of mixing of massive scalar-photon in magnetized media

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## Introduction

In the areas of high energy particle physics and cosmology. They are some problems: (1) explanation of the current state of acceleration of the universe and (2) unification of the basic four forces of nature. Though these two problems appear to be diverse in their origin, one associated with largest and the other with smallest length scale, however there is a hope that there may be a common solution to both of these issues.
There are observational evidences [1] that the universe is currently undergoing acceleration. One of the ways to resolve this problem is by introducing a new type of radiation field that has negative pressure. Generally the existence of a new type of massive scalar field are postulated that acts as 'dark matter' and this field couples to ordinary matter fields.
In this paper we are performing the interaction of photon with massive scalar (like dilaton, graviexiton, chameleon etc.) field in presence of background magnetic field. The interaction of pseudoscalar or scalar field ($\phi$) with photon ($\gamma$) through dimension-five operators originates in many theories beyond the framework of standard model of particle physics. Interaction of photon with massless scalar field have described in Refs. [2]-[4] and interaction of pseudoscalar with photon have described in Refs. [5]-[6]. These type of interaction terms appear in the lagrangian of bosonic sector of unified theories of electromagnetism and gravity. Since photon-scalr interaction turns the vacuum into a birefringent and dichoric one [7], as polarized light passes through such a medium, its plane of polarization keeps rotating i.e optical activity.
Celestial compact stars, like white-dwarfs, neutron star pulsars etc., have very strong magnetic field strength near about $10^{13}G$. The polarized spectrum of photons are generated through synchrotron ( or curvature) radiation as the charged particles accelerate along the curved dipole magnetic field lines of the compact star. Therefore compact stars can be considered as preferred laboratories for such studies.

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## Equations of Motion

In this paper, we are working in flat four dimensional space time. The suitable action for coupled photon-scalar system is defined as

$$S = \int d^4x[\frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^2 - \frac{1}{4}g_{\phi\gamma\gamma}\phi F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}]. \quad (1)$$

Where $g_{\phi\gamma\gamma}$ is the coupling constant between photon field and scalar field, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor and $m$ is the mass of the scalar particle.
Here we are applying the variational principle on Eq. (1), for obtained the equations of motion for interacting photon scalar system. Here we break the electromagnetic field in two parts i.e., $F^{\mu\nu} = \bar{F}^{\mu\nu} + f^{\mu\nu}$. First part is background magnetic field and second part is the fluctuation field. With this assumption the equations of motion for photon and scalar field are given as

$$\partial_\mu\left[f^{\mu\nu} + g_{\phi\gamma\gamma}\phi\bar{F}^{\mu\nu}\right] = 0,$$
$$\partial_\mu\partial^\mu\phi + m^2\phi + \frac{1}{2}g_{\phi\gamma\gamma}f_{\alpha\beta}\bar{F}^{\alpha\beta} = 0. \quad (2)$$

Equation (2) describe that the photon couples with scalar field and scalar field couple with photon. The photon has two degrees of freedom and another degree of freedom corresponds to scalar field. We can study the dynamics of coupled photon-scalar system in the presence of background magnetic field. Here we use the Bianchi Identity i.e.,

$$\partial_\mu f_{\nu\lambda} + \partial_\nu f_{\lambda\mu} + \partial_\lambda f_{\mu\nu} = 0. \tag{3}$$

After performing some algebra, we introduce two new variables, $\psi = \frac{f\bar{F}}{2}$, and $\tilde{\psi} = \frac{f\tilde{F}}{2}$ and go to Fourier space. The resulting equations of motion in momentum space are:

$$\begin{aligned} k^2\psi &= g_{\phi\gamma\gamma}\left(k_\alpha \bar{F}^{\alpha\nu}\bar{F}_{\nu\lambda}k^\lambda\right)\phi, \\ k^2\tilde{\psi} &= 0, \\ (k^2 - m^2)\phi &= g_{\phi\gamma\gamma}\psi. \end{aligned} \tag{4}$$

Equation (4) would in general provide three equations, corresponding to two transversely polarized states of the photon and the scalar field. Redefining $\Phi = \omega\mathcal{B}_T\phi$ for symmetry. The momentum space representation of the equations of motion can be written in matrix form,

$$\begin{pmatrix} k^2 & 0 & 0 \\ 0 & k^2 & -g_{\phi\gamma\gamma}\omega\mathcal{B}_T \\ 0 & -g_{\phi\gamma\gamma}\omega\mathcal{B}_T & k^2 - m^2 \end{pmatrix} \begin{pmatrix} \tilde{\psi} \\ \psi \\ \Phi \end{pmatrix} = 0.$$

Where $\mathcal{B}_T = \mathcal{B} sin\Theta$ is the transverse magnetic field, and $\Theta$ is the angle between $\mathcal{B}$ and propagation vector.

Here one polarization state of photon $\psi$ mixed with $\Phi$ and other polarization state $\tilde{\psi}$ propagate without any interaction. Therefore the matrix become $\left[\ k^2 I + M\ \right] \begin{pmatrix} \psi \\ \Phi \end{pmatrix} = 0.$ Where $M$ is a 2x2 mixing matrix

$$M = \begin{pmatrix} 0 & -g_{\gamma\gamma\phi}\mathcal{B}_T\omega \\ -g_{\gamma\gamma\phi}\mathcal{B}_T\omega & -m^2 \end{pmatrix}.$$

The strength of the mixing is characterized by the ratio of off diagonal terms in matrix. The mixing angle for scalar $\Phi$ and parallel component of polarization vector $\psi$ is given by $\theta = \frac{1}{2}\arctan\left[\frac{2g_{\gamma\gamma\phi}B_T\omega}{m^2}\right]$. The solutions for three degrees of freedom are defined as

$$\begin{pmatrix} \tilde{\psi} \\ cos\theta\ \psi + sin\theta\ \Phi \\ -sin\theta\ \psi + cos\theta\ \Phi \end{pmatrix} = \begin{pmatrix} A_0 e^{i(\omega t - k.x)} \\ A_1 e^{i(\omega_+ t - k.x)} \\ A_2 e^{i(\omega_- t - k.x)} \end{pmatrix} \tag{5}$$

Here we consider the following boundary conditions, $\Phi(0,0) = 0$ and $\psi(0,0) = 1$. With this condition we have, $\frac{A_2}{sin\theta} = -1$ and $A_1 = cos\theta$. The solns. for $\psi$ and $\Phi$ turn out to be:

$$\begin{aligned} \psi(t,x) &= \left[cos^2\theta\ e^{i(\omega_+ t - k.x)} + sin^2\theta\ e^{i(\omega_- t - k.x)}\right], \\ \Phi(t,x) &= \frac{1}{2}sin2\theta\left[e^{i(\omega_+ t - k.x)} - e^{i(\omega_- t - k.x)}\right]. \end{aligned} \tag{6}$$

When $\theta = \frac{1}{2}\arctan\left[\frac{2g_{\gamma\gamma\phi}\mathcal{B}_T\omega}{m^2}\right]$.

With the help of solutions we can calculate optical parameters like polarization, ellipticity and total degree of polarization of a given light beam, can be found from the components of the coherency matrix constructed from the correlation functions stated. The stokes parameters are:

$$\begin{aligned} \mathrm{I} &= <\psi^*\psi> + <\tilde{\psi}^*\tilde{\psi}>, \\ \mathrm{Q} &= <\psi^*\psi> - <\tilde{\psi}^*\tilde{\psi}>, \\ \mathrm{U} &= 2\mathrm{Re} <\psi^*\tilde{\psi}>, \\ \mathrm{V} &= 2\,\mathrm{Im} <\psi^*\tilde{\psi}>. \end{aligned} \tag{7}$$

Where I is the intensity, Q and U are linear polarization and V is circular polarization of electromagnetic radiation. The ellipticity angle ($\chi$), and polarization angle ($\Psi$) can be calculated by use of stokes parameters, and defined as $\tan 2\chi = \frac{\mathrm{V}}{\sqrt{\mathrm{Q}^2+\mathrm{U}^2}}$, and $\tan 2\Psi = \frac{\mathrm{U}}{\mathrm{Q}}$.

## References


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