The attoclock and tunnelling time

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Abstract. Ultrafast laser pulses have enabled experiments probing the temporal dynamics of an electron tunnelling out of an atom. A quintessential example of such is known as the ‘attoclock’. While the investigation is ongoing, the window for non-zero ‘tunnelling times’ in this context appears to have largely closed.

The role of time in quantum mechanics is under ever greater scrutiny due to the development and application of ultrafast pulsed lasers. Similar to a snapshot camera, by interacting with a system on a timescale comparable with its dynamics you gain access to its underlying temporal nature. With pulse durations now commonly in the few-femtosecond \(10^{-15}\) s or even attosecond \(10^{-18}\) s domain, the motion of electrons within atoms is within reach. Such systems are sufficiently fundamental that experiments provide unprecedented tests of theory at the heart of quantum mechanics.

A quintessential example of this is a class of experiments known as the ‘attoclock’. In such, the rotating electric field vector of a (near)-circularly polarised laser pulse applied to a target atom or molecule maps the timing of the resultant tunnel ionisation onto the photoelectron momentum. From the distribution of this momentum a measurement of the ‘tunnelling time’ for the process is derived. However, despite a decade passing since the techniques inception \[1\], lack of consensus persists over its interpretation, in no small part due to the notion of tunnelling time itself.

First examined by MacColl \[2\] in 1932 the concept of a tunnelling time has received great attention and is the subject of a recent review \[3\]. A quantity using this moniker has been defined in several different contexts, but the definitions are often mutually incompatible as each are fundamentally different methods of quantifying the underlying physical process. The question is, does the attoclock contain any physics attributable to a tunnelling time, and if so, is it compatible with an existing definition or is yet of another form? While this question remains somewhat open, there is an increasing volume of evidence that the answer to the precondition is, in fact, “no”.

For an attoclock experiment to conclude an observation of tunnelling time the rotation observed in the photoelectron momentum distribution must be unexplained by classical trajectories assuming instantaneous tunnelling. For the earliest reported attoclock measurements this was not found to be the case \[4, 5\]. In stark contrast, the results of Landsman et al. \[6\] observed rotations far beyond what could be explained by such trajectories. However, to this date, the data remains unexplained by \textit{ab initio} theory despite considerable efforts \[7, 8\]. The remaining suggestion of tunnelling times in attoclock problems is from Camus et al. \[9\].
This work relies on the finding that the difference in rotations from two atomic targets is not well explained by trajectories with instantaneous tunnelling and zero initial velocity.

On the theoretical side, for a simplified attoclock problem\(^1\) using near single-cycle pulses the nature of the rotation has been found to be of entirely Coulombic origin [10, 11]. To experimentally confirm this finding it has been suggested to examine negative ions [12]. Further evidence is provided via backpropagation [13] or through application of an additional linearly polarised field [14]. Most convincing however, is the recent work of Sainadh \textit{et al.} [15] which presents agreement between theory and experiment for an atomic hydrogen target, and concludes that they see no rotations attributable to a delay in the tunnelling process.

For the attoclock, the window for any physics that would be attractively described by a tunnelling time appears to have all but closed. What keeps the door ajar is the aforementioned not yet fully understood experiments of Camus and Landsman.

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**Figure 1.** Left column: 3D-TDSE calculated photoelectron spectra from hydrogen for short (top) and long (bottom) pulses. The short pulse is approximately 1.6 fs FWHM in intensity of peak $0.86 \times 10^{14}$ W/cm$^2$, 800 nm, ellipticity 1.0, and anti-clockwise helicity. Its corresponding distributions assume CEP stability. The long pulse is approximately 6 fs FWHM in intensity of peak $1.5 \times 10^{14}$ W/cm$^2$, 770 nm, ellipticity 0.85, and clockwise helicity. Its corresponding distributions are averaged over CEP. Right column: As for left but from a Yukawa potential (screening parameter $a = 1$) of hydrogenic binding energy. The colouration of probability is linear and normalised from red (min) to black (max).

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\(^1\) It should be noted that the simplified problem has the advantage of perfectly symmetric photoelectron distributions as there are no effects of inter-cycle interference (see Figure 1). Accordingly there is no ambiguity in characterising said distribution by a single angle and corresponding trajectory.
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