Nearly massless pseudoscalar particles and polarization of starlight

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The existence of nearly massless pseudoscalar particles may lead to a polarization of starlight. The polarimetric data available are used to derive limitations on the effective coupling constant.

The possible existence of massless or very light pseudoscalar Goldstone particles has been discussed in many papers (see, e.g., the review by Ansel'm and Ural'tsev[1] and the bibliography there). Their effective interaction with an electromagnetic field is described by[2]

$$L = \frac{1}{M}(\mathbf{E}\cdot\mathbf{B})A,$$

where A is a pseudoscalar, $\mathbf{E}$ is the electric field, and $\mathbf{B}$ is the magnetic field. Severe limitations on the coupling constant M follow from an analysis of the energy loss of stars. The most reliable of these limitations is the "solar" limitation[3]: $M > 3\times 10^8$ GeV for $m < 1$ keV. The results of laboratory experiments are weaker; for example, the limitations[4] which have been obtained on the coupling constant of an arion[1] with certain fermions may correspond to $M > 10^6$ GeV. Laboratory experiments have been proposed [5] to search for pseudoscalars by studying the photon-pseudoscalar conver-

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sion in a magnetic field; these experiments would have a sensitivity to M on the order of 10^8–10^{11} GeV. The amplitude of the γ-A transition is

$$V = i\frac{|\mathbf{B}_\perp|}{M} ,$$

where $\mathbf{B}_\perp$ is the component of the vector $\mathbf{B}$ which is directed perpendicular to the light propagation direction. It can be seen from (1) that only the polarization of the light parallel to $\mathbf{B}_\perp$ participates in this process.

Direct observations[6,7] show that the light of stars in the interstellar medium is polarized. On the other hand, there is evidence for the existence of a large-scale galactic magnetic field with $B \approx 3\times 10^{-6}$ G (Refs. 7 and 8). Let us examine γ-A oscillations in the interstellar medium:

$$i\frac{d}{dt}\begin{pmatrix} a_\gamma \\ a_A \end{pmatrix} = \begin{pmatrix} V_\gamma & V \\ V^* & V_A \end{pmatrix}\begin{pmatrix} a_\gamma \\ a_A \end{pmatrix} .$$

Here a_γ is the amplitude of the photon state with polarization parallel to $\mathbf{B}_\perp$; a_A is the amplitude of the psedoscalar state; V_γ corresponds to the forward scattering of a photon in the interstellar medium; and $V_A \approx m^2/2\omega$, where m is the mass of the pseudoscalar, and ω is the energy of the photon. If the scattering of the light by the medium does not select any polarization, the degree of linear polarization of the light at a distance l from the star, under the initial conditions $a_\gamma(0) = 1$, $a_A(0) = 0$, will be

$$P = \frac{1 - |a_\gamma(l)|^2}{1 + |a_\gamma(l)|^2} \approx \frac{1}{8}\left[\frac{V_B}{W}\sin(Wl)\right]^2$$

$$W = \frac{1}{2}\sqrt{(V_\gamma - V_A)^2 + V_B^2}, \qquad V_B = 2\frac{B_\perp}{M} .$$

We first consider the case $m = 0$ (an arion). Most of the forward scattering is caused[7] by hydrogen atoms and free electrons:

$$V_\gamma = V_{\mathrm{H}} + V_e ; \quad V_{\mathrm{H}} = -\frac{2\pi e^2}{m_e}\frac{n_{\mathrm{H}}\,\omega}{\omega_0^2 - \omega^2}, \; V_e = \frac{2\pi e^2}{m_e}\frac{n_e}{\omega} .$$

Here n_H and n_e are the densities of hydrogen atoms and electrons, ω is the photon energy, and $\omega_0 = 13.6$ eV. We might note that V_H and V_e differ in sign. Consequently, there exists a frequency $\omega_{\max}$ at which the relation $V_\gamma = 0$ holds, and at which oscillations can occur with the maximum amplitude. For the mean galactic values[7] $n_H = 1\ \mathrm{cm}^{-3}$ and $n_e = 0.03\ \mathrm{cm}^{-3}$, for example, we would have $\omega_{\max} = 2.3$ eV (visible light).

The polarization of the light in the interstellar medium is currently explained on the basis of a scattering by nonspherical dust grains which are oriented in the galactic magnetic field.[7] Dust grains polarize the light in the direction parallel to the magnetic field, while the pseudoscalars, in constrast, would polarize it in the direction perpendicular to the magnetic field. In the simplest case of a simultaneous effect the result would be equal in magnitude to the difference between the effects and would be directed toward the larger of them. It would seem to be a simpler matter to reconcile the observed polarization of starlight with independent data on the direction of the magnetic field[6,7] by talking in terms of dust grains. For completeness, however, we should add that our analysis also applies to a scalar field φ with an effective interaction

$$L_s = \frac{1}{M_s} (\mathbf{E}\cdot\mathbf{E} - \mathbf{B}\cdot\mathbf{B})\varphi .$$

In this case the γ-φ oscillations polarize the light in the direction parallel to the magnetic field direction. The values of M_s in which we are interested cannot be ruled out entirely by the severe limitations which have been found previously[9] on the coupling constant φ for the coupling with electrons and u and d quarks.

The complete picture of the polarization, including dust grains and (pseudo) scalars, a complicated picture, depends on many parameters, which have been determined only within large errors. We will reproduce here only the limitation found from an analysis of data on nearby stars.[6] Their light—within the errors—is unpolarized. Let us assume that the (pseudo) scalar polarization does not exceed the measurement error. Assuming $B = 3\times 10^{-6}$ G and $n_H = 0.1$ cm^{-3} (Refs. 7 and 8), we find, for $n_e/n_H \leqslant 10\%$ (the mean galactic value is 3%),

$$V_B < 6\times 10^{-3}\ \mathrm{ps}^{-1}, \qquad M, M_s > 10^{10}\ \mathrm{GeV}.$$

In the presumably worse case $n_e = 0.03$ cm^{-3} we would have M, $M_s > 2\times 10^9$ GeV.

The arguments above are valid for $qL \lesssim 1$ (cf. Van Bibber *et al.*[5]), where $q = m^2/2\omega$ is the momentum transferred to the magnetic field, m is the mass of the (pseudo) scalar, ω is the energy of the photon, and L is the length scale of the field variations. In our case, we would have $L \approx 10^2$ pc (Refs. 7 and 8) and $m < 10^{-12}$ eV.

We note in conclusion that the galactic magnetic field could also have some significant effects in other cases. In particular, the existence of a magnetic moment of a neutrino[10,11] would lead to oscillations of neutrinos from the observable left-hand type into the sterile right-hand type. At a magnetic moment $\mu = 10^{-10}\,\mu_{\mathrm{B}}$ (this value was cited in Ref. 10 in order to explain the results of the Davis experiment) the oscillation length would be $l = 2\pi(\mu B)^{-1} \approx 20$ pc. The same would be true of the case in which the neutrino had an electric dipole moment.[12]

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