# Amplitude and Phase: From Cross Sections to Delays in Photoionization

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**Synopsis** In this tutorial we will discuss the concept of *delay in photoionization*, how it can be understood and calculated, and in particular how this is connected to our ability to handle photoionization cross sections and atomic structure.

Photoionization is a fundamental process where light interacts with matter and electrons are released. A complete description of the ionized electron wave packet requires the knowledge of both its spectral amplitude and phase. Information about the amplitude has since the first half of the previous century been obtained through cross section measurement. The fantastic development of light sources and techniques since the field was born, from lasers and synchrotrons to high-harmonic generation and free-electron lasers, has over the years produced precise cross section data for a wide range of quantum systems as well as photon energies. The phase of the wave packet was, however, always more elusive. There are some traditional routes to phase information: as the angular dependence of the photoelectrons [1] where the relative phase of different angular momentum channels come into play, or the asymmetric line profiles [2] produced by the interference of different ionization paths, but the attosecond (as) techniques that have been exploding since the beginning of this century, have provided many more ways to obtain phase information.

Through the process of high-harmonic generation, pulses, or trains of pulse, with a subfemtosecond duration, are produced. The temporal resolution they allow for is routinely in the region of a few ten attoseconds [3]. From Bohr's model of the atom we can estimate the "revolution" time for the electron in the hydrogen ground state to be around 150 as, and thus it clear that we are in the position to study electron dynamics.

In this tutorial lecture I will discuss how the electron dynamics, and especially the *delayed* response to photoabsorption, is encoded in the phase of the electron wave packet. We will see how "old" subjects such as angular anisotropy or resonances due to quasi-bound states can be studied from a new angle when also the phase is accounted for. The focus will be on the theoretical understanding and treatment where the quantum many-body problem remains a challenge.

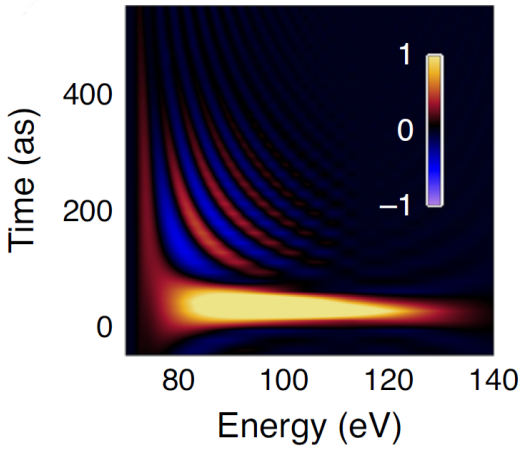


**Figure 1**. The Wigner representation of photoelectrons emitted after absorption of photon energies in the vicinity of the threshold for 4*d*-ionization in xenon showing the different time-scales of the contributing resonances, from Ref. [4]

## References

[1] Cooper J and Zare, R N (1968) J. Chem. Phys. **48** 942
[2] Fano U (1961) Phys. Rev. **124** 1866
[3] Isinger M,*et al* (2017) Science, **358** 893
[4] Zhong S *et al* (2020) Nat. Comm., **11** 5042

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