Attosecond time delays in photoionization: A theoretical perspective

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The question of the status of the time variable in Quantum Mechanics, i.e. whether it is a parameter or an operator, has called the attention of the specialists since the foundation of the theory. In other words, the question is to decide if time is a parameter (as in classical mechanics) or a measurable quantity associated to a hermitian operator expressed in terms of dynamical variables. For years, answering this problem has been considered as being an academic exercise and it attracted mainly the specialists' attention. This was because the required time resolution, as needed to evidence characteristic time differences in electronic transitions and collision processes, was estimated to range in the attosecond (or even shorter) time scale. For many years, this was assumed to be well beyond the experimental capabilities.

A renewal of interest has taken place in the 1980s with the advent of a new generation of experiments related to Scanning Tunnelling Microscopy (STM), semi-conductor devices and Josephson junctions measurements. This was linked to the concept of "tunnelling time", *i.e.* to the possibility of answering the question of *how long does it take a particle to tunnel through a barrier?* In spite of an abundant literature that has been devoted to the subject, no consensus has been reached yet on how to define such tunnelling times.

One step forward has been taken thanks to the advent of a new generation of sources of coherent XUV harmonic radiation delivering "attosecond" pulses, thus making feasible to investigate the photoionization process in the time domain with unprecedented time resolution. Here, we shall present a theoretical analysis of recent experiments that have evidenced the existence of attosecond time delays between the emission times of photoelectrons ejected from different sub-shells in noble gas atoms [1], [2]. These experiments were realized via 2-colour schemes involving the presence of an IR laser pulse with controlled delay, in addition to the attosecond XUV pulse, the IR field providing a convenient "reference clock".

The theory analysis of this class of processes indicates that the measured delays result from the combination of two phenomena: i) one is related to the so-called "Wigner time delays" as defined in collision theory, while ii) the other is related to the measurement technique itself, *i.e.* it results from the "dressing" of the photoelectron by the IR laser field [2], [3].

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