GENERAL THEORY OF CARRIER-ENVELOPE PHASE EFFECTS IN LINEARLY POLARIZED PULSES

V. Roudnev* and B. D. Esry†

* Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky, USA
† J.R. Macdonald Laboratory, Kansas State University, Manhattan, Kansas, USA

Short pulses having only a few oscillations of the laser field can now be produced [1, 2]. In contrast to the more conventional case, when the laser pulse is much longer than the carrier period, the phase of the carrier wave with respect to the pulse envelope maximum becomes an important parameter for short intense pulses. This phase is called the carrier-envelope phase (CEP). It has been demonstrated experimentally, for instance, that the CEP can significantly influence ionization of Kr atoms by infrared laser pulses [1]. Similar experiments were performed with Rydberg states of Rb atoms ionized by a few-cycle 25 MHz pulse [3] where the spatial distribution of the ionized electrons showed sensitivity to the CEP. Potentially stronger effects were predicted theoretically for dissociation of HD^+ in a laser field [4] and related experiments have been performed [5]. Here, we provide a rigorous and universal description of CEP effects applicable to each of these cases.

Consider a quantum system interacting with a short, intense, linearly polarized laser pulse via

$$V(t) = -\mathbf{d}\cdot\mathbf{E_0}\; e^{-(\frac{t}{\tau})^2}\cos(\omega t+\varphi)\ ,$$

where $\mathbf{d}$ is the electric dipole operator, $\mathbf{E_0}$ is the peak value of the electric field, and φ is the carrier-envelope phase. The pulse duration τ and the carrier frequency ω define two different time scales of the external field. In order to separate these time scales and to access the benefits of the Floquet representation, we employ the two-dimensional time representation [6]. In this representation, the time-dependent Schrödinger equation can be made CEP-independent

$$i\partial_s\mathbf{\Phi} = \mathbf{H}(s)\mathbf{\Phi},$$

where s is the second time coordinate and $\mathbf{\Phi} = \{\ldots,\Phi_{-1},\Phi_0,\Phi_1,\ldots\}$ is an infinite vector of s-dependent Floquet components. The physical wave function corresponding to the CEP φ can be recovered from the components using

$$\Psi(t;\varphi) = \sum_{n=-\infty}^{\infty} e^{in\varphi}e^{in\omega t}\Phi_n(s)\mid_{s=t}\ \ .$$

This expression provides a straightforward connection between the laser carrier-envelope phase φ and the wave function. It allows any CEP effect to be interpreted as an interference between the Floquet components Φ_n that correspond to different numbers of photons n exchanged between the quantum system and the laser field. Moreover, it shows that CEP effects can be calculated analytically for all φ once the Floquet components are known for one value of φ.

We employ a two-level system to illustrate the theory. This illustration suggests the following qualitative properties of the CEP effects:
• CEP effects become exponentially small at low intensities;
• CEP effects can, in principle, be observed even for laser pulses much longer than a few periods;
• the CEP-dependence of any observed physical quantity becomes more complex with increasing peak intensity;
• the pulse shape and the physical system both influence the observability of CEP effects.

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