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## DECAY OF PHOTON WITH HIGH AS WELL AS LOW ENERGY

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**Abstract:** The decay of photon by the influence of magnetic field is considered. It is shown here that if the photon energy is greater than 1 MeV then photon can decay electron positron pair, but if it remains below 1 MeV then photon decays into neutrino antineutrino pair. The decay rates for both of the processes are calculated. All possible Feynman diagrams are taken into account to construct the matrix element for either of the processes. In the second process all three type of neutrinos are considered. The significance of these processes are discussed briefly.

**Keywords:** photon decay, electron-positron pair emission, neutrino-antineutrino pair emission, strong magnetic field, decay rate

### I INTRODUCTION

The photon splitting phenomenon brought the attention to the scientists and researchers. Apparently it may not be possible for the massless photon to be decayed into the massive particles. But in presence of strong magnetic field the photon breaks up into electron positron pair when its energy is very high, whereas in the comparatively low energy it gets decayed weakly into neutrino antineutrino pair having very little mass. First time such possibility was considered by Adler [1]. After that many researchers calculated this process. In 1996 the process was considered and recalculated by Adler and Schubert [2] below the pair production threshold using a variant world line path integral approach to the Bern-Kosower formalism. Wilke and Wunner [3] calculated numerically the photon splitting process and their results confirmed the asymptotic approximations in the low as well as high magnetic field. Some works were started to consider the photon decay into neutrino pair. DeRaad et al. [4] considered the decay of photon into neutrino antineutrino pair to study the significance of this process during stellar evolution. In 1998 Kuznetsov et al. [5] calculated the probability of the decay of photon into such neutrino pair in presence of strong magnetic field and evaluated the contribution of the process to the neutrino luminosity in some astrophysical circumstances. Here the calculations are carried out for the high energy as well as relatively low energy photon. Such high energetic photon may be created in the laboratory and also during some astrophysical phenomena like supernova. Here the low energy photon decay would have a structural similarity with the decay of anisotropic

plasma into neutrino antineutrino pair. One must follow the usual rules of quantum electrodynamics when the final particles are electron positron pair, whereas in case of photon decay into neutrino antineutrino pair the calculations are carried out in the framework of electro-weak theory.

### II DECAY OF PHOTON INTO ELECTRON POSITRON PAIR

It is already stated that the photon with very high energy can be decayed into electron positron pair. It is very interesting that mass less photon breaks up into a pair of massive particles, although here the energy of the photon would be so high that the rest energy of the electron can be neglected. In presence of strong magnetic field the photon acquires a rest mass that is considered as the magnetic mass. The decay rate is to be calculated and in this context the Feynman diagram, given by Figure-1, is taken into account. Let us construct the matrix element as

$$M_{fi}^e = ie^3 \varepsilon_\mu \Pi^{\mu\rho}(k) \frac{\bar{u}(q_1) \gamma_\rho v(q_2)}{(q_1 + q_2)^2} \quad (2.1)$$

The term  $\Pi^{\mu\rho}(k)$  present in the matrix element represents the response tensor. It is quite clear that the term  $\Pi^{\mu\rho}$  arises due to the electron-positron loop present in the diagrams. It will not have any diverging term since the gauge invariance imposes the restriction

$$k_\mu \Pi^{\mu\rho}(k) = 0 \quad (2.2)$$

The response tensor depends on the magnetic field as well as four momentum of the photon in plasma. If these two parts are separated the response tensor takes the form

$$\Pi^{\mu\rho}(k) = A(k^\mu k^\rho - g^{\mu\rho} k^2) \quad (2.3)$$

Clearly this equation satisfies the gauge invariance restriction (2.2). Note that the dimensionless quantity  $A$  depends on the magnetic field i.e.,

$$A = A(H)$$

where,  $H$  represents the magnetic field.

With the same argument the term  $k$  is free from magnetic field. The decay rate is obtained from the following expression.

$$\tau_e = \frac{4\pi S}{2\omega} \int \sum |M_{fi}|^2 \frac{N_{q_1} d^3 q_1 N_{q_2} d^3 q_2}{2q_1^0 (2\pi)^3 2q_2^0 (2\pi)^3} \delta^4(k - q_1 - q_2) \quad (2.4)$$

where  $N_i$  ( $i = 1; 2$ ) is twice the mass of the corresponding fermion and  $S$  represents the degeneracy factor for the outgoing particles.

Calculating the squared sum matrix element term, finally, the decay rate is obtained as follows.

$$\tau_e = \alpha^2 \frac{k^2}{\omega^5} |Ak^2|^2 \quad (2.5)$$

Now we can evaluate the term  $|Ak^2|^2$  as

$$|Ak^2| \approx \frac{4\sqrt{\alpha}}{3\pi^2} \left( \frac{H}{H_c} \right) m_e^2 \frac{|\vec{k}|}{\omega} \quad (2.6)$$

Finally the decay rate for this process can be obtained as

$$\tau_e \approx 4.69 \times 10^9 \times \left( \frac{H}{H_c} \right)^2 \left( \frac{m_e}{m_H} \right)^3 f_e(\eta) \text{ sec}^{-1} \quad (2.7)$$

The function  $f_e(\eta)$  is defined as

$$f_e(\eta) = \eta^5 (1 - \eta^2) \quad (2.8)$$

and

$$\eta = \frac{m_H c^2}{\hbar\omega} \quad (2.9)$$

where  $m_H$  stands for the effective mass of the photon appearing due to the presence of high magnetic field, which is given by

$$m_H = r \left( \frac{H}{H_c} \right)^{\frac{1}{2}} m_e \quad (2.10)$$

Here  $r$  is a constant which makes the effective mass of the photon (due to the presence of magnetic field) greater than the electron mass.

We can evaluate the value of  $r$  as  $2(H/H_c)^{1/2}$  in the rest frame. In the equation (2.8) the term is very small which makes the effective decay rate lower. In Table-1 we compute the decay rate of photon in the energy range 10-100 MeV and then also in 1-100 GeV.

### III DECAY OF PHOTON INTO NEUTRINO ANTINEUTRINO PAIR

In the calculation of decay rate it is considered the case when the photon energy is relatively low. The Feynman diagrams for this process are given by the Figure-2(a) and (b) indicating neutrino emission takes place through the exchange of Z-boson and W-boson respectively. The matrix element for this process is constructed as

$$M_{fi}^{\nu} = -ie \frac{G_F}{\sqrt{2}} \varepsilon_\mu [g_V \Pi^{\mu\rho}(k) + g_A \Pi_A^{\mu\rho}(k)] \bar{u}_\nu(q_1) \gamma_\rho (1 - \gamma_5) v_\nu(q_2) \quad (3.1)$$

whereas  $\Pi_A^{\mu\rho}(k)$  stands for the same, but associated with axial vector part.

In equation (3.1) the term  $g_A$  and  $g_V$  are defined by

$$g_V = 2 \sin^2 \theta_W + \frac{1}{2} \quad \text{and} \quad g_A = -\frac{1}{2} \quad \text{for } \nu_e$$

$$g_V = 2 \sin^2 \theta_W - \frac{1}{2} \quad \text{and} \quad g_A = \frac{1}{2} \quad \text{for } \nu_\mu \text{ and } \nu_\tau$$

The term  $\Pi^{\mu\rho}(k)$  would be defined in the same way as it is defined in the equation (2.1) and the same gauge invariance condition defined by the equation (2.2) will be applicable here. Similarly one can find the expression for the axial vector part. It is almost same as the equation (2.1), only difference is the presence dimensionless term  $A_5$  instead of  $A$ . The decay rate for this process for all three type of neutrinos is calculated as

$$\tau_\nu = G_F^2 \alpha \frac{k^2}{\omega} |(g_V A + g_A A_5) k^2|^2 \quad (3.2)$$

To calculate the term  $|(g_V A + g_A A_5) k^2|^2$  the result obtained by Kennett and Melrose [6] in studying the decay of anisotropic plasma may be exploited, although it is to be remembered that the decay of ordinary photon is considered. Using that result it is found

$$|(g_V A + g_A A_5) k^2| \approx \frac{\sqrt{\alpha}}{3\pi^2} \left( \frac{H}{H_c} \right) m_e^2 \frac{|\vec{k}|}{\omega} \quad (3.3)$$

Finally the decay rate for this process can be obtained as

$$\tau_\nu \approx 3.295 \times 10^{-10} \times \left( \frac{H}{H_c} \right)^2 \frac{\hbar\omega}{m_e c^2} f_\nu(\eta) \text{ sec}^{-1} \quad (3.4)$$

The function  $f_\nu(\eta)$  is defined to be

$$f_e(\eta) = \eta^2(1 - \eta^2) \tag{3.5}$$

The equation (3.4) represents the decay rate of the splitting of photon into neutrino pair in the C.G.S. unit.

TABLE 1

The decay rate of the photon at the magnetic field  $H= 10^5$  G in the energy range 10 – 100 MeV and 1 – 100 GeV.

$E$ (MeV)	$\tau_e$ (sec <sup>-1</sup> )	$E$ (GeV)	$\tau_\nu$ (sec <sup>-1</sup> )
10	$3.48 \times 10^{-7}$	1	$2.15 \times 10^{-22}$
20	$1.09 \times 10^{-8}$	10	$2.15 \times 10^{-27}$
30	$1.43 \times 10^{-9}$	20	$6.72 \times 10^{-29}$
40	$3.4 \times 10^{-10}$	30	$8.86 \times 10^{-30}$
50	$1.11 \times 10^{-10}$	40	$2.1 \times 10^{-30}$
60	$4.48 \times 10^{-11}$	50	$6.89 \times 10^{-31}$
70	$2.07 \times 10^{-11}$	60	$2.77 \times 10^{-31}$
80	$1.06 \times 10^{-11}$	70	$1.28 \times 10^{-31}$
90	$5.9 \times 10^{-12}$	80	$6.57 \times 10^{-32}$
100	$3.48 \times 10^{-12}$	90	$3.64 \times 10^{-32}$
-----	-----	100	$2.15 \times 10^{-32}$

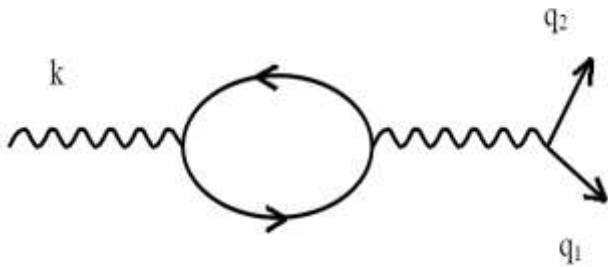
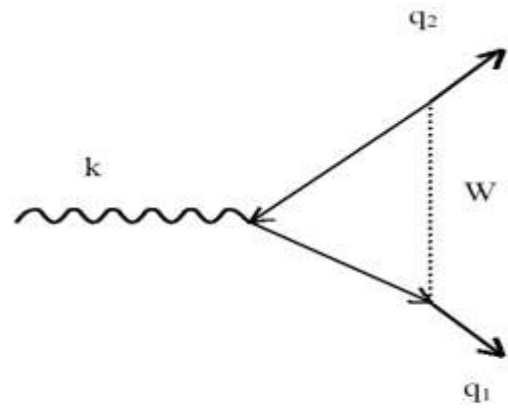
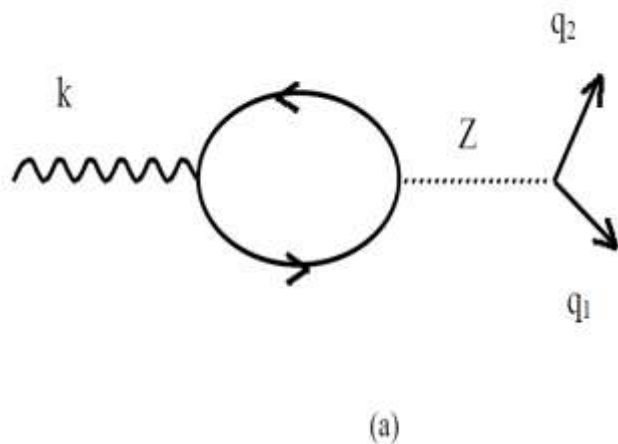


Figure 1 Feynman diagram for photon decay in presence of magnetic field into electron-positron pair.



(b)

Figure 2 Feynman diagrams for photon decay in presence of magnetic field into neutrino-antineutrino pair through (a) exchange of Z boson and (b) exchange of W boson.

IV CONCLUSION

In the equation (2.7) the decay rate is calculated for high energy photon. Such a high energy photon can be created in the laboratory to verify the correctness of our calculation since the charged electron positron pair is formed. The decay rate is computed at a particular magnetic field ( $10^5$  G) that can be generated in the laboratory. It is worth noting that a higher magnetic field can be generated in the laboratory, which depends on the experimental setup of the magnets. In that case the decay rate will be increased a bit. The decay of photon into electron positron pair is possible when the energy of the photon is much higher than 1 MeV, but the result in this article shows that the decay rate will slowly diminish with increasing the photon energy, especially when the energy goes to the GeV range. It indicates that the decay of photon becomes insignificant when the photon energy is extremely high. This is an important consequence because it excludes the possibility of the divergence of decay rate for the photon with extremely high energy, which is not possible to verify in the laboratory. The high energy photon decay can occur during the late stages of the stellar evolution. The quantization of the gamma ray can provide high energetic photon that may decay into electron positron pair. There may also be some circumstances, for example, the cooling of highly magnetized neutron stars and magnetars the intensity of the magnetic field may reach to  $10^{16}$  G and in presence of such super strong magnetic field the decay rate might not be very small, but it is quite impossible to verify such phenomenon experimentally. In case of low energy photon the decay process yields neutrino antineutrino pair, although the decay rate would be very small compared to the decay of plasma in presence as well as in absence of magnetic field. In stellar core both of the decay processes, considered here, occur simultaneously. The weak decay of photon into neutrino antineutrino pair may contribute to the

energy loss mechanism as the mean free path of the neutrino is longer than the stellar radii. Hence, the photon decay is an important process in either case i.e., when the energy of the photon is very high as well as low.

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