

Cheiron School, SPring-8, Japan

October 15, 2010

Studies on atoms and molecules
using synchrotron radiation

Kiyoshi Ueda

***Institute of multidisciplinary research for advanced materials
Tohoku University, Sendai 980-8577, Japan***

Introduction of myself

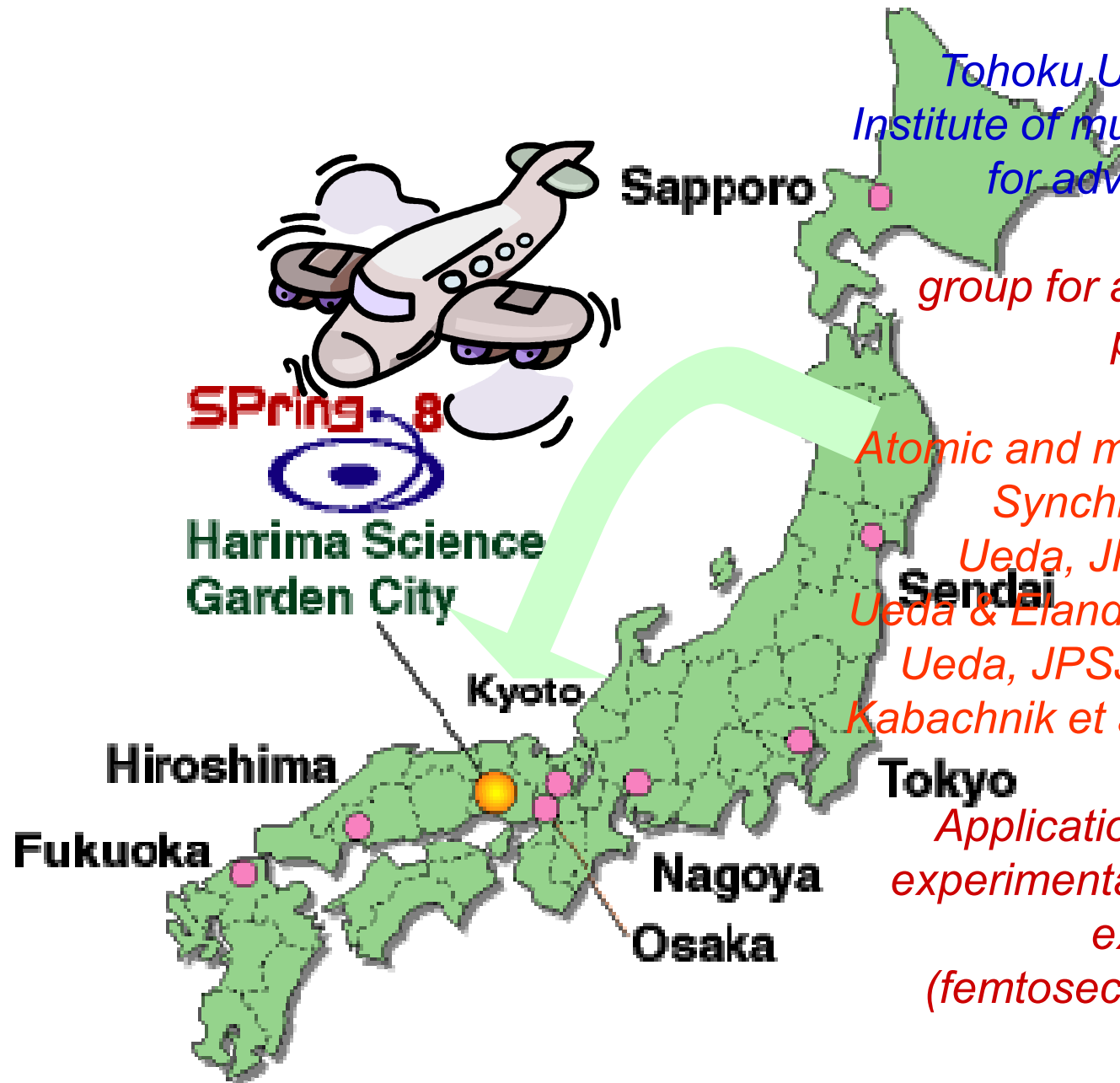
Prof. Kiyoshi Ueda
at

Tohoku University (Sendai)
Institute of multidisciplinary research
for advanced materials

Leading
group for analysis of quantum
processes

Atomic and molecular science using
Synchrotron Radiation
Ueda, JPB 36, R1 (2003);
Ueda & Eland, JPB 38, S839 (2005);
Ueda, JPSJ 75, 032001 (2006);
Kabachnik et al. PR 451, 155 (2007).

Application of the SR-based
experimental techniques to laser
experiments
(femtosecond laser and FEL)



Outline

1. *Introduction to quantum world*
2. *Atomic resonant photoemission spectroscopy*
 - *Introduction to the quantum interference*
3. *Vibrationally-resolved core-level photoelectron spectroscopy*
 - *Adiabatic approximation and Franck-Condon analysis*
 - *Young's double-slit experiments*
 - *Intermission* -
4. *Multiple-ion momentum imaging*
 - *Snapshots of molecular deformation within a few fs*
5. *Electron-ion momentum imaging*
 - *Molecular-frame photoelectron angular distributions*
6. *Interatomic Coulombic decay*
7. *Towards single shot molecular imaging by XFEL*

Photoelectric effect

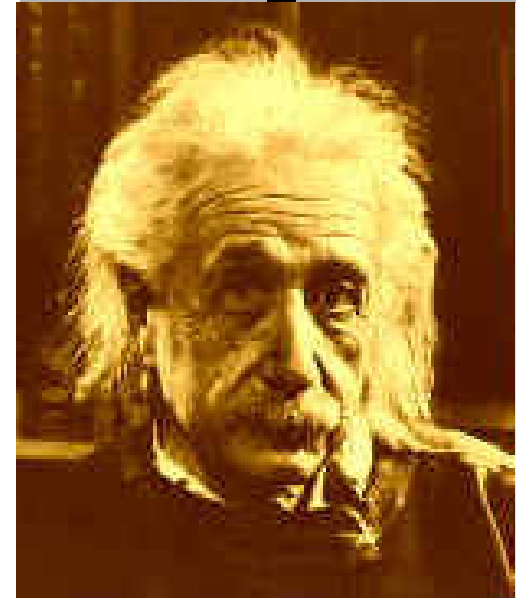
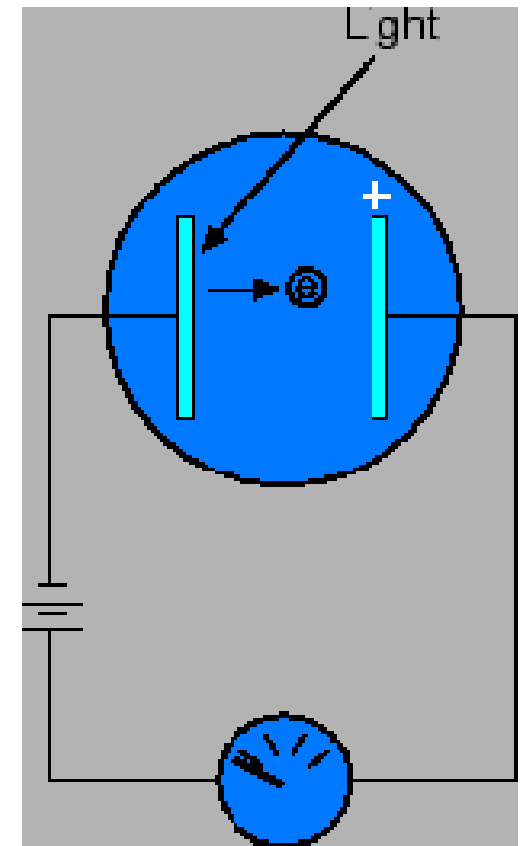
When matter is shined by the light, electron is emitted from the surface.

- (i) Frequency of the light needs to be larger than ν_0 .
- (ii) Kinetic energy of the electron is determined by the frequency of the light.
- (iii) Number of electrons is proportional to the intensity of the light.

Einstein's explanation

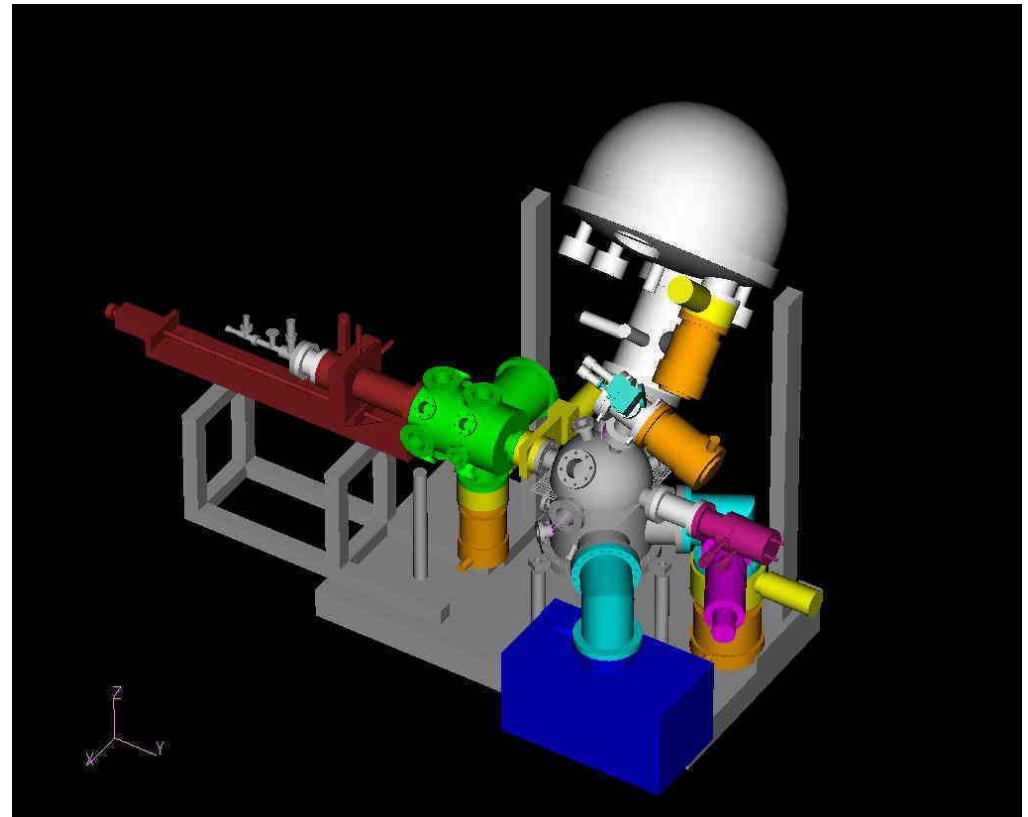
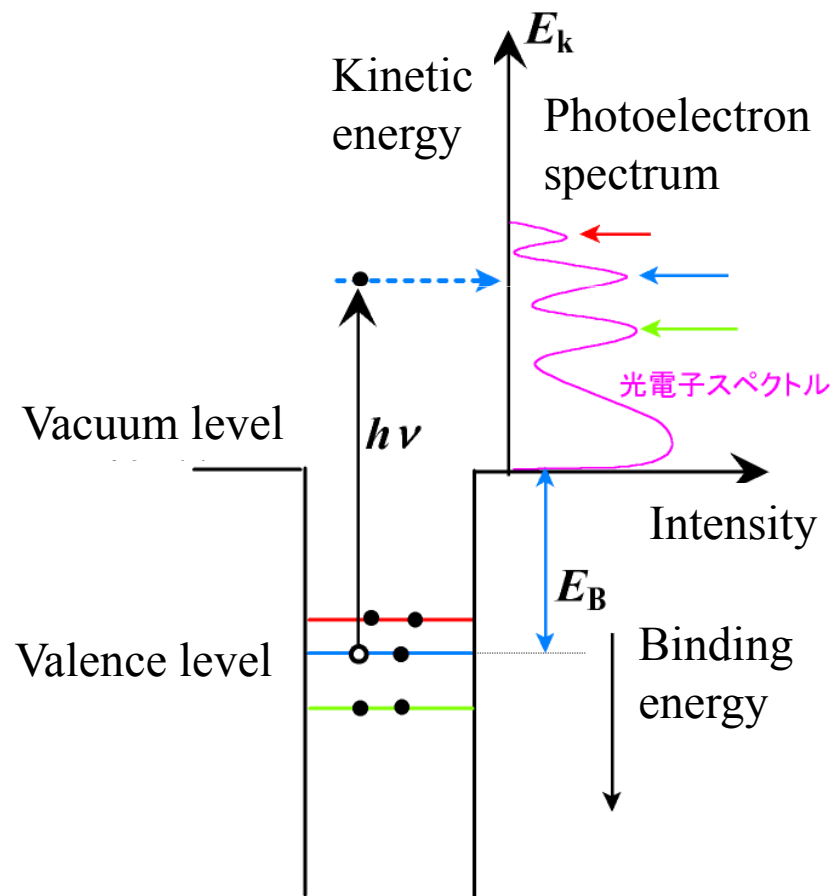
Light at frequency of ν is considered to be a group of particles (photons) and each photon has energy $h\nu$. An electron gets the energy $h\nu$ when it absorb one photon.

The electron in the matter is bound. For the electron to be emitted from the matter, the electron needs to receive the energy more than the work function W . Then the kinetic energy KE of the emitted electron can be given as $KE = h\nu - W$.

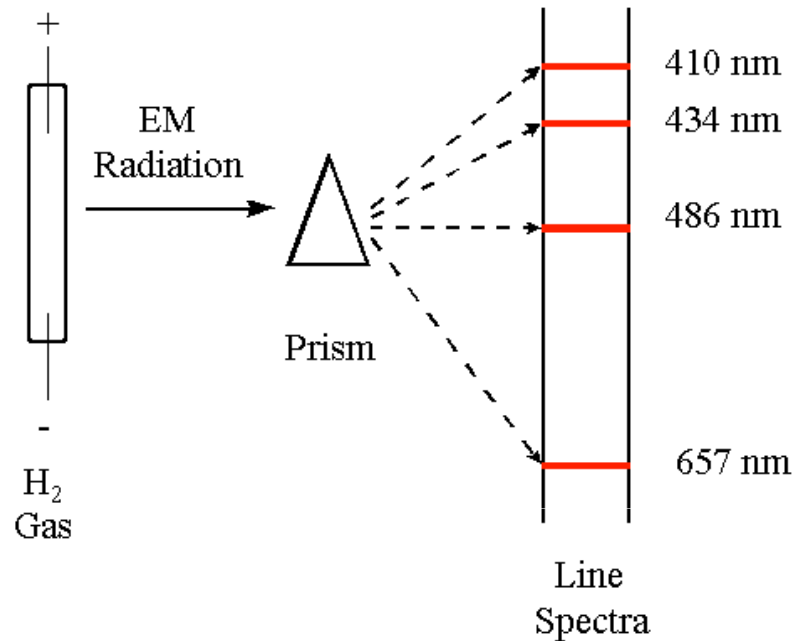


Photoelectron spectroscopy (UPS, XPS)

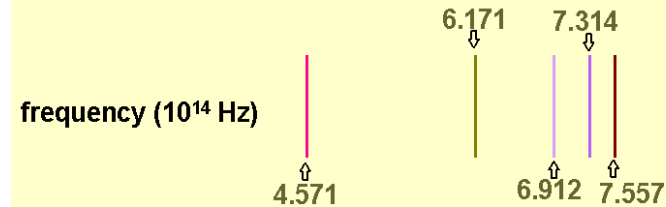
Precision measurements for kinetic energies of photoelectrons emitted via Einstein's photoelectric effects



Balmer and Rydberg formulae



Hydrogen Spectrum: Balmer series



Balmer Formula: $\nu = \nu_0 \left(\frac{1}{n^2} - \frac{1}{m^2} \right)$

$$32.91 \left(\frac{1}{4} - \frac{1}{9} \right) = 4.571$$

$$32.91 \left(\frac{1}{4} - \frac{1}{16} \right) = 6.171$$

$$32.91 \left(\frac{1}{4} - \frac{1}{25} \right) = 6.911$$

$$32.91 \left(\frac{1}{4} - \frac{1}{36} \right) = 7.313$$

$$32.91 \left(\frac{1}{4} - \frac{1}{49} \right) = 7.556$$

IT WORKS!

Balmer found beautiful regularity in the H spectrum!

$$\text{Rydberg formula: } \frac{\nu}{c} = \frac{1}{\lambda} = R \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

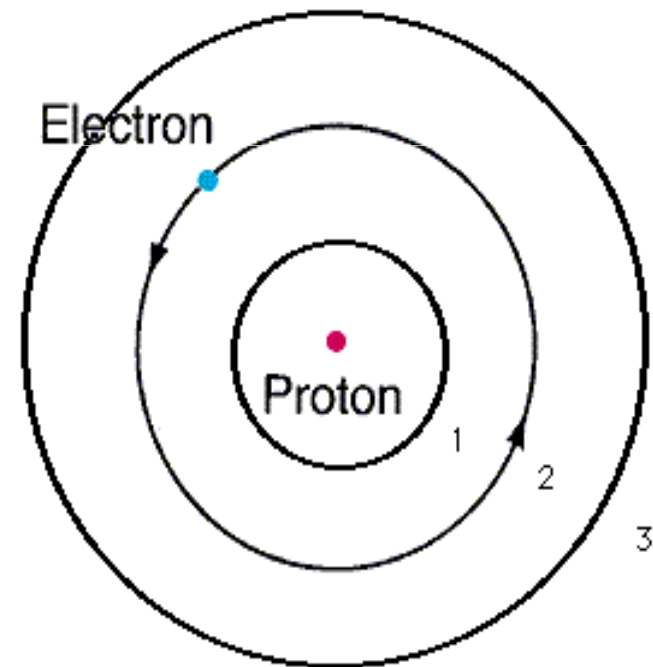
c , speed of light; λ , wavelength; R , Rydberg constant ($R=109737.309 \text{ cm}^{-1}$)

Bohr's atomic model

Electron orbits exist only when the classical orbits satisfy the following condition of quantization:

$$\int_0^{2\pi} p_\varphi d\varphi = nh$$

φ , angle of rotation; $p_\varphi = m_e r^2 d\varphi/dt$, angular momentum; r , radius; m_e , electron mass



The electron binding energies are discrete:

$$\bar{E}_n = -hcR/n^2$$

Schrödinger equation of H atom (in atomic units)

$$H\Psi(r) = E\Psi(r)$$

$$H = T + U(r)$$

Hamiltonian

$$T = \frac{p^2}{2} = -\frac{1}{2} \frac{\partial^2}{\partial r^2}$$

kinetic energy

$$p = i \frac{\partial}{\partial r}$$

momentum

$$U(r) = -\frac{1}{r}$$

potential energy

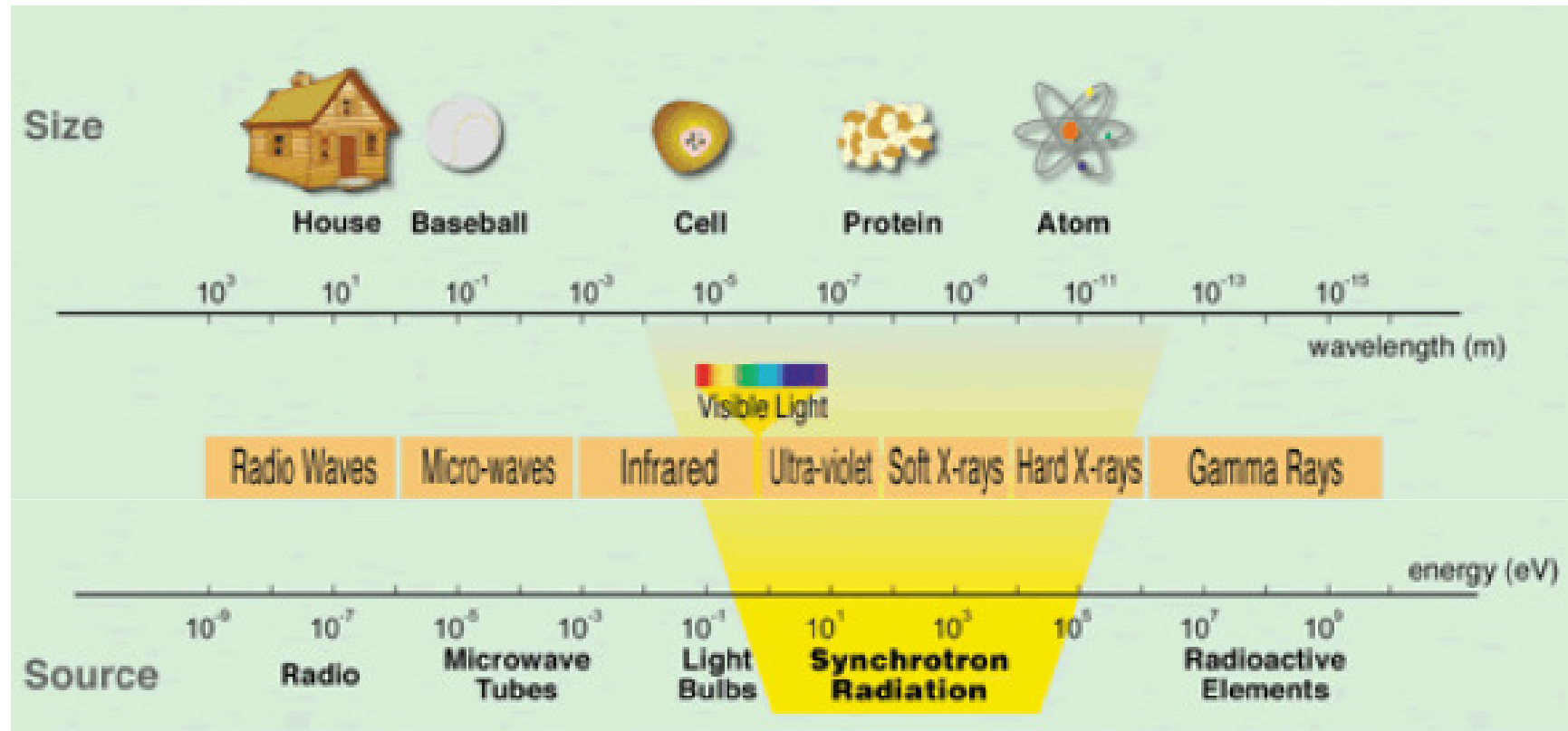
$$E_n = -\frac{1}{2n^2}$$

Ψ : wave function

complex number (with phase!)

Atomic and molecular science now

Target: single atom or molecule; size: $\sim 1 \text{ \AA}$ ($= 0.1 \text{ nm} = 10^{-10} \text{ m}$)



How to use synchrotron radiation to study atoms and molecules

We use monochromatic synchrotron radiation to excite atoms and molecules and to study their electronic structures as well as electron and nuclear dynamics in the excited states.

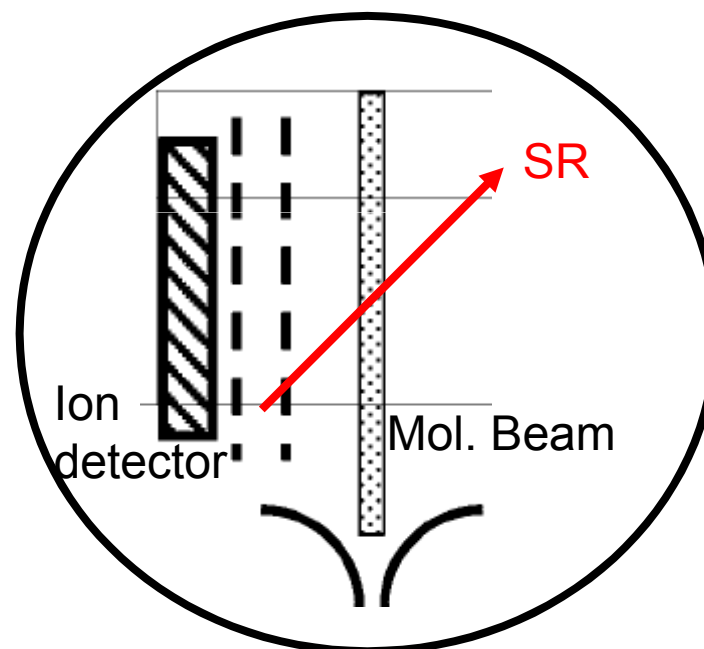
A single photon should be absorbed by a single atom or molecule first!

What photon energies to be used

Electron binding energies (eV) Vacuum ultraviolet light!

Element	K 1s	L ₁ 2s	L ₂ 2p _{1/2}	L ₃ 2p _{3/2}
1 H	13.6			
2 He	24.6*			
3 Li	54.7*			
4 Be	111.5*			
5 B	188*			
6 C	284.2*			
7 N	409.9*	37.3*		
8 O	543.1*	41.6*		
9 F	696.7*			
10 Ne	870.2*	48.5*	21.7*	21.6*

The experiments need to be in the vacuum!



The easiest experiment: ion yield spectroscopy

SPring-8 BL27SU

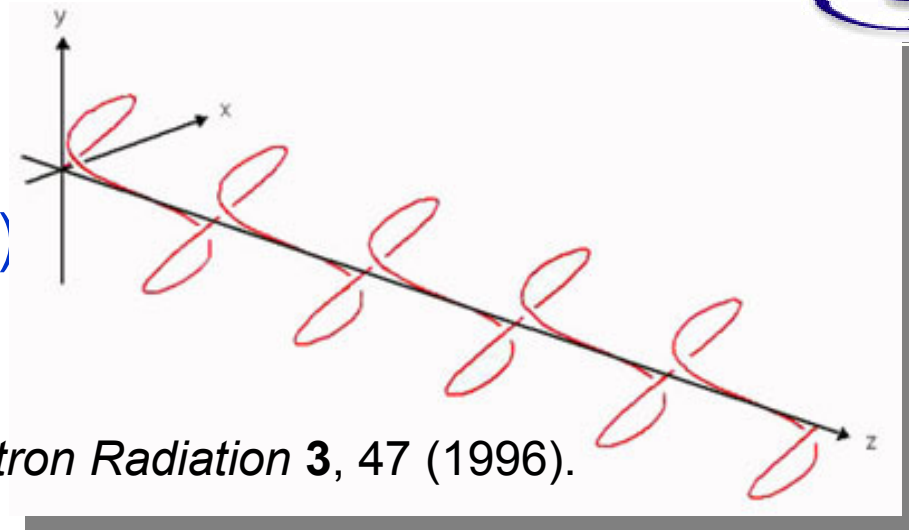


Figure-8 undulator

Linearly polarized light

Horizontal polarization (1st)

Vertical polarization (0.5th)



T. Tanaka and H. Kitamura, *J. Synchrotron Radiation* **3**, 47 (1996).

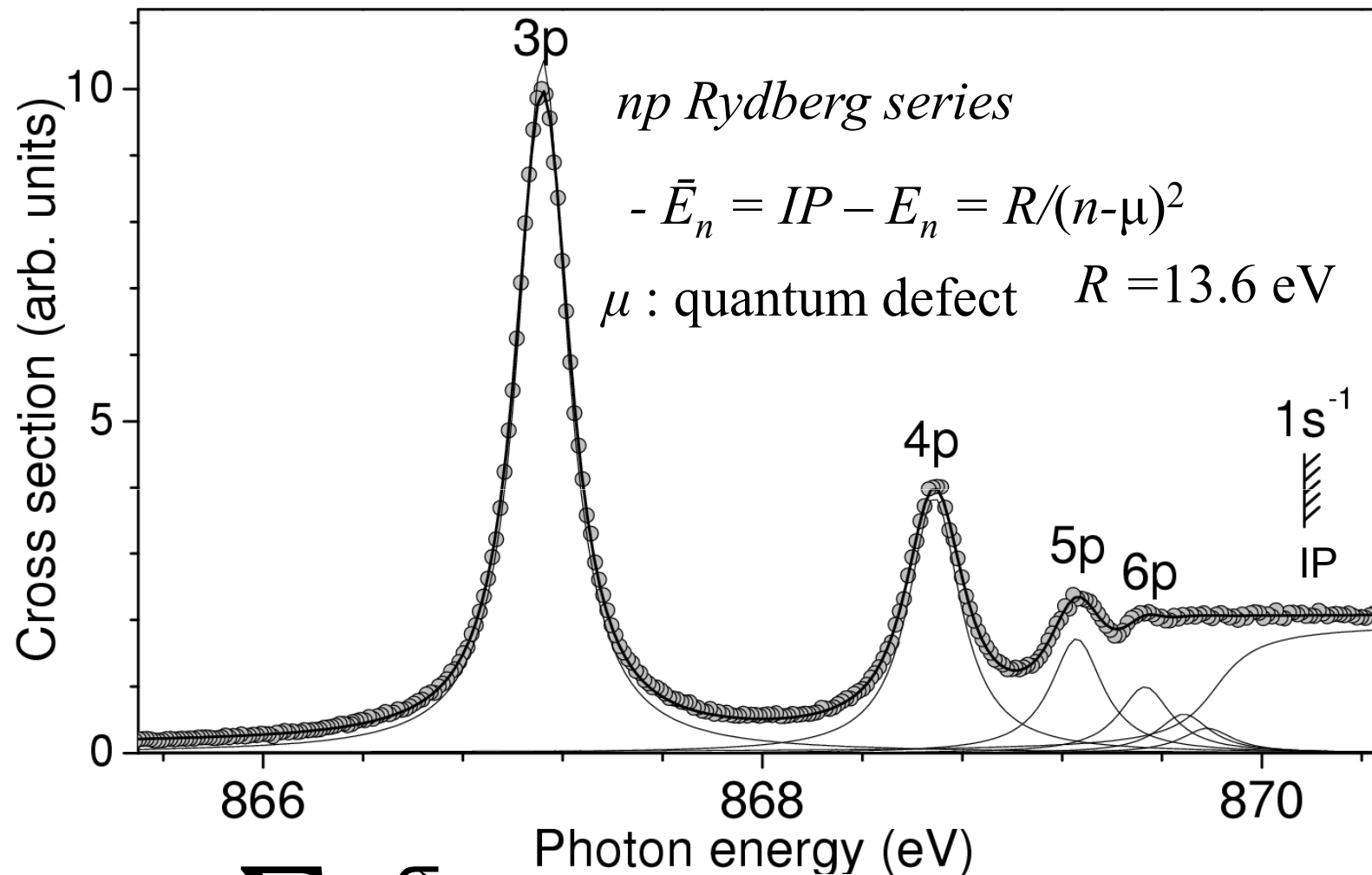
Soft X-ray monochromator

Hettrick type: varied line spacing plane grating

Energy range	0.15 ~ 2.5 keV
Photon Flux	> 10 ¹¹ photon/s
Energy resolution	10000 - 20000

H. Ohashi, Y. Tamenori, E. Ishiguro *et al. Nucl. Instr. Methods A* **467**, 533 (2001).

Ne 1s total ion yield spectrum

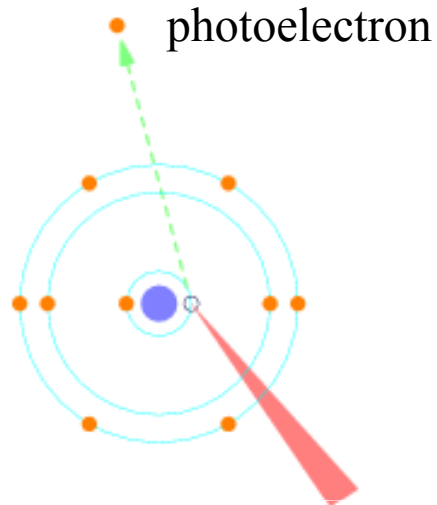


$$\sigma = \sigma_{dir} + \sum_n \frac{\sigma_n}{1 + \frac{\varepsilon_n^2}{2}} + \sigma_{ls} \quad \varepsilon = (h\nu - E_n)/(\Gamma_n/2)$$

$$\sigma_n \propto 1/(n - \mu)^3 \quad \Gamma_n = \text{const!}$$

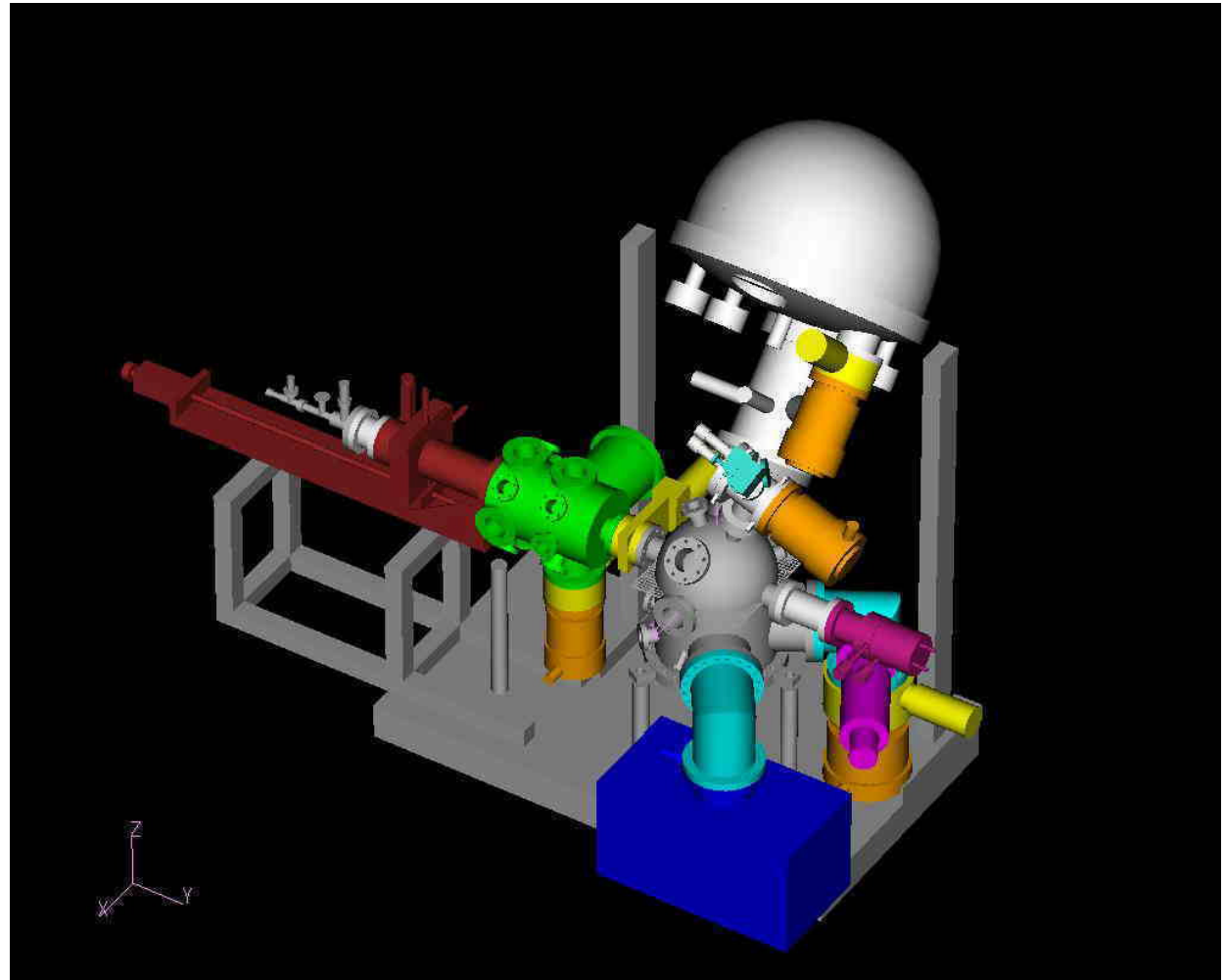
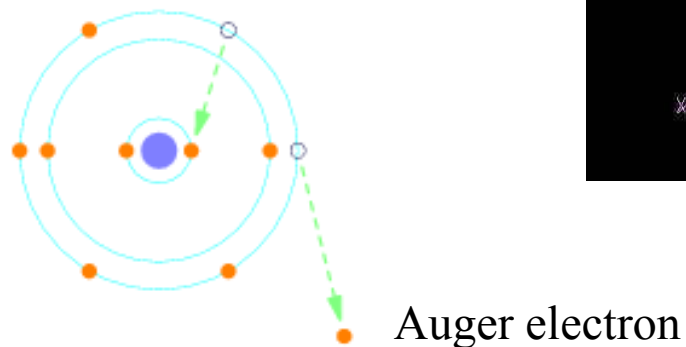
Auger decay and Auger electron spectroscopy

(a) Core ionization



(b) Auger decay:

Core hole lifetime
defines the line width!



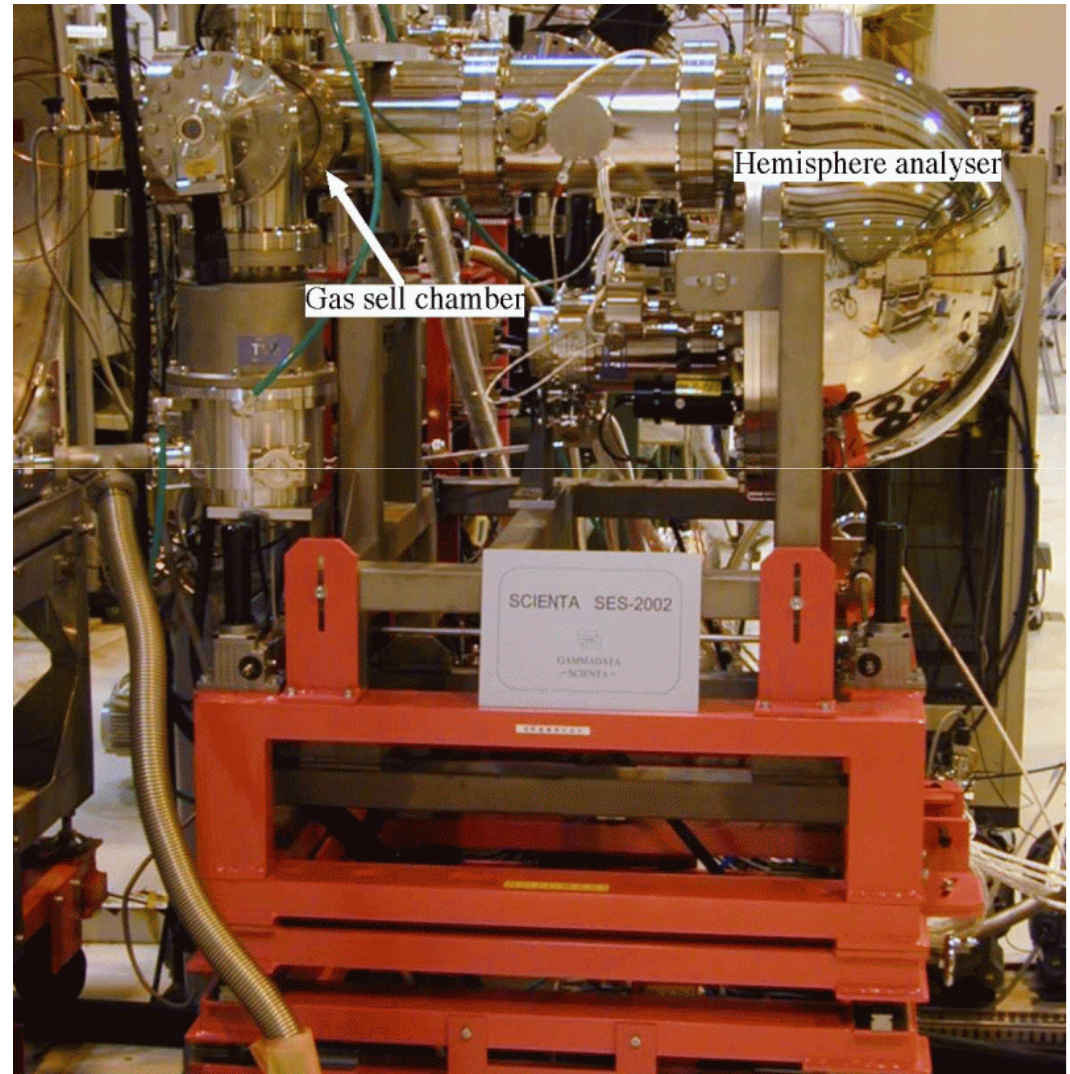
SES2002 analyzer

- Electrostatic hemispherical analyzer
 - Mean radius 200 mm
 - $\Delta E/PE=1/1600$
(66 meV at pass 100 eV)
 - **MCP+CCD camera**
or MCP+Delay line anode
 - **Gas cell system**
or Doppler-free molecular beam source

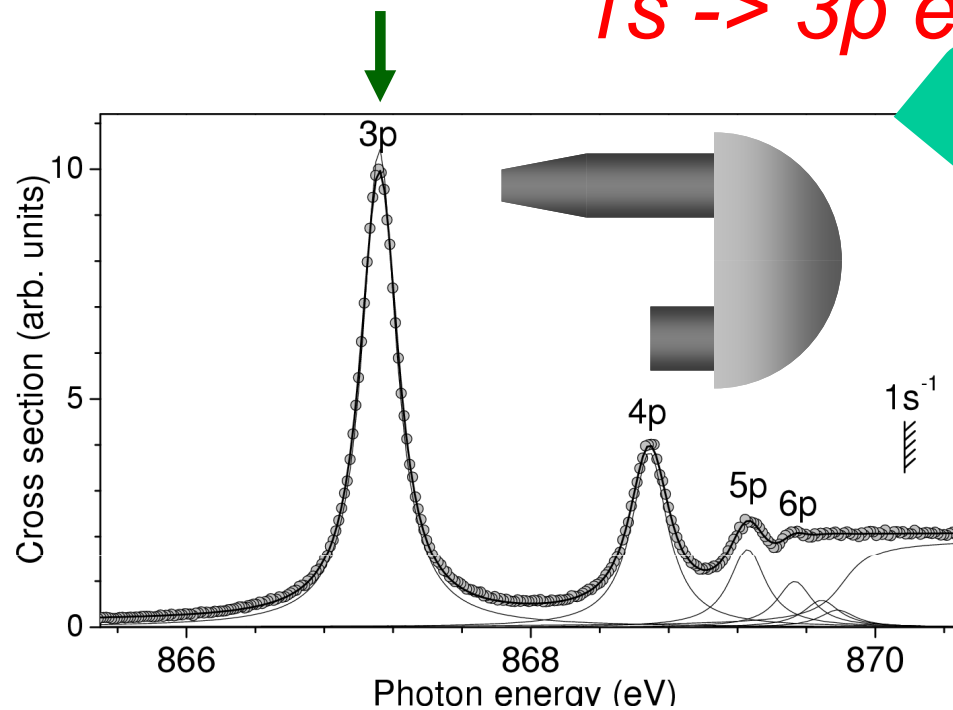
Ueda *et al.* *PRL* . **90**, 153005
(2003)

or effusive beam + momentum
resolved ion spectrometer

Prümper *et al.* *PRA* **71**, 052704,
(2005).



Angle-resolved resonant Auger spectra of Ne at 1s -> 3p excitation

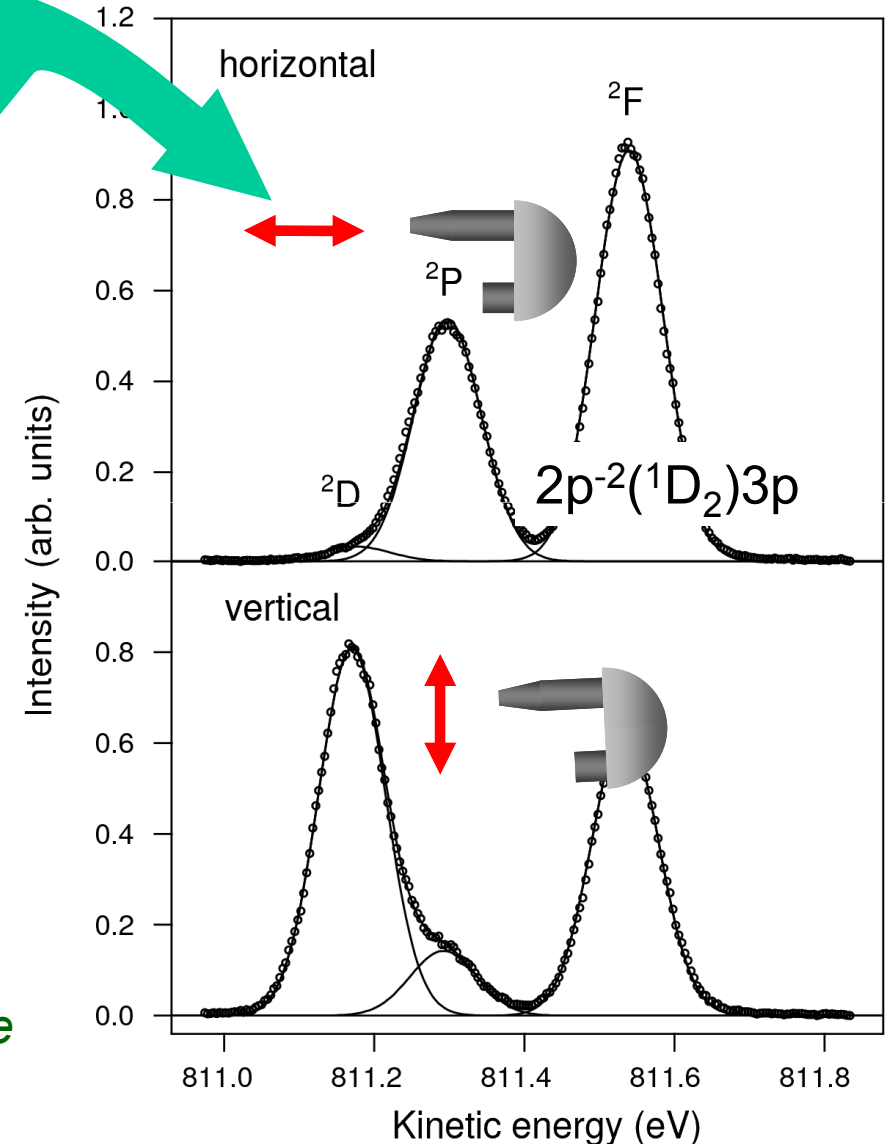


$$\frac{d\sigma}{d\theta} = \frac{\sigma}{4\pi} [1 + \beta P_2(\cos \theta)]$$

$$P_2(\cos \theta) = [3 \cos \theta - 1] / 2$$

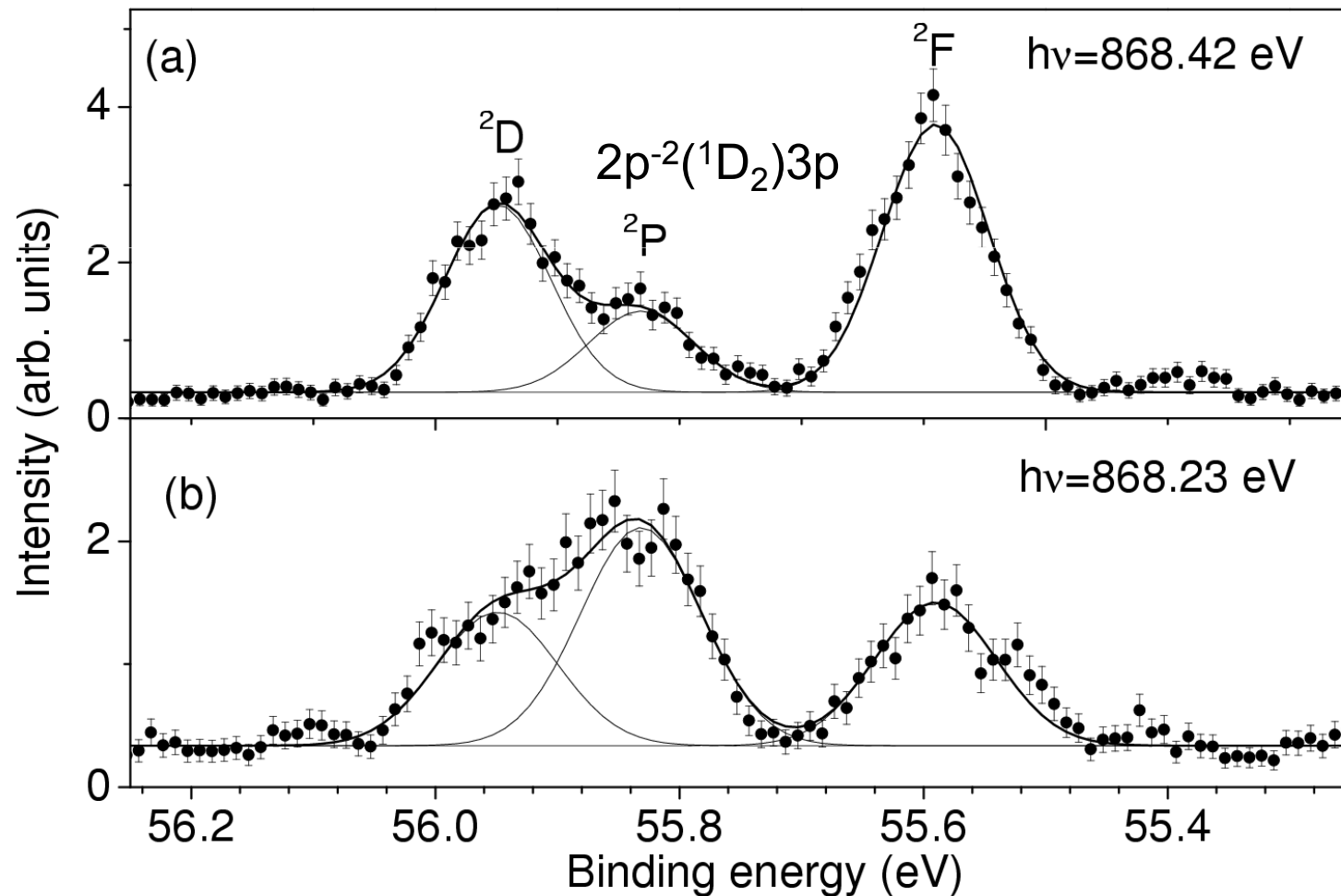
β : asymmetry parameter

Measured angular distributions tell us how the angular momenta are coupled in the atom, allowing us the spectroscopic assignment!



Resonant Auger spectra of Ne “between” 1s -> 3p and 1s -> 4p excitations

$$\frac{d\sigma}{d\theta} = \frac{\sigma}{4\pi} [1 + \beta P_2(\cos \theta)] \quad \sigma \propto I(0) + 2 \times I(90)$$



Interference effects between the two paths

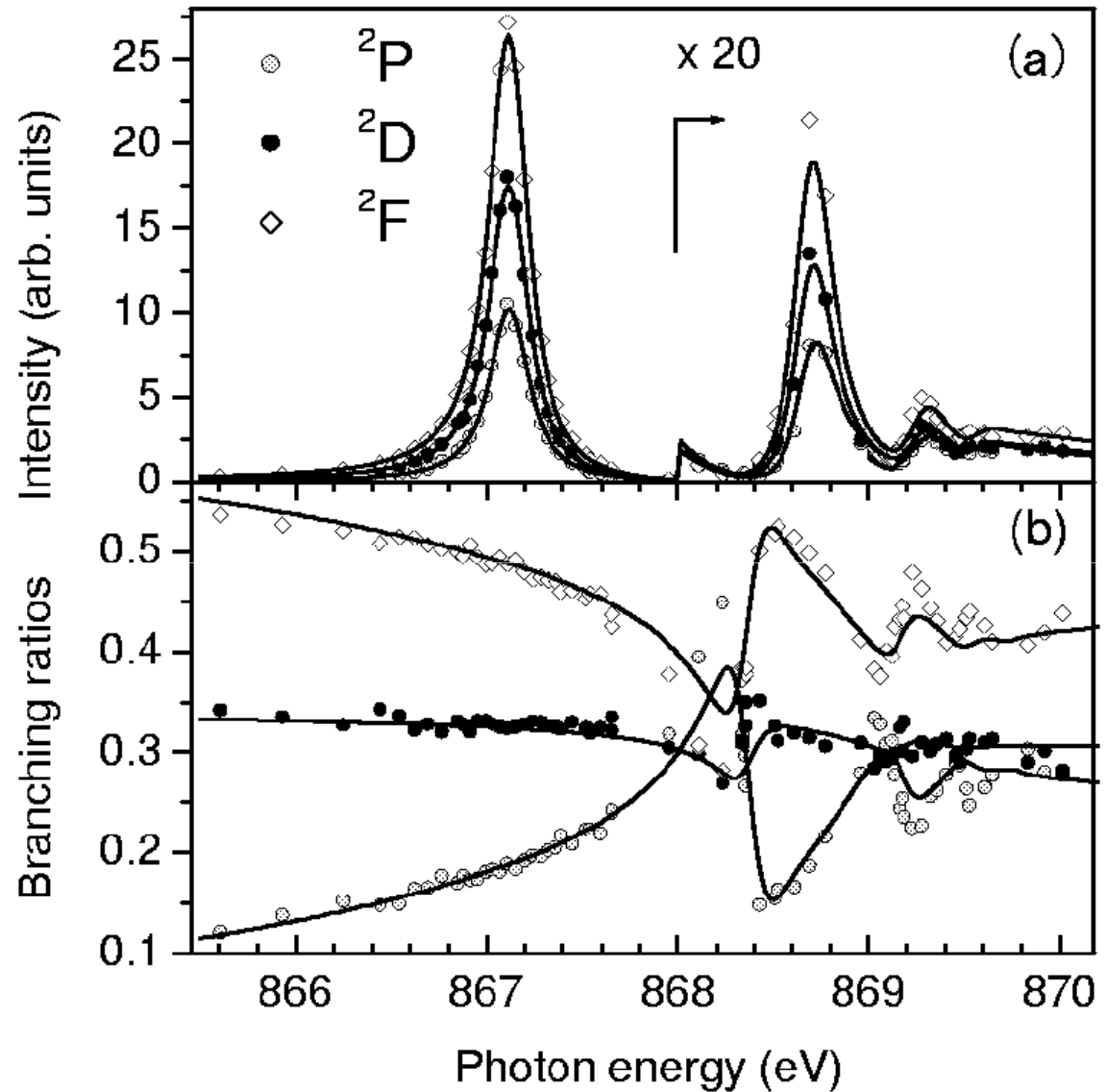
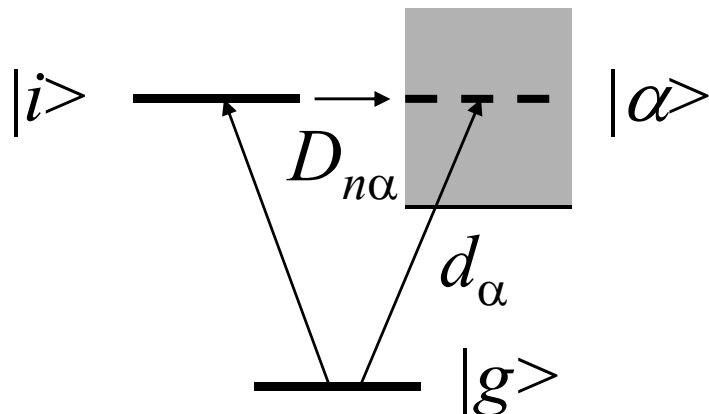
$$A_{\alpha} = d_{\alpha} + \sum_n \frac{D_{n\alpha}}{i + \varepsilon_n}$$

$$\sigma_{\alpha} = |A_{\alpha}|^2$$

$$\varepsilon_n = (h\nu - E_n)/(\Gamma_n/2)$$

$$d_{\alpha} = \langle g | r | \alpha \rangle$$

$$D_{n\alpha} = \langle g | r | i_n \rangle \langle i_n | \alpha \rangle$$



De Fanis *et al.* Phys. Rev. Lett. **89**, 023006 (2002).

Sendai City



Jozenji Street



Statue of Load Date



Introduction of molecular world

$$H\Psi(R, r) = E\Psi(R, r) \quad H = T_R + T_r + V(r, R)$$

$$T_R = -\frac{\hbar}{2} \sum_k \frac{\partial^2}{M_k \partial R_k^2} \quad \text{KE of nucleus} \quad T_r = -\frac{\hbar}{2m} \sum_j \frac{\partial^2}{\partial r_j^2} \quad \text{KE of electrons}$$

$$H = H_0 + T_R \quad H_0 = T_r + V(r, R)$$

$$[H_0 - \varepsilon_n(R)]\varphi(R, r) = 0$$

$\varepsilon_n(R)$: adiabatic potential energy

$$\Psi(R, r) = \sum_n \Phi_n(R) \varphi_n(R, r)$$

$$[T_R + \varepsilon_m(R)]\Phi_{mv}^0(R) = E_{mv}^0 \Phi_{mv}^0(R)$$

Nuclear motion is within the adiabatic potential energy surface!

Born-Oppenheimer approximation

Franck-Condon approximation for photoionization

$$\sigma_{iv'}^+(E) \sim \left| \int X_{iv'}^*(R) D_E(R) X_0(R) dR \right|^2$$

$X_{iv'}^*(R), X_0(R)$: Vibrational wavefunctions of ionic iv' and ground 0 states

$$D_E(R) = \int \varphi_E^*(r, R) r \varphi_{\text{core}}(r, R) dr$$

$\varphi_E(r, R), \varphi_{\text{core}}(r, R)$: Electronic wavefunctions of the continuum E and core orbitals

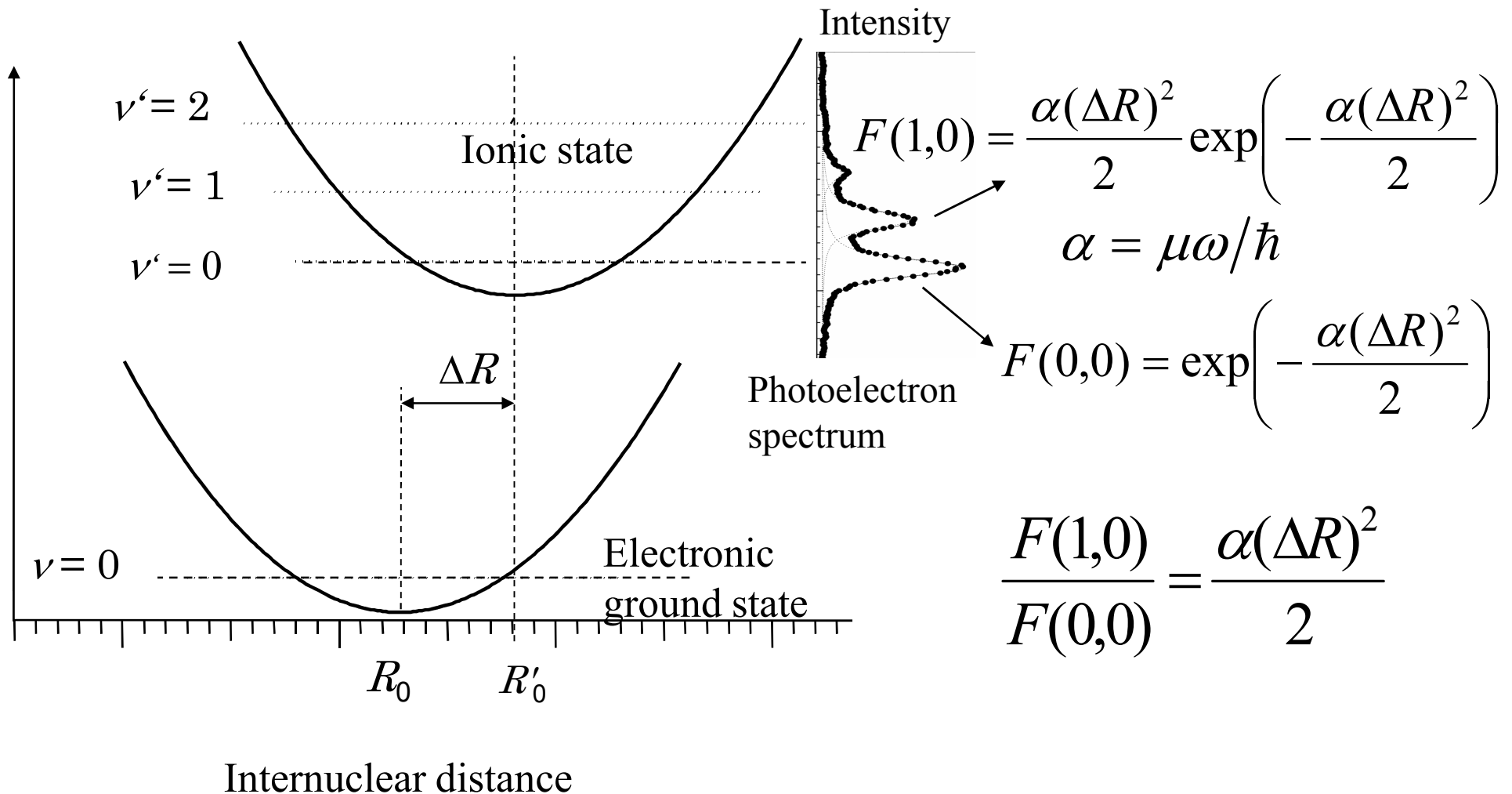
Assume that the dipole moment $D_E(R)$ does not depend on R

$$\sigma_{iv'}^+(E) \sim |D_E(R_e)|^2 F(v'0)$$

$$F(v'0) = \left| \int X_{iv'}^*(R) X_0(R) dR \right|^2 \quad \text{Franck-Condon factor}$$

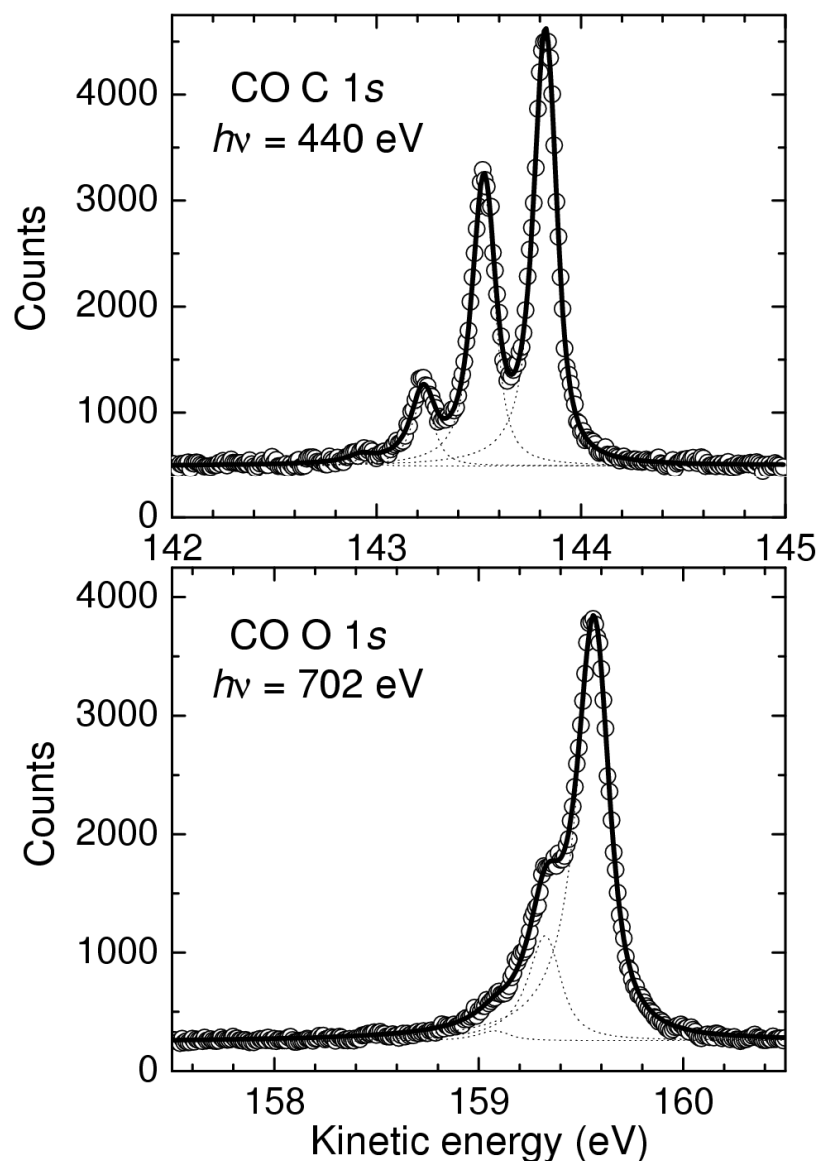
Vibrational intensity distribution in the photoelectron spectrum is determined by the Franck-Condon factors

Franck-Condon analysis based on harmonic approximation
Linear coupling model



One can extract ΔR from photoelectron spectroscopy!

Franck-Condon analysis for the vibrational structure of the C 1s and O 1s mainlines of CO



$$I \sim |\langle \psi_v^+ | \psi_0 \rangle|^2 : \text{FC factor}$$

ψ_0 : v=0 vibrational wave function in the ground state

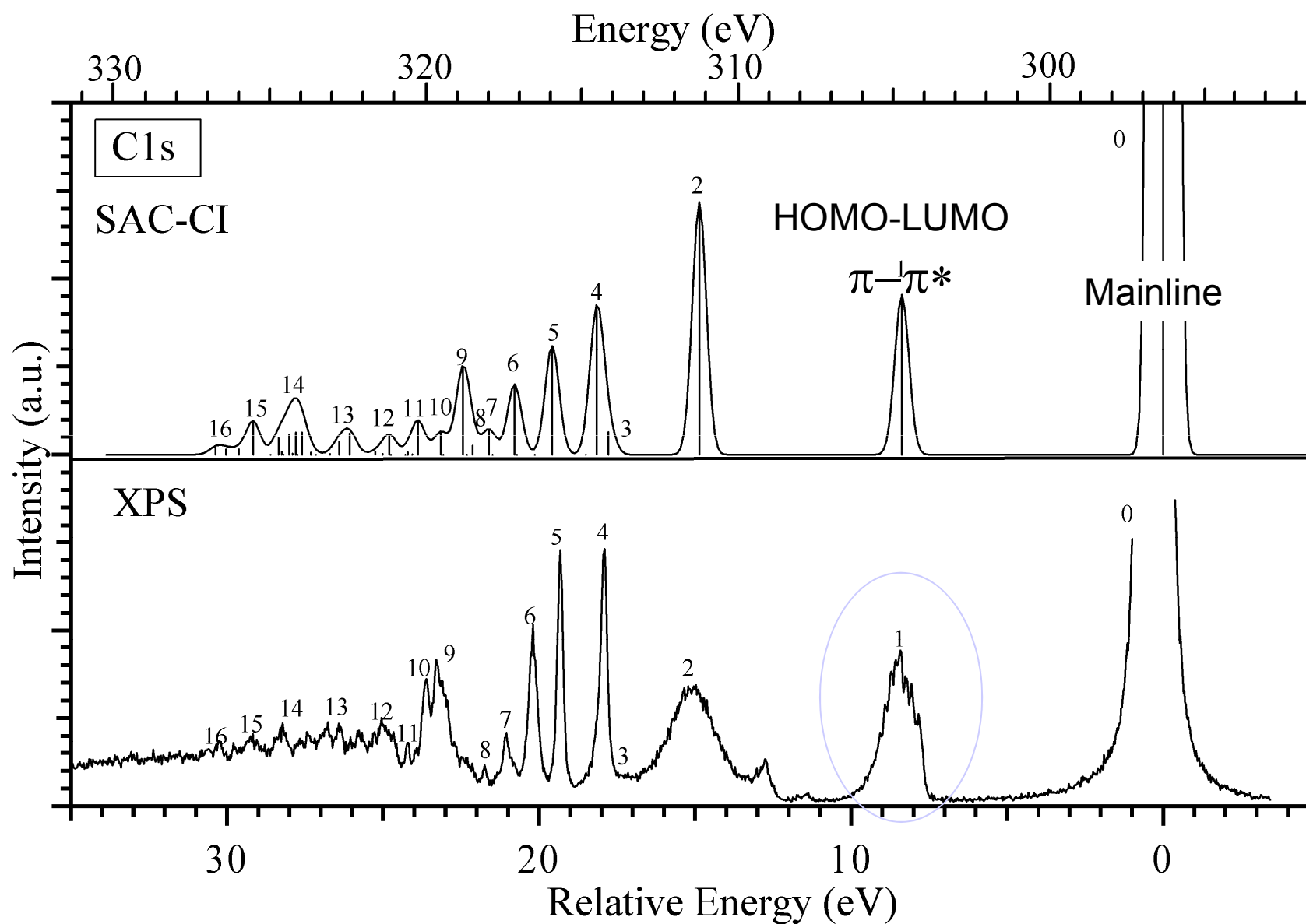
ψ_v^+ : v-th vibrational wave function in the core-ionized state

Stable geometry of the core-ionized state extracted from the vibrational structure

	Exper.	Theory
C 1s ⁻¹		
ΔR_e (Å)	-0.051 (1)	-0.051
O 1s ⁻¹		
ΔR_e (Å)	0.037(2)	0.028

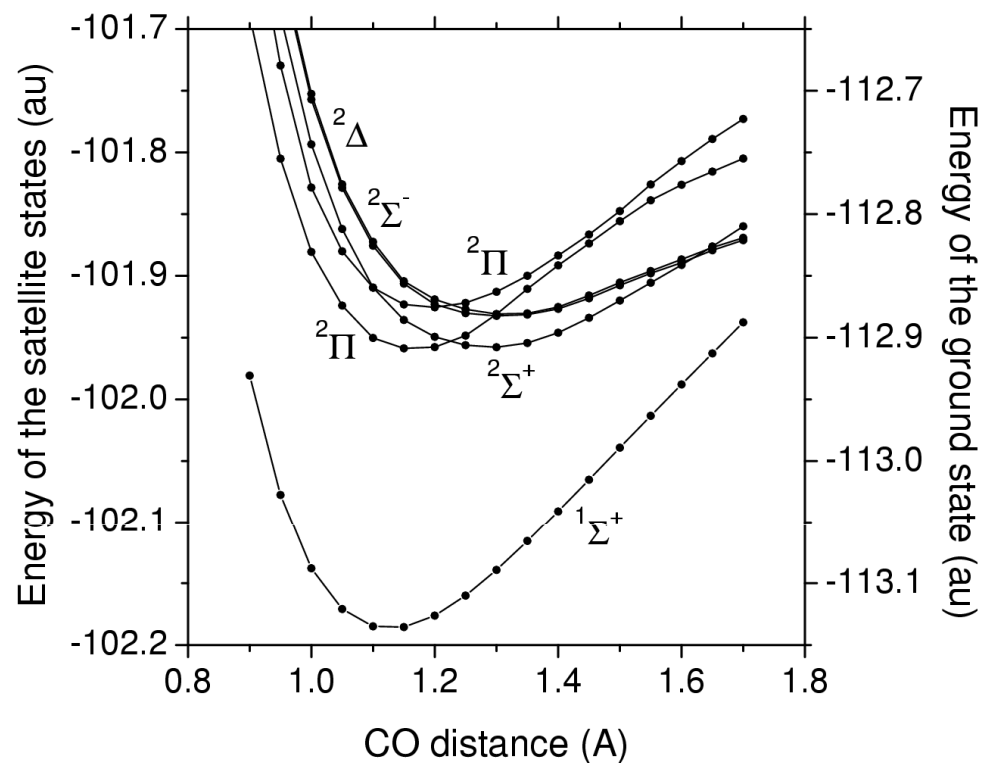
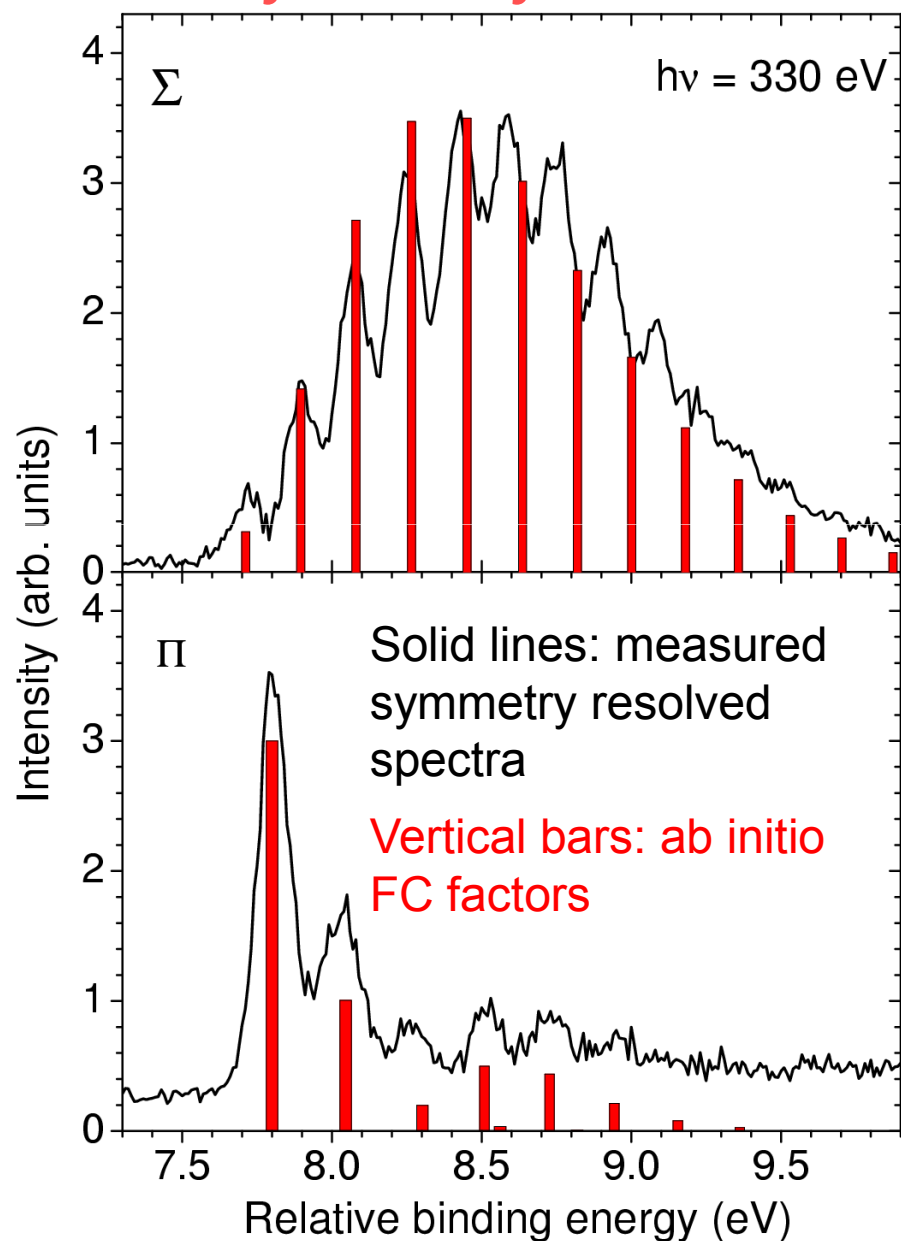
Matsumoto *et al.* Chem. Phys. Lett. **417**, 89-93 (2006).

Satellite spectrum in core-level photoemission in CO



Ehara *et al.* J. Chem. Phys. **125**, 114304 (2006).

Franck-Condon analysis of the vibrational structure in the symmetry-resolved C 1s satellite bands of CO

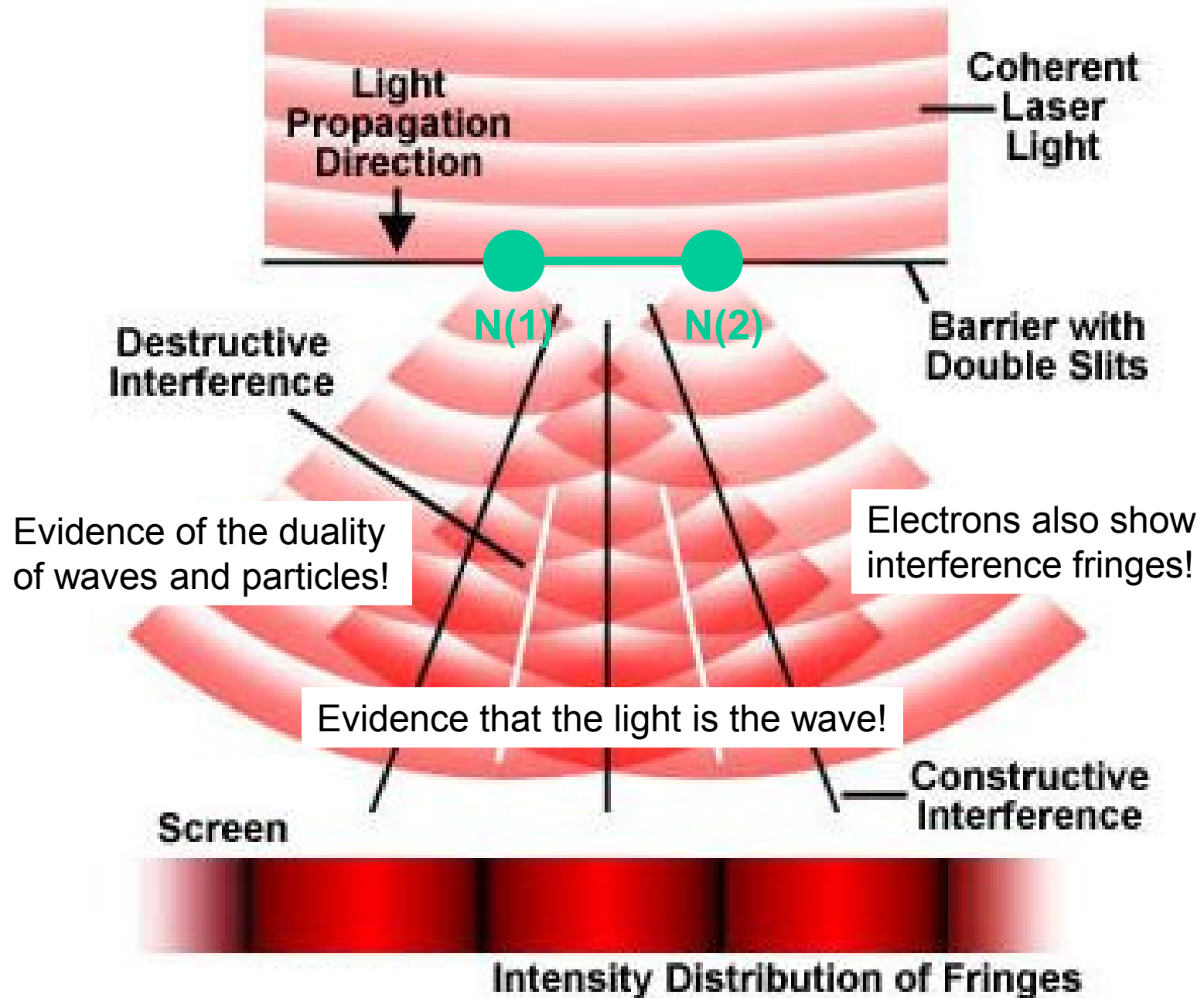


Ab initio potential curves

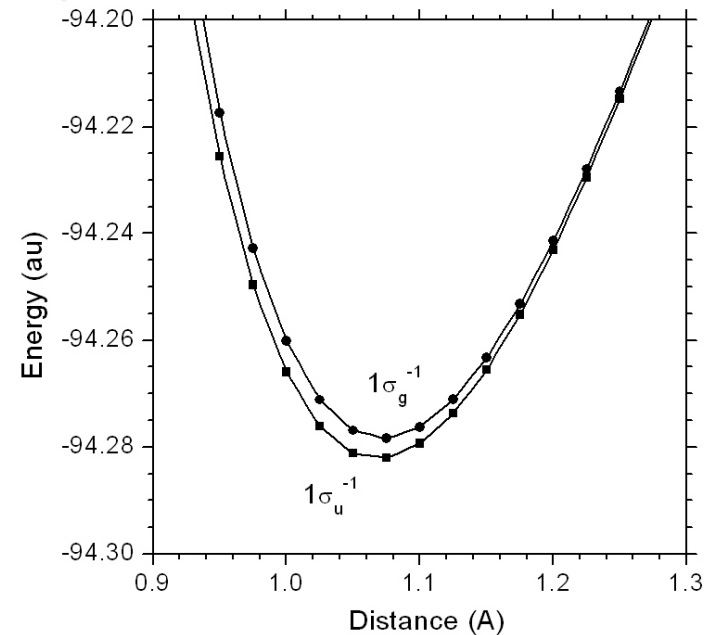
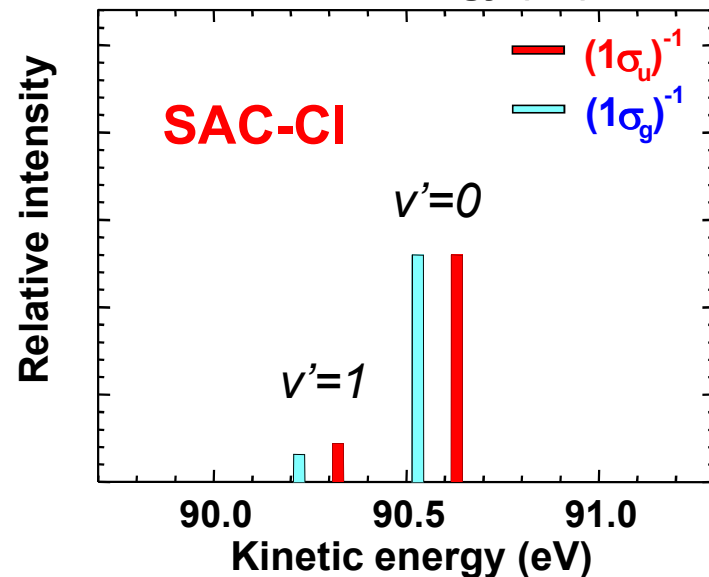
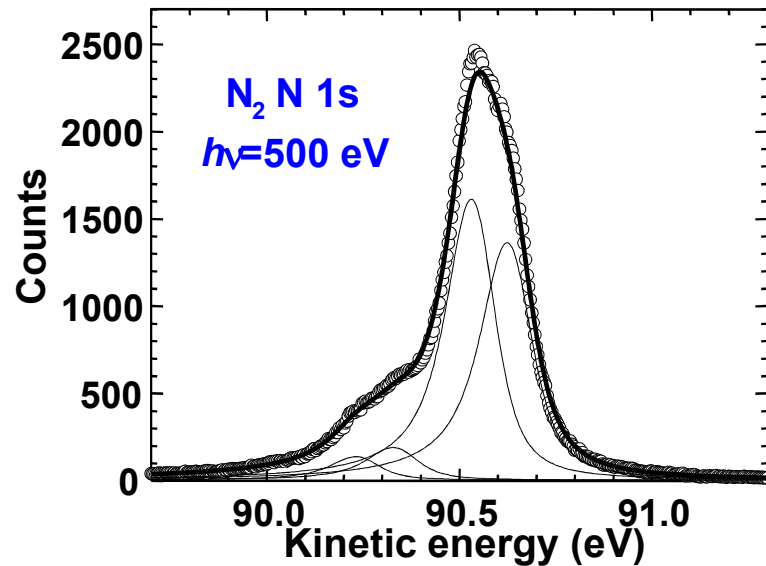
Ab initio FC factors reproduce the measured vibrational distributions.

Ueda *et al.*, Phys. Rev. Lett. **94**, 243004 (2005).

Young's Double Slit Experiment



Franck-Condon analysis for the vibrational structure of the N 1s $1\sigma_u$ and $1\sigma_g$ mainlines of N_2



Equilibrium geometries of the core-ionized states extracted from the vibrational structure

	Exper.	Theory
N $1\sigma_u^{-1}$		
ΔR_e (Å)	-0.023(1)	-0.021
N $1\sigma_g^{-1}$		
ΔR_e (Å)	-0.018(1)	-0.017

Ehara *et al.* JCP **124**, 124311 (2006)

Cohen-Fano two-center interference

Two 1s orbitals in N_2 correspond to Young's double slits.

Molecular core-level orbitals: $1\sigma_{g,u} = \frac{1s_1 \pm 1s_2}{\sqrt{2}}$.

Core-level photoemission from fixed-in-space N_2 :

$$\sigma_{g,u}(\omega) \propto \frac{1}{2} \left| e^{i\mathbf{k} \cdot \mathbf{R}_1} \pm e^{i\mathbf{k} \cdot \mathbf{R}_2} \right|^2 = 1 \pm \cos(\mathbf{k} \cdot \mathbf{R}) ,$$

Two center photoelectron wave *Interference fringe*

where $\mathbf{k}$: photoelectron momentum; $\mathbf{R}_1, \mathbf{R}_2$: position vectors of N (1) and N(2)

$$\mathbf{R} = \mathbf{R}_1 - \mathbf{R}_2.$$

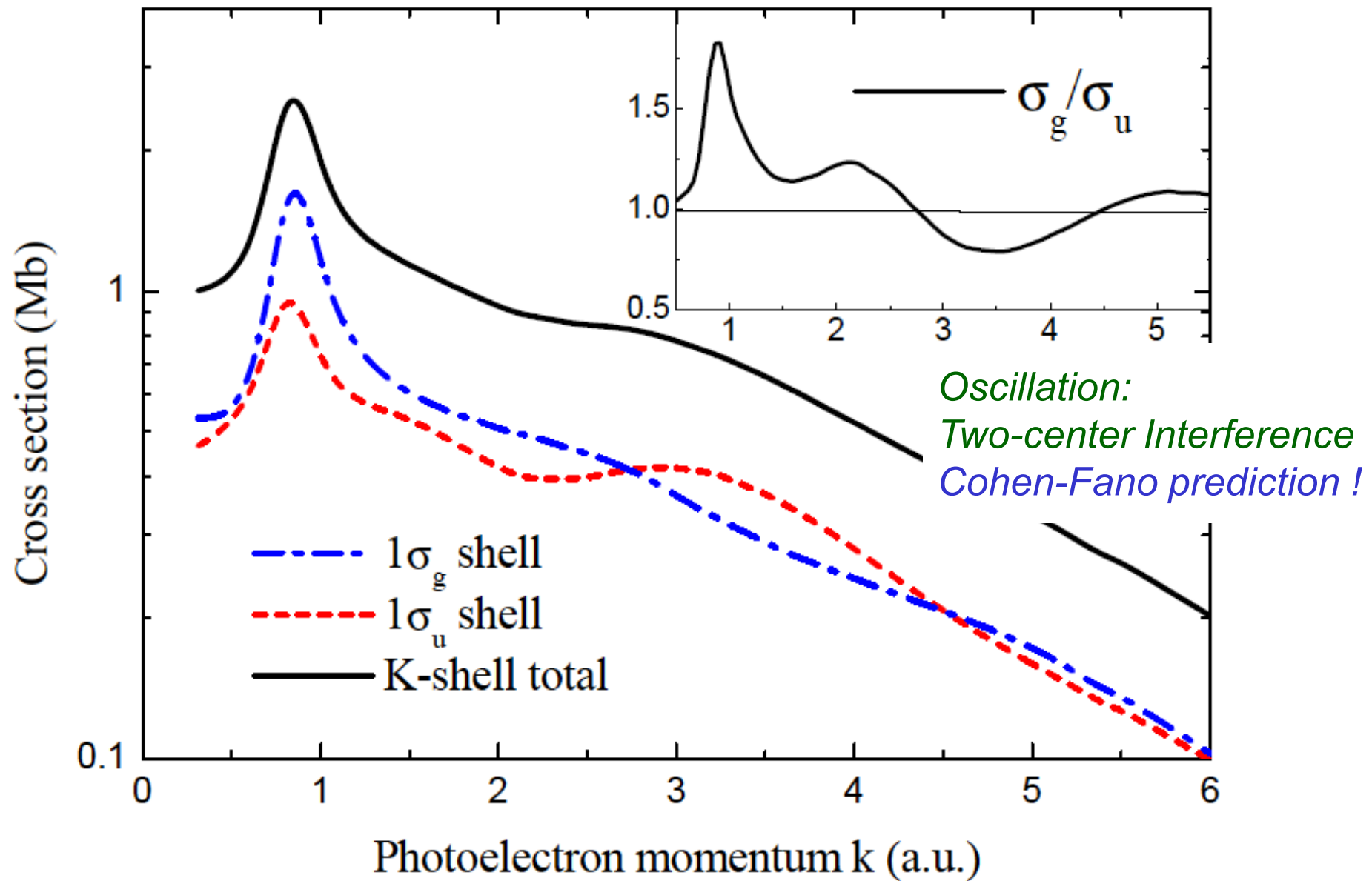
Orientational average: Cohen-Fano formula

$$\sigma_{g,u}(\omega) = \sigma_0(\omega) [1 \pm \chi_{CF}(k)] , \quad \chi_{CF}(k) = \frac{\sin kR}{kR}$$

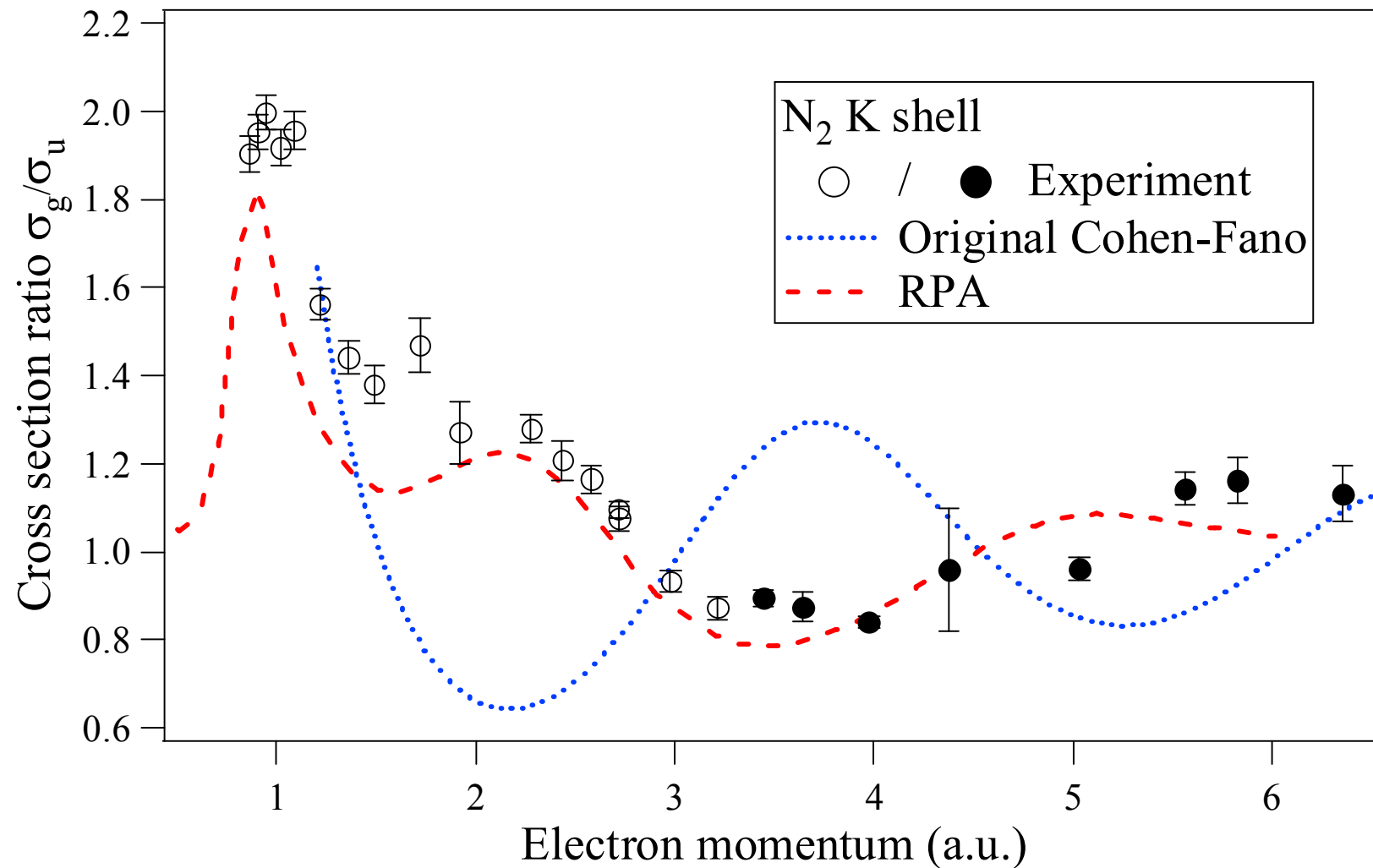
Interference oscillatory structure becomes much smaller but remains!

H.D. Cohen and U. Fano, Phys. Rev. **150**, 30 (1966).

Ab initio N 1s $1\sigma_u$ and $1\sigma_g$ photoionization cross sections of N_2



σ_g/σ_u ratio: experiment vs ab initio and Cohen-Fano



Both experimental and ab initio interference fringes shift from the prediction by Cohen-Fano formula!

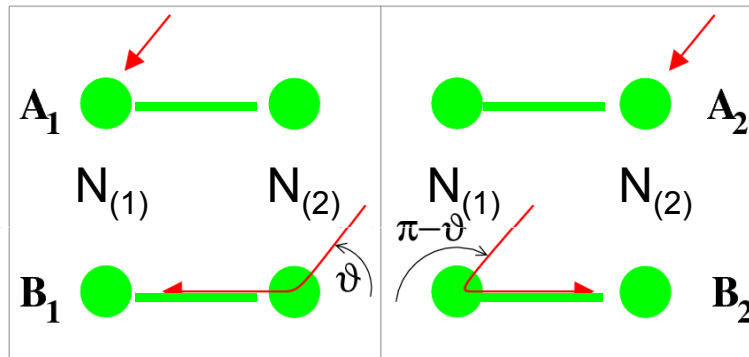
Liu *et al.*, J. Phys. B. **39**, 4801-4817 (2006); JESRP **156-158**, 73-77 (2007).

Photoelectron scattering by the neighboring N atom

The amplitude of the photoelectron wave from one center:

$$\psi_1 = \underbrace{\hat{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{R}_1}}_{A_1} + \underbrace{\hat{\mathbf{R}} \frac{e^{ikR}}{R} f(\vartheta) e^{i\mathbf{k} \cdot \mathbf{R}_2}}_{B_1} . \quad \psi_2 = A_2 + B_2$$

The amplitude of the photoelectron wave from two centers: $\psi_1 \pm \psi_2$



Cohen-Fano interference
A₁A₂ interference term

$$\chi_{\text{CF}}(k) = \frac{\sin kR}{kR}$$

The cross section $\sim |\psi_1 \pm \psi_2|^2 = |(A_1 + B_1) \pm (A_2 + B_2)|^2$

$$\frac{\sigma_{g,u}(\omega)}{\sigma_0(\omega)} = 1 - \frac{1}{kR^2} \text{Im} \left\{ f(\pi) e^{2i[kR + \delta_1(k)]} \right\} \pm \chi(k) ,$$

A₁B₁ and A₂B₂ one-center interference terms

$$\chi(k) = \frac{1}{kR} \sin [kR + 2\delta_1(k)] \quad \delta_1(k): \text{scattering phase}$$

CF A₁A₂ interference term

A₁B₂ and A₂B₁ two-center interference terms !

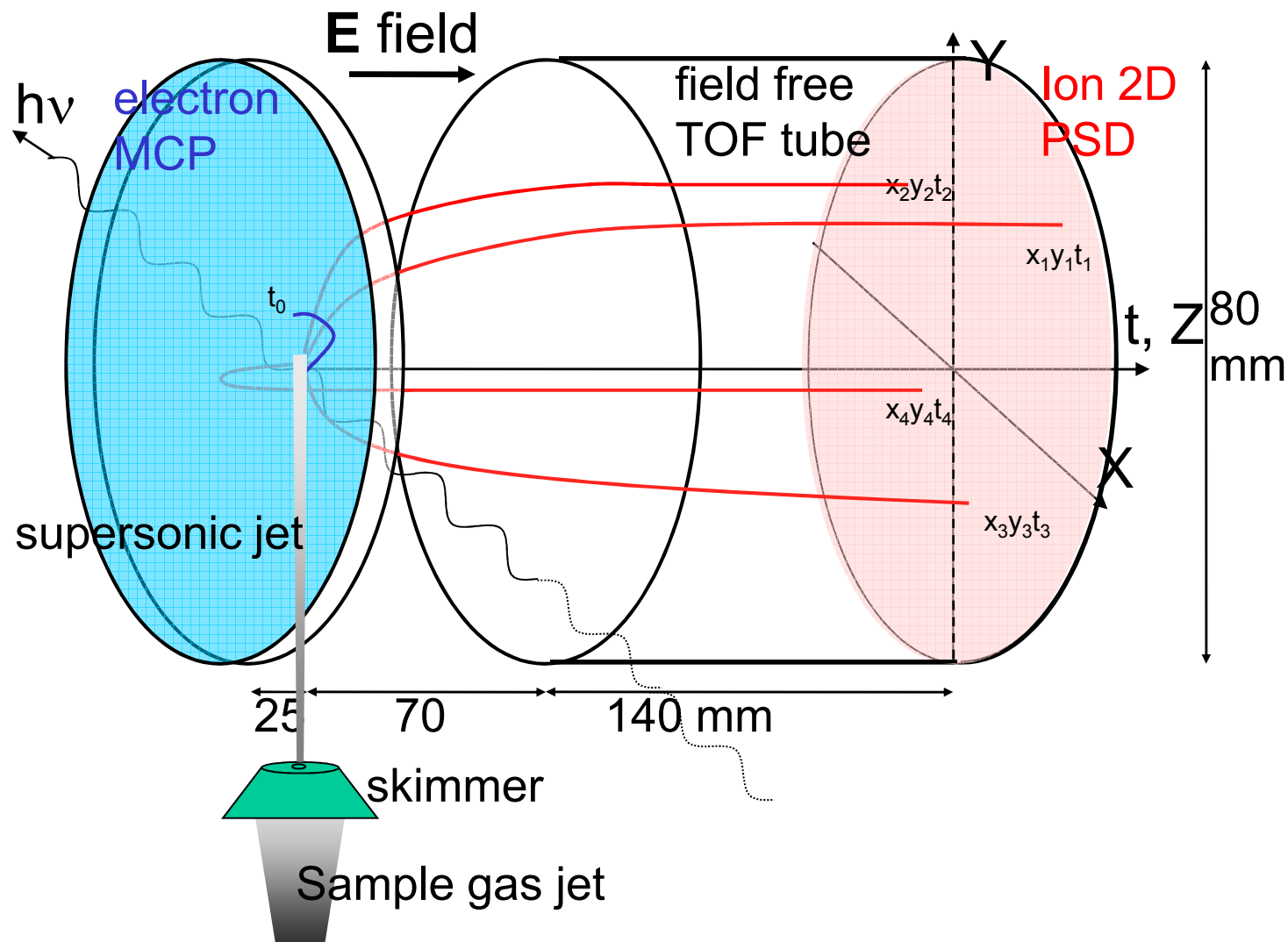


*Sendai
in summer*



Tanabata festival

Multiple-ion coincidence imaging setup



position & time of flight (x,y,t) $\longrightarrow$ *3D momentum of each particle*

How to obtain 3D momentum

$$p_x = \frac{m(x - x_0)}{t}, \quad p_y = \frac{m(y - y_0)}{t}, \quad p_z = qE(t - t_0)$$

t : ion time-of-flight

t_0 : ion TOF at rest

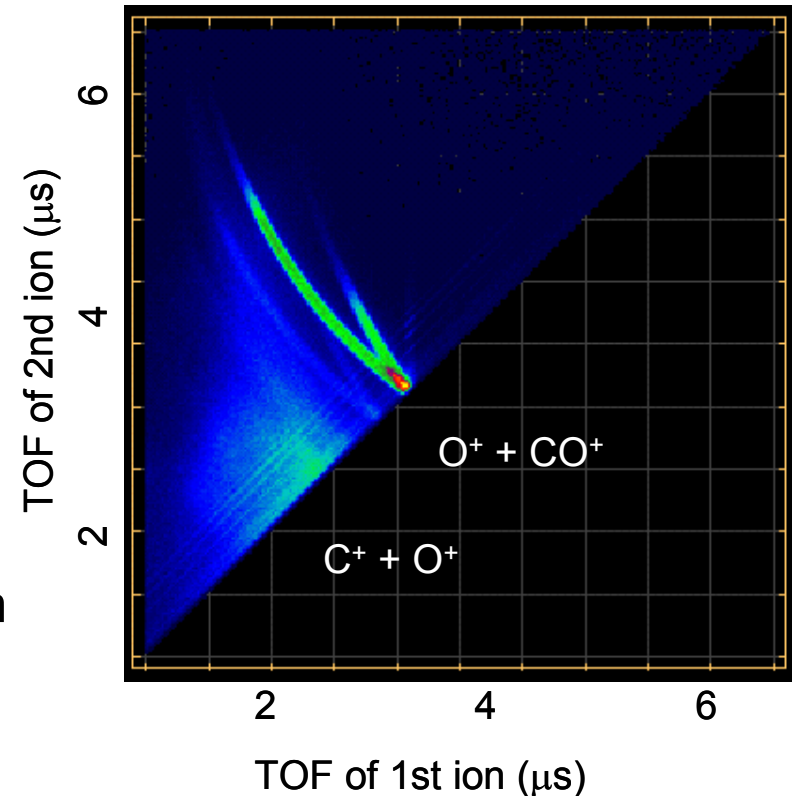
x, y : arrival position on the detector.

x_0, y_0 : initial position of the ion

m : ion mass

q : ion charge

E : electric field in the acceleration region



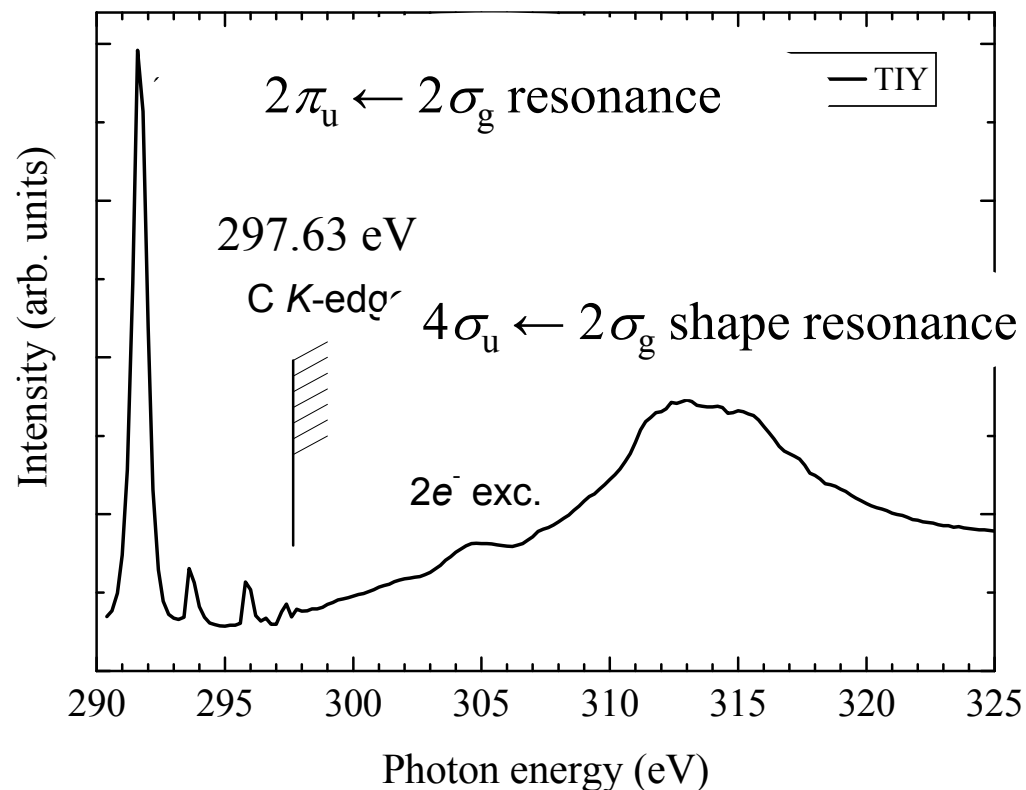
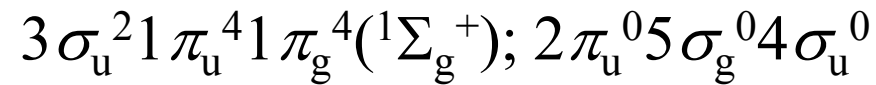
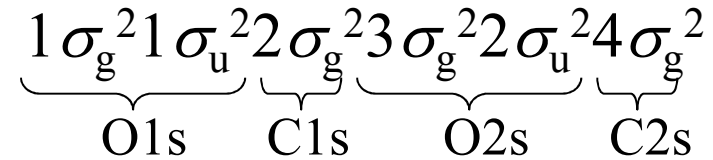
To be exact P_z becomes nonlinear



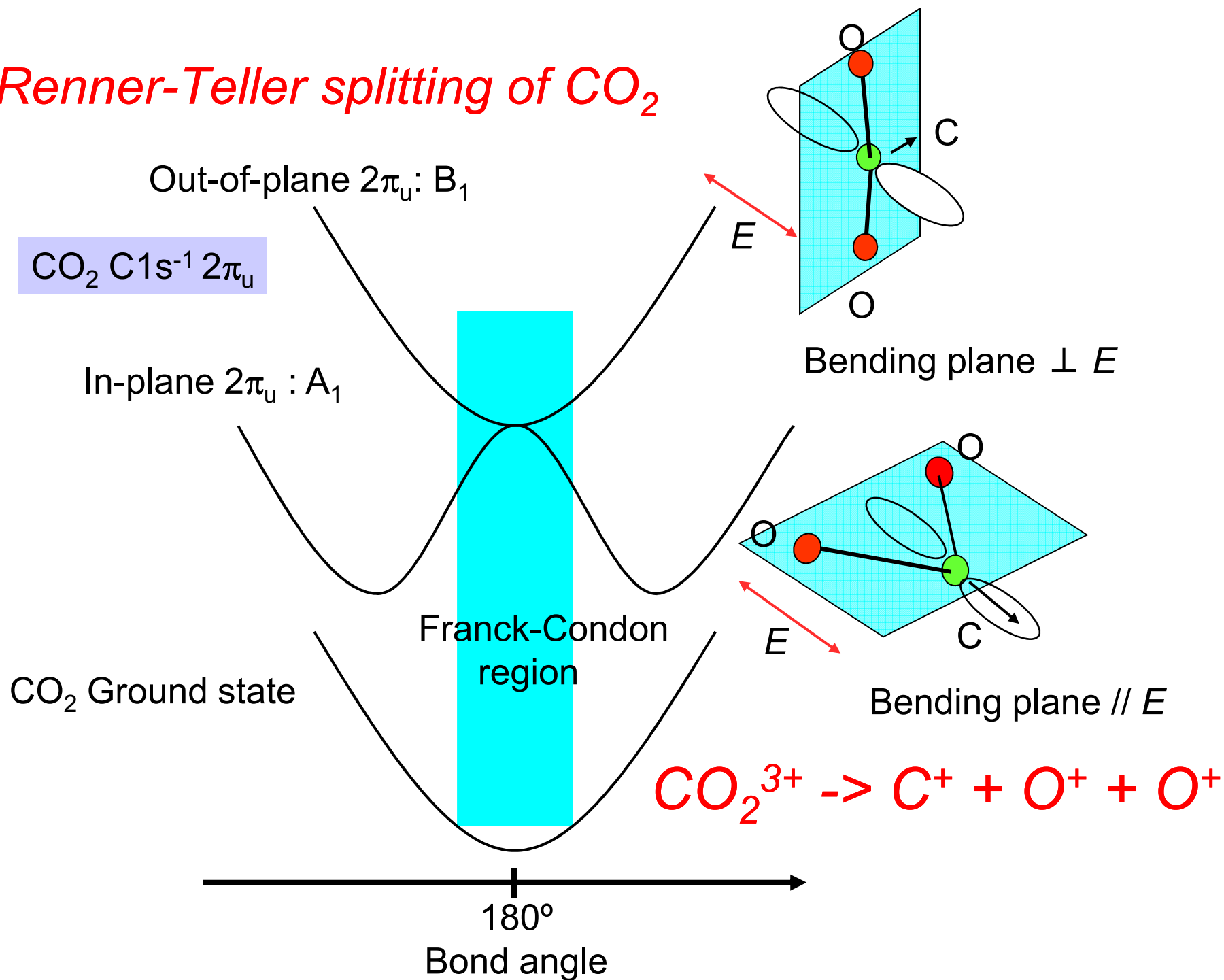
Iterative procedure

Total electron yield spectrum of CO₂ in the C1s ionization region

CO₂ ground state configuration:

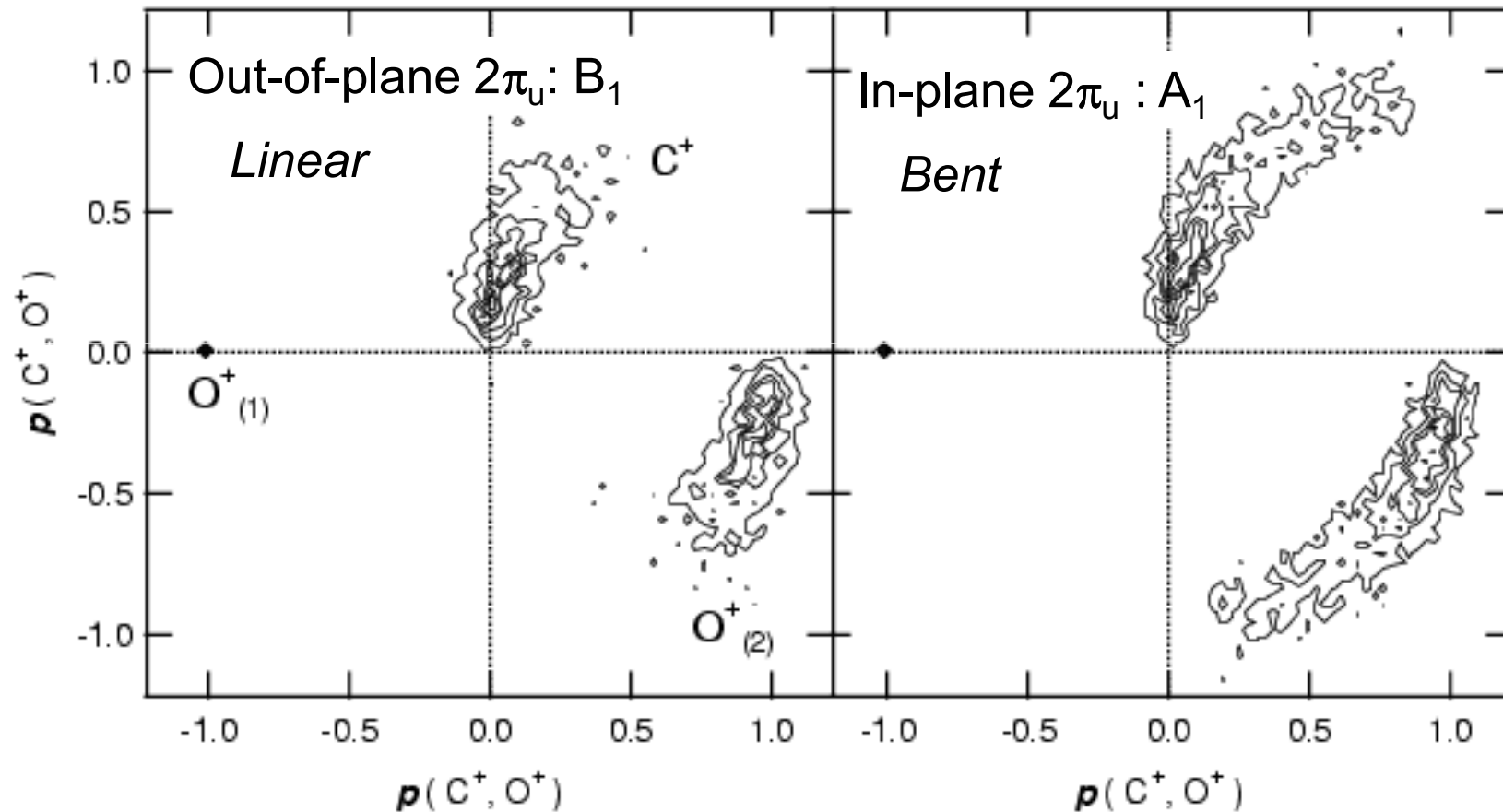


Renner-Teller splitting of CO_2



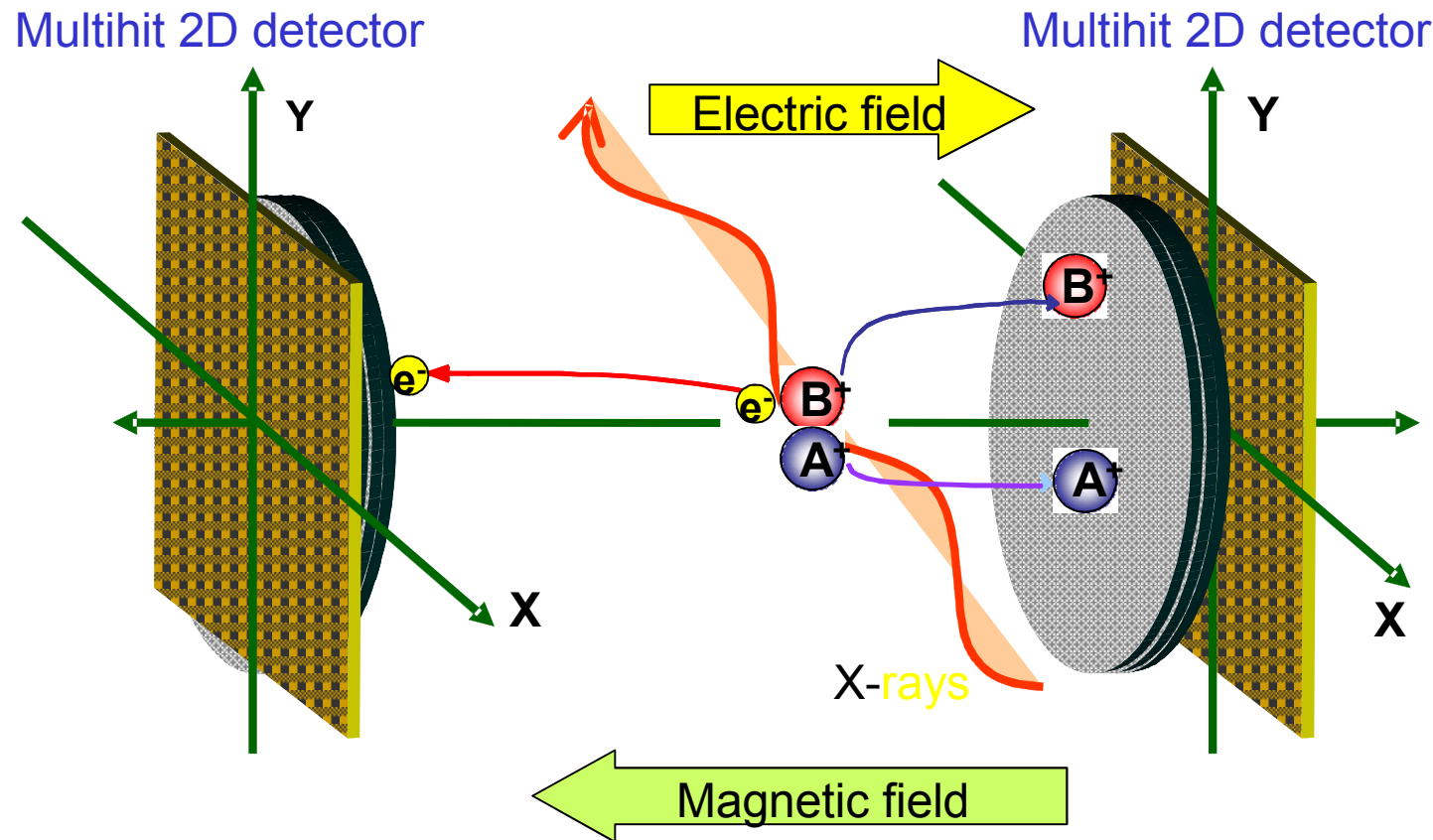
*Snapshot of the bending motion in the core-excited state
with a lifetime ~ 7 fs*

Newton Diagram



Muramatsu et al. Phys. Rev. Lett. 88, 133002 (2002).

Electron-ion coincidence momentum imaging



Ion-ion coincidence

→ *Molecular axis*

Ion momentum conservation

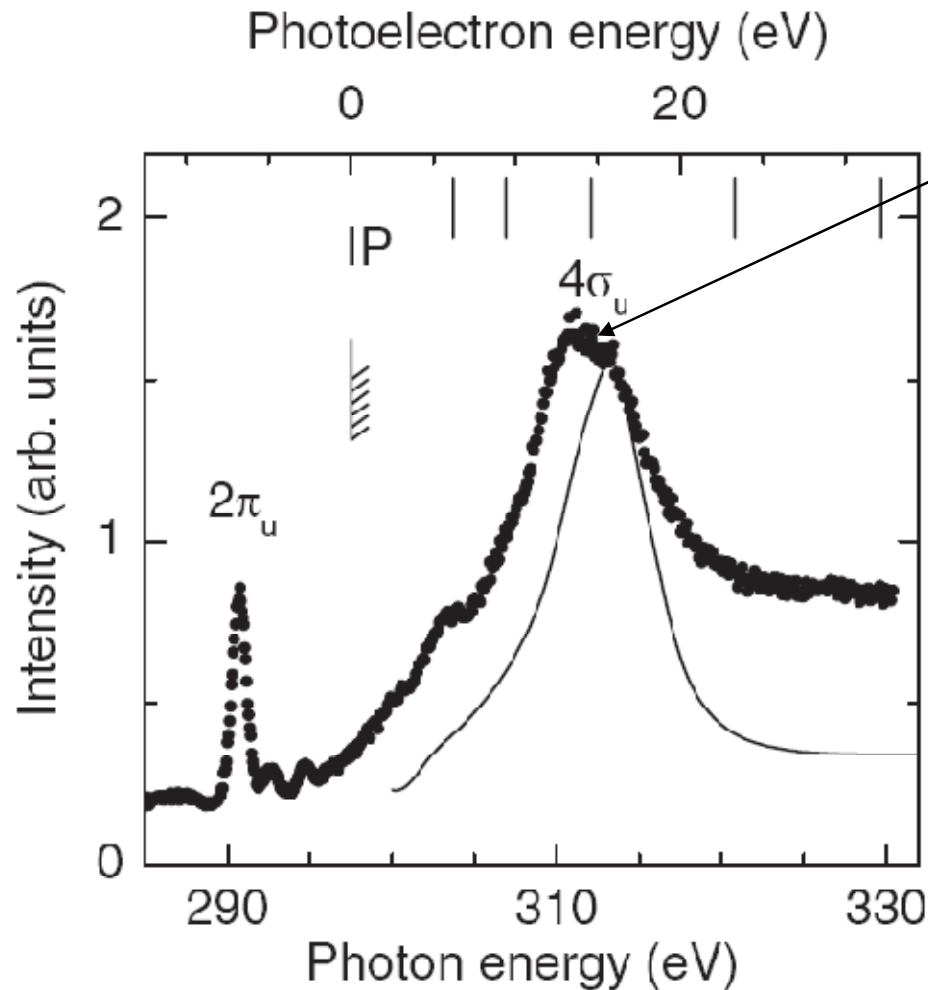
→ *Retrieval of the source point*

Electron-ion-ion coincidence

→ *Molecular-frame e⁻ angular distribution*

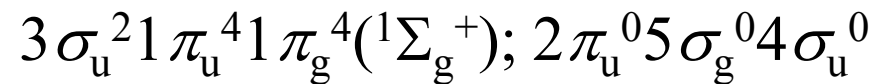
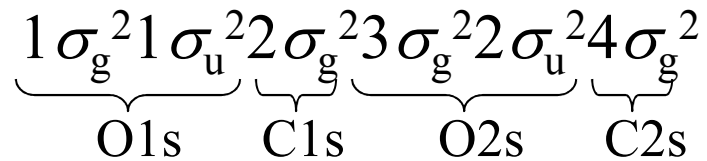
Towards photoelectron diffraction measurement

Total electron yield spectrum of CO₂ in the C1s ionization region



$4\sigma_u \leftarrow 2\sigma_g$ shape resonance

CO₂ ground state configuration:

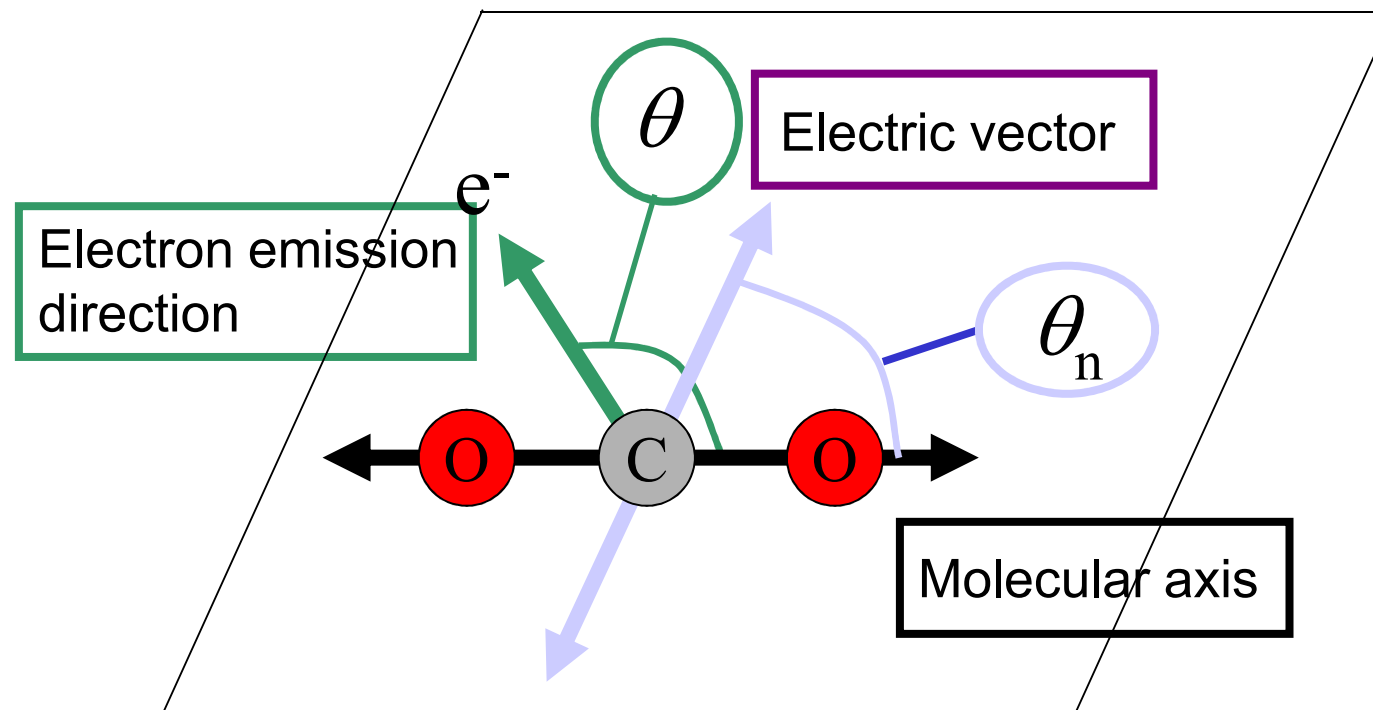


C 1s threshold
297.63 eV

N. Saito *et al.*, J. Phys. B, **36** L25 (2003).

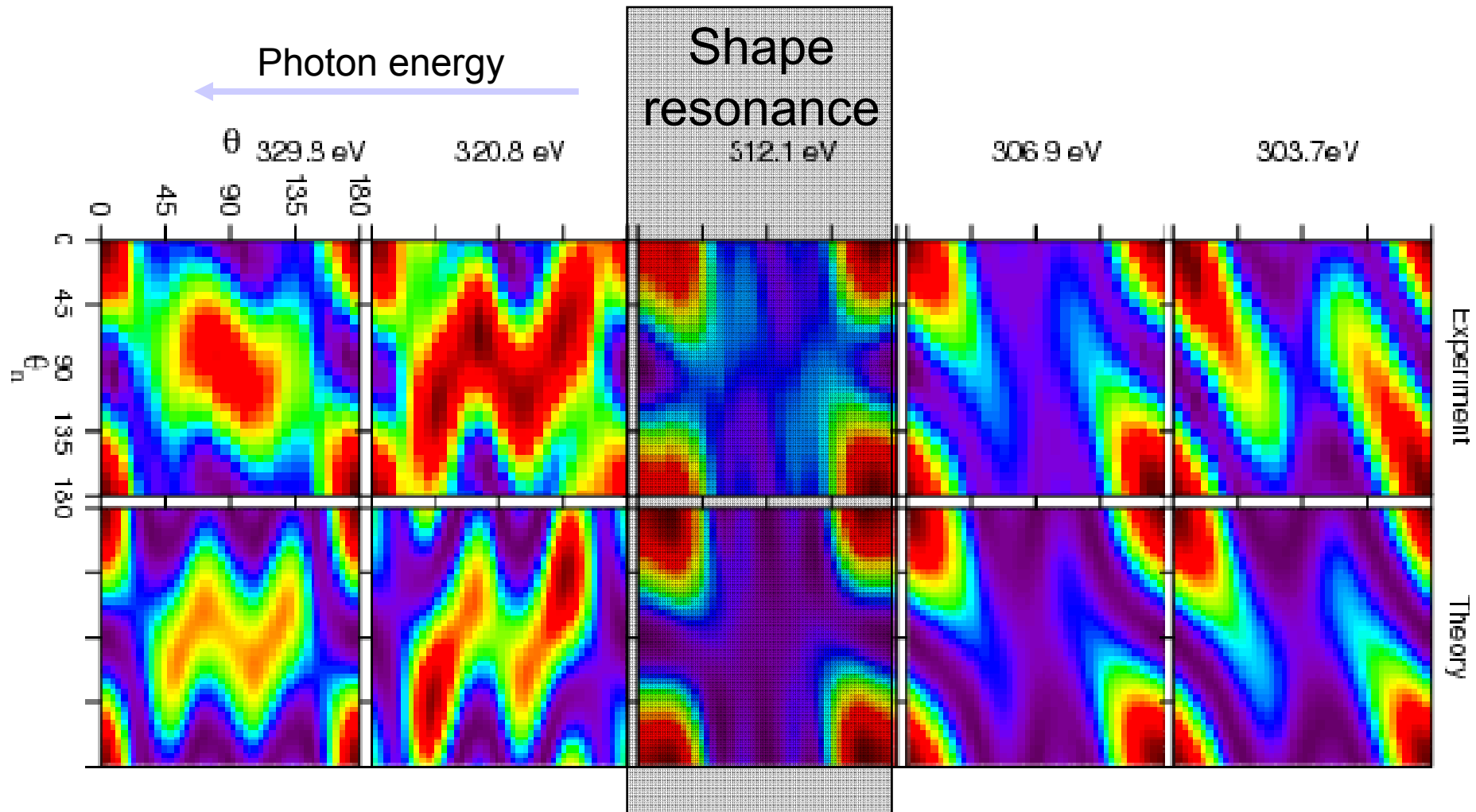
Reaction plane

Reaction plane = plane defined by the E vector and molecular axis



We focus on the electron emission within this reaction plane

MFPADs for C1s emission from CO₂: comparison between experiment and theory

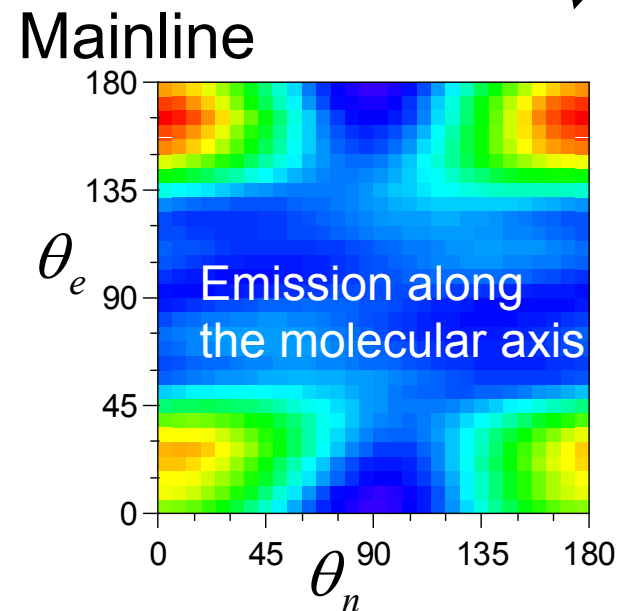
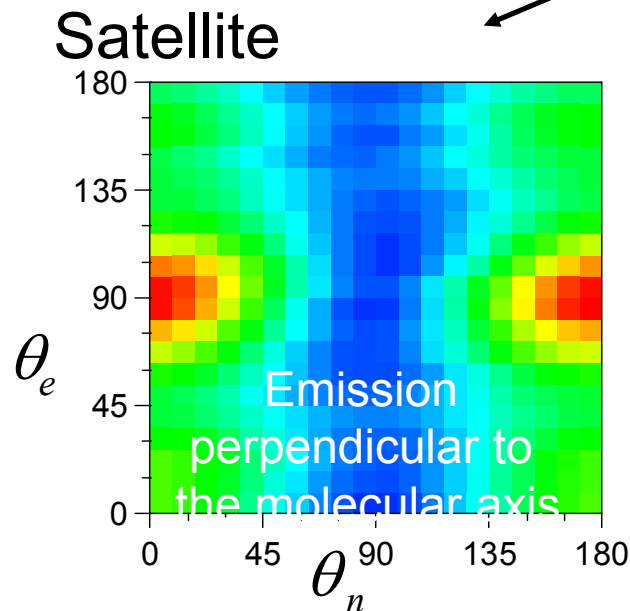
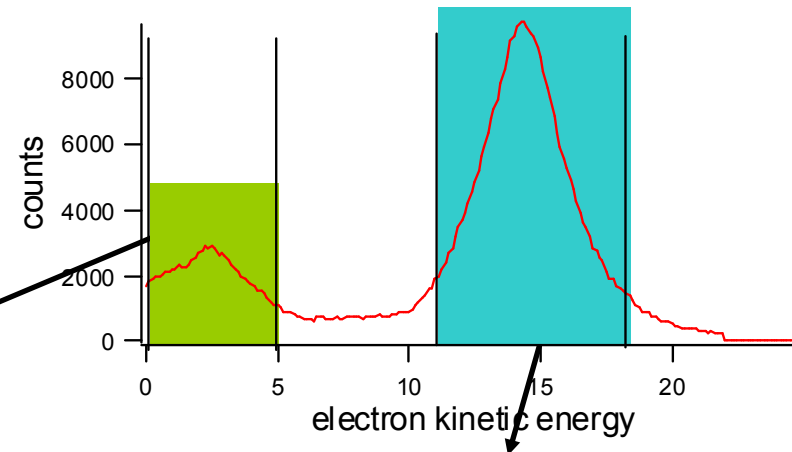
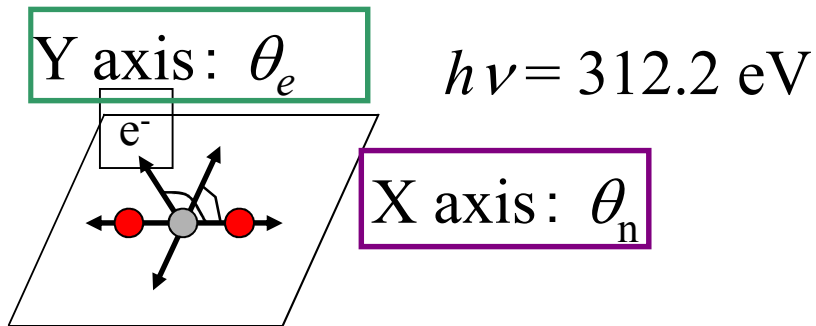


The general agreement between experiment and theory is reasonable.

Liu *et al.* Phys. Rev. Lett. **101**,083001(2008).

Satellite line vs Main line

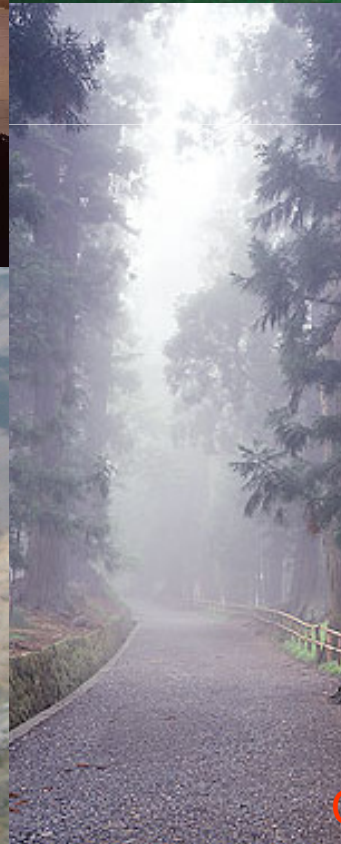
Photoelectron spectrum



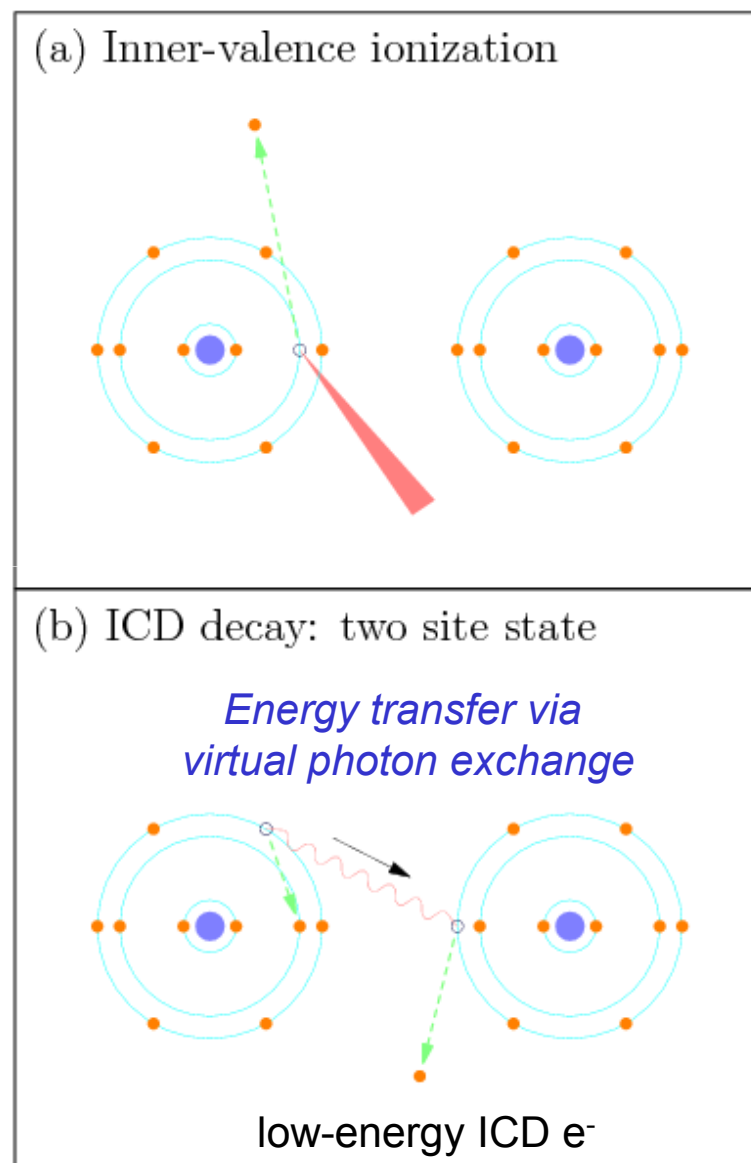
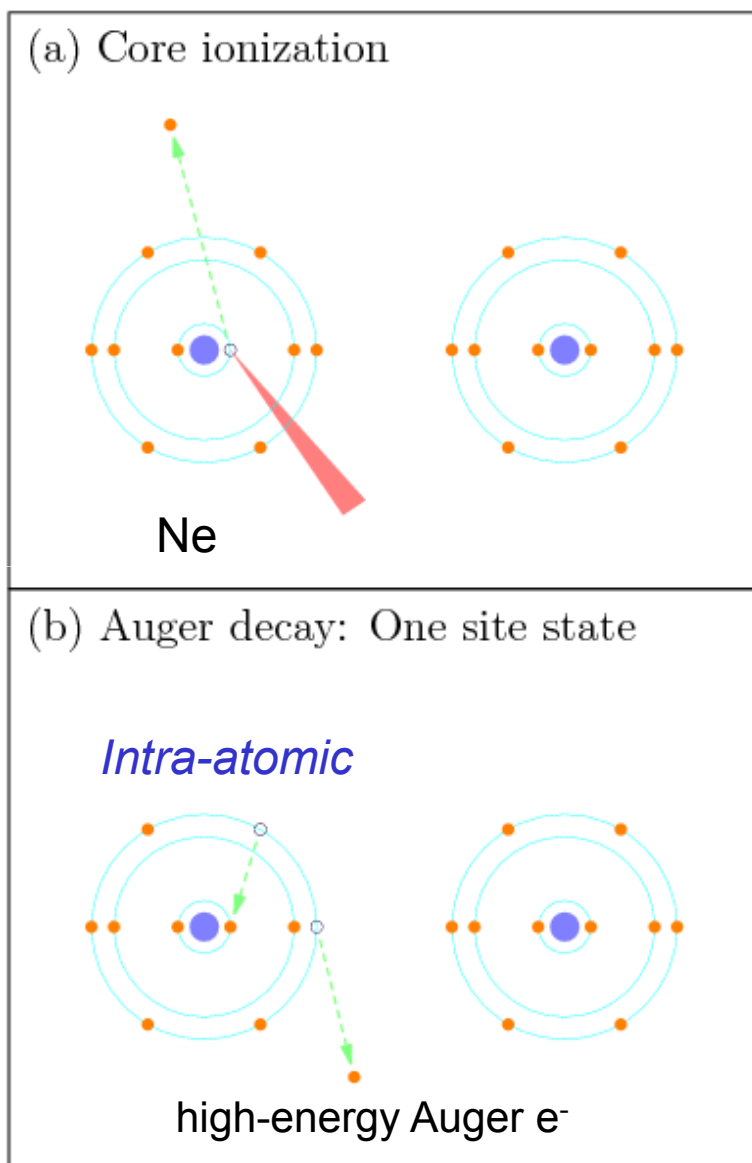
In both cases, the intensity drop at $\theta_n = 90^\circ$ i.e. $\Sigma-\Sigma$ parallel transition. The electron emission directions are completely different.

Liu *et al.* Phys. Rev. Lett. **101**, 023001 (2008).

Near Sendai



Auger vs Interatomic Coulombic Decay (ICD)



ICD rate is R dependent!

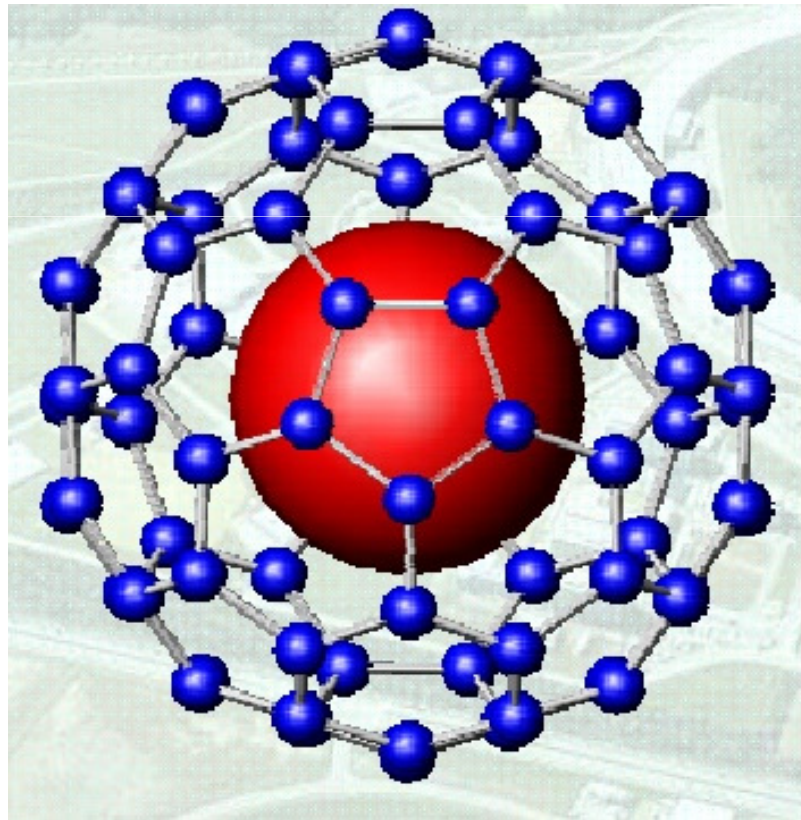
Why is ICD important?

ICD: electronic decay where the environment plays a role!

ICD takes place in van der Waals clusters, in hydrogen bonding clusters, in metallofullerenes, in bio-molecules in the living cell, etc

ICD is everywhere!

ICD is one of the key players in energy and charge transfer in these systems.



Metal atom in C_{60}

Interatomic Coulombic Decay (ICD)

Theoretical

First prediction - HF cluster:

L.S. Cederbaum, J. Zobeley, and F. Tarantelli, Phys. Rev. Lett. 79, 4778 (1997).

Prediction - Ne dimer:

R. Santra, J. Zobeley, L.S. Cederbaum *et al.*, Phys. Rev. Lett. 85, 4490 (2000).

Experimental

First observation - Ne cluster:

U. Hergenhahn and coworkers, Phys. Rev. Lett. 90, 203401 (2003).

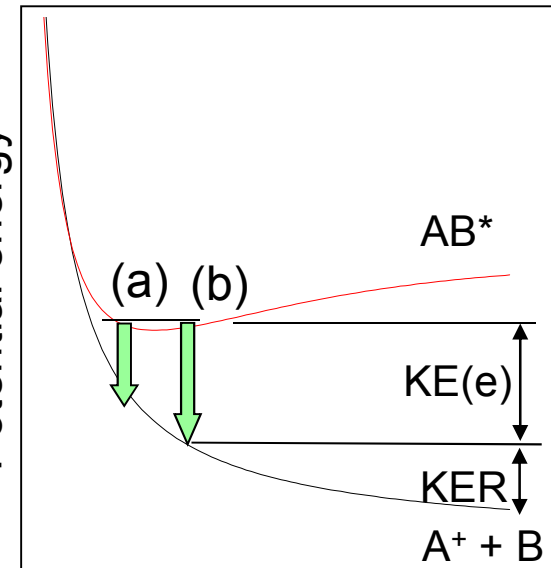
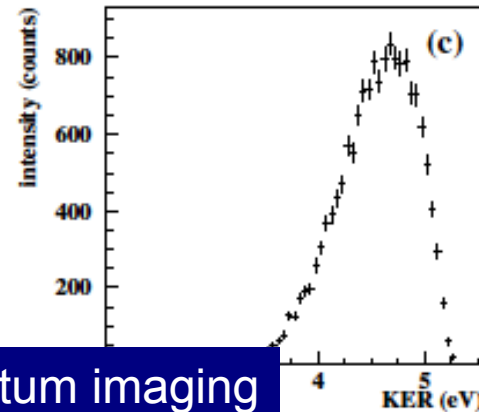
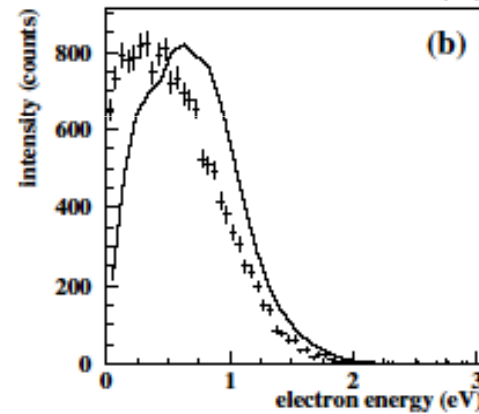
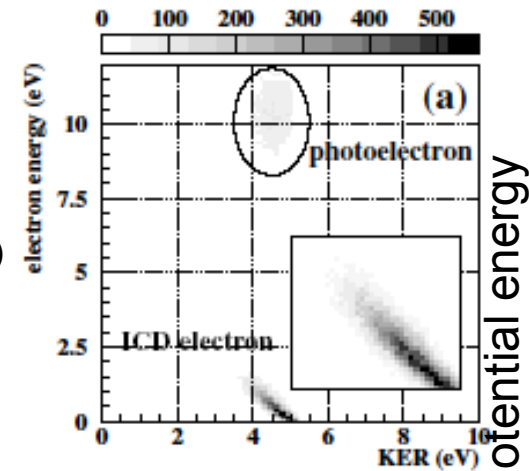
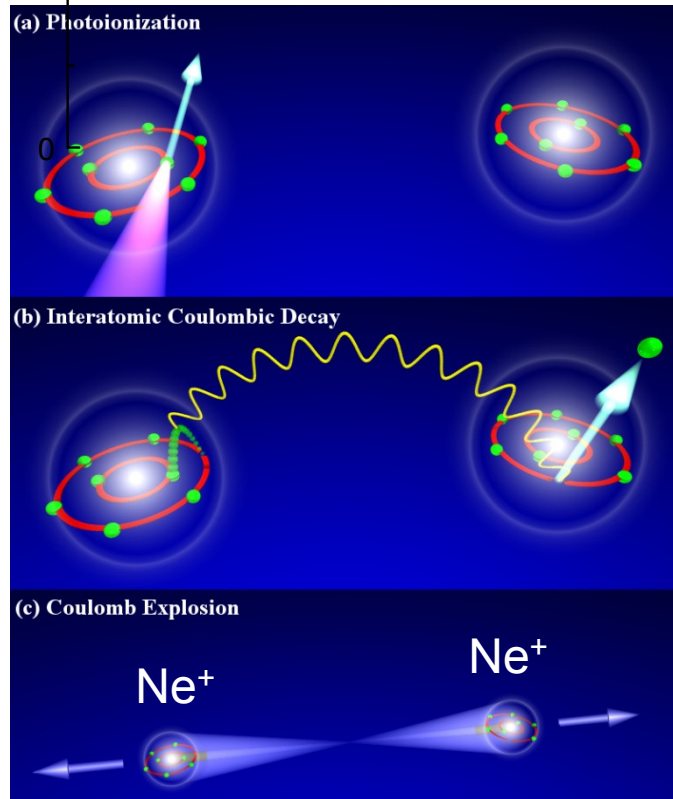
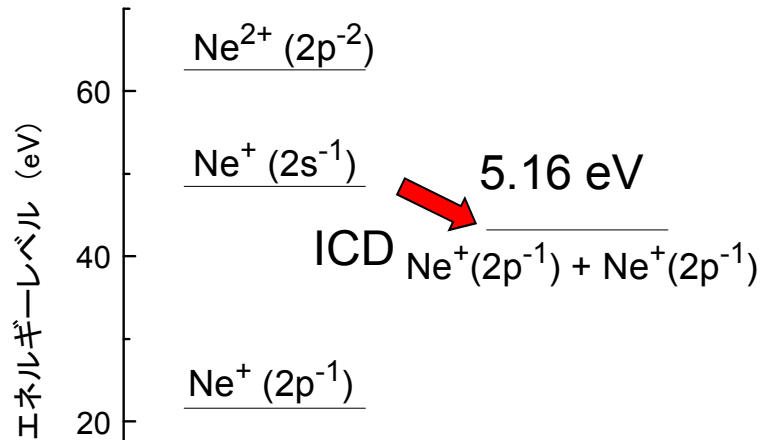
Cluster-size-dependent lifetime:

G. Öhrwall *et al.*, Phys. Rev. Lett. 93, 173401 (2004).

Ne₂ e-ion-ion coincidence:

R. Dörner and coworkers, Phys. Rev. Lett. 93, 163401 (2004).

Observation of ICD in Ne_2 by Frankfurt group



R

$$\text{KE(e)} + \text{KER} = 5.16 \text{ eV}$$



T. Jahnke *et al.*
Phys. Rev. Lett.
93, 163401 (2004)

Electron-ion-ion coincidence momentum imaging

Interatomic Coulombic Decay after Auger decay

Prediction - ICD from Auger final states in Ne dimer:

*R. Santra and L.S. Cederbaum, Phys. Rev. Lett. **90**, 153401 (2003).*

Why is ICD after Auger decay interesting and important?

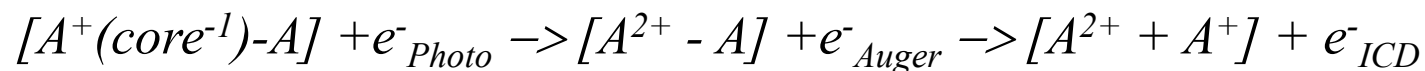
Radiation damage caused in bio-molecules in the living cell

Radiation damage, caused by e.g., X-ray radiation, is initiated by core ionization.

Radiation damage is known to be caused by low energy electron collisions, not high energy Auger electrons.

ICD is one of the important mechanisms to produce low energy electrons after Auger decay!

Labeling electron emission site via the ionic charge state

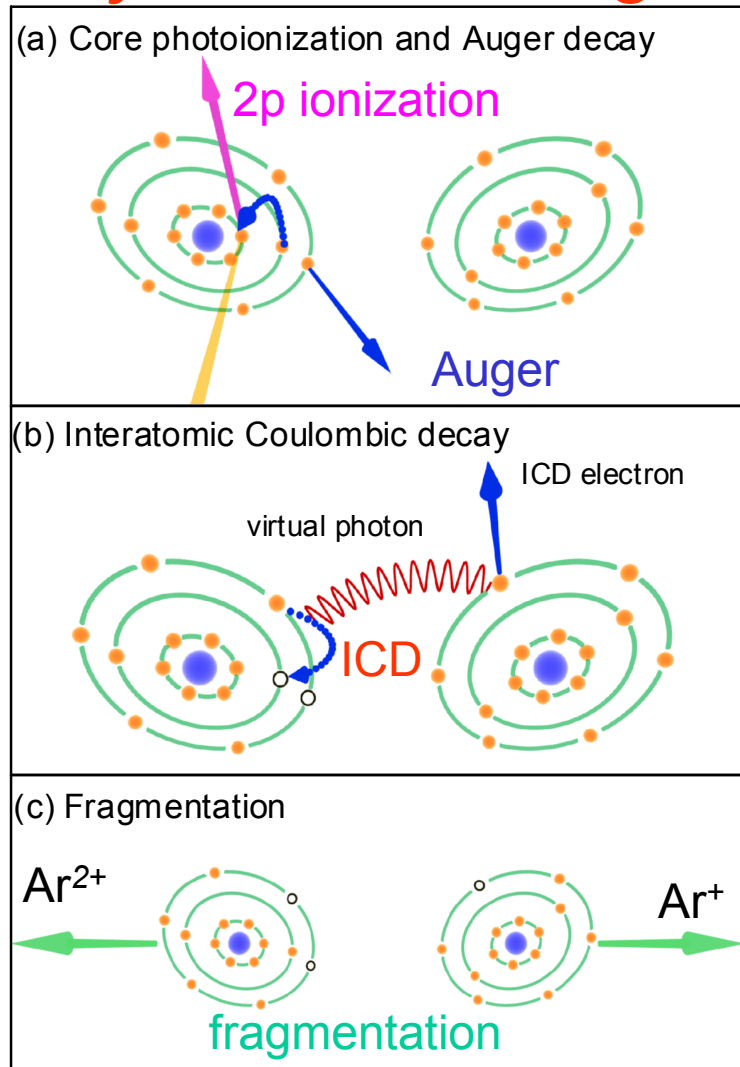


Is the ICD electron ejected from the A^+ site or A^{2+} ?

Can the A^+ or A^{2+} be which-way information of the double slit experiment ?

We can experimentally answer to this very basic question!

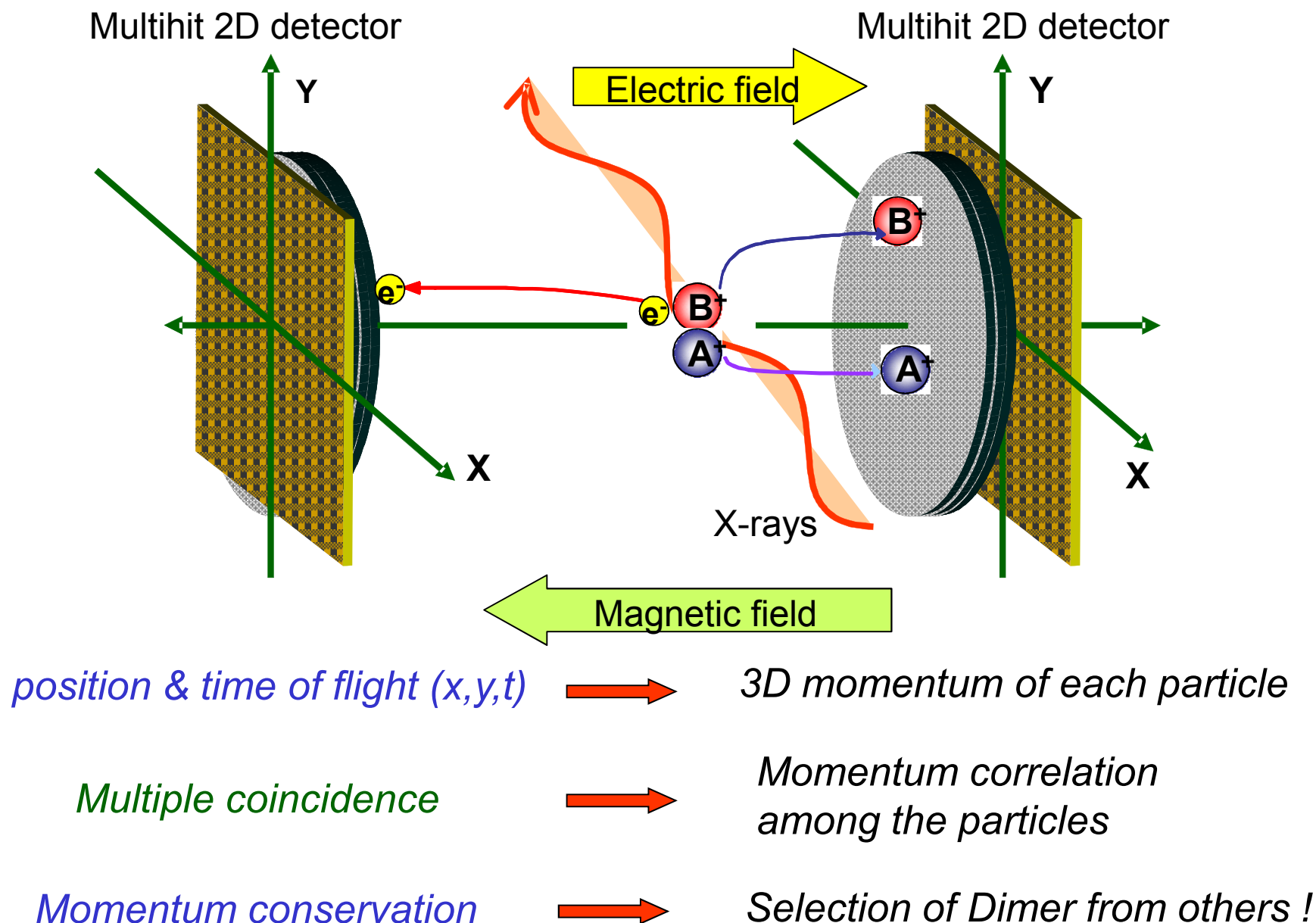
Experimental evidence of interatomic Coulombic decay from the Auger final states in argon dimers



Morishita *et al.* Phys. Rev. Lett. **96**, 243402 (2006).

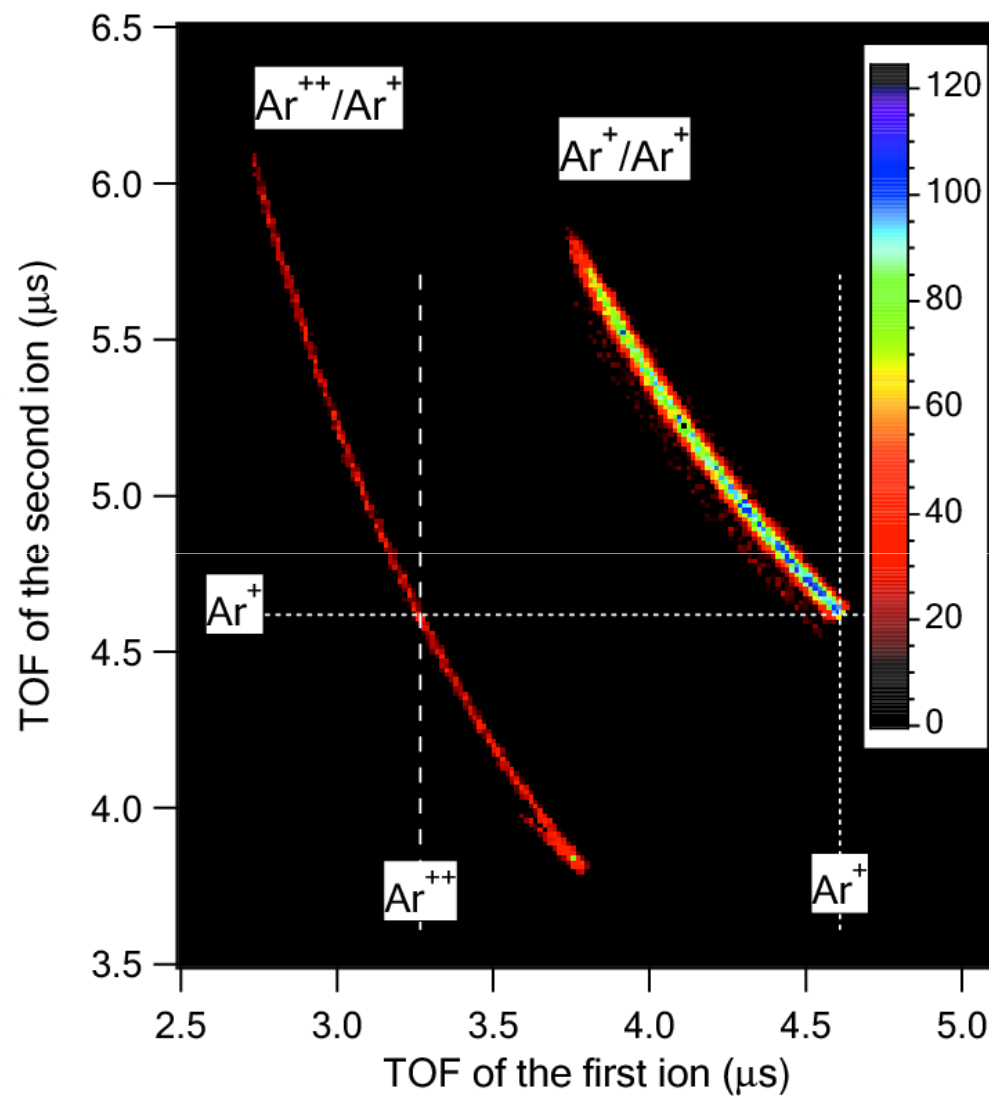
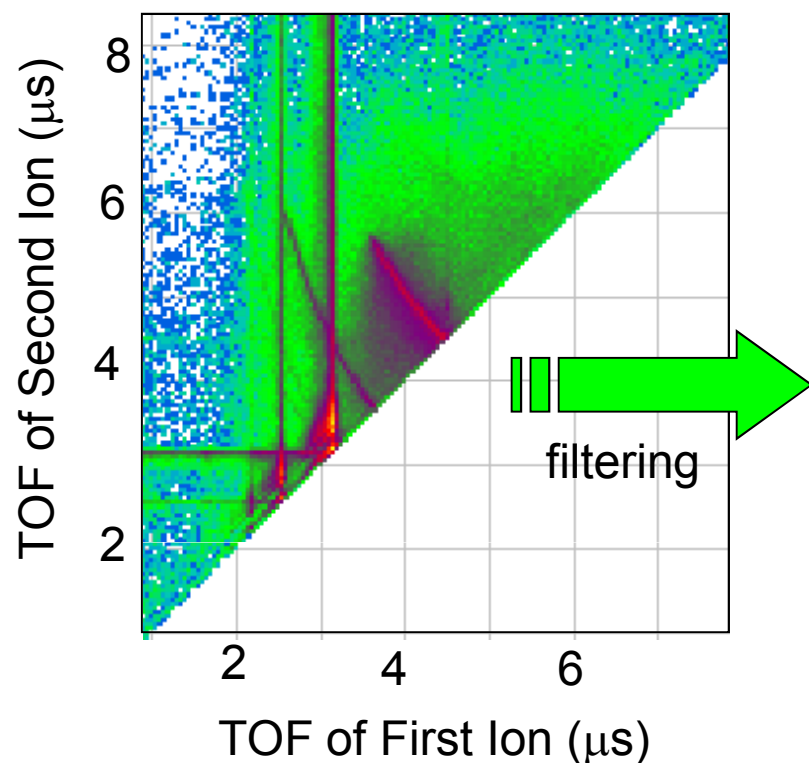
We detect ICD electrons in coincidence with Ar^+ and Ar^{2+} using e-i-i coincidence momentum spectroscopy

Multiple coincidence momentum imaging



Ar_2

PIPICO spectrum



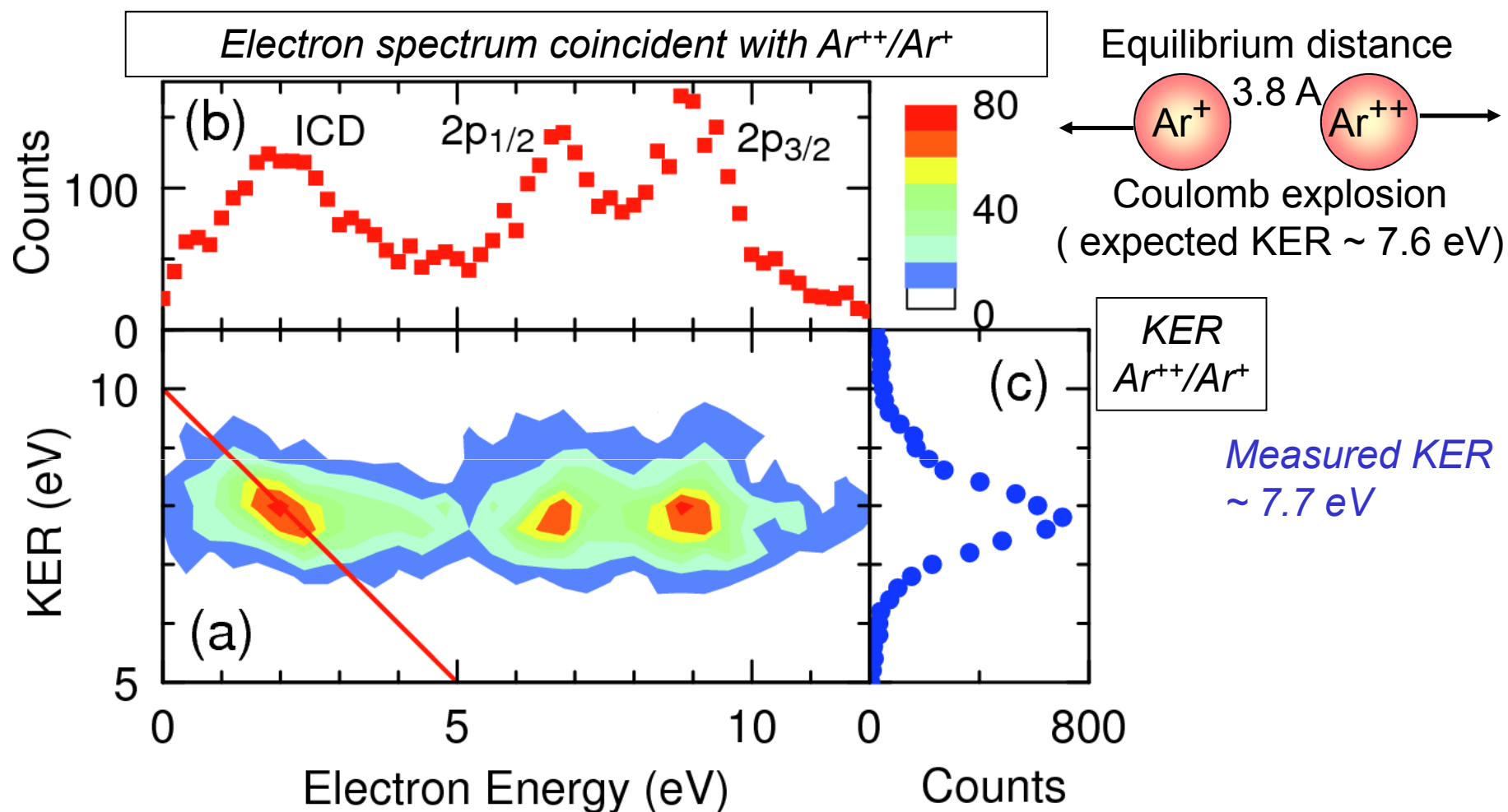
Filter conditions:

Ar^+/Ar^+ : the sum of the momentum of Ar^+ and Ar^+ ~ 0

Ar^{++}/Ar^+ : the sum of the momentum of Ar^{++} and Ar^+ ~ 0

Ar^{++}/Ar^+ comes from ICD !?

Electron spectrum, KER, and their correlation



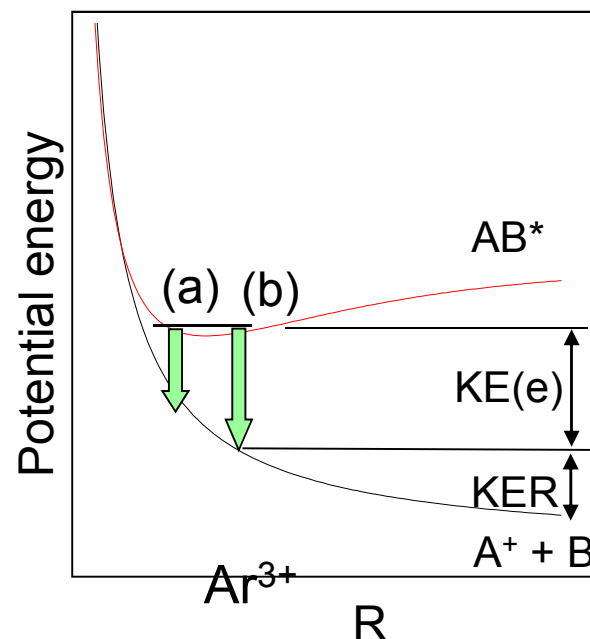
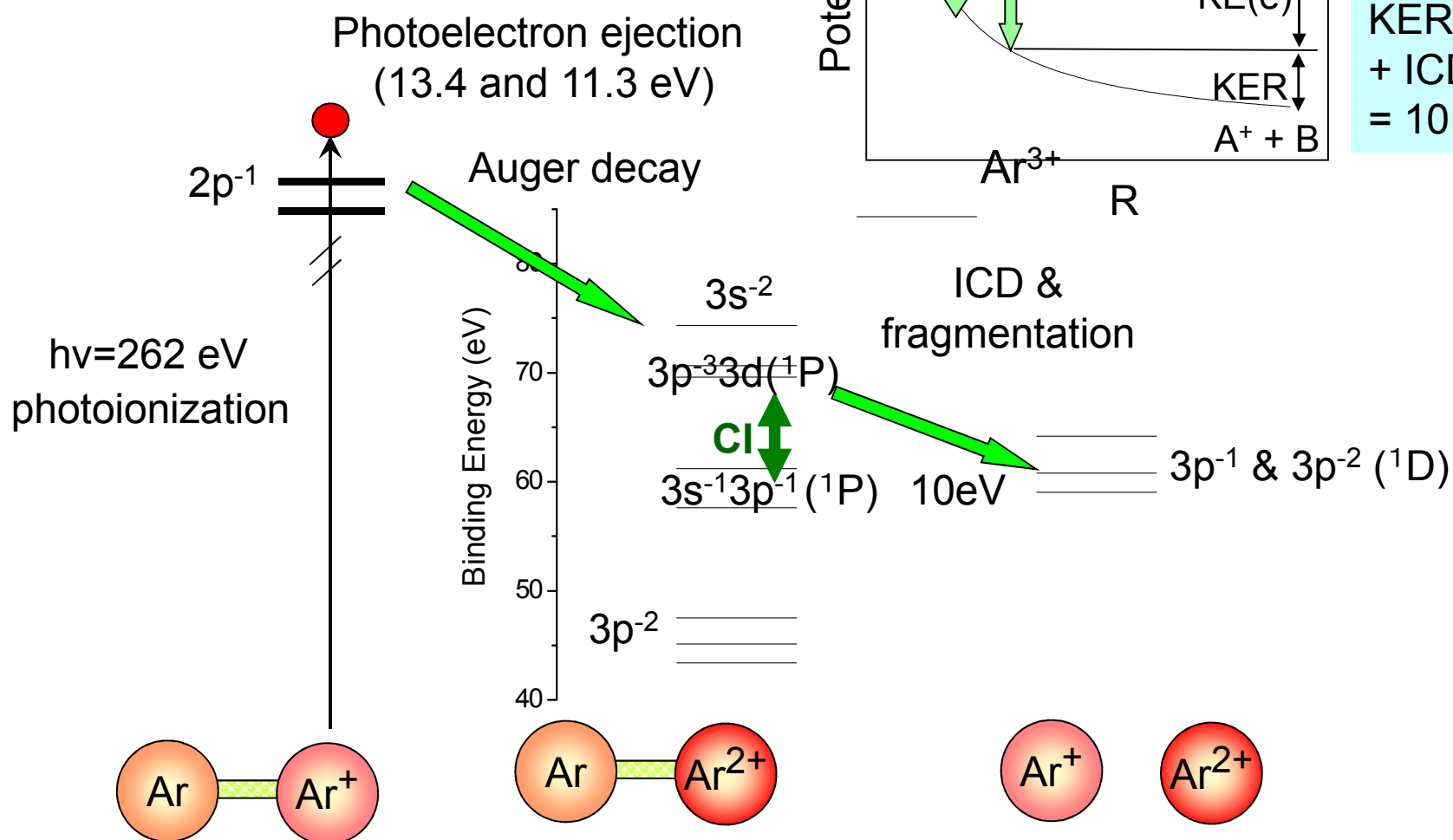
ICD: $\text{KER} + \text{KE}(\text{ICD electron}) \sim \text{constant}$

Islands of slope -1 are ICDs !

Breakup following ICD takes place almost instantaneously.

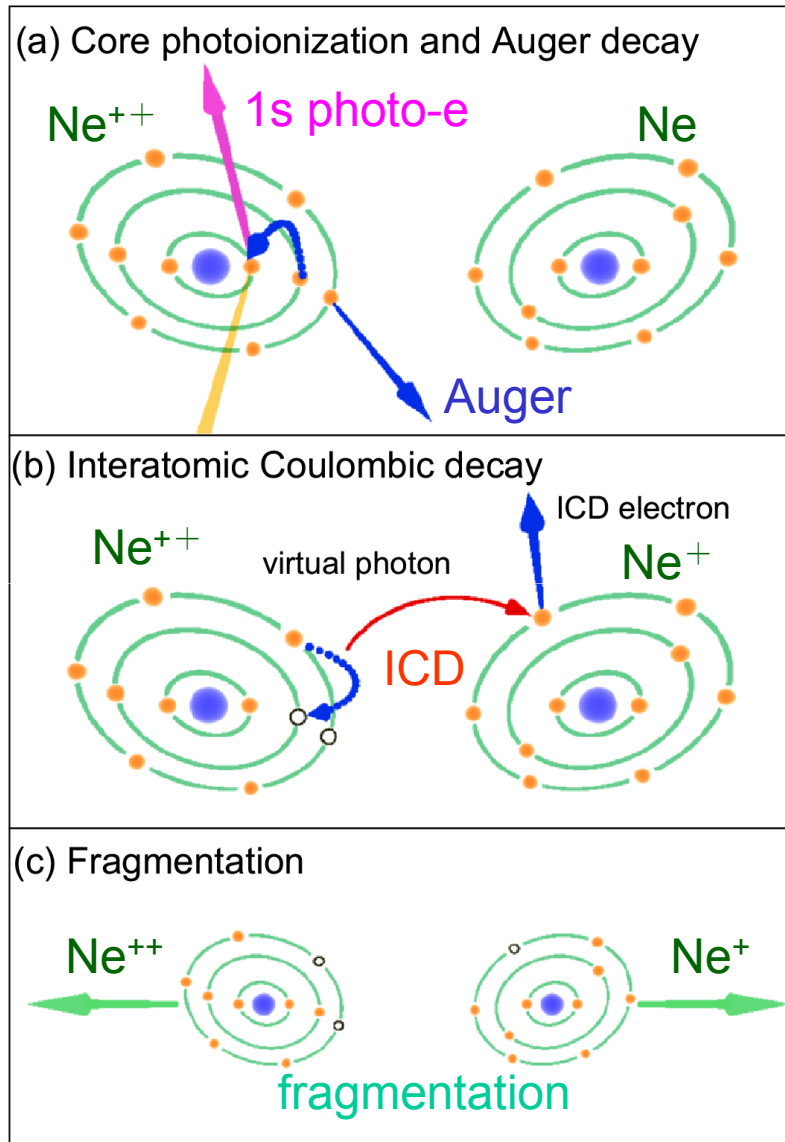
ICD is very fast!

Energy diagram of the ICD process in Ar_2



KER
+ ICD electron
= 10 eV

ICD from the Auger final states in Ne dimer

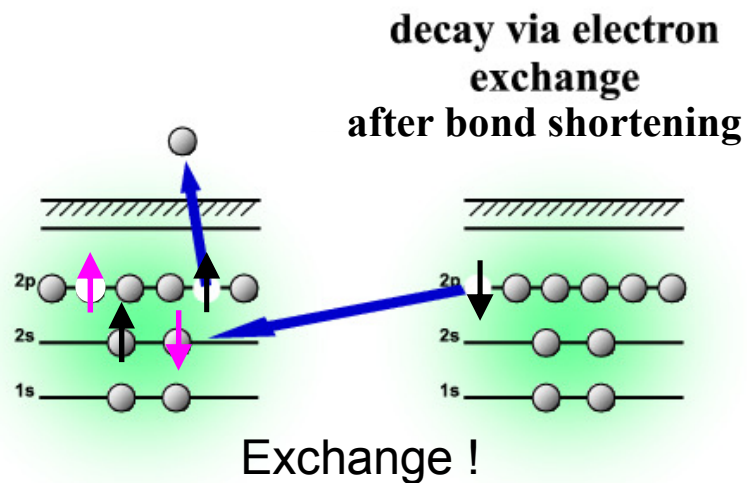
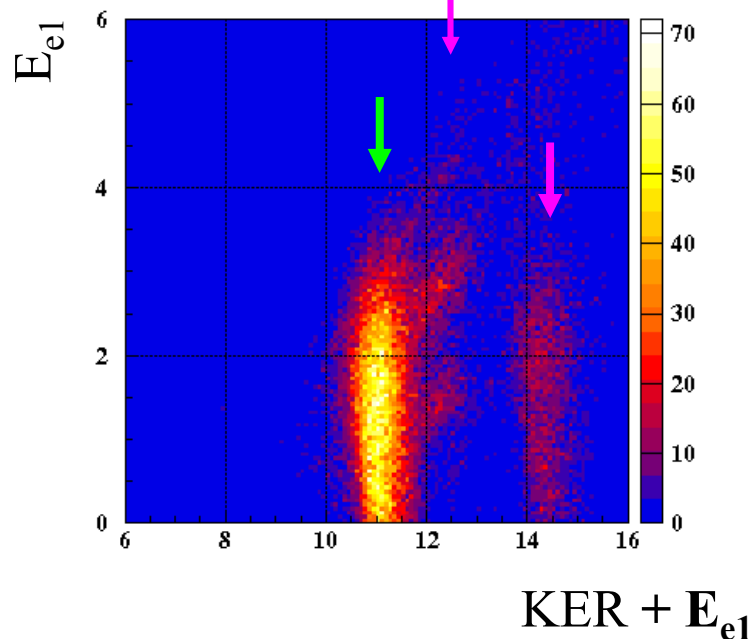
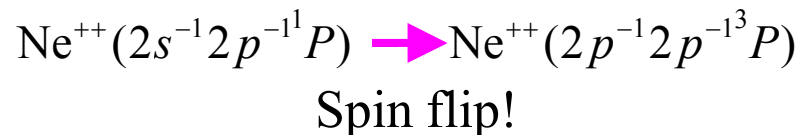
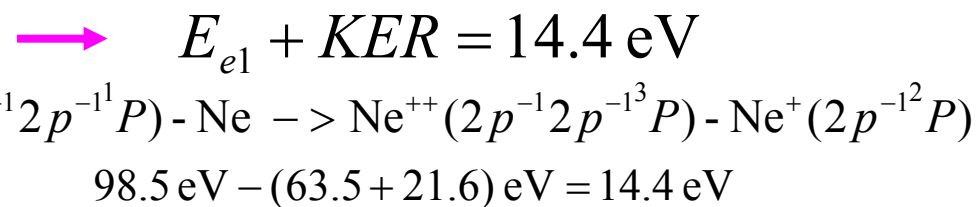
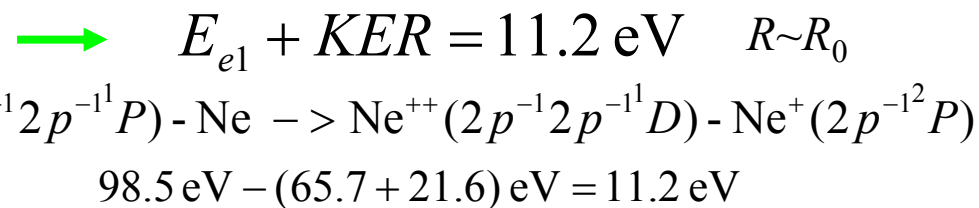
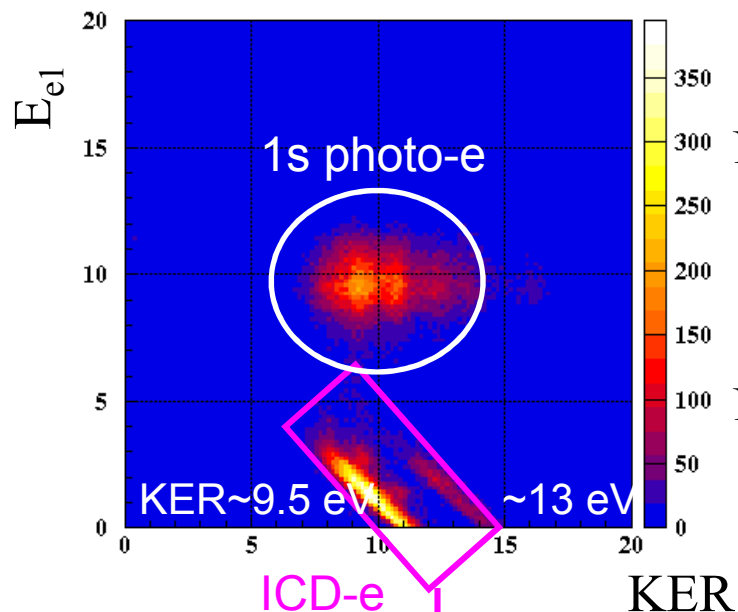


Kreidi et al. J. Phys. B. 41, 101002 (2008).



We detect ICD electrons in coincidence with Ne^+ and Ne^{2+} using e-i-i coincidence momentum spectroscopy

ICD channels in Ne_2 after KL_1L_{23} Auger



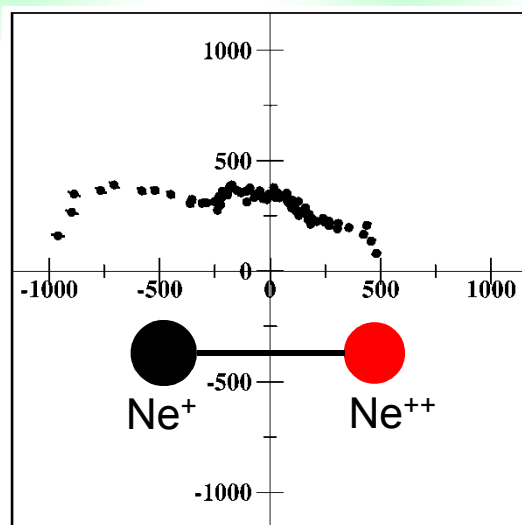
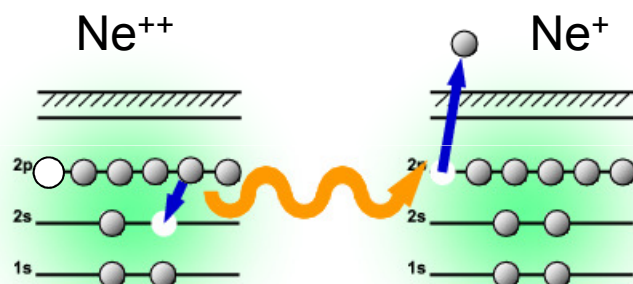
$R \sim 2.2 \text{ \AA} < R_0 = 3.2 \text{ \AA}$

Molecular frame electron angular distributions emitted via ICD

ICD by virtual photon exchange
(direct integral)

ICD electron is emitted from Ne^+ site

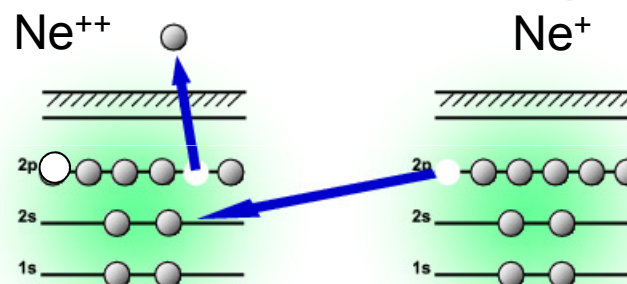
decay via virtual photon
exchange



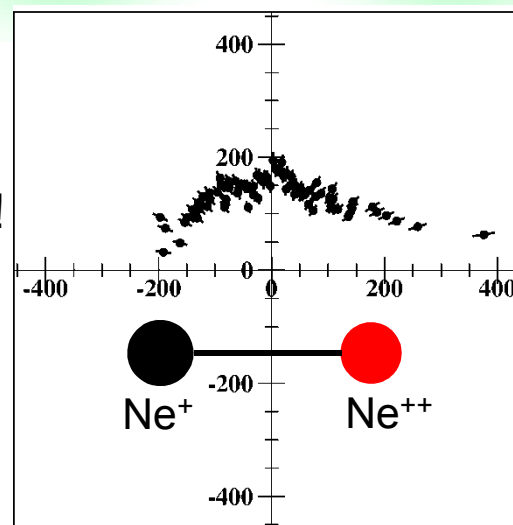
ICD by electron transfer
(exchange integral)

ICD electron is emitted from Ne^{++} site

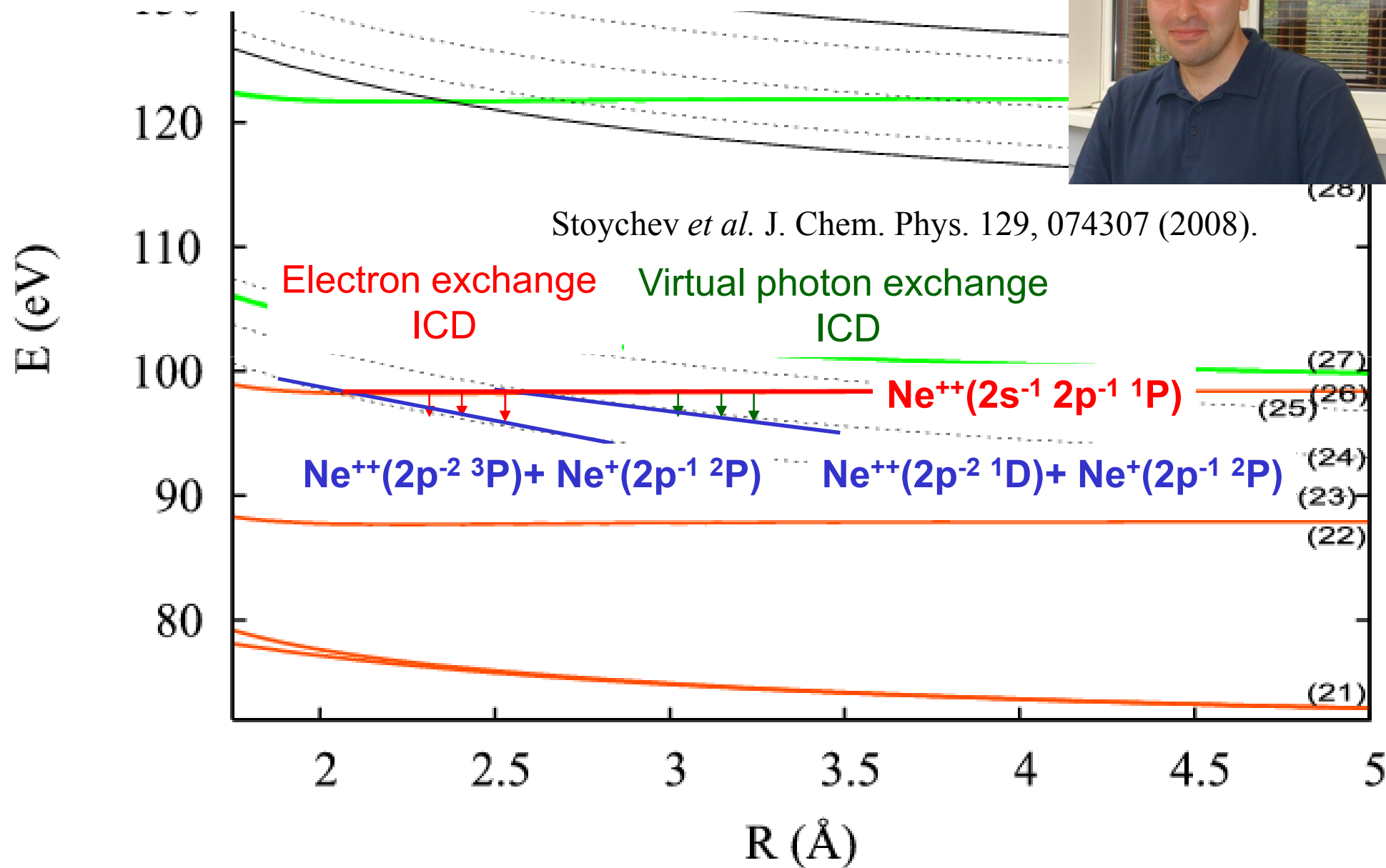
decay via electron
exchange



Flipped!



Wave packet dynamics on *ab initio* potential energy curves



Heidelberg U. ICD gangs in Germany and Japan ! AIST



Lenz



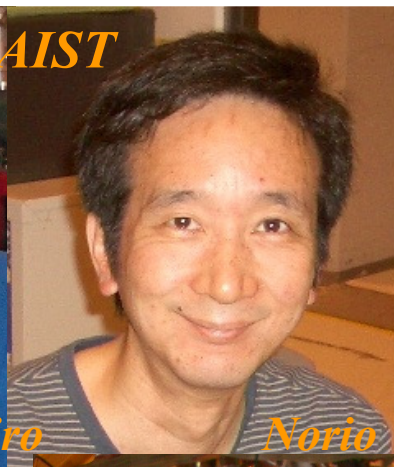
Spas



Alex



Yuichiro



Norio



Reinhard



Markus



Kathi



Till



Hiroshi



Hironobu



Kentaro



Georg



Xiao-Jing



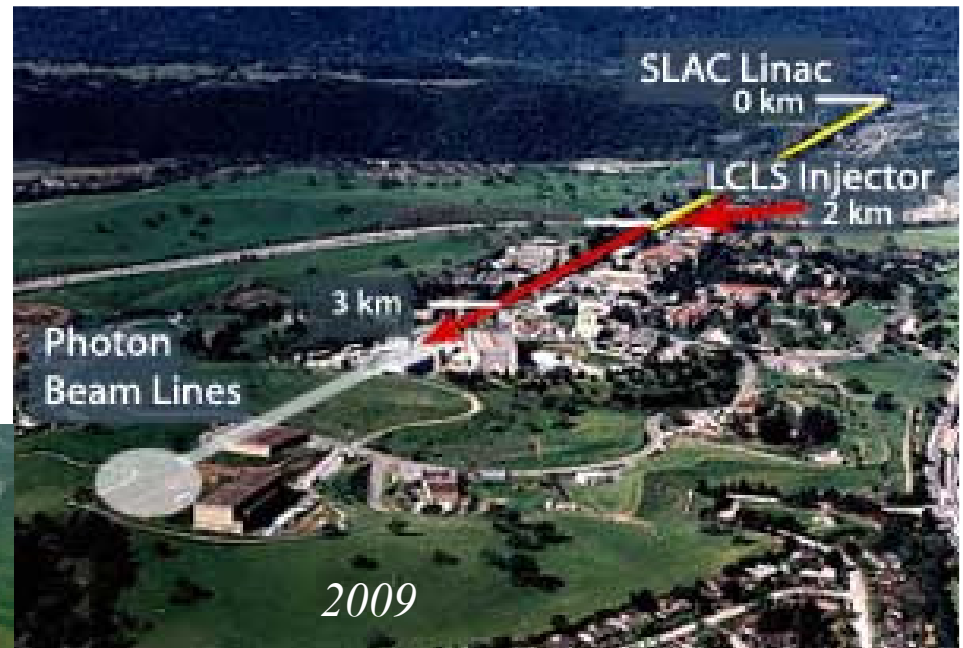
Kiyonobu

Frankfurt U.

Tohoku U.

Kyoto U.

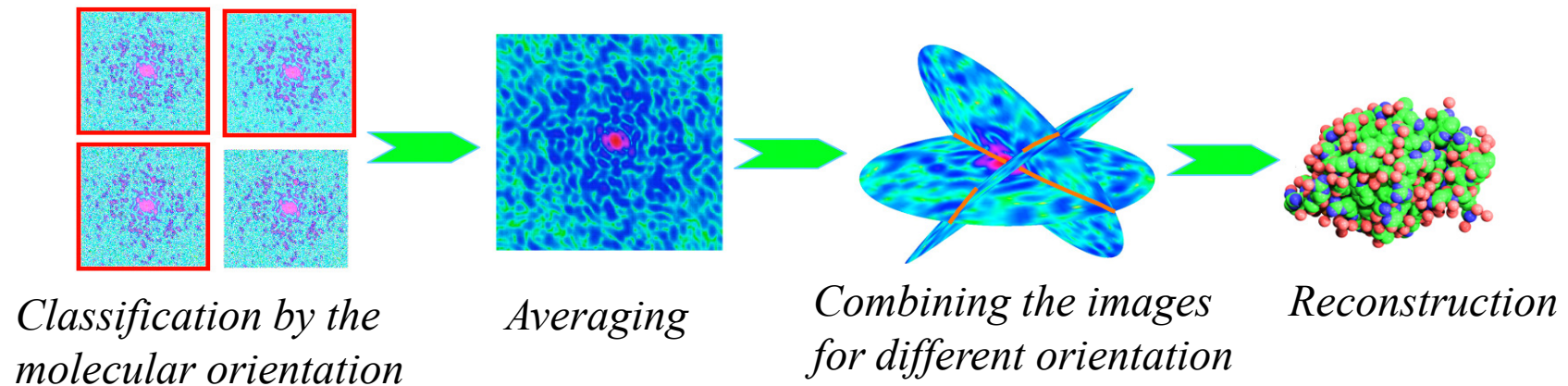
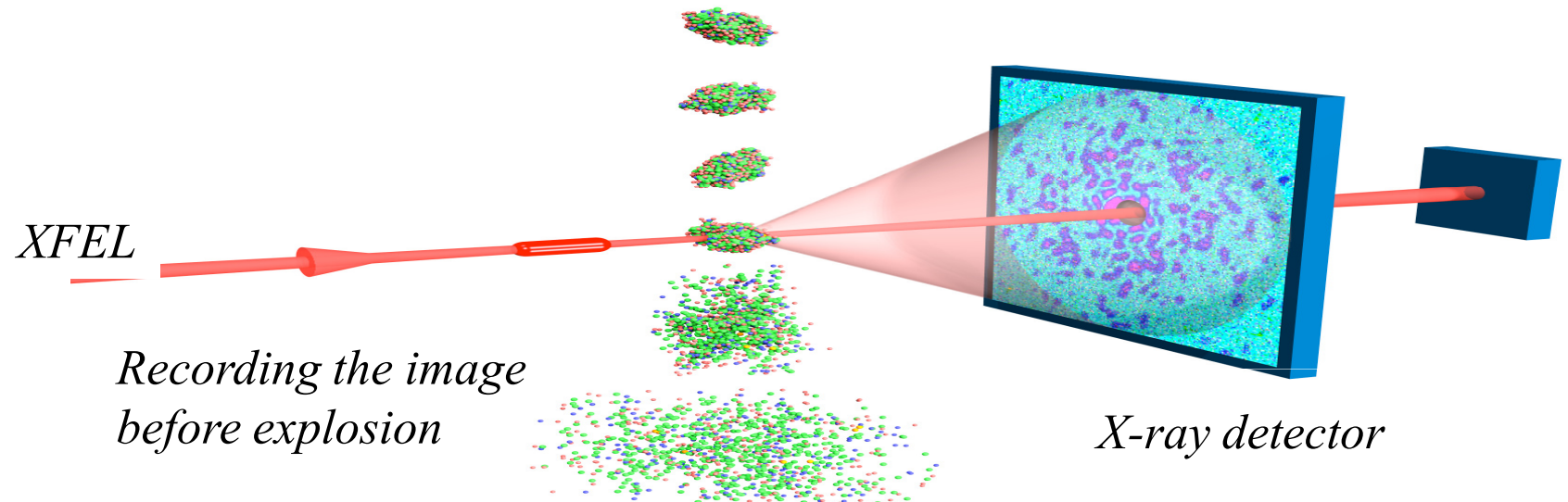
Ultrafast imaging of a single molecule using XFEL



Coherent X-ray diffraction imaging of a single molecule

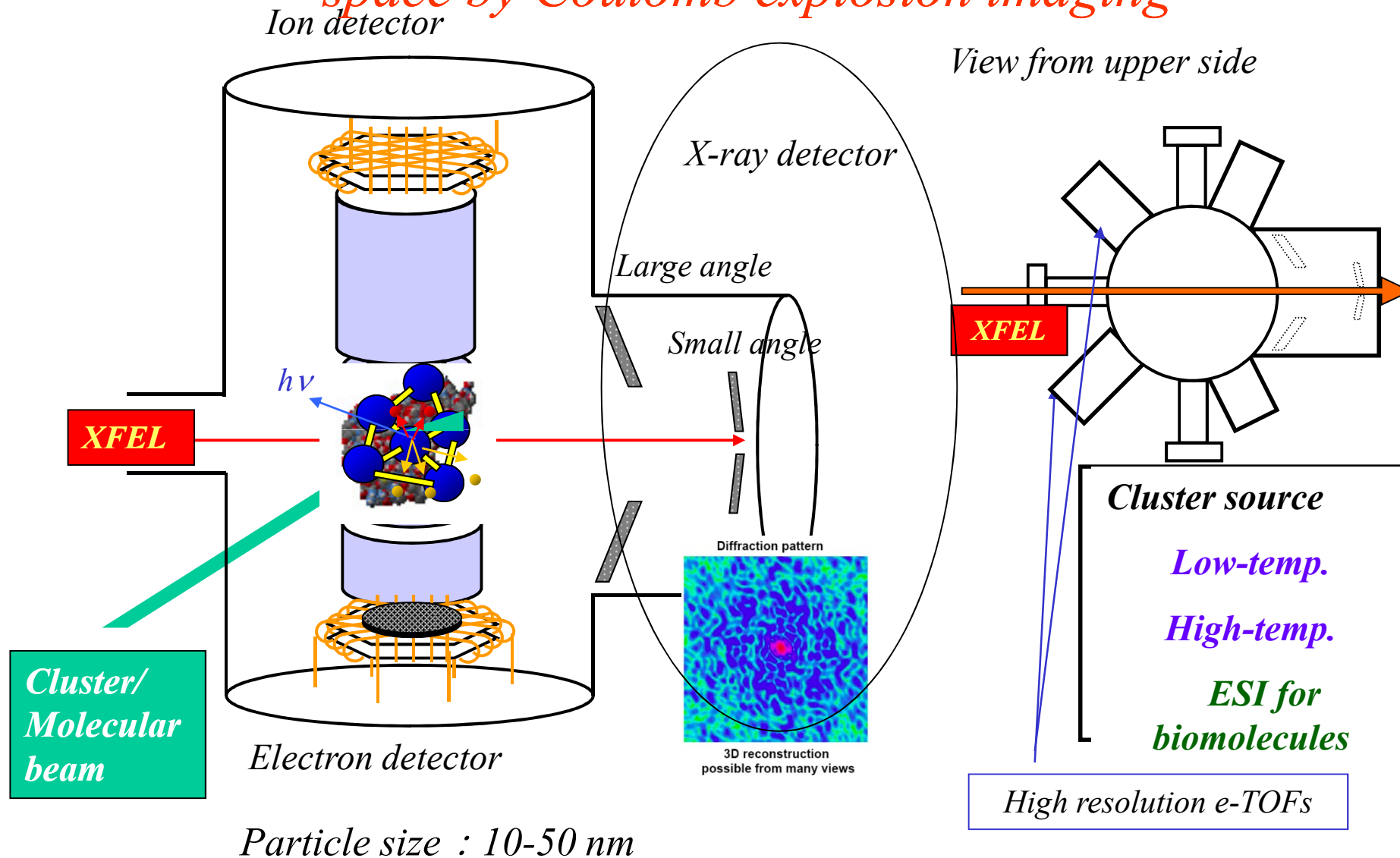
Neutze, Wouts, van der Spoel, Weckert, Hajdu Nature 406, 752 (2000)

Gösta Huldt, Abraham Szöke, Janos Hajdu (J.Struct Biol, 2003 02-ERD-047)



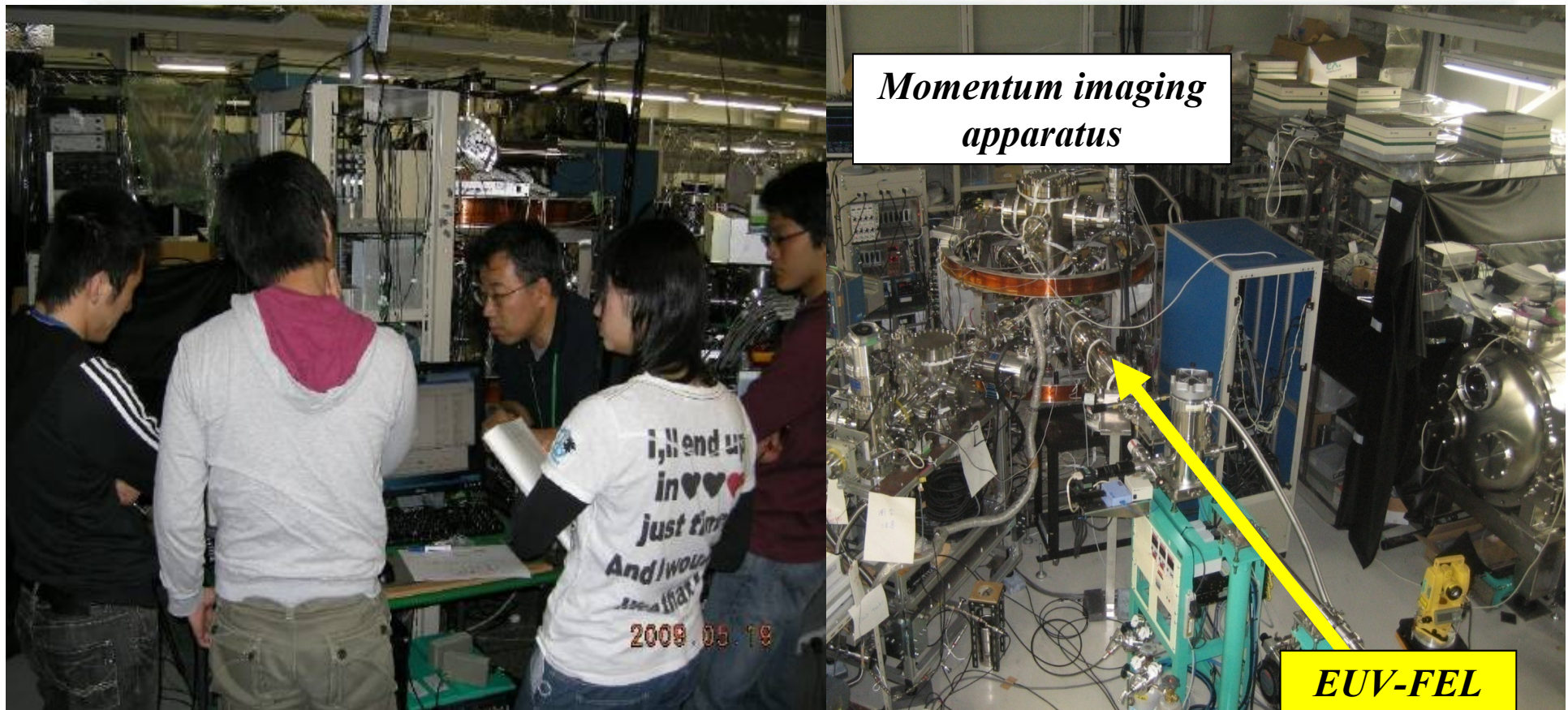
Ion momentum imaging might help for classification....

Coherent diffractive imaging of a single particle fixed-in-space by Coulomb explosion imaging



CEI provides us with the information about spatial alignment of the molecule

SCSS test accelerator : EUV-FEL (51-61 nm)

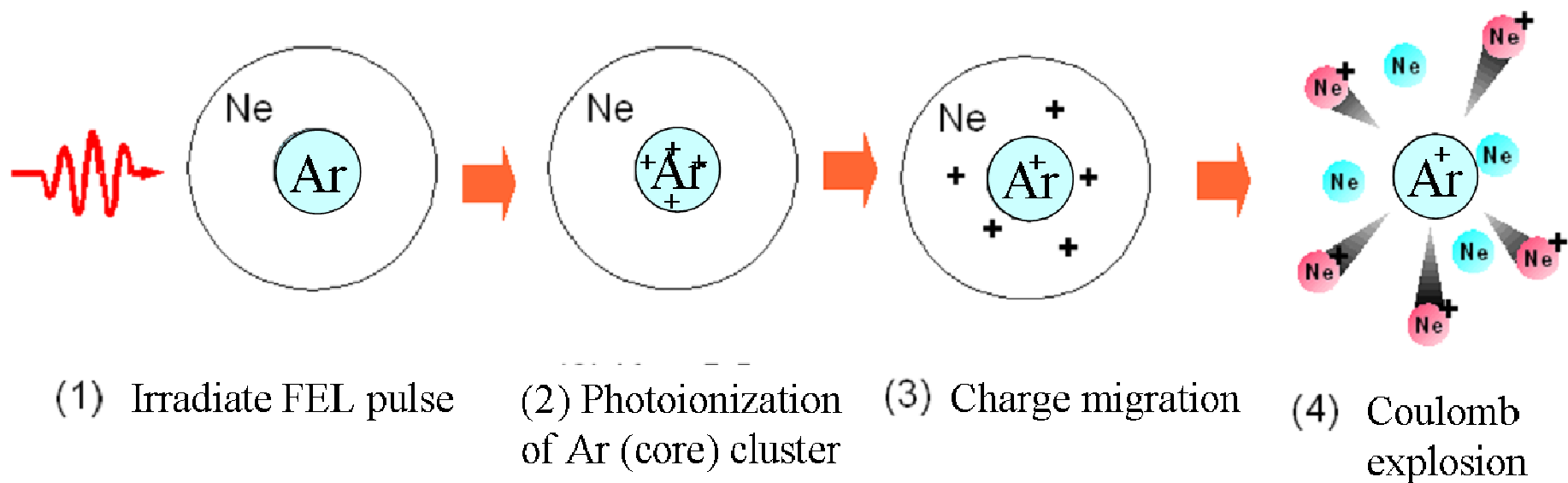


Multiple ionization of Ne-Ar mixed clusters @ 20 eV photon energy

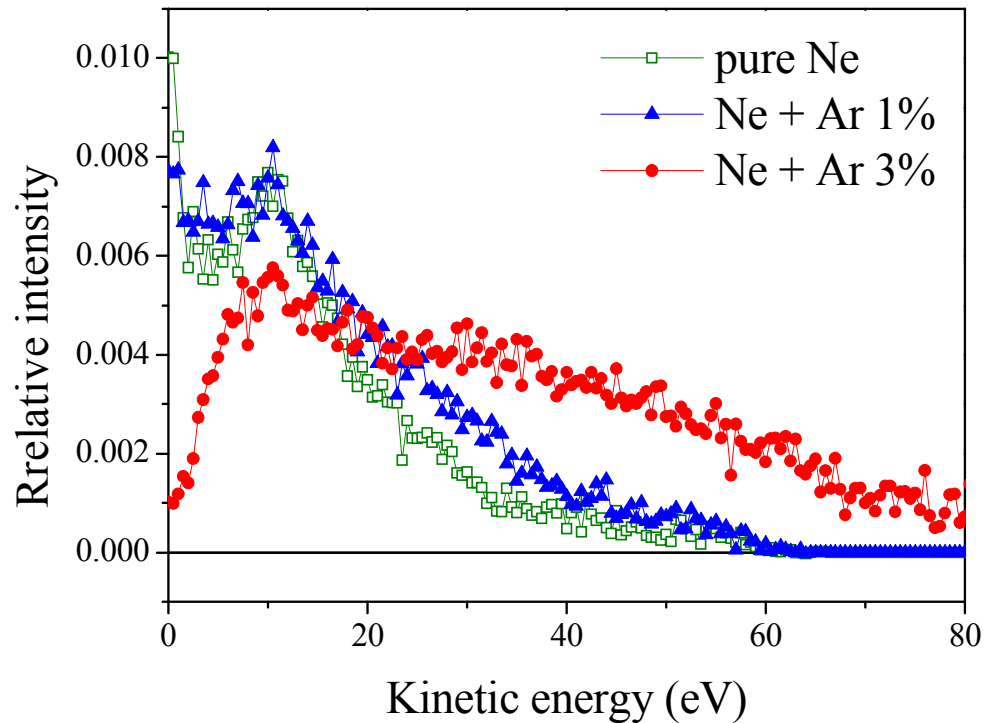
Ne cannot be ionized by single photoabsorption of 20 eV photons.

Ionization energy of Ne = 21.56 eV

Ionization energy of Ar = 15.76 eV



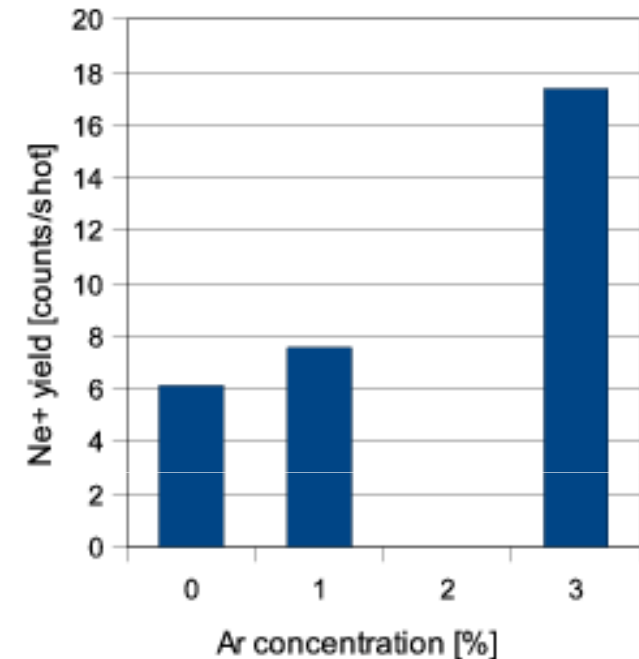
Kinetic energy distributions of Ne^+ from Ne-Ar mixed clusters @ 20 eV



Average kinetic energy of Ne^+ increases with increasing the amount of Ar.



Charge state of the cluster increases.



Ne^+ yields increase with increasing the amount of Ar.



Charge transfer from Ar to Ne occurs.

Collaborators

Tohoku U.

H. Fukuzzwa

X.-J. Liu

K. Motomura

G. Prümper

C. Wang

A. Yamada

M. Okunishi

K. Shimada

K. Ueda

*Apparatus &
Measurements*

Tohoku U.

T. Harada

M. Toyoda

M. Yanagihara

M. Yamamoto

Optics

Kyoto U.

K. Nagaya

H. Iwayama

A. Sugishima

H. Murakami

M. Yao

Cluster source

AIST

N. Saito

*Analysis
software*

LBL.

A. Belkacem

Optics

Special Thanks

RIKEN SCSS test accelerator operation group; IMRAM technical service section, Tohoku U.; LBL optics group.

MPG ASG CFEL

/ MPI Heidelberg

A. Rudenko

K.-U. Kühnel

M. Kurka

J. Ullrich

Measurements

Frankfurt U.

L. Foucar

A. Czash

O. Jagutzki

H. Shimidt-Böcking

R. Dörner

Acquisition software

Uppsala U.

R. Feifel

Measurements

RIKEN

M. Nagasono

K. Tono

A. Higashiya

T. Togashi

M. Yabashi

T. Ishikawa

T. Tanaka

Light source

RIKEN/JASRI

H. Kimura

H. Ohashi

Beam line

The end

Thank you very much for your attention!

