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Circularly polarized laser field-induced rescattering plateaus in electron–atom scattering

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Abstract

We analyze the laser ellipticity dependence of n-photon differential cross sections $(\mathrm{d}\sigma_n/\mathrm{d}\Omega)$ for electron–atom scattering in an intense elliptically polarized laser field. We show that there exist two plateau-like structures in the dependence of $\mathrm{d}\sigma_n/\mathrm{d}\Omega$ on n for any ellipticity, including for the case of circular polarization. We present numerical predictions for e–H scattering in a CO_2-laser field and an analytical description of the plateau features in terms of the rescattering scenario.

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1. Introduction

Plateau structures in intense laser–atom interactions (i.e., a nearly constant dependence of multiphoton cross sections on photon number n over a wide interval of n up to a cutoff at $n_{\max}$) are among the most interesting and intensively studied nonlinear phenomena in laser–atom physics. These structures have a one-electron origin and are well-studied both experimentally and theoretically for the processes of above-threshold ionization (ATI) and high harmonic generation (HHG) [1]. Recently, plateau structures have been predicted also for the process of laser-assisted electron–atom scattering (LAES) [2]. Detailed theoretical analyses of plateau effects have been performed for the case of linear laser polarization, for which a one-dimensional model of electron motion along the direction of laser polarization is applicable and for which a numerical analysis of the time-dependent Schrödinger equation is simplified owing to the conservation of the electron's angular momentum projection along the direction of laser polarization. The

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rescattering picture [3] provides a transparent physical explanation for the appearance of plateau structures: an intense oscillating laser field returns ionized electrons back to the parent ion, whereupon they either gain additional energy from the laser field during laser-assisted collisional events, thereby forming the high-energy plateau in the ATI spectrum, or recombine with the parent ion, emitting high-order harmonic photons. A similar interpretation of the high-energy plateau for LAES as well as analytical estimates for $n_{\max}$ for the case of a linearly polarized field are given in Ref. [2].

For the case of an elliptically polarized laser field, rescattering effects in LAES spectra have not yet been analyzed. The high-energy (rescattering) plateaus in ATI and HHG spectra, however, are known to gradually disappear with increasing degree of circular polarization $|\xi|$ $(-1 \leqslant \xi \leqslant +1)$ [1]. Indeed, for the case of pure circular polarization ($\xi = \pm 1$), the process of HHG by free atoms is strictly forbidden, whereas plateau structures in ATI simply disappear. Thus it has been generally assumed that rescattering effects vanish for the case of circular polarization owing to the impossibility for the electron to return to its parent ion. However, for free–free transitions (such as LAES), rescattering effects can take place even for the case of circular polarization, as follows from quite general arguments. For the case of bound–bound or bound–free transitions (i.e., HHG or ATI), the angular momentum l of the bound electron (having energy E_0) is fixed, so that dipole selection rules for the angular momentum projection m in a circularly polarized field, $|\Delta m| = 1$, forbid HHG and suppress rescattering effects in ATI. (The suppression of ATI occurs because after absorption of $n > n_0 \approx (|E_0|/\hbar\omega)$ photons, the ionized electron acquires a large additional angular momentum, $\Delta l = n$, whose centrifugal potential barrier makes recollision improbable.) For the case of LAES, however, both incoming and scattered electron waves are superpositions of continuum states with different l and m. Hence, for LAES the selection rules should not lead to such drastic differences in the physics of strong field phenomena for the cases of linear and circular polarizations as they do for ATI and HHG.

The main purpose of this Letter is to demonstrate the existence of rescattering effects (and corresponding plateau features) for free–free electron transitions in the presence of a circularly polarized laser field. In contrast to ATI and HHG, where the height of plateau structures decreases rapidly with increasing ellipticity, we find that for the case of LAES the plateau height is almost insensitive to the degree of circular polarization ξ, whose magnitude and sign determine only the extent of the high-energy plateau region. These features of plateau structures in LAES are shown to follow from an exact quantum solution of the problem, which allows also for a simple classical interpretation in terms of the rescattering picture.

2. Formulation of the problem and basic equations

Theoretical analysis of LAES from a neutral atom is simpler than the analysis of either ATI or HHG since the atomic potential $U(r)$ does not involve a long-range Coulomb tail. Therefore, for slow incident electrons (the case for which rescattering effects are most important) the electron–atom interaction can be modelled by a zero-range potential (ZRP), which supports a weakly-bound s-state having energy $E_0 = -\hbar^2\kappa^2(2m)^{-1}$. For LAES, this approximation represents a time-dependent extension of the standard scattering length approximation for the description of low-energy, s-wave electron scattering from atoms that have negative ions with s-electron ground states [4].[1]

In the dipole approximation, we describe the laser field by the electric vector,

$$\mathbf{F}(t) = F\,\mathrm{Re}\{\mathbf{e}\exp(-\mathrm{i}\omega t)\},$$
$$\mathbf{e} = \left(\hat{\boldsymbol{\varepsilon}} + \mathrm{i}\eta[\hat{\mathbf{k}} \times \hat{\boldsymbol{\varepsilon}}]\right)/\sqrt{1+\eta^2},$$

where F, ω and $\mathbf{e}$ are the amplitude, frequency and complex polarization vector, $(\mathbf{e}\cdot\mathbf{e}^* = 1)$. The unit vectors $\hat{\boldsymbol{\varepsilon}}$ and $\hat{\mathbf{k}}$ define the major semiaxis of the laser polarization ellipse and the direction of the laser beam. Instead of the ellipticity η, it is convenient to use the degrees of linear (ℓ) and circular (ξ) polarization: $\ell = \mathbf{e}\cdot\mathbf{e} = (1-\eta^2)/(1+\eta^2)$, $\xi = \mathrm{i}\hat{\mathbf{k}}\cdot[\mathbf{e}\times\mathbf{e}^*] = 2\eta/(1+\eta^2)$. Since $|E_0|$ (or the scattering length κ^{-1}) is the only free parameter of the prob-

[1] Note that the effective range theory [4] may be used to provide a more precise account of $U(r)$ by introducing the effective range, r_0, as well as the scattering length κ^{-1}. (ATI in this approach has been considered in [5].) However, we have found that the present results for LAES are not changed qualitatively by introducing r_0.