

# Attosecond time delay in photoemission and electron scattering near threshold

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Hot Topic 10A Photons SF/Atto

ICPEAC 2017

1<sup>st</sup> August, Cairns, Australia

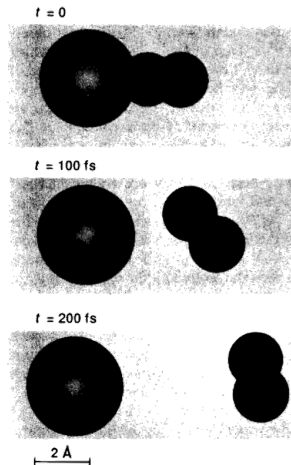
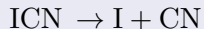
# Time resolved molecular collisions



## 1999 Nobel Prize

“Real-time laser femtochemistry”

[Zewail et al. 1988]



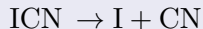
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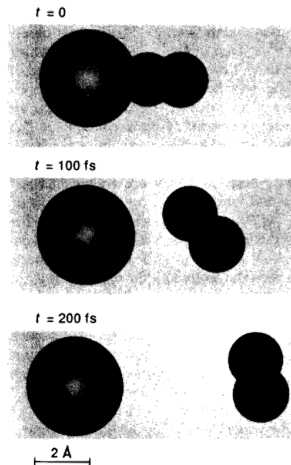
[Zewail et al. 1988]



$$1 \text{ fs} = 10^{-15} \text{ s}$$

vibrational period of

$$\text{H}_2 \approx 8 \text{ fs}$$



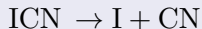
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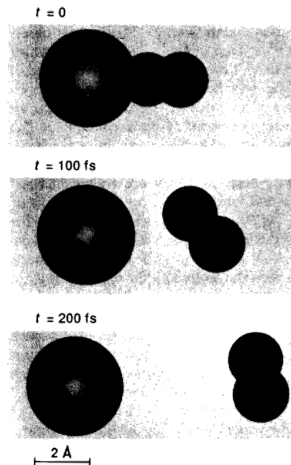
$$1 \text{ as} = 10^{-18} \text{ s}$$

vibrational period of

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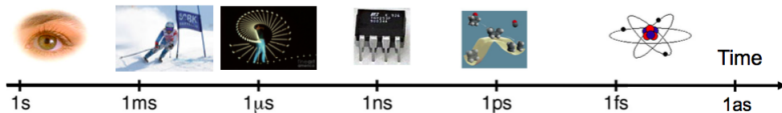
orbital period of e<sup>-</sup> in

$$\text{H} \approx 150 \text{ as}$$



# Time resolved atomic collisions?

## ■ Attosecond Streak Camera [Itatani et al. 2002]

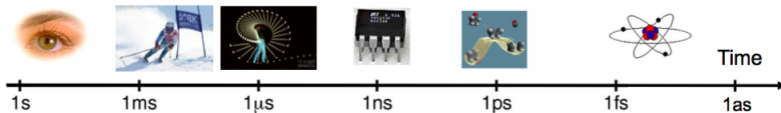


U. Keller, "Attosecond ionization time delays", April 2016, Canberra Physics Colloquium



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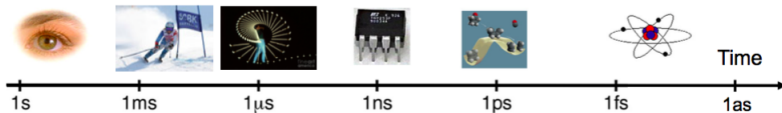
"A delay in photoemission (...) would compromise the accuracy of setting the zero of time for clocking microscopic processes on the atomic time scale."

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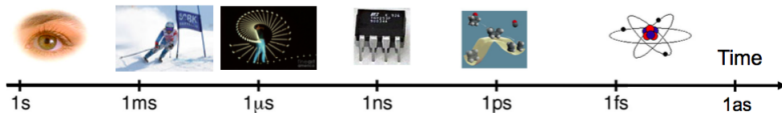
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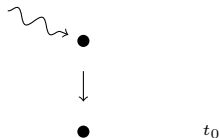


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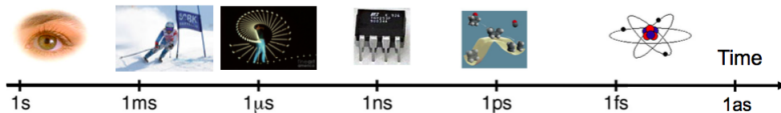






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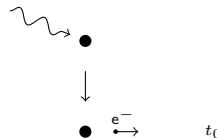


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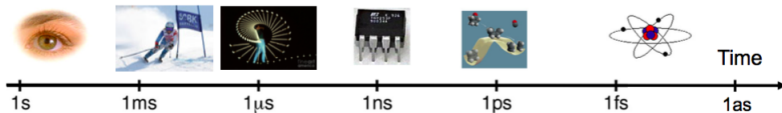
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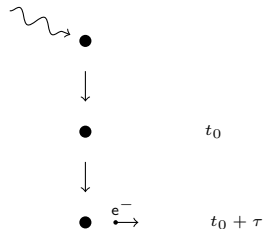


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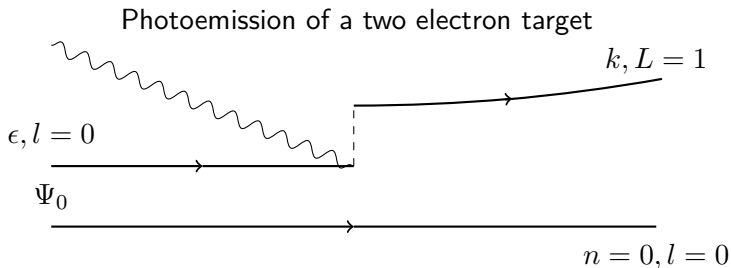
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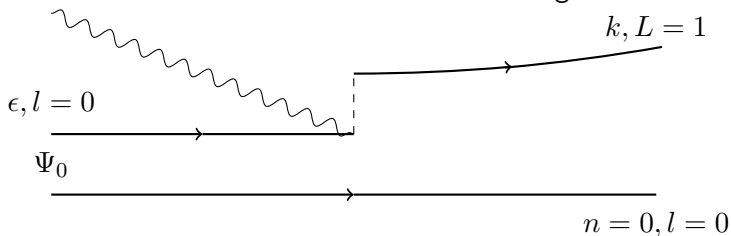
# Photoemission



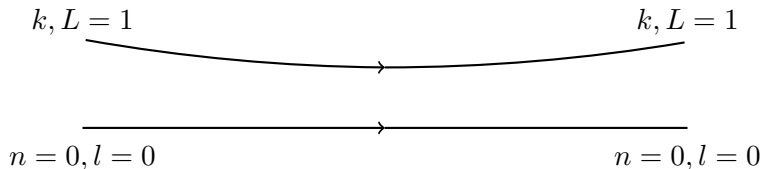
# Photoemission



## Photoemission of a two electron target



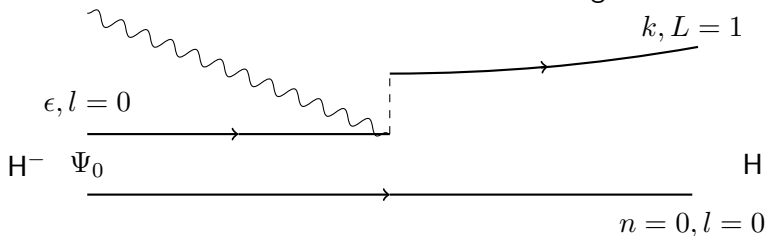
## Associated elastic scattering event



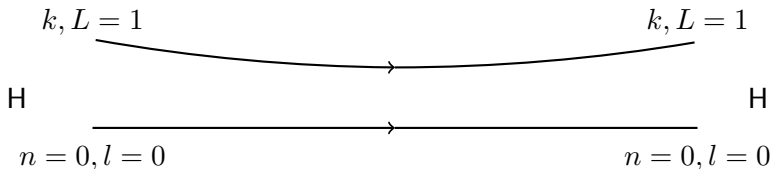
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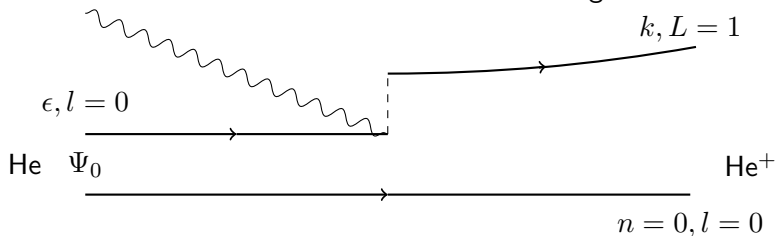
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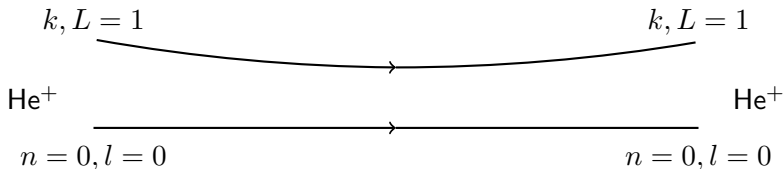
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## Photoemission of a two electron target



## Associated elastic scattering event



# Scattering formulation

## Cross section

$$\sigma_{fi} \propto |\langle \mathbf{k}_f \phi_f | V | \Psi_i^{(+)} \rangle|^2$$

index  $i$  initial

index  $f$  final

$\sigma_{fi}$  cross section from state  $i \rightarrow f$

$\Psi^{(+)}$   $(H_a + V)|\Psi^{(+)}\rangle = E|\Psi^{(+)}\rangle$

$\mathbf{k}$  projectile state

$\phi$  target (pseudo)state

$V$  interaction potentials

# Scattering formulation

## Cross section

$$\begin{aligned}\sigma_{fi} &\propto |\langle \mathbf{k}_f \phi_f | V | \Psi_i^{(+)} \rangle|^2 \\ &\equiv |\langle \mathbf{k}_f \phi_f | T | \phi_i \mathbf{k}_i \rangle|^2\end{aligned}$$

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index  $i$  initial

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$E$  total energy  $E = k_i^2/2 + \epsilon_i$

$\epsilon$  target energy

$\mathbf{k}$  projectile state

$\phi$  target (pseudo)state

$V$  interaction potentials

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## Convergent close-coupling

$$\begin{aligned}\langle \mathbf{k}_f \phi_f | T | \phi_i \mathbf{k}_i \rangle &= \langle \mathbf{k}_f \phi_f | V | \phi_i \mathbf{k}_i \rangle \\ &+ \sum_{n=1}^N \int d^3k \frac{\langle \mathbf{k}_f \phi_f | V | \phi_n \mathbf{k} \rangle \langle \mathbf{k} \phi_n | T | \phi_i \mathbf{k}_i \rangle}{E + i0 - \epsilon_n - k^2/2}\end{aligned}$$

# Photoemission with CCC



## Dipole Matrix

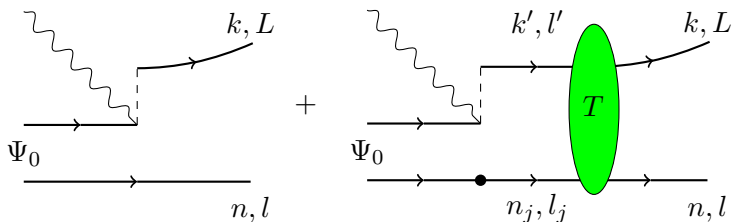
$$\begin{aligned}
 \langle Lkln || D || \Psi_0 \rangle &= \langle Lkln || d || \Psi_0 \rangle \\
 &+ \sum_{l_j n_j} \sum_{L'} \sum_{k'}^f \frac{\langle Lkln || T || n_j l_j k' L' \rangle}{E + i0 - \epsilon_j - k'^2/2} \langle L' k' l_j n_j || d || \Psi_0 \rangle
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Diagrammatically:



# Wigner Time Delay

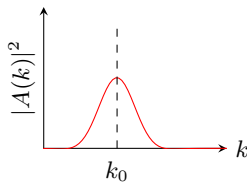
- “Delay in atomic photoionisation” [[Kheifets and Ivanov 2010](#)]

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Wavepacket of angular momentum  $L$   
centred about  $k_0$  for  $r \rightarrow \infty$ ,  $t > T$

$$\int A(k) \exp\{i(kx - \omega(k)t)\} dk$$



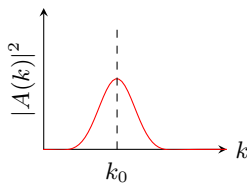
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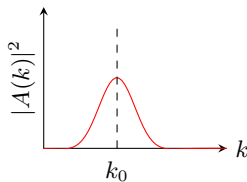
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$\delta_L$  phase shift in  $L$ -th partial wave

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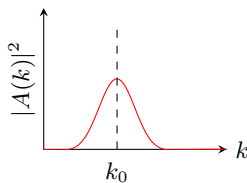
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$$\delta_L^{\text{el}}(k) \propto \arg(\langle Lkln || S || nlkL \rangle) / 2$$

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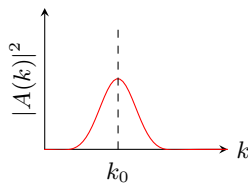
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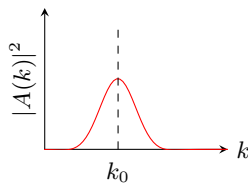
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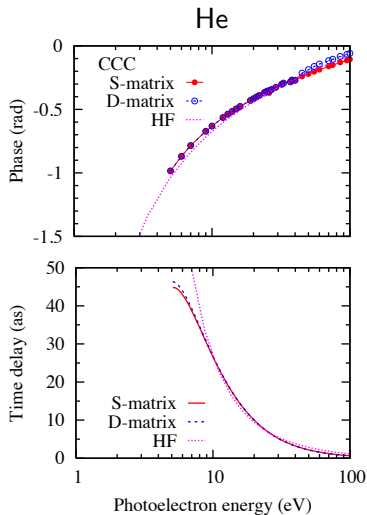
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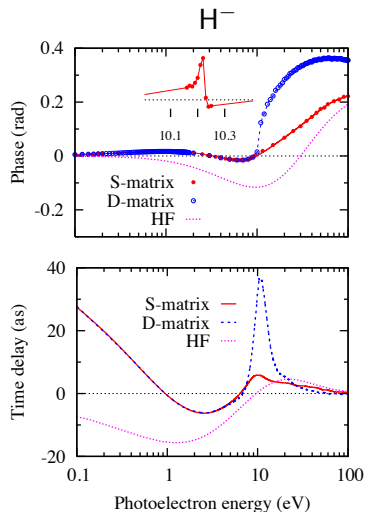
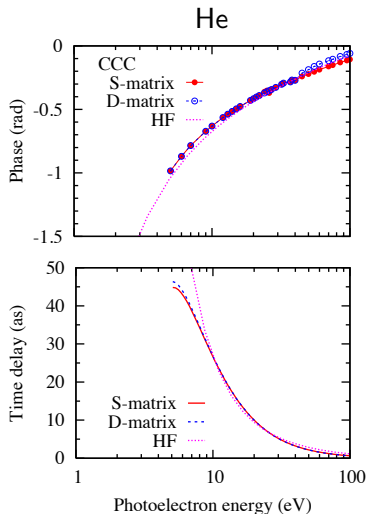
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(not quite the whole story)

# Photoemission and elastic scattering delay

 $H^-$

# Photoemission and elastic scattering delay



A.S. Kheifets et al., *Phys. Rev. Lett.* **117**, 143202

# Concluding remarks

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- Develop a TDSE based approach in combination with CCC