

lecture 8.12.2011 (after the Einstead night)

we had so far:

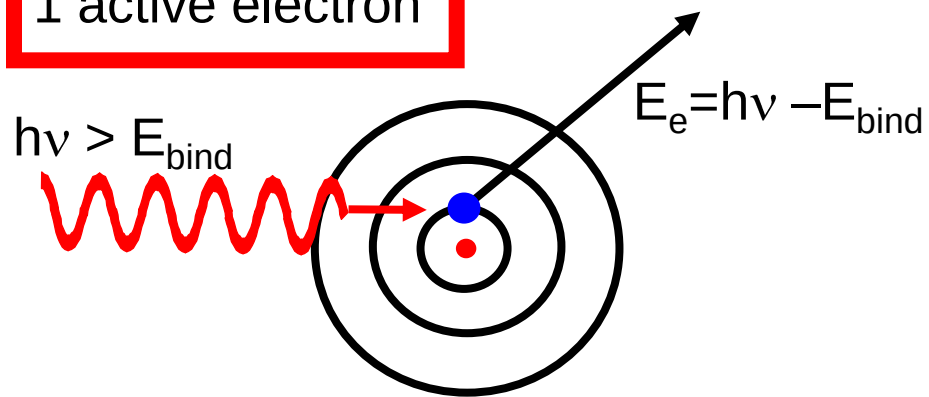
- photoionization
- correlated processes, detection
- momentum detection with COLTRIMS

now:

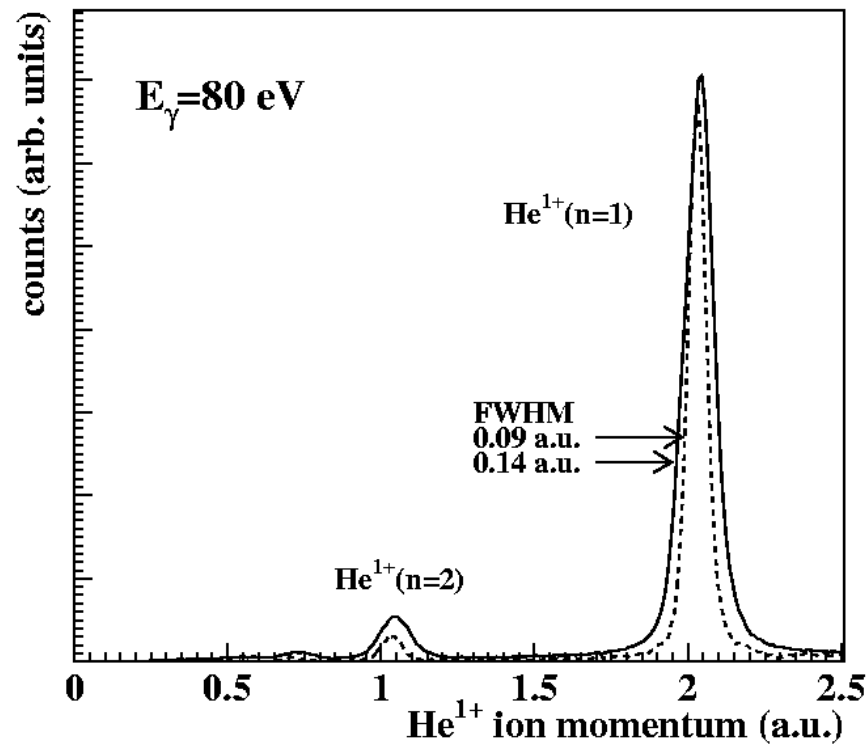
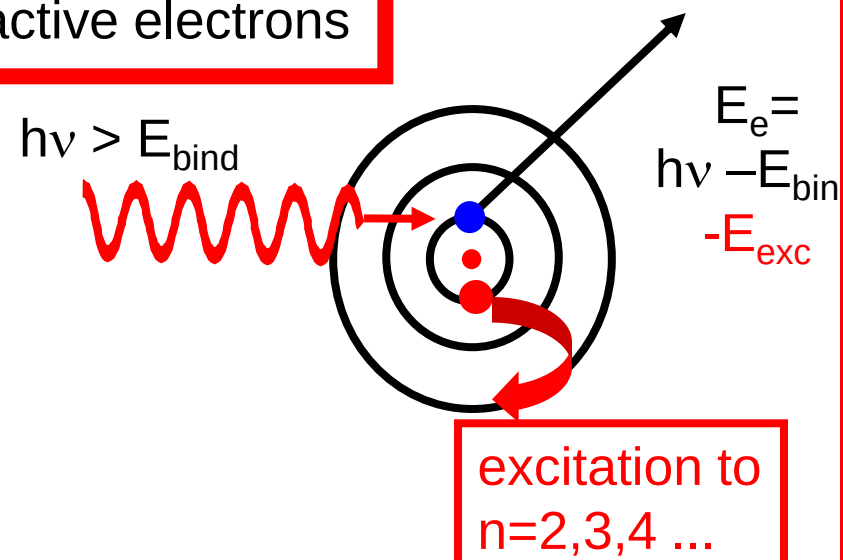
- correlated electron and ion emission
- interatomic Coulomb decay
- velocity map imaging detector

- next topic cluster physics

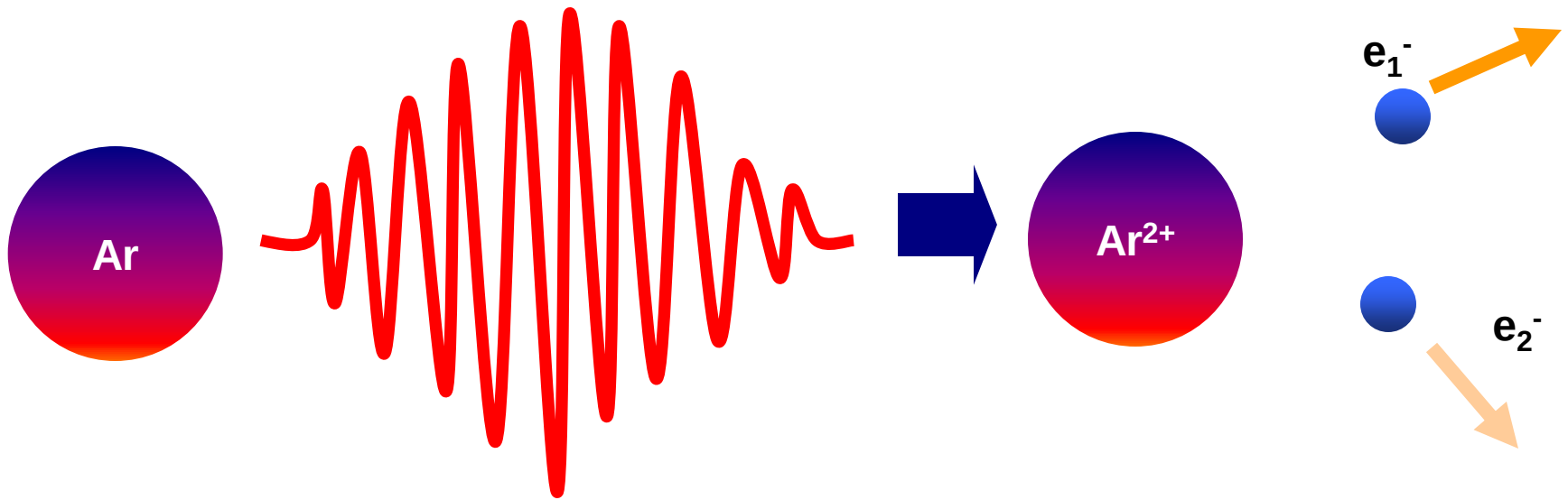
1 active electron



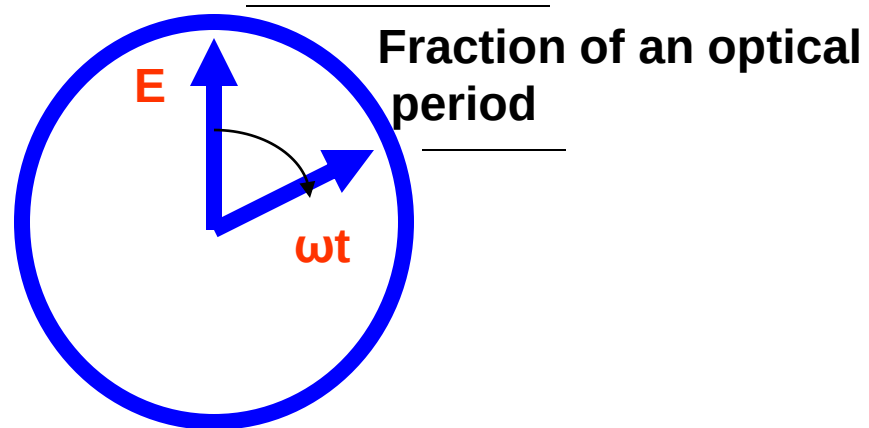
2 active electrons



One of the many current questions:
Correlation in the sequential release of two electrons from atomic targets by short laser pulses



Sub femto-second
Electrons dynamics



Optical period at 800 nm: 2.6 fs

COLTRIMS: A “Cloud Chamber” for μeV Particles:

Position
sensitive
multi-hit
ion
detector

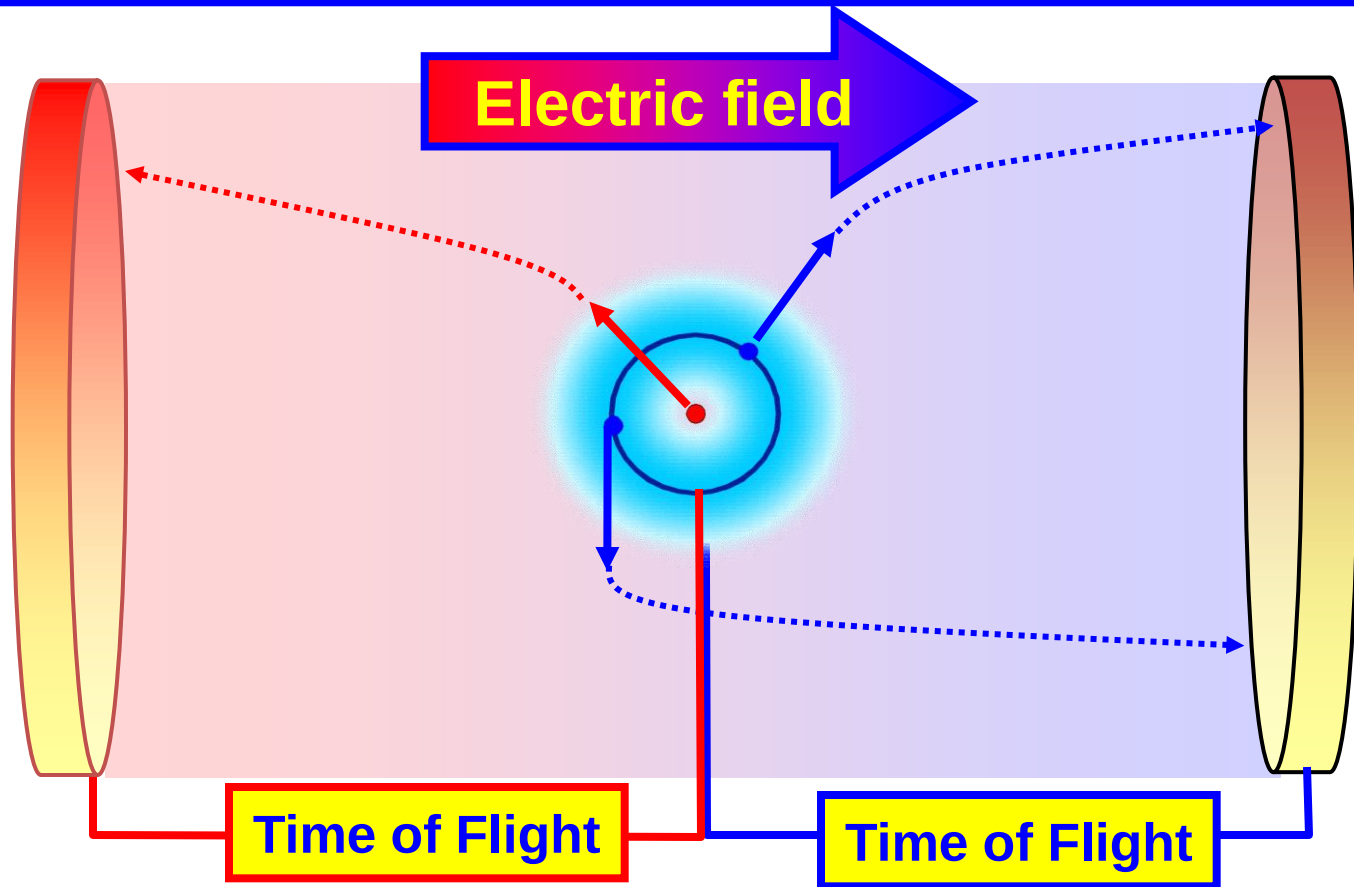
Electric field

Position
sensitive
multi-hit
electron
detector

Time of Flight

Time of Flight

Time of flight &
2dim positions
 $\Rightarrow$ 3 dim momentum vector



COLTRIMS: A “Cloud Chamber” for μeV Particles:

Position
sensitive
multi-hit
ion
detector

Electric field

Position
sensitive
multi-hit
electron
detector

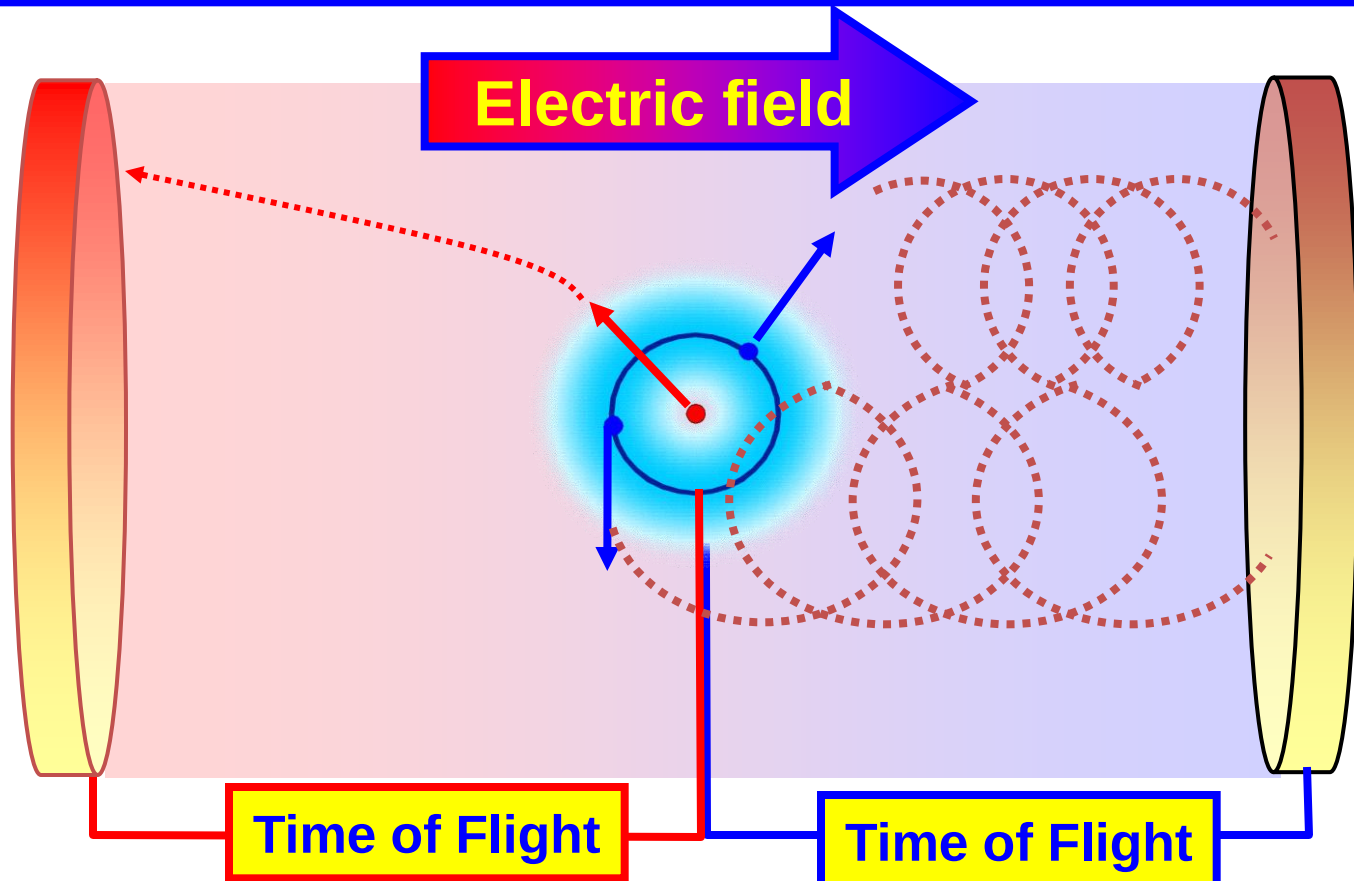
Time of Flight

Time of Flight

B-field

+ time dependent field
+ lenses

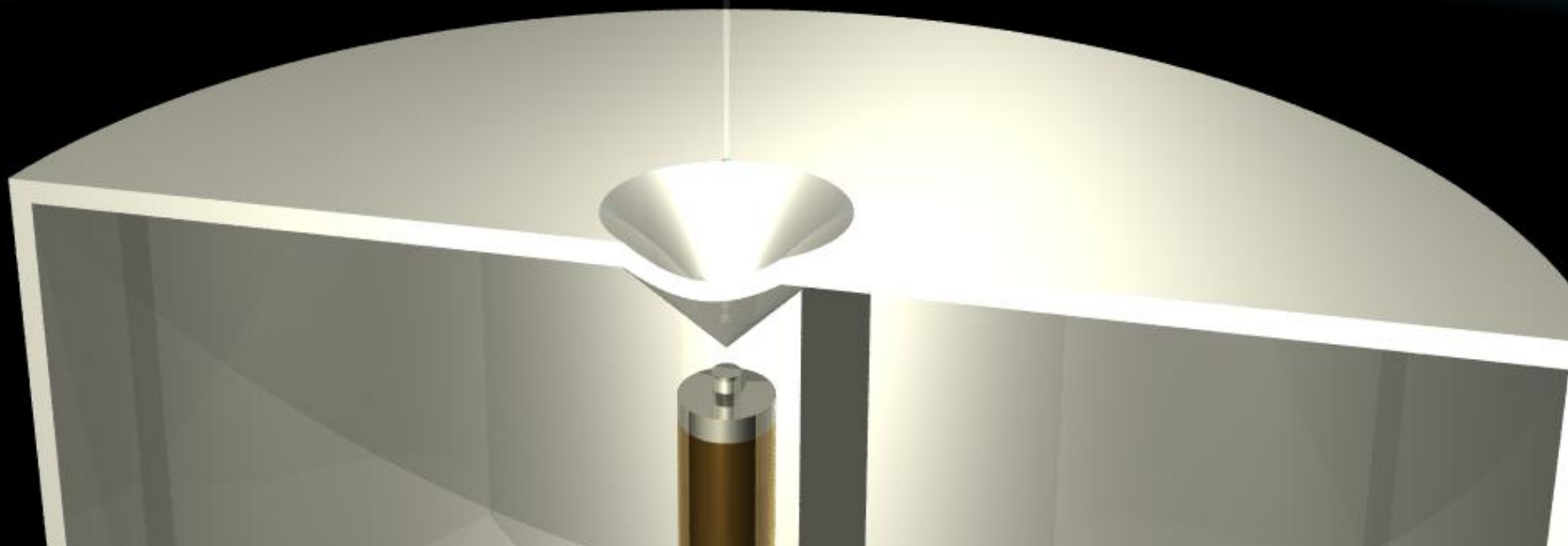
Time of flight &
2dim positions
 $\Rightarrow$ 3 dim momentum vector



Localized Gas

Target:

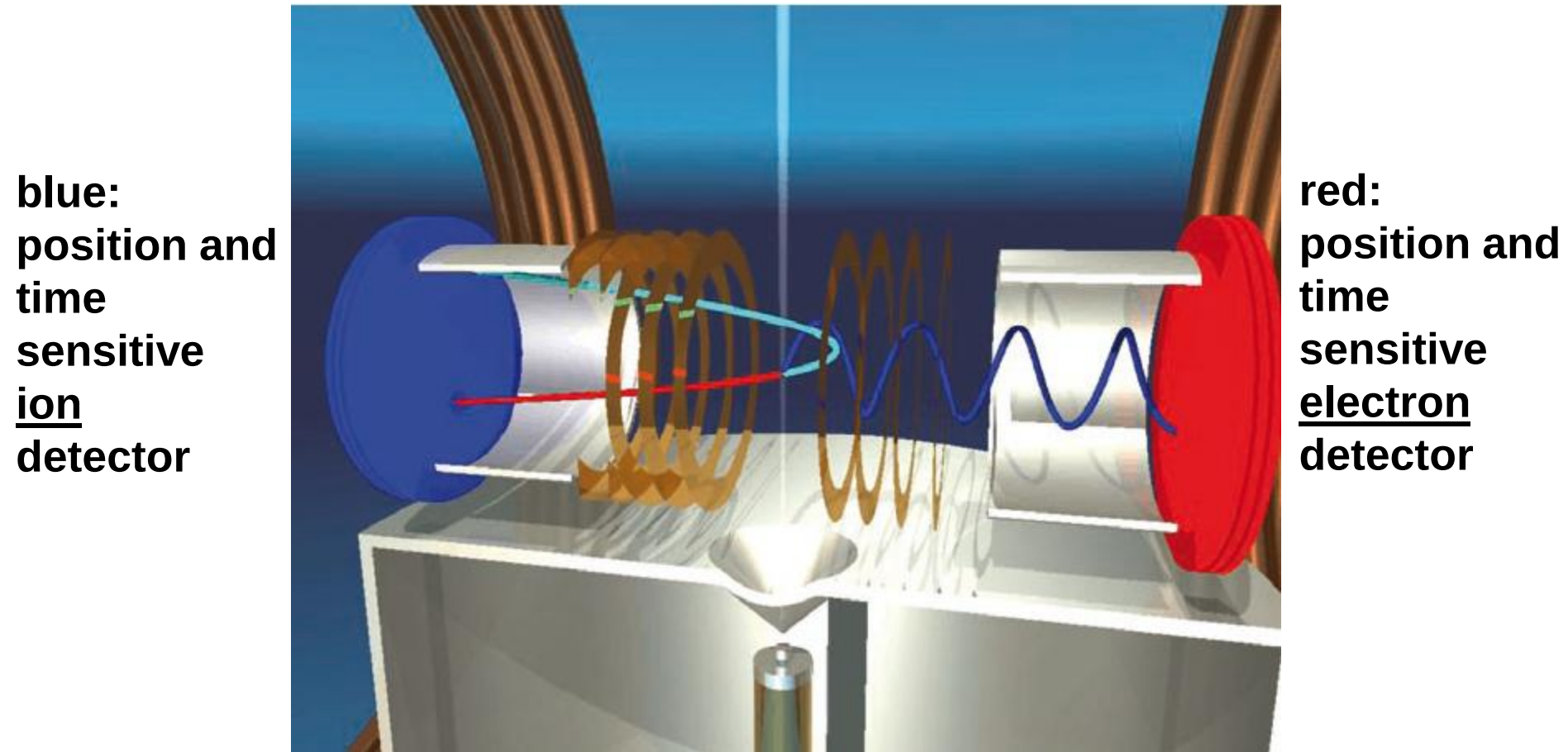
precooled supersonic
gas jet
 $\ll 10\text{ K}$



ion and electron momentum spectrometer

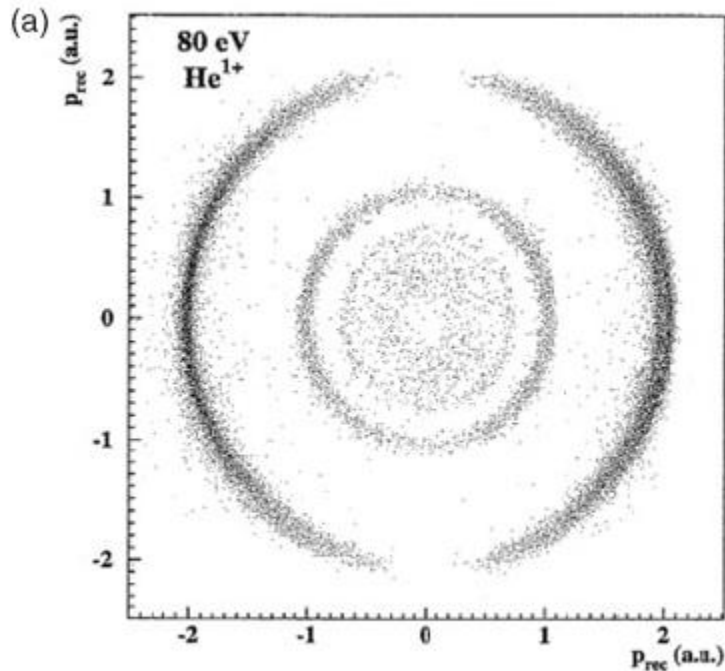
COLTRIMS: cold target recoil ion momentum spectrometer

the 'bubble chamber' of atomic physics

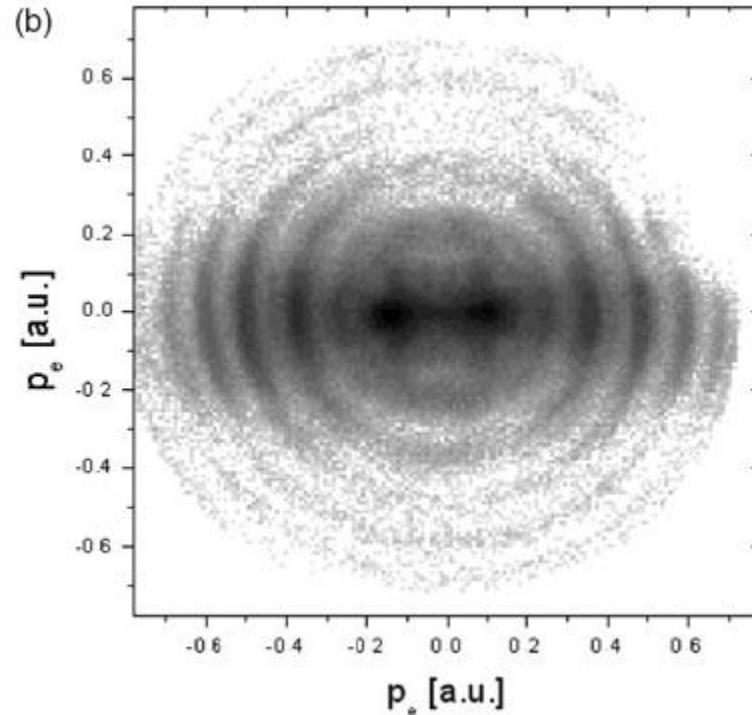


Horst Schmidt-Böcking, Stern-Gerlach medal 2010
of the German Physical Society (DPG)

momentum distributions from He ionization

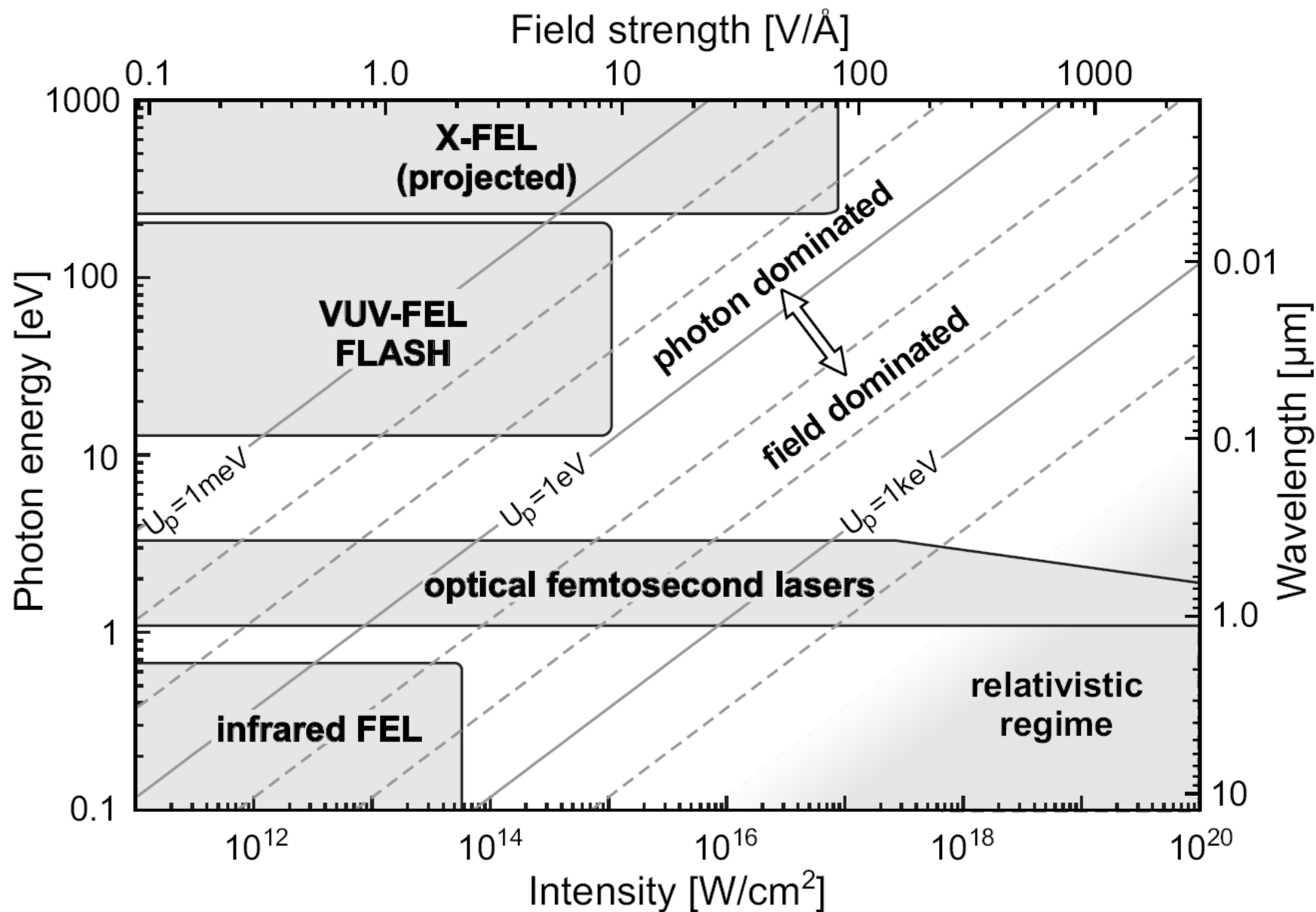


single ionization with 80 eV

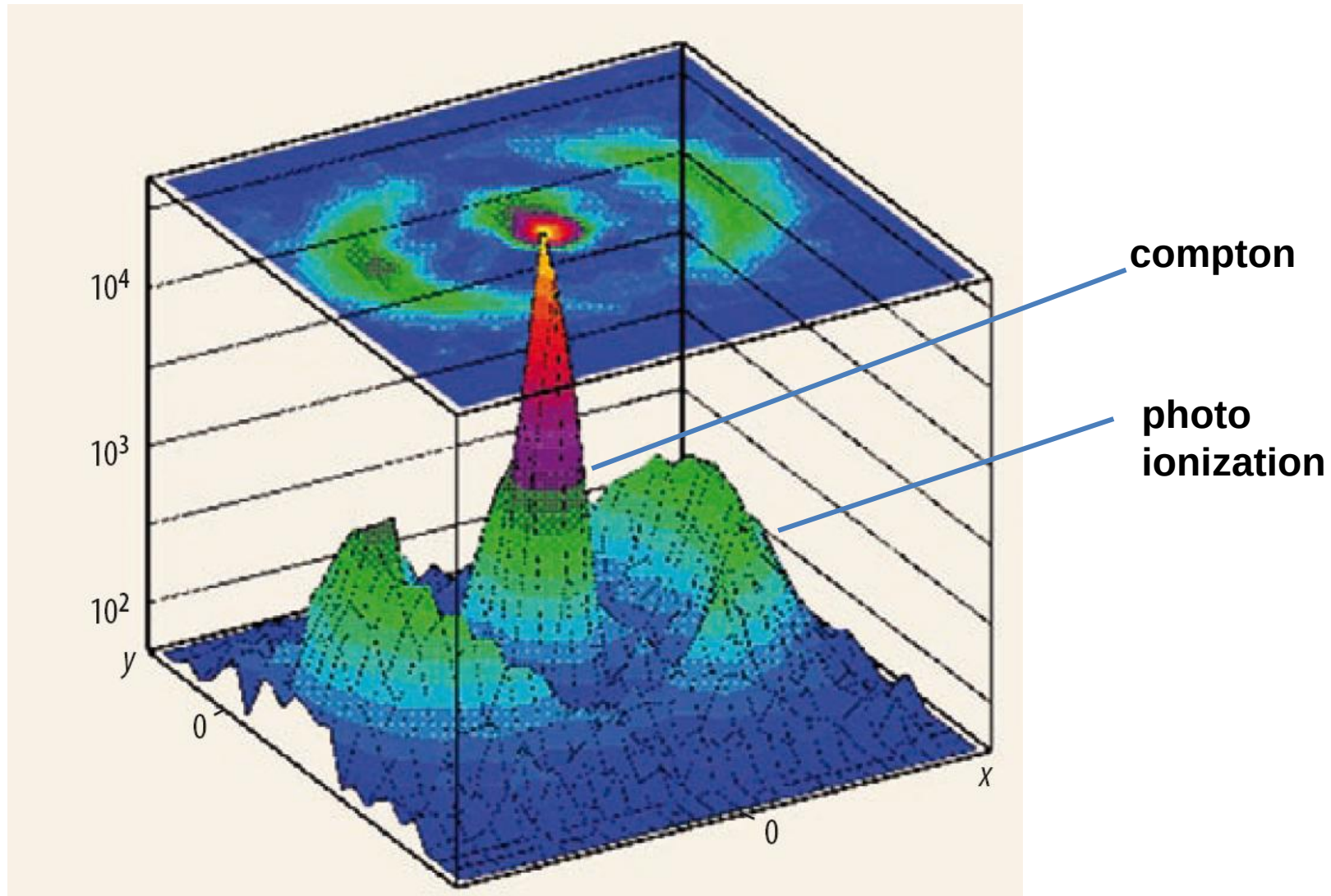


multiphoton single ionization
with 25 fs at 800 nm
10exp15 W/cm²

Laser intensity regimes



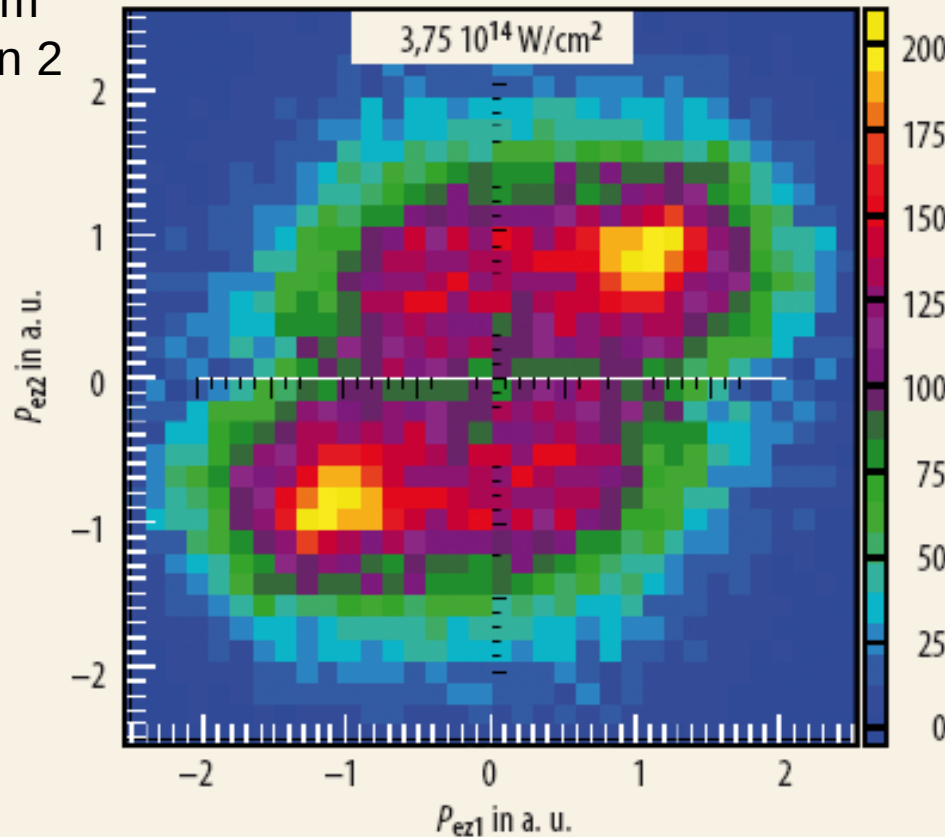
He⁺ momentum distribution for photoabsorption at 8.8 keV



from momentum distributions PI and Compton scattering can be disentangled

2-electron momentum correlation for double ionization in Ar

momentum
of electron 2



momentum of electron 1

**electron correlation in
strong laser field ionization**

**both electrons are
simultaneously emitted (non-
sequential)**

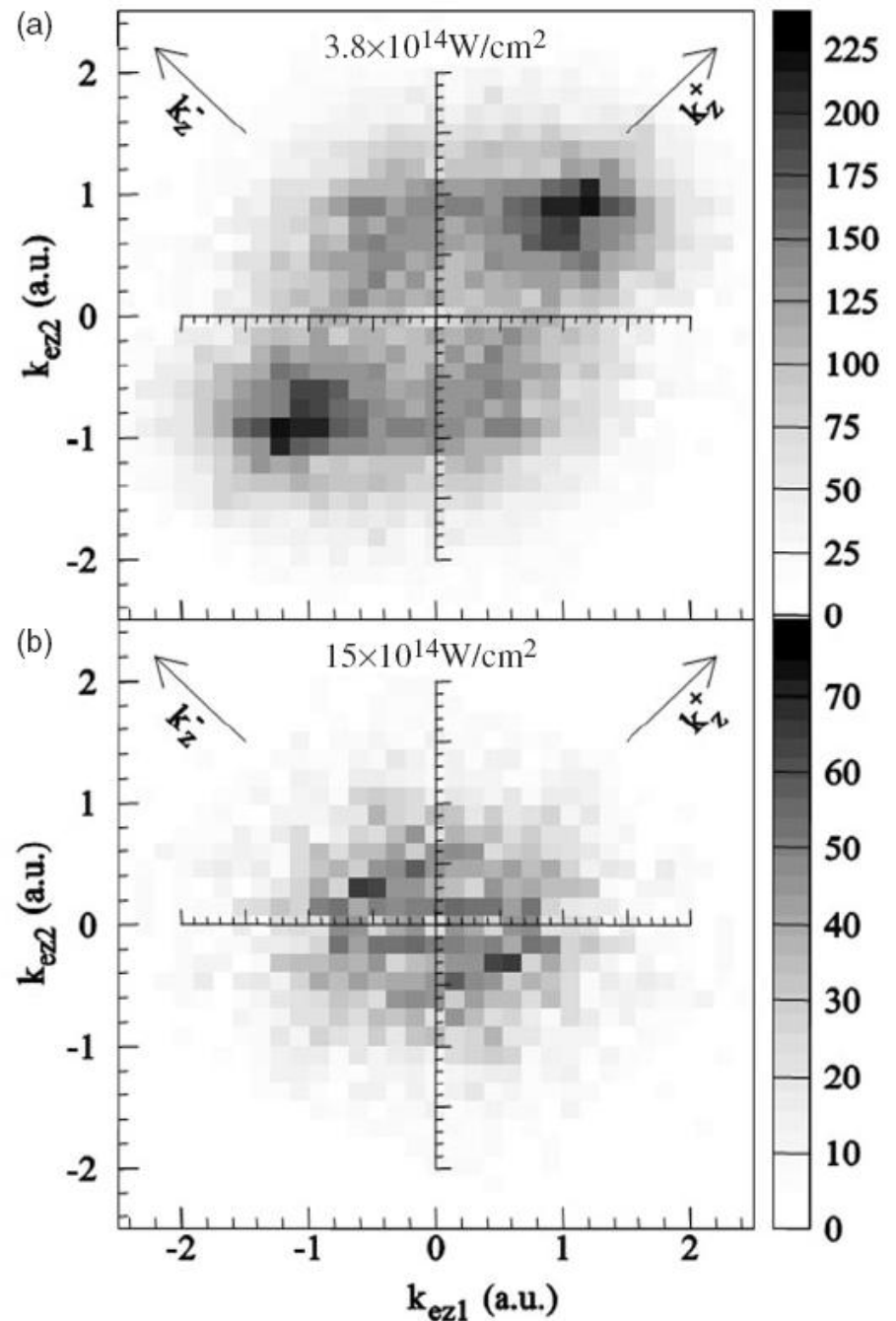
**proof of electron rescattering
process**

2-electron momentum correlation for double ionization in Ar

as before:
non-sequential
regime

sequential regime

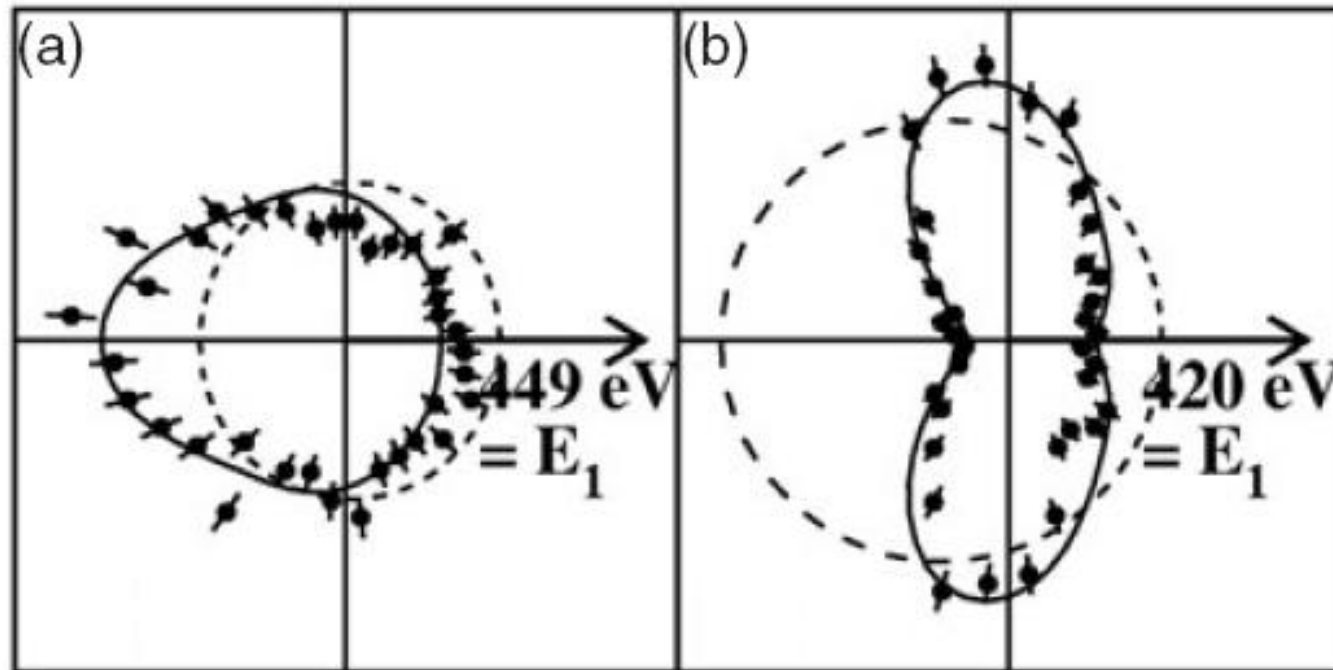
depending on the
laser power!



He photo double ionization at 529 eV photon energy

Arrow: direction of electron 1 (with given energy)

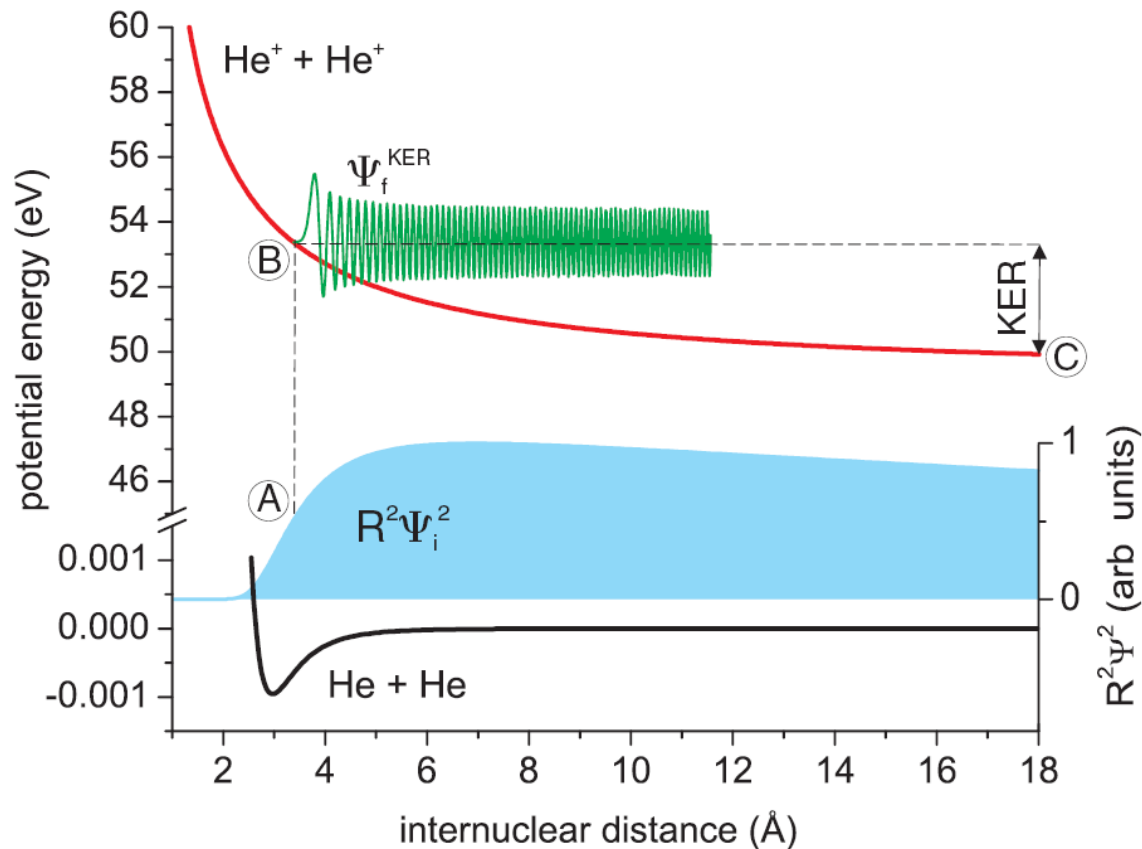
symbols: emission of electron 2 (at 2 eV, left, and 30 eV)



newest result: single photon double ionization of the helium dimer

Havermeier et al., Phys. Rev. Lett. 104, 153401 (2010)

a single photon can ionize the two helium atoms of the helium dimer in a distance up to 10 Å

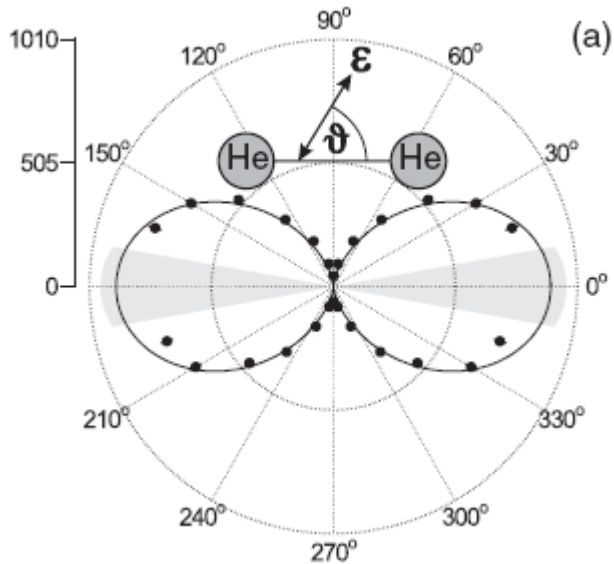


classically:
photoexcitation from A
to B, kinetic energy
release KER

QM: overlap of the green
and blue wave functions
replace the KER(R)

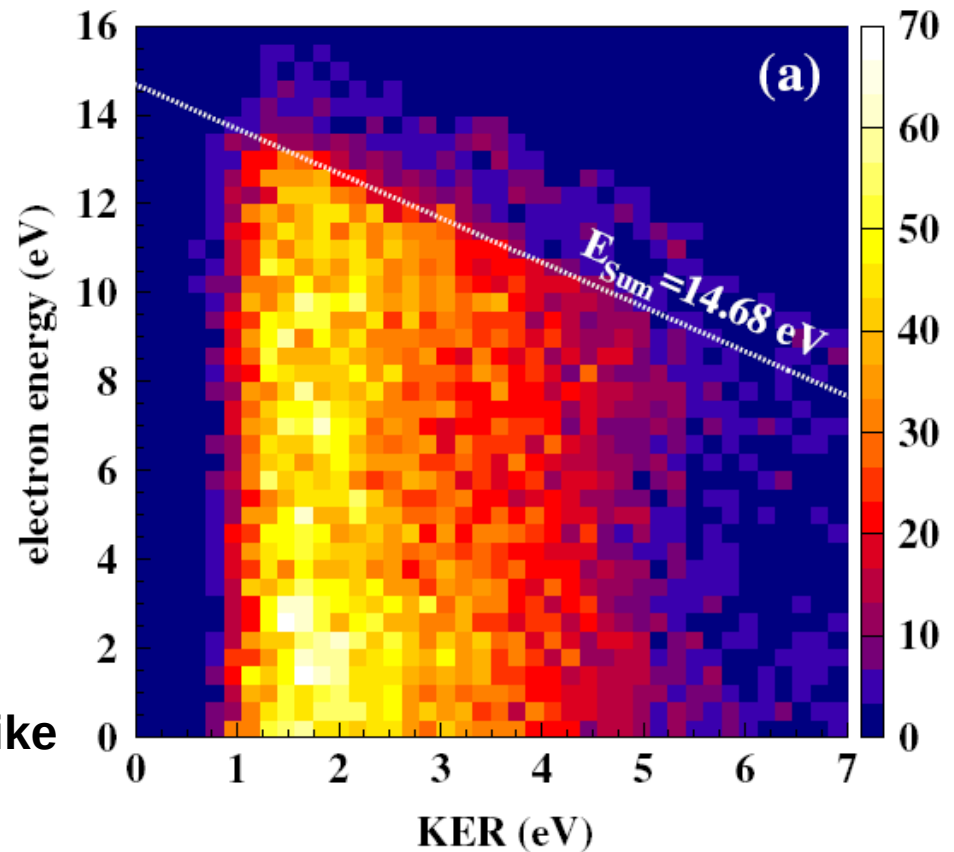
double ionization of He dimer by one 63.86 photon

angular distribution of KER



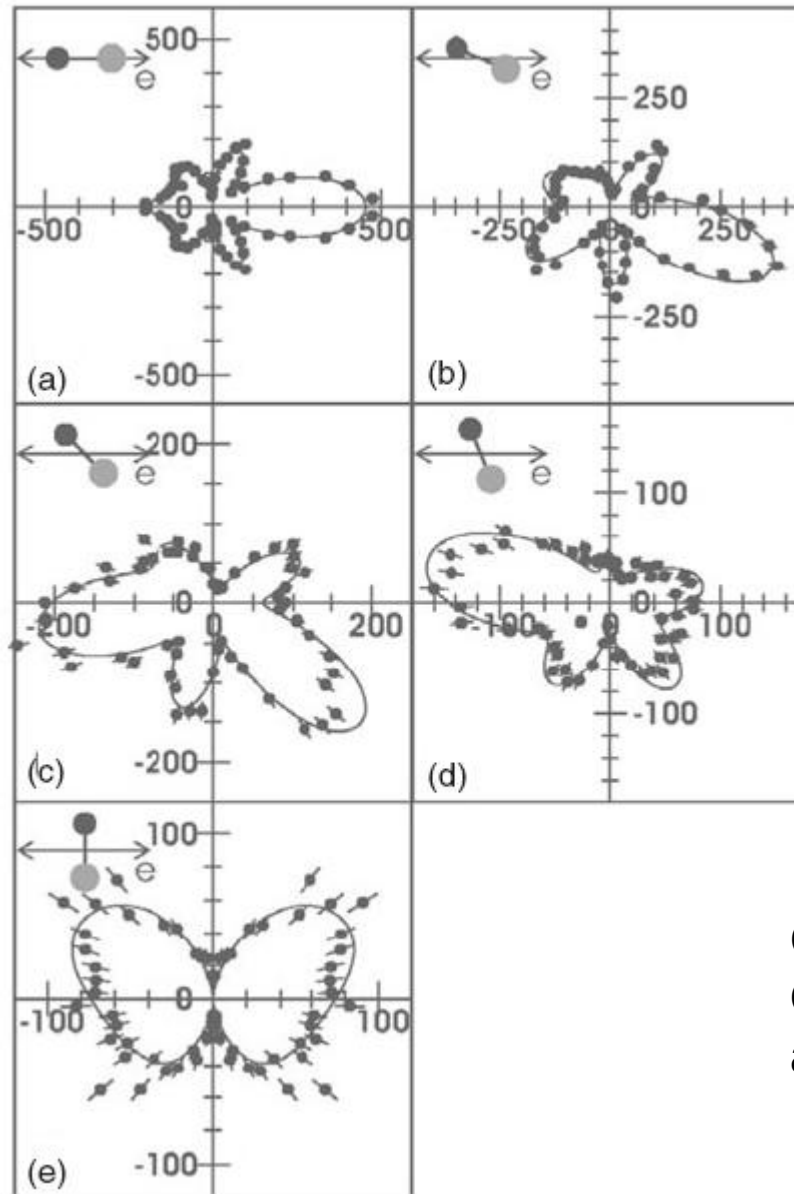
KER in coincidence with energy of one electron

line: total available energy. $IP(He) = 24.59$ eV



interpretation: 'knock-off' process like in electron-atom collisions ($e, 2e$).
Possible up to $R=1$ nm

Carbon k-shell photoelectrons from CO at 10 eV energy

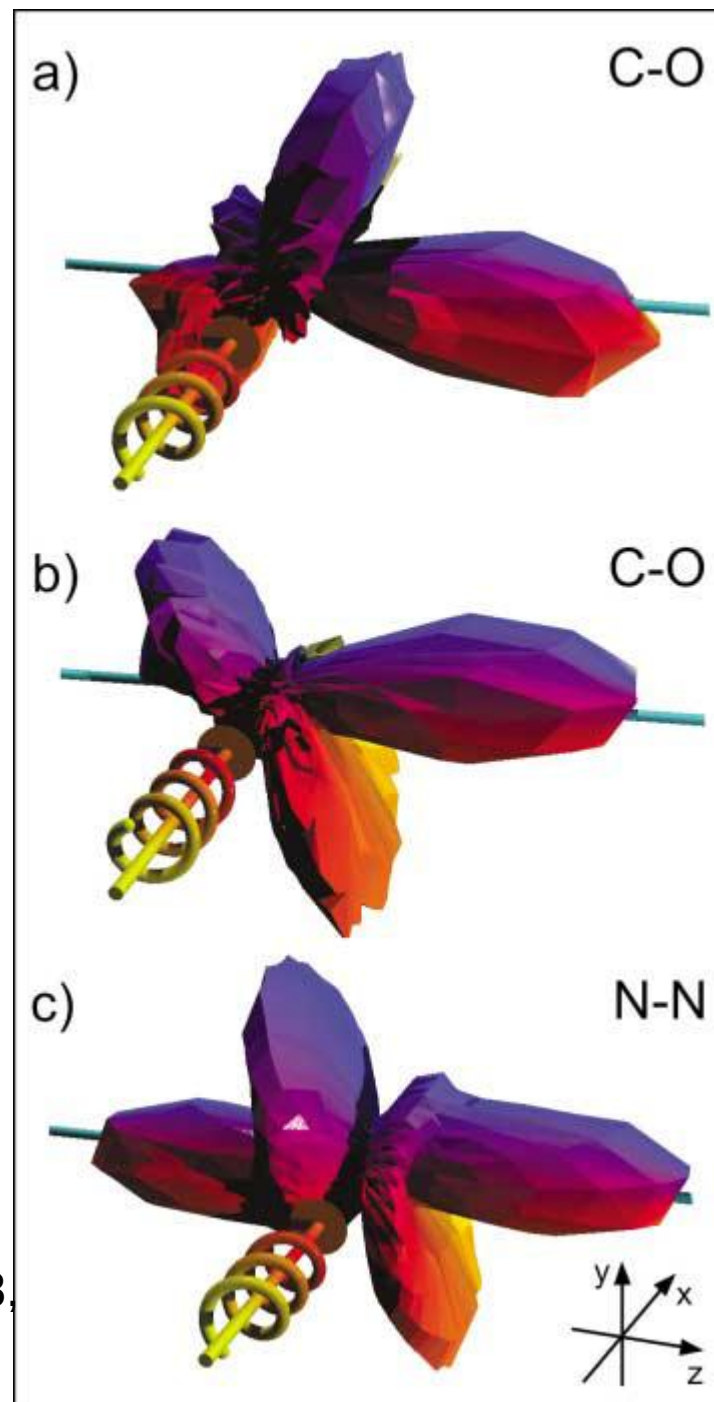


C : black
O: grey
arrow: light polarization

even the light polarization matters

a) and b): Angular distributions of C(1s) photoelectrons (10 eV kinetic energy) emitted from a CO molecule by absorption of left and right circularly polarized photons. Molecules aligned along z.

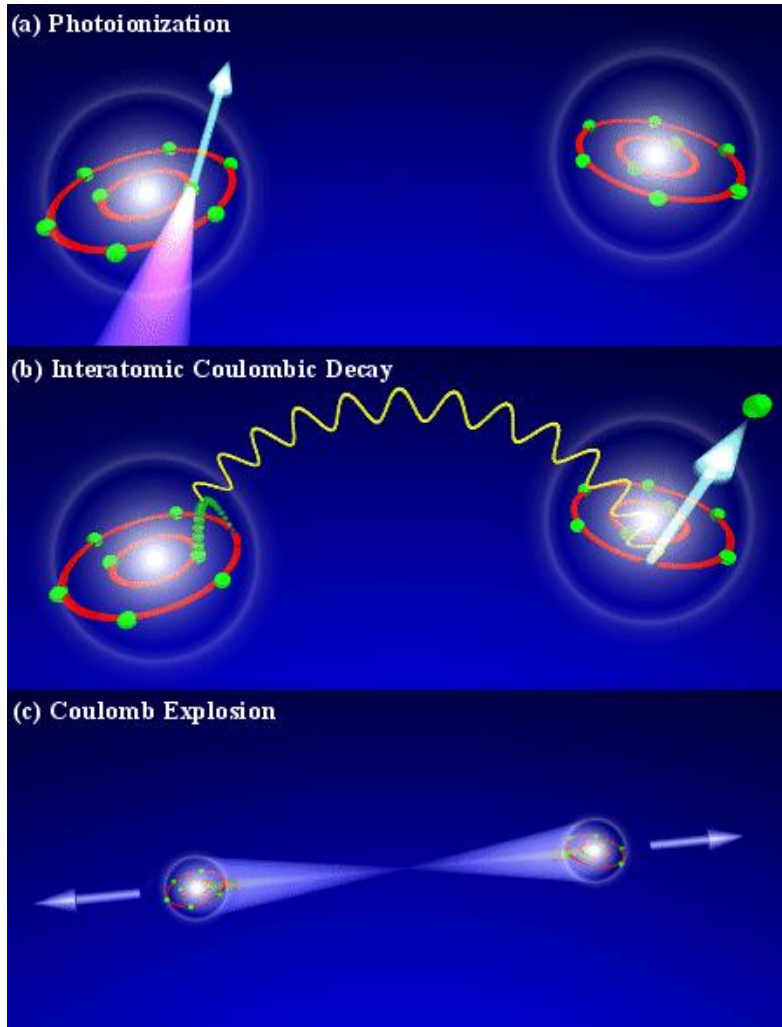
c) Analogous distribution of N (1s) photoelectrons at 9 eV from N₂



Jahnke et al., Phys. Rev. Lett. 88, 073002 (2002)

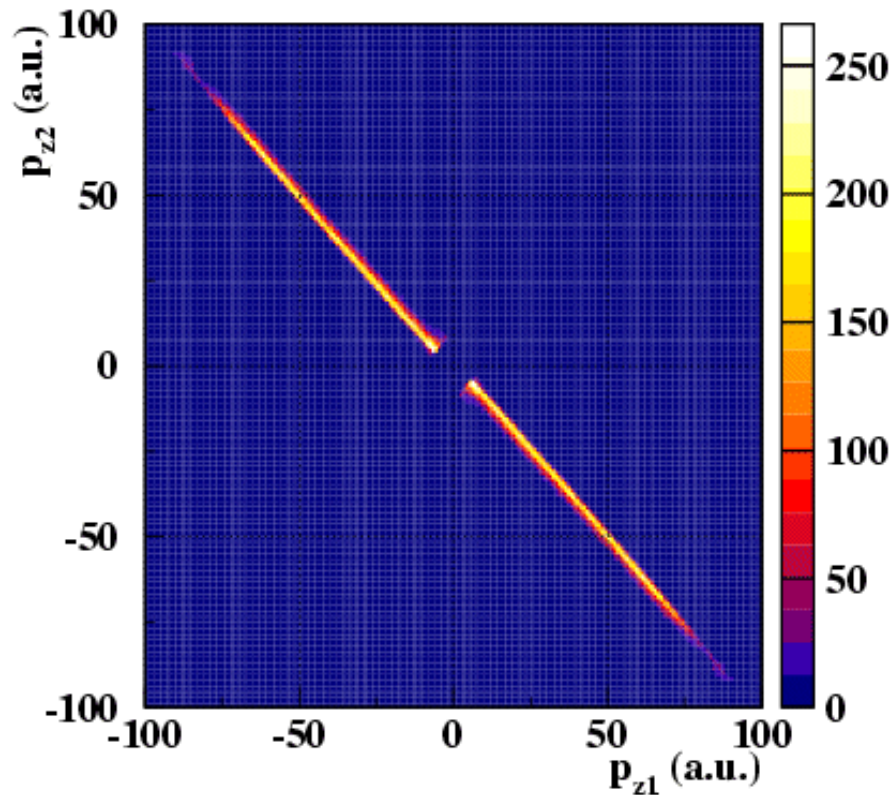
Interatomic Coulombic Decay (ICD) in Neon Dimers

well known: Auger emission, which is always from the same atom (1925)
new effect: Auger-like electron can come from a neighboring atom (1997)



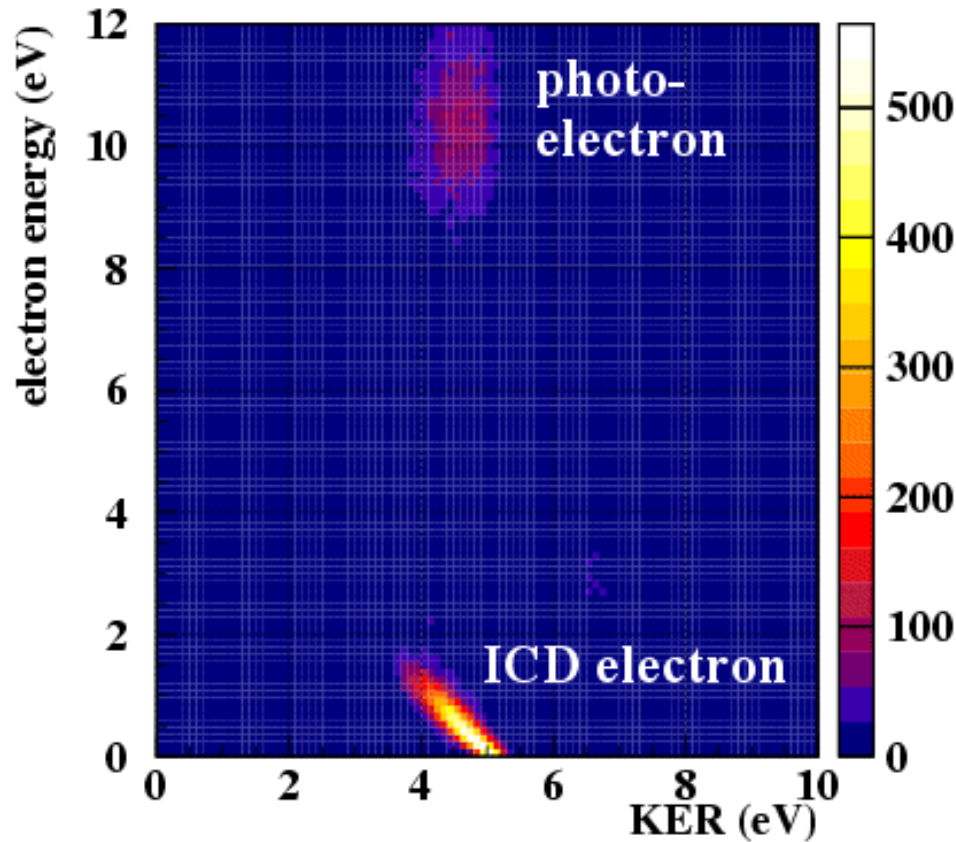
- a) Creation of a 2s hole in a neon dimer by photoionization
- b) Successive Interatomic Coulombic Decay: the 2s hole is filled by a 2p electron, the excess energy is transferred to the neighboring neon atom causing the ejection of one of its 2p electrons.
- c) Back-to-back emission of the fragments after **Coulomb explosion** of the Ne-dimer

momenta of the emitted particles are measured in coincidence



Coincidentally measured momenta of the two Ne1+ ions. The events are found along a diagonal line $p_{z1} = -p_{z2}$, where $p_{z1;2}$ is the momentum component of ion 1 and 2. This proves directly that the two ions result from a Coulomb explosion of a dimer, i.e. it unambiguously identifies step (c)

electron energy in coincidence with the kinetic energies of the ions



theory says:

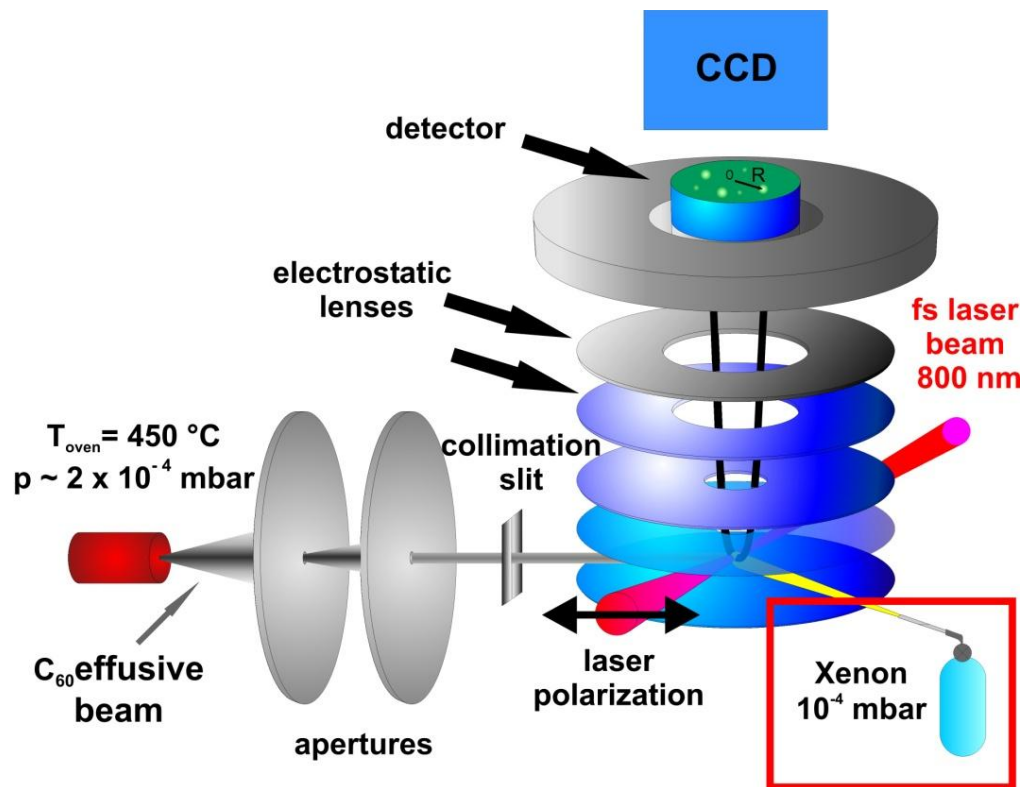
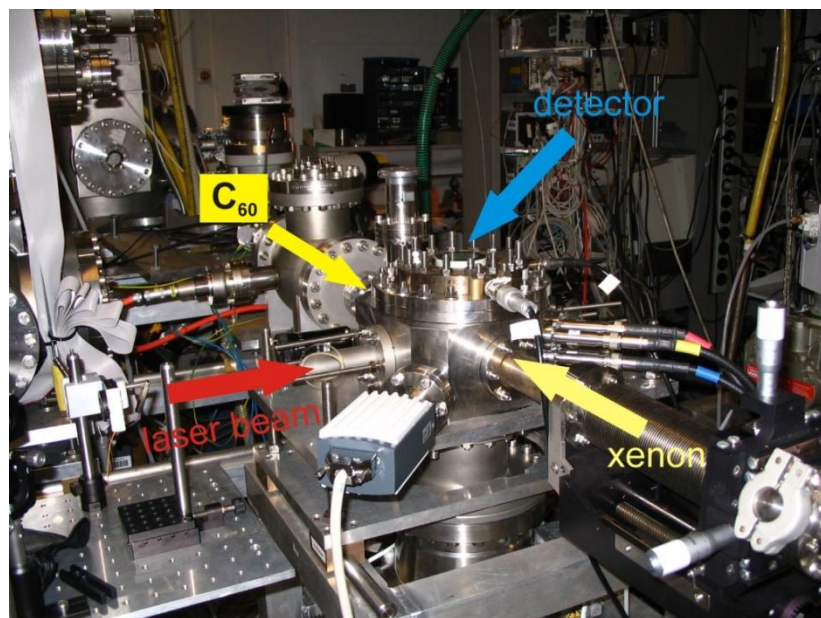
In ICD, the sum of the ICD electron's energy and the kinetic energy of the ionic fragments is a constant. Therefore by looking at the relation of the electron's energy and the kinetic energy of the ionic fragments events of ICD appear on a diagonal line

Cederbaum Theory, Hergenhahn, Dörner Experiments

last method: velocity map imaging spectrometer VMI

work by Slawomir Skruszewicz

Instrumental resolution $\Delta E_{\text{instr.}} / E = 0.07$ at 1 eV



Laser parameters:

$$\lambda = 800 \text{ nm}, \tau_{\text{pulse}} = 80 \text{ fs},$$

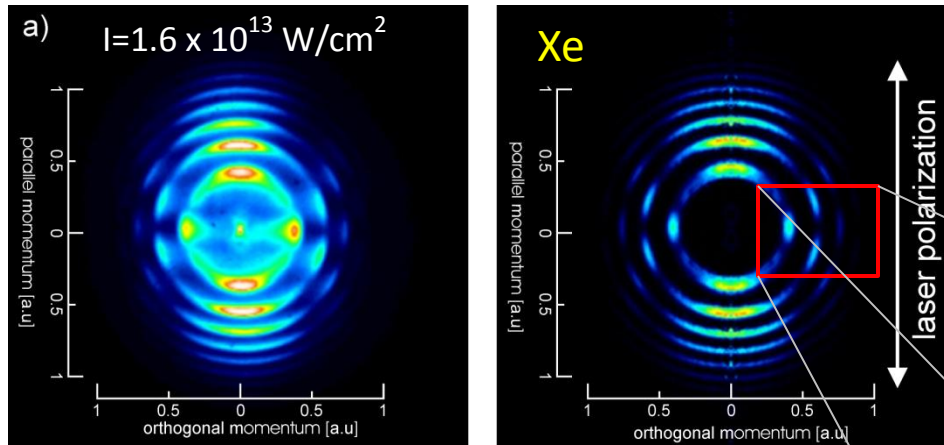
$$\Delta E_{\text{laser}} = 70 \text{ meV}$$

$$I = 10^{12} \dots 10^{14} \text{ W/cm}^2$$

- brightness $\leftarrow$ photoelectron yield
- spot position R $\leftarrow$ photoelectron momentum
- adjustable kinetic energy detection range

above-threshold ionization in Xenon atoms

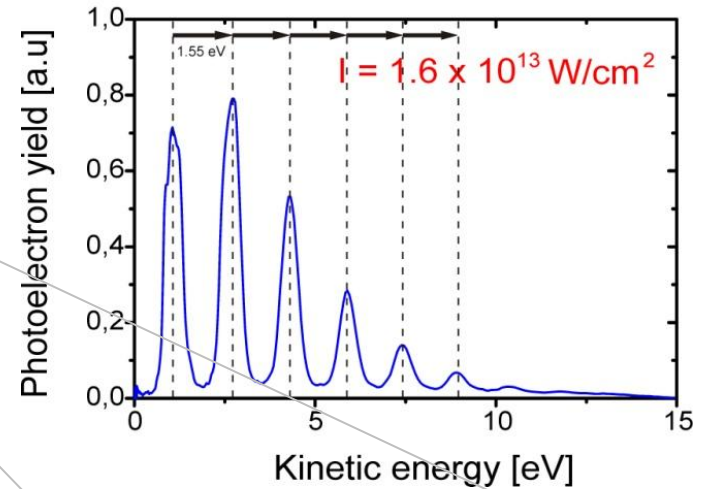
Imaging Spectra



raw

deconvoluted by an
onion peeling algorithm

Angle-Integrated Spectra



Energy spectrum shows signatures of above threshold ionization

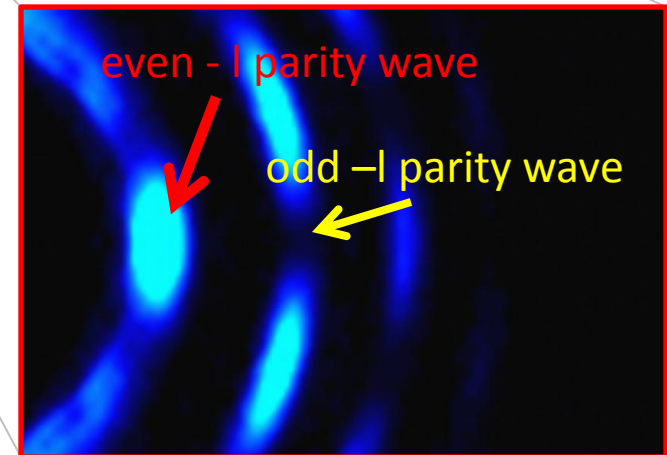
Peaks are spaced by photon energy

Rich structure in **angular-resolved spectrum**

Enhanced emission in direction of laser polarization axis

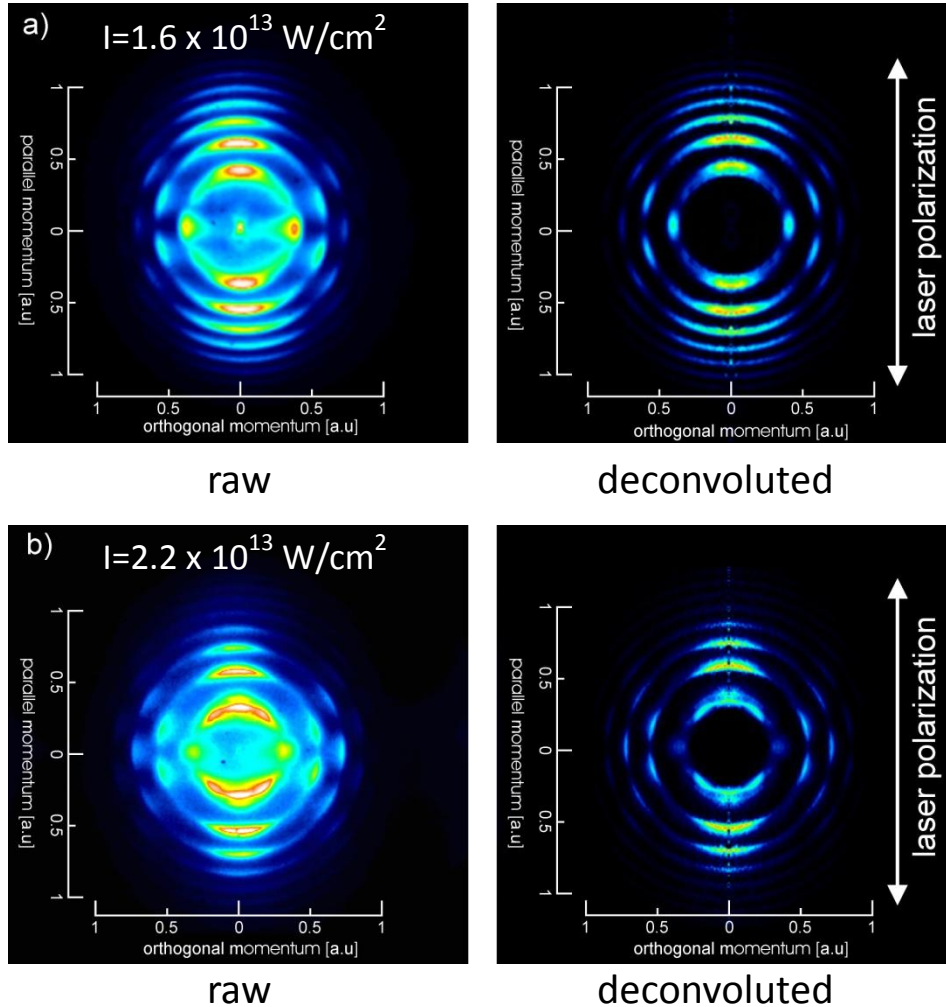
Each ring has own fingerprint

Change in parity of outgoing electron wave

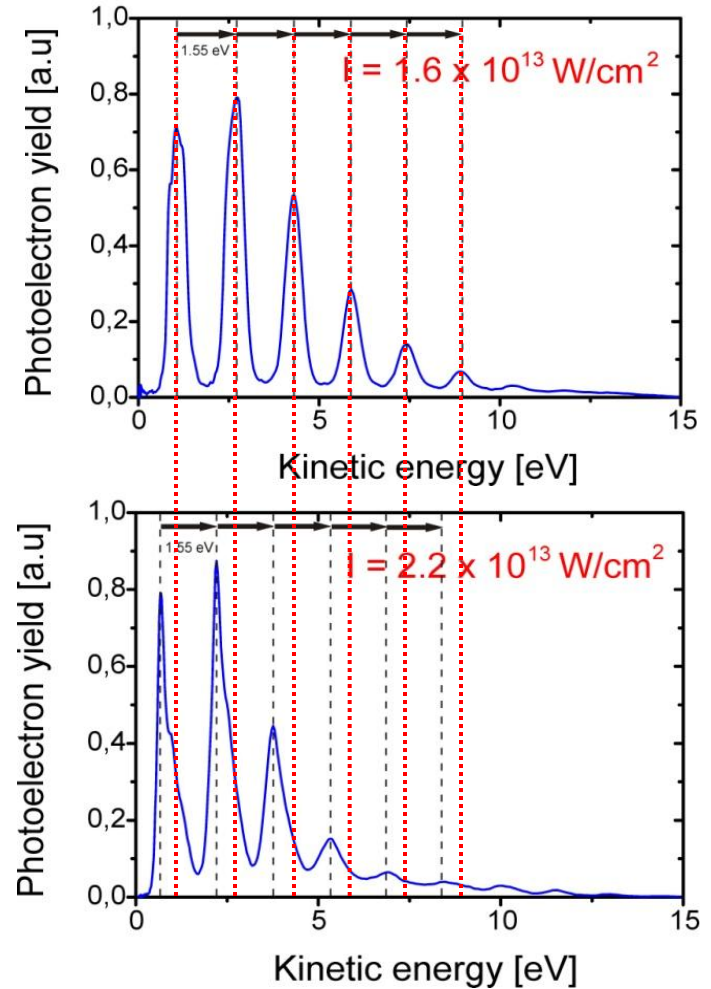


above-threshold ionization in Xenon

Imaging Spectra



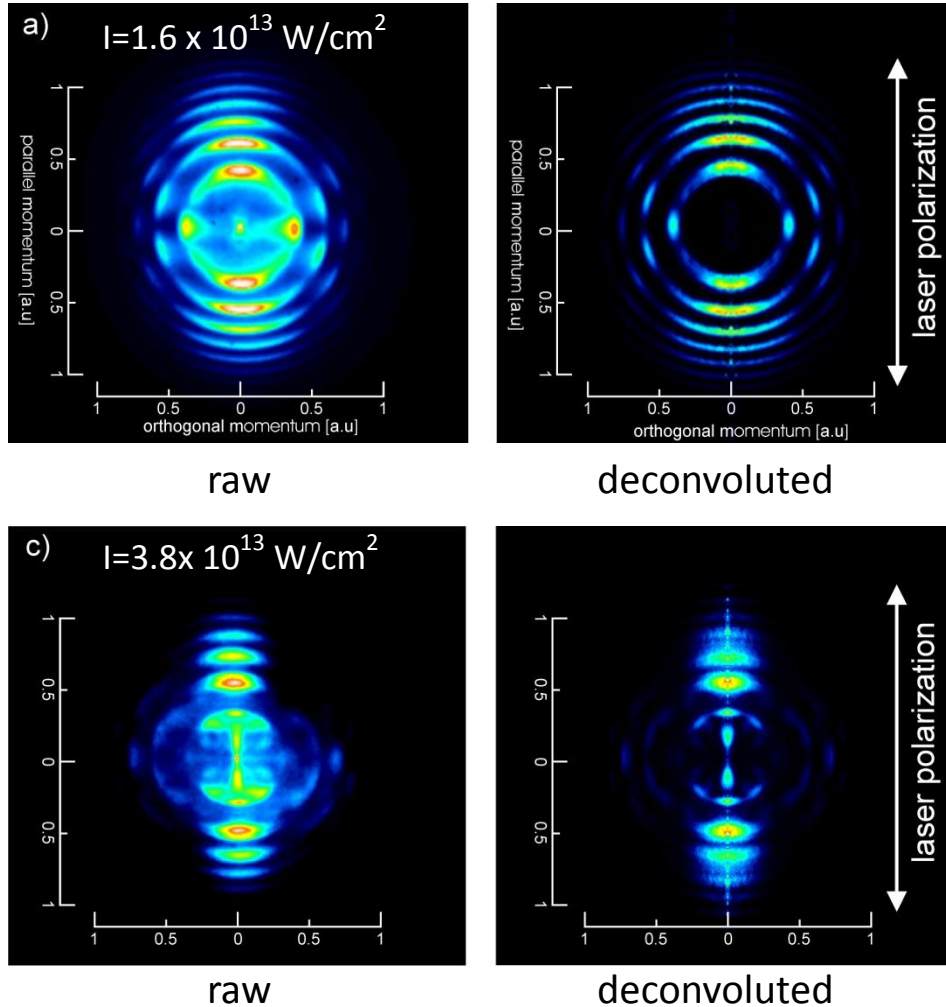
Angle-Integrated Spectra



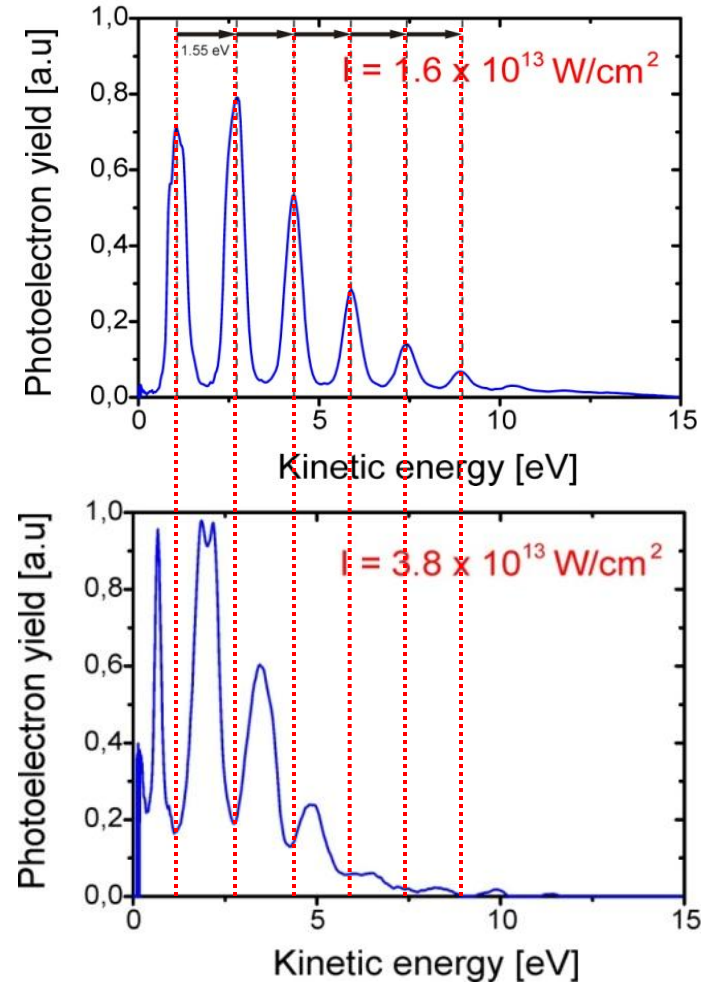
Peak position changes as function of laser intensity

above-threshold ionization in Xenon

Imaging Spectra



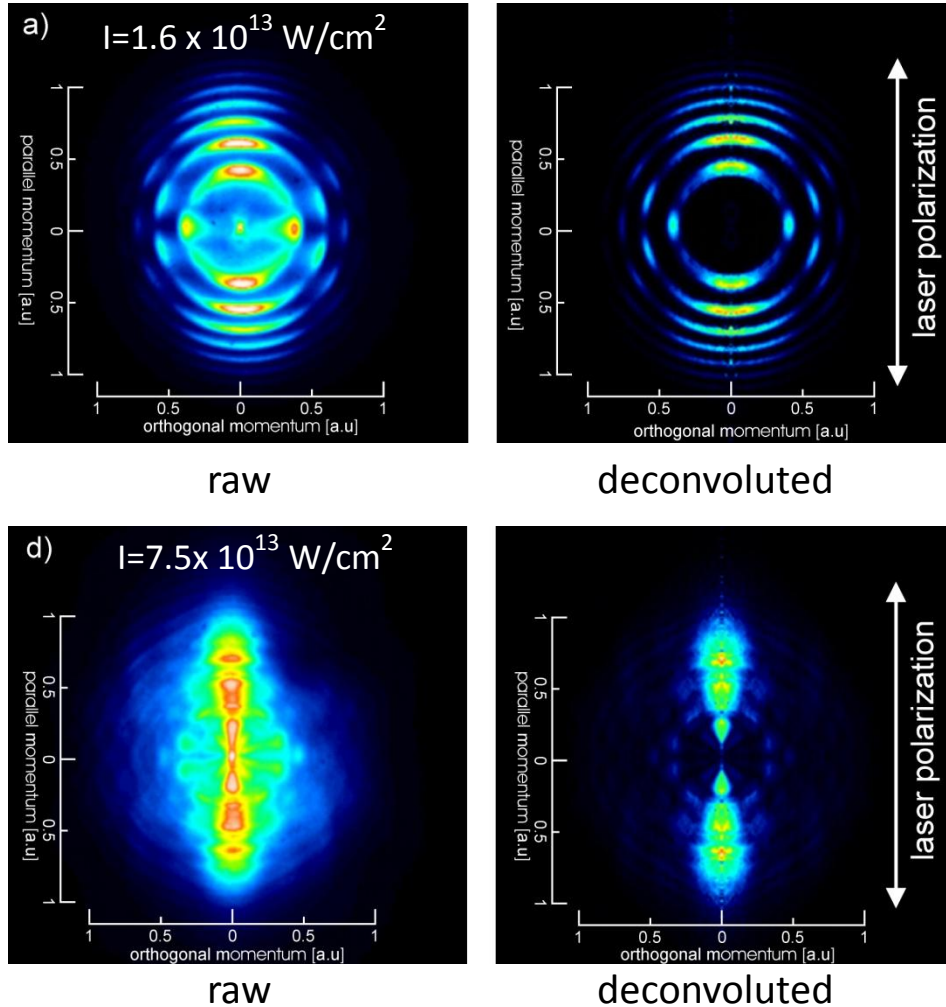
Angle-Integrated Spectra



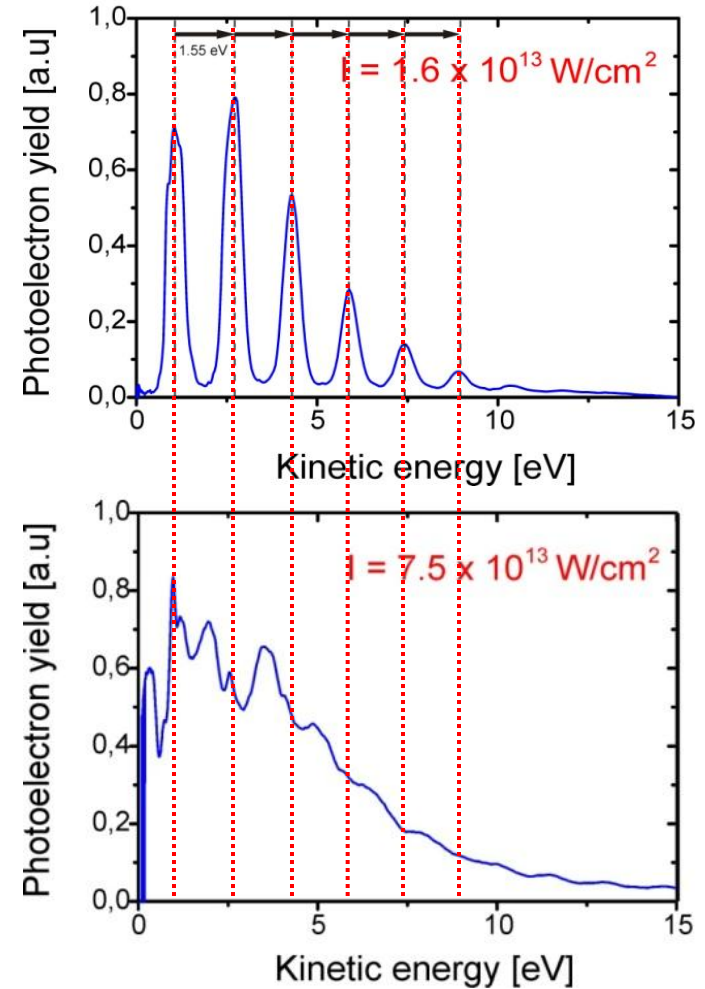
Angular pattern changes as function of laser intensity

above-threshold ionization in Xenon

Imaging Spectra

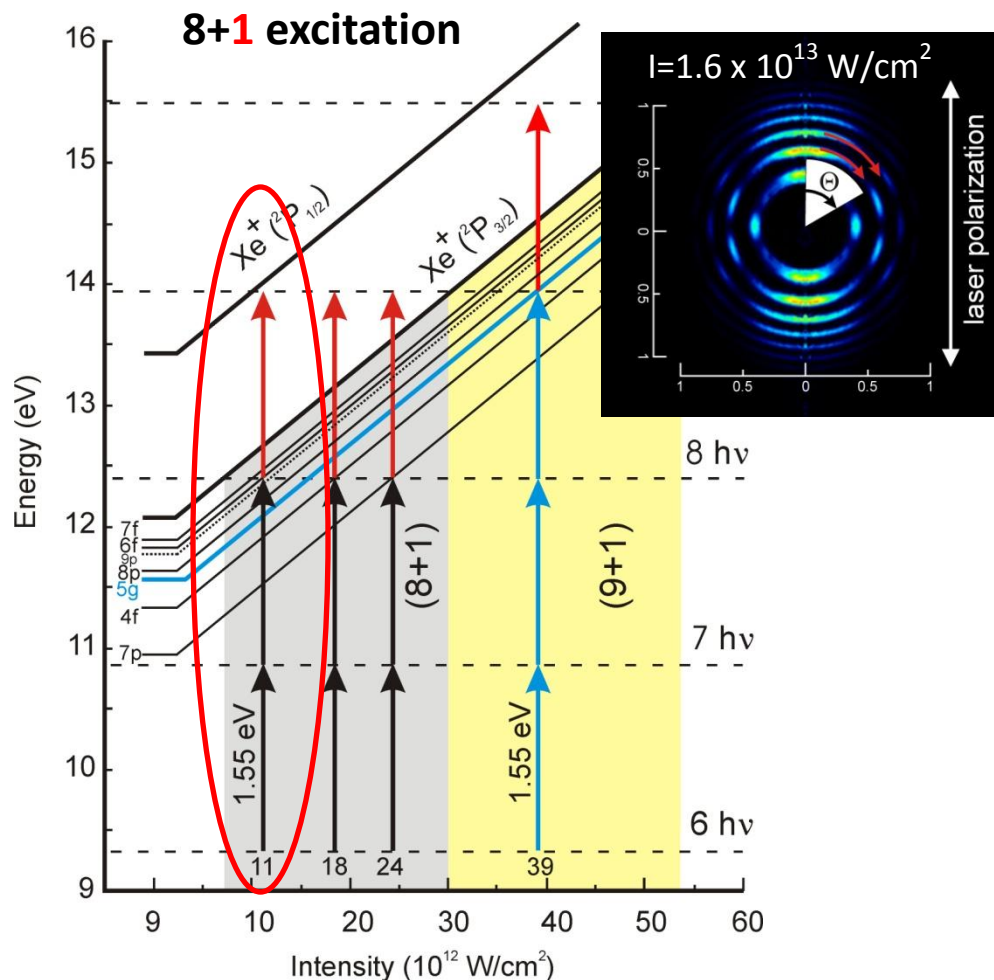


Angle-Integrated Spectra

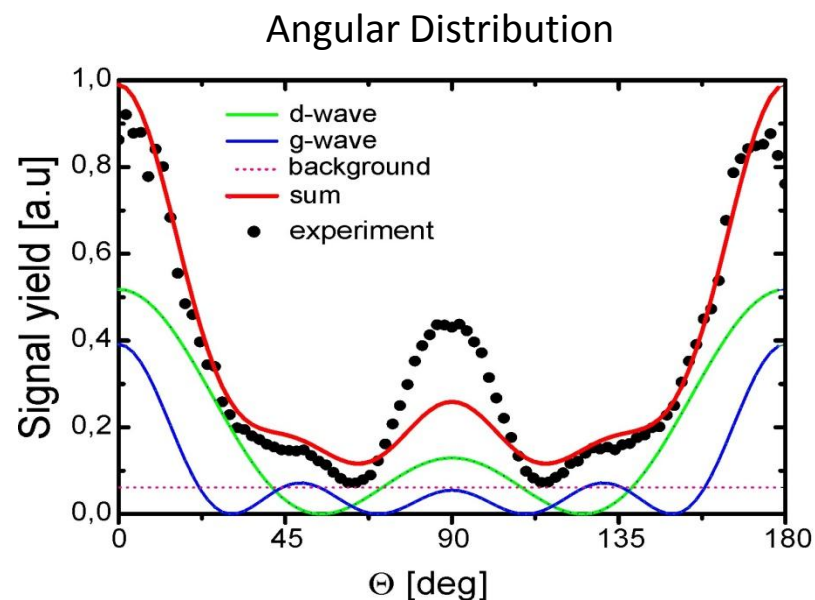
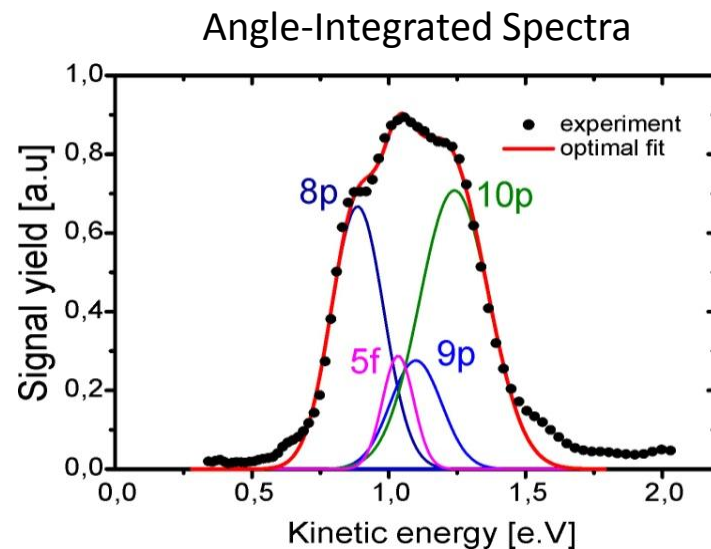


ATI pattern washes out at high laser intensity

Freeman resonances

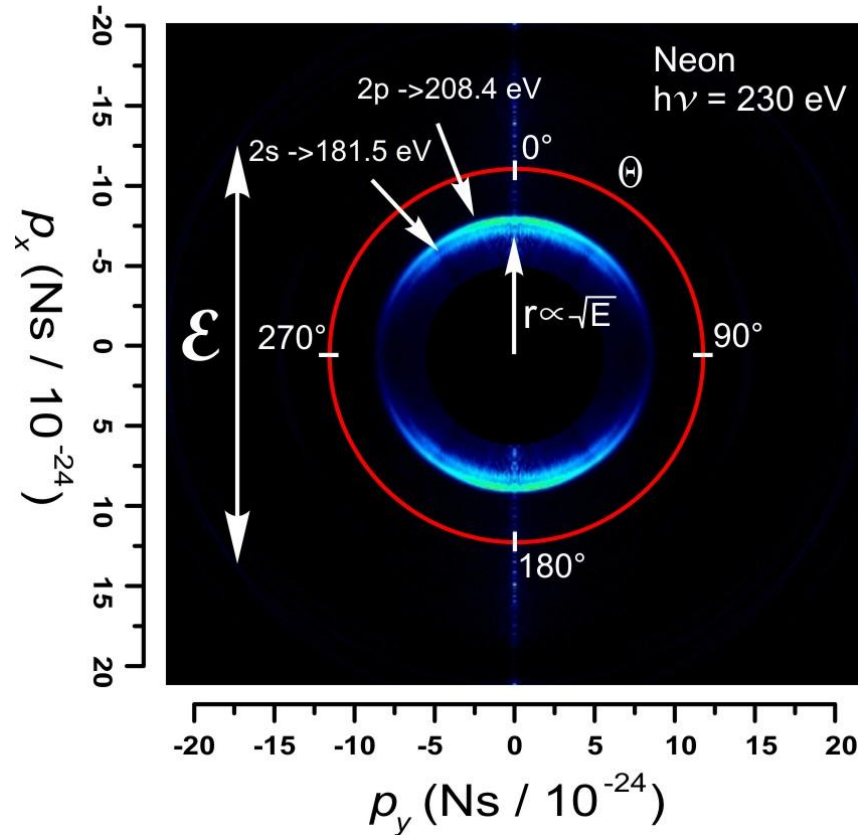


Analysis supports assumption of even- l parity outgoing electron wave

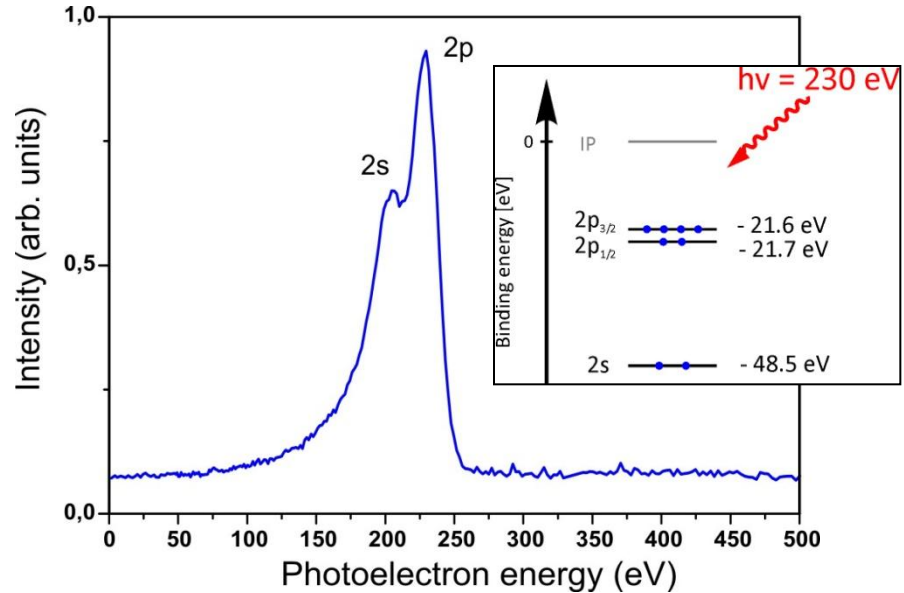


high photon energies - Neon atoms

Imaging spectrum of Neon atoms $h\nu = 230$ eV



Photoelectron spectrum of Neon



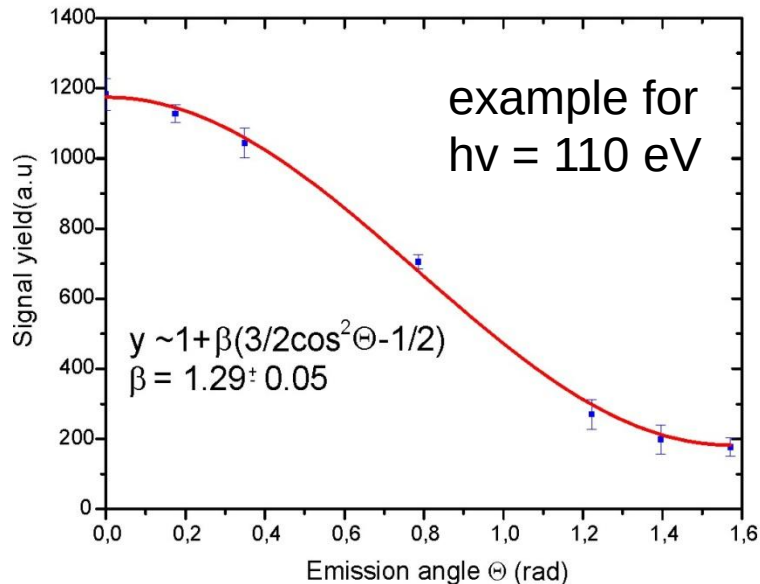
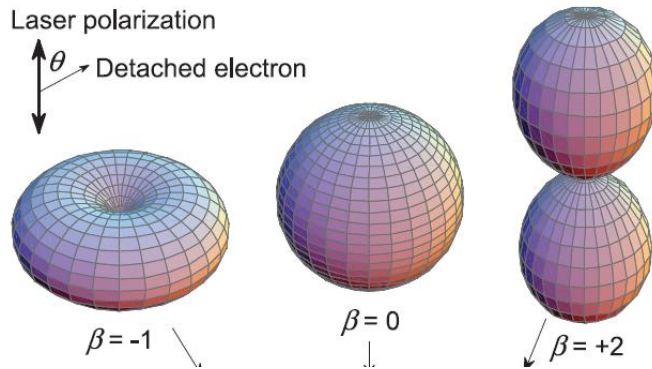
- single photon ionization of 2p and 2s
- difference in total yield due to different ionization cross sections
- spin-orbit splitting of p-state not resolved due to high electron energies

Neon - angular distributions

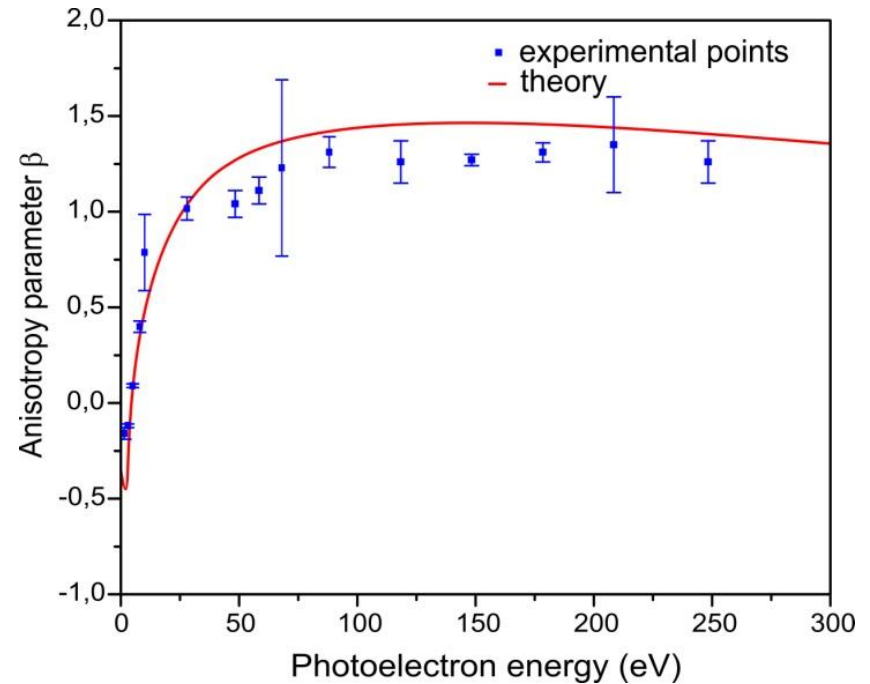
angular distribution:

$$I(\Theta) = (1 + \beta P_2(\cos \Theta))/4\pi$$

with $P_2(x) = (3x^2 - 1)/2$ the second order Legendre polynomial



anisotropy parameter β



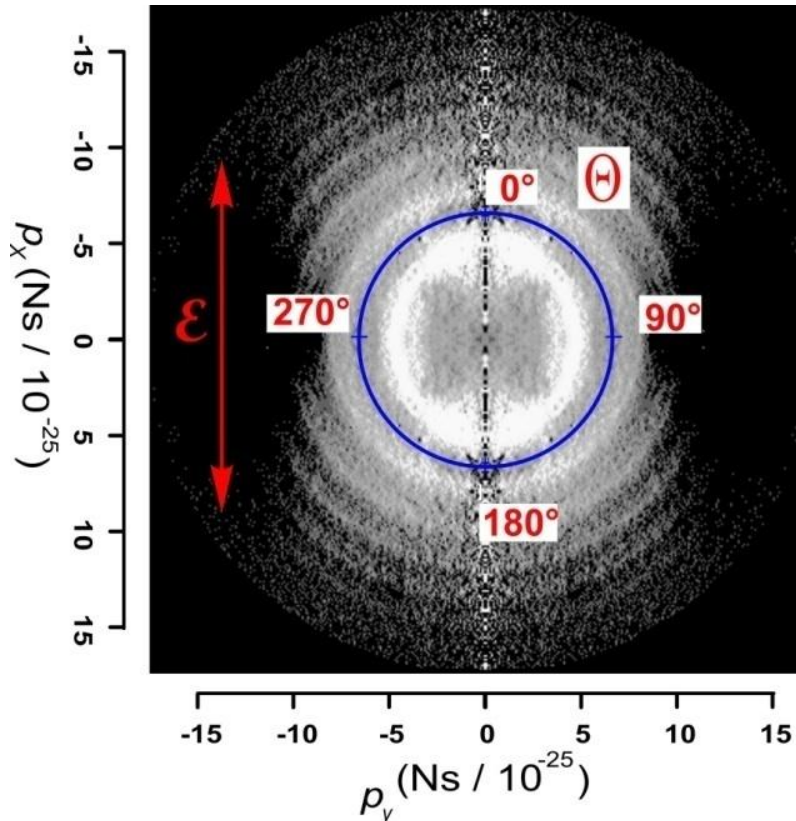
- strong dependence of β below 50eV
- anisotropy parameter increases from -0.2 up to 1 for low energies
- for higher energies β reaches 1.3
- good agreement with theory

theory: D. J. Kennedy and S. T. Manson Phys. Rev. A, **5**, 227, (1972)

C₆₀ in intense laser fields

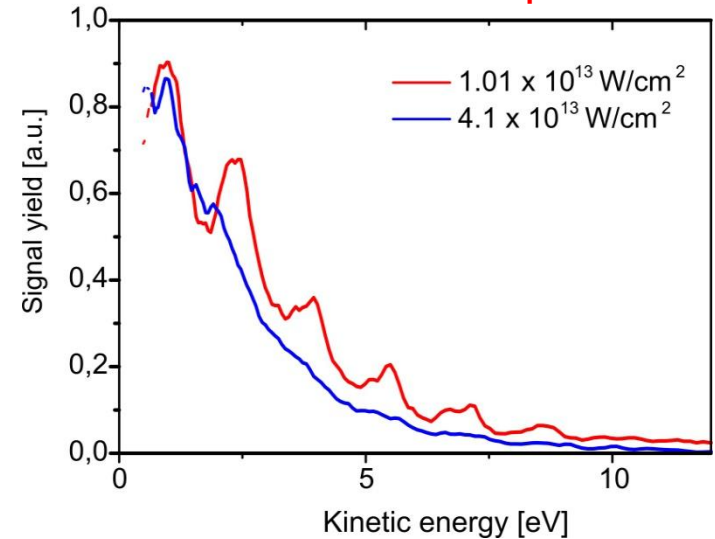
... at low electron energies

fs laser pulses $t_{\text{FWHM}} = 52$ fs

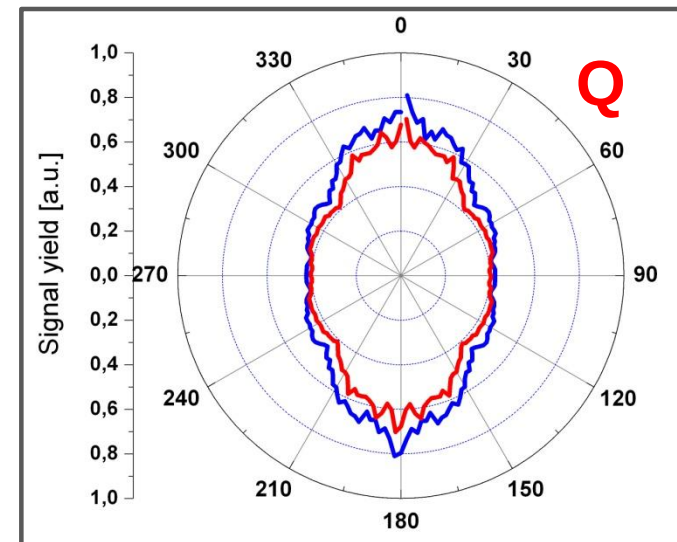


- observation of discrete peaks at lower laser intensity
- peaks wash out as intensity is increased
- enhancement emission along laser polarization

Photoelectron spectrum



Angular distribution



really the end of atomic physics

now: cluster physics

in some respect
clusters can be considered
as giant atoms

