Multipole mixing and polarization effects

in the x-ray emission from highly-charged ions

S. Fritzsche

Universität Oulu und GSI Darmstadt

Moscow, 14th May 2012

Thanks to Dynasty Foundation

FAIR: Facility for Antiproton and Ion Research

GSI **Helmholtz Centre for Ion Research**

HELMHOLTZ GEMEINSCHAFT

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electron-photon interaction

electron-electron interaction

Thanks to:

A.N. Grum-Grzhimailo, N.M. Kabachnik, A. Surzhykov (theory)

T. Stöhlker and AP@GSI (experiment)

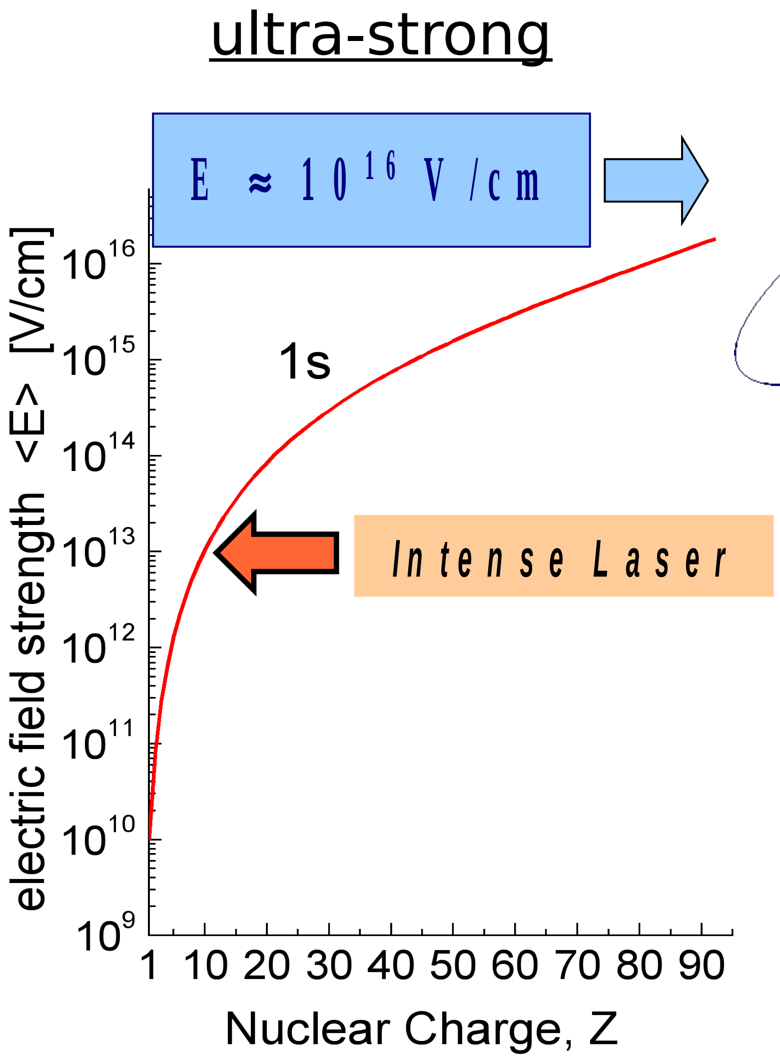
Deutsche Forschungsgemeinschaft DFG

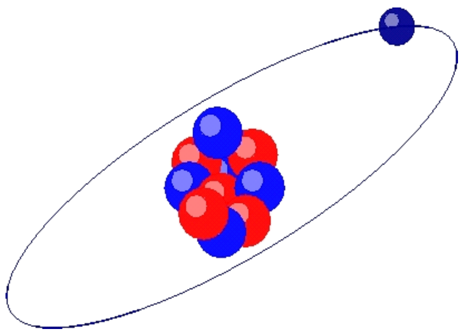
GSI

SUOMALAINEN TIEDEAKATEMIA *1908*

Highly-charged ions provide a „exciting“ tool

-- for probing the quantum dynamics in strong fields





Highly-charged ions provide a „exciting“ tool

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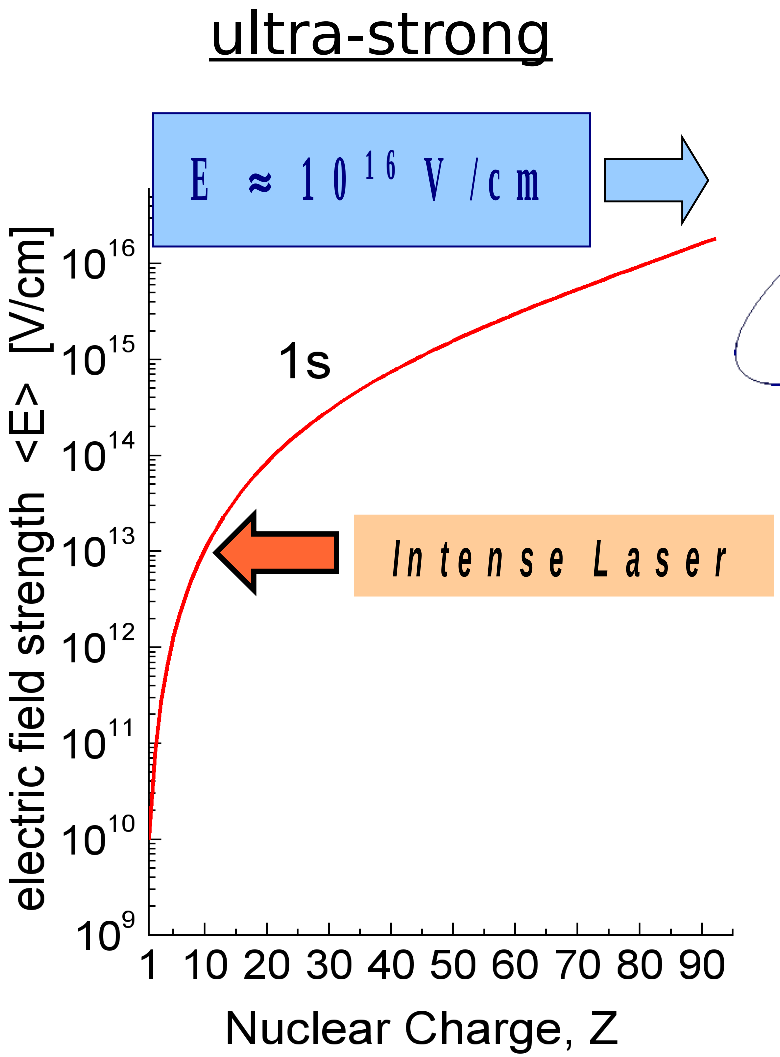
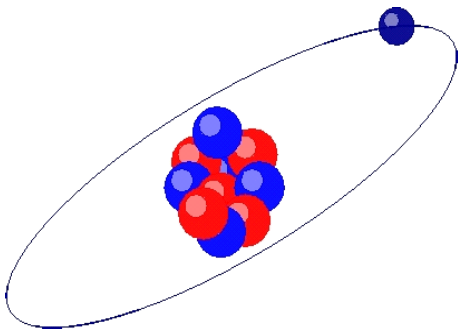


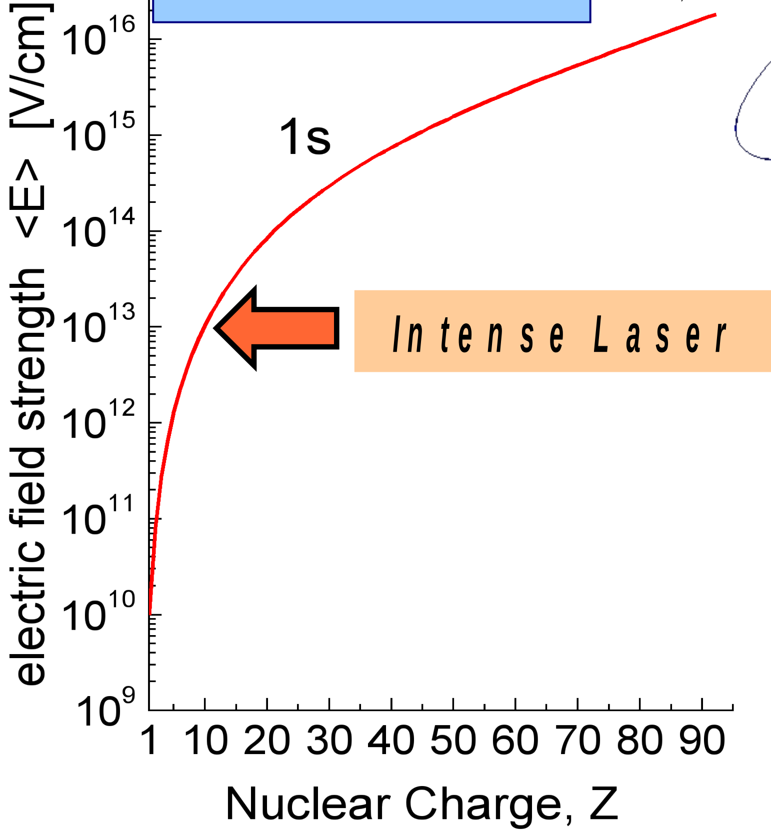


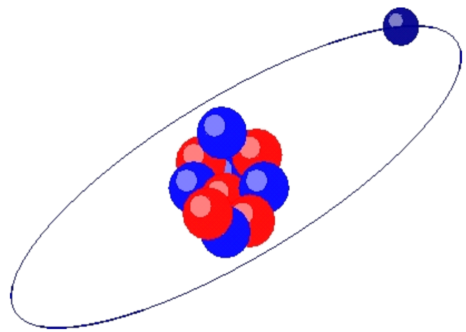
Highly-charged ions provide a „exciting“ tool

-- for probing the quantum dynamics in strong fields

ultra-strong

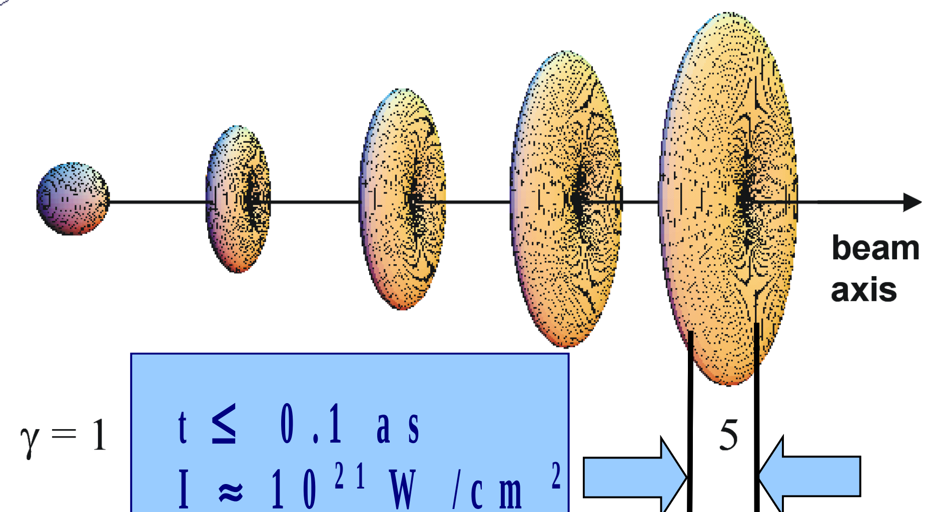
$E \approx 10^{16}$ V/cm





ultra-short

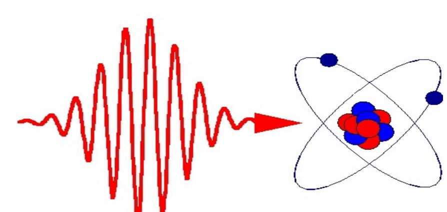
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$



$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm^2

In contrast to:

few-cycle laser pulses



Interaction of atoms and ions with the radiation field

-- typically based upon the dipole approximation

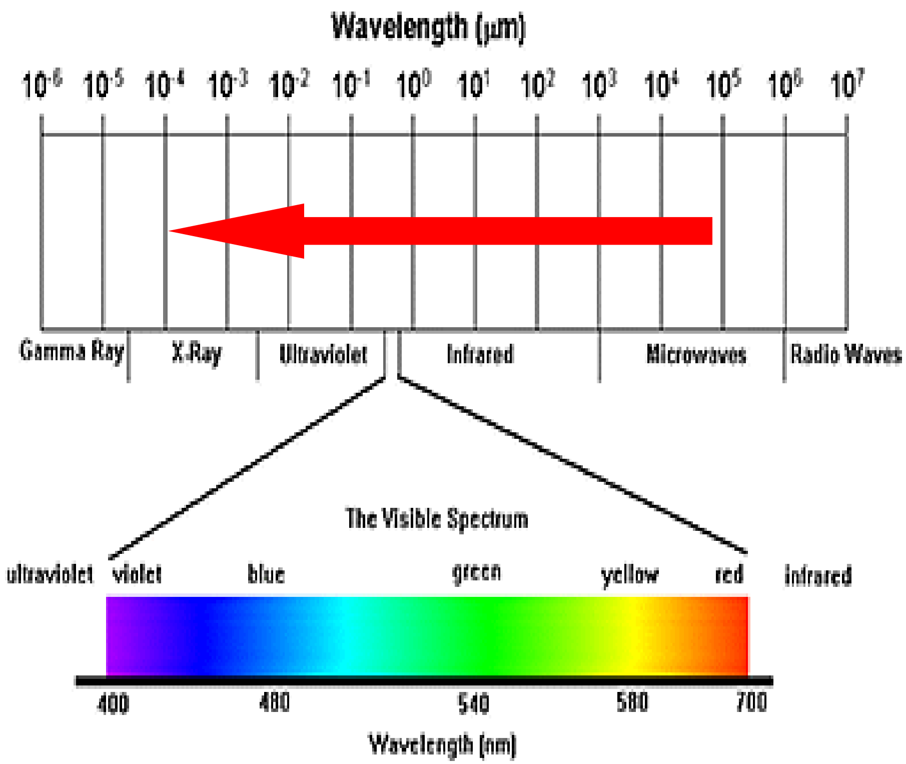
Transition matrix element can be evaluated by making a “multipole expansion” of the electron-photon interaction operator:

$$M_{ab} = \int \psi_a^+(r)\, \alpha\, \varepsilon\, e^{i\,\mathbf{kr}}\, \psi_b(r)\, dr$$

$$e^{i\,\mathbf{kr}} = 1 + i\,\mathbf{kr} + \frac{1}{2}(i\,\mathbf{kr})^2 + \ldots$$

electric dipole term

magnetic dipole and electric quadrupole terms



X-rays: $k \approx 10^8\ cm^{-1}$

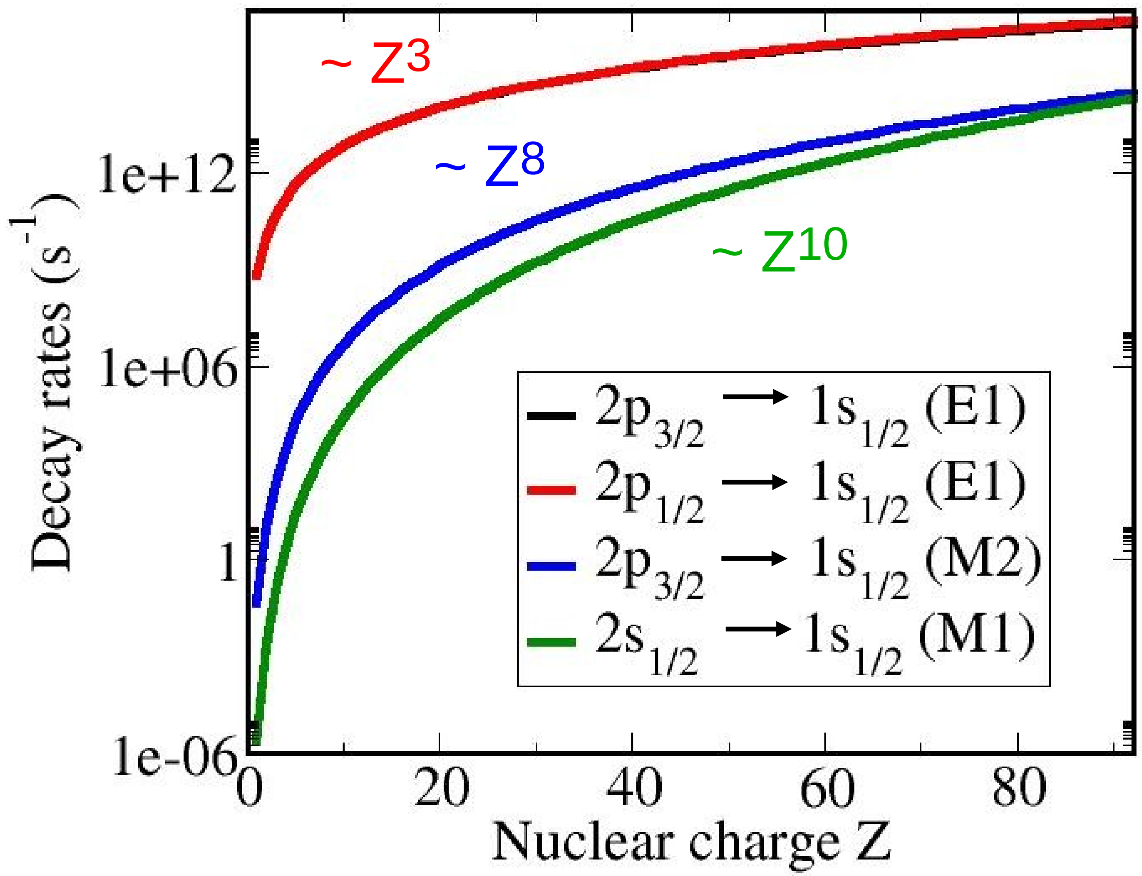
γ-rays: $k > 10^9\ cm^{-1}$

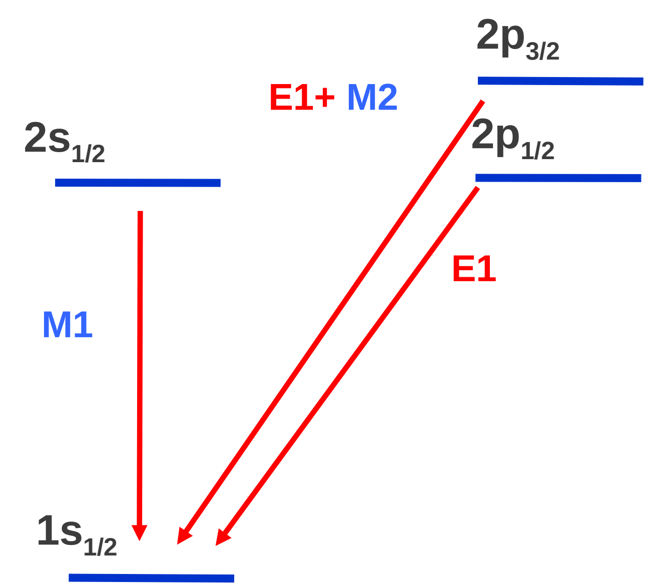
$$kr \approx 1$$

$$e^{i\,\mathbf{kr}} = 1 + i\,\mathbf{kr} + \frac{1}{2}(i\,\mathbf{kr})^2 + \ldots = E1 + M1 + E2 + M2 + E3 + \ldots.$$

Interaction of atoms and ions with the radiation field

... but higher multipoles become rapidly important for high-Z ions





$$e^{i\,\mathbf{kr}} = 1 + i\,\mathbf{kr} + \frac{1}{2}\left(i\,\mathbf{kr}\right)^2 + \ldots = E1 + M1 + E2 + M2 + E3 + \ldots.$$

Interaction of atoms and ions with the radiation field

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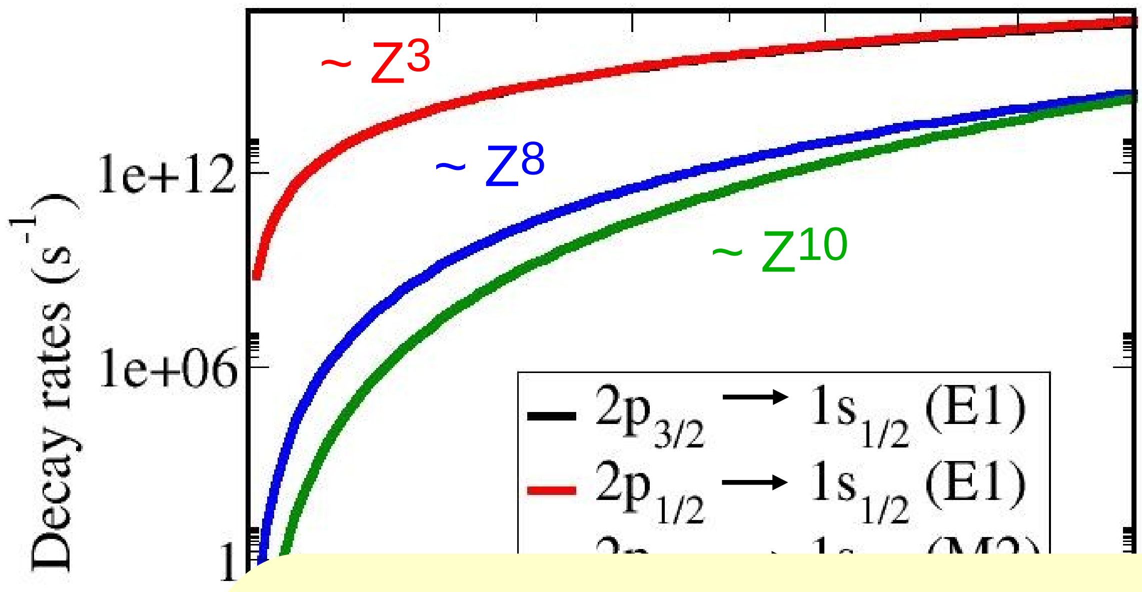
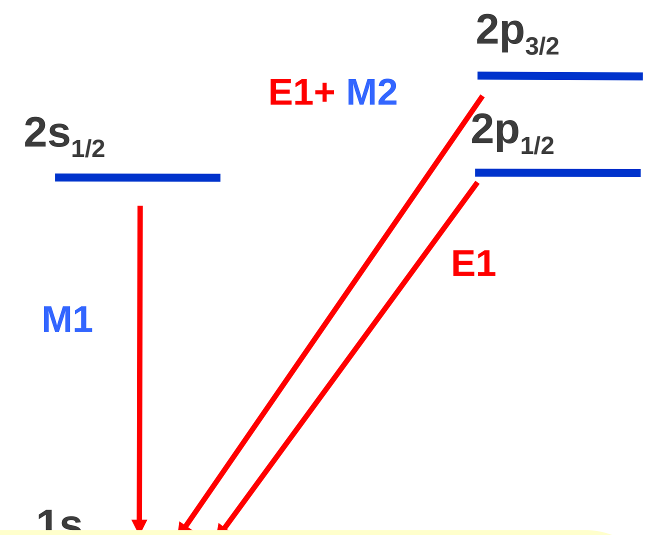




Plan of this lecture

I. “Relativistic electrons”: Electronic structure and collisions

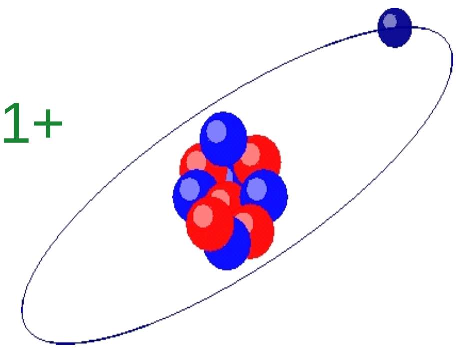
II. Electron capture into bare ions

III. Alignment of high-Z ions: Can we `see' the multipoles directly ?

IV. Dielectronic recombination: Testing the electron-electron interaction

"Relativistic electrons": Electronic structure

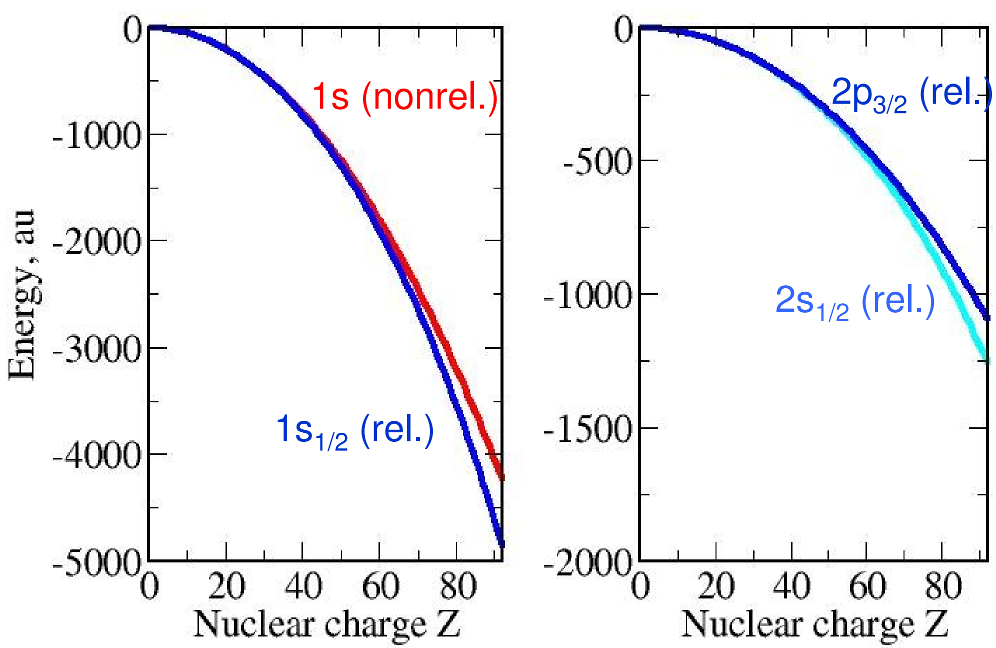
U^{91+}



- Velocity: $v = (\alpha Z)\, c$ ... speed of light
- Relativistic contraction
  ... direct vs. indirect effect
- Fine structure splitting (Dirac):

$$\psi(\mathbf{r}) = \frac{1}{r} \begin{bmatrix} P_{\varepsilon\kappa}(r)\, \Omega_{\kappa m}(\theta,\phi) \\ i\, Q_{\varepsilon\kappa}(r)\, \Omega_{-\kappa m}(\theta,\phi) \end{bmatrix},$$

$$\kappa = \pm(j+1/2) \qquad \text{für} \quad l = j \pm 1/2$$



“Relativistic electrons”: Electronic structure

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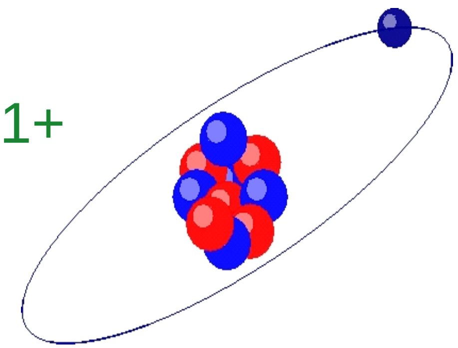
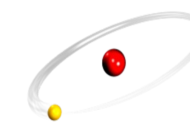


- Velocity: $v = (\alpha Z)\, c$ ... speed of light
- Relativistic contraction
  ... direct vs. indirect effect
- Fine structure splitting (Dirac):

hydrogen

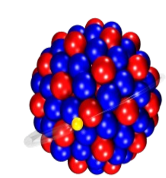


Z=1
E_b = 13.6 eV
$Z \cdot \alpha \ll 1$

- Test field of „atomic” QED

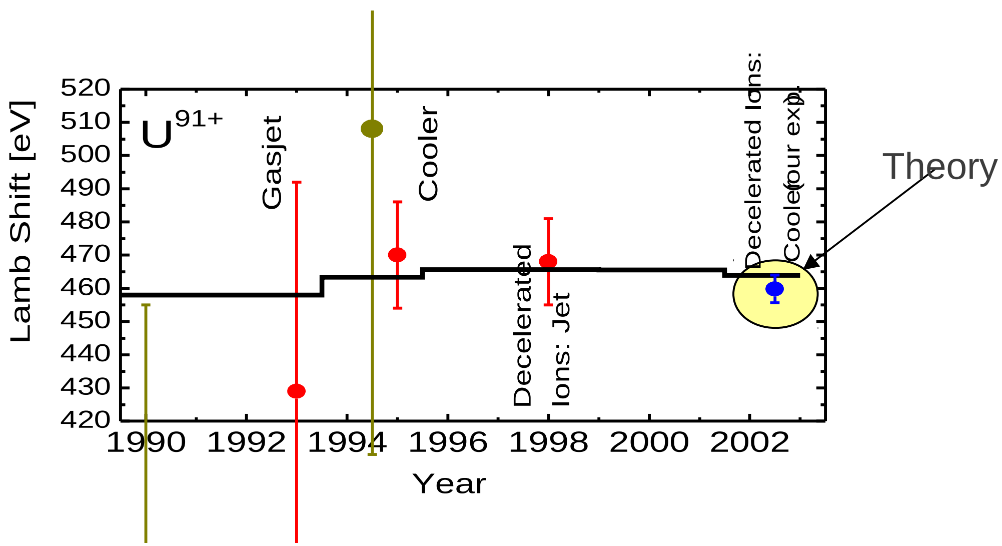
  1s Lamb shift
  g-factor
  hyperfine structure

uranium ion



Z=92
E_b = 132 keV
$Z \cdot \alpha \approx 1$

➡ towards supercritical fields



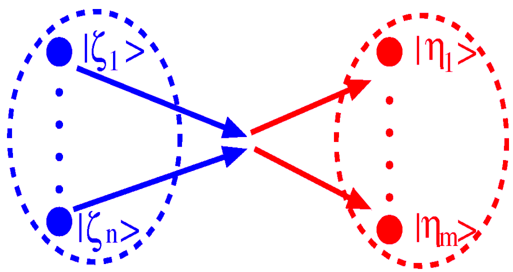
A. Gumberidze et al., PRL 94 (2005) 223001.

Relativistic collisions: A theoretician's viewpoint

Initial state

$\left(t \rightarrow -\infty\right)$

$\hat{\rho}_i$



Final state

$\left(t \rightarrow +\infty\right)$

$\hat{\rho}_f$

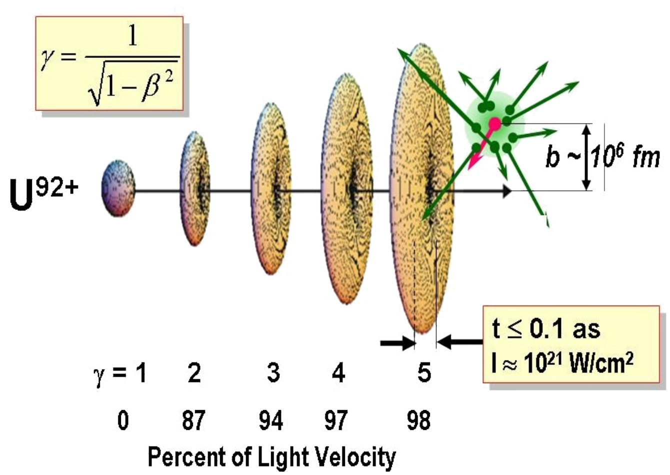
$\hat{S}$ - scattering operator

$$\hat{\rho}_f = \hat{S}\,\hat{\rho}_i\,\hat{S}^{+}$$

ρ = (μ_S, J, J'; E; l, μ_l ... density matrix)

Ensemble of collision systems: requires statistical description

for example, h-like U^{91+} + e^- ⟶ he-like U^{90+}



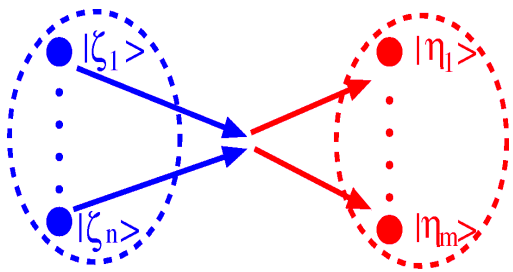
Versatile tool to study the dynamics under extreme conditions !

Relativistic collisions: A theoretician's viewpoint

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



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$\rho = (\mu_S, J, J'; E; l, \mu_l$ ... density matrix$)$

Measurement of physical properties:

- 'detector operator' describes the experimental setup: $\hat{P} = |\epsilon><\epsilon|$
- probability to get a 'click' at the detectors:

$$W = Tr\left(\hat{P}\,\hat{\rho}_f\right) = \sum_{\eta_1 \ldots \eta_m} \langle \eta_1 \ldots \eta_m | \hat{P}\,\hat{\rho}_f | \eta_1 \ldots \eta_m \rangle$$

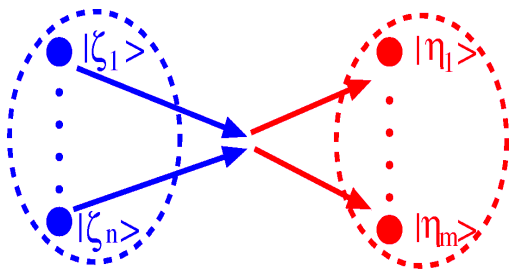
- Can be used easily to accompany the system through several (or even time-dependent) interactions, including the capture or emission of photons, electrons, etc. !

Relativistic collisions: A theoretician's viewpoint

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



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$$\sigma \sim \sum_{polarization} \int d\Omega\, |M|^2$$

total cross sections

$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

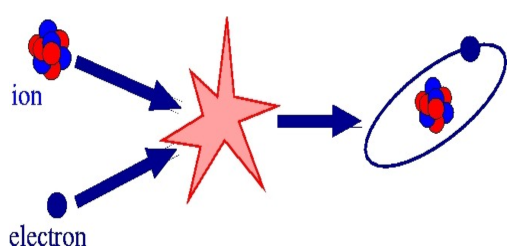
angular distribution

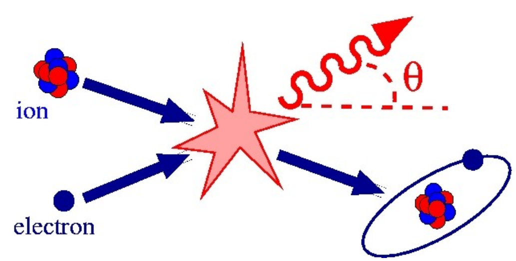
$$\sim\ |M|^2$$

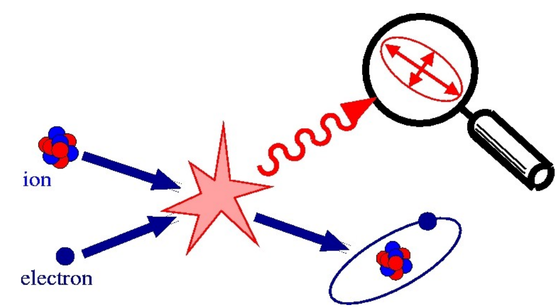
No summation over polarization states !

polarization & alignment

... simply differ in what is „averaged over“ (traced out) !







Relativistic collisions: A theoretician's viewpoint

Initial state

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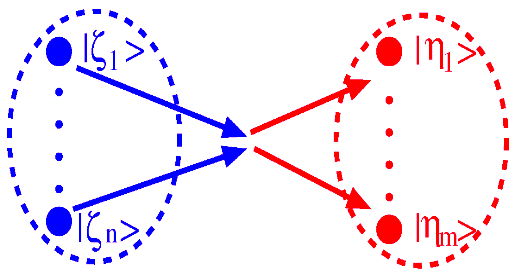

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angular distribution

$$\sim |M|^2$$

No summation over polarization states !

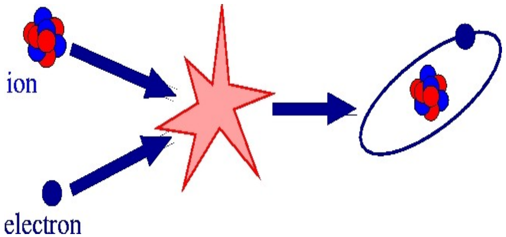
polarization & alignment

Electron-ion collision experiments at GSI and elsewhere:

- Radiative electron capture: Exploring the electron-photon interaction
- Projectile excitation: Testing the Lorentz-transformed „Coulomb field“
- Dielectronic recombination of high-Z ions: A detailed view on the electron-electron interactions

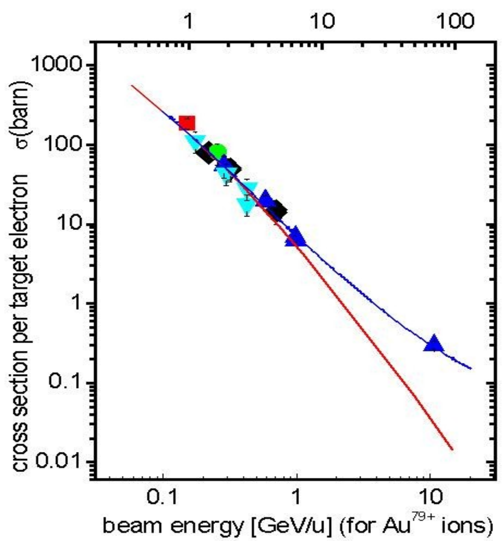
Electron capture by bare ions

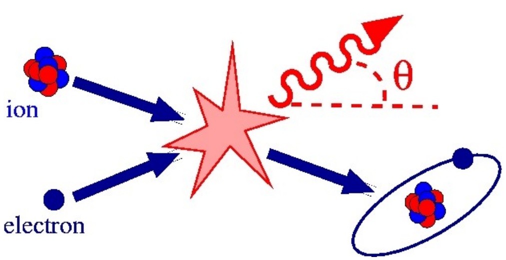
-- Exploring the electron-photon interaction



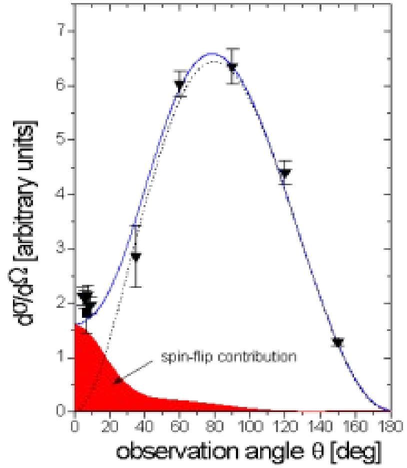
total cross sections

$$\sigma \sim \sum_{polarization} \int d\Omega \, |M|^2$$





angular distributions

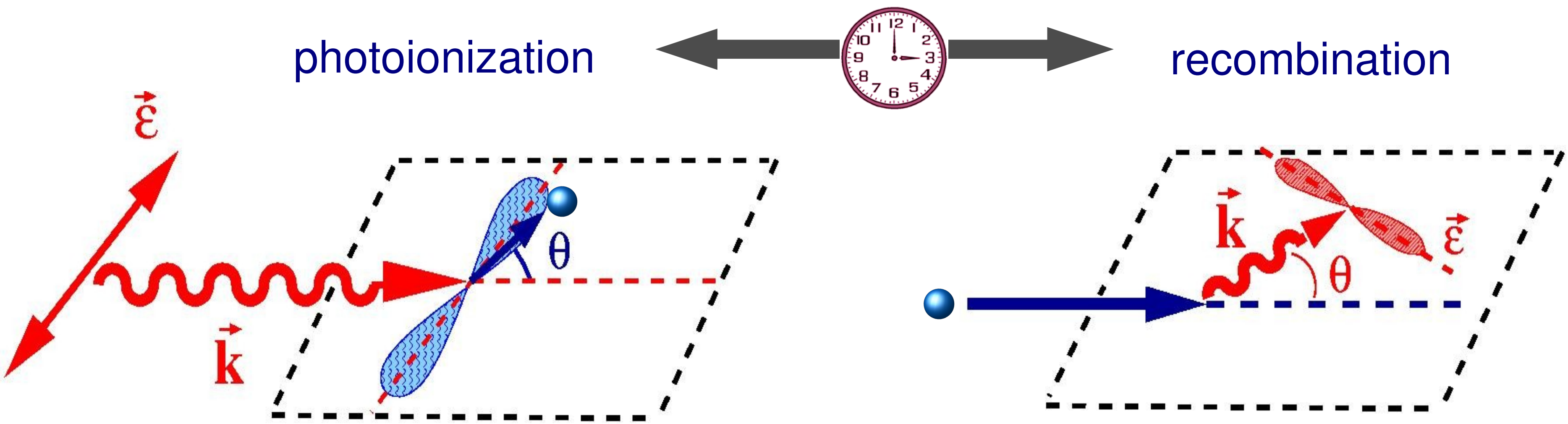


$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

photoionization  recombination

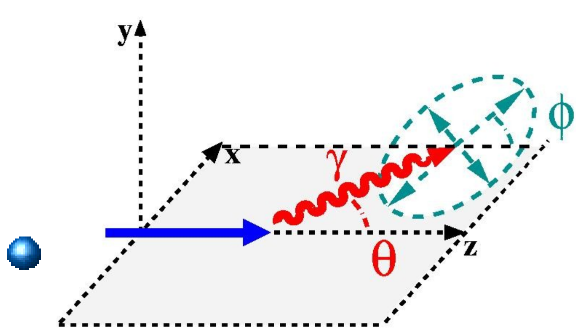
Linear polarization of emitted x-ray photons

-- theoretical expectation



electric dipole approximation

Linear polarization is described in the plane, perpendicular to the photon momentum.



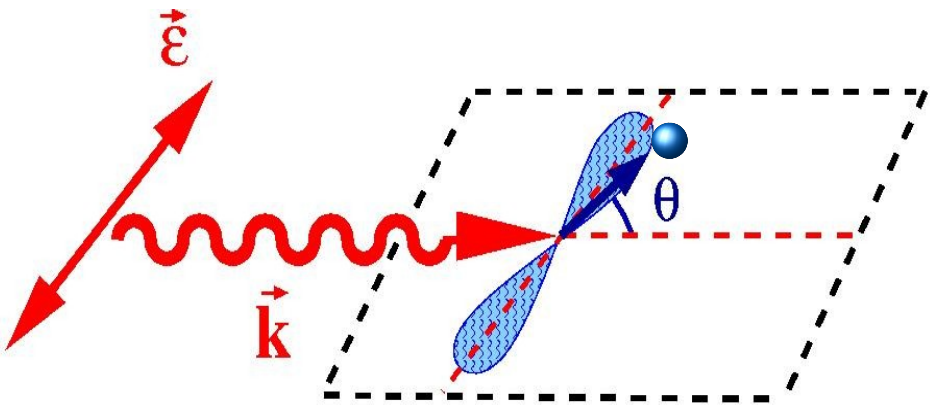
→ only 2 (Stokes) parameters are required !

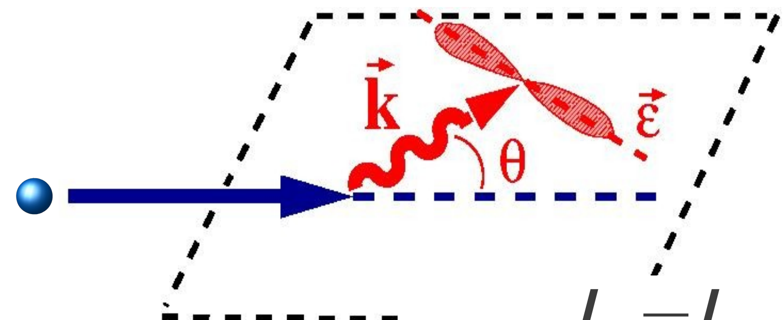
$$P_L = \sqrt{P_1^2 + P_2^2} \qquad \cos(2\phi) = \frac{P_1}{P_L}$$

Linear polarization of emitted x-ray photons

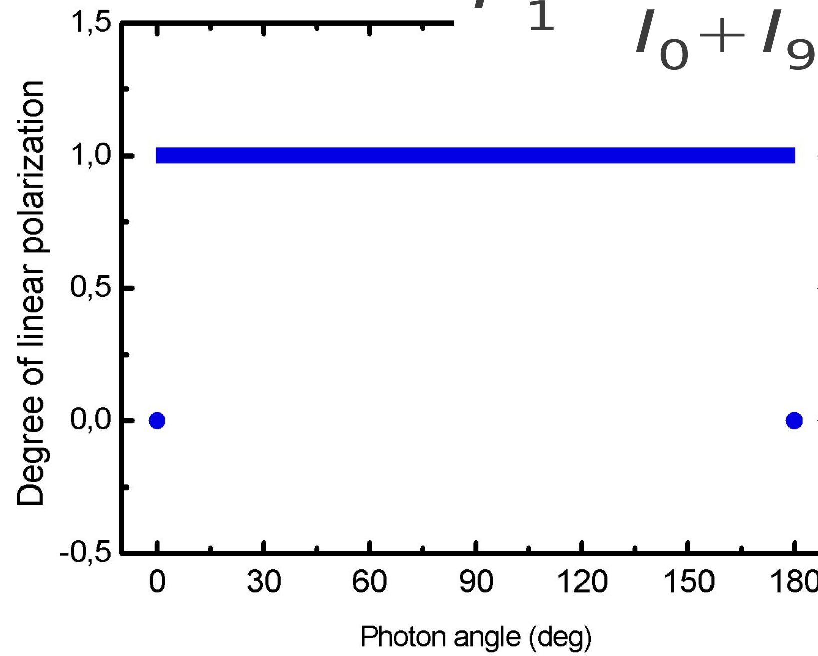
-- statistical characteristics for photon ensembles

photoionization  recombination





$$P_1 = \frac{I_0 - I_{90}}{I_0 + I_{90}}$$



electric dipole approximation

photoelectron angular distribution:

$$W_{PI} \propto \sin^2\theta \; \cos^2\phi$$

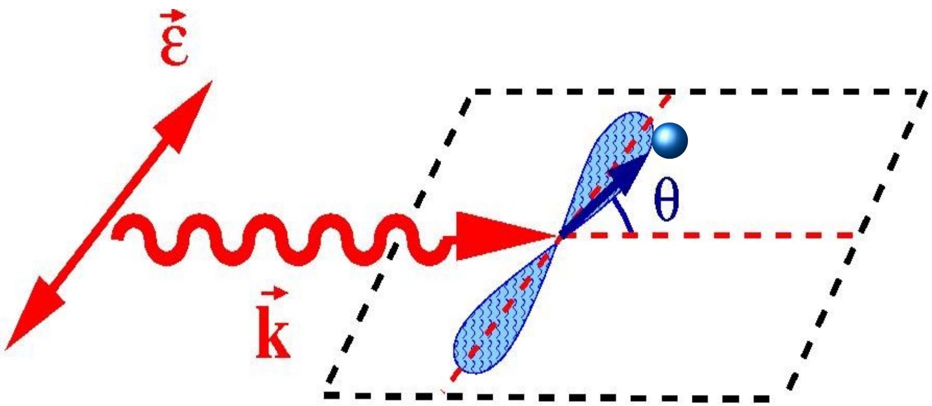
photoelectrons are emitted predominantly within the plane of the electric field

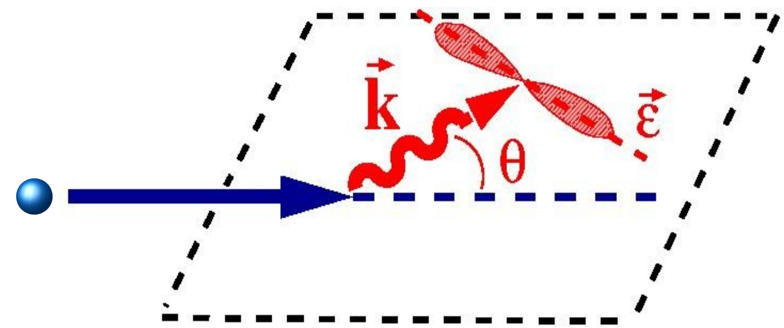
H. Stobbe, Ann. Phys. 5 (1930) 661

Linear polarization of emitted x-ray photons

-- Statistical characteristics for photon ensembles

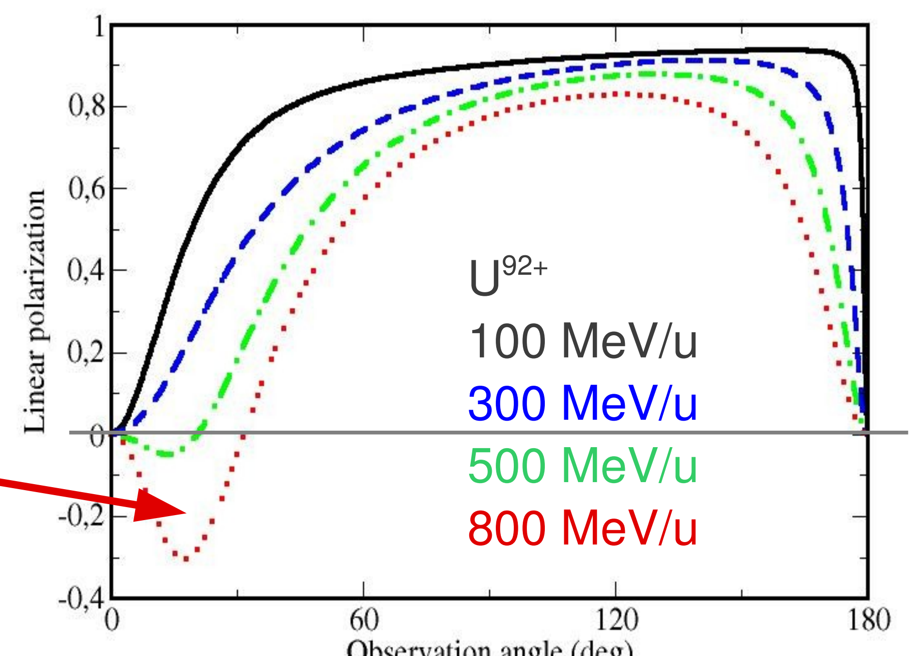
photoionization  recombination





- Magnetic interactions decrease the linear polarization !
- Cross-over behaviour !!

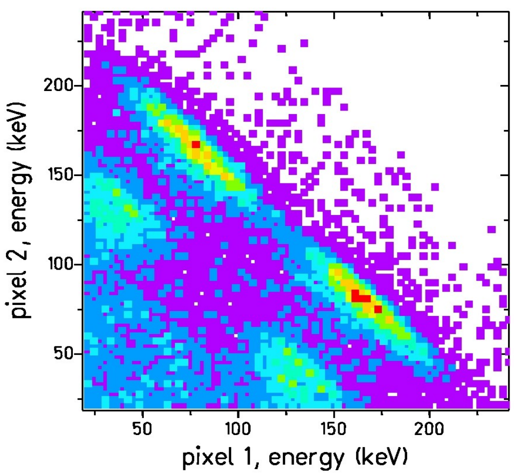
F. Sauter, Ann. Phys. 9 (1931) 217
U. Fano, Phys. Rev. 116 (1959) 1156

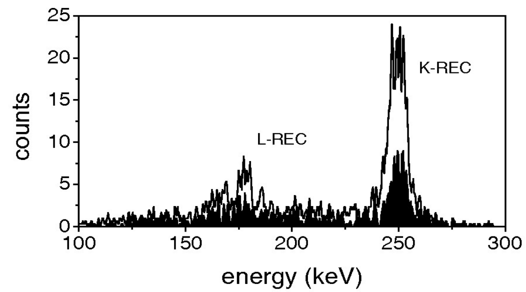


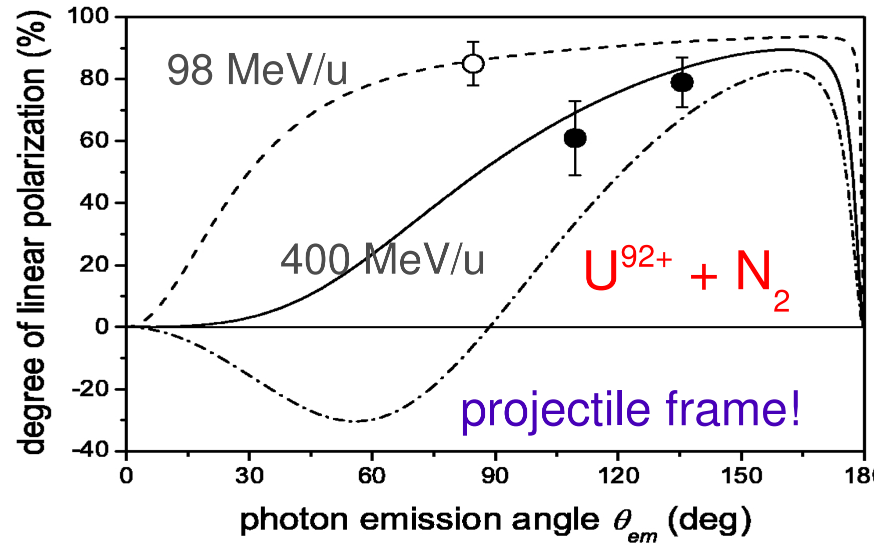
A. Surzhykov et al, PLA 289 (2001) 213;
J. Eichler et al, PRA 65 (2002) 052716.

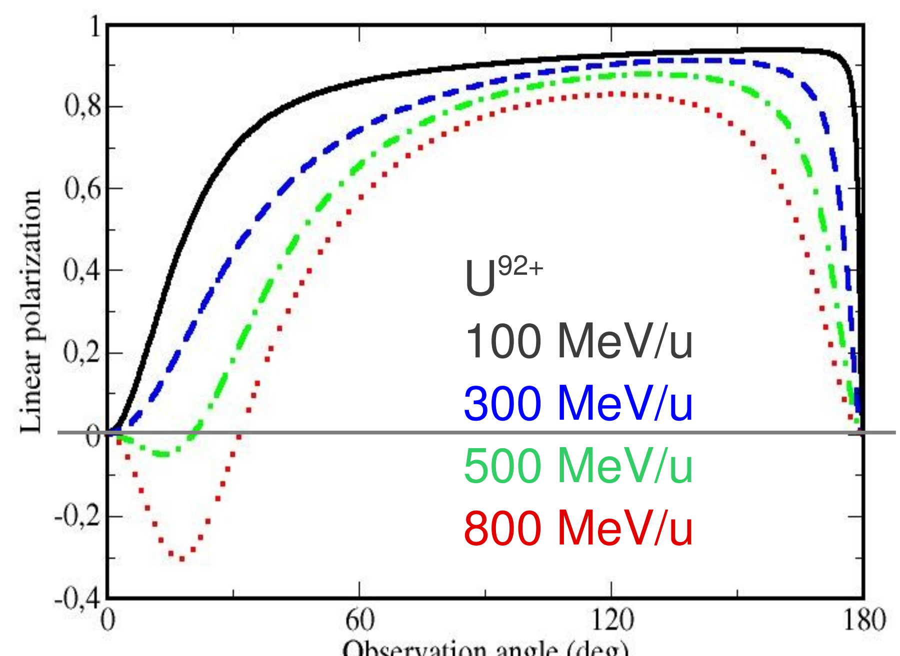
Linear polarization of emitted x-ray photons

-- Polarization dependence of Compton scattering









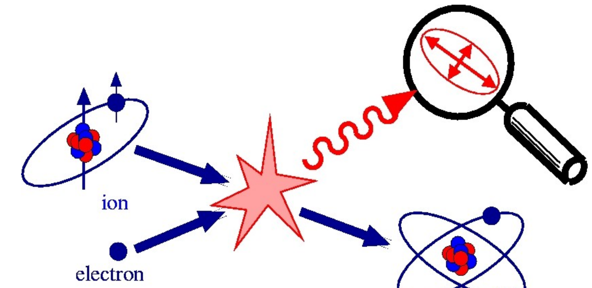
- Polarization measurements due to the use of position sensitive detectors !

S. Tashenov et al., PRL 97 (2006) 223202

Linear polarization of emitted x-ray photons: Applications

-- Diagnostics of highly-charged ion beams

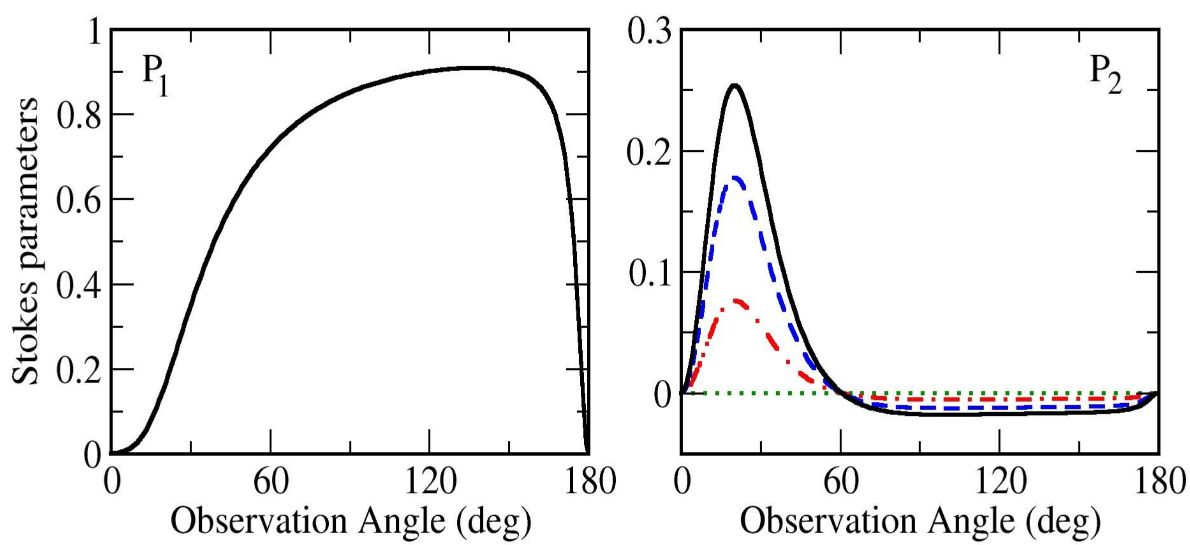
- Proposal: to use REC linear polarization as a probe for ion spin polarization.

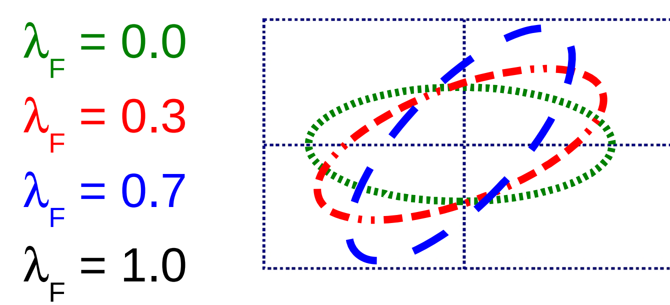


- Established theory from the "polarization transfer" in atomic photoionization.

U. Fano et al., Phys. Rev. 116 (1959) 1147;
R. Pratt et al., Phys. Rev. 134 (1964) A916.

- Calculations performed for the REC into (initially) hydrogen-like bismuth Bi^{82+} ions ($\boldsymbol{I}$ = 9/2) for the energy T_p = 420 MeV/u.





$$\tan 2\phi = \frac{P_2}{P_1} \sim \lambda_F \frac{I - 1/2}{I + 1/2}$$

A. Surzhykov et al., PRL 94 (2005) 203202.

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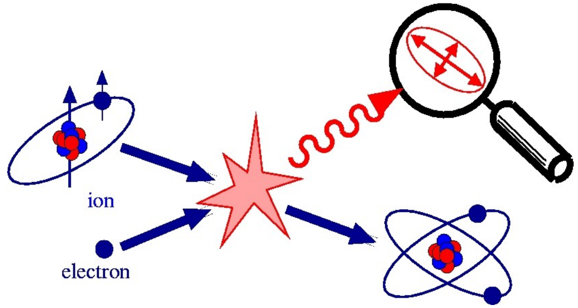

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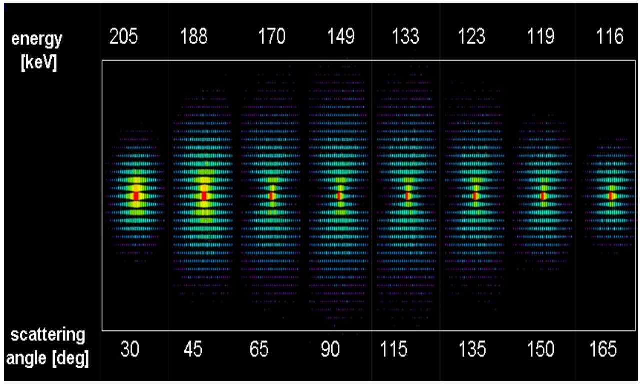

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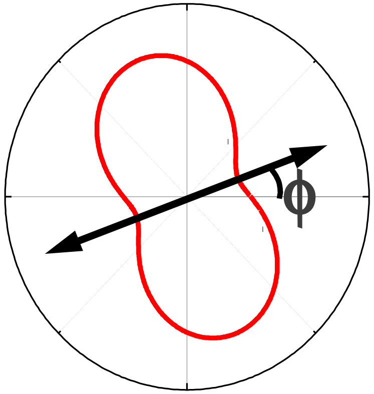
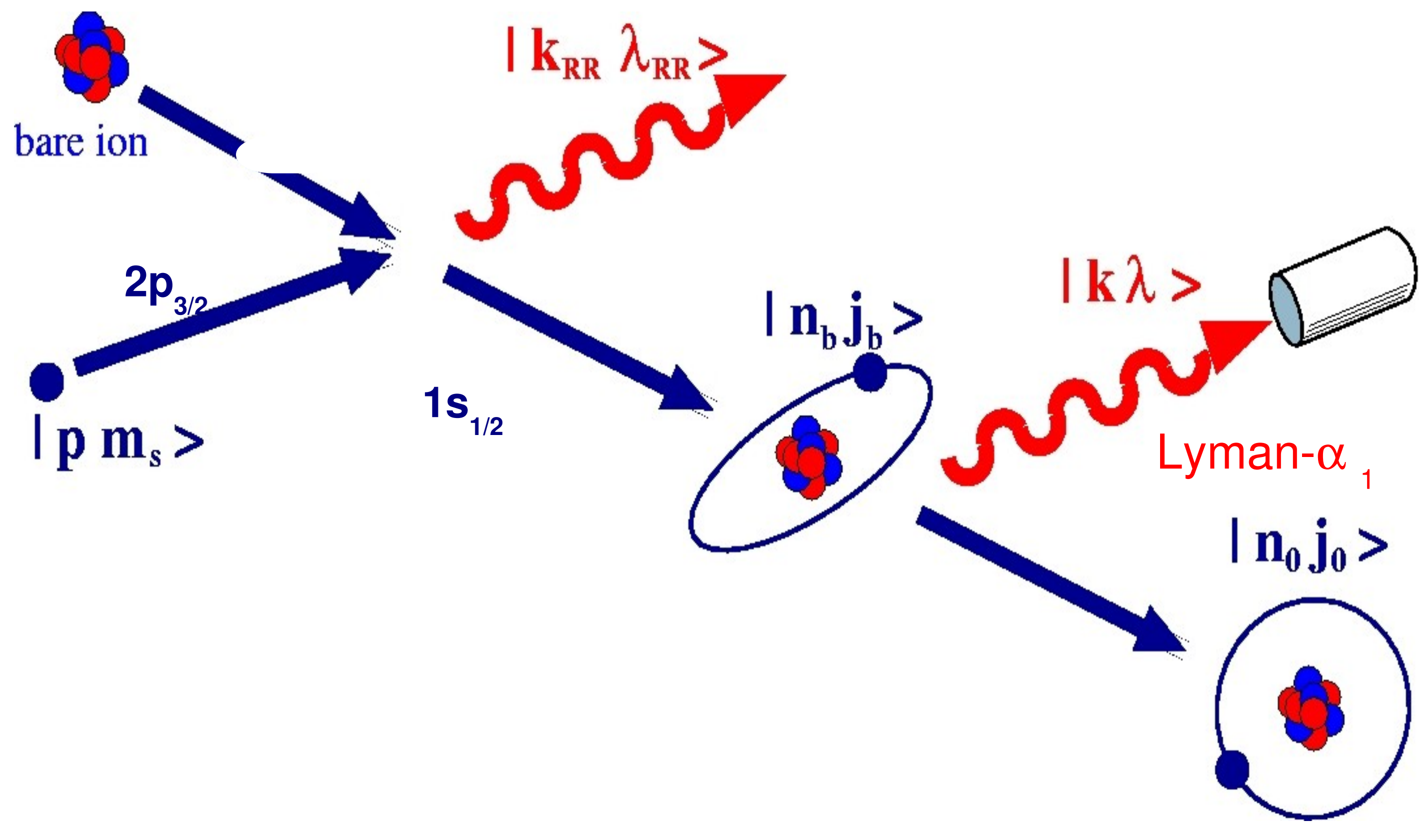


S. Tashenov et al., PRL 97 (2006) 223202;
A. Surzhykov et al., PRL 94 (2005) 203202.

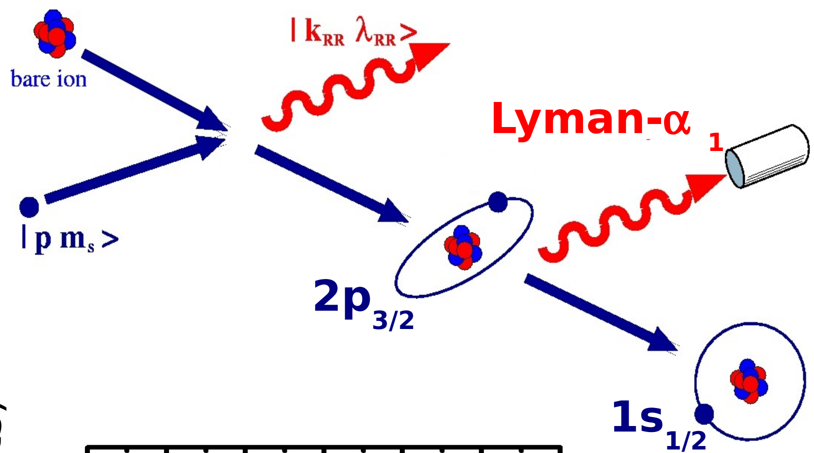
➜ Rotation angle ϕ provides information on the <u>degree</u> of ion polarization !

Alignment of high-Z ions: REC and Lyman-a

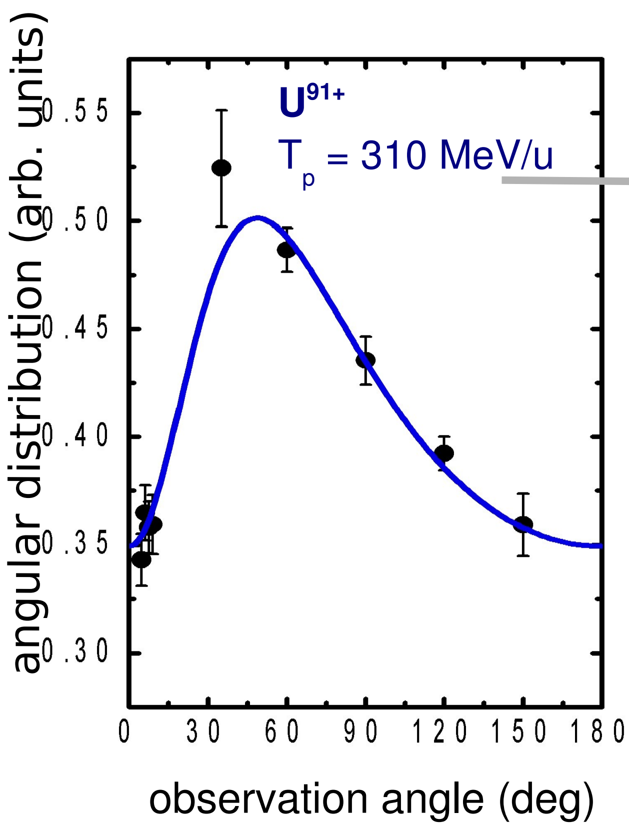
-- Understanding interferences of the photon field



Capture into the $2p_{3/2}$ excited states of initially bare ions

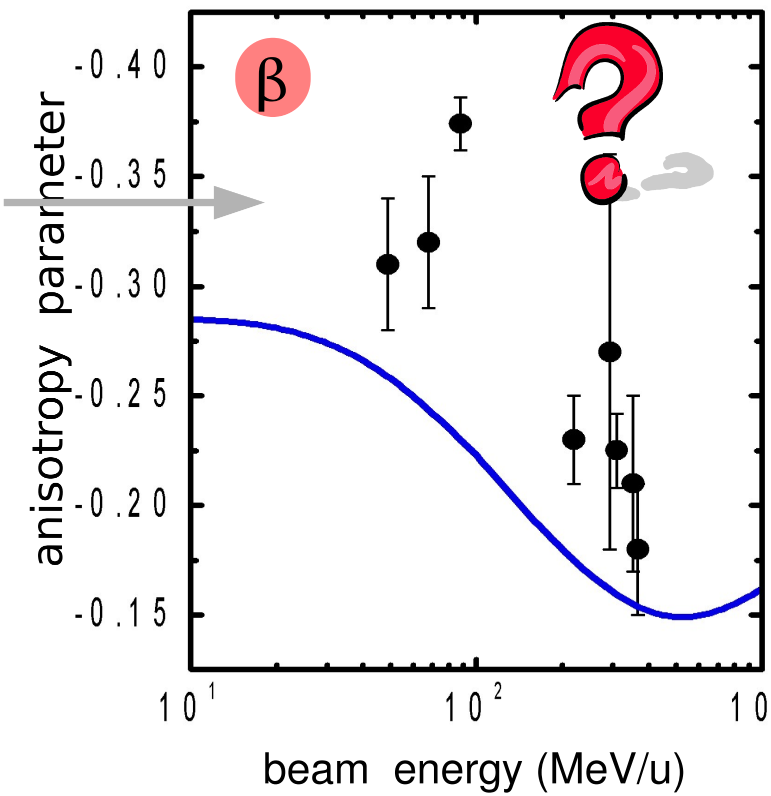


- Magnetic sublevel population of the residual ion can not be measured **directly**
- **But:** knowledge on population of excited ion state may be derived from the properties of subsequent decay



fitting

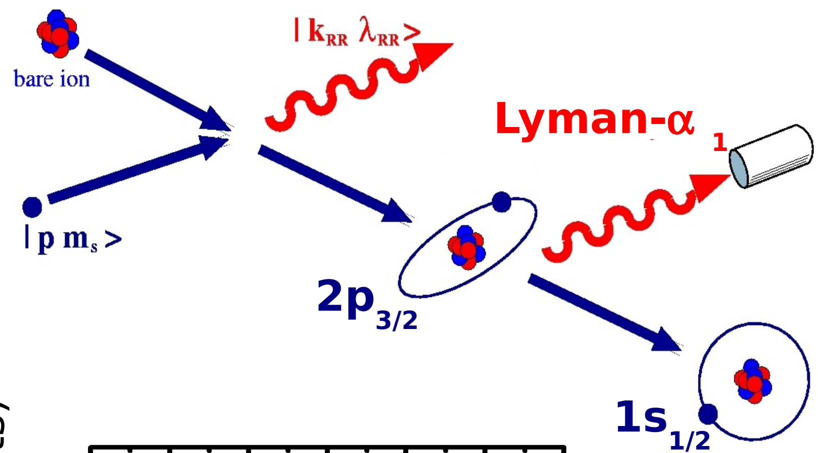
$$W(\theta) \propto 1 + \beta P_2(\cos\theta)$$



Th. Stöhlker et al., PRL 79 (1997) 3270.

J. Eichler et al., PRA 58 (1998) 2128.

Capture into the $2p_{3/2}$ excited states of initially bare ions



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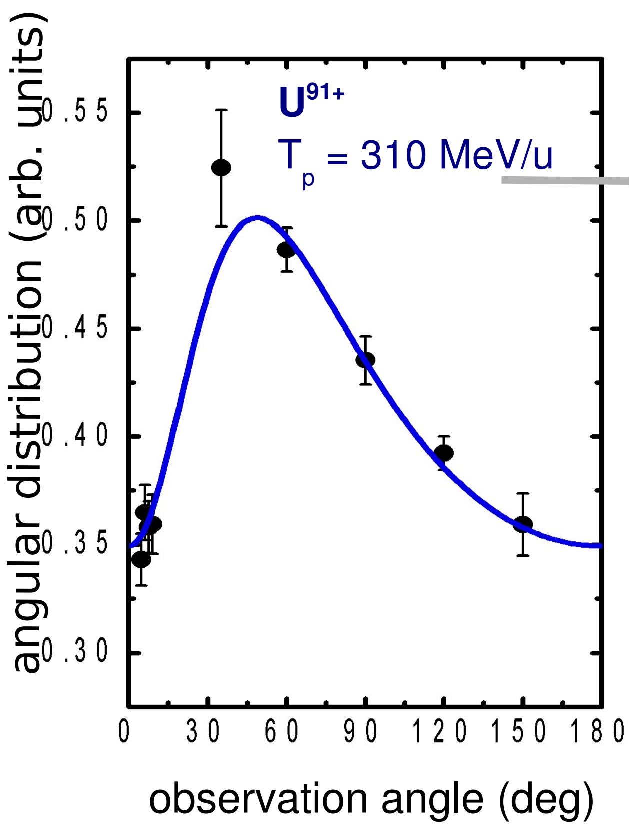


Th. Stöhlker et al., PRL 79 (1997) 3270.

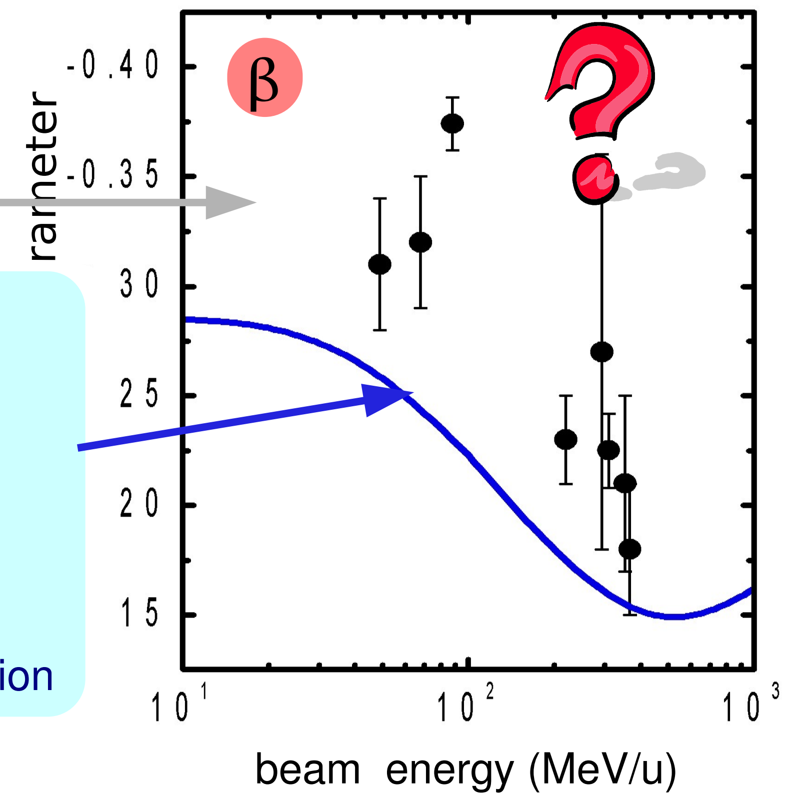
fitting

$$W(\theta) \propto 1 + \beta P_2(\cos\theta)$$

Theory:

$$\beta = \frac{1}{2}\,\frac{\sigma_{\mu_b=\pm 3/2} - \sigma_{\mu_b=\pm 1/2}}{\underbrace{\sigma_{\mu_b=\pm 3/2} + \sigma_{\mu_b=\pm 1/2}}}$$

alignment of the $2p_{3/2}$ state: relative sublevel $| j_b\, m_b >$ population



J. Eichler et al., PRA 58 (1998) 2128.

Effective anisotropy parameter: Multipole contributions

$$W(\theta) \propto 1 + \beta_{eff} P_2(\cos\theta)$$

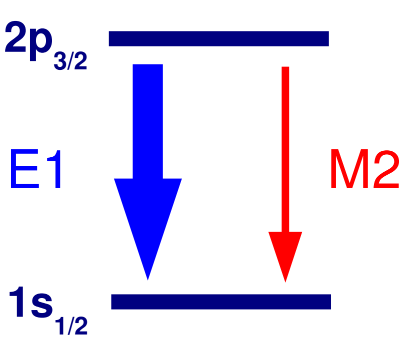
effective anisotropy parameter

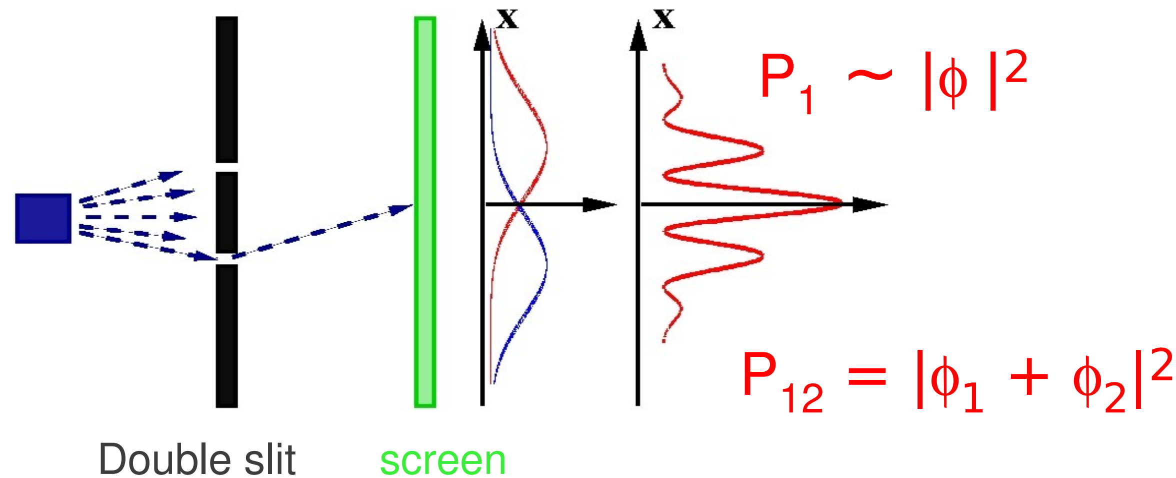
$$\beta_{eff} = \frac{1}{2} \underbrace{\frac{\sigma(\pm 3/2) - \sigma(\pm 1/2)}{\sigma(\pm 3/2) + \sigma(\pm 1/2)}} * \underbrace{f(E1, M2)}$$

alignment parameter (capture process)

structure function (ion)

$$f(E1, M2) \propto 1 + 2\sqrt{3} \frac{\langle |M2| \rangle}{\langle |E1| \rangle}$$





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effective anisotropy parameter

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alignment parameter (capture process) structure function (ion)

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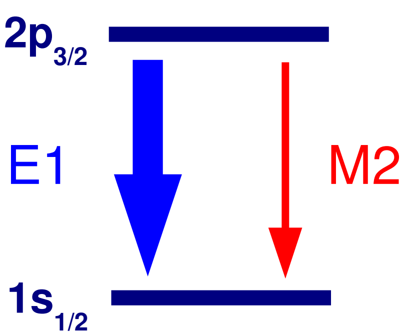

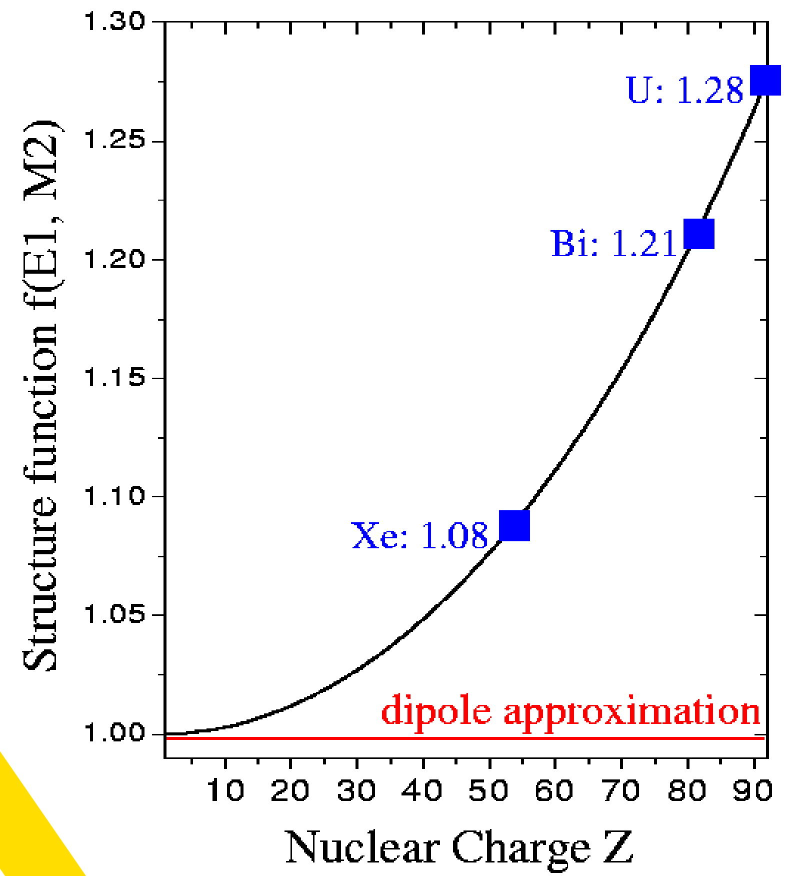

Not separable by measuring only angular distributions.

Effective anisotropy parameter: Multipole contributions

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effective anisotropy parameter

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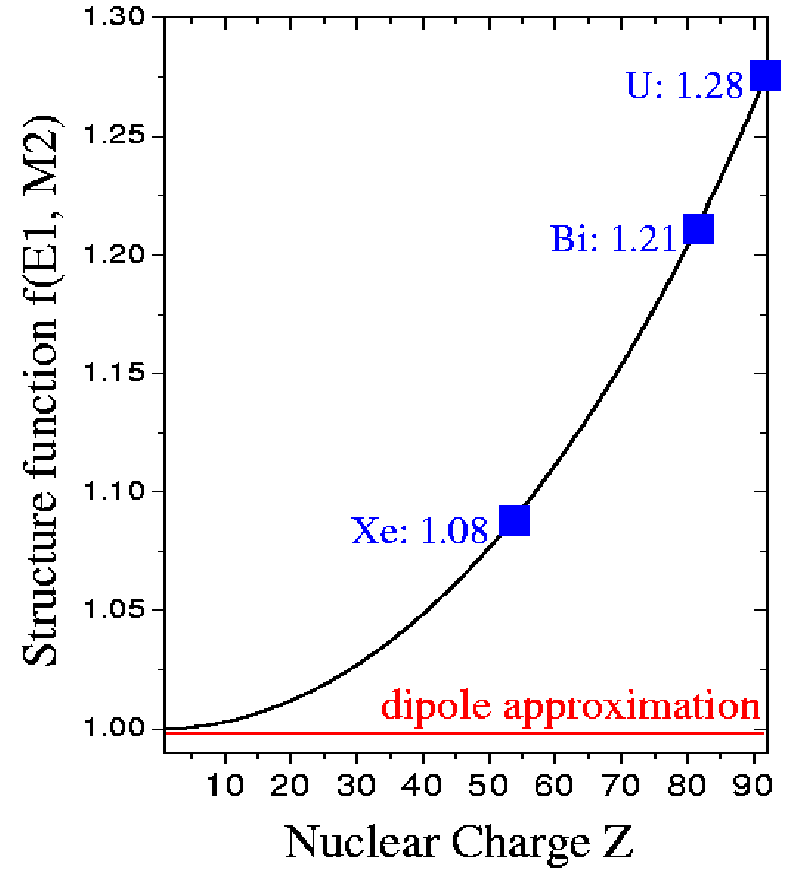
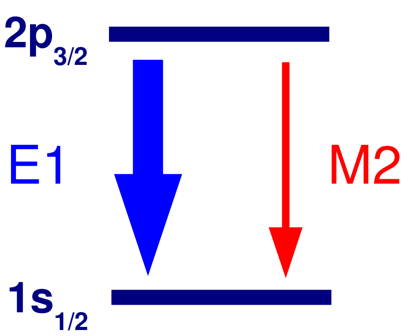




In contrast, contributions to decay rates appear additive:

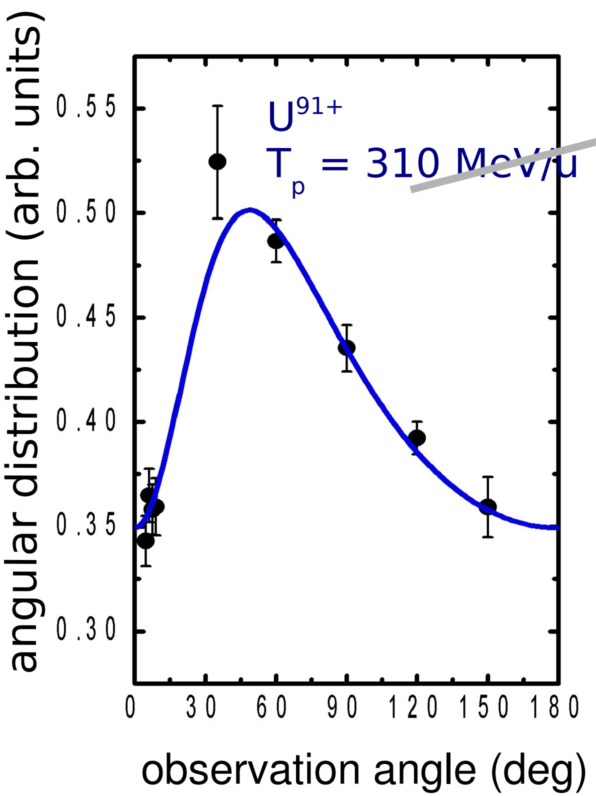
$$\frac{\Gamma_{M2}}{\Gamma_{tot}} \propto \frac{|\langle |M2| \rangle|^2}{|\langle |E1| \rangle|^2} \propto 0.008 \; !$$

even for U^{91+}

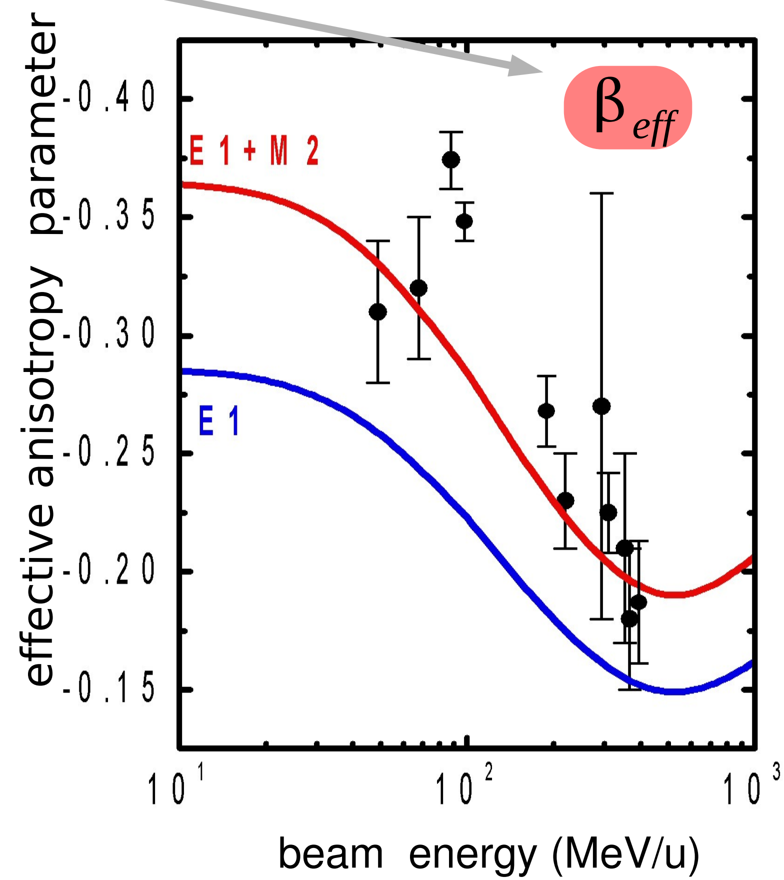
E1-M2 multipole mixing: Alignment of the $2p_{3/2}$ state

A. Surzhykov et al. PRL 88 (2002) 153001

$$W(\theta) \propto 1 + \beta_{eff} P_2(\cos\theta)$$



fitting

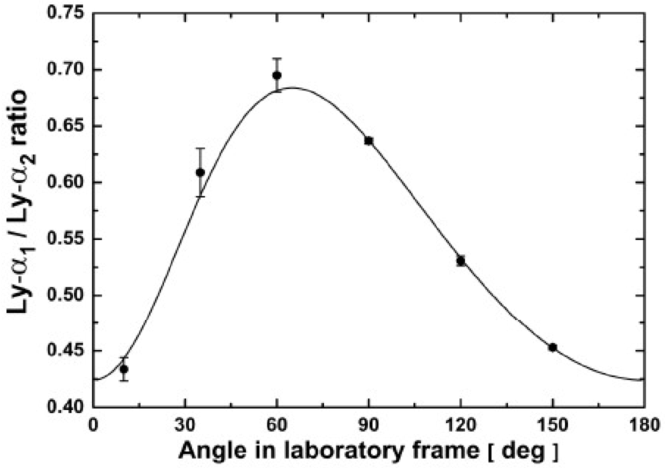


- Dynamical alignment studies enables one to explore magnetic interactions in the bound-bound transitions in H-like ions !

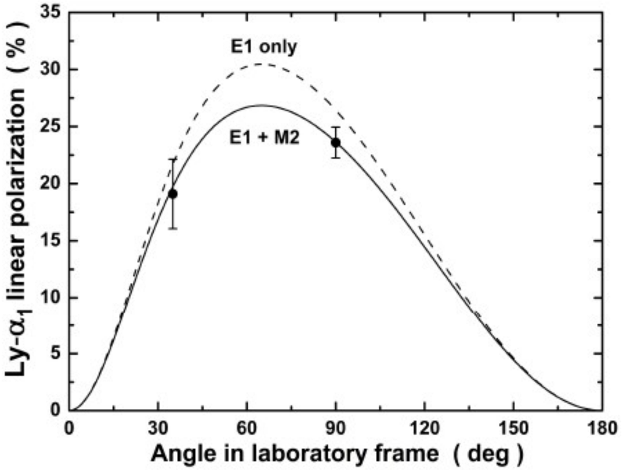
Elementary processes in strong Coulomb fields

– How can one directly ``measure'' multipole fields ?

Lyman-α_1 ($2p_{3/2}$ --> $1s_{1/2}$) for H-like U^{91+} ions:



Angular distribution



Linear polarization

$$W(\theta) \propto 1 + \beta_{20}^{\mathrm{eff}} \left(1 - \frac{3}{2} \sin^2 \theta \right)$$

$$P(\theta) = \frac{-\frac{3}{2}\gamma_{20}^{\mathrm{eff}} \sin^2 \theta}{1 + \beta_{20}^{\mathrm{eff}} \left(1 - \frac{3}{2} \sin^2 \theta\right)}$$

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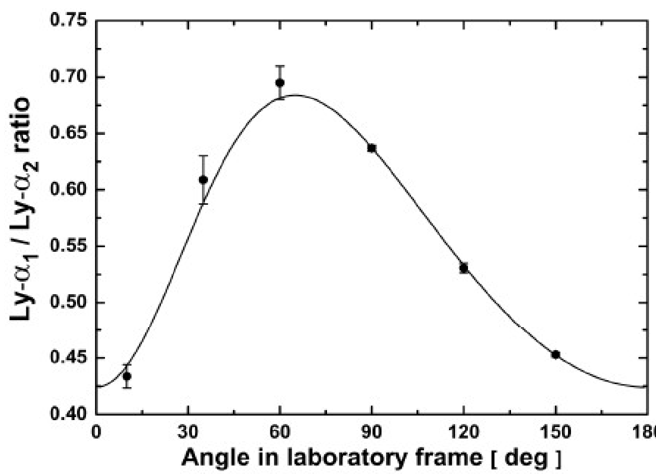
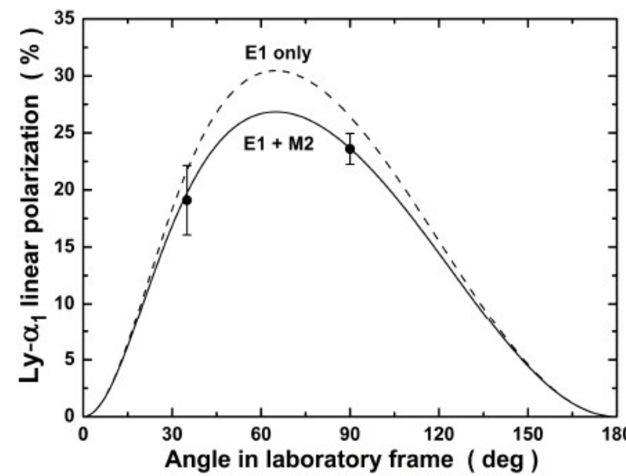


Angular distribution



Linear polarization

$$W(\theta) \propto 1 + \beta_{20}^{\mathrm{eff}} \left(1 - \frac{3}{2}\sin^2\theta\right)$$

$f\ (A_2,\ a_{M2}/a_{E1})$

$$P(\theta) = \frac{-\frac{3}{2}\gamma_{20}^{\mathrm{eff}} \sin^2\theta}{1 + \beta_{20}^{\mathrm{eff}}\left(1 - \frac{3}{2}\sin^2\theta\right)}$$

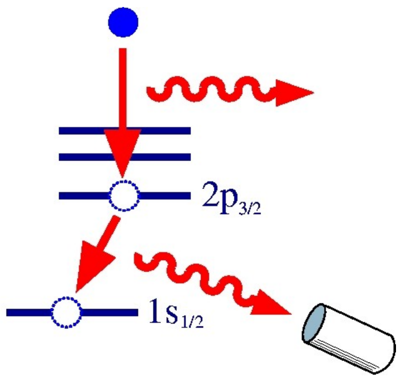
Alignment parameter $\mathcal{A}_2$		Amplitude ratio a_{M2}/a_{E1}	
Experiment	Theory	Experiment	Theory
-0.451 ± 0.017	-0.457	0.083 ± 0.014	0.0844

G. Weber et al., PRL 105 (2010) 243002.

→ Model-independent and precise determination of the alignment and amplitude ratio.

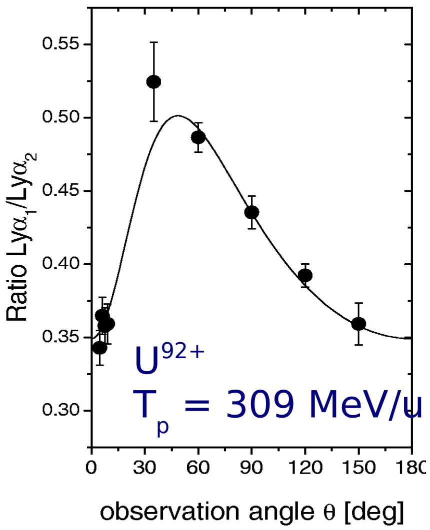
Details matter:

-- Lyman-a vs. K-a emission from high-Z ions



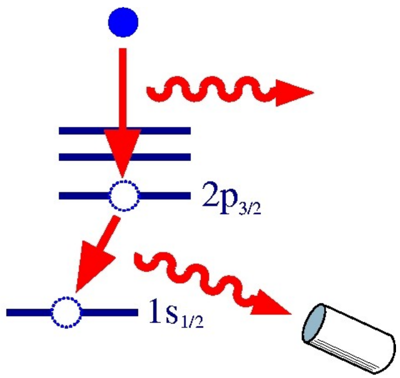
(initially) bare ion

Ly-α_1 is strongly anisotropic

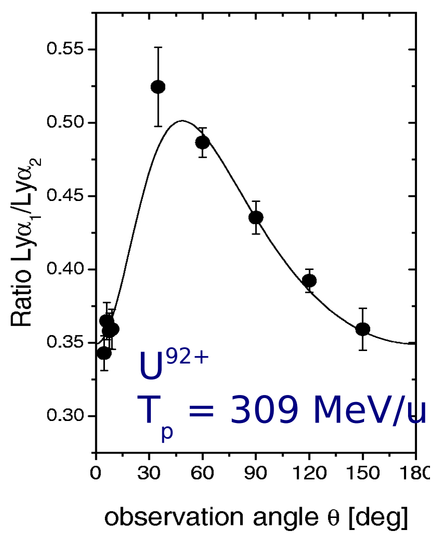


Details matter: Adding one electron

-- Lyman-a vs. K-a emission from high-Z ions



(initially) bare ion



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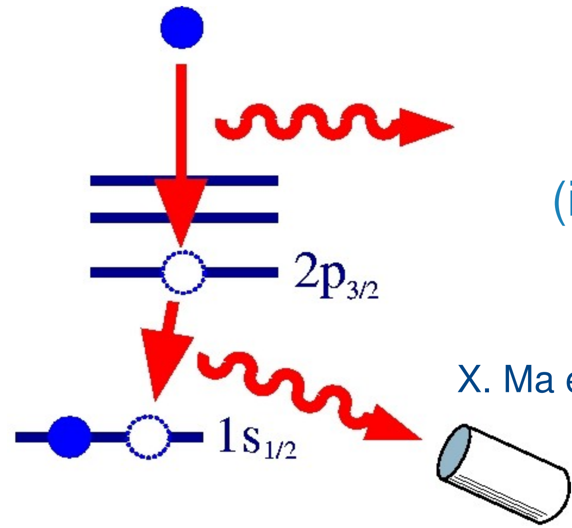
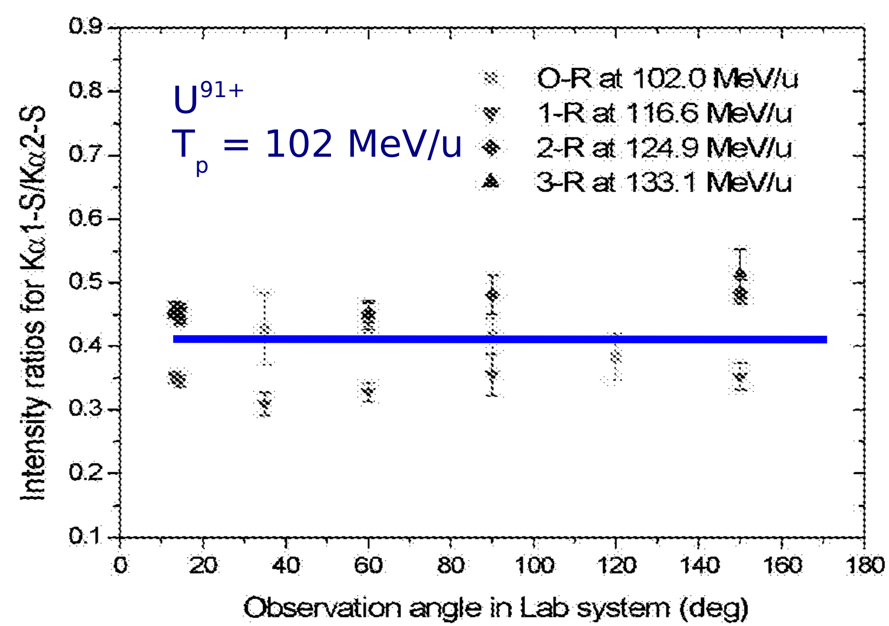


(initially) H-like ion

X. Ma et al, PRA 68 (2003) 042712.



K-α_1 is isotropic

Details matter: Adding one electron

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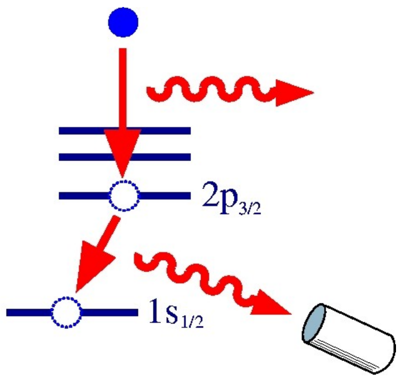
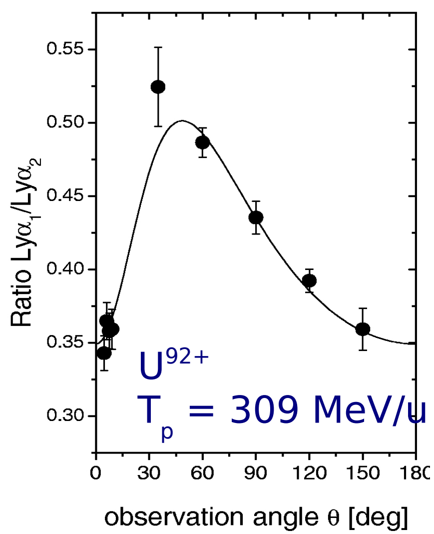
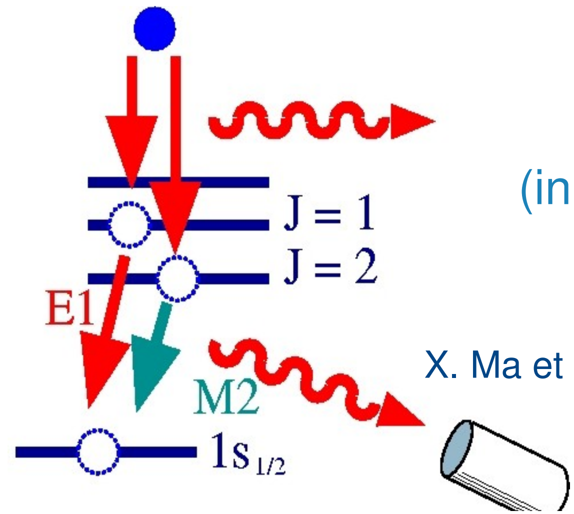


(initially) bare ion

Ly-α_1 is strongly anisotropic





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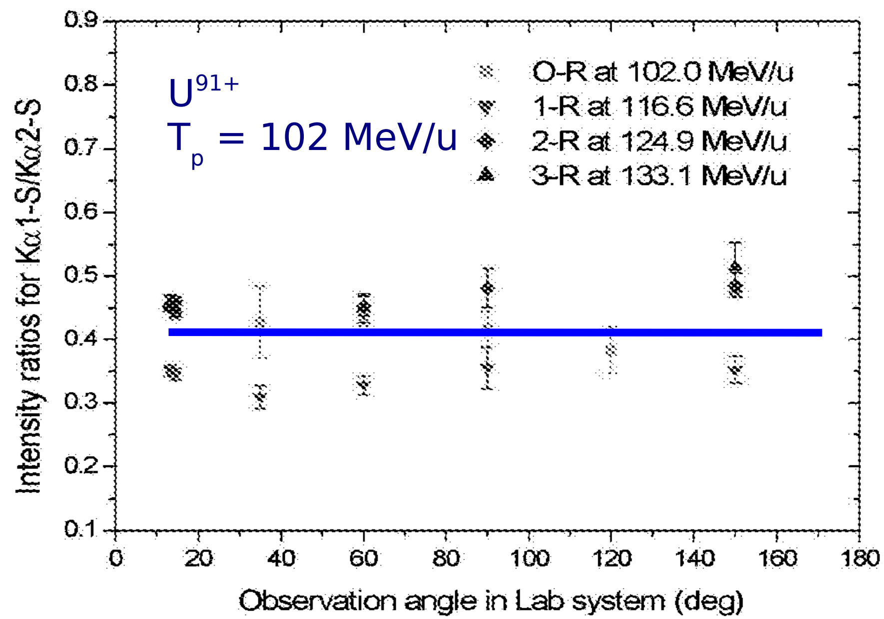
X. Ma et al, PRA 68 (2003) 042712.



K-α_1 is isotropic

E1: $$W(\theta)_{E1} \sim 1 + \frac{1}{\sqrt{2}} A_2(J=1) P_2(\cos\theta)$$

M2: $$W(\theta)_{M2} \sim 1 - \sqrt{\frac{5}{14}} A_2(J=2) P_2(\cos\theta)$$

K-a decay of highly-charged ions

-- angular distribution as „observed“ in experiments

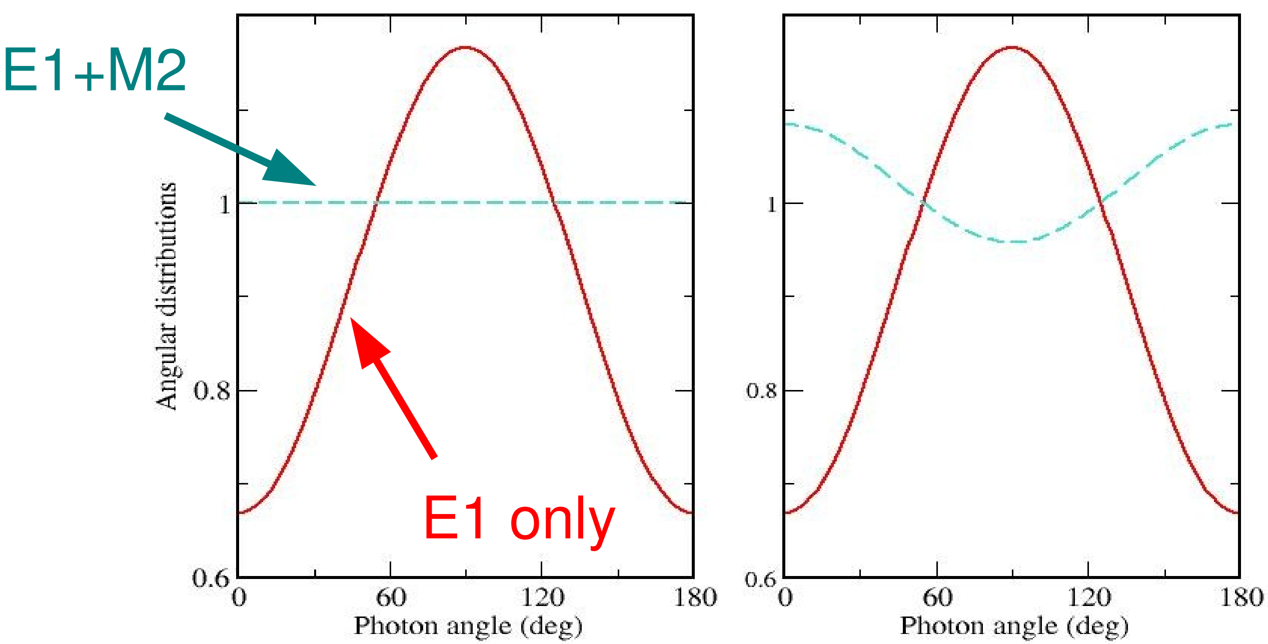
$$W(\theta)_{K\alpha_1} \sim N_{J=1} W_{E1}(\theta) + N_{J=2} W_{M2}(\theta)$$

A. Surzhykov et al., PRA 73 (2006) 032716.

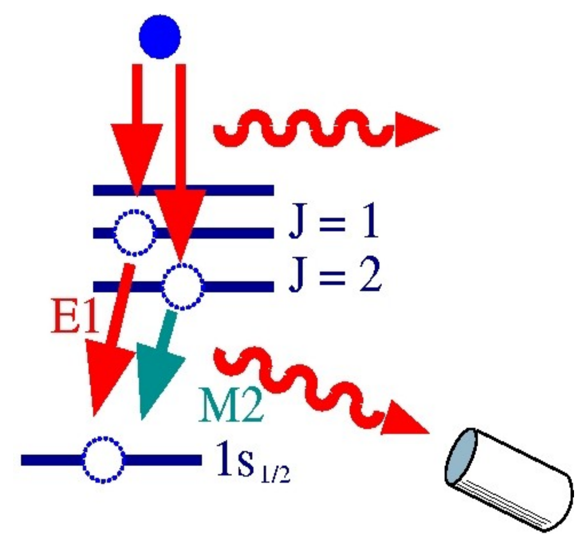
$$= 1 + \left(N_{J=1} \frac{1}{\sqrt{2}} A_2(J=1) - N_{J=2} \sqrt{\frac{5}{14}} A_2(J=2) \right) P_2(\cos\theta)$$

$N_{J=1}, N_{J=2}$ relative populations of J=1, 2 states

$$N_{J=1} = N_{J=2} = \frac{1}{2} \qquad N_{J=1} = \frac{3}{8} \quad N_{J=2} = \frac{5}{8}$$



Calculations have been done for L-REC of U^{91+} with T_p = 100 MeV/u



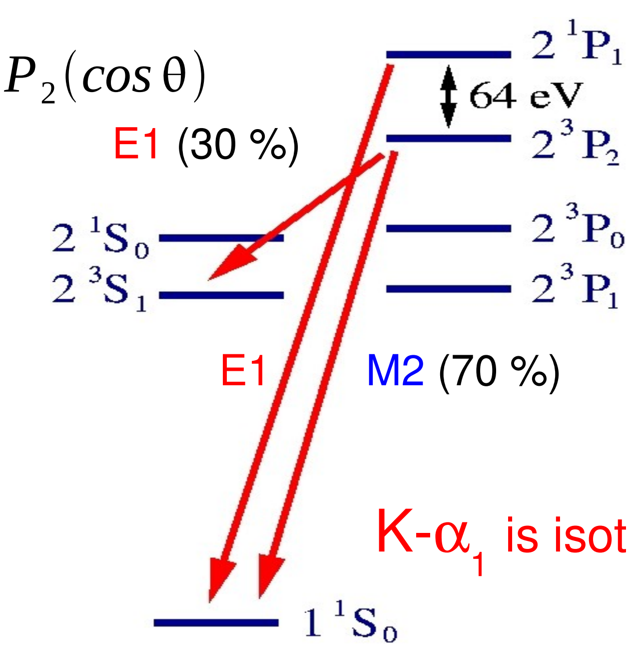
K-α decay of highly-charged ions

-- for 220 MeV/u U^{90+} ions following REC

$$W(\theta)_{K\alpha_1} \sim N_{J=1} W_{E1}(\theta) + N_{J=2} W_{M2}(\theta)$$

A. Surzhykov et al., PRA 73 (2006) 032716.

$$= 1 + \left(N_{J=1} \frac{1}{\sqrt{2}} A_2(J=1) - N_{J=2} \sqrt{\frac{5}{14}} A_2(J=2) \right) P_2(\cos\theta)$$



K-α_1 is isotropic

- Relative populations of the J = 1, 2 levels following REC (IPM model):

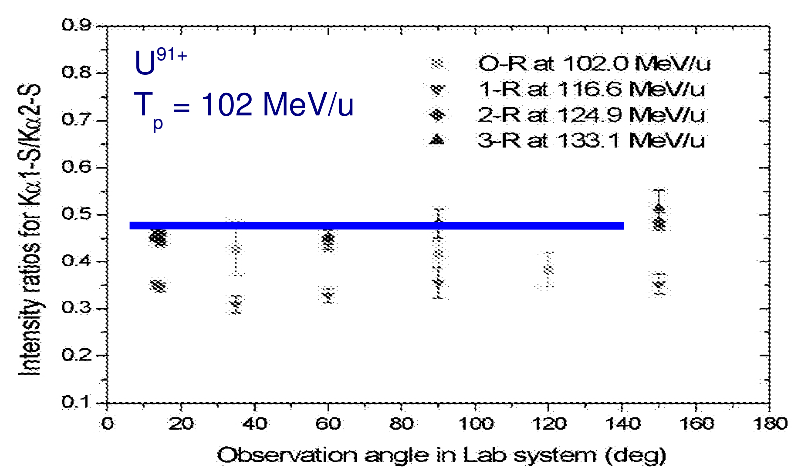
$$\frac{N_{J=1}}{N_{J=2}} = \frac{3}{5}$$

- By taking into account $^3P_2 \rightarrow {}^3S_1$ channel:

$$\frac{N_{J=1}}{N_{J=2}} = \frac{6}{7}$$

initial `capture' populations
+ branching fractions

$$\left(\frac{N_{J=1} - N_{J=2}}{N_{J=1} + N_{J=2}} \right)_{theory} \approx -0.08$$

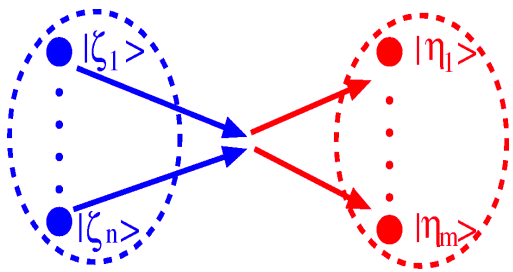


Relativistic collisions: A theoretician's viewpoint

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



Final state

$(t \to +\infty)$

$\hat{\rho}_f$

$\hat{S}$ - scattering operator

$$\hat{\rho}_f = \hat{S}\,\hat{\rho}_i\,\hat{S}^+$$

ρ = (μ_S, J, J'; E; I, μ_I ... density matrix)

$$\sigma \sim \sum_{polarization} \int d\Omega \, |M|^2$$

total cross sections

$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

angular distribution

$$\sim |M|^2$$

No summation over polarization states !

polarization & alignment

Electron-ion collision experiments at GSI and elsewhere:

- Radiative electron capture: Exploring the electron-photon interaction
- Projectile excitation: Testing the Lorentz-transformed „Coulomb field“
- Dielectronic recombination of high-Z ions: A detailed view on the electron-electron interactions

Elementary processes in strong Coulomb fields

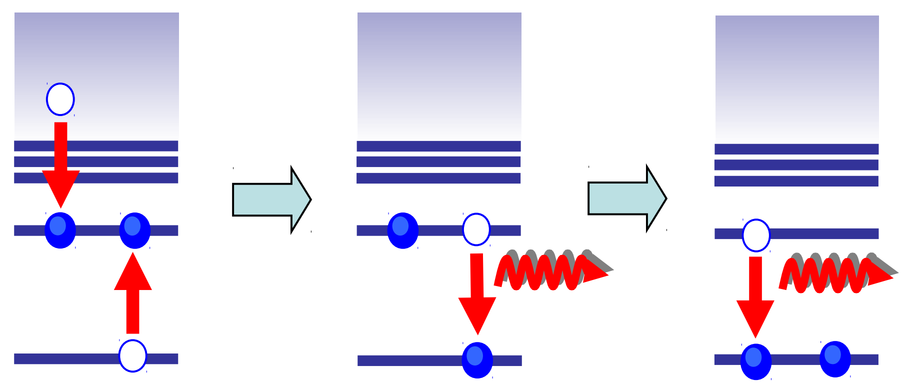
– electron-photon vs. electron-electron interactions

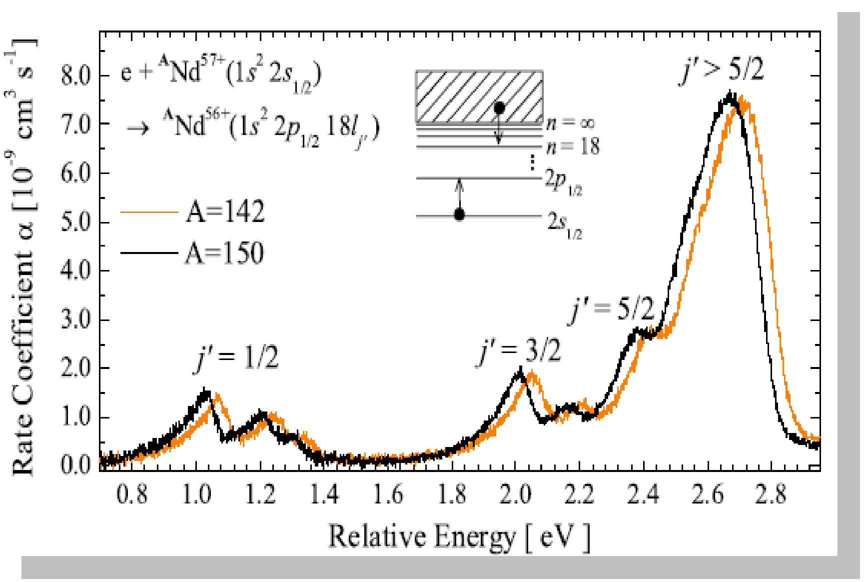
Photoionization

Autoionization

Radiative electron capture (REC)

Dielectronic recombination (DR)





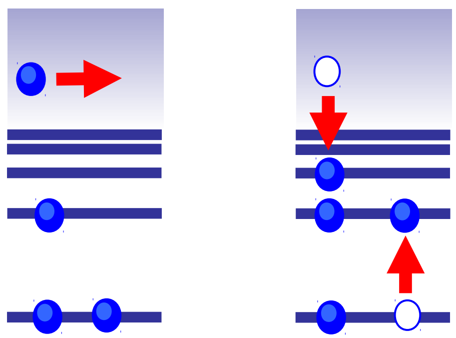
C. Brandau et al., PRL 100 (2008) 073201;
PRL 89 (2002) 053201; PRL 91 (2003) 073202

- Dielectronic recombination (DR) process provides a unique tool for precise spectroscopy of HCI and, especially, doubly excited ionic states.
- accurate QED and isotope studies
- finger print upon nuclear properties (nuclear spins and moment, isomeric states)
- Interactions in strong (Coulomb) fields
- Great importance for astro and plasma physics.

Elementary processes in strong Coulomb fields

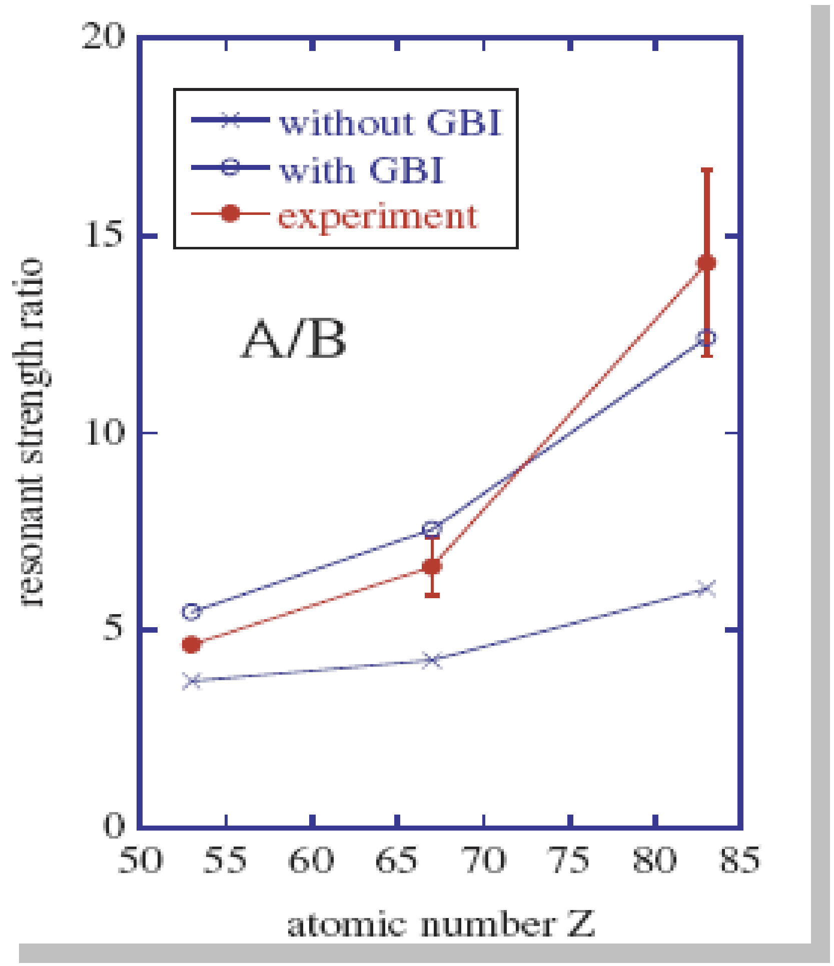
– finger prints upon magnetic and retarded interactions

K-LL DR into initially lithium-like ions:



$$\left[1s^2\ 2s\right]_{1/2} + e^- \Rightarrow \left[1s\ 2s^2\ 2p\right]_1$$

relative to the $1s\ 2s\ 2p^2\ J=1$ resonance



$$V_{ee} = V^C + V^B = \frac{1}{r_{12}} + \left(-\alpha_1 \alpha_2 \frac{\cos \omega r_{12}}{r_{12}} + \left(\alpha_1 \nabla_1\right)\left(\alpha_2 \nabla_2\right) \frac{\cos \omega r_{12}}{\omega^2\, r_{12}} \right)$$

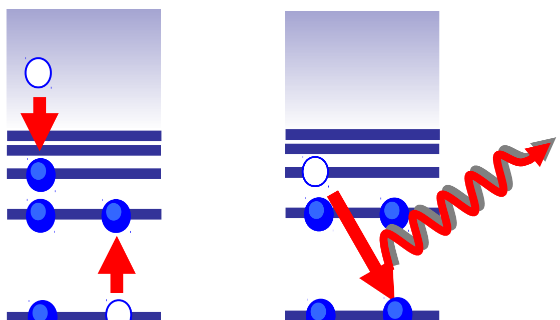
Breit interaction

EBIT measurements:
N. Nakamura et al., PRL 100 (2008) 073203.

Elementary processes in strong Coulomb fields

– finger prints upon magnetic and retarded interactions

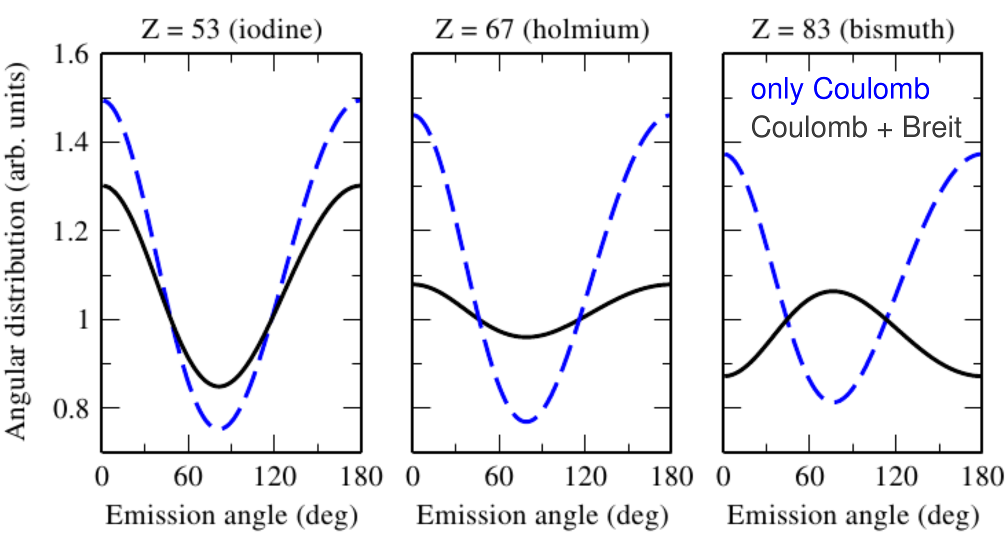
K-LL DR into initially lithium-like ions:



$$\left[1s\ 2s^2\ 2p\right]_1 \rightarrow \left[1s^2\ 2s^2\right]_0 + \gamma$$

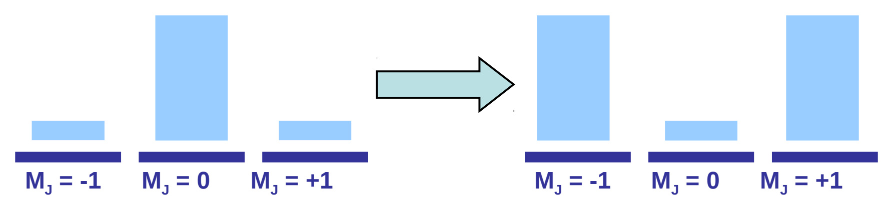
$$V_{ee} = V^C + V^B = \frac{1}{r_{12}} + \left(-\alpha_1 \alpha_2 \frac{\cos \omega r_{12}}{r_{12}} + (\alpha_1 \nabla_1)(\alpha_2 \nabla_2) \frac{\cos \omega r_{12}}{\omega^2 r_{12}} \right)$$

Angular distribution of emitted photons



S. Fritzsche et al., PRL 103 (2009) 113001.

only Coulomb → Coulom + Breit



only Coulomb: $A_2 = -0.516$

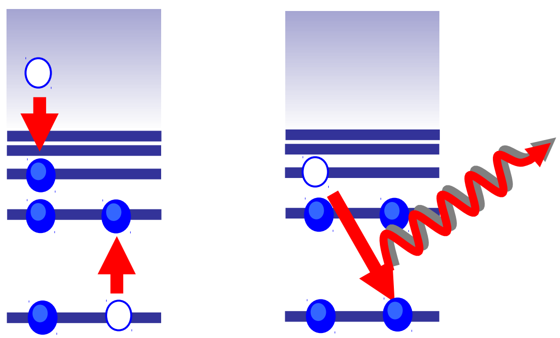
Coulom + Breit: $A_2 = +0.374$

$$W(\theta) \propto 1 + \frac{A_2}{\sqrt{2}} P_2(\cos\theta)$$

Elementary processes in strong Coulomb fields

– finger prints upon magnetic and retarded interactions

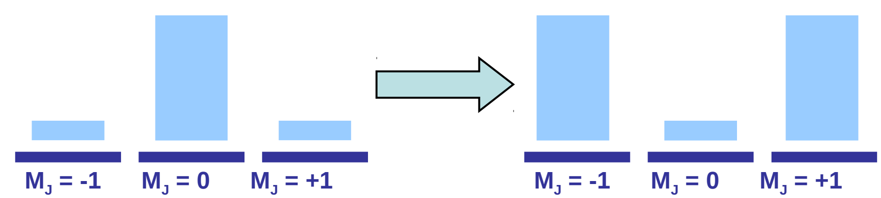
K-LL DR into initially lithium-like ions:



$$\left[1s\ 2s^2\ 2p\right]_1 \rightarrow \left[1s^2\ 2s^2\right]_0 + \gamma$$

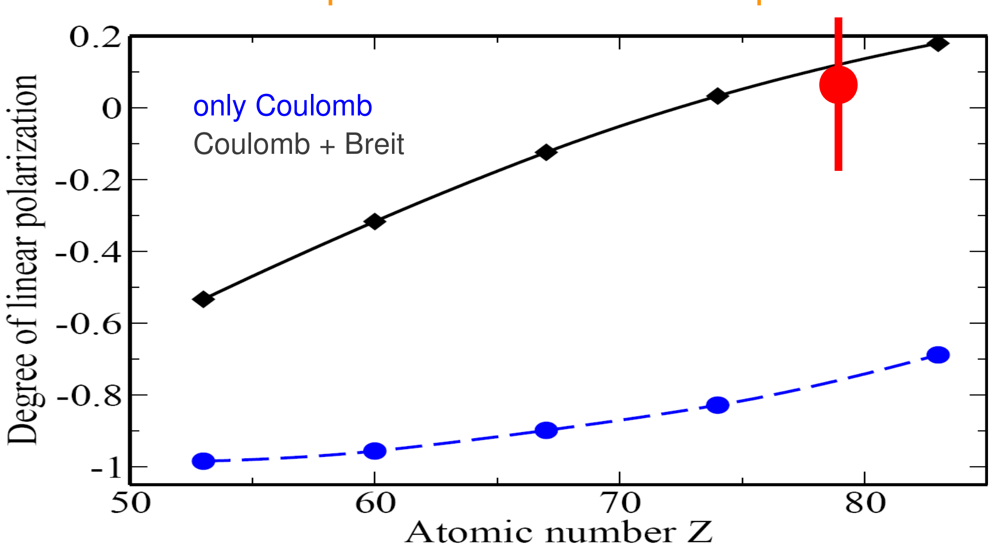
$$V_{ee} = V^C + V^B = \frac{1}{r_{12}} + \left(-\alpha_1 \alpha_2 \frac{\cos \omega r_{12}}{r_{12}} + (\alpha_1 \nabla_1)(\alpha_2 \nabla_2) \frac{\cos \omega r_{12}}{\omega^2 r_{12}} \right)$$

only Coulomb | Coulom + Breit



A_2 = -0.516 | A_2 = +0.374

Linear polarization of emitted photons



$$P(\theta = \pi/2) = \frac{-3\sqrt{2}A_2}{4 - \sqrt{2}A_2}$$

S. Fritzsche et al., PRL 103 (2009) 113001.

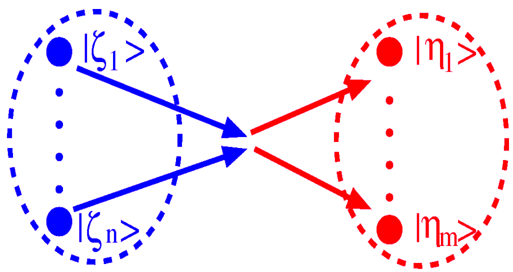
Z. Hu et al., PRL 108 (2012) 073002 (exp. confirmation).

Relativistic collisions: A theoretician's viewpoint

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



Final state

$(t \to +\infty)$

$\hat{\rho}_f$

$\hat{S}$ - scattering operator

$$\hat{\rho}_f = \hat{S}\,\hat{\rho}_i\,\hat{S}^+$$

ρ = (μ_S, J, J'; E; l, μ_l ... density matrix)

$$\sigma \sim \sum_{polarization} \int d\Omega\, |M|^2$$

total cross sections

$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

angular distribution

$$\sim |M|^2$$

No summation over polarization states !

polarization & alignment

Electron-ion collision experiments at GSI and elsewhere:

- Radiative electron capture: Exploring the electron-photon interaction
- Projectile excitation: Testing the Lorentz-transformed „Coulomb field“
- Dielectronic recombination of high-Z ions: A detailed view on the electron-electron interactions

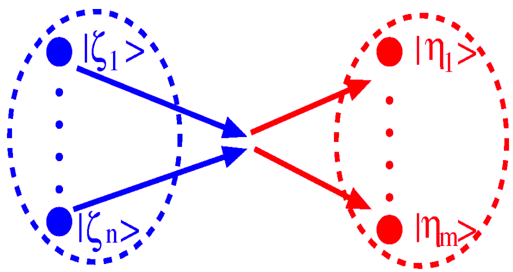
→ Two-photon decay processes; double REC; projectile ionization; annihilation after b^+ decay, ...

Relativistic collisions: A theoretician's viewpoint

Initial state

$(t \rightarrow -\infty)$

$\hat{\rho}_i$



Final state

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$$\sim |M|^2$$

No summation over

Electron-ion collision

- Radiative electron capt
- Projectile excitation: Te
- Dielectronic recombina
- Two-photon decay proc
annihilation afte

Current interests and challenges

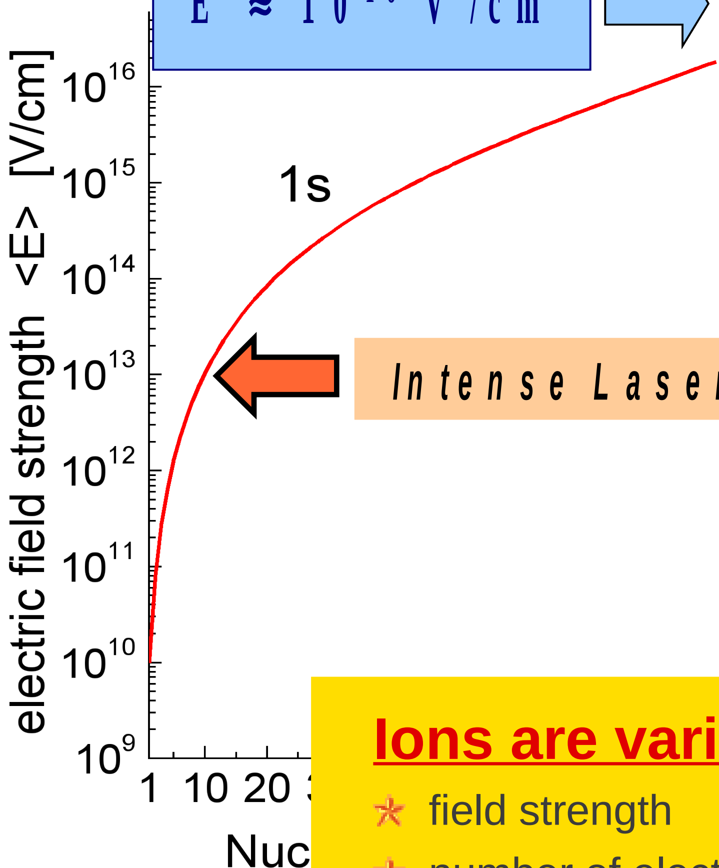
- Lifetime-induced depolarization
- Non-linear (two-photon) processes in strong `static' fields
- Polarization transfer in Rayleigh scattering
- Magnetic and retardation effects upon electron emission
- Parity non-conservation in HCI; polarized ion beams
- Studying fundamental constants (time variations, ...)

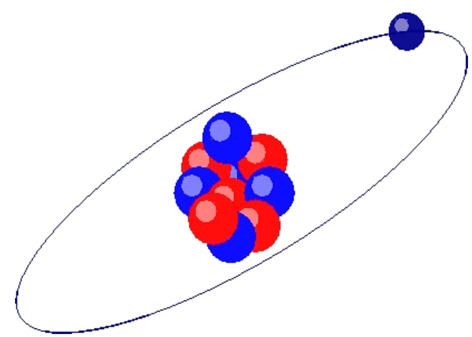
Highly-charged ions provide a „exciting“ tool

-- for probing the quantum dynamics in strong fields

<u>ultra-strong</u>

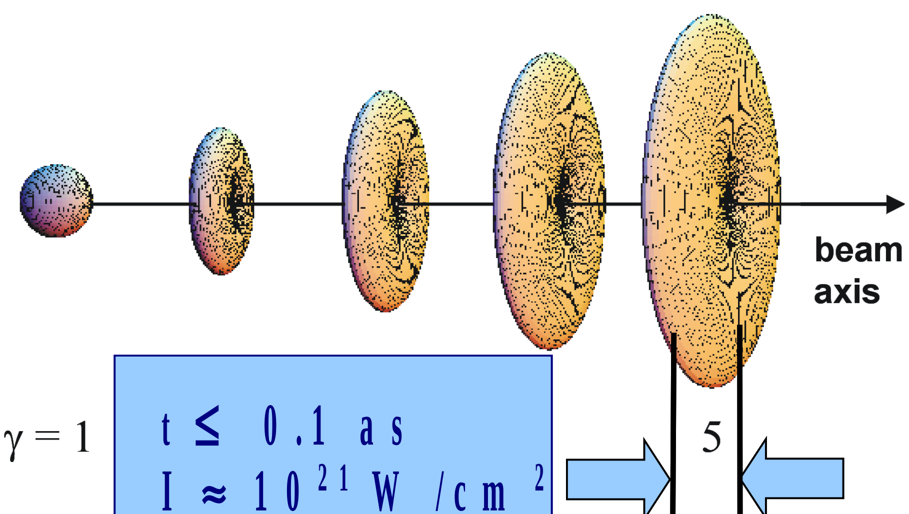
$E \approx 10^{16}$ V/cm





<u>ultra-short</u>

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$



$\gamma = 1$

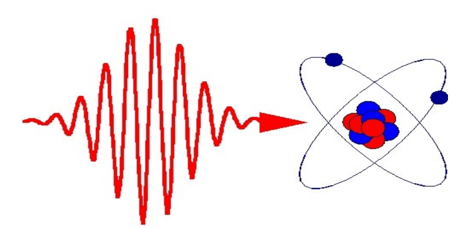
$t \leq 0.1$ as
$I \approx 10^{21}$ W/cm^2

<u>Ions are variable:</u>

- field strength
- number of electrons
- collision time (scale)

In contrast to:

<u>few-cycle laser pulses</u>



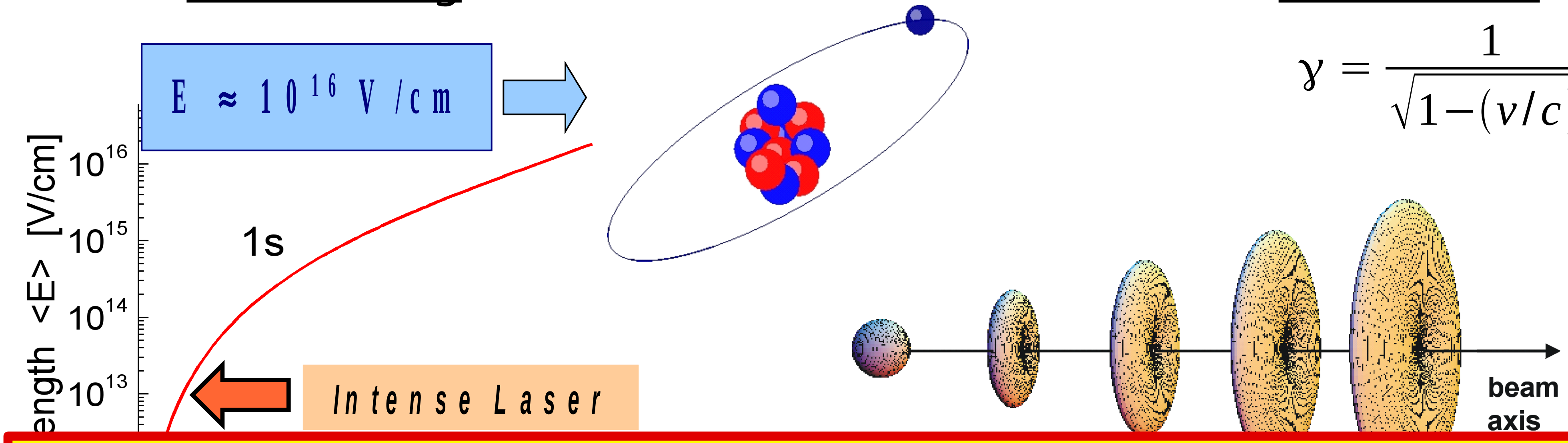
Summary: Highly-charged ions provide a „exciting“ tool

-- for probing the quantum dynamics in strong fields

<u>ultra-strong</u>

<u>ultra-short</u>

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$



<u>In the end</u>

- Ion-electron collisions: very suitable to explore elementary interactions.
- Higher multipoles: new insights into the coupling of light and matter.
- Few-electron systems: allow direct comparison of different mechanisms

  (no or less need for taking „averages“)