# Some importance of 'time delay' in quantum theory

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# Abstract

In general scattering processes involves a time delay to take place. Current state-of-the-art experimental techniques are capable of measuring the time delay in Photoionization, which can be described by the time reversed scattering process. This tiny time delay (of the order of attosecond) is very important, since the quantum description of the interaction of light and matter is to be understood clearly to derive the experimental results with better accuracy. In this presentation, a review of the recent works in this field will be given.

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# Time in quantum mechanics: Time delay

Time plays an important role in quantum mechanics. It is a parameter and "not measurable".

Yes, absolute time has no meaning. The passage time has a meaning. It depends on the evolution procedure of the system. Thus to get a good understanding of the system it is better to watch the system's evolution in real time.

Time resolved atomic and molecular process are hard to see since it takes a few atto to femto seconds to have a motion in atomic/molecular time scale.
Recent development of ultrafast laser technology have enabled us to see the electron motion in the atomic time scale. The tiny but finite **time delay** in electron responses have profound importance in the understanding of quantum structure and dynamics of the systems (atoms, molecules, aggregates ...)

# Every scattering process has some intrinsic natural time interval associated with it.

Now lets see how we can understand the concept of time delay. Consider the situation: say you have started for your office and meet with some of your close friend. You will be chatting and it may cause you a little late for the destination.

# sometime advance in time!

This is time delay in day to day life! Well, this time delay can be negative also. Consider the following situation: You have disappointed a dog on the road on your way.. it can lead to an earlier arrival to your destination point :P. Hence you experience a negative time delay (or time advance).

# A demonstration: Wave packet dynamics

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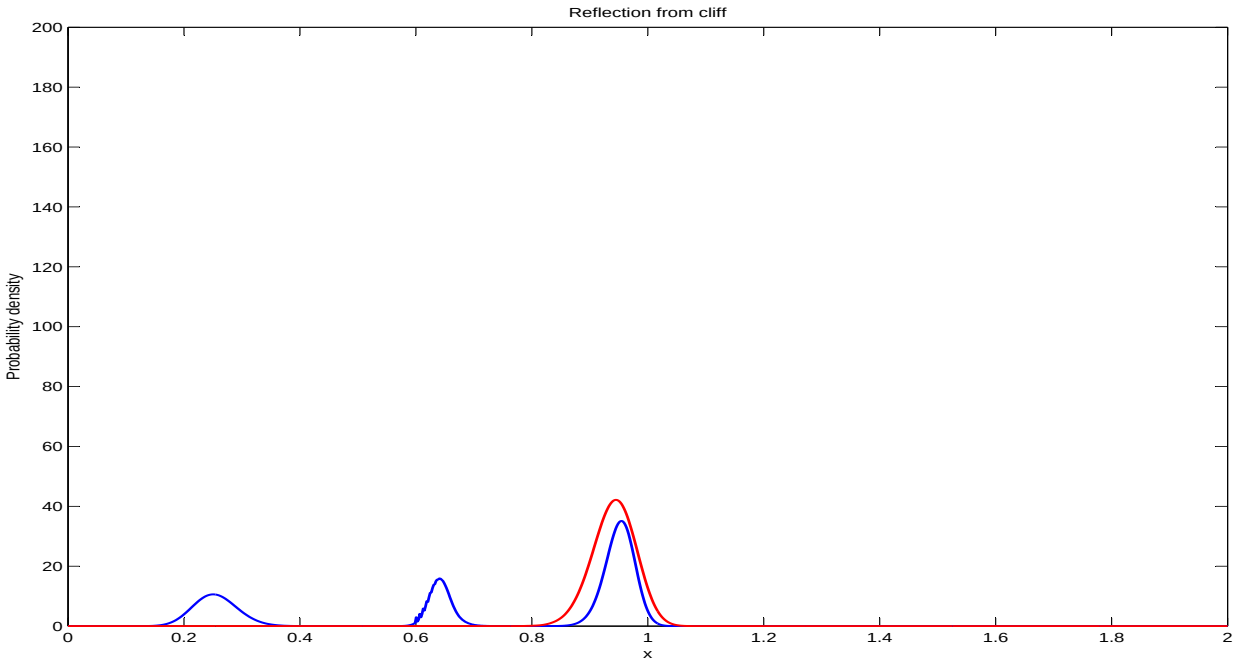
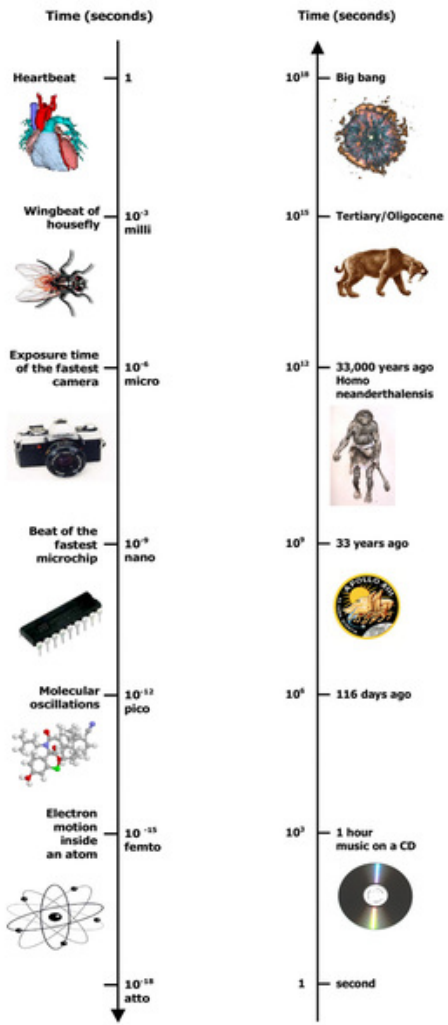


# Various time scales of event around us




It takes 150 attosecond ($10^{-18}$ sec) for an electron to make a rotation in Bohr hydrogen atom.

One attosecond is as small with respect to a second as one second is with respect to the age of the universe.

Picture courtesy

Max Planck Institute for Quantum Optics / Vienna University of Technology

# Photoionization

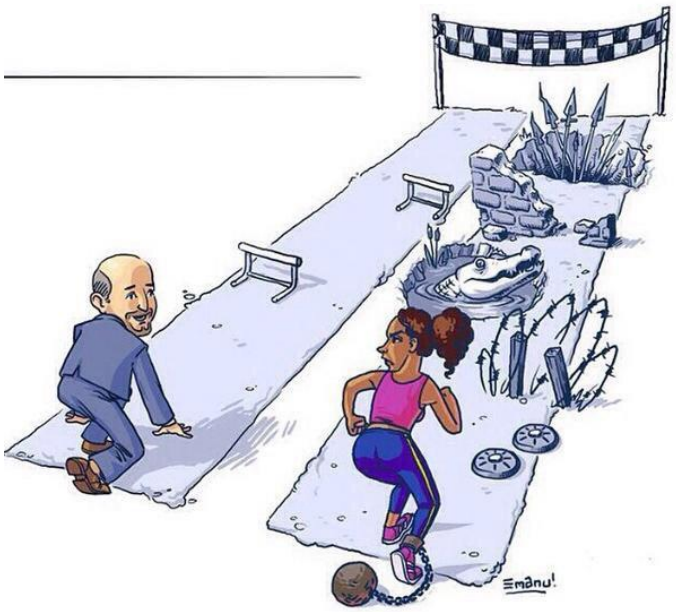
The process of the emission of an electron from an atom when a photon is absorbed by it.

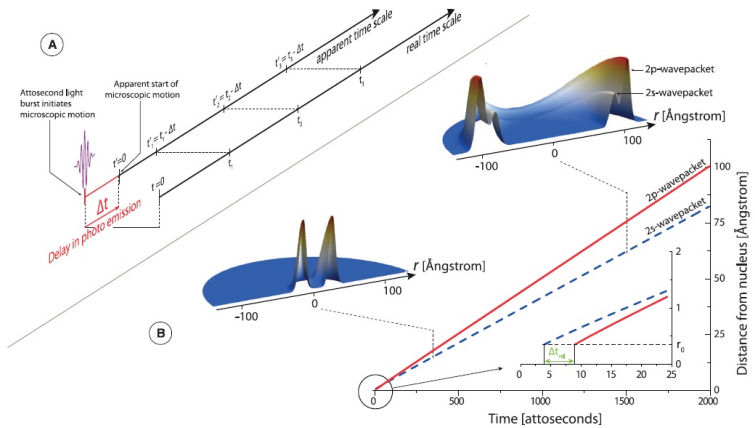
- Earlier contention $\rightarrow$ Photoemission is an instantaneous process.
- Recent Finding $\rightarrow$ There is a time delay between the absorption of electromagnetic pulse and the ejection of electron.

## Importance

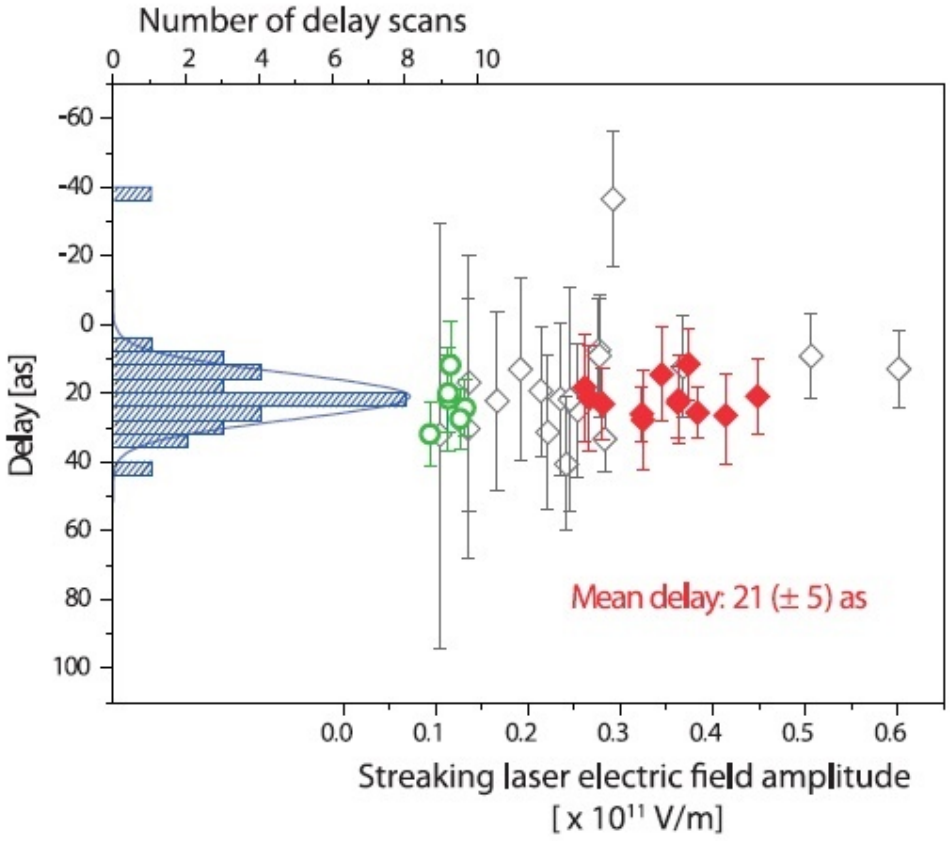
- To set the zero of time on atomic clock time scale.
- Provide a probe for modeling many electron dynamics.

The time scale of atomic process (evolution) depends on initial state as well as the interacting potential.




source: Science 328, 1658 (2010).




source: Science 328, 1658 (2010).

## What did they measure?

$$\tau_{streaking} = \tau_{EWS} + \tau_{CLC} + \tau_{dLC}^{(i)} + \tau_{dLC}^{(e-e)}. \quad (1)$$

where, $\tau_{EWS}$ is the EWS time delay, $\tau_{CLC}$ is the delay due to the simultaneous interaction of the Coulomb field and the external LASER field on the outgoing electron and last two terms are dipole LASER coupling terms which takes account of the polarization of the initial and the final ionic state respectively.

Reference: Journal of Physics: Conference Series 488 (2014) 012004

# Eisenbud-Wigner-Smith time delay

According to Eisenbud, Wigner and Smith, the phase accumulated by a scattered wave packet with respect to the free propagation of the same wave packet is related with the time it spend in the scattering process as,

$$\tau_{WES} = \hbar \frac{d\eta}{dE}|_{E_0} \tag{2}$$

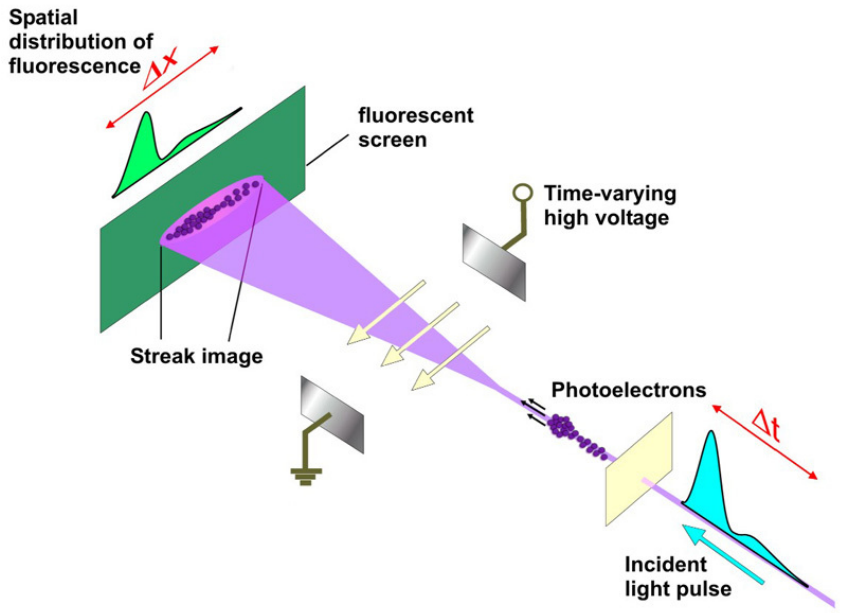
Eisenbud L. E; (1948); Ph. D. thesis; Princeton Univ.; (Unpublished).
Wigner E. P; (1955); Lower Limit for the energy Derivative of the Scattering Phase Shift; Physical Review 98; 145-147.
F. T. Smith; (1962); Lifetime Matrix in Collision Theory; Physical Review 118; 1.

# capture in as resolution

Attosecond streaking [Ferenc Krausz @ LMU and MPQ], RABBITT (Reconstruction of attosecond harmonic beating by interference of two-photon transitions), Attoclock [Ursula Keller @ ETHZ]

Streak camera is a very useful tool to characterize very short pulse of light (up to 100fs).

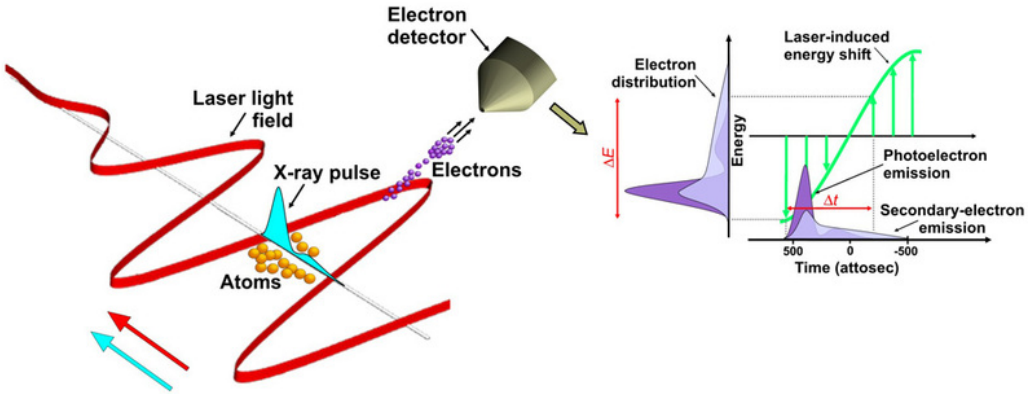
Fundamental idea $\rightarrow$ convert the light pulse to photoelectron, where the emitted photoelectron temporal profile will have one-to-one mapping with the temporal profile of the light pulse.




[Source: F. Krausz's group webpage 'attoworld']

# Attosecond streaking

Similar technique: momentum sweep with light field.




Source: F. Krausz's group webpage 'attoworld'

$$\vec{p}_{\text{final}} \cong \vec{p}_{\text{initial}} - \vec{A}_{\text{release instant}} \tag{3}$$

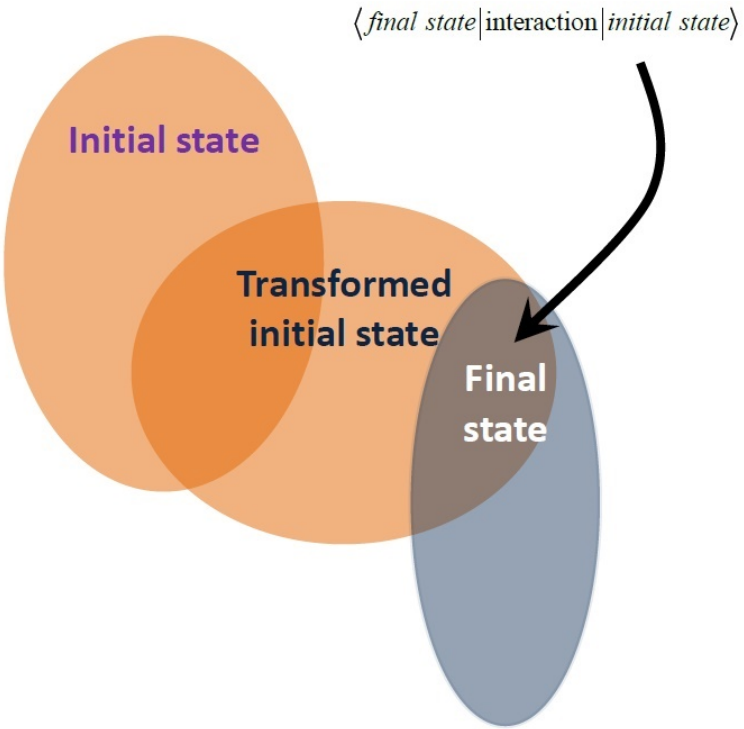
In the year 2010 Schultz et. al [1] measured a delay of 20 attosecond between the ejection of photoelectrons from 2s and 2p orbitals in Ne atom by using attosecond streaking technique.
In 2011 Klunder et.al [2] measured time delay between 3s and 3p orbitals of Ar atom using interferometric measurement technique which is of the order of attosecond.

Kheifets and Ivanov [3] used Hartree-Fock approximation to determine the time-delay in photoionization from atomic Ne, studied by Schultze et al. [1]. The group delay difference they got is 6.2as for 2s and 2p orbitals in the Ne atom and was enhanced by 2.2as including the RPA correlations.

Later Moore et al.[4] and Dahlstrm et al.[5] accounted for both the XUV and IR fields to measure the time delay in Ne atom and they obtained a delay of 10.2 1.3as and 12as respectively.

# Transition matrix

Photoionization can be described by a half scattering process.




$$M_{ba} = \langle b | e^{i\vec{k}\cdot\vec{r}}\,\hat{\varepsilon}\cdot\nabla | a \rangle$$

$$or, M_{ba} = \underbrace{\left| \langle b | e^{i\vec{k}\cdot\vec{r}}\,\hat{\varepsilon}\cdot\nabla | a \rangle \right|}_{\text{Cross-section}} e^{i\eta}$$

Time delay

# Motivation of our study

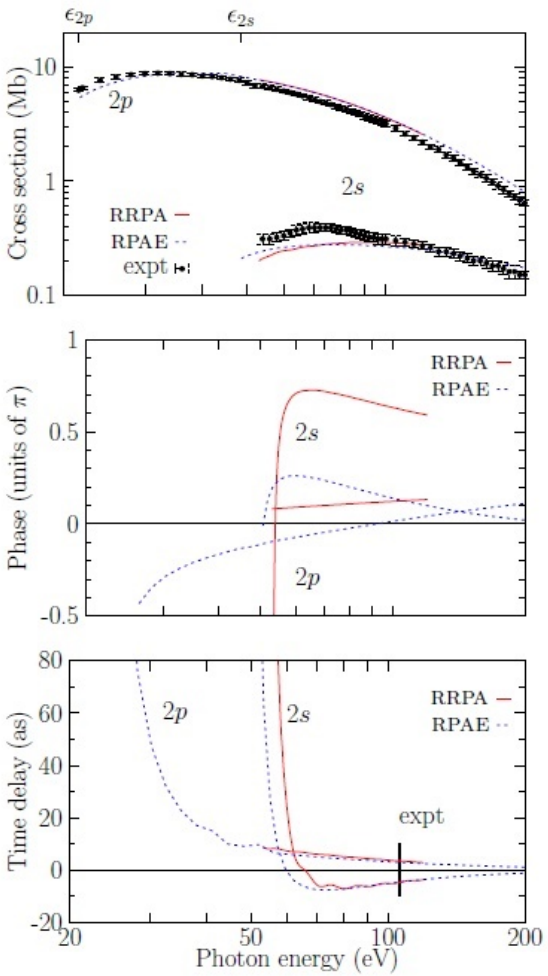
Most of the theoretical studies on time delay is based on the non relativistic many body formalism. Relativistic interactions have not been included in those studies.

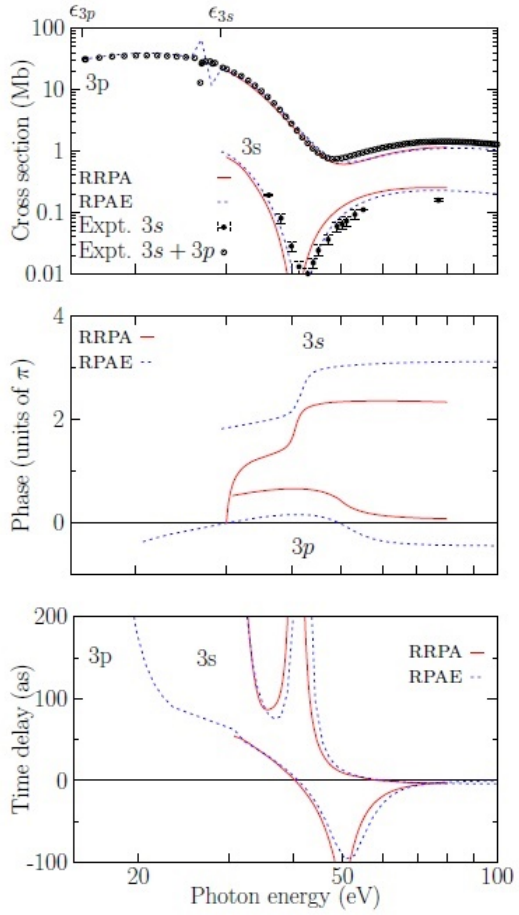
In our present studies we are using Relativistic Random Phase Approximation (RRPA) which is the relativistic version of RPA. The RRPA includes major electron correlations which play an important role in influencing the time delay. Further, the RRPA includes relativistic effects ab-initio and is thus especially suited for determining the time delay in spin-orbit split relativistic dipole channels.

Johnson W. R; Lin C. D; (1979); Physical Review A; 20, 964-977.
Grant I. P; (2007); Relativistic Quantum Theory of Atoms and Molecules; Springer Science Business Media, LLC; 233 Springer Street, New York, NY 10013, USA.
Johnson, W. R., Lin C. D, Cheng K. T., and Lee C. M; (1980); Physica Scripta; 21, 409-422.

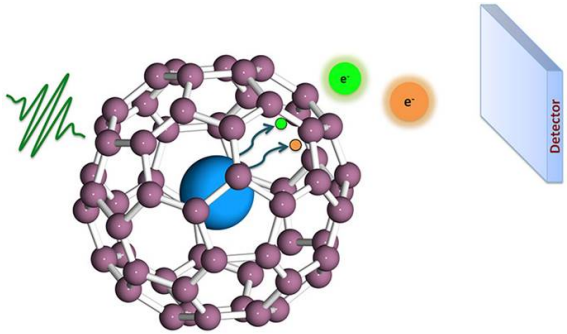
# EWS time delay near dipole Cooper minima

Reference: PHYSICAL REVIEW A 90, 053406 (2014)

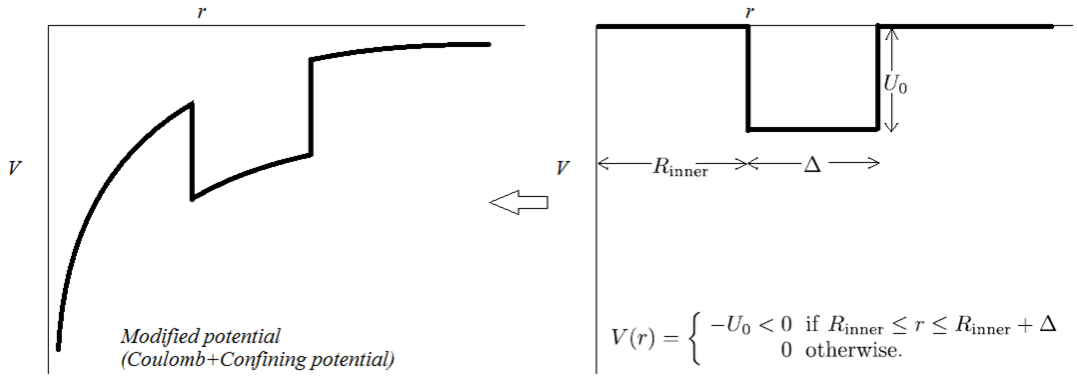


# Confinement oscillations on time delay

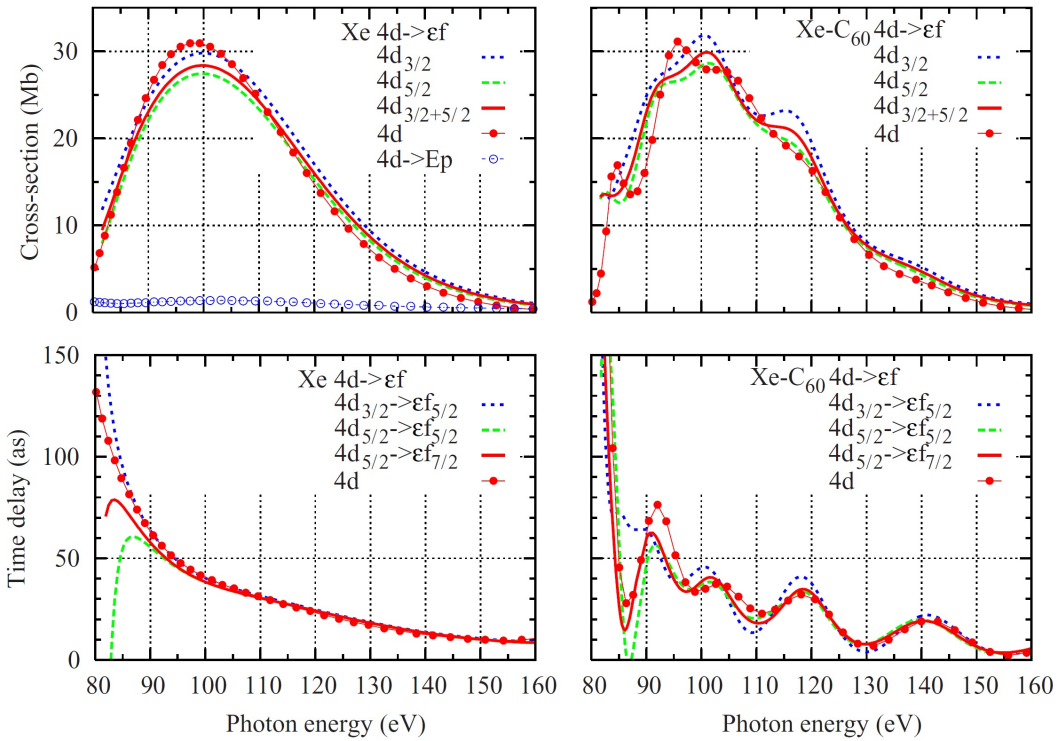



PHYSICAL REVIEW LETTERS 111, 203003 (2013).



# Confinement oscillations on time delay

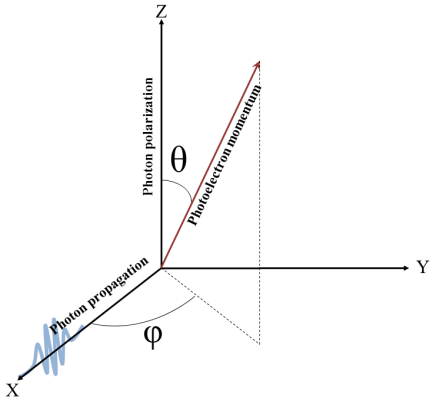
Reference: PHYSICAL REVIEW A 89, 053424 (2014)




This study depicts the presence of confinement resonance in time delay, and its prominence than that in cross-section.
The present work stresses the importance of time delay study in understanding confined systems.

# Angular dependence of time delay

Reference: PHYSICAL REVIEW A 94, 013423 (2016)

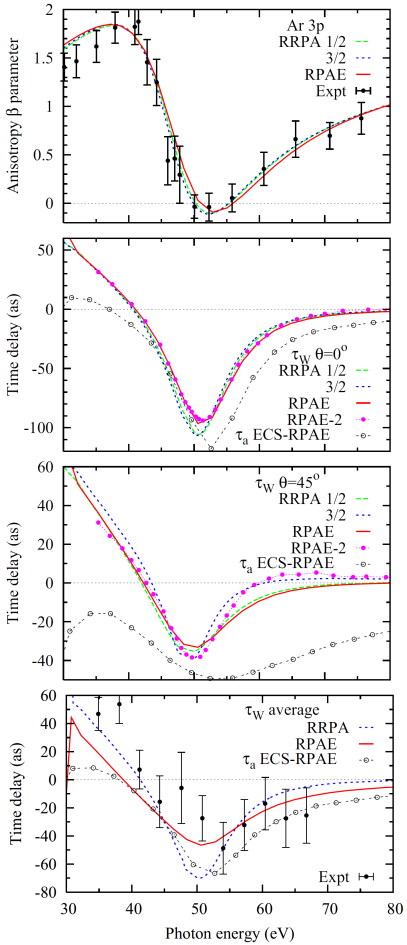


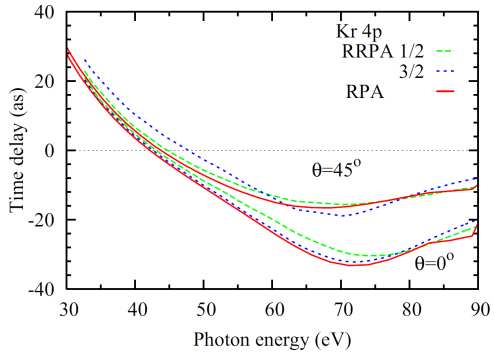

$$T_{10}^{1\pm} \equiv [T_{10}^{(1)}]_{\nu=\pm 1/2} = \sum_{\bar{\kappa}\bar{m}} C^{jM}_{l,M-\nu,1/2\nu} Y_{lm-\nu}(\hat{p})\chi_\nu$$
$$\times(-1)^{2\bar{j}+j+1-\bar{m}} \begin{pmatrix} \bar{j} & 1 & j \\ -\bar{m} & 0 & m \end{pmatrix} i^{1-\bar{l}} e^{i\delta_{\bar{\kappa}}} \left\langle \bar{a} \| Q_1^{(1)} \| a \right\rangle . \quad (4)$$

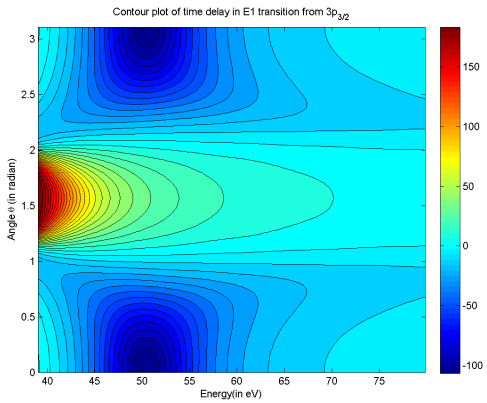
In general the dynamics of photoionization is anisotropic. Angular dependence of some photoionization parameters are well studied in literature. In this work we study the angular dependence of photoemission time from spin-orbit split initial np state of noble gas atoms.

# Angular dependence of time delay

Reference: PHYSICAL REVIEW A 94, 013423 (2016)



# Conclusion in brief

Importance of the study of time delay is manifold. It can bolster the foundation of the quantum theory and our basic understanding of the physical processes. Also it helps to set the zero of time on atomic time scale and provide a probe for modeling many electron dynamics. It can be a better probe to nanostructures.

# References


1. M. Schultze et al.,(2010); Delay in Photoemission; Science; 328; 1658-1662.
2. Klunder K et al.; (2011); Probing Single-Photon Ionization on the Attosecond Time Scale; PRL; 106; 143002(1-4).
3. Kheifets A. S. and Ivanov I. A; (2010); Delay in atomic photoionization, PRL; 105 (23).
4. Moore L. R et al.; (2011); Time delay between photoemission from the 2p and 2s subshells of neon, Physical Review A; 84.
5. Dahlstrm J. M, Carette T and Lindroth E; (2012); Diagrammatic approach to attosecond delays in photoionization; Physical Review A; 86.
6. Cartoon pictures are taken from internet (Google images) and edited accordingly.
7. Giordano, Nicholas J., and Hisao Nakanishi. Computational physics. Pearson Education India, 2006.

# Acknowledgments

Supervisor: Prof. P. C. Deshmukh (IITM)
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