Perturbative expansions for laser-atom interactions

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Synopsis We analyze the interaction of a one-active electron system with a strong laser field. In order to extract information about the interaction mechanisms, it is important to consider perturbative expansions of the ionization probability amplitude in terms of the Coulomb potential. Based on some of Faddeev ideas, we introduce a new perturbative series that involves both the Coulomb and the Volkov propagators. We show that for photon energies higher than the ionization potential, the series converges rapidly towards the exact result as calculated by solving numerically the time-dependent Schrödinger equation. In the same conditions, the well known strong field approximation series is shown to diverge.

The strong field approximation (SFA) has been the principal tool to describe and explain processes in the domain of laser-matter interactions. It provides valuable insight into the mechanism underlying processes such as the ionization of atoms or molecules exposed to strong infrared fields, high-order harmonic generation and even processes involving more than one electron like non-sequential double photoionization. However, SFA has several flaws which have been discussed in detail in [1]. In particular, the convergence of the SFA series is still an unsolved question. It has been shown in [1] that in a very simple case, the first order SFA can describe the problem reasonably well whereas the series is clearly diverging.

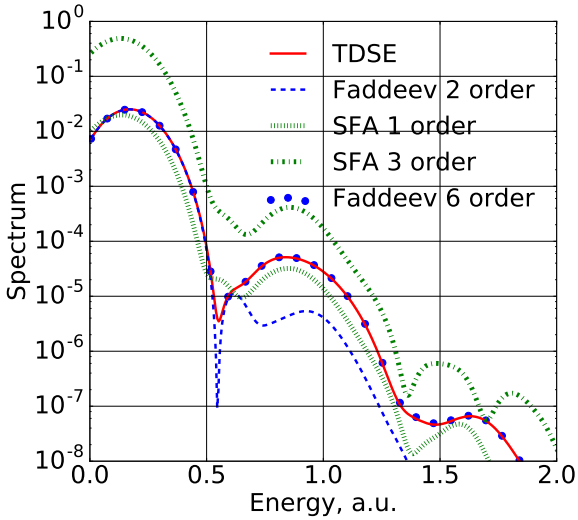

Figure 1. Electron energy spectrum in the forward direction for atomic hydrogen exposed to a 4 optical cycle sine squared pulse of 10^{14} W/cm^2 peak intensity and 0.7 a.u. photon energy. TDSE results in velocity gauge (full line) are compared with SFA results of first order (dotted line) and third order (dot-dashed line) and with our new Faddeev like series of second order (dashed line) and sixth order (dots). The first order of our new expansion coincides with the SFA first order term.

In order to calculate the high-order terms of the SFA series, we first write the full electron wave packet as $|\Phi(t)\rangle = |\varphi_0(t)\rangle + |F(t)\rangle$, where $|\varphi_0(t)\rangle$ is the hydrogen atom ground state. By treating the Coulomb potential V_c as a perturbation, we solve iteratively the following inhomogeneous time-dependent Schrödinger equation (TDSE) for $|F(t)\rangle$ [1]:

$$\left[\mathrm{i}\frac{\partial}{\partial t} - H_0 - V_c - V_d(t)\right]|F(t)\rangle = V_d(t)|\varphi_0(t)\rangle, \quad (1)$$

where $V_d(t)$ is the dipole interaction potential and H_0, the kinetic energy operator.

In our new Faddeev like approach [2] , we write the full wave packet as $|\Phi(t)\rangle = |\Phi_1(t)\rangle + |\Phi_2(t)\rangle$ where $|\Phi_1(t)\rangle$ and $|\Phi_2(t)\rangle$ obey

$$(i\frac{\partial}{\partial t} - H_0)|\Psi_1(t)\rangle = V_c|\Psi(t)\rangle, \quad |\Psi_1(0)\rangle = |\varphi_0(0)\rangle,$$
$$(i\frac{\partial}{\partial t} - H_0)|\Psi_2(t)\rangle = V_d(t)|\Psi(t)\rangle, \quad |\Psi_2(0)\rangle = 0.$$

In Fig. 1 and in a simple case, we compare TDSE results for the electron energy spectrum to those obtained within the SFA and the new expansion. While SFA series is diverging as shown in [1], our new Faddeev like approach converges rapidly. Already at the 6th order, it fully coincides with the exact TDSE result. However, for lower frequencies we expect slower convergence.

References

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