One- and two-electron systems in strong IR- and XUV-fields

Anatoli Kheifets and Igor Ivanov

THE AUSTRALIAN NATIONAL UNIVERSITY

Igor Bray

Centre for Antimatter-Matter Studies

One- and two-electron systems in strong IR- and XUV-fields

Numerically accurate atomic physics
in strong field regime

Anatoli Kheifets and Igor Ivanov

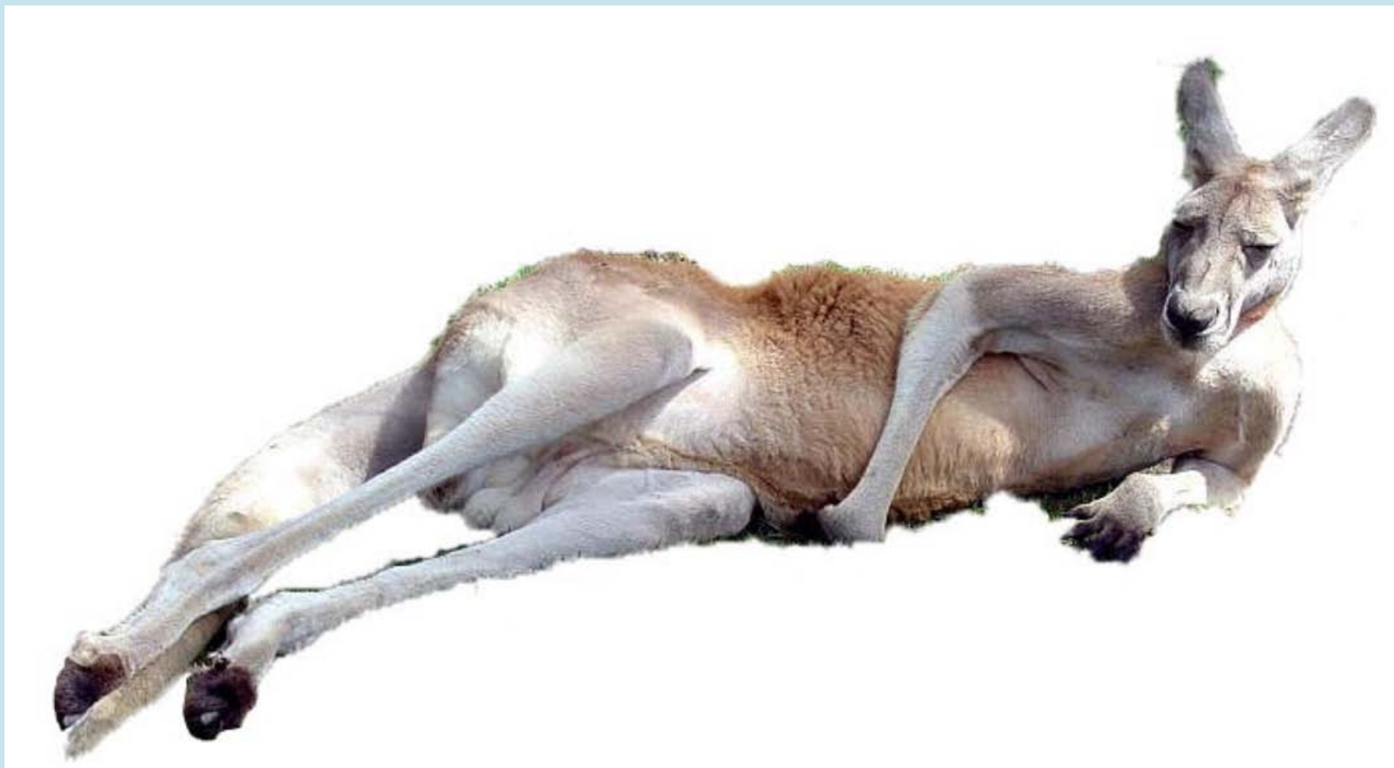
THE AUSTRALIAN NATIONAL UNIVERSITY

Igor Bray

Centre for Antimatter-Matter Studies

One- and two-electron systems in strong IR- and XUV-fields

Numerically accurate atomic physics
in strong field regime



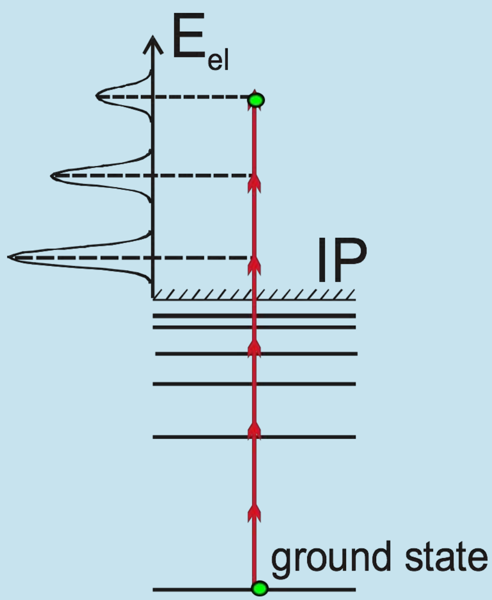
One- and two-electron systems in strong IR- and XUV-fields

Numerically accurate atomic physics
in strong field regime

Regimes of strong field ionization

Regimes of strong field ionization

Multiphoton-ionization
-low intensity,
 E-field of laser weak
 compared to atomic field
- perturbative regime



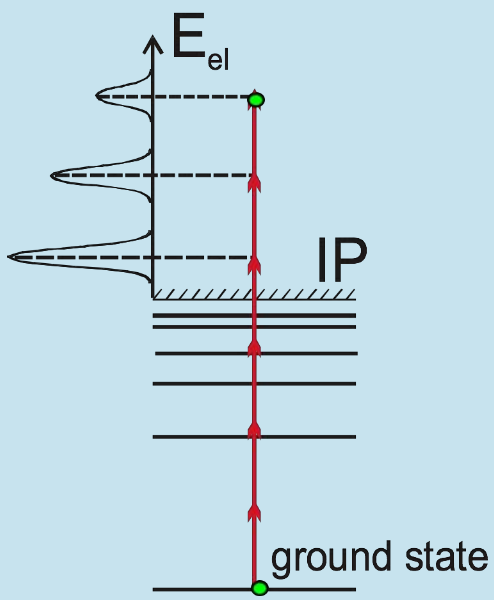
$$\gamma >> 1$$

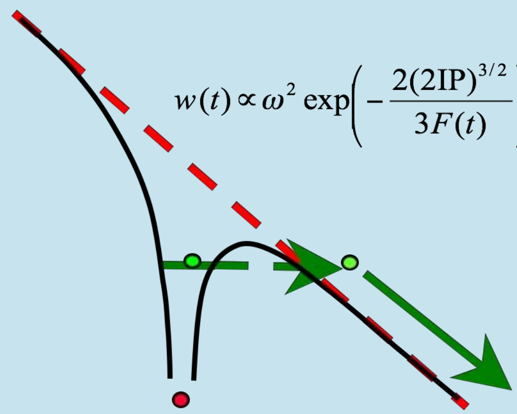
Regimes of strong field ionization

Multiphoton-ionization
-low intensity,
 E-field of laser weak
 compared to atomic field
- perturbative regime

→

Tunneling-ionization
- high intensity
- classical field picture
- field ionization in
  quasistatic laser field





$$w(t) \propto \omega^2 \exp\left(-\frac{2(2\mathrm{IP})^{3/2}}{3F(t)}\right)$$

$$\gamma >> 1$$

$$\gamma = \sqrt{\frac{4\mathrm{IP}}{I}\omega^2}$$

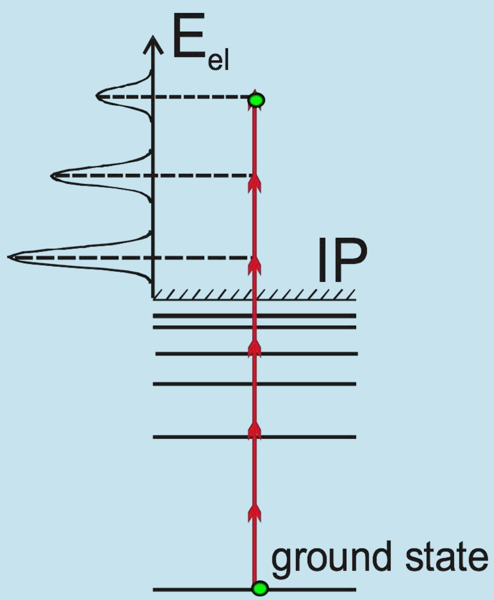
$$U_p = I/4\omega^2$$

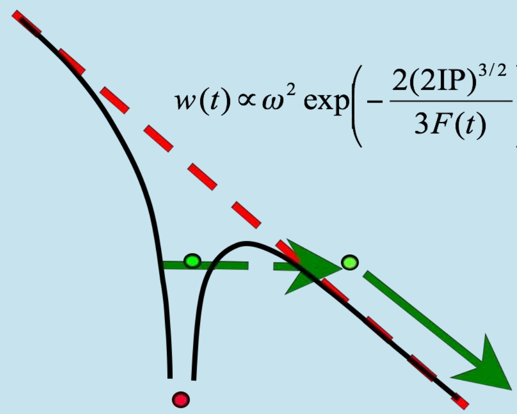
Regimes of strong field ionization

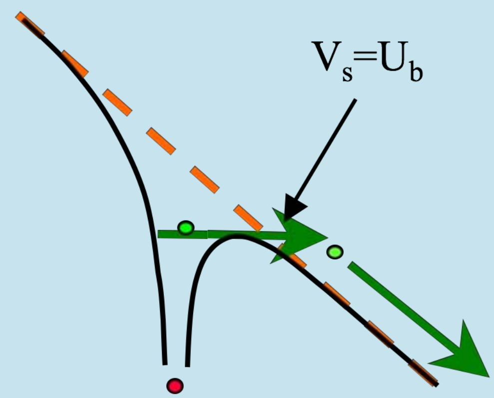
Multiphoton-ionization
-low intensity,
E-field of laser weak compared to atomic field
- perturbative regime

Tunneling-ionization
- high intensity
- classical field picture
- field ionization in quasistatic laser field

Over-the-barrier-ionization
- highest intensities
- complete suppression of the Coulomb-barrier of bound state
-Atomic system dominated by external field







$$\gamma >> 1$$

$$\gamma = \sqrt{\frac{4\mathrm{IP}}{I}\omega^2}$$

$$\gamma < 1$$

$$U_p = I / 4\omega^2$$

Case studies:

Case studies:

- Strong Field Ionization

Case studies:

- Strong Field Ionization
  - SFA does not work
    - Single ionization of H @ IR: 5.5 fs pulses, 750 nm, 10^{14-15} W/cm^2

Case studies:

- Strong Field Ionization
  - SFA does not work
    - Single ionization of H @ IR: 5.5 fs pulses, 750 nm, $10^{14\text{-}15}$ W/cm^2
  - Accurate atomic potential is essential
    - Single ionization of Li @ IR: 25 fs pulses, 785 nm, $10^{11\text{-}14}$ W/cm^2

Case studies:

- Strong Field Ionization
  - SFA does not work
    - Single ionization of H @ IR: 5.5 fs pulses, 750 nm, $10^{14\text{-}15}$ W/cm^2
  - Accurate atomic potential is essential
    - Single ionization of Li @ IR: 25 fs pulses, 785 nm, $10^{11\text{-}14}$ W/cm^2
  - Many-electron correlation is essential
    - Double ionization of He @ XUV:

Case studies:

- **Strong Field Ionization**
  - SFA does not work
    - Single ionization of H @ IR: 5.5 fs pulses, 750 nm, 10^{14-15} W/cm^2
  - Accurate atomic potential is essential
    - Single ionization of Li @ IR: 25 fs pulses, 785 nm, 10^{11-14} W/cm^2
  - Many-electron correlation is essential
    - Double ionization of He @ XUV:
- **Time-resolved atomic reactions**
  - *Electron correlation resolved in time*
    - *Double ionization of He*
    - *Single ionization of noble gases*

Outline

- Theoretical model

Outline

- Theoretical model
  - Time-dependent Schrödinger equation
    - *Basis based integration vs coordinate space integration*

Outline

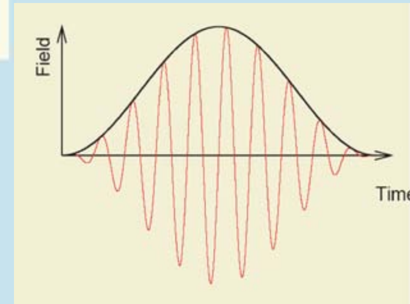
- Theoretical model
  - Time-dependent Schrödinger equation
    - *Basis based integration vs coordinate space integration*
  - Field-free atomic states
    - *One-electron HF states*
    - *Two-electron CCC states*

Outline

- Theoretical model
  - Time-dependent Schrödinger equation
    - *Basis based integration vs coordinate space integration*
  - Field-free atomic states
    - *One-electron HF states*
    - *Two-electron CCC states*
  - Discretization of continuum
    - *Pseudostates vs continuum states*

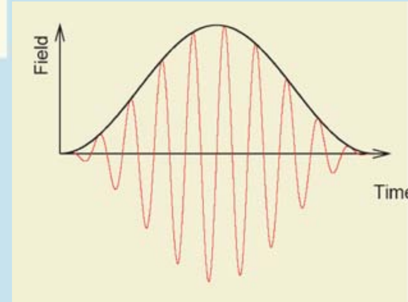
Theoretical Model

Theoretical Model



Field on:

Theoretical Model

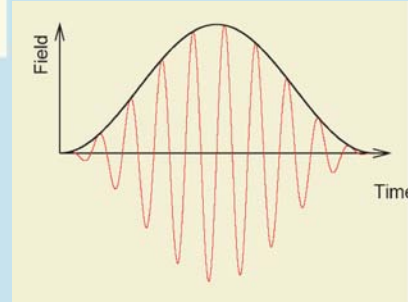


Field on:

Time-Dependent Schrödiger equation $i\frac{\partial \Psi}{\partial t} = \hat{H}\Psi$

$$\hat{H} = \frac{\boldsymbol{p}_1^2}{2} + \frac{\boldsymbol{p}_2^2}{2} - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|} + \boldsymbol{D}\cdot\boldsymbol{F}_{\mathrm{AC}} \cos \omega t$$

Theoretical Model



Field on:

Time-Dependent Schrödiger equation $i\frac{\partial \Psi}{\partial t} = \hat{H}\Psi$

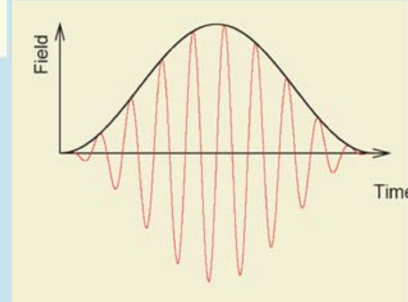
$$\hat{H} = \frac{\boldsymbol{p}_1^2}{2} + \frac{\boldsymbol{p}_2^2}{2} - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|} + \boldsymbol{D}\cdot\boldsymbol{F}_{\mathrm{AC}} \cos \omega t$$

Solution:

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = \sum_{j \equiv \left\{ {n_1 n_2 N \atop l_1 l_2 \; L} \right\}} a_j(t)\, \phi^N_{n_1 l_1}(r_1) \phi^N_{n_2 l_2}(r_2)\, |l_1(1) l_2(2) L\rangle$$

Pseudostate basis: $\langle \phi_i^N | \hat{H} | \phi_j^N \rangle = E_i \delta_{ij}$

Theoretical Model



Field on:

Time-Dependent Schrödiger equation $i\frac{\partial \Psi}{\partial t} = \hat{H}\Psi$

$$\hat{H} = \frac{\boldsymbol{p}_1^2}{2} + \frac{\boldsymbol{p}_2^2}{2} - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|} + \boldsymbol{D}\cdot\boldsymbol{F}_{\mathrm{AC}} \cos \omega t$$

Solution:

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = \sum_{j \equiv \left\{ \begin{smallmatrix} n_1 n_2 N \\ l_1 l_2 \ L \end{smallmatrix} \right\}} a_j(t)\, \phi^N_{n_1 l_1}(r_1) \phi^N_{n_2 l_2}(r_2)\, |l_1(1) l_2(2) L\rangle$$

Pseudostate basis: $\langle \phi_i^N | \hat{H} | \phi_j^N \rangle = E_i \delta_{ij}$

Matrix notations:

$$i\boldsymbol{R}\cdot\dot{\boldsymbol{a}}(t) = \boldsymbol{H}\cdot\boldsymbol{a}(t)\,, \quad \text{with intial condition} \ \ \Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, t = 0) = \Psi_0(\boldsymbol{r}_1, \boldsymbol{r}_2)$$

Theoretical Model

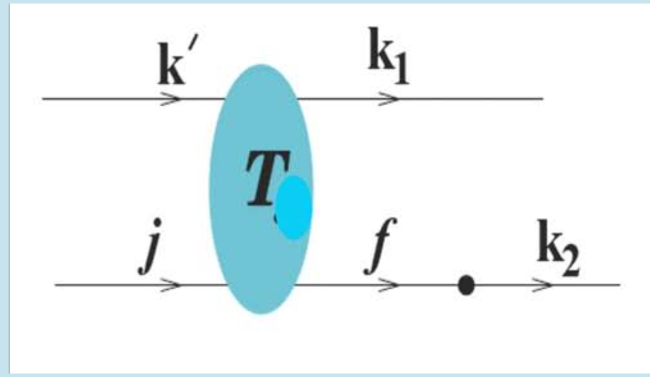
Theoretical Model

Field off:

Theoretical Model

Field off:

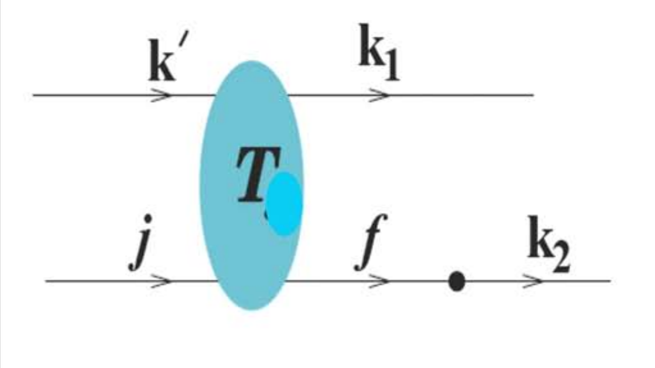
CCC expansion for two-electron continuum



Theoretical Model

Field off:

CCC expansion for two-electron continuum



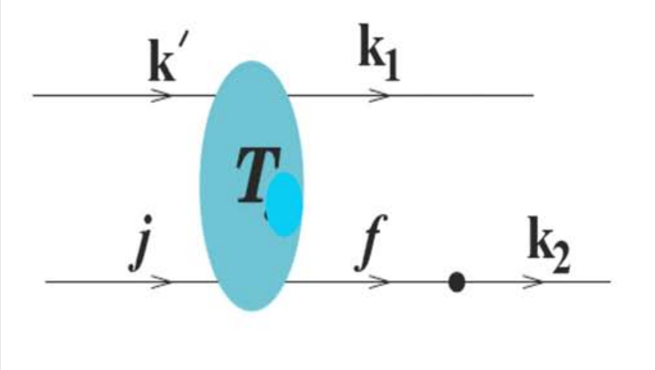
$$\Psi_{\boldsymbol{k}_1\boldsymbol{k}_2}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \Psi_{\boldsymbol{k}_1 f}(\boldsymbol{r}_1,\boldsymbol{r}_2)\langle \boldsymbol{k}_2|f\rangle \quad , \quad \epsilon_f = k_2^2/2$$

$$\Psi_{\boldsymbol{k}f}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \chi_{\boldsymbol{k}}(\boldsymbol{r}_1)\phi_f(\boldsymbol{r}_2) + \sum_{\boldsymbol{k}'j} \frac{\langle \boldsymbol{k}f|T_J|\boldsymbol{k}'j\rangle}{E - k'^2/2 - \varepsilon_j + i0}\, \chi_{\boldsymbol{k}'}(\boldsymbol{r}_1)\phi_j(\boldsymbol{r}_2)$$

Theoretical Model

Field off:

CCC expansion for two-electron continuum



$$\Psi_{\boldsymbol{k}_1\boldsymbol{k}_2}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \Psi_{\boldsymbol{k}_1 f}(\boldsymbol{r}_1,\boldsymbol{r}_2)\langle \boldsymbol{k}_2|f\rangle \quad , \quad \epsilon_f = k_2^2/2$$

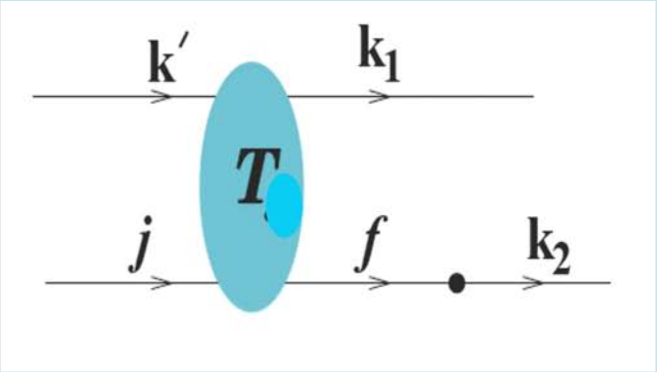
$$\Psi_{\boldsymbol{k}f}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \chi_{\boldsymbol{k}}(\boldsymbol{r}_1)\phi_f(\boldsymbol{r}_2) + \sum_{\boldsymbol{k}'j} \frac{\langle \boldsymbol{k}f|T_J|\boldsymbol{k}'j\rangle}{E - k'^2/2 - \varepsilon_j + i0}\,\chi_{\boldsymbol{k}'}(\boldsymbol{r}_1)\phi_j(\boldsymbol{r}_2)$$

Coulomb wave

Theoretical Model

Field off:

CCC expansion for two-electron continuum



$$\Psi_{\boldsymbol{k}_1\boldsymbol{k}_2}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \Psi_{\boldsymbol{k}_1 f}(\boldsymbol{r}_1,\boldsymbol{r}_2)\langle \boldsymbol{k}_2 | f\rangle \quad , \quad \epsilon_f = k_2^2/2$$

$$\Psi_{\boldsymbol{k}f}(\boldsymbol{r}_1,\boldsymbol{r}_2) = \chi_{\boldsymbol{k}}(\boldsymbol{r}_1)\phi_f(\boldsymbol{r}_2) + \sum_{\boldsymbol{k}'j} \frac{\langle \boldsymbol{k}f|T_J|\boldsymbol{k}'j\rangle}{E - k'^2/2 - \varepsilon_j + i0}\,\chi_{\boldsymbol{k}'}(\boldsymbol{r}_1)\phi_j(\boldsymbol{r}_2)$$

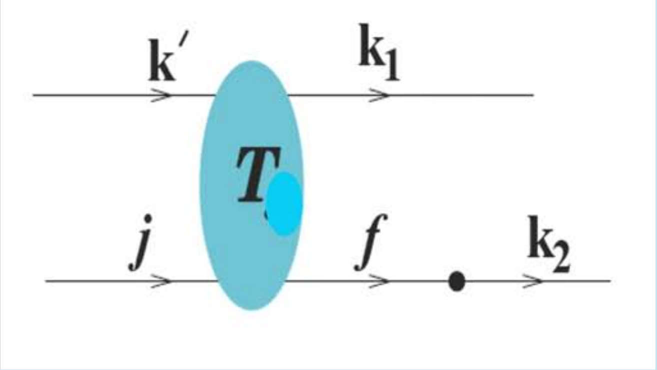
Coulomb wave

Pseudostate

Theoretical Model

Field off:

CCC expansion for two-electron continuum



$$\Psi_{\boldsymbol{k}_1\boldsymbol{k}_2}(\boldsymbol{r}_1,\boldsymbol{r}_2)=\Psi_{\boldsymbol{k}_1 f}(\boldsymbol{r}_1,\boldsymbol{r}_2)\langle\boldsymbol{k}_2|f\rangle \quad , \quad \epsilon_f=k_2^2/2$$

$$\Psi_{\boldsymbol{k}f}(\boldsymbol{r}_1,\boldsymbol{r}_2)=\chi_{\boldsymbol{k}}(\boldsymbol{r}_1)\phi_f(\boldsymbol{r}_2)+\sum_{\boldsymbol{k}'j}\frac{\langle\boldsymbol{k}f|T_J|\boldsymbol{k}'j\rangle}{E-k'^2/2-\varepsilon_j+i0}\chi_{\boldsymbol{k}'}(\boldsymbol{r}_1)\phi_j(\boldsymbol{r}_2)$$

Coulomb wave

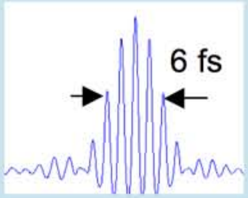
Pseudostate

Fully differential cross-section

$$\frac{d\sigma}{d\boldsymbol{k}_1 d\boldsymbol{k}_2}=\left|\langle\Psi(\boldsymbol{r}_1,\boldsymbol{r}_2,t=T)|\Psi_{\boldsymbol{k}_1\boldsymbol{k}_2}(\boldsymbol{r}_1,\boldsymbol{r}_2)\rangle\right|^2 \quad T=N\frac{2\pi}{\omega} \quad , \quad N\gg 1$$

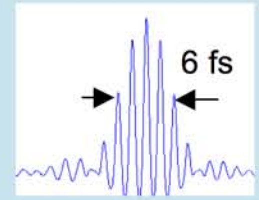
Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, $I = 10^{14\text{-}15}$ W/cm^2



Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, $I = 10^{14\text{-}15}$ W/cm^2



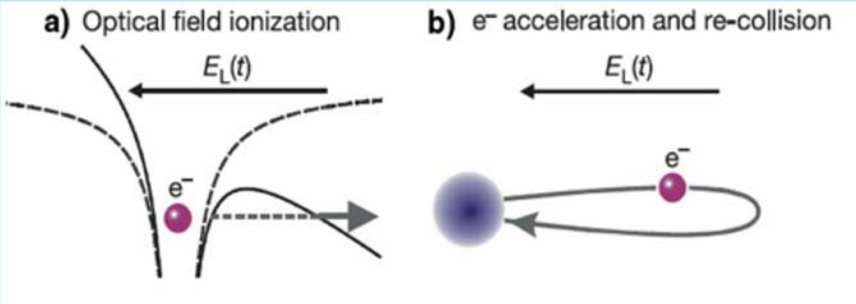
$I = 10^{14}$ W/cm^2

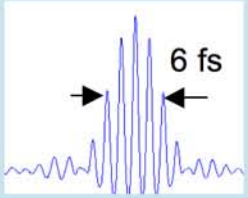
$\gamma \approx 1$, $U_p = 0.25$au, $\zeta = U_p / \omega \approx 5$

$E_{cut} \approx 10U_p$ $N = E_{cut} / \omega \approx 50$

Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, $I = 10^{14\text{-}15}$ W/cm^2





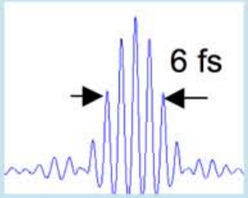
$I = 10^{14}$ W/cm^2

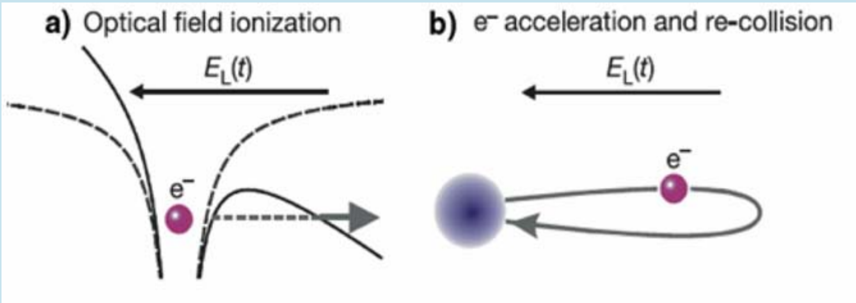
$\gamma \approx 1$, $U_p = 0.25$au, $\zeta = U_p / \omega \approx 5$

$E_{cut} \approx 10U_p$ $N = E_{cut} / \omega \approx 50$

Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, $I = 10^{14\text{-}15}$ W/cm^2



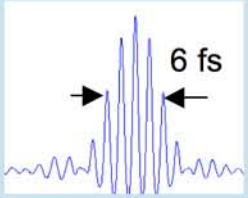


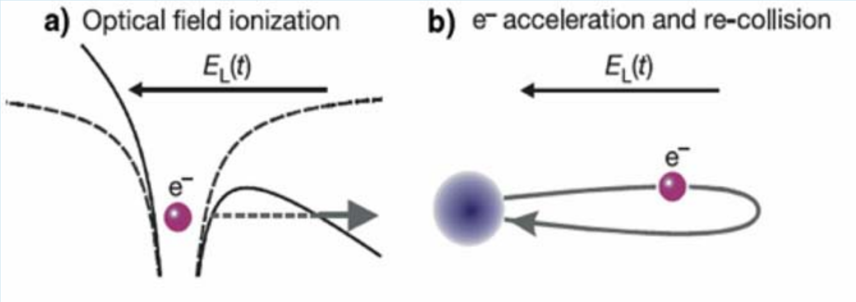
$I = 10^{14}$ W/cm^2
$\gamma \approx 1$, $U_p = 0.25au$, $\zeta = U_p / \omega \approx 5$
$E_{cut} \approx 10U_p$ $N = E_{cut} / \omega \approx 50$

TDSE

Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, I = $10^{14\text{-}15}$ W/cm^2



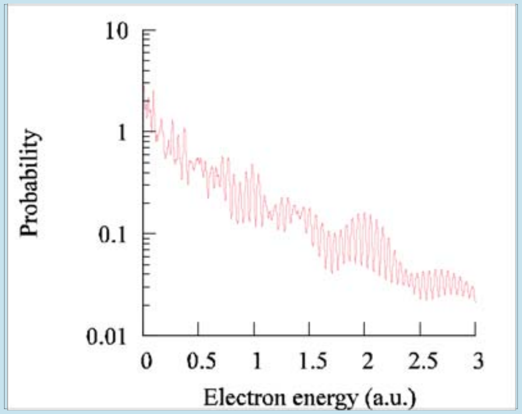


$I = 10^{14}$ W/cm^2

$\gamma \approx 1,\ U_p = 0.25$au, $\zeta = U_p / \omega \approx 5$

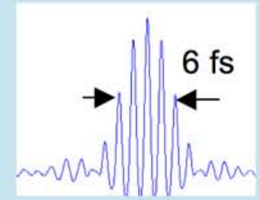
$E_{cut} \approx 10U_p\ \ N = E_{cut} / \omega \approx 50$

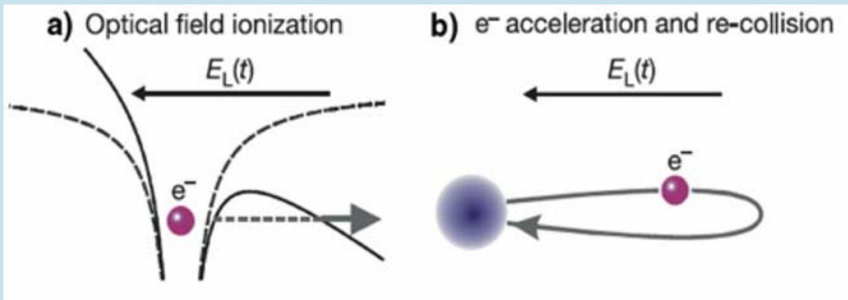
TDSE



Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, I = $10^{14\text{-}15}$ W/cm^2



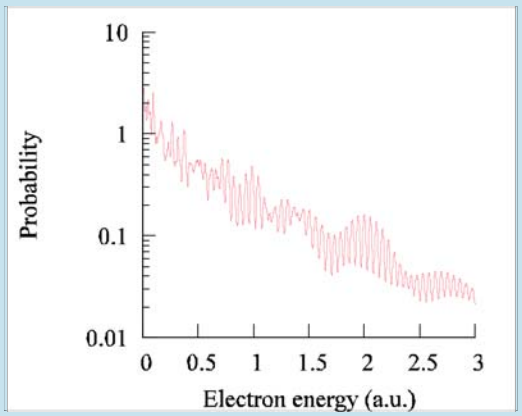


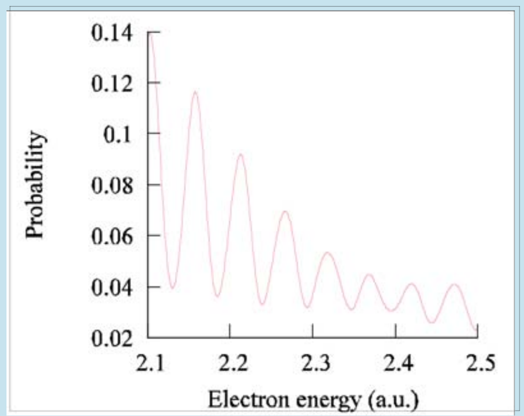
$I = 10^{14}$ W/cm^2

$\gamma \approx 1,\ U_p = 0.25au,\ \ \zeta = U_p / \omega \approx 5$

$E_{cut} \approx 10U_p\ \ N = E_{cut} / \omega \approx 50$

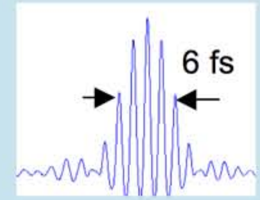
TDSE

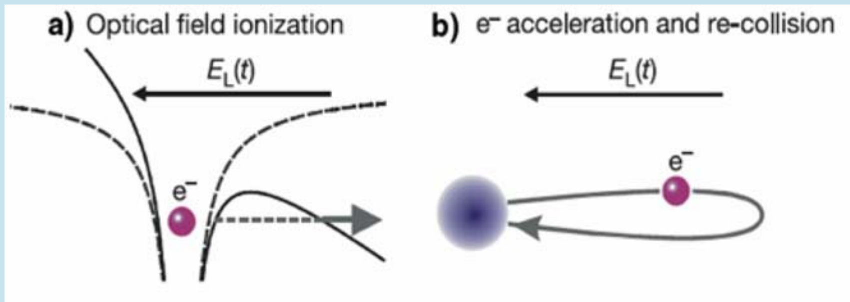




Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, I = $10^{14\text{-}15}$ W/cm^2



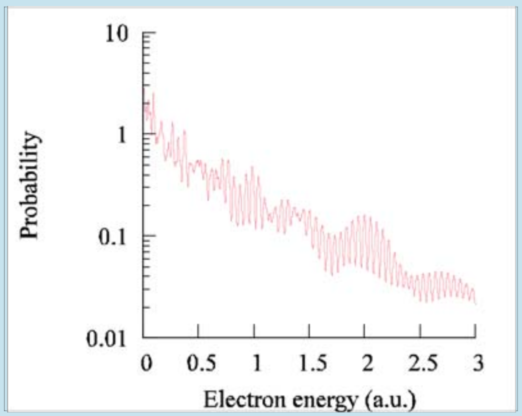


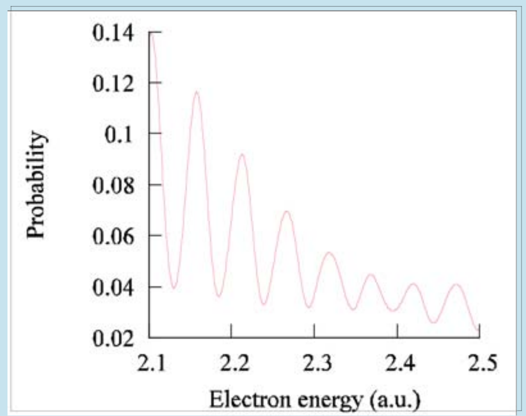
$I = 10^{14}$ W/cm^2

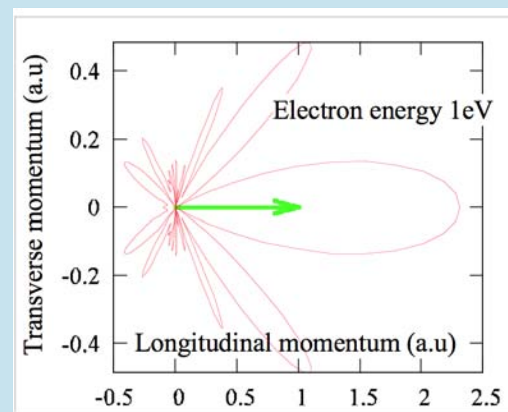
$\gamma \approx 1$, $U_p = 0.25$au, $\zeta = U_p / \omega \approx 5$

$E_{cut} \approx 10U_p$ $N = E_{cut} / \omega \approx 50$

TDSE



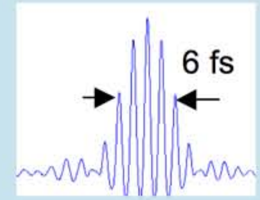


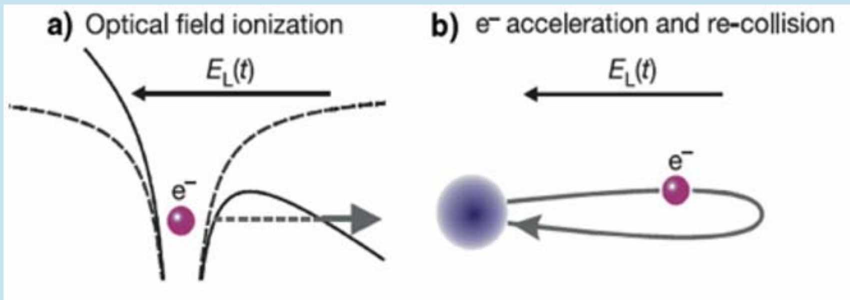


AASF
Australian Attosecond Science Facility

Strong IR Field Ionization of Hydrogen

IR: 750 nm, ω =1.5 eV, T=2.5 fs, FWHM=5.5 fs, $I = 10^{14\text{-}15}$ W/cm^2



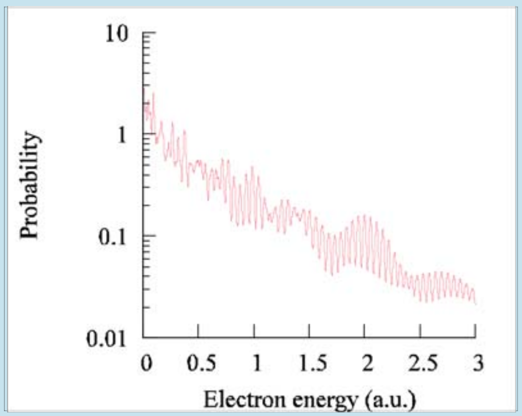


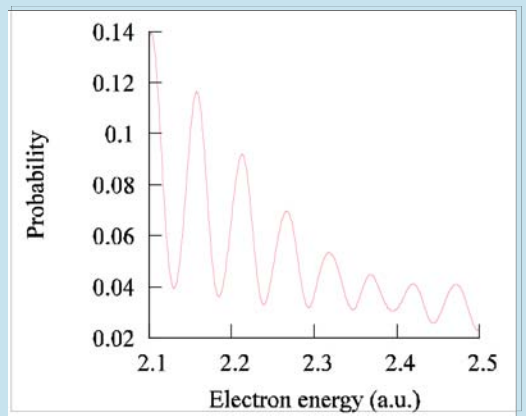
$I = 10^{14}$ W/cm^2

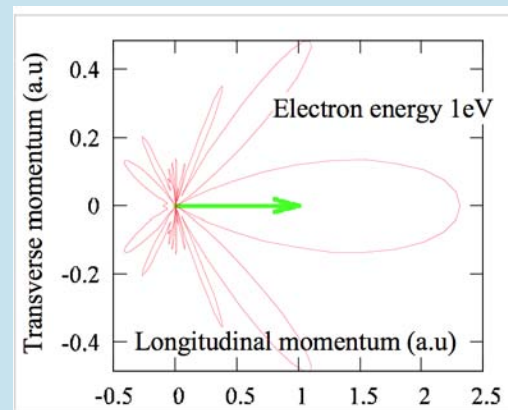
$\gamma \approx 1,\ U_p = 0.25au,\ \ \zeta = U_p / \omega \approx 5$

$E_{cut} \approx 10U_p\ \ N = E_{cut} / \omega \approx 50$

TDSE







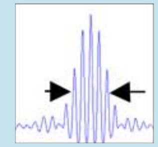
SFA / ADK

$$a_k = -i \int_0^{T_1} \langle \Psi_k(\tau) | \hat{p} A(\tau) | \Psi_g \rangle \, d\tau$$

Ψ_k - Volklov state

Strong IR Field Ionization of Hydrogen

IR: 750 nm, $\hbar\omega = 1.5$ eV, $T = 2.5$ fs, FWHM=5.5 fs, $I \leq 10^{15}$ W/cm^2

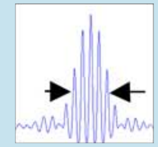


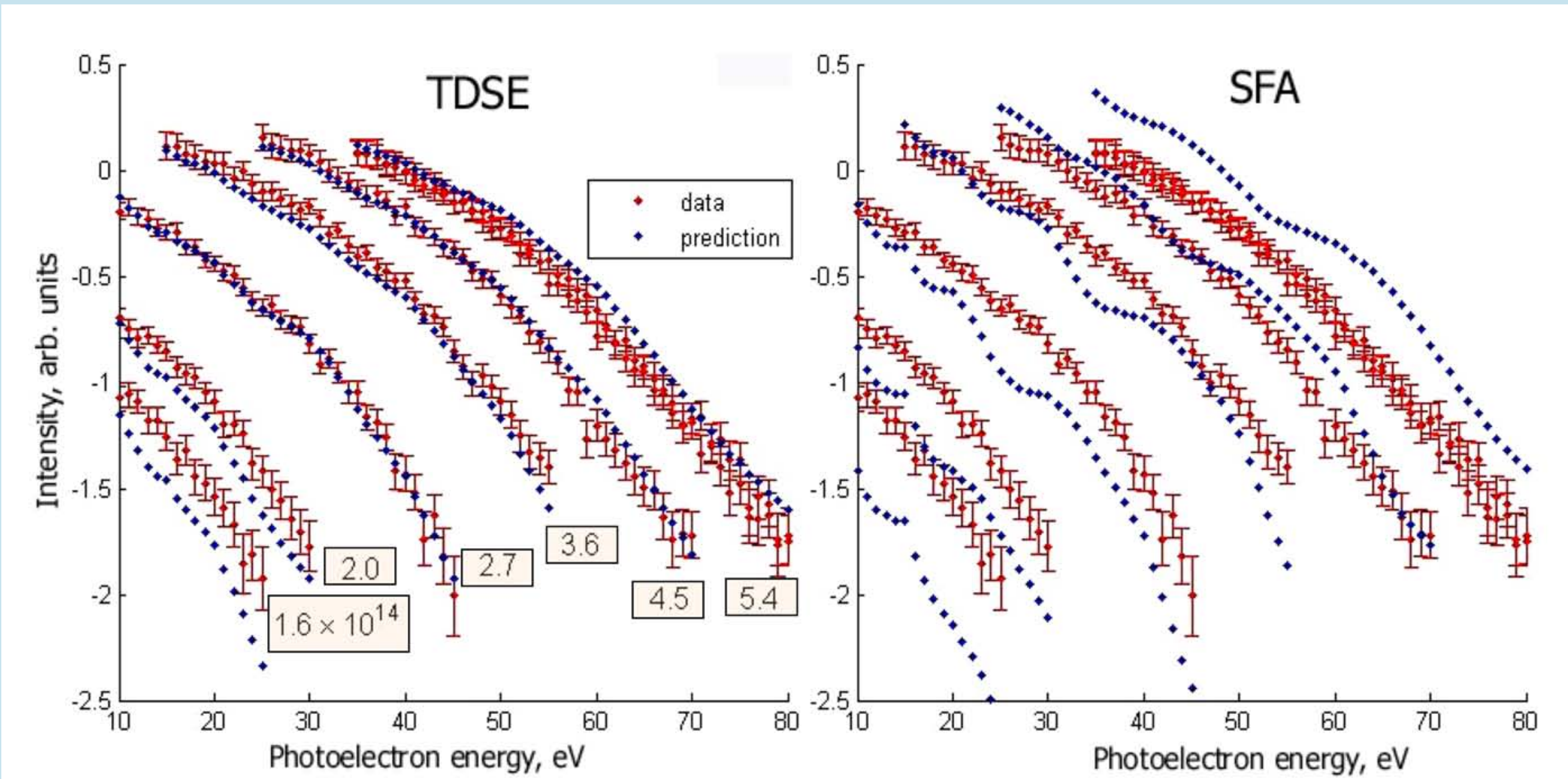
6 fs

Australian Attosecond Science Facility

Strong IR Field Ionization of Hydrogen

IR: 750 nm, $\hbar\omega = 1.5$ eV, $T = 2.5$ fs, FWHM=5.5 fs, $I \leq 10^{15}$ W/cm^2

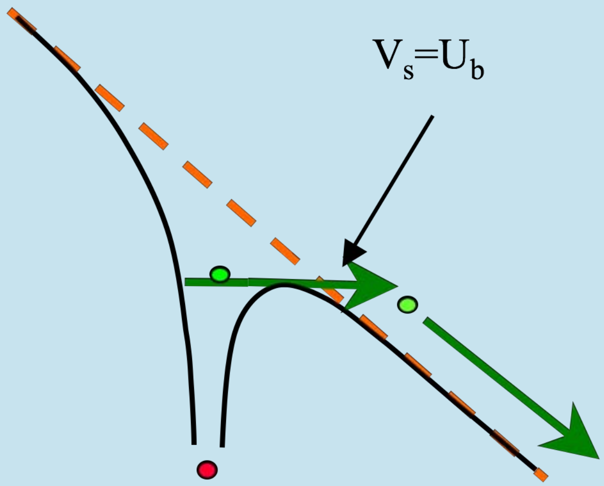




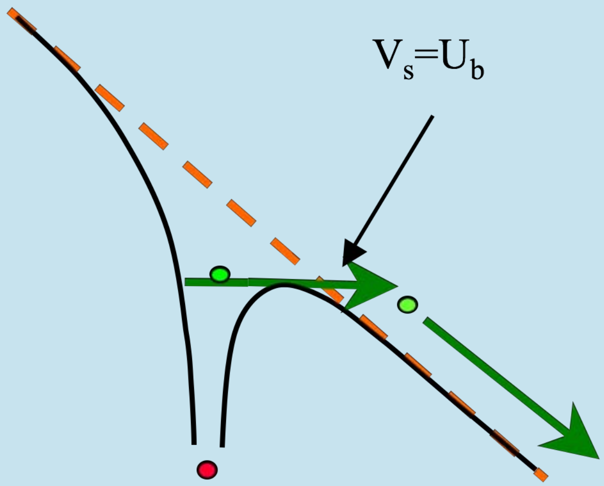
Australian Attosecond Science Facility

Over-the-barrier ionizaton

Over-the-barrier ionizaton

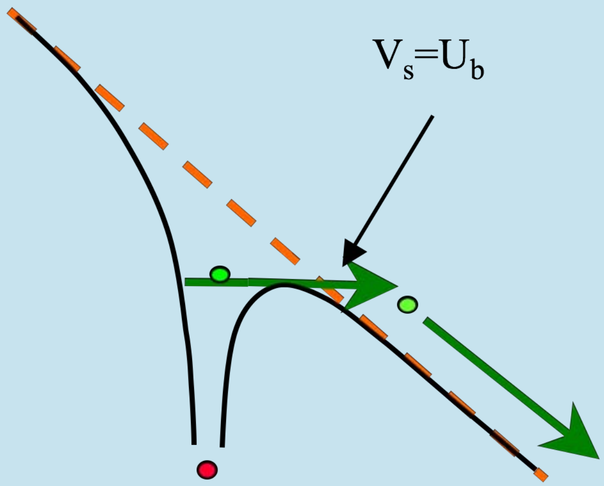


Over-the-barrier ionizaton



@795nm	IP[eV]	I_{OBI}[W/cm^2]	$\Gamma(I_{OBI})$
Li	5.4	$3.38*10^{12}$	5.2
He	24.6	$1.46*10^{15}$	0.5
Ne	20.2	$2.33*10^{14}$	1.2
Ar	15.8	$8.72*10^{13}$	1.8

Over-the-barrier ionizaton



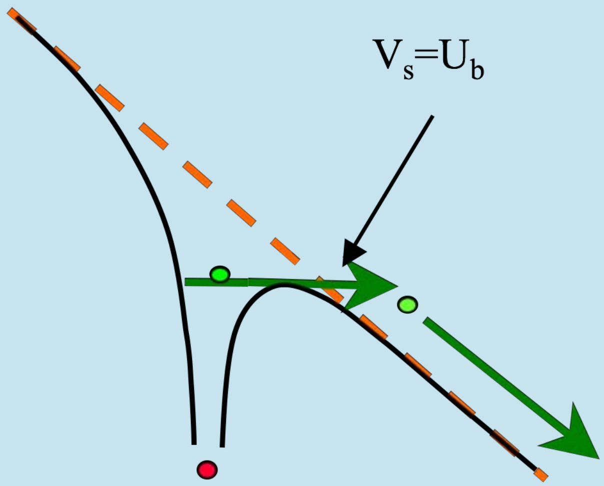
@795nm	IP[eV]	I_{OBI}[W/cm^2]	$\Gamma(I_{OBI})$
Li	5.4	$3.38*10^{12}$	5.2
He	24.6	$1.46*10^{15}$	0.5
Ne	20.2	$2.33*10^{14}$	1.2
Ar	15.8	$8.72*10^{13}$	1.8

Over-the-barrier field strength (from 1D-model):

$$F_{\text{OBI}} = \frac{\text{IP}^2}{4Z} \longrightarrow$$

Ionization probability approaches 1

Over-the-barrier ionizaton



@795nm	IP[eV]	I_{OBI}[W/cm^2]	$\Gamma(I_{OBI})$
Li	5.4	3.38*10^{12}	5.2
He	24.6	1.46*10^{15}	0.5
Ne	20.2	2.33*10^{14}	1.2
Ar	15.8	8.72*10^{13}	1.8

Over-the-barrier field strength (from 1D-model):

$$F_{\mathrm{OBI}} = \frac{\mathrm{IP}^2}{4Z} \longrightarrow$$

Ionization probability approaches 1

Over-the-barrier intensity:

$$I_{\mathrm{OBI}}[\mathrm{W/cm}^2] = \frac{\pi^2 c \varepsilon_0^3 \mathrm{IP}^4}{2e^6 Z^2} = 4\times10^9 (\mathrm{IP[eV]})^4 Z^2$$

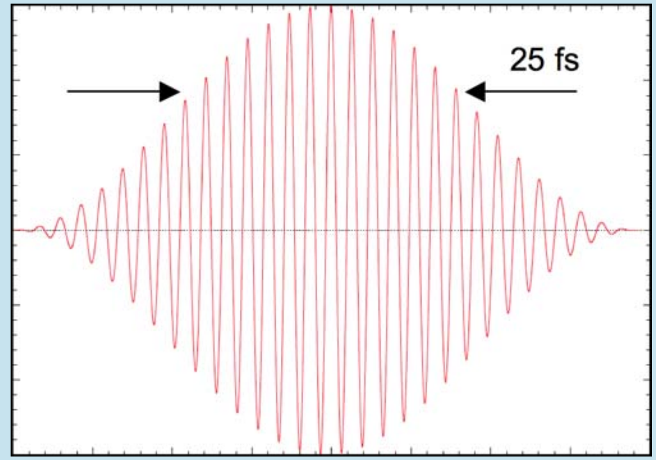
Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs*, $I = 2\cdot 10^{11\text{-}14}$ W/cm^2

MPIK, Heidelberg

Strong Field Ionization of Lithium

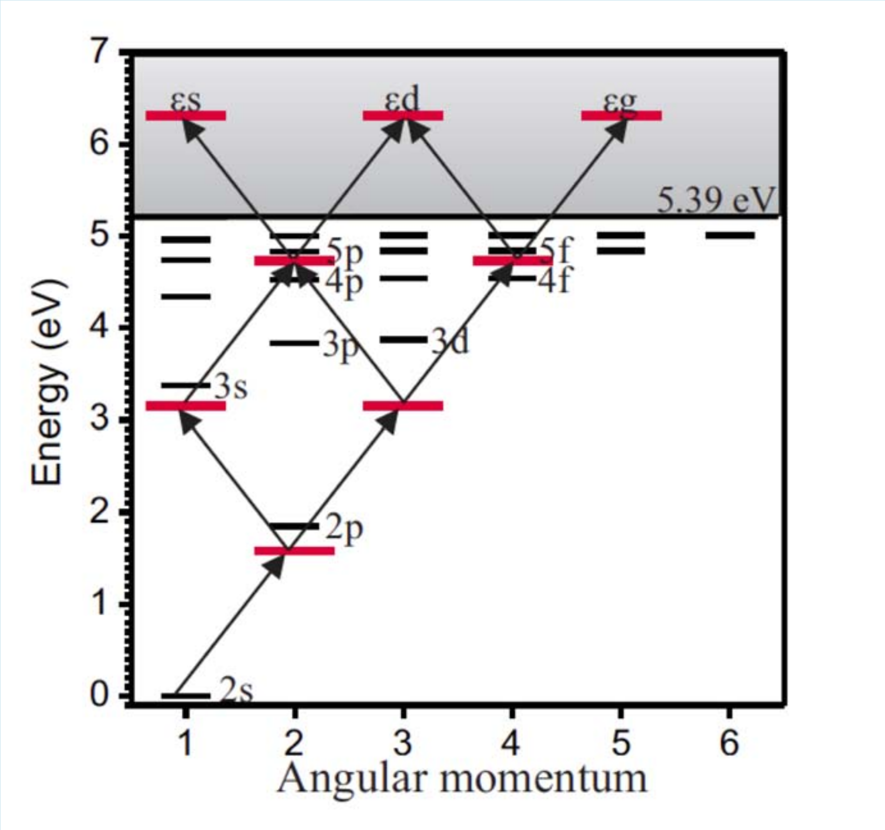
IR: 785 nm, *FWHM=25 fs*, $I = 2 \cdot 10^{11\text{-}14}\ W/cm^2$

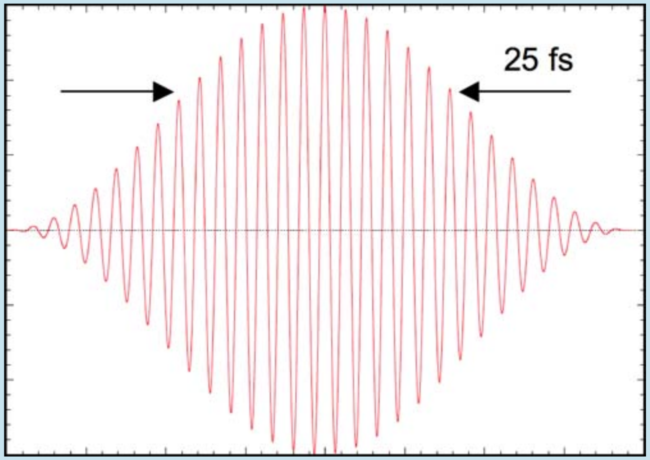


MPIK, Heidelberg

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs, I = $2 \cdot 10^{11\text{-}14}$ W/cm^2*





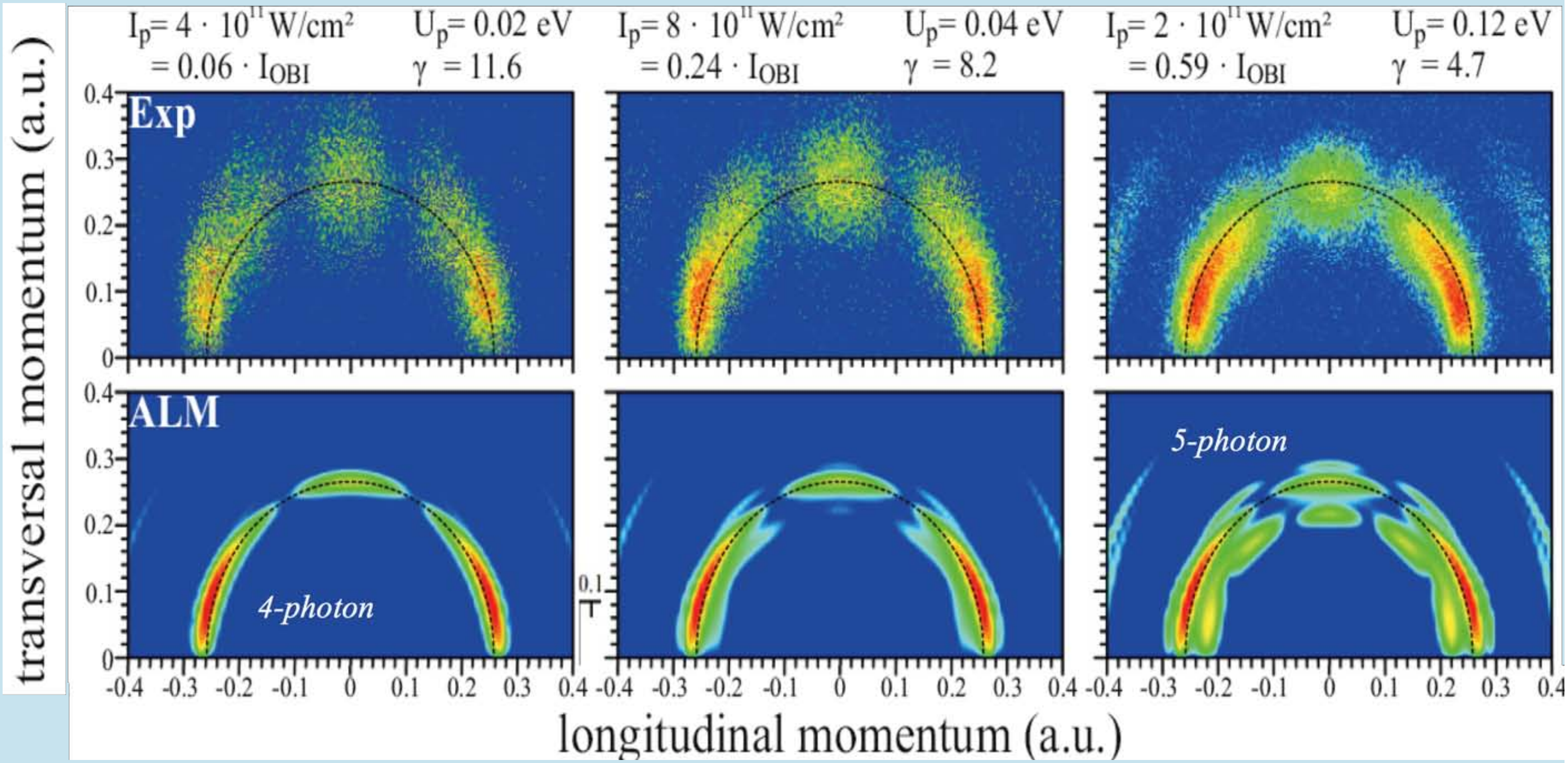
MPIK, Heidelberg

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs*, $I \leq 2 \cdot 10^{11}$ *W/cm²*

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs*, $I \leq 2 \cdot 10^{11}$ *W/cm²*

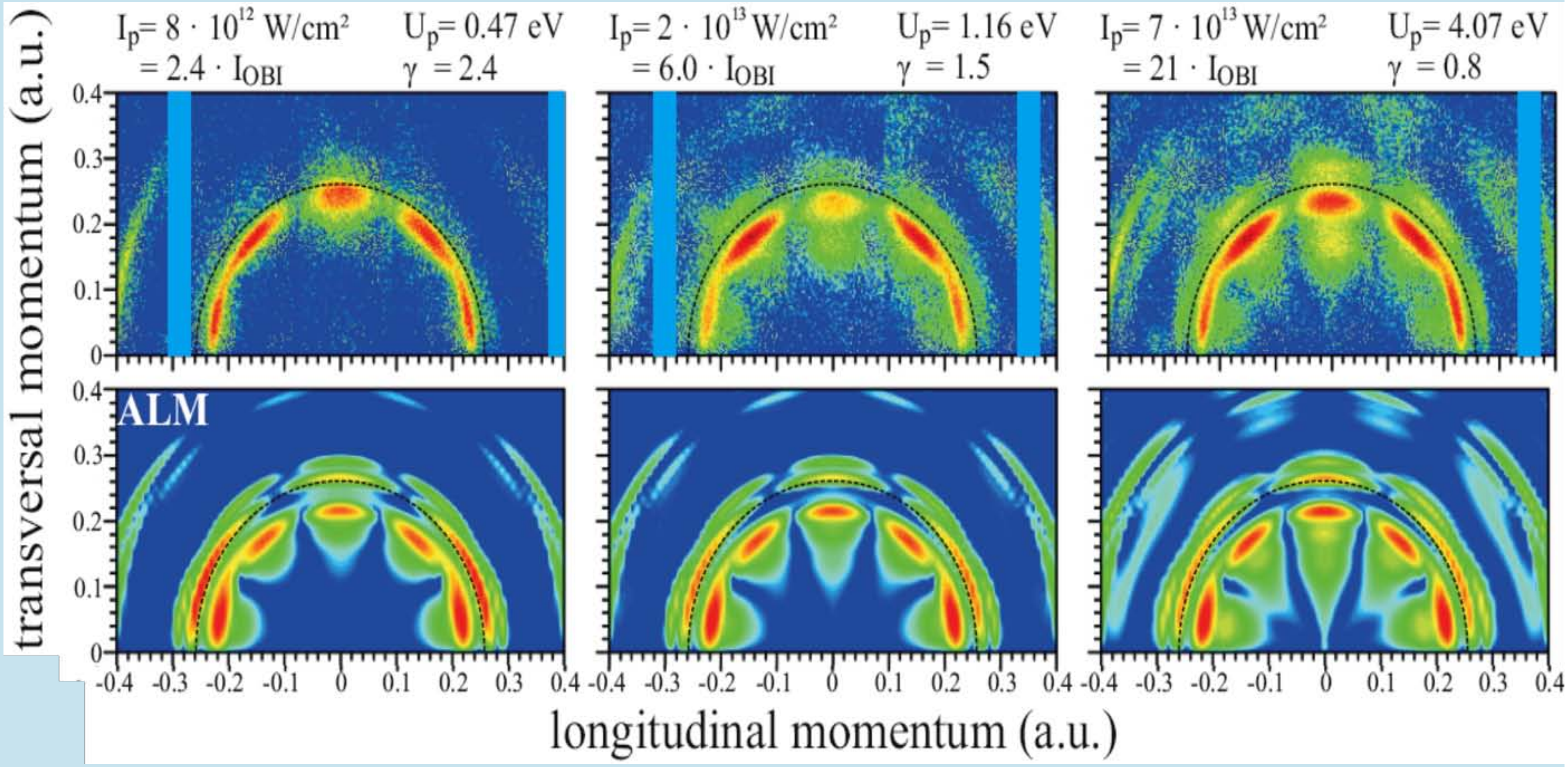


Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs,* $I \leq 7 \cdot 10^{13}$ W/cm^2

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs, I ≤ 7·10^13 W/cm^2*



MPIK, Heidelberg

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs*, $I = 2 \cdot 10^{13}$ *W/cm*^{2}

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs*, $I = 2\cdot10^{13}$ *W/cm²*

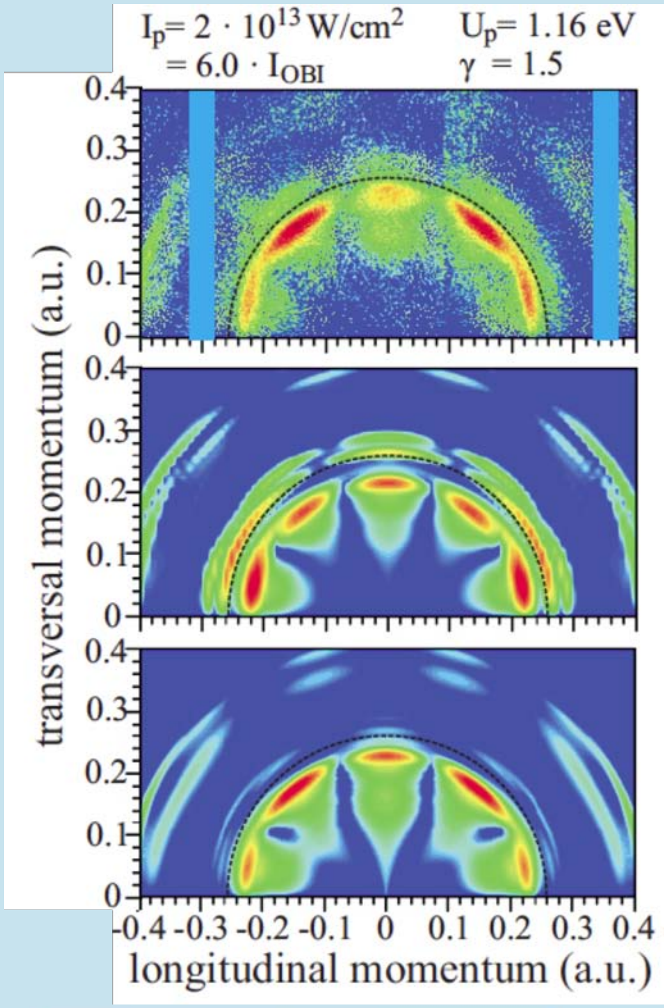
Li Atom potentials

A. Sarsa, F. J. Galvez, and E. Buendia, At. Data Nucl. Data Tables **88**, 163 (2004).

K. Bartschat, *Computational Atomic Physics* (Springer-Verlag (Heidelberg, New York), 1996).

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs, I = 2·10^{13} W/cm^{2}*



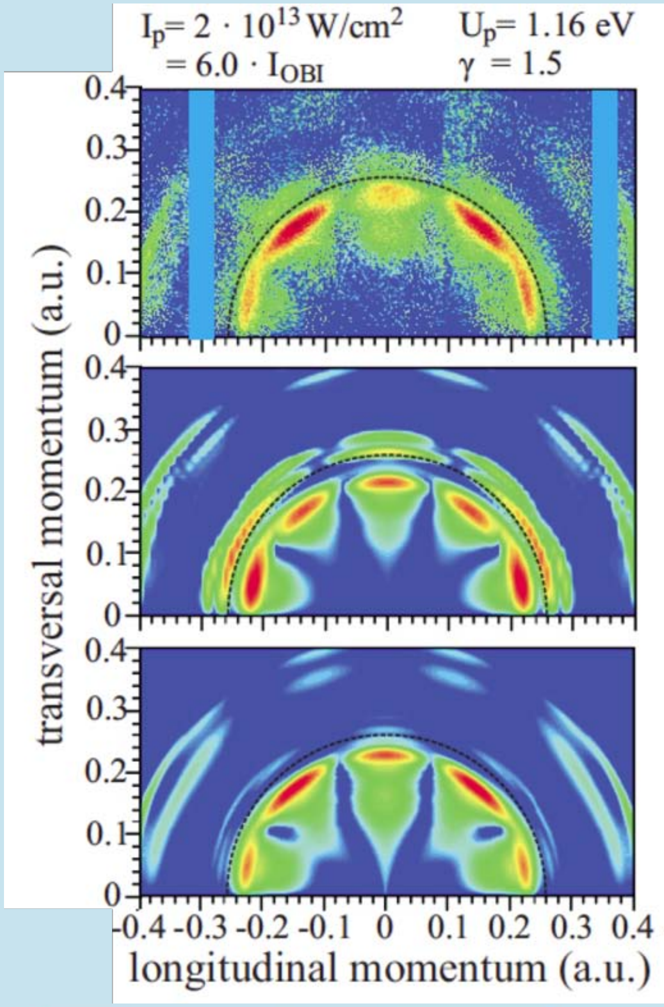
Li Atom potentials

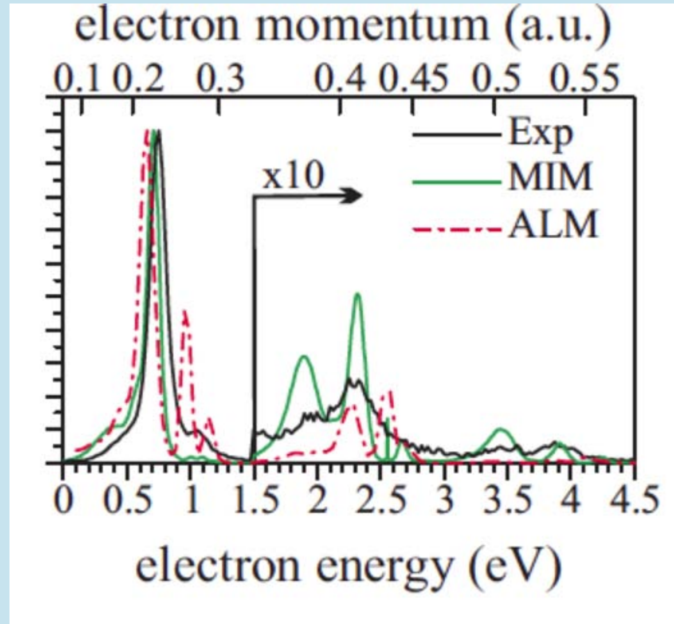
A. Sarsa, F. J. Galvez, and E. Buendia, At. Data Nucl. Data Tables **88**, 163 (2004).

K. Bartschat, *Computational Atomic Physics* (Springer-Verlag (Heidelberg, New York), 1996).

Strong Field Ionization of Lithium

IR: 785 nm, *FWHM=25 fs, I = 2·10^13 W/cm^2*





Li Atom potentials

A. Sarsa, F. J. Galvez, and E. Buendia, At. Data Nucl. Data Tables **88**, 163 (2004).

K. Bartschat, *Computational Atomic Physics* (Springer-Verlag (Heidelberg, New York), 1996).

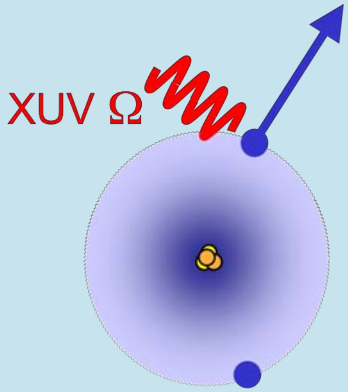
Mechanisms of double photo-ionization

Mechanisms of double photo-ionization

Shake-off

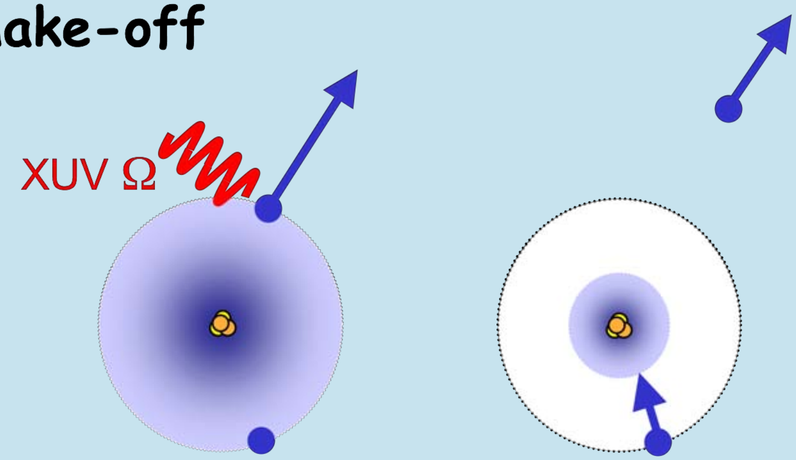
Mechanisms of double photo-ionization

Shake-off



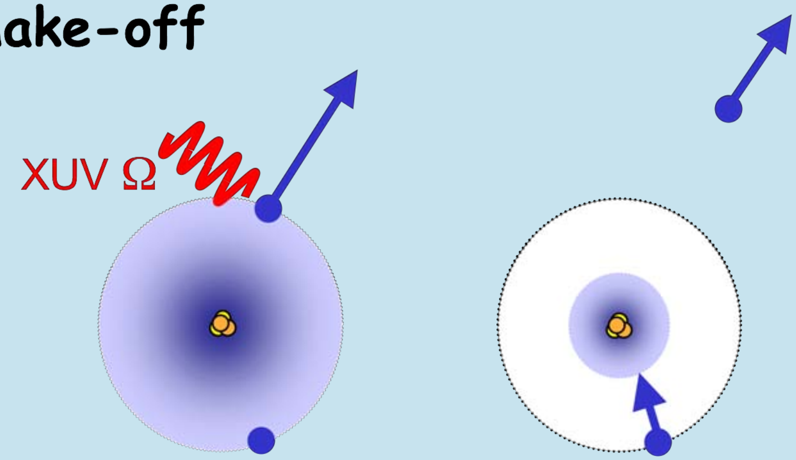
Mechanisms of double photo-ionization

Shake-off



Mechanisms of double photo-ionization

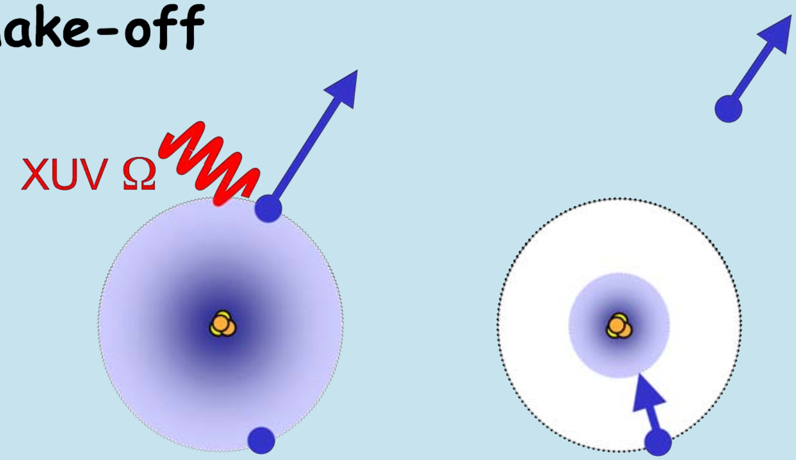
Shake-off



Fast, $\Omega >> DIP$

Mechanisms of double photo-ionization

Shake-off

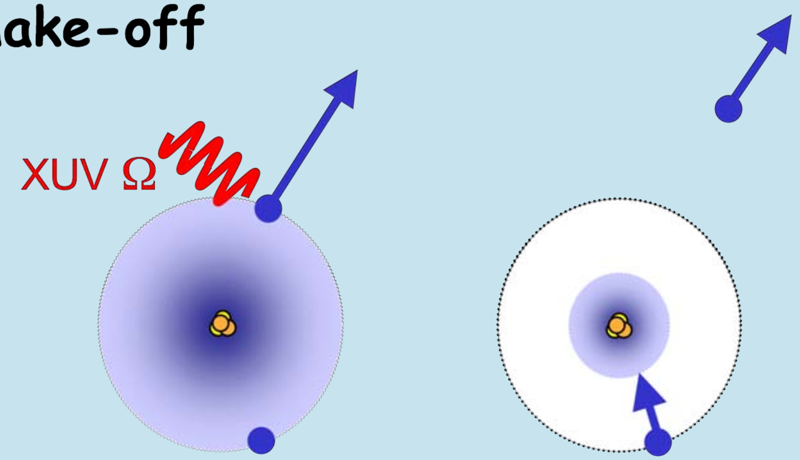


Fast, $\Omega >> DIP$

$$\tau_{\rm so} \simeq (E^{+}_{\rm atom} - E^{+}_{\rm ion})^{-1} \simeq 20 \text{ as}$$

Mechanisms of double photo-ionization

Shake-off



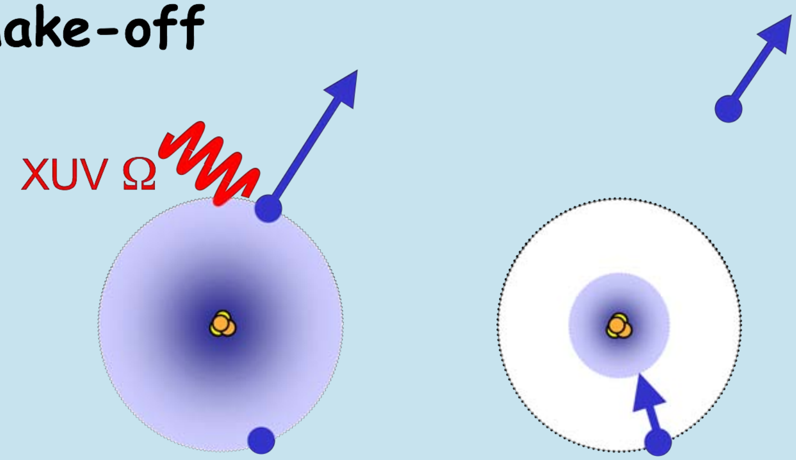
Fast, $\Omega >> DIP$

$$\tau_{\rm so} \simeq (E^+_{\rm atom} - E^+_{\rm ion})^{-1} \simeq 20 \text{ as}$$

Recollision, or knock-out

Mechanisms of double photo-ionization

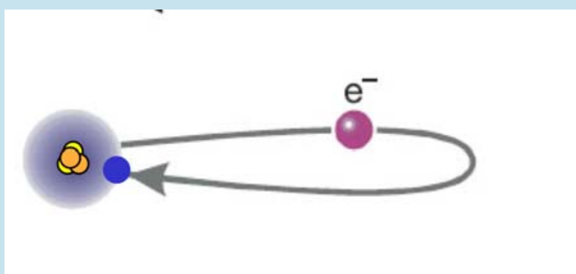
Shake-off



Fast, *Ω >> DIP*

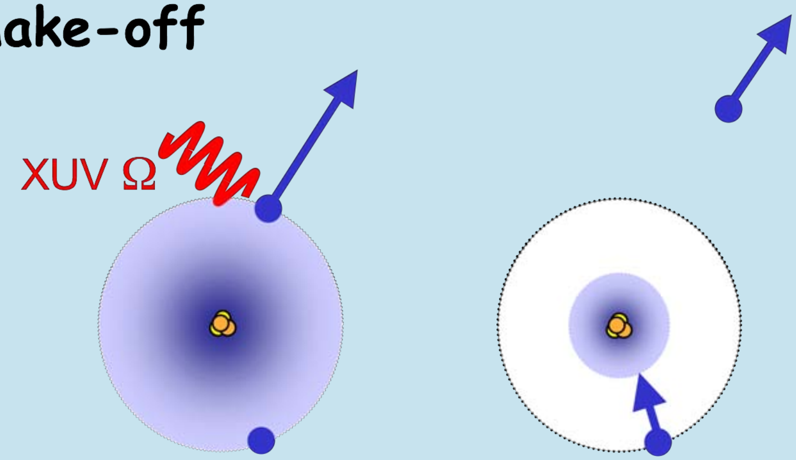
$$\tau_{so} \simeq (E^{+}_{atom} - E^{+}_{ion})^{-1} \simeq 20 \text{ as}$$

Recollision, or knock-out



Mechanisms of double photo-ionization

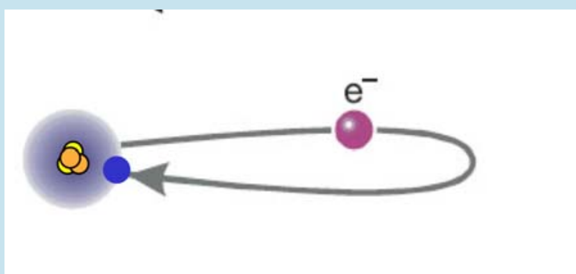
Shake-off



Fast, $\Omega >> DIP$

$$\tau_{so} \simeq (E^{+}_{atom} - E^{+}_{ion})^{-1} \simeq 20 \text{ as}$$

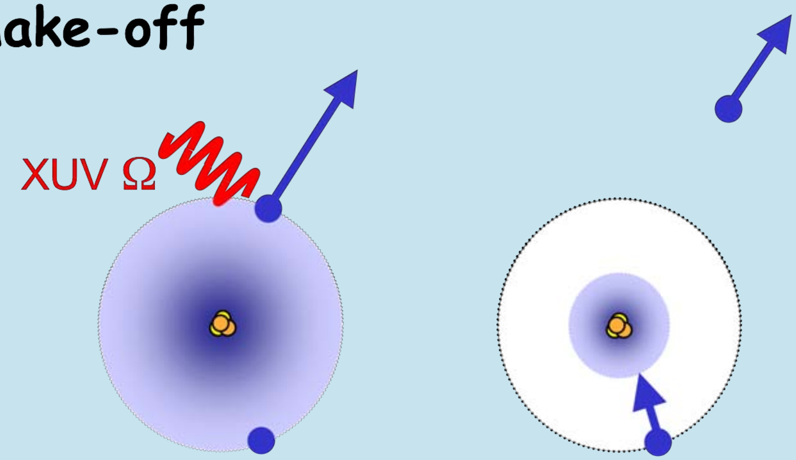
Recollision, or knock-out



Slow, $\Omega - DIP << DIP$

Mechanisms of double photo-ionization

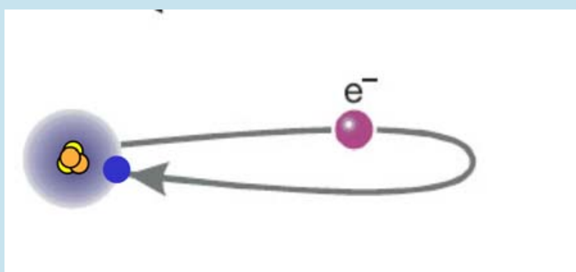
Shake-off



Fast, $\Omega >> DIP$

$$\tau_{so} \simeq (E^{+}_{atom} - E^{+}_{ion})^{-1} \simeq 20 \text{ as}$$

Recollision, or knock-out



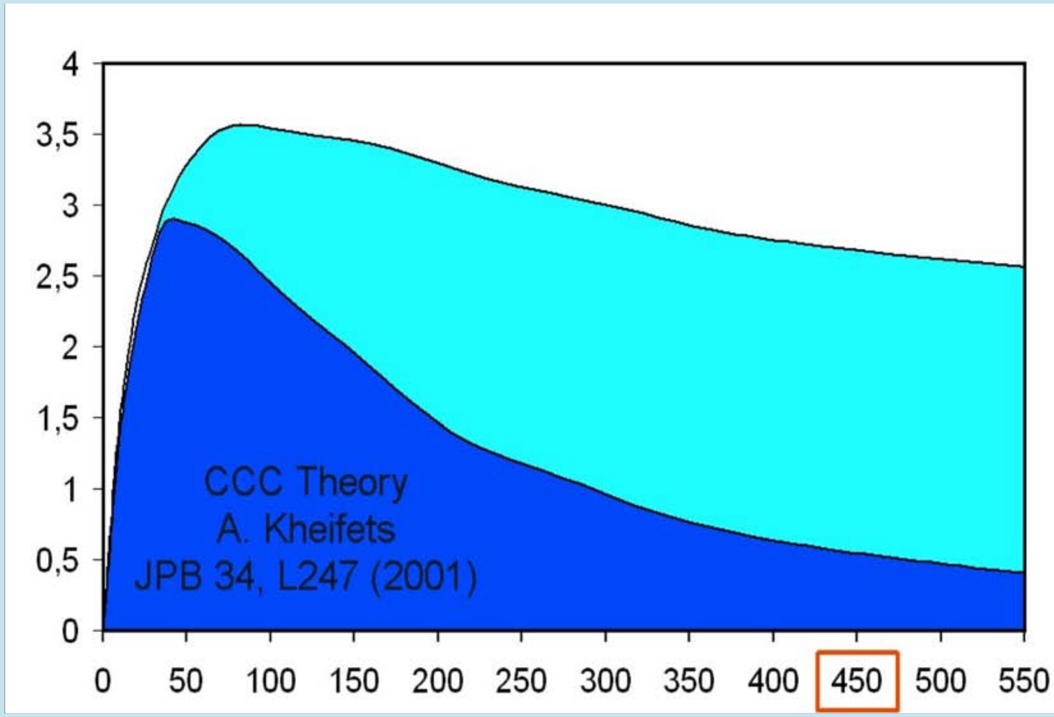
Slow, $\Omega - DIP << DIP$

$$\tau_{ko} \simeq (E_{Z^*} - E_{exact})^{-1} \simeq 200 \text{ as}$$

Ratio of double to single ionization in He

Ratio of double to single ionization in He

$\frac{\sigma^{++}}{\sigma^{+}}[\%]$

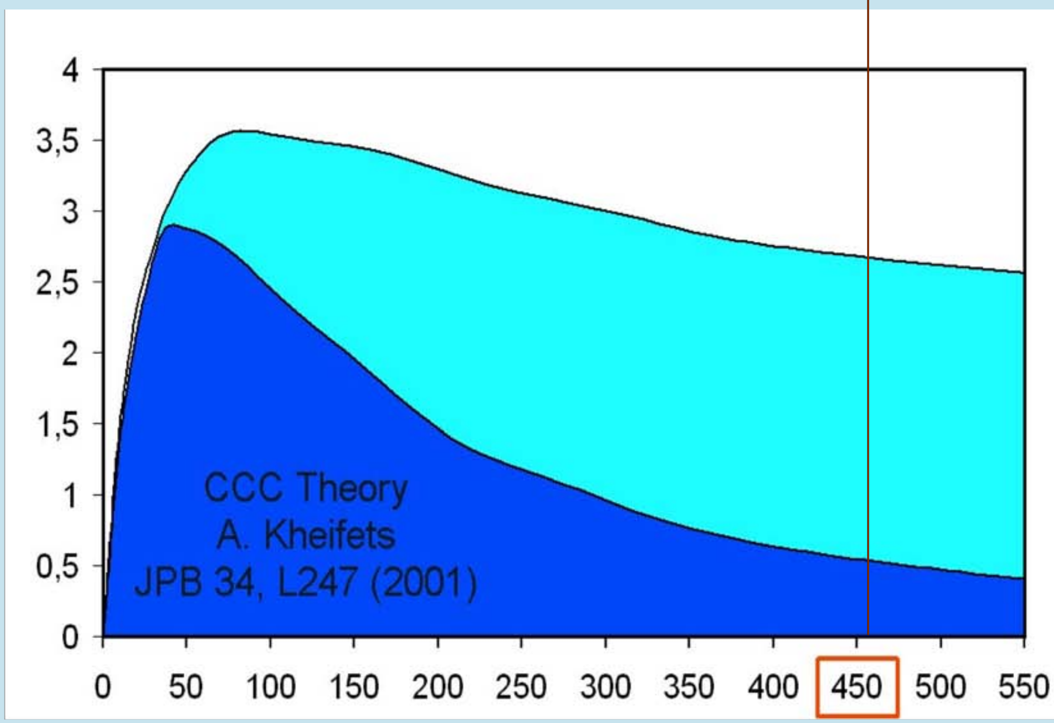


Photon energy above the threshold [eV]

Ratio of double to single ionization in He

COLTRIMS experiment
Knapp *et al* PRL **89**:033004, 2002

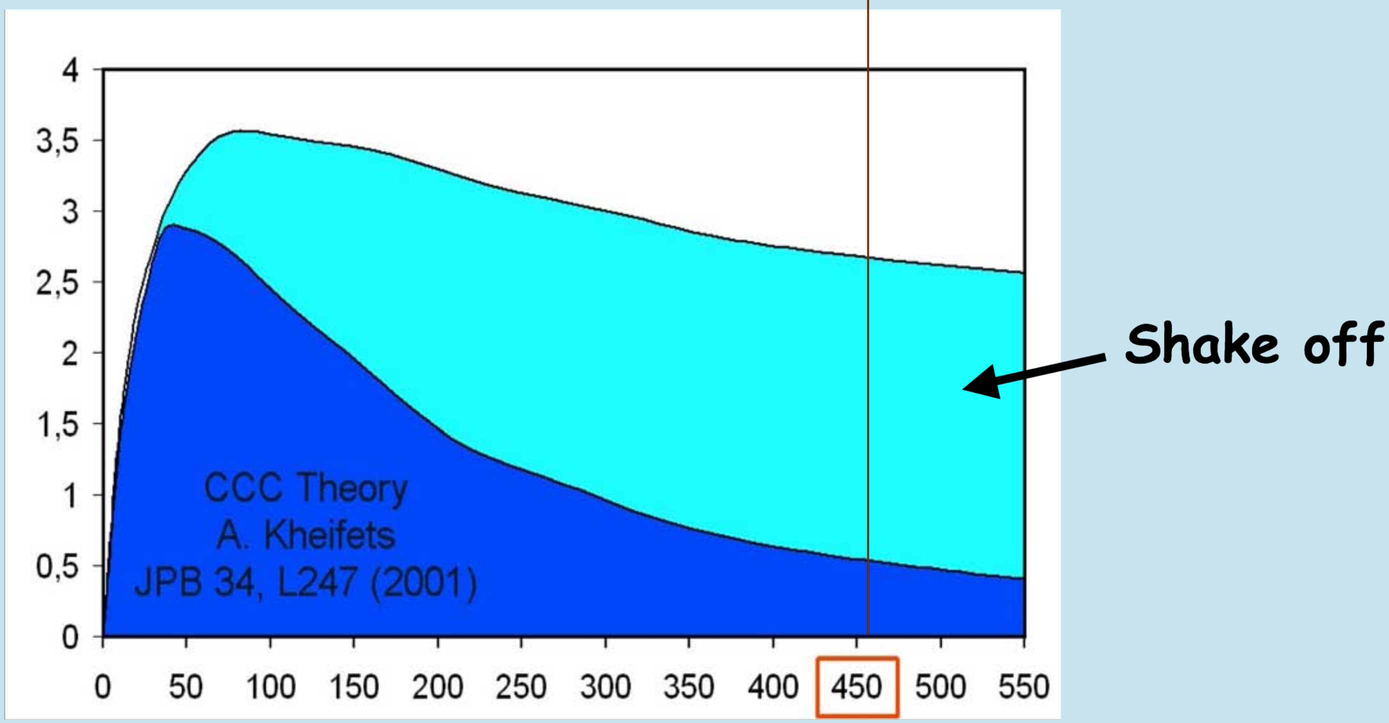
$$\frac{\sigma^{++}}{\sigma^{+}}[\%]$$



Photon energy above the threshold [eV]

Ratio of double to single ionization in He

COLTRIMS experiment
Knapp *et al* PRL **89**:033004, 2002



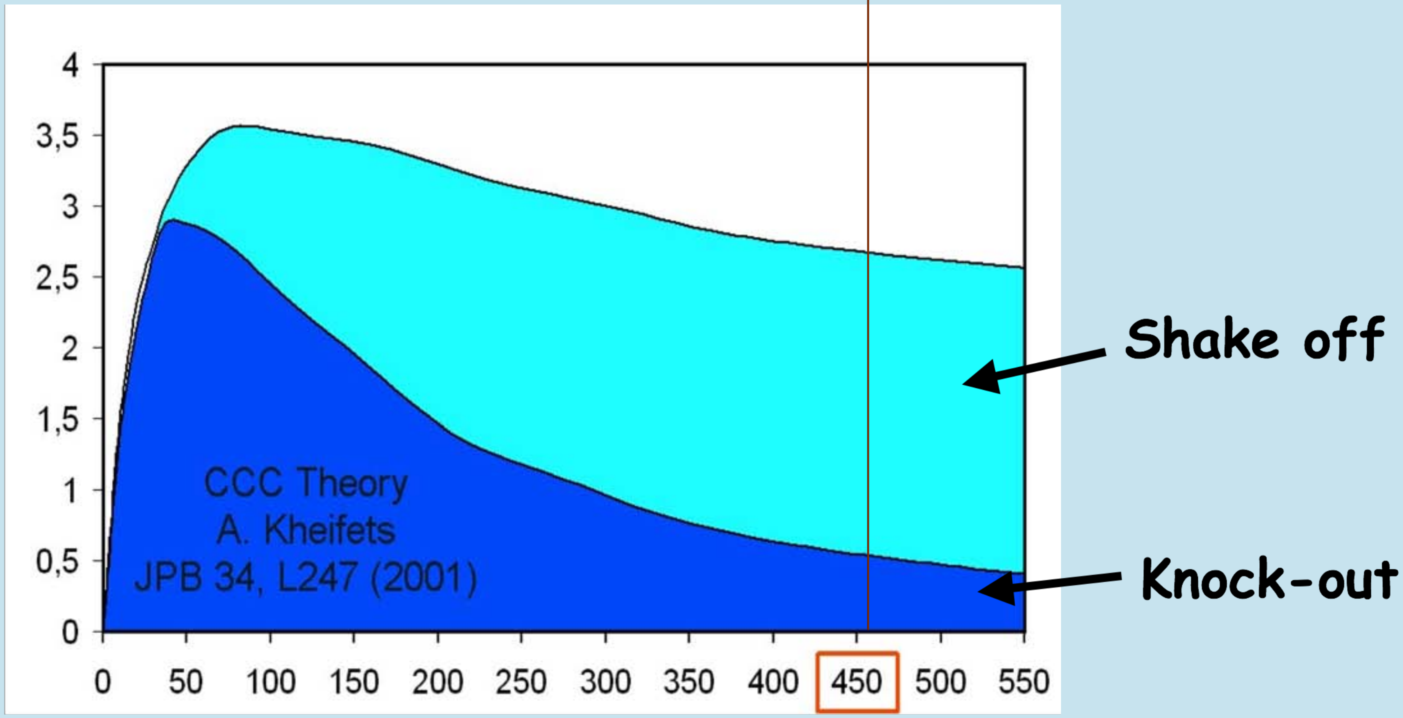
$\frac{\sigma^{++}}{\sigma^{+}}[\%]$

Photon energy above the threshold [eV]

Ratio of double to single ionization in He

COLTRIMS experiment
Knapp *et al* PRL **89**:033004, 2002

$\frac{\sigma^{++}}{\sigma^{+}}[\%]$



Photon energy above the threshold [eV]

PRL **94,** 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

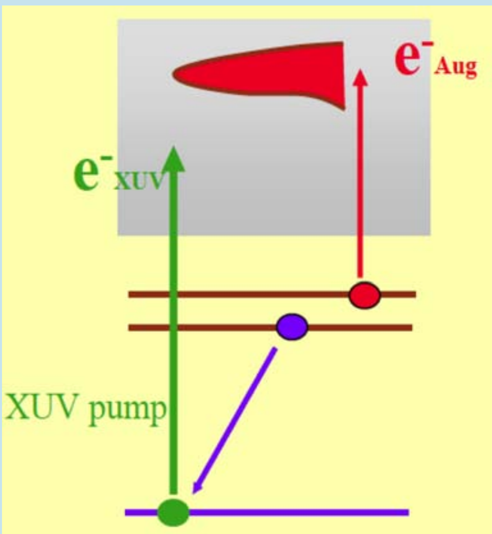
Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

PRL 94, 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

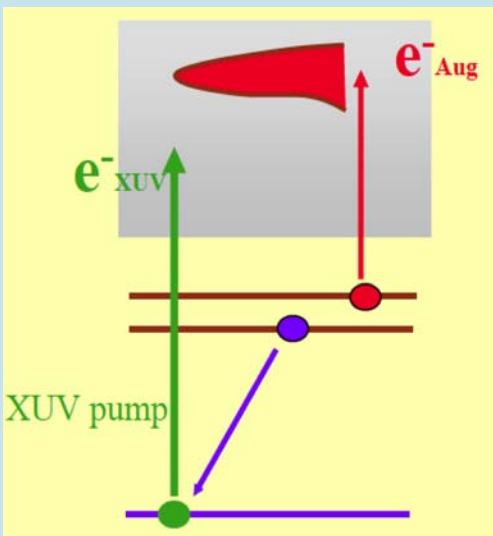


PRL 94, 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

IR field $E\cos(\omega t)$

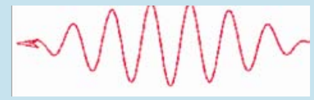


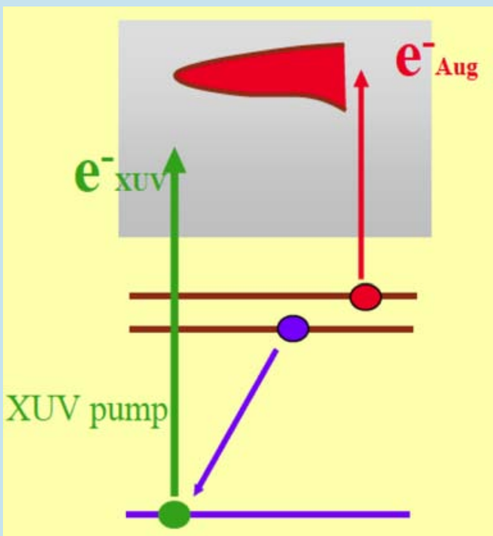
PRL **94,** 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

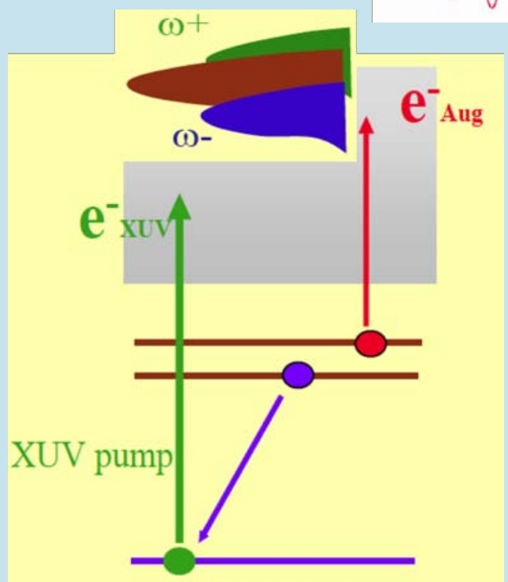
Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

IR field Ecos(ωt)





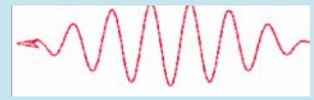


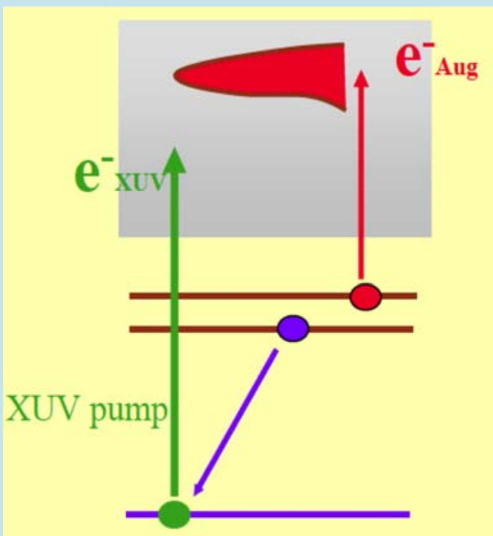
PRL **94,** 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

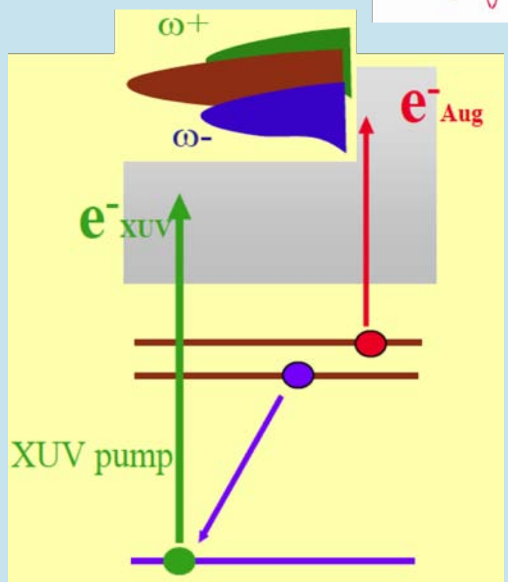
Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

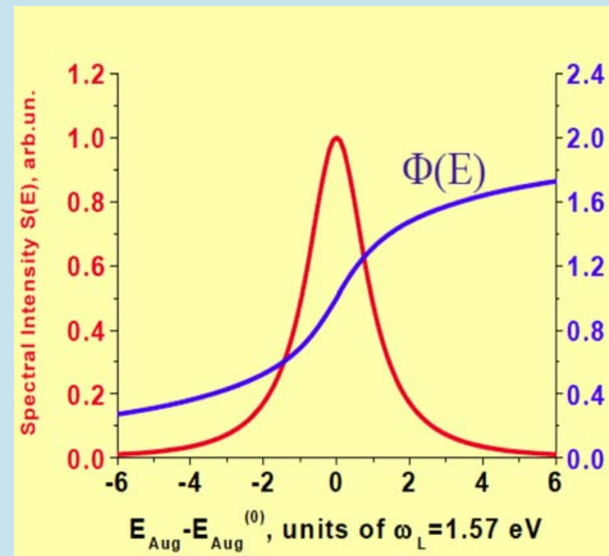
Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

IR field Ecos(ωt)







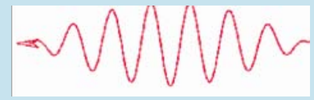


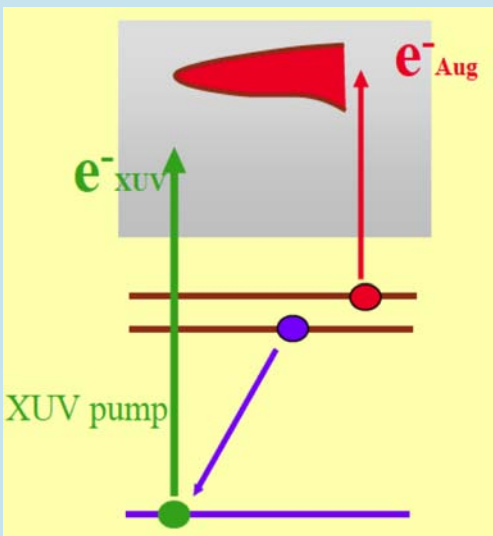
PRL **94,** 213001 (2005) PHYSICAL REVIEW LETTERS week ending 3 JUNE 2005

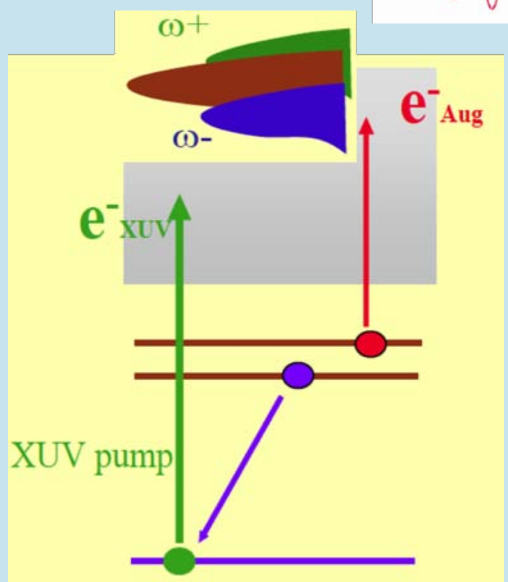
Use of Electron Correlation to Make Attosecond Measurements without Attosecond Pulses

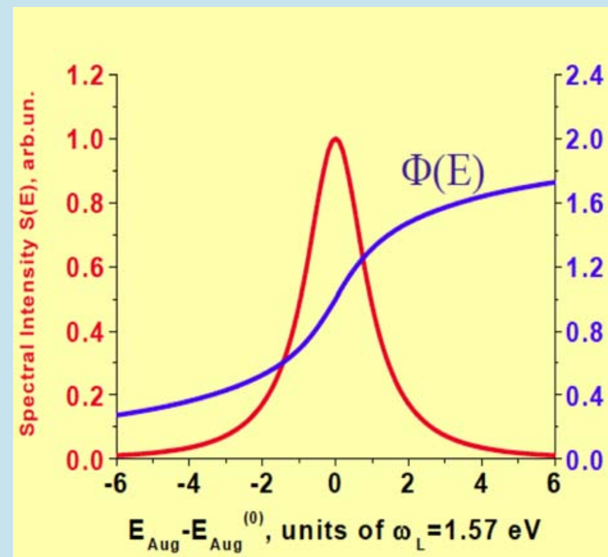
Olga Smirnova,[1] Vladislav S. Yakovlev,[2] and Misha Ivanov[3]
[1]*Photonics Institute, Vienna University of Technology, Gusshausstrasse 27/387, A-1040 Vienna, Austria*
[2]*Department für Physik, Ludwig-Maximilians-Universität München, am Coulombwall 1, D-85748 Garching, Germany*
[3]*NRC Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6 Canada*

IR field Ecos(ωt)









Dynamics of the decay: direct time domain measurement OR the spectral phase Φ(E)
Correlated **A**tto-Second **T**wo-electron **O**ptical **R**econstruction

SPIDER

SPectral shearing Interfereometry for Direct Electric field Reconstruction

SPIDER

SPectral shearing Interfereometry for Direct Electric field Reconstruction

$$E(\omega) = |E(\omega)| \quad e^{i\varphi(\omega)}$$

$$S(\omega,\tau) = \left|E(\omega) + e^{i\omega\tau} E(\omega+\Omega)\right|^2 =$$

$$= \left|E(\omega)\right|^2 + \left|E(\omega+\Omega)\right|^2 + \left|E(\omega)\right|\left|E(\omega+\Omega)\right| \cos\left(\omega\tau + \underbrace{\varphi(\omega+\Omega) - \varphi(\omega)}_{\theta(\omega)}\right)$$

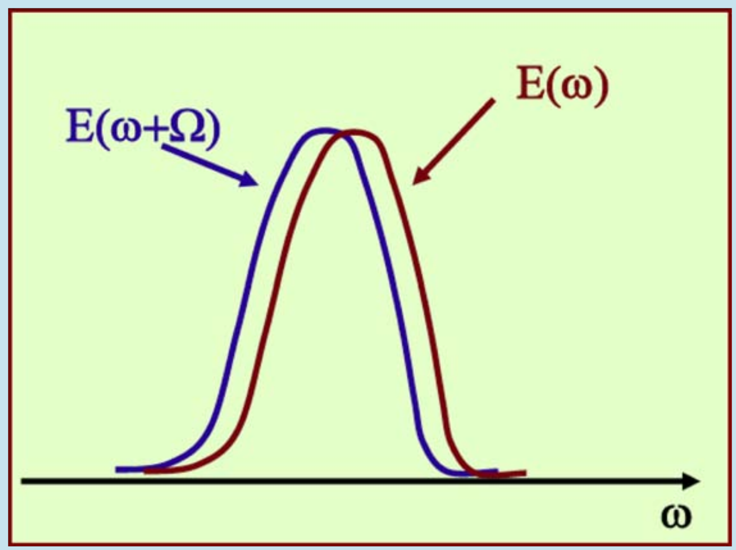
SPIDER

SPectral shearing Interfereometry for Direct Electric field Reconstruction

$$E(\omega) = |E(\omega)| \quad e^{i\varphi(\omega)}$$

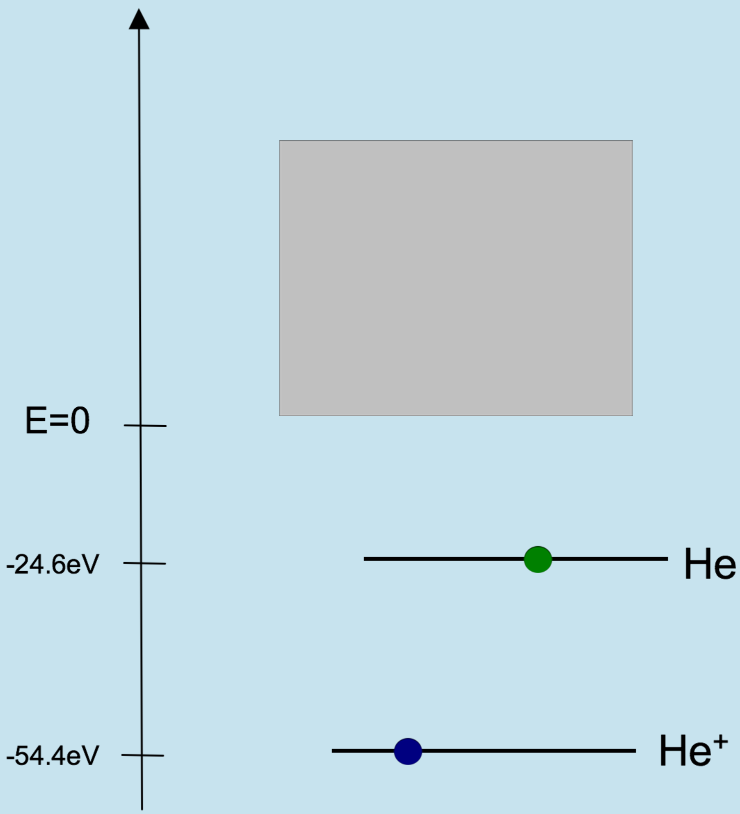
$$S(\omega,\tau) = \left|E(\omega) + e^{i\omega\tau} E(\omega+\Omega)\right|^2 =$$

$$= \left|E(\omega)\right|^2 + \left|E(\omega+\Omega)\right|^2 + \left|E(\omega)\right|\left|E(\omega+\Omega)\right| \cos\Big(\omega\tau + \underbrace{\varphi(\omega+\Omega) - \varphi(\omega)}_{\theta(\omega)}\Big)$$



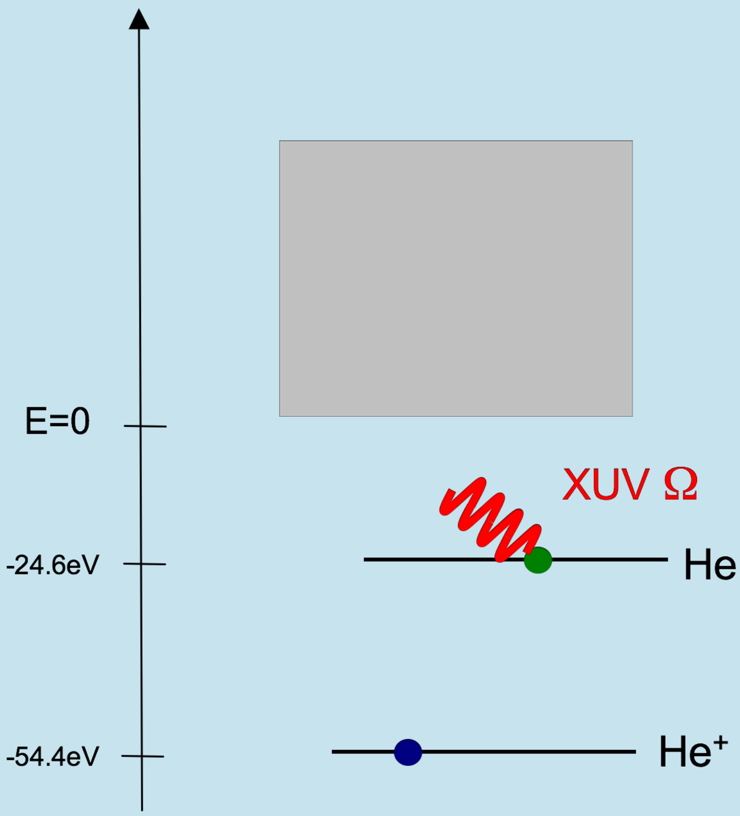
Photoelectron energy distribution in He
XUV only

Photoelectron energy distribution in He
XUV only

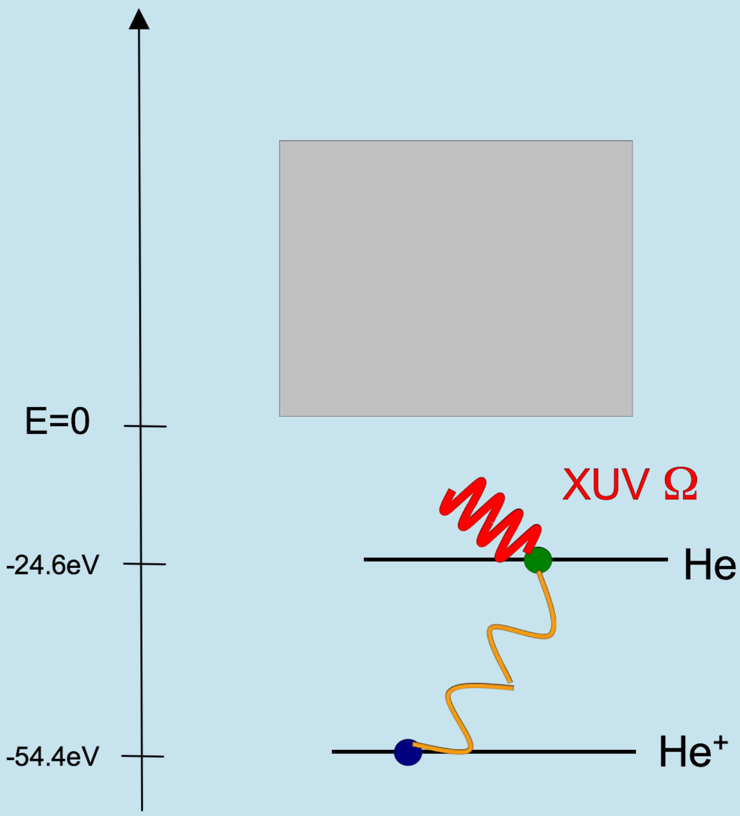


Photoelectron energy distribution in He

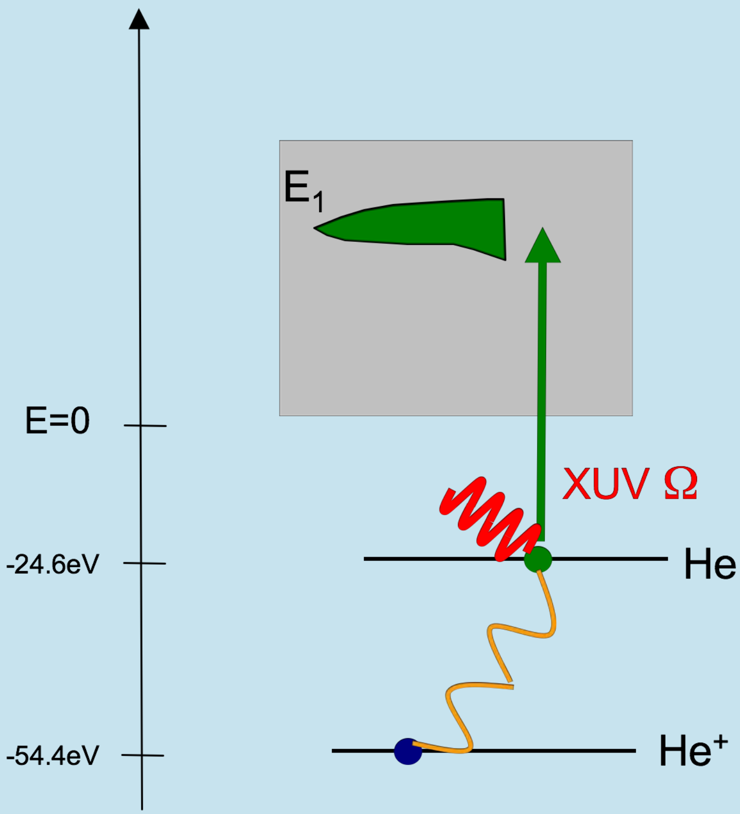
XUV only



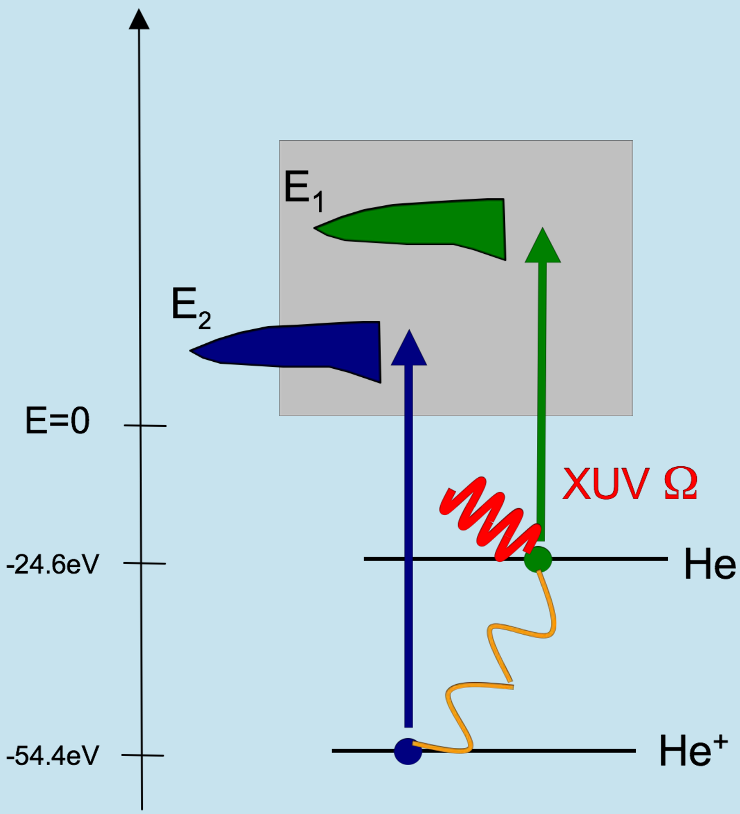
Photoelectron energy distribution in He
XUV only



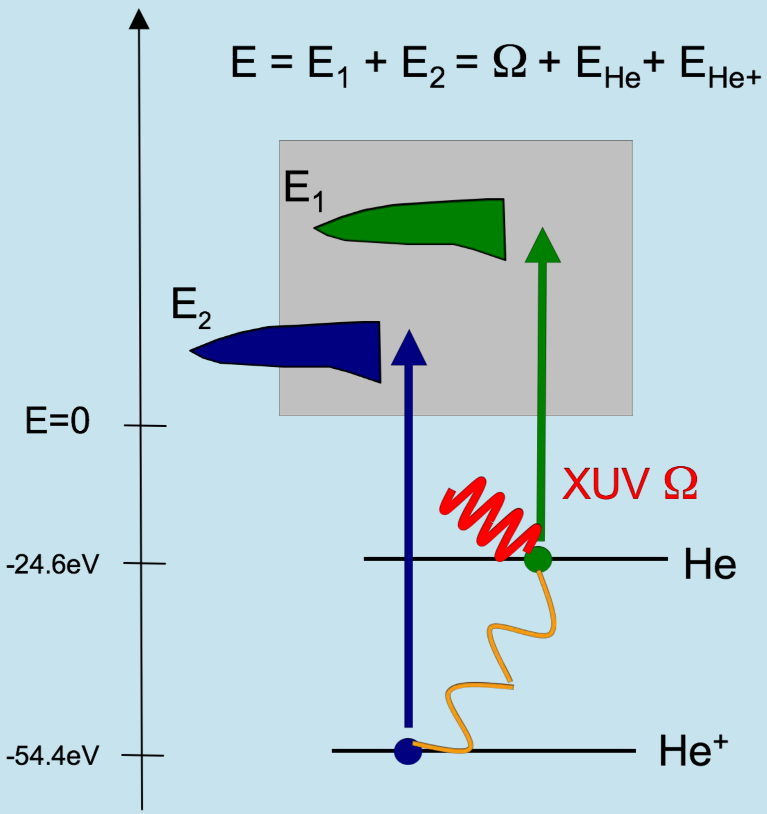
Photoelectron energy distribution in He
XUV only



Photoelectron energy distribution in He
XUV only

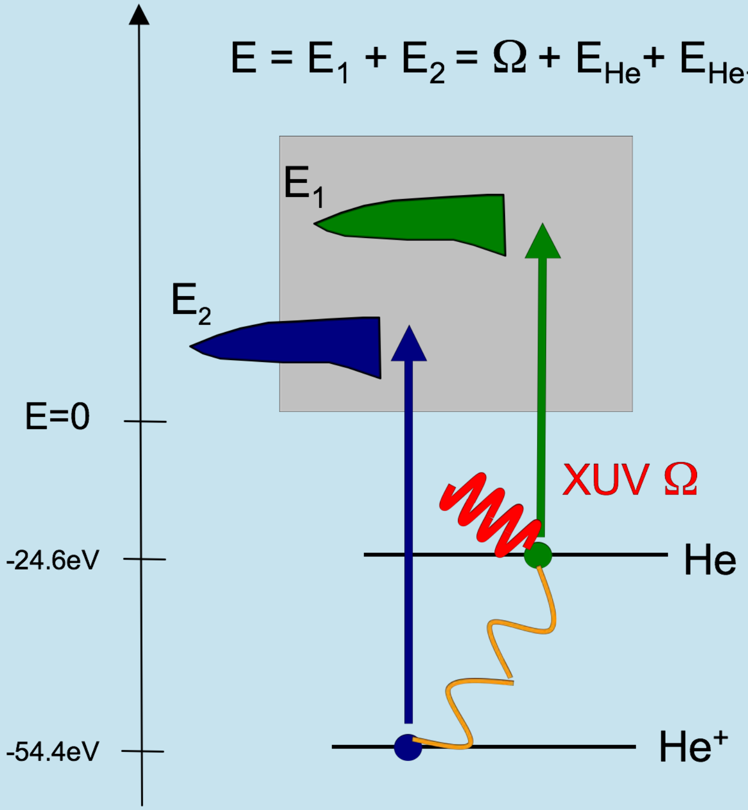


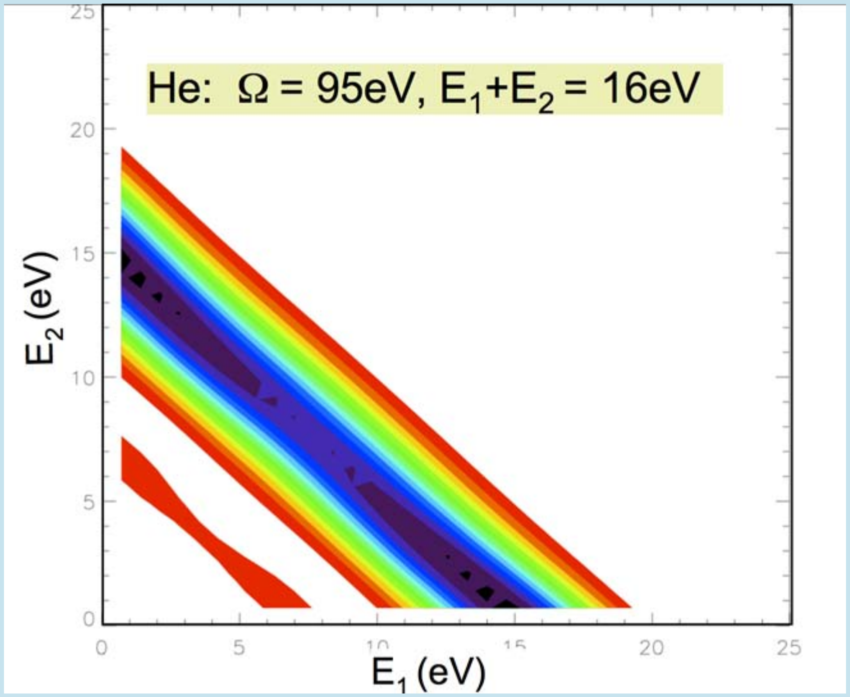
Photoelectron energy distribution in He
XUV only



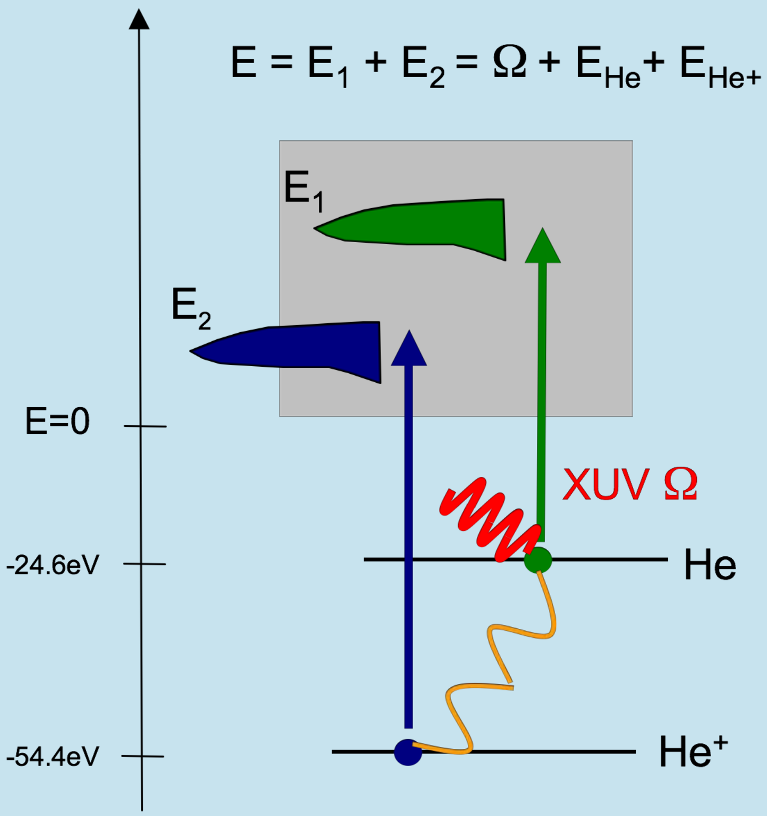
Photoelectron energy distribution in He
XUV only

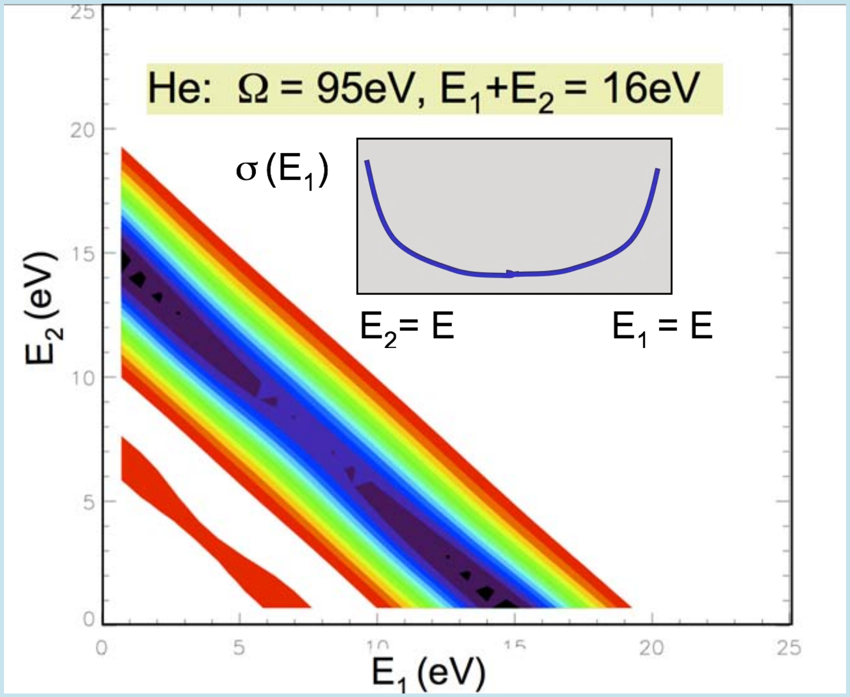
$$E = E_1 + E_2 = \Omega + E_{He} + E_{He+}$$





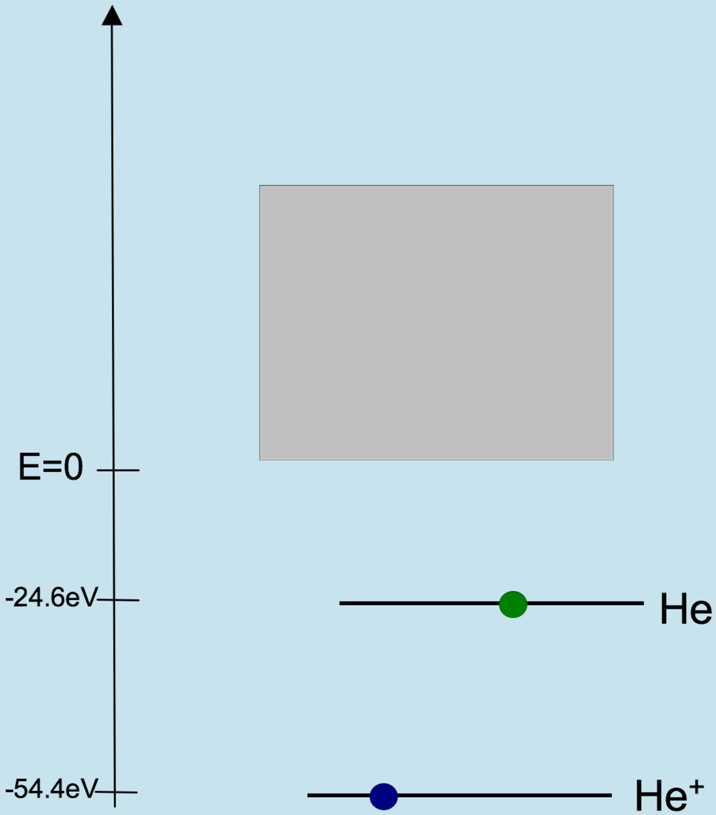
Photoelectron energy distribution in He
XUV only



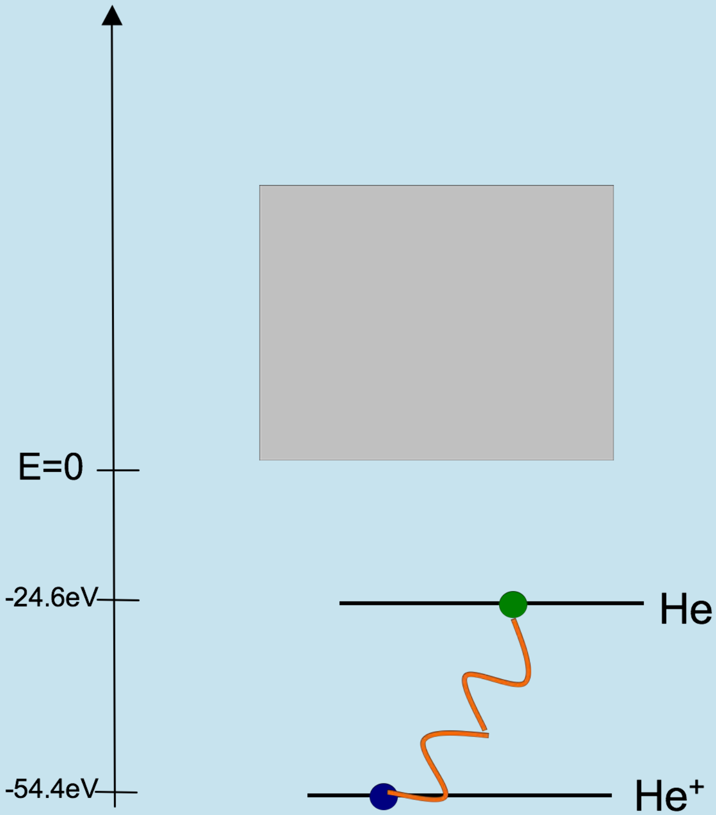


Photoelectron energy distribution in He
XUV + IR

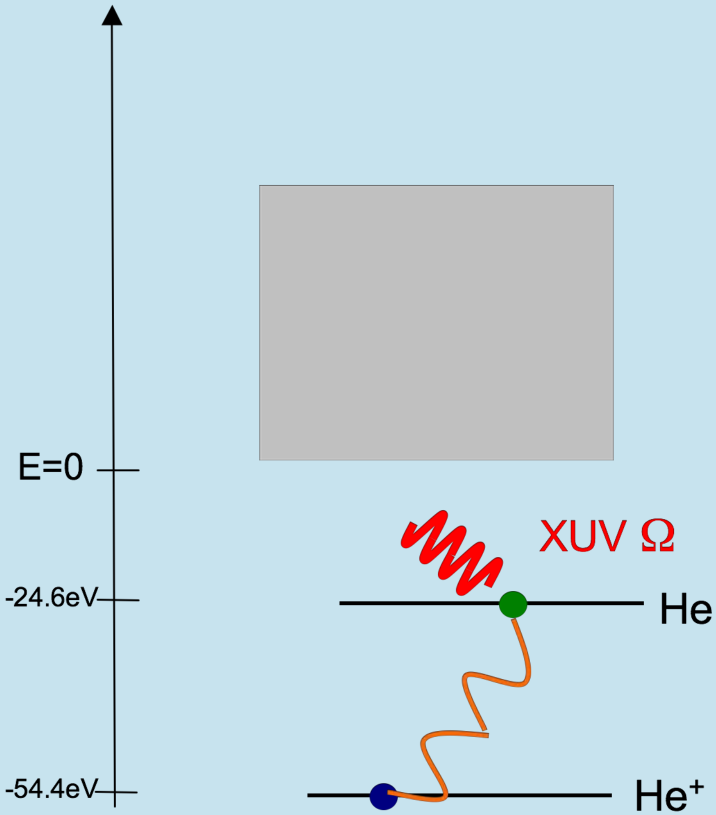
Photoelectron energy distribution in He
XUV + IR



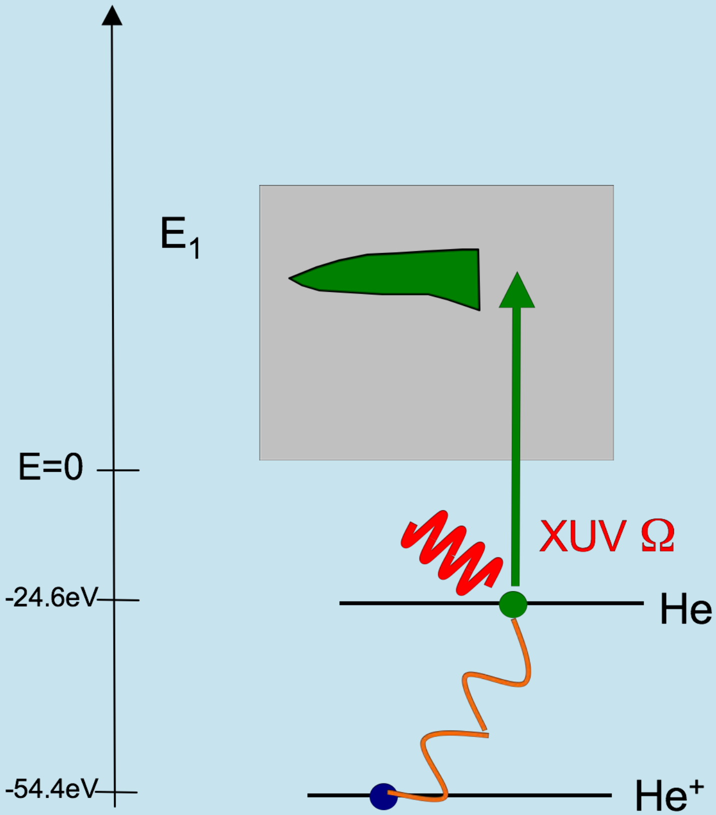
Photoelectron energy distribution in He
XUV + IR



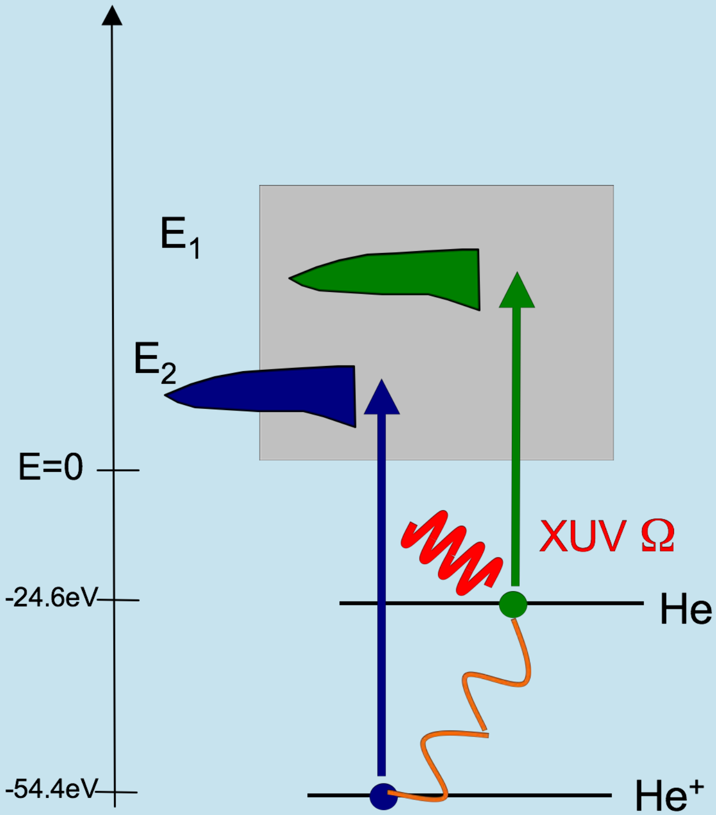
Photoelectron energy distribution in He
XUV + IR



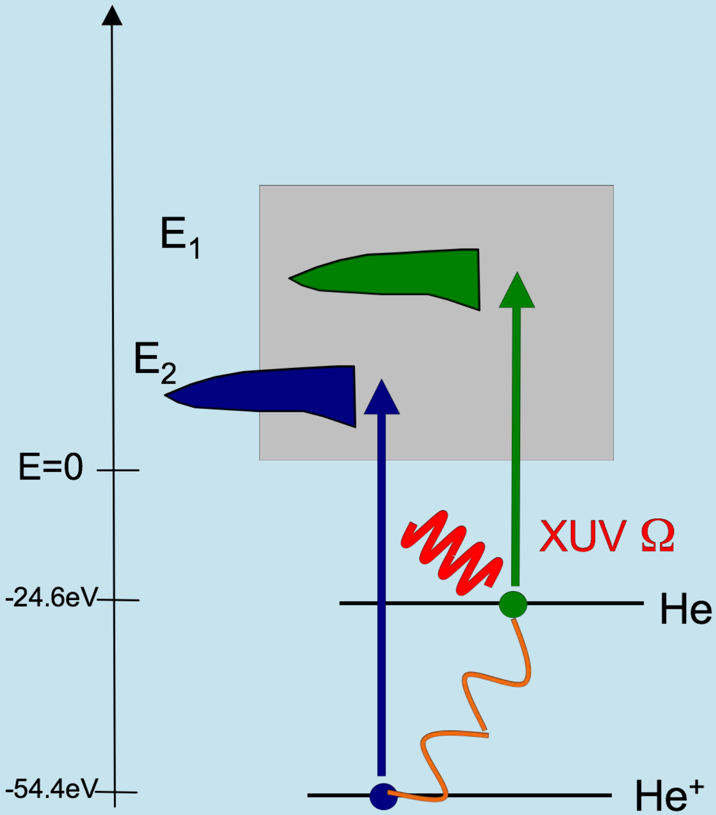
Photoelectron energy distribution in He
XUV + IR

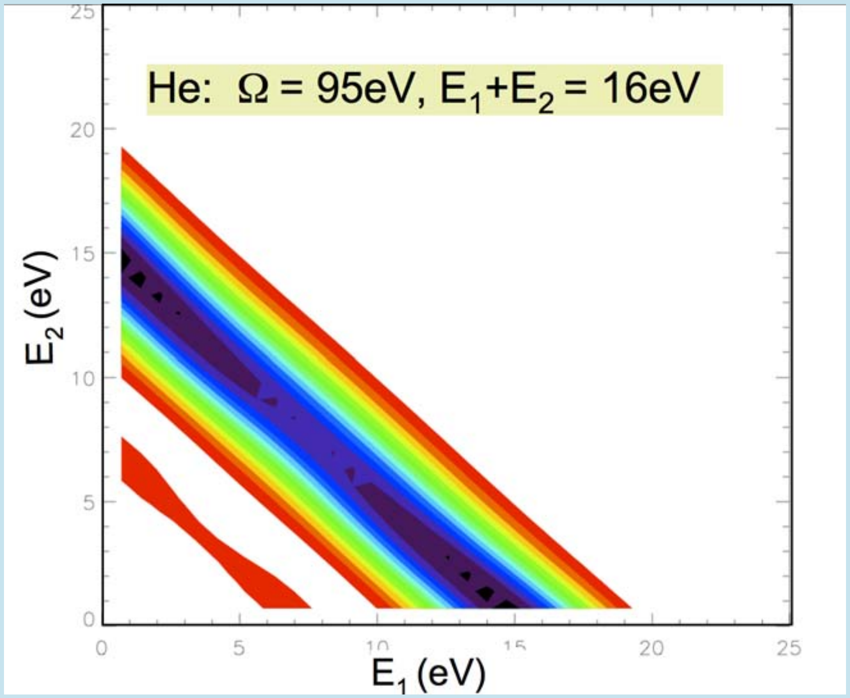


Photoelectron energy distribution in He
XUV + IR

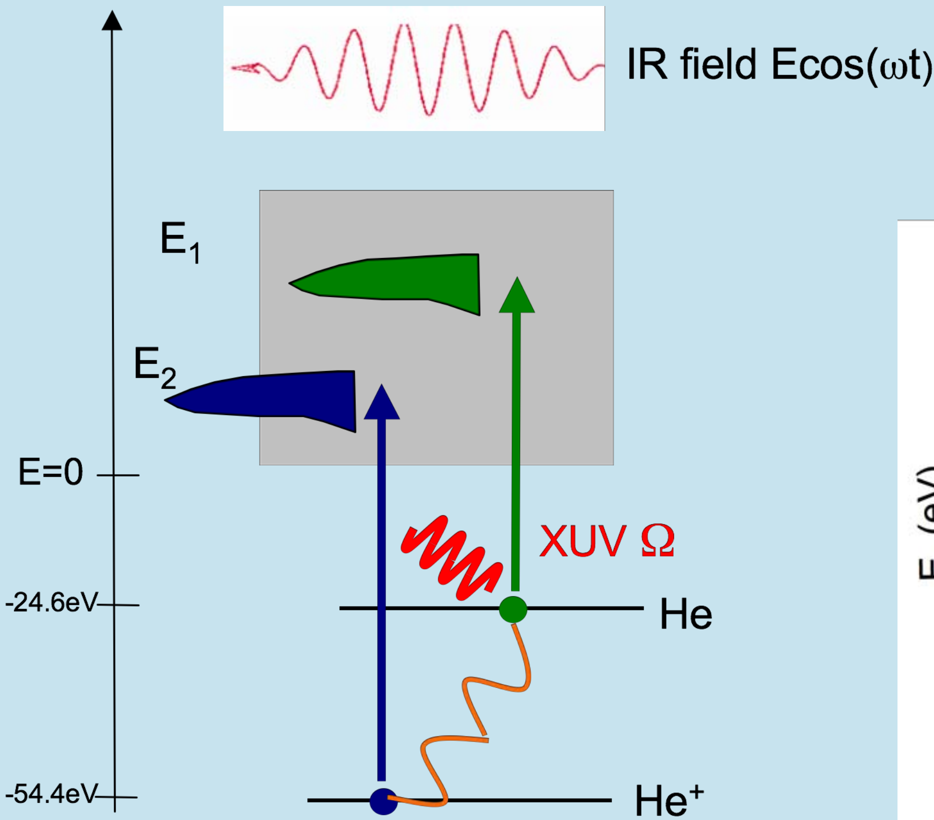


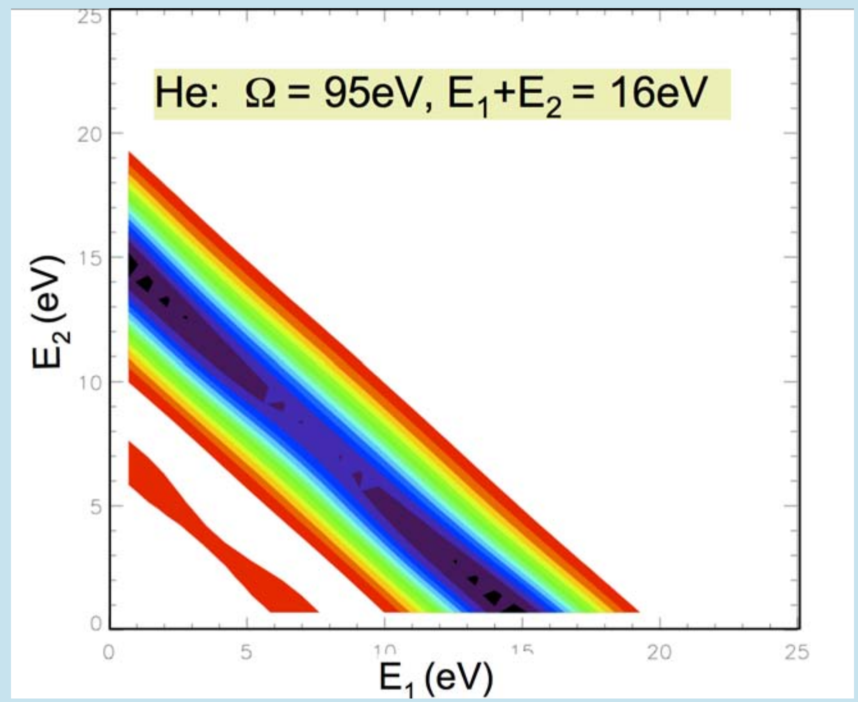
Photoelectron energy distribution in He
XUV + IR



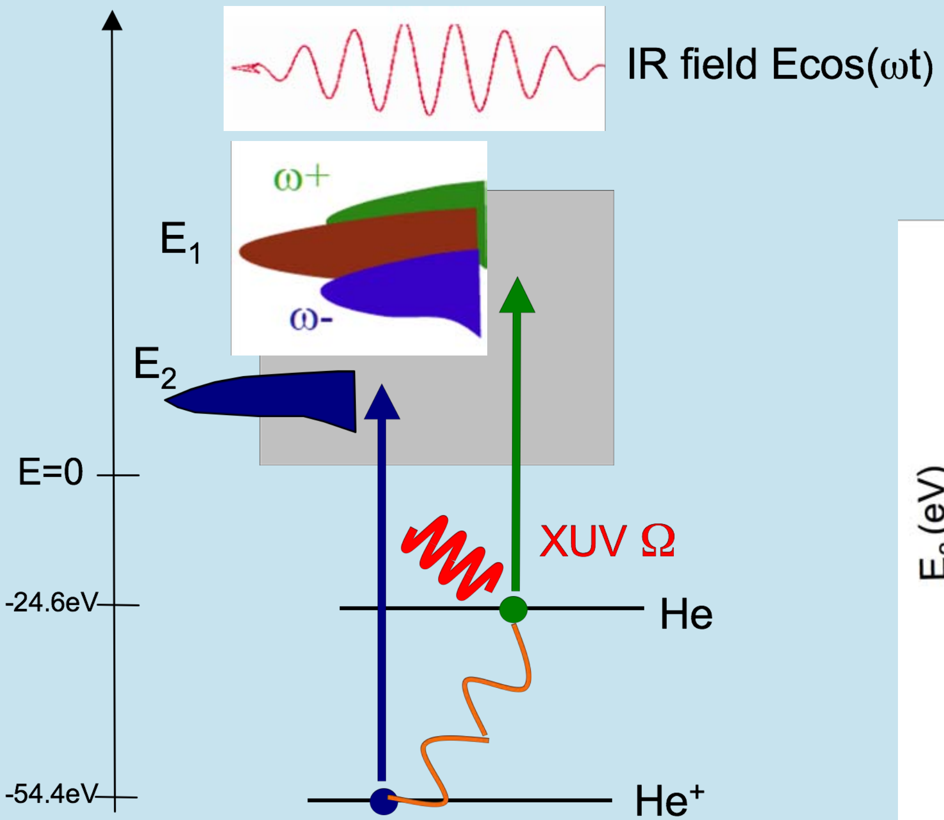


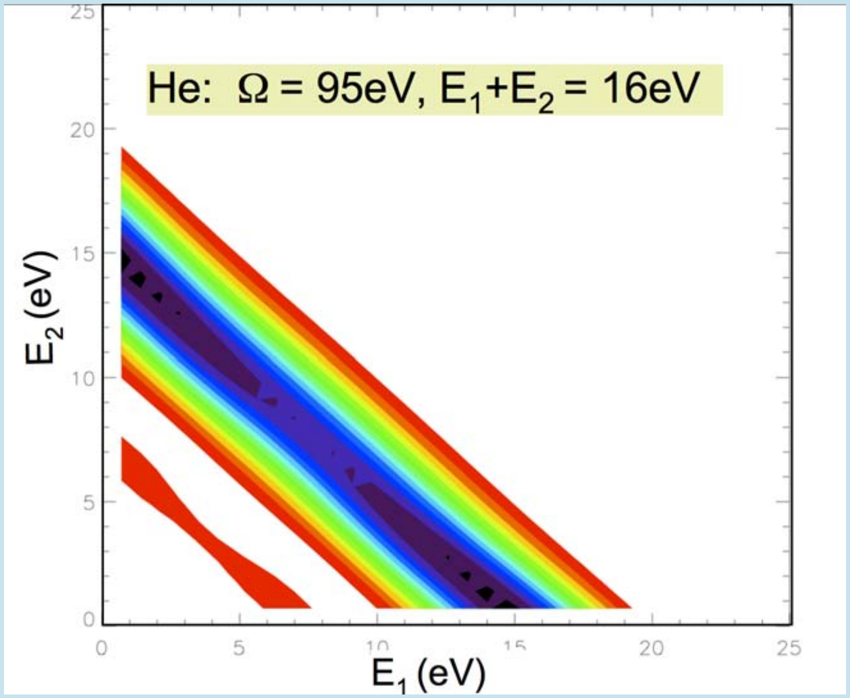
Photoelectron energy distribution in He
XUV + IR



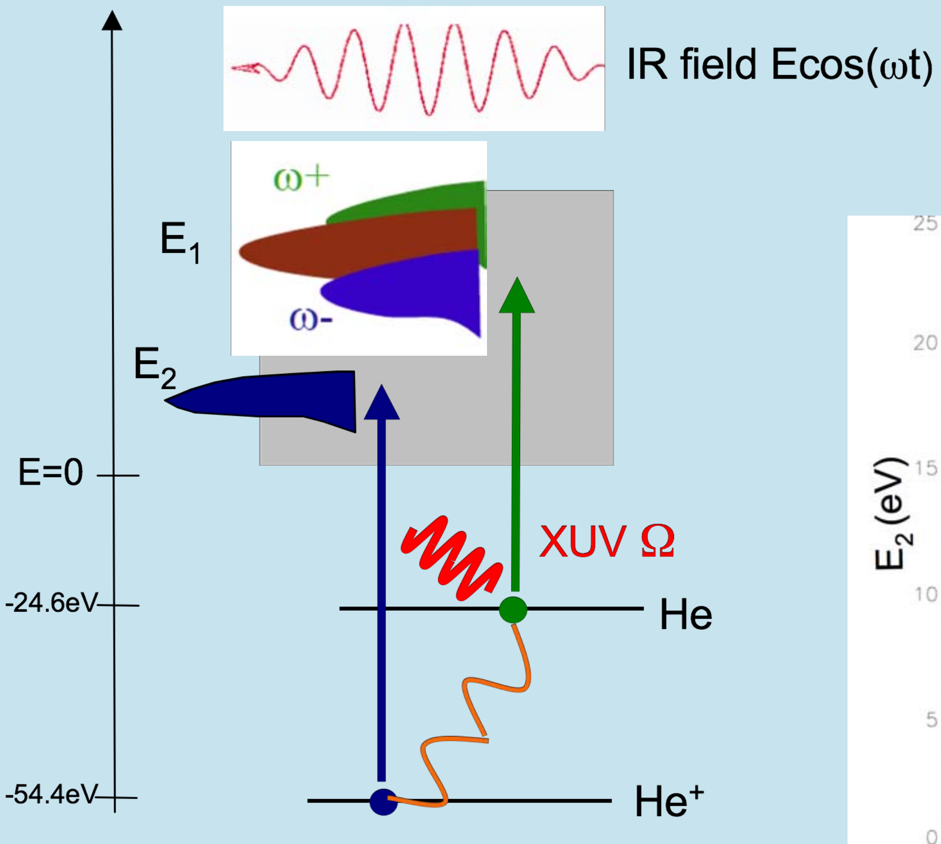


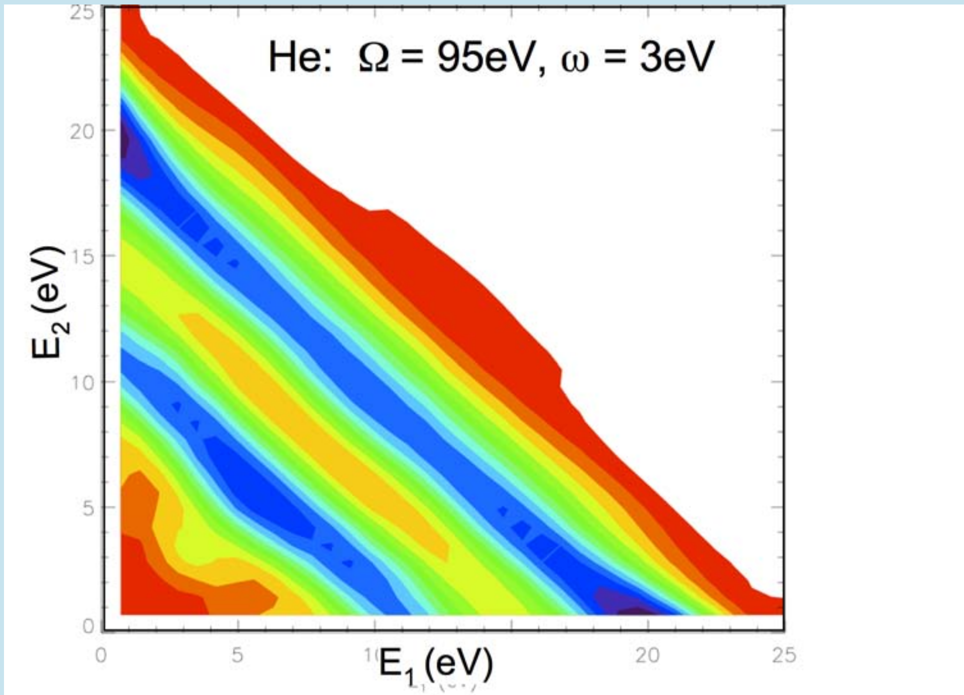
Photoelectron energy distribution in He
XUV + IR





Photoelectron energy distribution in He
XUV + IR





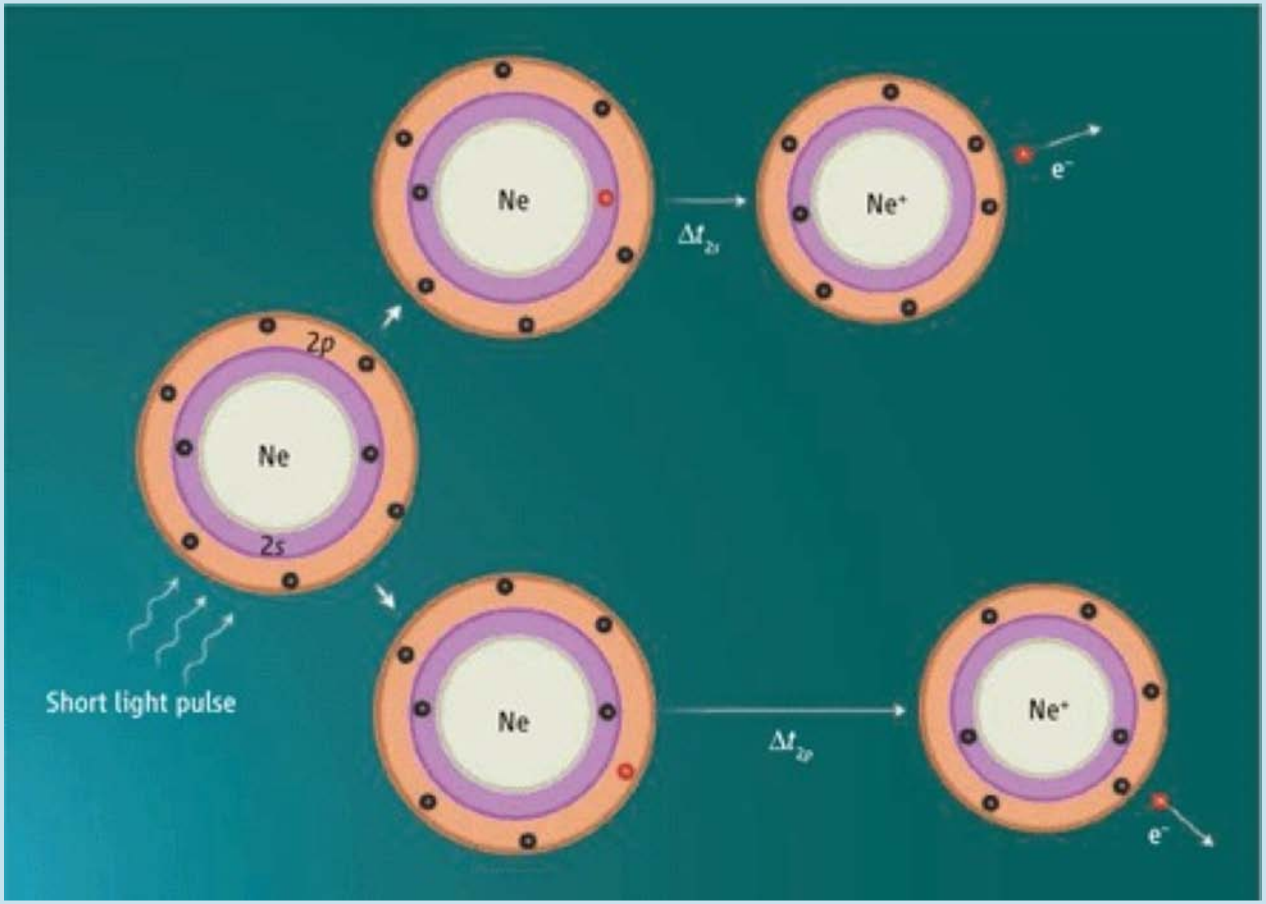
When Does Photoemission Begin?

When Does Photoemission Begin?

sub–10-as regime has been enabled by waveform-controlled near–single-cycle pulses (duration ~3.3 fs) of near-infrared (NIR, carrier wavelength ~750 nm) light (*26*). These pulses permit the generation of isolated sub–100-as extreme ultraviolet (XUV) pulses via high-order harmonic generation

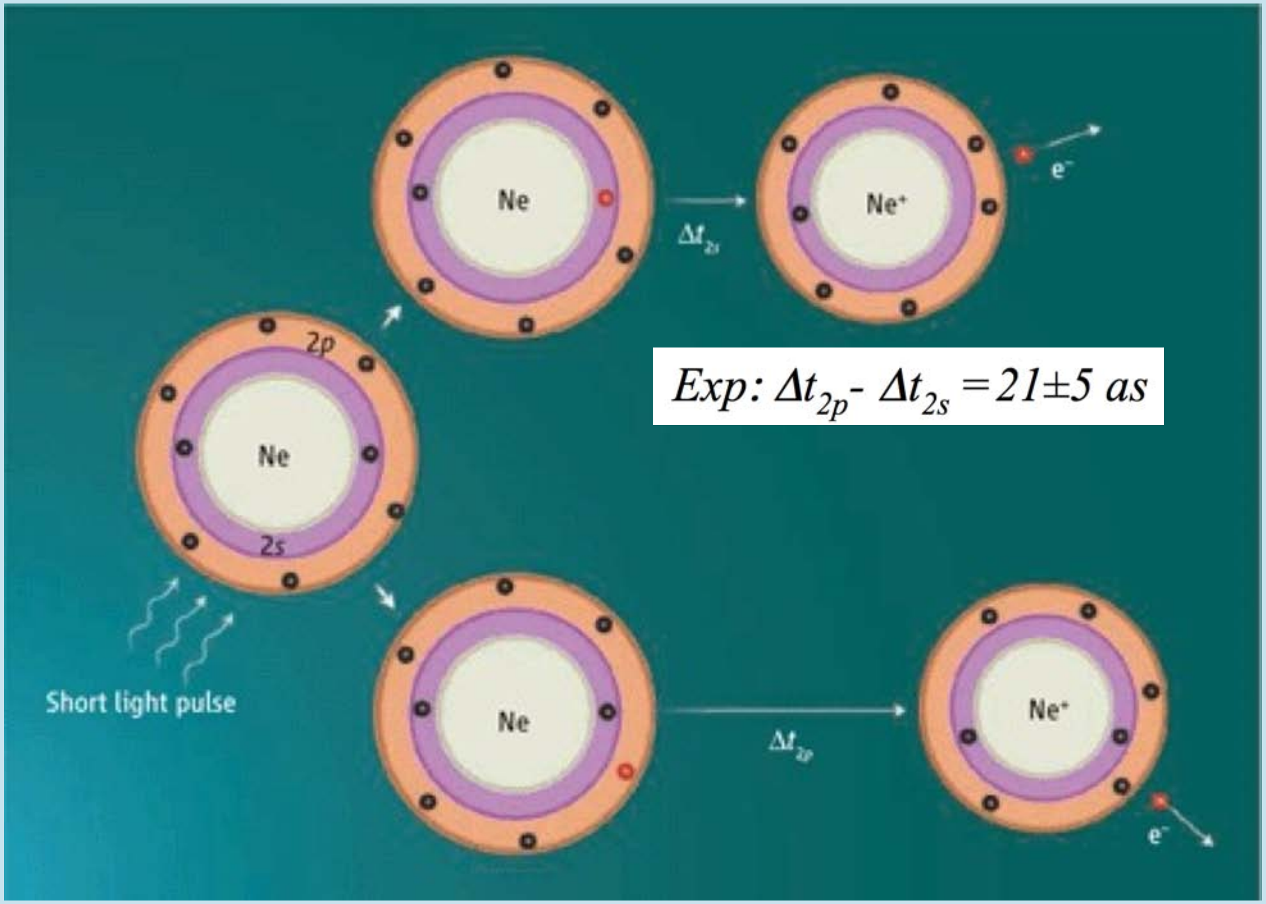
When Does Photoemission Begin?

When Does Photoemission Begin?



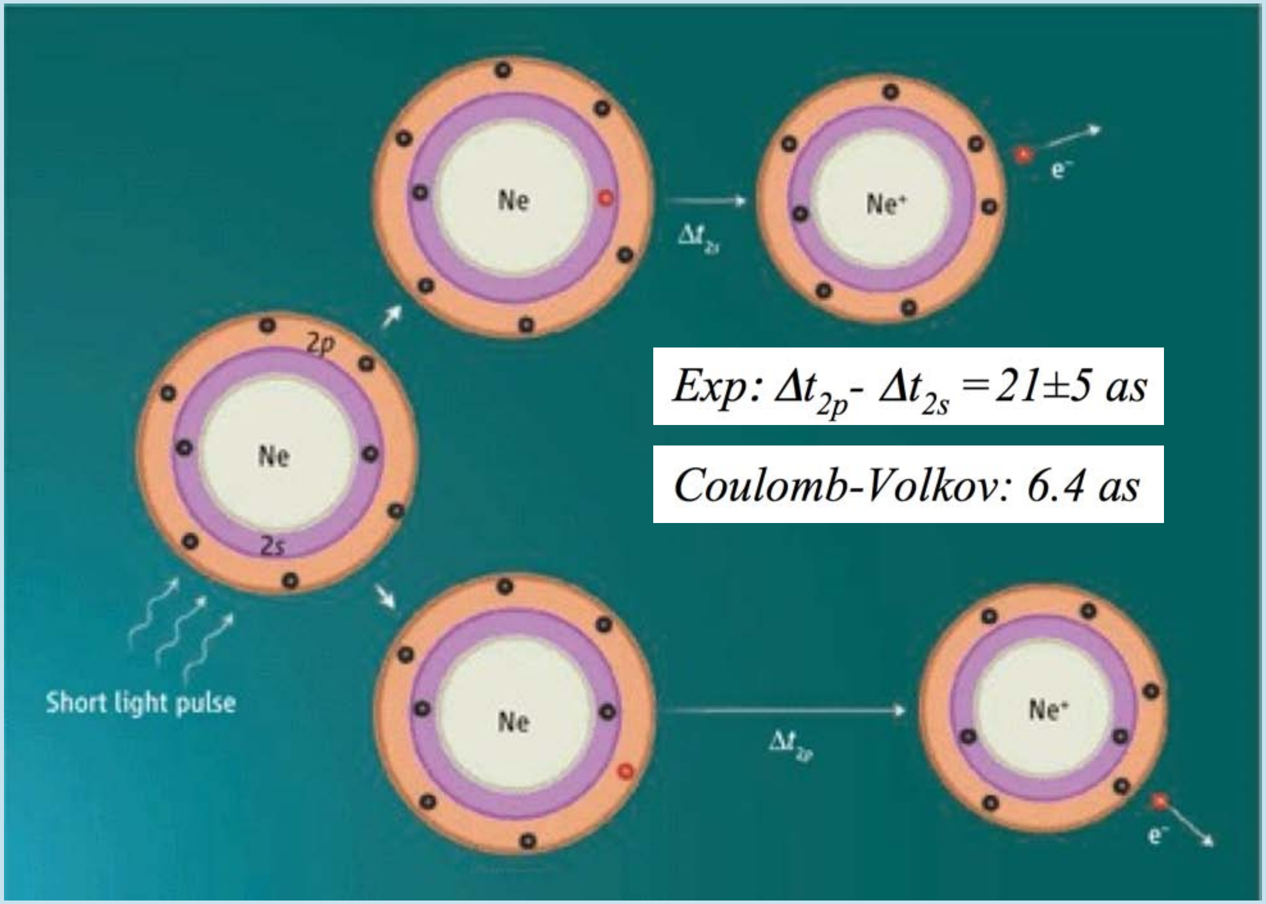
Delay in Photoemission
M. Schultze, *et al.*
Science **328**, 1658 (2010)

When Does Photoemission Begin?



Delay in Photoemission
M. Schultze, *et al.*
Science **328**, 1658 (2010)

When Does Photoemission Begin?



Science AAAS

Delay in Photoemission
M. Schultze, *et al.*
Science **328**, 1658 (2010)

Conclusion

Conclusion

- Numerical solution of TDSE applied to

Conclusion

- Numerical solution of TDSE applied to
  - Ionization
    - $(N\gamma, e)$ on H
    - $(4\gamma, e)$ on Li

Conclusion

- Numerical solution of TDSE applied to
  - Ionization
    - *(Nγ,e) on H*
    - *(4γ,e) on Li*
  - *Electron correlation resolved in time*
    - *Double ionization of He*

- Further directions
    - *Single ionization of noble gases*