Electron-spin dynamics induced by photon spins

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Abstract
The photonic spin density of standing light waves with elliptical polarization can induce electron-spin precession. This effect is of similar origin as the well-known spin-orbit coupling. The spin-precession frequency is proportional to the product of the laser field's intensity and its spin density. The electron-spin dynamics is analyzed by employing exact numerical methods as well as time-dependent perturbation theory based on the fully relativistic Dirac equation and on the nonrelativistic Pauli equation that is amended by a relativistic correction that accounts for the light's spin density. Although, the predicted spin precession is a genuine relativistic effect it may be observed also at nonrelativistic laser intensities.

Motivation

Employing novel light sources such as the ELI-Ultra High Field Facility, for example, which envisage to provide field intensities in excess of $10^{20}\,\mathrm{W/cm^2}$ and field frequencies in the x-ray domain [1], relativistic light-matter interaction may be probed experimentally. Relativistic quantum mechanics predicts various new phenomena to occur in this regime [2, 3] including spin effects [4–9]. Not only electrons also elliptically polarized light carries spin angular momentum. It is well-known that different angular momentum degrees of freedom may couple to each other (e.g., spin-orbit coupling). Here, we study the quantum mechanical coupling of electronic and photonic spin degrees of freedom.

Electron spin precession in elliptically polarized light

The Coulomb gauge vector potential of two elliptically polarized laser fields with the electric peak amplitude $\hat{E}$, the angular frequency ω and the wave number k propagating into the positive or negative direction of the x axis is given by

$$\boldsymbol{A}_{1,2}(\boldsymbol{r},t) = -\frac{\hat{E}}{\omega}\left(\mp\sin(kx\mp\omega t)\,\boldsymbol{e}_y \mp \sin(kx\mp\omega t\pm\eta)\,\boldsymbol{e}_z\right)\,. \tag{1}$$

The parameter $\eta\in(-\pi,\pi]$ determines the degree of the light beam's ellipticity with $\eta=0$ and $\eta=\pi$ corresponding to linear polarization and $\eta=\pm\pi/2$ to circular polarization. Each of the electromagnetic fields specified by (1) carries the photonic spin density

$$\varepsilon_0\boldsymbol{E}_{1,2}\times\boldsymbol{A}_{1,2} = \frac{\varepsilon_0\hat{E}^2\lambda\sin\eta}{2\pi c}\boldsymbol{e}_x\,. \tag{2}$$

As one can show via the Volkov solution of the Dirac equation a single plane wave as given in (1) cannot change the spin orientation of an electron. Therefore, we consider a standing wave, which is formed by superimposing the two counterpropa-gating waves given in (1). Solving the time-dependent Dirac equation for an electron with charge q and mass m with a common eigenstate of the free Dirac Hamiltonian, the momentum operator, and the z-component of the Foldy-Wouthuysen spin operator as initial condition shows that the electron's spin precesses around the propagation axis of the electromagnetic fields [10, 11] with an angular frequency that is proportional to the light's intensity and the photonic spin density (2).

The role of the photonic spin density for the electronic spin precession becomes evident by examining the weakly relativistic limit of the Dirac equation. Considering the relativistic correction due to the electromagnetic wave's spin density as the only relativistic correction to the nonrelativistic Pauli equation, the relativistic electron motion may be described by a Pauli equation that is amended by the operator $\frac{q^2\hbar}{4m^2c^2}\boldsymbol{\sigma}\cdot(\boldsymbol{E}(\boldsymbol{r},t)\times\boldsymbol{A}(\boldsymbol{r},t))$, which couples the electron spin $\hbar\boldsymbol{\sigma}/2$ to the photonic spin density $\varepsilon_0\boldsymbol{E}\times\boldsymbol{A}$. Numerical calculations indicate that this relativistic Pauli equation fully reproduces the spin dynamics as predicted by the fully relativistic Dirac equation.

References

[1] G. Mourou, N. Fisch, V. Malkin, Z. Toroker, E. Khazanov, A. Sergeev, T. Tajima, and B. Le Garrec, *Opt. Commun.* **285**, 720 (2012).
[2] F. Ehlotzky, K. Krajewska, and J. Z. Kamiński, *Rep. Prog. Phys.* **72**, 046401 (2009).
[3] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, *Rev. Mod. Phys.* **84**, 1177 (2012).
[4] S. X. Hu and C. H. Keitel, *Phys. Rev. Lett.* **83**, 4709 (1999).
[5] M. W. Walser, D. J. Urbach, K. Z. Hatsagortsyan, S. X. Hu, and C. H. Keitel, *Phys. Rev. A* **65**, 043410 (2002).
[6] F. Faisal and S. Bhattacharyya, S., *Phys. Rev. Lett.* **93**, 053002 (2004).
[7] G. Brodin, M. Marklund, J. Zamanian, and M. Stefan, *Plasma Phys. Controlled Fusion* **53**, 074013 (2011).
[8] S. X. Hu and C. H. Keitel, *Phys. Rev. Lett.* **83**, 4709 (1999).
[9] S. Ahrens, H. Bauke, C. H. Keitel, and C. Müller, *Phys. Rev. Lett.* **109**, 043601 (2012).
[10] H. Bauke, S. Ahrens, C. H. Keitel, and R. Grobe, *New Journal of Physics* **16**, 103028 (2014).
[11] H. Bauke, S. Ahrens, and R. Grobe, *Phys. Rev. A* **90**, 052101 (2014).