MULTIPLE IONIZATION/EXCITATION OF ATOMS AND IONS IN XUV SHORT FIELDS

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High Order Harmonic Generation

Free Electron Laser

X-ray Lasers

→

- -XUV domain
- -High intensities
- -Short pulses

↓

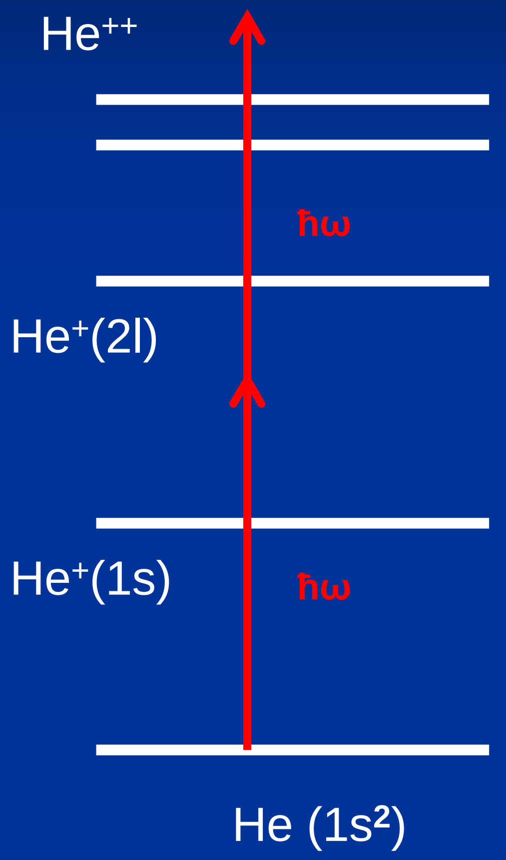
XUV laser-matter interaction in the non-linear domain

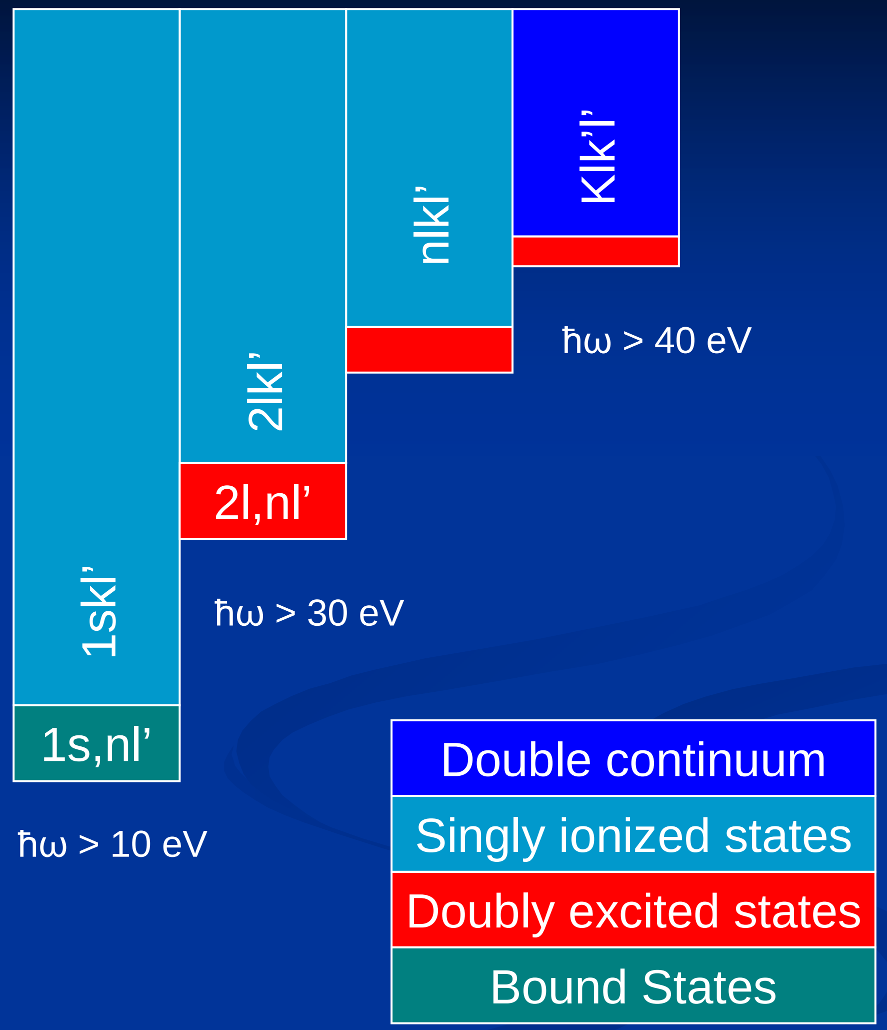
$I \sim 10^{12}$-10^{13} W/cm^2 $\hbar\omega$ = 10 eV - 80 eV

$K_{Keldysh}=(I_p/2U_p)^{1/2}$ $K_{Keldysh} >> 1$

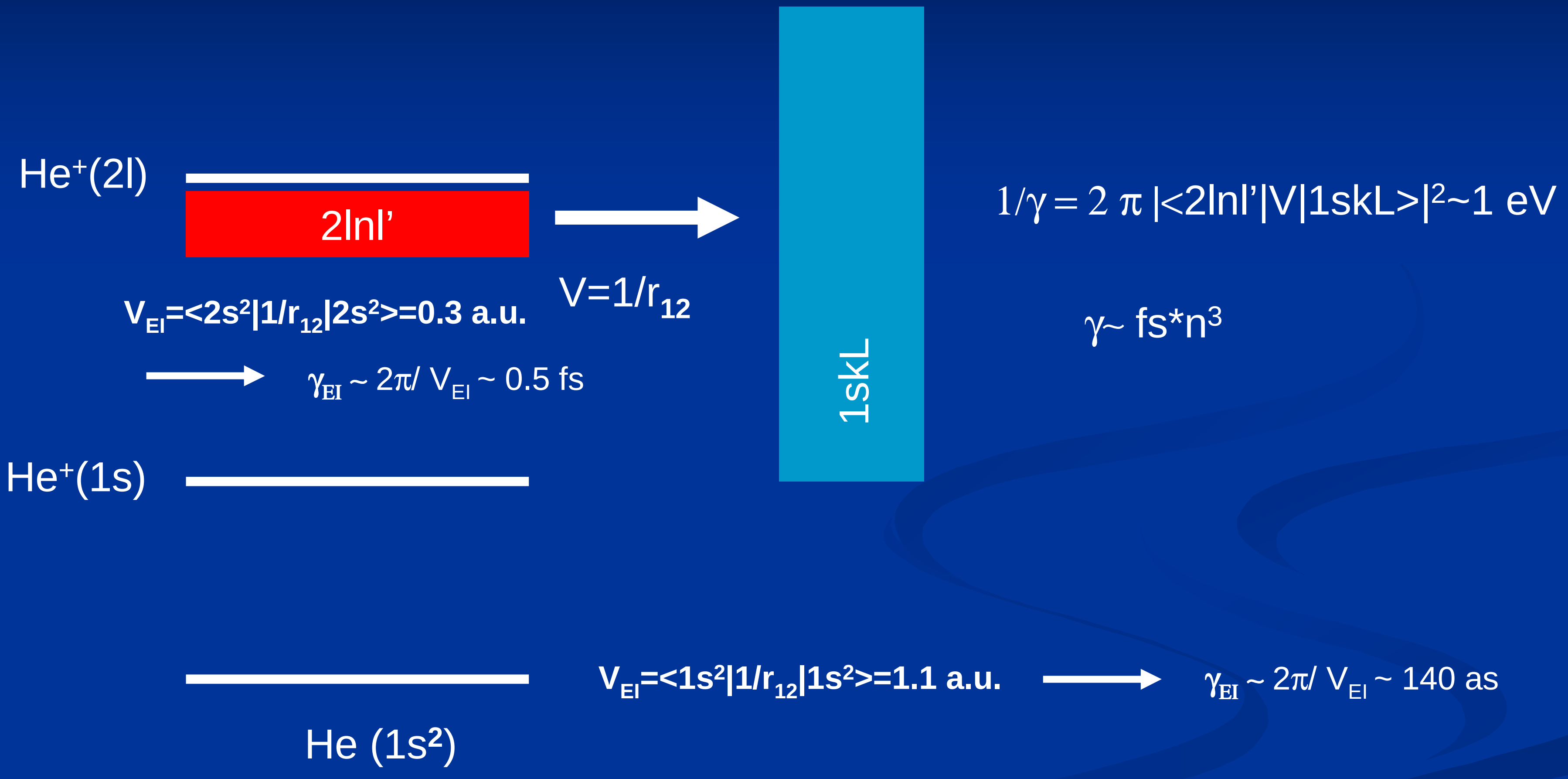
multiphoton regime - absorption of two photons - helium

WAVELENGTH RANGE FOR TWO-PHOTON ABSORPTION IN HELIUM

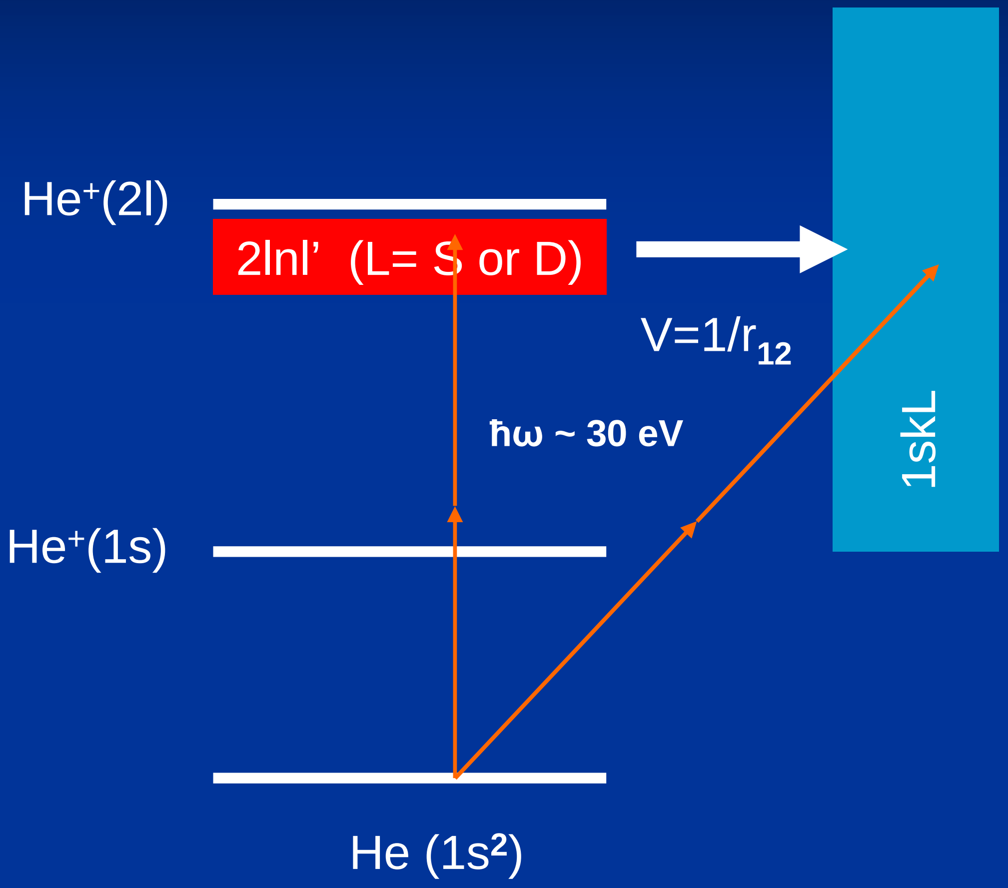




CORRELATIONS EFFECTS AND ASSOCIATED DURATIONS – FROM FEMTO TO ATTO SECONDS



<u>TWO-PHOTON TWO-ELECTRON EXCITATION</u>: He case



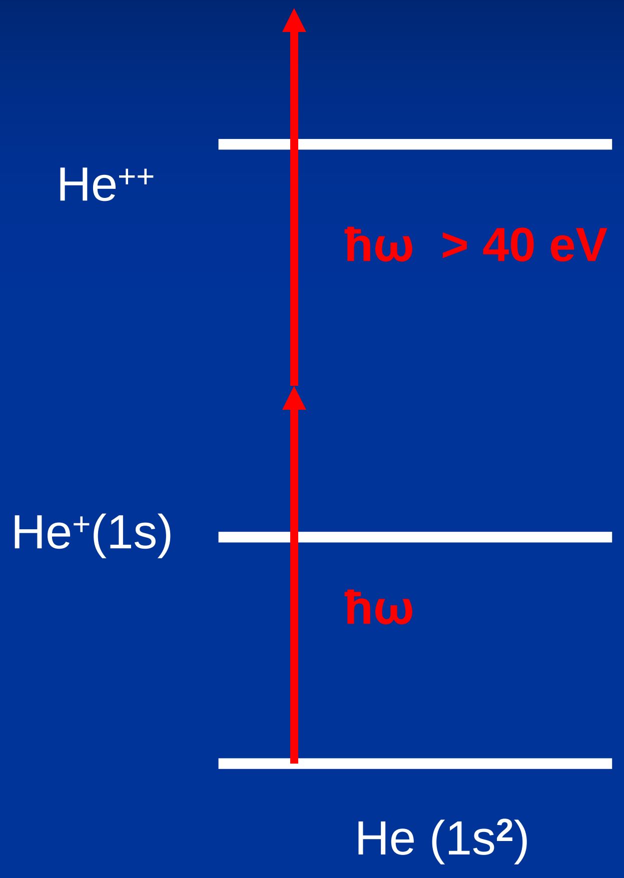
T < fs ; T > fs

T : pulse duration

- T << γ

- deviation from Fano profile
Hasbani et al, J. Phys B **33** (2000)

TWO-PHOTON DOUBLE IONIZATION (TPDI): HELIUM CASE



V_{EI}: MAJOR ROLE IN TPDI

$V_{EI}=\langle 1s^2|1/r_{12}|1s^2\rangle=1.1$ a.u. → $\gamma_{EI} \sim 2\pi/V_{EI} \sim 140$ as

OUTLINE

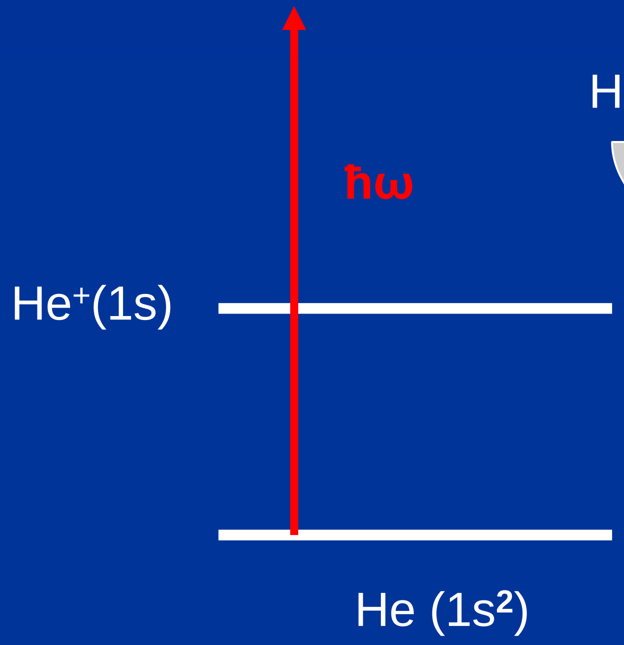
- TWO-PHOTON TWO-ELECTRON EXCITATION

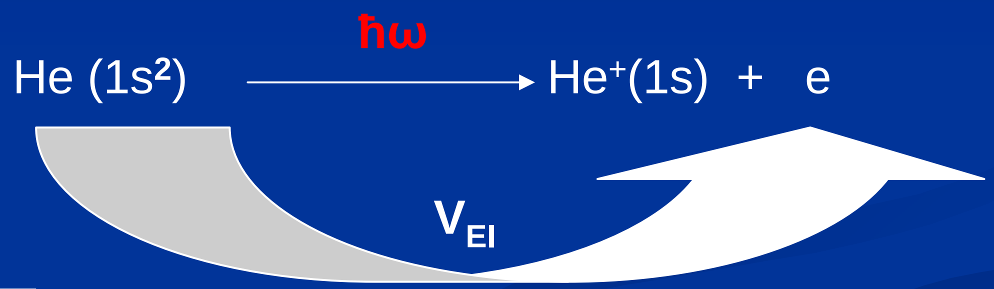
- **TWO-PHOTON DOUBLE IONIZATION (TPDI)**
    - **SEQUENTIAL REGIME**
    - DIRECT REGIME

- CONCLUSIONS AND PERSPECTIVES

TWO-PHOTON DOUBLE IONIZATION (TPDI): HELIUM CASE

SINGLE IONIZATION

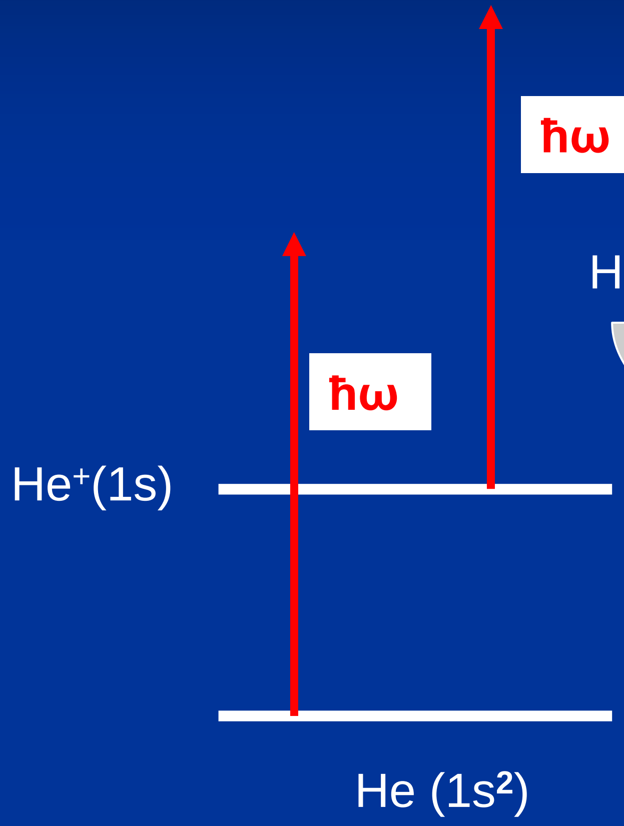


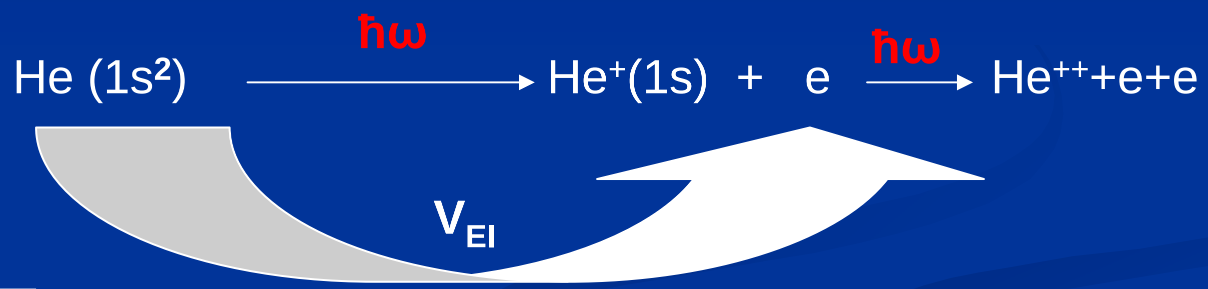


V_{EI}=<1s²|1/r_{12}|1s²>=1.1 a.u. ⟶ $\gamma_{EI} \sim 2\pi / V_{EI} \sim 140$ as

TWO-PHOTON DOUBLE IONIZATION: HELIUM CASE

SEQUENTIAL REGIME (ħω > 54.4 eV or 2 a.u.)



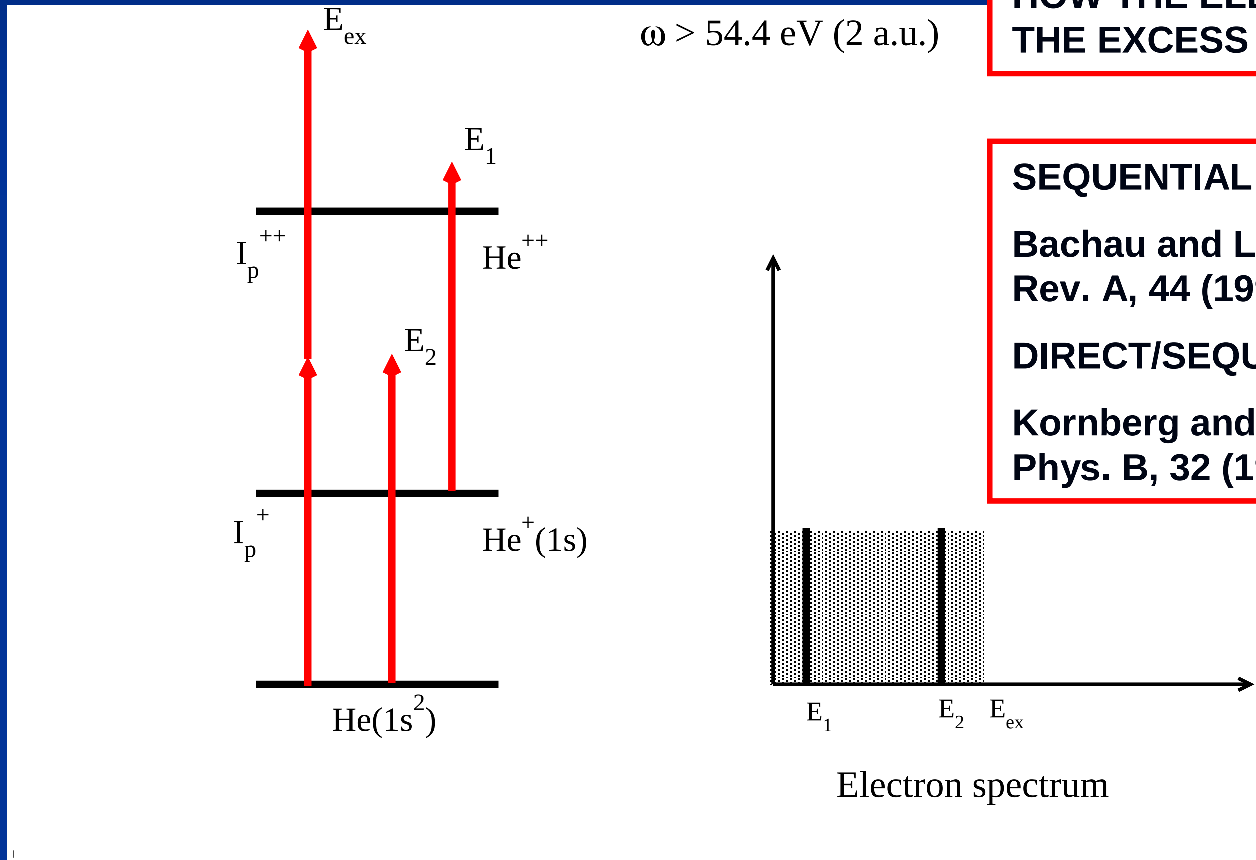


V_{EI}=<1s²|1/r_{12}|1s²>=1.1 a.u. ⟶ $\gamma_{EI} \sim 2\pi/V_{EI} \sim 140$ as

TWO-PHOTON DOUBLE IONIZATION: HELIUM CASE

SEQUENTIAL REGIME (ħω > 54.4 eV)

- **DIRECT/SEQUENTIAL (TWO STEPS) REGIME**



HOW THE ELECTRONS SHARE THE EXCESS ENERGY ?

SEQUENTIAL TPDI:

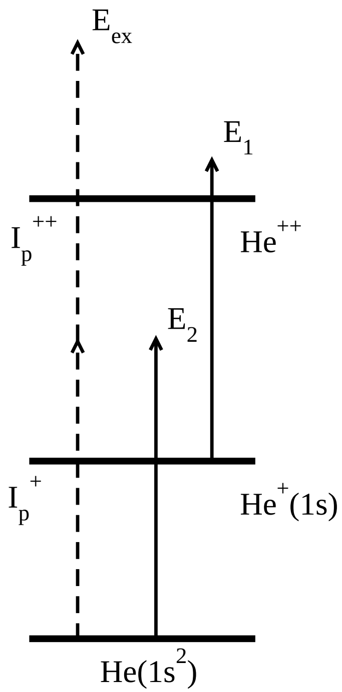
Bachau and Lambropoulos, Phys. Rev. A, 44 (1991) R9

DIRECT/SEQUENTIAL TPDI:

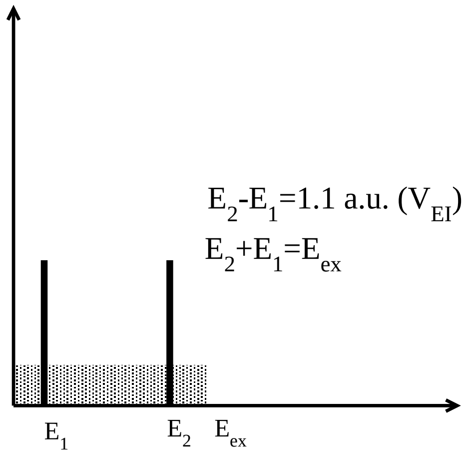
Kornberg and Lambropoulos, J. Phys. B, 32 (1999) L603

- $T \gg \gamma_{EI} \sim 2\pi / V_{EI} \sim 140$ as

- sequential DI dominates
- $|E_1 - E_2| = V_{EI}$
- rate ~ T^2 provided the intensity is not too large (10^{13} W/cm^2, P. Lambropoulo et al 2008)
- simple formula (resolvent operator formalism-only including sequential double ionization channels) gives the peaks positions and witdhs



1a)



1b)

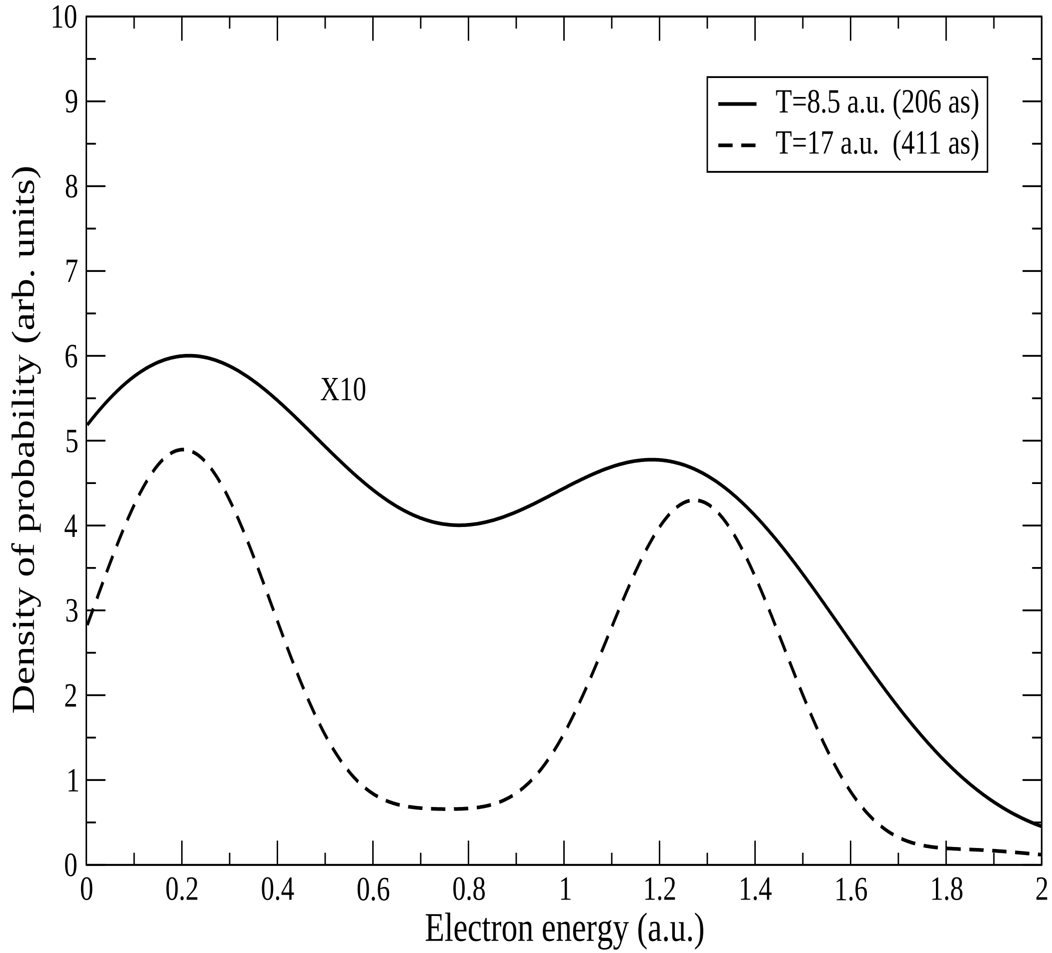
$$\frac{\gamma_{He}\gamma_{He^+}}{[(\varepsilon_1+\varepsilon_2-E_{ex})^2+|\gamma_{He}|^2/4]\,[(\varepsilon_1-E_1)^2+|\gamma_{He^+}|^2/4]}$$

Ionization rates of He and He⁺

- $T \longrightarrow \gamma_{EI} \sim 2\pi / V_{EI} \sim 140$ as
- resolvent operator formalism- only including sequential ionization channels)
- $\hbar\omega$ = 60 eV

- two pulse durations (insert)

- Widths of peaks given by the laser bandwidth



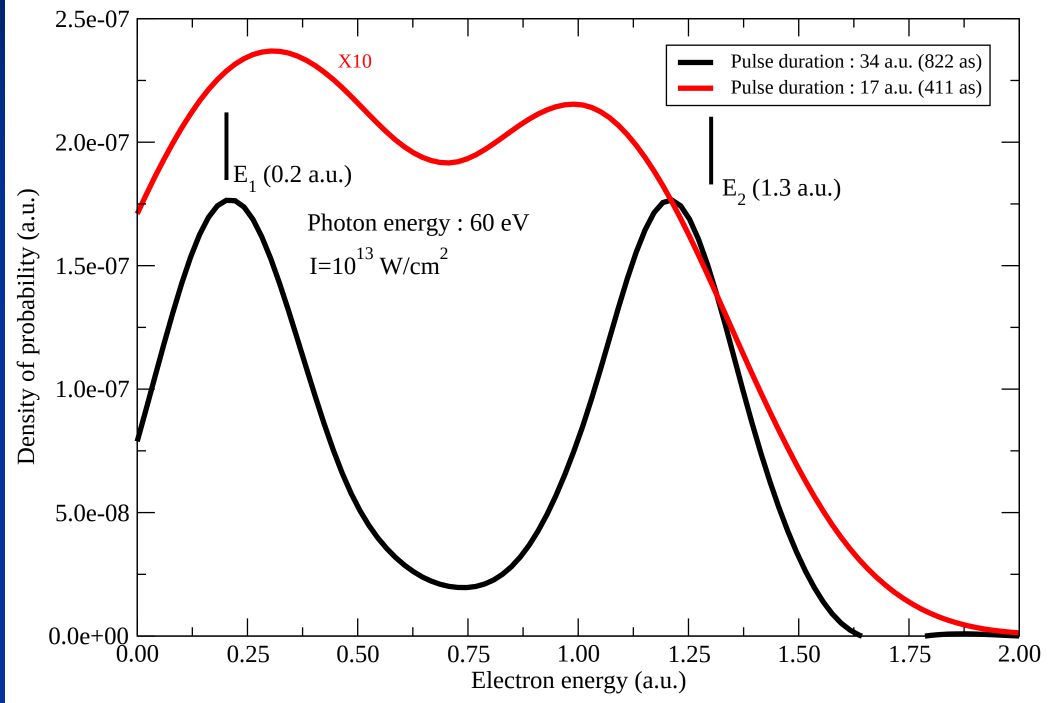
- T ⟶ $\gamma_{EI} \sim 2\pi / V_{EI} \sim 140$ as

- We resolve the time-dependent Schrödinger equation (TDSE)

- Calculations involve direct and sequential channels

- The second photon “probes” the ionization of He

- **The concept of direct and sequential processes are not meaningful for ultra short pulses**



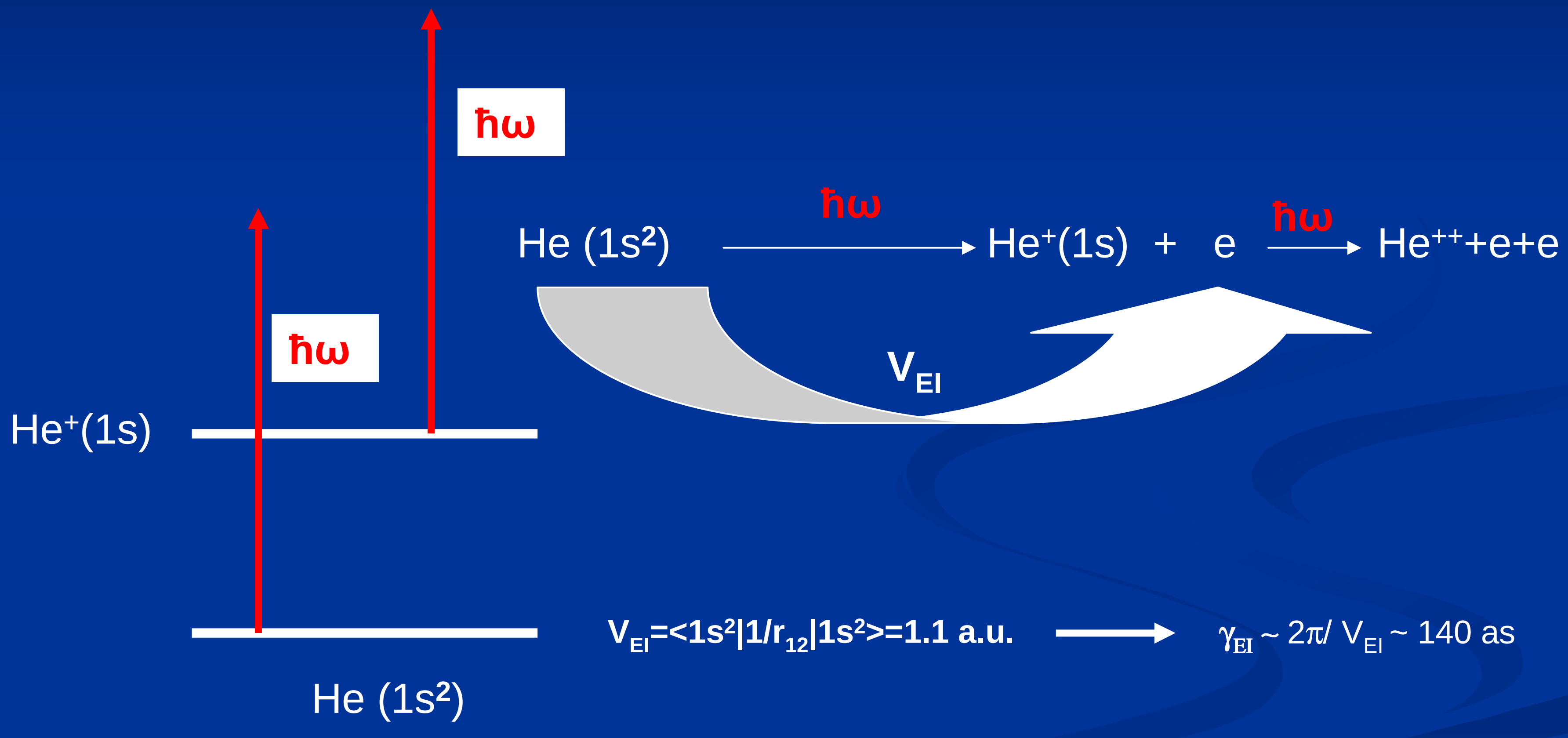
TPDI, sub-fs regime:

Foumouo et al J. Phys. B, 39 (2006) S427

Foumouo et al New J. Phys., 10 (2008) 025017

<u>TWO-PHOTON DOUBLE IONIZATION</u>: HELIUM CASE

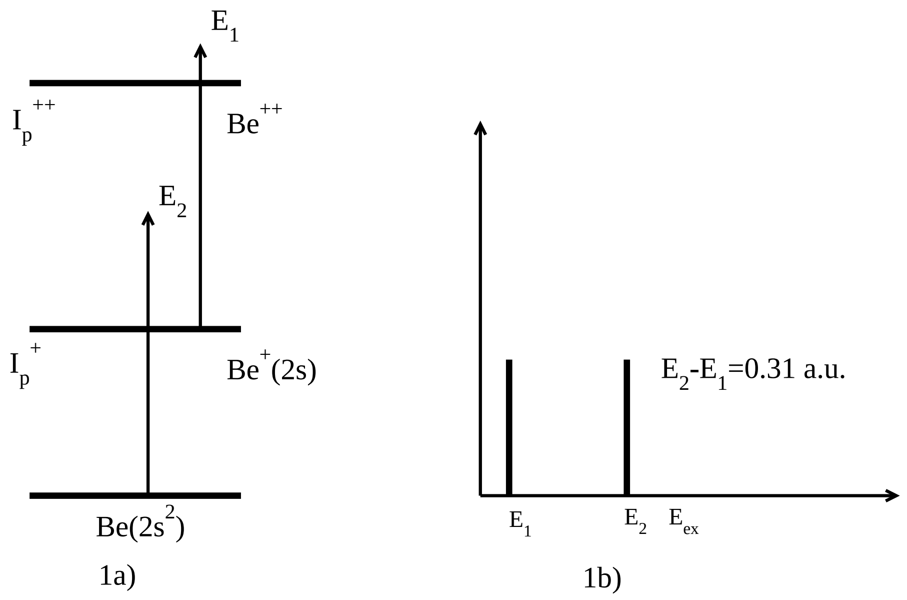
<u>SEQUENTIAL REGIME (ħω > 54.4 eV)</u>



$V_{EI}=\langle 1s^2|1/r_{12}|1s^2\rangle=1.1$ a.u. $\longrightarrow$ $\gamma_{EI} \sim 2\pi/ V_{EI} \sim 140$ as

● LIMIT OF 140 as UNREALISTIC ? THE CASE OF BERYLLIUM

- In Be V_{EI} ~ 0.31 a.u.
- $\gamma_{EI} \sim 2\pi / V_{EI} \sim 0.5$ fs
- $\hbar\omega > 18$ eV
- Effects expected for larger pulse durations



S. Laulan and H. Bachau, Phys. Rev. A 69 (2004) 033408

OUTLINE

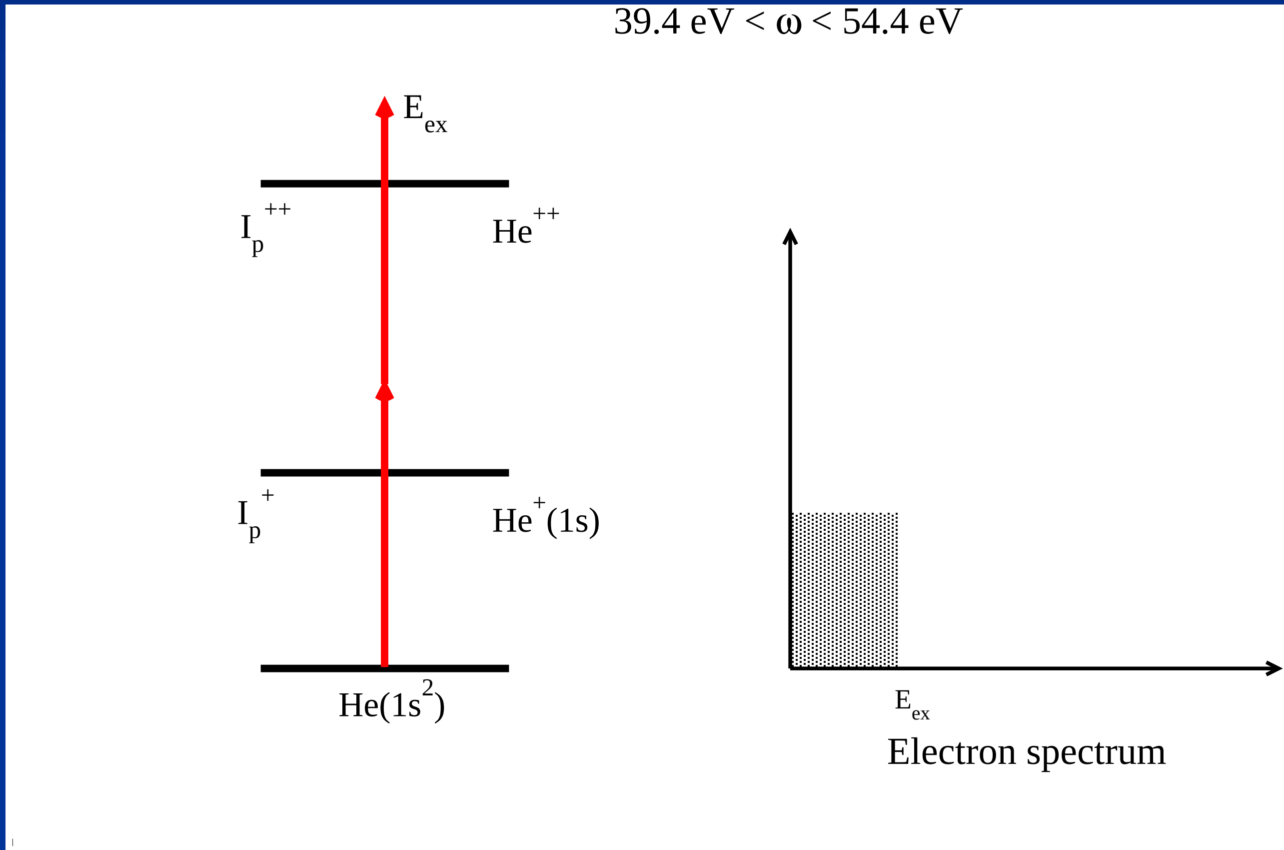
- TWO-PHOTON TWO-ELECTRON EXCITATION

- **TWO-PHOTON DOUBLE IONIZATION (TPDI)**
    - SEQUENTIAL REGIME
    - **DIRECT REGIME**

- CONCLUSIONS AND PERSPECTIVES

TWO-PHOTON DOUBLE IONIZATION (TPDI): HELIUM CASE

DIRECT REGIME (39.4 eV < ħω < 54.4 eV)



● THEORETICAL ASPECTS

$$i \frac{\partial}{\partial t}\Psi(\mathbf{r}_1,\mathbf{r}_2,t) = [H + (\mathbf{p}_1 + \mathbf{p}_2).\mathbf{A}(t)] \quad \Psi(\mathbf{r}_1,\mathbf{r}_2,t)$$

H : *Hamiltonian for helium*

Field potential (*from* $-T/2$ *to* $T/2$):

$$\mathbf{A}(t) = \mathbf{e}_z A_0 \quad (\cos\frac{\pi \ t}{T})^2 \quad \cos\omega t$$

$\mathbf{e}_z$: *polarization vector* (*linear pol.*)

● SOLVE THE TDSE

- P. Lambropoulos et al, Phys. Rep., 305 (1998)
- H. Bachau et al, Rep. Prog. Phys., 64 (2001)

● DIFFICULTY: CALCULATING THE DOUBLE CONTINUUM (ROLE OF ELECTRON CORRELATIONS)

● INFORMATIONS:

- PROVIDED THE INTENSITY IS NOT TOO LARGE THE TPDI CROSS-SECTION EXIST (TPDI~T) AND CAN BE EXTRACTED FROM TDSE (OR DIRECTLY CALCULATED USING LOPT)

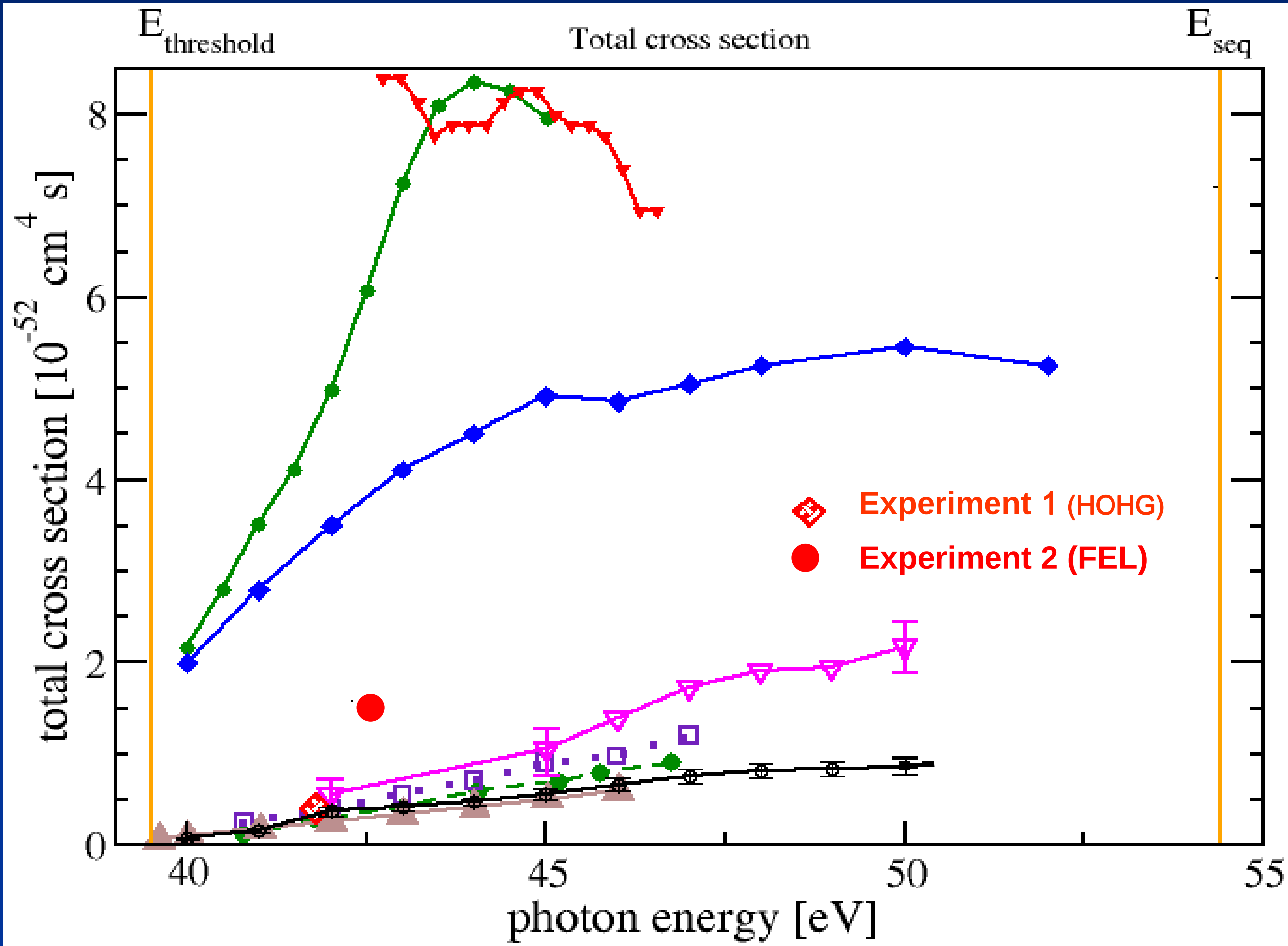
- ELECTRON ENERGY DISTRIBUTIONS

- ELECTRON ANGULAR DISTRIBUTIONS

- RECOIL ION MOMENTUM DIST.

E. Foumouo, Ph. Antoine, B. Piraux, L. Malegat, H. Bachau and R. Shakeshaft, J. Phys. B, 41 (2008) 051001 (Fast Track Communication)

- **TPDI CROSS-SECTION**



By decreasing order of magnitude

L. A. A. Nikolopoulos and P. Lambropoulos, J. Phys. B **40**, 1347 (2007)

L. A. A. Nikolopoulos and P. Lambropoulos, J. Phys. B **34**, 545 (2001)

E. Foumouo, G. L. Kamta, G. Edah, and B. Piraux, Phys. Rev. A **74**, 063409 (2006)

I. A. Ivanov and A. S. Kheifets, Phys. Rev. A **75**, 033411 (2007)

B. Piraux, J. Bauer, S. Laulan, and H. Bachau, Eur. Phys. J. D **26**, 7 (2003)

L. Feng and H. W. van der Hart, J. Phys. B **36**, L1 (2003)

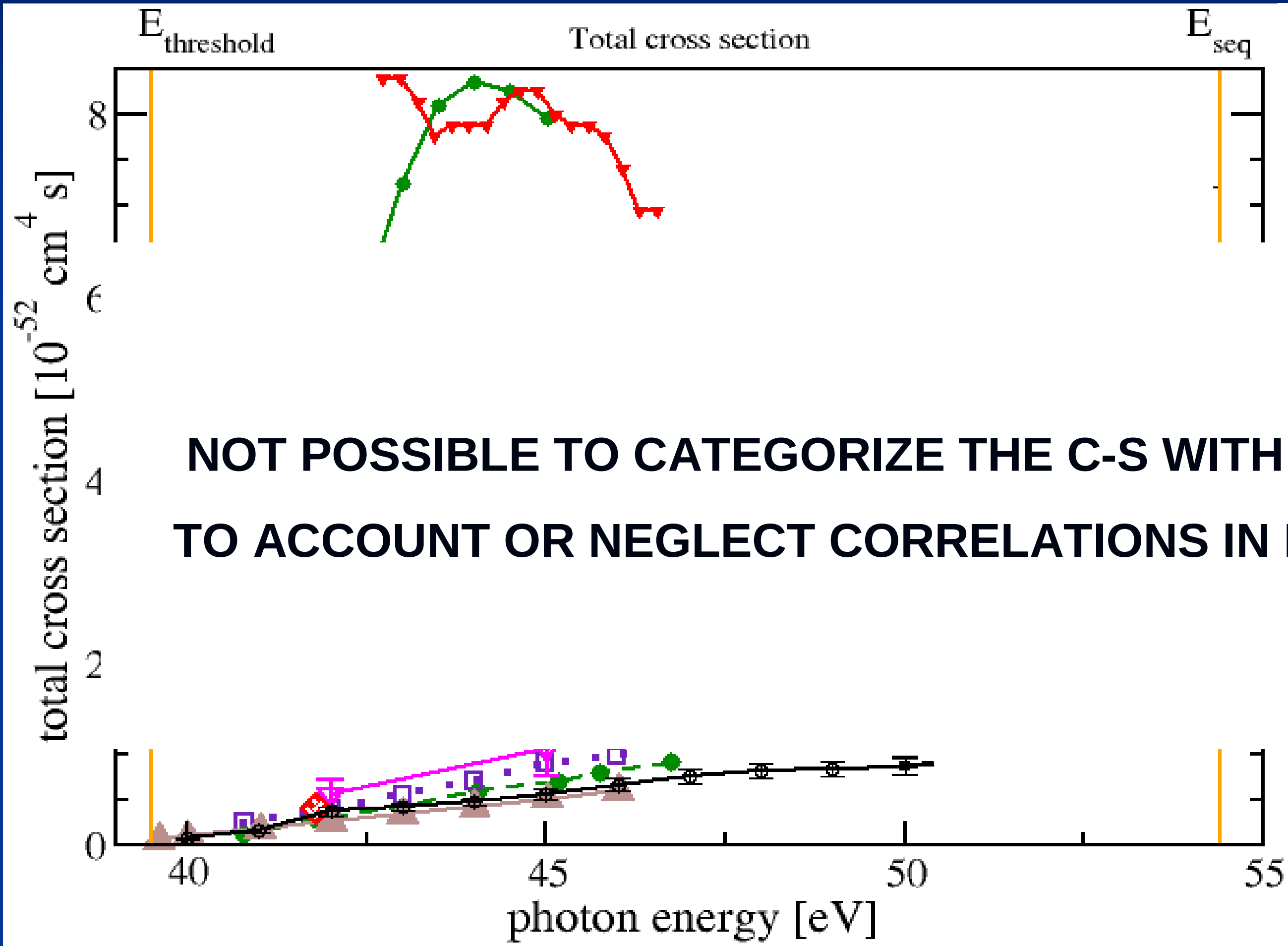
S. X. Hu, J. Colgan, and L. A. Collins, J. Phys. B **38**, L35 (2005)

Horner et al, Phys. Rev. A 76 (2007) 030701

Experiment 1: H. Hasegawa et al , Phys. Rev. A **71**, 023407 (2005)

Expériment 2: A.A. Sorokin et al, Phys. Rev. A 75, 051402 (2007)

- **TPDI CROSS-SECTION**



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. Phys. B

lins, J.

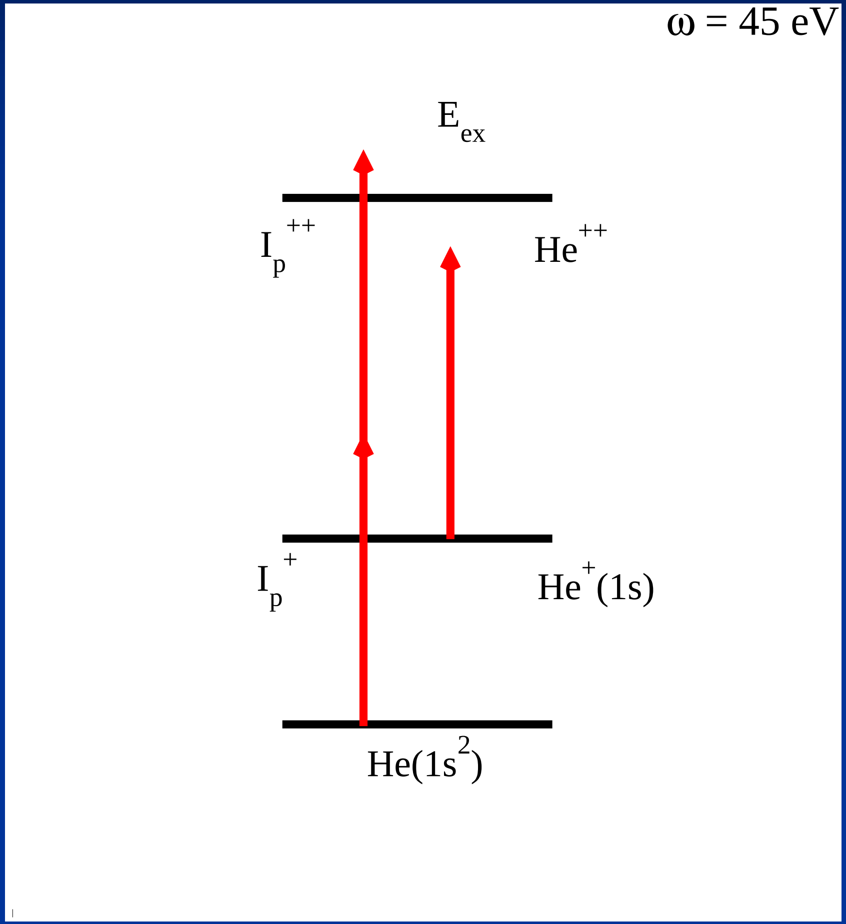
NOT POSSIBLE TO CATEGORIZE THE C-S WITH RESPECT TO ACCOUNT OR NEGLECT CORRELATIONS IN FINAL STATE

Martin et al (priv. com.), ECS method

Experiment 1: H. Hasegawa et al , Phys. Rev. A **71**, 023407 (2005)

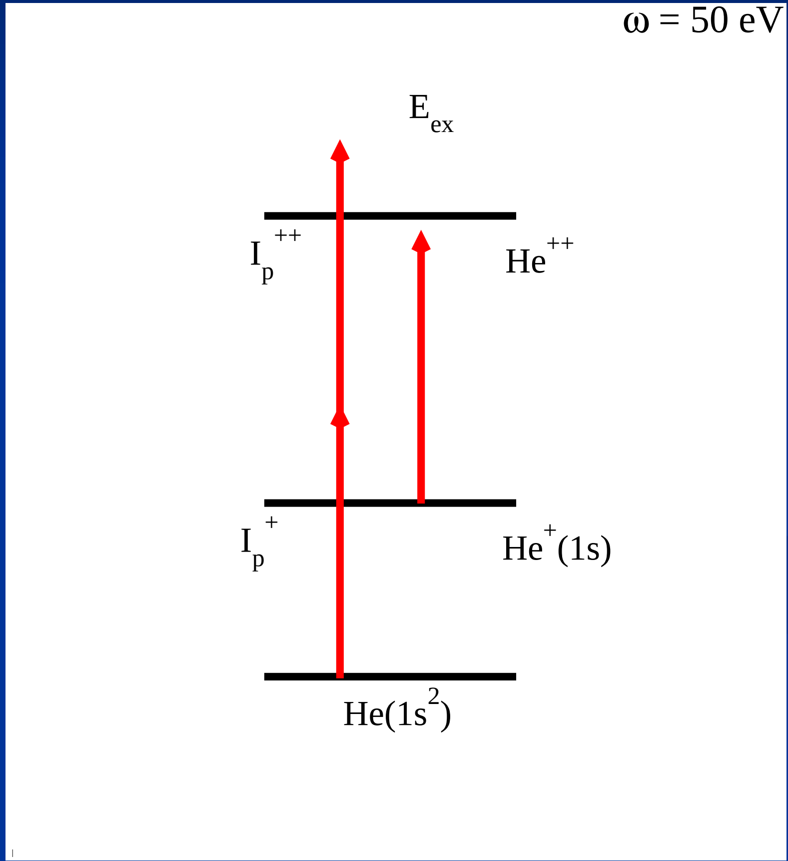
Expériment 2: A.A. Sorokin et al, Phys. Rev. A 75, 051402 (2007)

- **TPDI (ħω= 45 eV)**



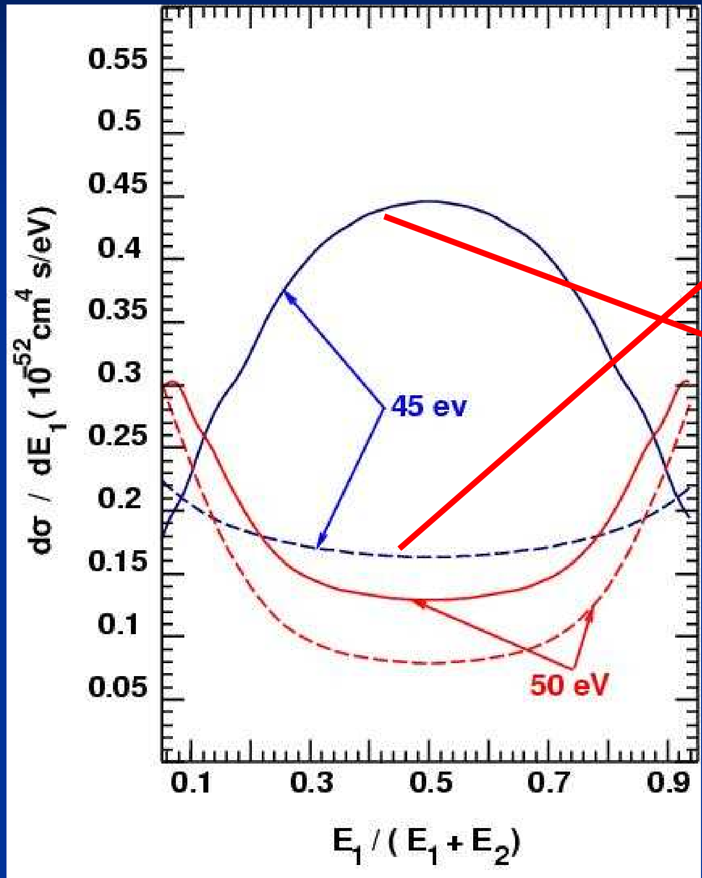
Excess energy : 0.4 a.u. (11 eV)

- TPDI (ħω = 50 eV), close to the threshold for sequential TPDI



Excess energy : 0.77 a.u. (21 eV)

● ENERGY DISTRIBUTION (HOW THE ELECTRONS SHARE E_{ex})



Integrated energy distribution (E_k) – *Method 1*:

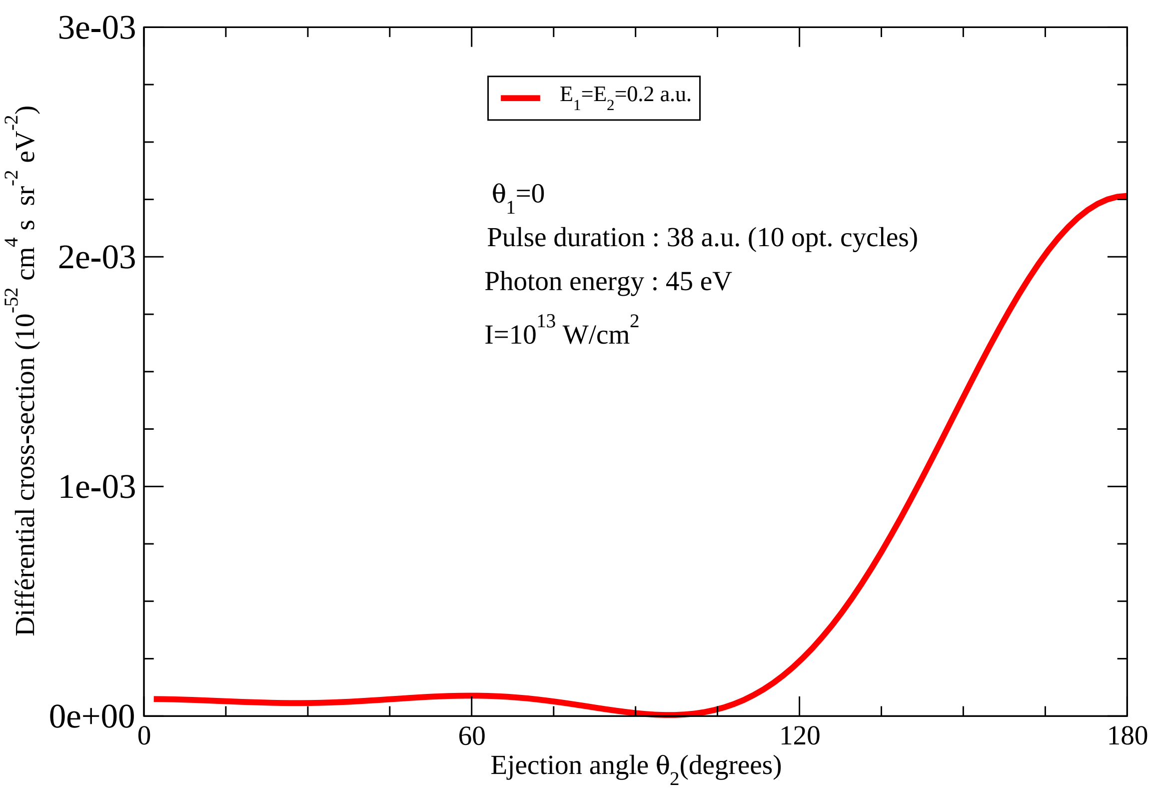
$$\frac{d\,P^{L,M}_{l_1,l_2}}{dE_k}=\int\left|\left\langle \psi^{l_1}_{E_k}(\mathbf{r}_1)\psi^{l_2}_{E_{k'}}(\mathbf{r}_2)+1\square\ 2\right|\Psi(t=\frac{T}{2})\right\rangle\Big|^2\, dE_{k'}$$

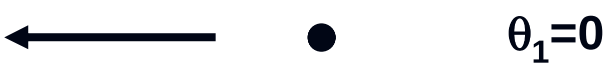
Integrated energy distribution (E_k) –
Method 2 (*J – matrix, Foumouo et al*):

$$\frac{d\,P^{L,M}_{l_1,l_2}}{dE_k}=\int\left|\left\langle \psi^{l_1}_{E_k}(\mathbf{r}_1)\psi^{l_2}_{E_{k'}}(\mathbf{r}_2)+1\square\ 2\right|\Psi(t=\frac{T}{2})-\Psi_{SI}\right\rangle\Big|^2\, dE_{k'}$$

D.A. Horner et al, Phys. Rev. A 76 (2007),
ECS with electron correlations included in
final state : **U-shaped energy distribution**

- TPDI ANGULAR DISTRIBUTION (ħω = 45 eV)



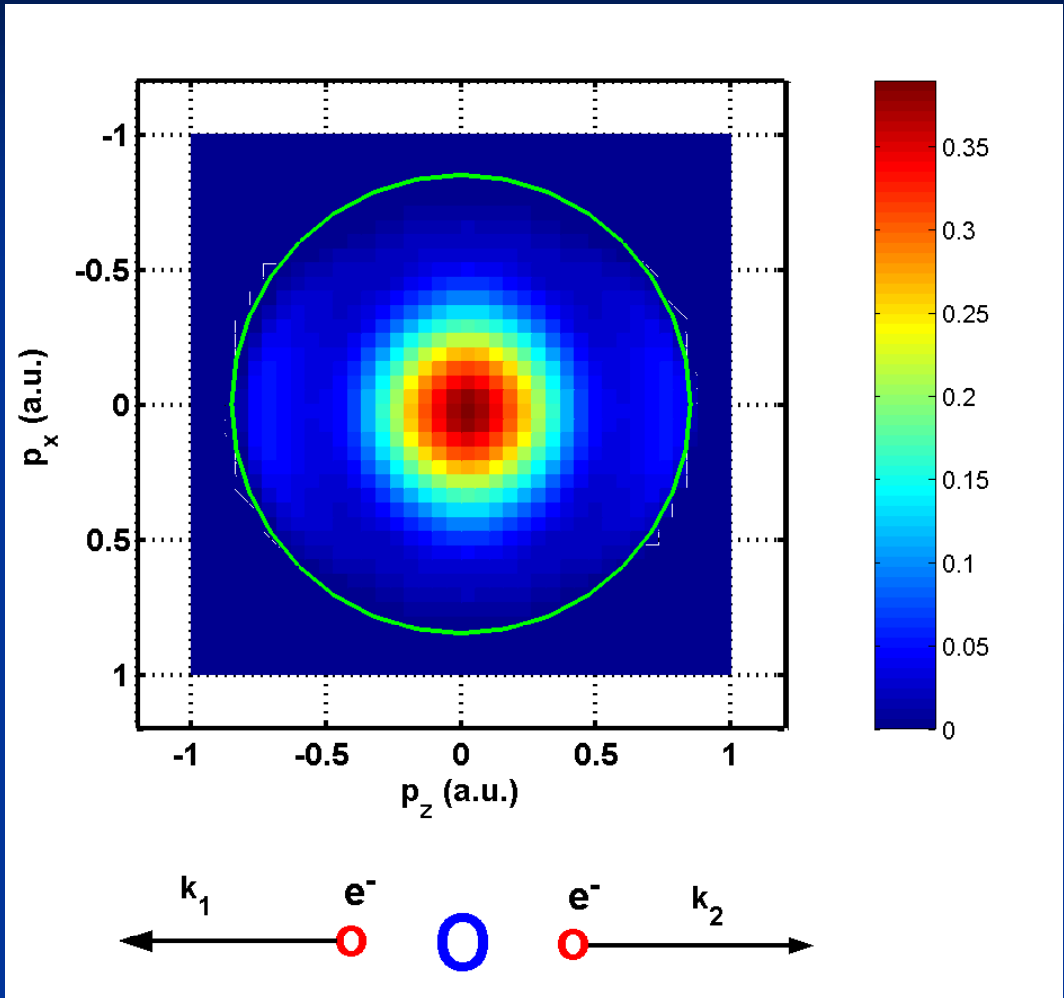


Excess energy : 0.4 a.u. (11 eV)

E_1=0.2 a.u.

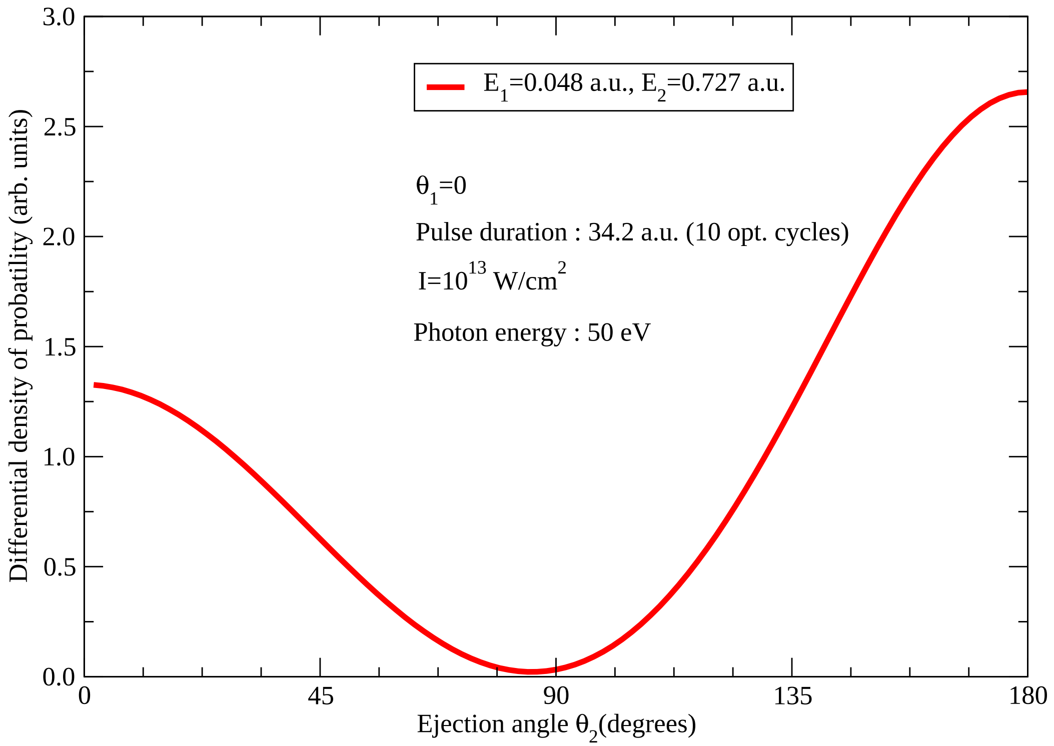
E_2=0.2 a.u.

- **RECOIL ION MOMENTUM DISTRIBUTION (ħω = 42 eV)**



E. Foumouo et al, J. Phys. B, 41 (2008) 051001 (Fast Track Communication)

- TPDI ANGULAR DISTRIBUTION ($\hbar\omega$ = 50 eV)

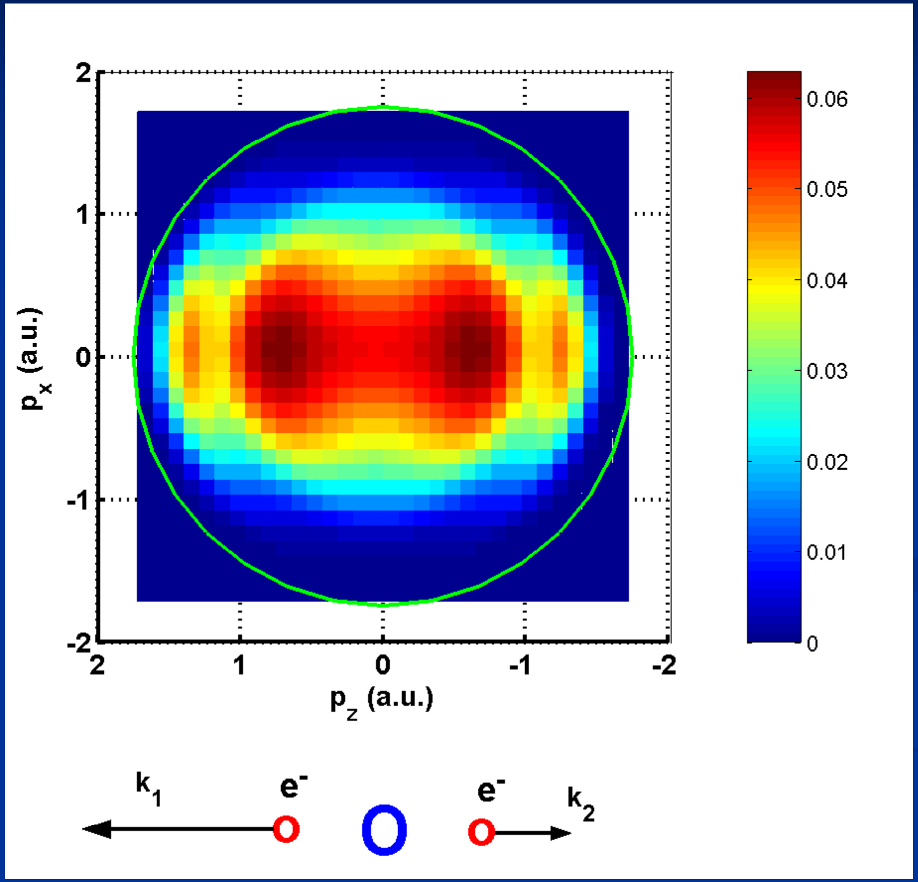


Excess energy : 0.77 a.u. (21 eV)

E_1=0.048 a.u.

E_2=0.727 a.u.

- **RECOIL ION MOMENTUM DISTRIBUTION (ħω = 50 eV)**



● CONCLUSIONS AND PERSPECTIVES

- DEVELOPMENT OF SHORT AND INTENSE XUV LASER PULSES + SOPHISTICATED DETECTION TECHNIQUES OPENS NEW “AVENUES” IN A&M PHYSICS
- SPECTROSCOPY OF IONS AND ATOMS
- DYNAMICS OF FUNDAMENTAL PROCESSES LIKE DOUBLE IONIZATION
- **Experiment are needed -recoil-ion momentum of crucial interest - already applied in Ne (FLASH) (R. Moshammer et al, PRL 98 (2007) 203001)**
- HIGHER ORDER PROCESSES
- APPLICATIONS ON MOLECULES (VIB. MOTION ~FS)

- **THANK YOU**