Non-perturbative approach to multiphoton ionisation of the hydrogen and helium atoms.

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Abstract

Laser light intensities, currently obtained in the laboratories, make it possible to o observe many multi-photon phenomena in the interaction of light and matter (such as multi-photon ionisation, or MPI process). Theoretical description of such phenomena necessitates the use of essentially non-perturbative framework. We present such an approach based on the recasting of the Schrodinger equation for the system atom +field into a set of coupled integral equations of the Lippmann-Schwinger type.

Key words: multi-photon ionization, nonperturbative phenomena, Kramers-Henneberger Hamiltonian, strong laser fields
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1. Introduction.

In recent years, the process of multiphoton ionization (MPI) of atomic and molecular species has been a subject of intensive experimental and theoretical studies ([1–3]. Rapid progress in this field has been largely driven by advancement in high-power short-pulse laser techniques. The laser intensities which may go beyond 10^{13} Wcm^{-2} make it possible to observe many striking phenomena such as MPI and above-threshold ionization. Accurate theoretical description of ionization processes occurring in laser fields of such intensities should necessarily go beyond a simple perturbative picture. Starting from the pioneering work of Keldysh [4] a number of theoretical methods have been proposed to describe the non-perturbative regime of the atom-EM field interaction [5–9].

In the present paper, we outline a quantum formalism for MPI which we intend to use for practical computations on complex atomic systems. More detailed description of the formalism is given in [10,11].

We employ the operator formalism [12]. In this formalism, the MPI process is treated as a decay phenomenon. The partial decay rates and the energy level shifts are evaluated via the matrix elements of the transition operator which are found by solving a coupled set of the integral Lippmann-Schwinger equations. In this approach the matrix elements of the transition operator should be taken between the field-free atomic states accompanied by an integer number of the laser photons.

For one-electron targets, evaluation of the field-free states is trivial. For two-electron targets, an accurate set of target states, both discrete and continuous, can be generated by the so-called convergent close coupling (CCC) method. This method has been extensively tested for processes with two electrons in the continuum such as electron scattering on atomic hydrogen [13] and low-field double ionization of helium [14]. We use the same set of target states for MPI of He in the non-perturbative strong-field regime.

2. Theoretical framework for the non-perturbative description of the MPI process.

Let us consider a system which consists of a number of photons with a given frequency ω and momentum vector $\mathbf{k}$ corresponding to an incident plane-wave, and a target (atom or ion). We shall describe the field fully quantum-mechanically and write the Hamiltonian of the system as

$$\hat{H} = \hat{H}_{\rm atom} + \hat{H}_{\rm field} + \hat{H}_{\rm int} \,. \qquad (1)$$

Here $\hat{H}_{\rm atom}$ and $\hat{H}_{\rm field}$ have the usual meaning of the Hamiltonians of the atom and the field. As for explicit form of $\hat{H}_{\rm int}$ it well be specified later.

We shall be interested in the following process. At the moment $t = 0$ the system "atom plus external field" is prepared in the eigenstate $|\alpha\rangle$ of the Hamiltonian $\hat{H}_0 = \hat{H}_{\rm atom} + \hat{H}_{\rm field}$. Then interaction $\hat{H}_{\rm int}$ between atomic and photon subsystems is switched on. Our aim is to describe possible outcomes of this event. The partial rates of the decay of the initial states $|\alpha\rangle$ into various open channels $|\beta\rangle$ are given by the expressions

$$\Gamma_\beta = 2\pi |T^{\beta\alpha}(E)|^2 d\rho(E), \qquad (2)$$

where $\rho(E)$ denotes the density of states in the final state, and the transition operator T satisfies the integral equation of the Lippmann-Schwinger type [12]

$$T^{\beta\alpha} = \hat{H}^{\beta\alpha}_{\rm int} + \sum_{\gamma\neq\alpha} \frac{\hat{H}^{\beta\gamma}_{\rm int}\, T^{\gamma\alpha}}{E_\alpha + \Delta E_\alpha - E_\gamma + i\epsilon} \qquad (3)$$

To make the whole approach practicable we must be able to compute matrix elements of the operator $\hat{H}_{\rm int}$, "switched" between the atomic states. If we employ customatily used length of velocity gauge for $\hat{H}_{\rm int}$ the matrix elements correponding to free-free transitions turn out to be divergent. We employ, therefore, the so-called Kramers- Henneberger form of the operator $\hat{H}_{\rm int}$, which reads:

$$\hat{H}^{\rm KH}_{\rm int} = \sum_{i=1}^{N} \left(\frac{Z}{r_i} - \frac{Z}{|\mathbf{r}_i + \hat{\alpha}|} \right), \qquad (4)$$

where $\hat{\alpha} = \hat{\mathbf{F}}/\omega^2$, $\hat{\mathbf{F}}$ is the operator of the electric field intensity. With this choice of the interaction Hamiltonian all the matrix elements in the Eqs.(3) are finite and well-defined. The solution of this set of equations for hydrogen and helium target systems allowed to us obtain the following results for the MPI processes in these atoms.

2.1. *Hydrogen.*

In the table below we present the results which the approach based on the Eqs.(3) gives for three-photon ionization from the gound state of atomic hydrogen. The results are compared with the data on MPI in hyfrogen available in the literature.

Table 1
Total ionization rates and shifts for atomic hydrogen in a linearly polarized field of frequency ω and strength F (a.u.).

Angular	Field	Total ionization rate		Shift	
frequency	strength	Present	[15]	Present	[15]
0.184	0.0169	9.2×10^{-6}	8.8×10^{-6}	-0.002910	-0.002543
	0.0534	1.33×10^{-3}	1.40×10^{-3}	-0.0280	-0.0257

2.2. *Helium.*

For helium we consider two-photon ionization from the ground state. Our results are presented in the Figure below in comparison with other calculations [16,17] available in the literature. In the region of the photon energies considered we achieve quite a satisfactory agreement with the literature values.

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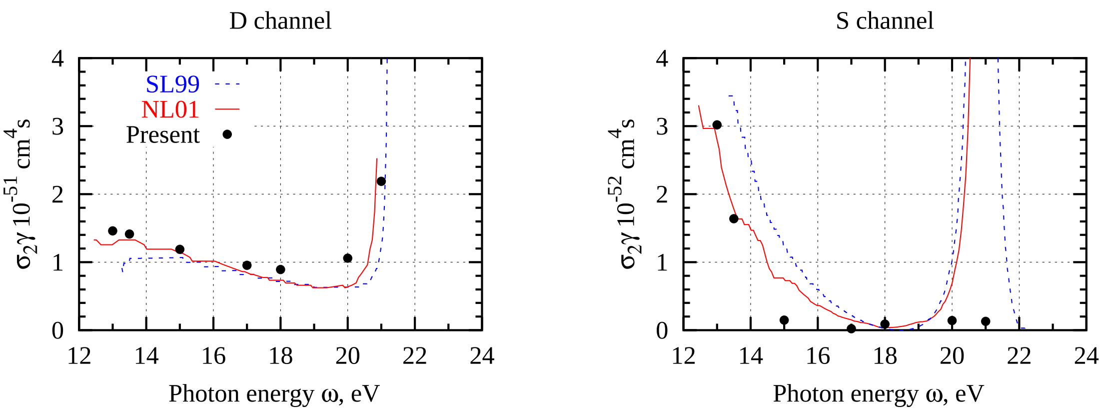

Fig. 1. Cross section of the two-photon ionization from the ground state of helium. Comparison is made with literature values marked as SL99 [16] and NL01 [17]

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