SPIN-POLARIZATION EFFECTS OF THE RESONANT COMPTON SCATTERING PROCESS IN A SUPERCRITICAL MAGNETIC FIELD

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A study of resonant photon scattering on an electron in subcritical and supercritical magnetic fields has been conducted. The case is considered where photons propagate perpendicular to the magnetic field, the initial and final electrons are in the ground spin state and at the ground Landau level, while the intermediate electron is at the first excited level. It is shown that if the initial photon has normal or anomalous linear polarization, the final photon will have the same polarization. In the case of right- or left-handed circular polarization of the initial photon, the polarization of the final photon will be a combination of right- or left-handed circular and linear polarization.

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INTRODUCTION

The existence of neutron stars, such as pulsars and magnetars, with their extreme magnetic fields, makes theoretical studies of quantum electrodynamics (QED) in strong magnetic fields highly relevant. In theoretical models of such objects, elementary QED processes play a key role, particularly in the generation of electron-positron plasma near the poles, which is primarily associated with the pair production process.

It is worth noting that in recent years, significant interest has been given to the experimental verification of nonlinear QED effects, particularly the effect of vacuum birefringence. Attempts have been made to detect this effect under laboratory conditions, notably in the PVLAS (Polarization of the Vacuum with LASer) experiment [1]. Additionally, experiments using high-power lasers are planned. Such experiments will be conducted at HIBEF (the Helmholtz International Beamline for Extreme Fields) using the XFEL facility (European X-ray Free Electron Laser, Germany) [2] as well as at ELI (Extreme Light Infrastructure, Czech Republic, Romania, Hungary) [3]. Furthermore, the first results of studies on the polarization of optical radiation from neutron stars, where the magnetic field strength is close to the critical value, have emerged. In particular, for the first time, the degree of optical photon polarization for the isolated neutron star RX J1856.5-3754 has been determined, which may be a manifestation of vacuum polarization in a strong magnetic field [4].

The process of Compton scattering in an external magnetic field has been studied in several works [5-13]. In [5], the scattering cross-section was obtained using the Schwinger method for the case when the photon propagates along the magnetic field. In [6], the differential cross-section was determined for the case where both the initial and final electrons are at the ground Landau level. The process of photon scattering by an electron, where the initial electron is in the ground state with resonances taken into account, was considered in [7]. The case of low Landau levels was examined in [8], taking into account the two-photon Compton scattering process, showing that its probability in resonance is comparable to the non-resonant single-photon process. In [9], the scattering of soft photons by relativistic electrons moving along the direction of a strong magnetic field was studied. In [10], a comparison of two relativistic processes photon absorption by an electron and Compton scattering was performed, taking into account particle spins. It was shown that in resonance, these cross-sections are equal. In [11], the scattering of a photon by an electron was analyzed in both resonant and non-resonant regimes, considering the polarization of radiation when a relativistic electron moves along the field. In [12], resonant and inter-resonant Compton scattering was studied, taking into account the electron's spin. Under resonant conditions, the differential cross-section was presented in the Breit-Wigner form. It was shown that in a magnetic field close to the critical value, the resonant cross-section exceeds the inter-resonant cross-section by several orders of magnitude. In [13], differential cross-sections were obtained for this process, valid in both subcritical and supercritical magnetic fields, for the case where the initial photon propagates along the field with the electron's spin taken into account.

Despite the significant body of research dedicated to the study of Compton scattering in a magnetic field, the influence of particle polarization on the cross-section of the process in the case of a supercritical magnetic field remains insufficiently studied. This issue is addressed in the present work.

KINEMATICS

In a magnetic field, the laws of conservation of energy and the longitudinal component of momentum relative to the magnetic field are fulfilled

$$\begin{cases} E_l + \omega = E_{l'} + \omega', \\ p_z + k_z = p'_z + k'_z, \end{cases}$$

where E_l, p_z, l are the energy, longitudinal momentum and Landau level number of the initial electron, ω, k_z are the energy and longitudinal momentum of the photon, the dash indicates the corresponding values of the final electron and photon.

The paper considers the case when the initial electron has zero longitudinal momentum with respect to the magnetic field, which does not affect the generality of the problem, since we can always use Lorentz transformations to move to a reference frame in which longitudinal momentum is absent. In this case, we can find that

$$\omega' = \frac{1}{s'^2}(m_l + \omega - \omega u u' -$$

$$-\sqrt{(\omega(u-u')-m_l u')^2+m_l^2 s'^2}),$$

where $m_l = m\sqrt{1+2hl}$, $h = H/H_c$, $u = \cos\theta$, $s = \sin\theta$, H_c is the critical Schwinger magnetic field, θ is the polar angle of the initial photon.

In the case when $u' = \pm 1$, then we have

$$\omega' = \frac{(m_l+\omega)^2-\omega^2 u^2-m_{l'}^2}{2(m_l+\omega-\omega u u')}.$$

Fig. 1 shows the dependence of the frequency of the final photon on its angle of departure and the frequency of the initial photon for the case when the initial electron has zero longitudinal momentum, $l = l' = 0, h = 10, u = 0$. The figure shows that the frequency of the emitted photon increases with increasing energy of the initial photon and has a maximum at $u' = 0$.

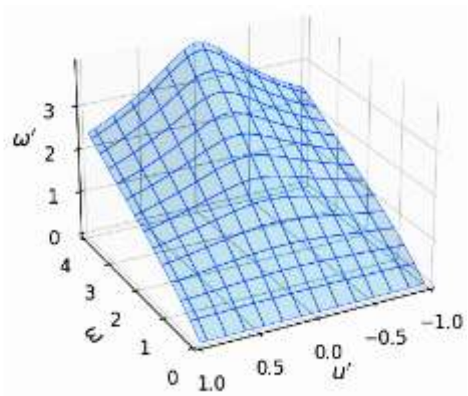

Fig. 1. Dependence of the frequency of the final photon on the cosine of its polar angle and the frequency of the initial photon at $l = l' = 0, h = 10$ and when the initial photon propagates perpendicular to the field

RESONANCE CROSS-SECTION OF THE PROCESS

The paper considers the process of Compton scattering of a photon by an electron, where the intermediate particle goes on-shell, and the probability exhibits a resonant character. A specific case is analyzed in which the initial and final electrons are at the ground Landau levels and in the ground spin states, while the intermediate electron is at the first excited level.

In this case, only one Feynman diagram contributes to the amplitude, which is shown in Fig. 2. From this diagram, it is evident that the initial electron sequentially absorbs the initial photon and then emits the final one.

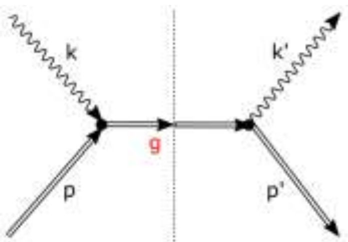

Fig. 2. Feynman diagram g of resonant Compton scattering

The resonant frequency of the initial photon in the case of its perpendicular propagation has the following form

$$\omega_0 = \sqrt{m_l^2+2(n_g-l)m^2 h}-m_l,$$

n_g is Landau level of the intermediate electron.

The differential cross-section in this case can be written as follows

$$\frac{d\sigma}{du'} = \frac{\pi e^4\omega^2\eta^2 e^{-2\eta}}{2(\omega+m+E_g)^2\left((\omega-\omega_0)^2+\frac{\Gamma^2}{4}\right)}\Xi(\xi_i,\xi'_i),$$

$$\Xi(\xi_i,\xi'_i) = (1+\xi_3)(1+\xi'_3)+\frac{2}{\eta}(\xi_1\xi'_1+\xi_2\xi'_2)+$$
$$+\frac{1}{\eta^2}(1-\xi_3)(1-\xi'_3),$$

where Γ is the resonance width, ω_0 is the resonant frequency, ξ_i are the Stokes parameters of the initial photon, $\eta = \omega^2/2hm^2$.

POLARIZATION PROPERTIES

From the expression for the cross-section, it is evident that it does not factorize, unlike the non-relativistic case. From the analysis of the resonant cross-section of the process, it can be found that the Stokes parameters of the final radiation are as follows

$$b_1 = \frac{2\eta\xi_1}{1-\xi_3+\eta^2(1+\xi_3)}, b_2 = \frac{2\eta\xi_2}{1-\xi_3+\eta^2(1+\xi_3)},$$
$$b_3 = \frac{-1+\xi_3+\eta^2(1+\xi_3)}{1-\xi_3+\eta^2(1+\xi_3)}.$$

As can be seen from the above expressions, the polarization depends on the polarization of the initial photon, its frequency, and the values of the magnetic field, and the radiation is completely polarized.

Let us consider individual cases depending on the polarization of the initial photon.

1) Normal and anomalous polarization of the initial photon ($\xi_{1,2} = 0, \xi_3 = \mp 1$):

$$b_{1,2} = 0, b_3 = \mp 1.$$

In this case, the polarization of the final radiation coincides with the polarization of the initial one.

2) Polarization at an angle $\pm 45°$ ($\xi_{2,3} = 0, \xi_1 = \pm 1$):

$$b_1 = \pm\frac{2\eta}{1+\eta^2}, b_2 = 0, b_3 = \frac{\eta^2-1}{1+\eta^2}.$$

The polarization of the final photon will depend on the frequency of the initial one and the value of the magnetic field strength.

3) Right and left circular polarization ($\xi_{1,3} = 0, \xi_2 = \pm 1$):

$$b_1 = 0, b_2 = \pm\frac{2\eta}{1+\eta^2}, b_3 = \frac{\eta^2-1}{1+\eta^2}.$$

The polarization of the final photon will be the sum of the right or left circular and linear polarization.

4) Unpolarized radiation ($\xi_i = 0$):

$$b_{1,2} = 0, b_3 = \frac{\eta^2 - 1}{1 + \eta^2}.$$

In this case, the polarization of the final photon is linear.

Figs. 3 and 4, derived from the process cross-section, show the differential cross-section's dependence on photon energy and magnetic field. We observe an asymmetry around the resonance frequency that lessens with increased magnetic field, and a reduction in the resonance cross-section as the magnetic field strengthens.

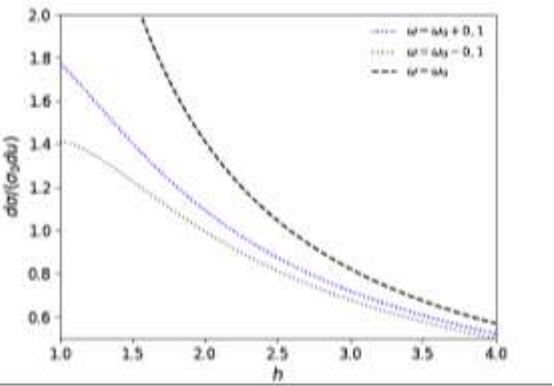

Fig. 3. Dependence of the differential cross-section of the process on the magnetic field strength for the cases of the resonance frequency of the initial photon and the corresponding detunings

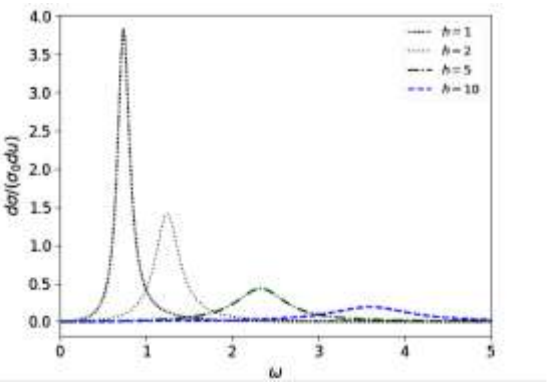

Fig. 4. Dependence of the differential cross-section of the process on the photon frequency for different values of the magnetic field

CONCLUSIONS

Within the framework of a theoretical study of photon scattering on an electron in an external magnetic field, it has been shown that the cross-section of the process does not factorize, unlike in the non-relativistic approximation. It was found that in the case of linear polarization of the initial photon, the final photon will have the same polarization. If the initial radiation is polarized at angles of $\pm 45°$, the polarization of the radiation will depend on the energy of the initial photon and the strength of the magnetic field. In the case of circular polarization of the initial photon, the final polarization will be a combination of circular and linear polarization. It has been shown that an asymmetry in the cross-section of the process is observed relative to the resonance frequency, and this asymmetry decreases with increasing magnetic field strength. Additionally, an increase in the magnetic field leads to a decrease in the resonant cross-section of the process.

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