Publ. Astron. Obs. Belgrade No. 89 (2010), 59-62 *Contributed Paper*

THE ROLE AND CHARACTER OF RESONANT STATES IN PHOTOIONIZATION OF ATOMS BY STRONG INFRARED LASER FIELD

SVETLANA VUČIĆ[1] and R. M. POTVLIEGE[2]
[1]*Institute of Physics,University of Belgrade, 11080 Zemun, Serbia*
E-mail: vucic@ipb.ac.rs
[2]*Departement of Physics, Durham University, South Road, Durham DH1 3LE, UK*
E-mail: r.m.potvliege@durham.ac.uk

Abstract. The rate of ionization of atomic hydrogen in a strong infrared laser field is calculated in the framework of non-Hermitian Floquet theory. The high dressed excited states responsibles for the resonance enhancements in the photoionization spectrum are large-α_o KH states of the high-frequency Floquet theory.

1. INTRODUCTION

Exposed to a long infrared laser pulse an atom may ionize through different mechanisms, which may be broadly distinguished according to the value of Keldysh parameter

$$\gamma = (2I_p)\omega/F$$

where I_p is the ionization potential and ω and F are frequency and field strength of the linearly polarized laser light. For $\gamma \geq 1$, applicable not to very strong fields, ionization occurs by the electron which passes through a series of virtual bound levels of the atom (real levels in the case of the resonant transitions). When the electron is promoted into the continuum, it can continue to absorbs photons and forms the higher peaks in the above threshold photoionization spectrum. The multiphoton ionization (MPI) is periodic and relatively slow process, because the matrix element of the multiphoton transition is small.

For $\gamma \leq 1$, ionization occurs by the alternative mechanisms. The active atomic electron 'sees' the resultant oscillating potential barrier formed by the Coulomb interaction with the atomic core and the instantantenous incident electric field. Above a certain 'critical' incident field, the potential barrier is low enough that the electron can pass directly over it. The process is rapid, for optical frequencies it can occur for some portion of the optical cycle, once the critical field is reached. For intensities below the critical intensity, the electron can tunnel through the bar-

rier, or it may be first excited to higher levels by multiphoton absorptions of photons, and then passes through or over the barrier.

Our aim is is to study how the resonant transitions affect the ionization dynamics when the laser intensity gradually increases from the multiphoton to the "over the barrier" regime. We calculate the rate of ionization of hydrogen atoms exposed to a linearly polarized laser light of 800nm wavelength and the intensity varying from 10 to 300TW/cm^2. The value of Keldysh parameter for such fields is 3.37, 1.07, 0.75 or 0.6 respectively. The corresponding amplitudes for the free electron quiver oscillations are 5.2au, 16.4au, 23.2au or 28.5au, respectively. The critical intensity for over the barrier ionization is 227 TW/ cm^2.

The calculations are performed by using the non-perturbative, non-hermitian Floquet theory. The method relies on using the Floquet anzatz for the wave function of an atom in a perfectly periodic monochromatic laser field. This allows the expansion of the anzatz in the Fourier series. The n-th order harmonic component of the series is interpreted as a wavefunction of a virtual electron which has absorbed net number of n photons. The radial part of the harmonic components are subsequently expanded onto a discrete complex Sturmian basis set, which implement implicitly the correct boundary conditions. Inserting this anzatz into the time dependent Schrodinger equation produces an infinite set of time-dependent coupled equations, whose solutions are complex quasienergies that represent decaying states.

2. RESULTS

We show in Fig. 1 the photoionization rate of hydrogen in the intensity interval from 10^{13} W/cm^2 to 10^{14} W/cm^2. The vertical dashed lines mark the intensities corresponding to the 11^{th}, 12^{th} and 13^{th} photoionization thresholds. In weak fields, the atom must absorb at least n_o photons in order to ionize. As the intensity increases all the energy levels of the atom are shifted to some extent due to the quiver motion: this is the ponderomotive ac Stark shift. The continuum threshold as well as the high Rydberg states are shifted apwards relative to the lower states (which are screened by the Coulomb potential) by approximately the ponderomotive energy, which is the cycle averaged kinetic energy of a free electron in the laser field. For an n-photon threshold intensity, the shift in the energy is large enough that just n-photon absorption promotes the electron into the low continuum. The study of composition of the resonant states shows that these states have well defined character, with a dominant contribution of one Floquet component with the dominant partial wave.

In order to study the resonance behaviour in the "tunneling" and "over the barrier" dynamical regime we present in Fig. 2 the photoionization rate of hydrogen for intensities from 100TW/cm^2 to 300TW/cm^2. The resonances with intermediate excited states significantly affect ionization from the dressed ground state at all the intensities considered. There is the general tendency of broadening of the resonant peaks with the intensity. In general, the importance of resonances in the ionization

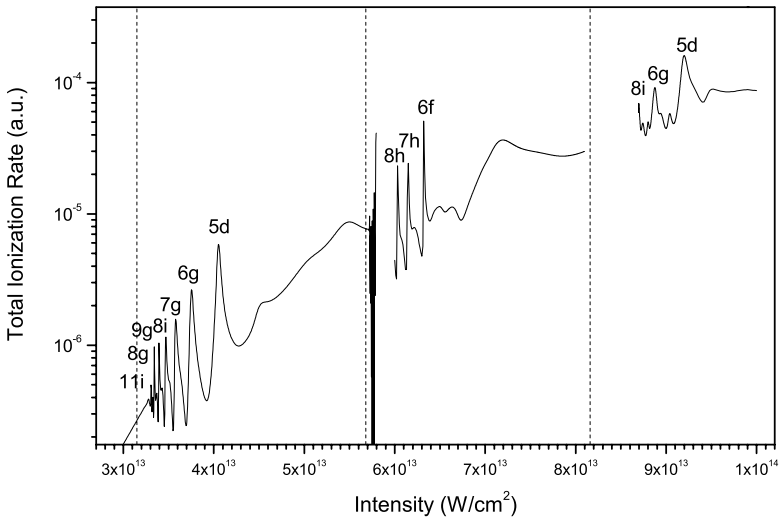

Figure 1: The rate of ionization from the ground state of atomic Hydrogen at 800nm wavelength.

process tends to decrease with intensity. We explain this trend by the increasing amplitude of the quiver oscillations, which tends to decrease the spatial overlap of the resonant states with the ground state. At the highest intensities considered, resonances with excited states tend to suppress ionization rather than to increase it.

In order to understand the role of resonant excited states in strong laser field ionization, we remember that in super strong field ionization rate can be negligible on the time scale of the typical laser pulse. For this to happen the photon energy of the incident field must be larger than the electron binding energy, and the laser field strength felt by the bound electron must be much larger than the Coulomb field strentgh. Under these conditions, the electron is quasi-free and quiver in the field polarization direction with the amplitude $\alpha_o = F/\omega^2$. Since the spatial orbital is very extended, the electron spend little time in the vicinity of the nucleus where it can absorb real photons and it is prevented to ionize. This mechanism of the supression of ionization has been investigated by Gavrila et al. in the Kramers-Henneberger frame of motion, in which the time dependence of the incident electric field is transformed to the time dependence of the atomic potential. In the lowest order approximation, one could replace the time dependent KH frame potential $V(\mathbf{r} + \alpha(t))$, by the time averaged potential $V_o(\alpha(t); \mathbf{r})$. Since then the system 'atom+laser field' is described by time-independent eigenstates in the potential $V_o(\alpha(t); \mathbf{r})$, there are no transitions between the eigenstates, and the atom is stable to ionize. We can conclude that the multiphoton resonances of the ground state with higher intermediate states play a crucial role in suppression of ionization in

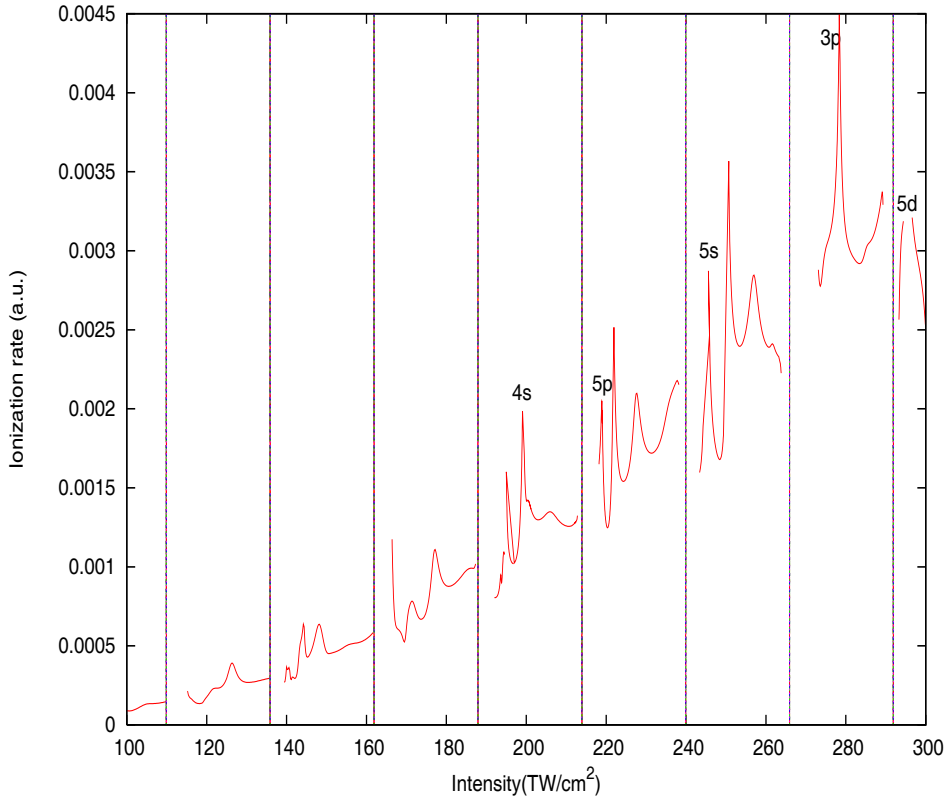

Figure 2: The same as in Fig. 1, but for ithe intensity interval from 100TW/cm^2 to 300TW/cm^2. The resonant states with well defined character are denoted in the Figure.

infrared fields at not to super strong intensities.These states have very small binding energies so that the critical intensity for the ionization supression is much lowered. In addition, the character of these states is similar to that of KH states, with the non-negligible contribution of many partial waves, with no dominant one. It has been shown recently by Potvliege et al., that at very high intensities and for wavelengths of 800nm and 400nm, the spectra of hydrogen, helium or argon depend on the field parameters only through the amplitude α_o; therefore all of these spectra are similar for large values of $\alpha_o > 15$au.

References

Potvliege, R. M., Mese E. and Vučić, S. accepted for publication in *Phys. Rev. A.*
van de Ree, J., Kaminski, J. Z., Gavrila, M.: 1988, *Phys. Rev. A*, **37**, 4536.