Unified time and frequency picture of ultrafast atomic excitation in strong fields

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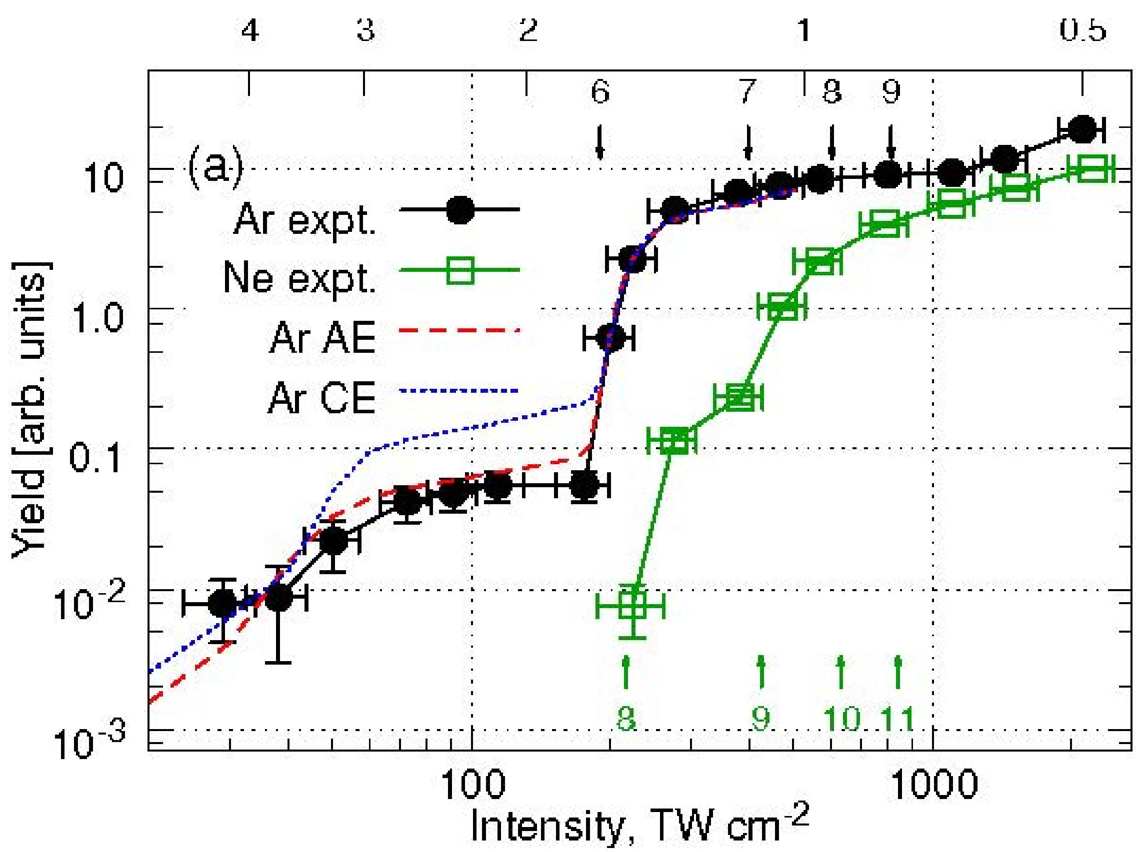

Fig. 1: Yield of excited atoms as a function of the laser intensity. At a laser intensity of 200TW/cm^2, in the vicinity of a 6 photon channel closing, a strong resonant enhancement of a factor 100 is visible. For the argon data, the theoretical curve is also displayed (red dashed curve), which is in excellent agreement with the experimental data. Credit: Forschungsverbund Berlin e.V. (FVB)

The insight that light sometimes needs to be treated as an electromagnetic wave and sometimes as a stream of energy quanta called photons is as old as quantum physics. In the case of interaction of strong laser fields with atoms the dualism finds its analogue in the intuitive pictures used to explain ionization and excitation: The multiphoton picture and the tunneling picture. In a combined experimental and theoretical study on ultrafast excitation of atoms in intense short pulse laser fields scientists of the Max Born Institute succeeded to show that the prevailing and seemingly disparate intuitive pictures usually used to describe interaction of atoms with intense laser fields can be ascribed to a single nonlinear process. Moreover, they show how the two pictures can be united. The work appeared in the journal *Physical Review Letters* and has been chosen to be an Editors' suggestion for its particular importance, innovation and broad appeal. Beside the fundamental aspects the work opens new pathways to determine laser intensities with high precision and to control coherent Rydberg population by the laser intensity.

Although the Keldysh parameter, introduced in the 1960's by the eponymous Russian physicist, clearly distinguishes the multiphoton picture and the tunneling picture, it has remained an open question, particularly in the field of strong field excitation, how to reconcile the two seemingly opposing approaches.

In the multiphoton picture the photon character shines through as resonant enhancement in the excitation yield whenever an integer multiple of the photon energy matches the excitation energy of atomic states. However, the energy of atomic states is shifted upwards with increasing laser intensity. This results in resonant-like enhancements in the excitation yield, even at fixed laser frequency (photon energy). In fact, the enhancement occurs periodically, whenever the energy shift corresponds to an additional photon energy (channel closing).

In the tunneling picture the laser field is considered as an electromagnetic wave, where only the oscillating electric field is retained. Excitation can be viewed as a process, where initially the bound electron is liberated by a tunneling process, when the laser field reaches a cycle maximum. In many cases the electron does not gain enough drift energy from the laser field to escape the Coulomb potential of the parent ion by the end of the laser pulse, which would lead to ionization of the atom. Instead, it remains bound in an excited Rydberg state. In the tunneling picture there is no room for resonances in the excitation since tunneling proceeds in a quasi-static electric field, where the laser frequency is irrelevant.

In the study the excitation yield of Ar and Ne atoms as a function of the laser intensity has been directly measured for the first time, covering both the multiphoton and tunneling regimes. In the multiphoton regime pronounced resonant enhancements in the yield have been observed, particularly in the vicinity of the channel closings, while in the tunneling regime no such resonances appeared. However, here excitation has been observed even in an intensity regime which lies above the threshold for expected complete ionization.

The numerical solution of the time dependent Schrödinger equation for the investigated atoms in a strong laser field provided excellent agreement of the theory with the experimental data in both regimes. A more detailed analysis revealed that both pictures represent a complementary description in the time and frequency domain of the same nonlinear process. If one considers excitation in the time domain one can assume that electron wave packets are created periodically at the field cycle maxima. In the multiphoton regime it can be shown that the wave packets are created predominantly close to the maximum intensity of the pulse and thus interfere constructively only if the intensity is close to a channel closing. With this, regular enhancement in the excitation spectrum results effectively only at the photon energy separation. In the tunneling regime the wavepackets are also created periodically at the field cycle maxima, however, predominantly at the rising edge of the laser pulse which, in turn, leads to an irregular interference pattern and consequently, to irregular variations in the excitation spectrum. These rapid variations are not resolved in the experiment and the detected excitation spectrum is smooth.

More information: H. Zimmermann et al. Unified Time and Frequency Picture of Ultrafast Atomic Excitation in Strong Laser Fields, *Physical Review Letters* (2017). DOI: 10.1103/PhysRevLett.118.013003

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