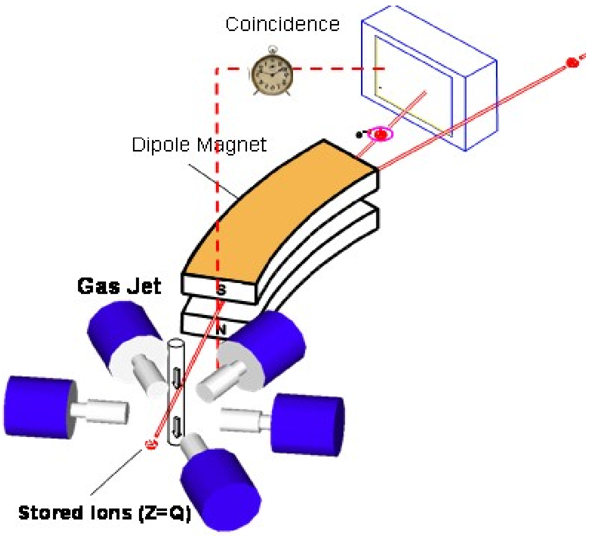
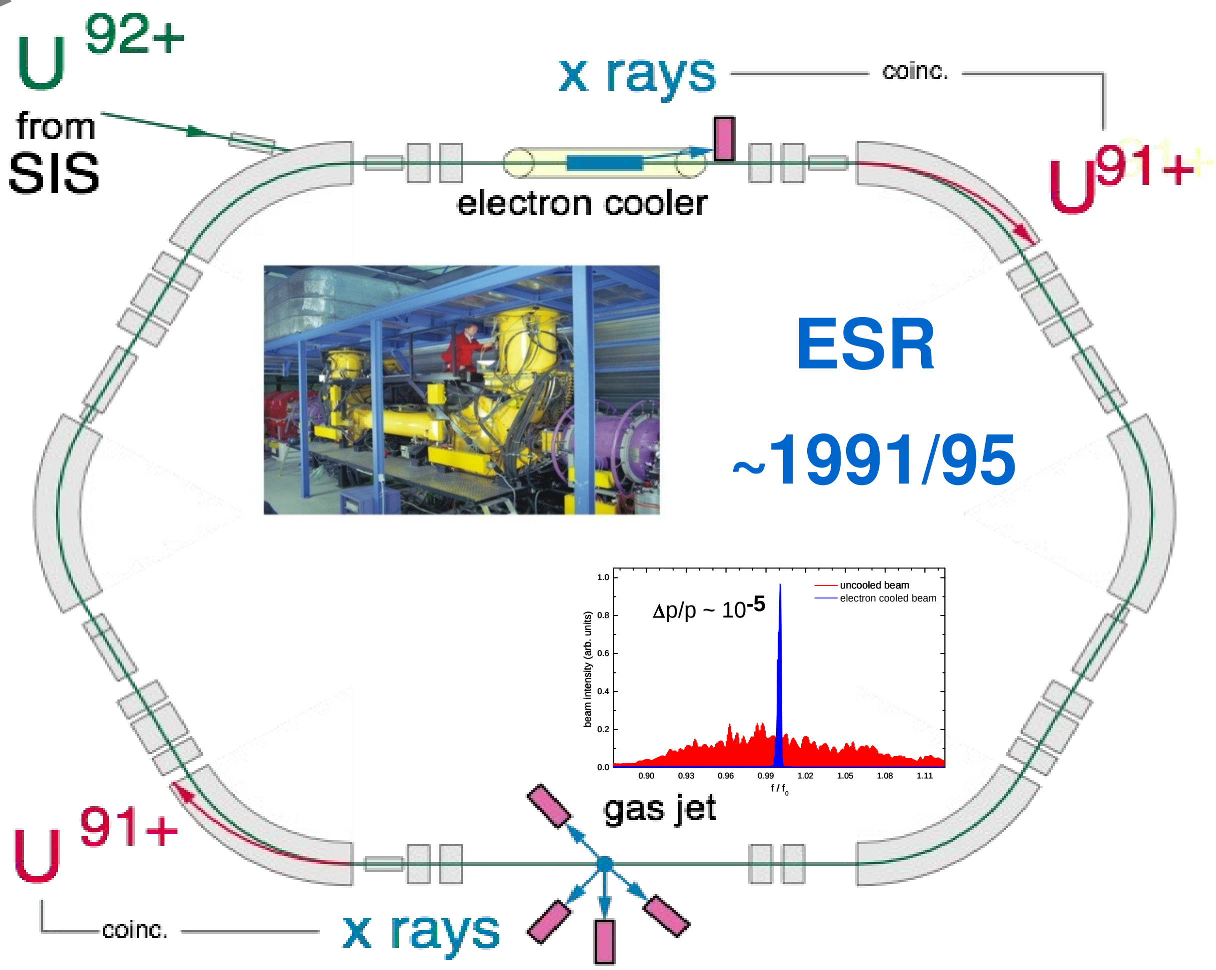
# Atomic excitations in relativistic heavy-ion collisions

Stephan Fritzsche
Helmholtz-Institute Jena &
Theoretisch-Physikalisches Institut Jena
7th July 2015

# Atomic excitations in relativistic heavy-ion collisions

Successful experiments
for the last 20 years !

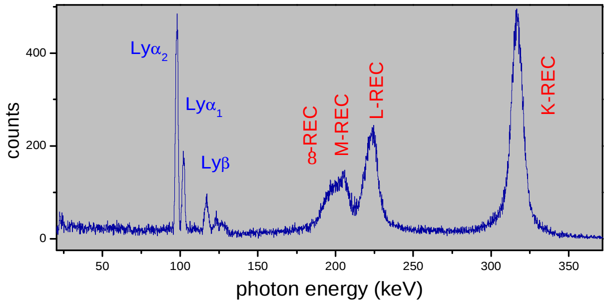


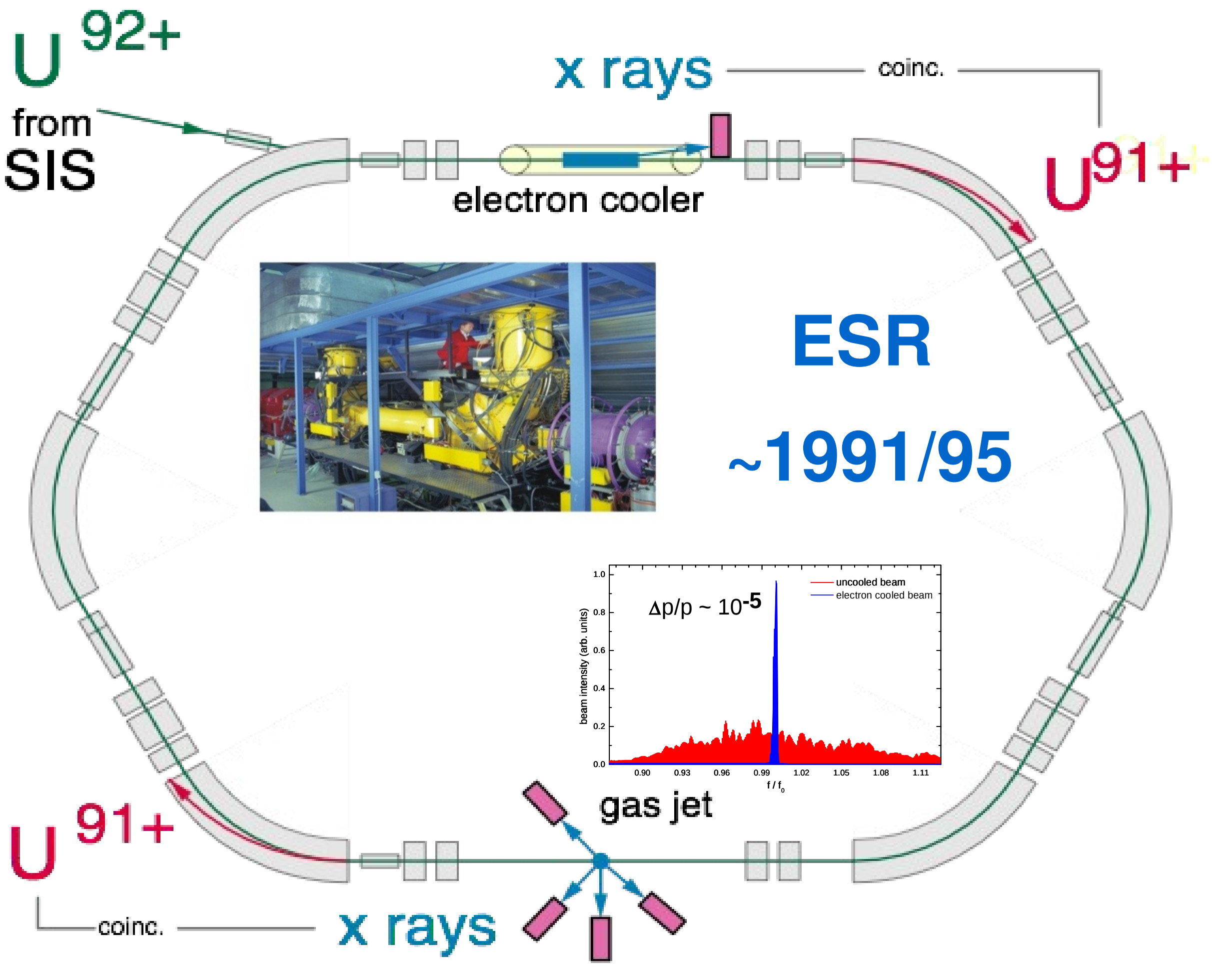


J. Eichler and T. Stöhlker, Phys. Reports 439 (2007) .

# Atomic excitations in relativistic heavy-ion collisions

$U^{92+} + N_2$ @ 295 MeV/u





## X-ray emission due to:

- Radiative electron capture (RR & REC)
- Characteristic transitions (Ly-α & K-α)
- Dielectronic recombination
- Coulomb excitation & ionization
- ...

J. Eichler and T. Stöhlker, Phys. Reports 439 (2007) .

# Atomic excitations in relativistic heavy-ion collisions

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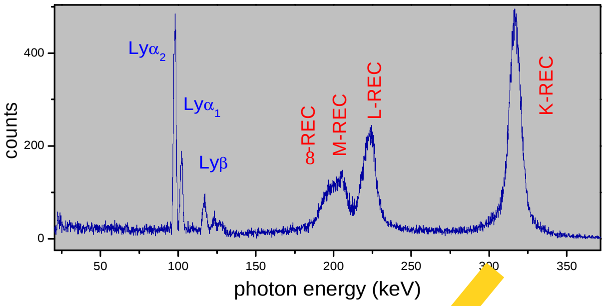
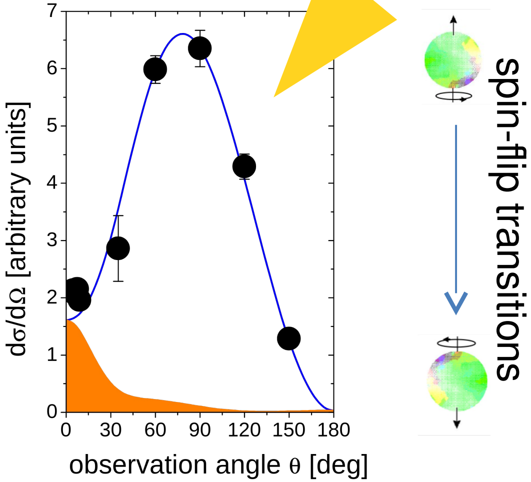
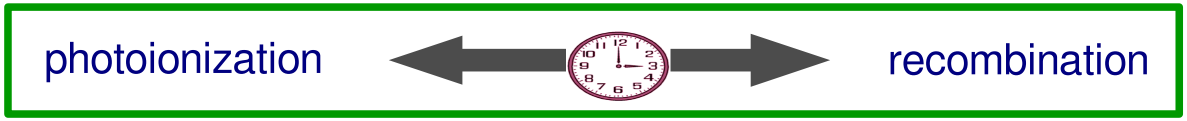


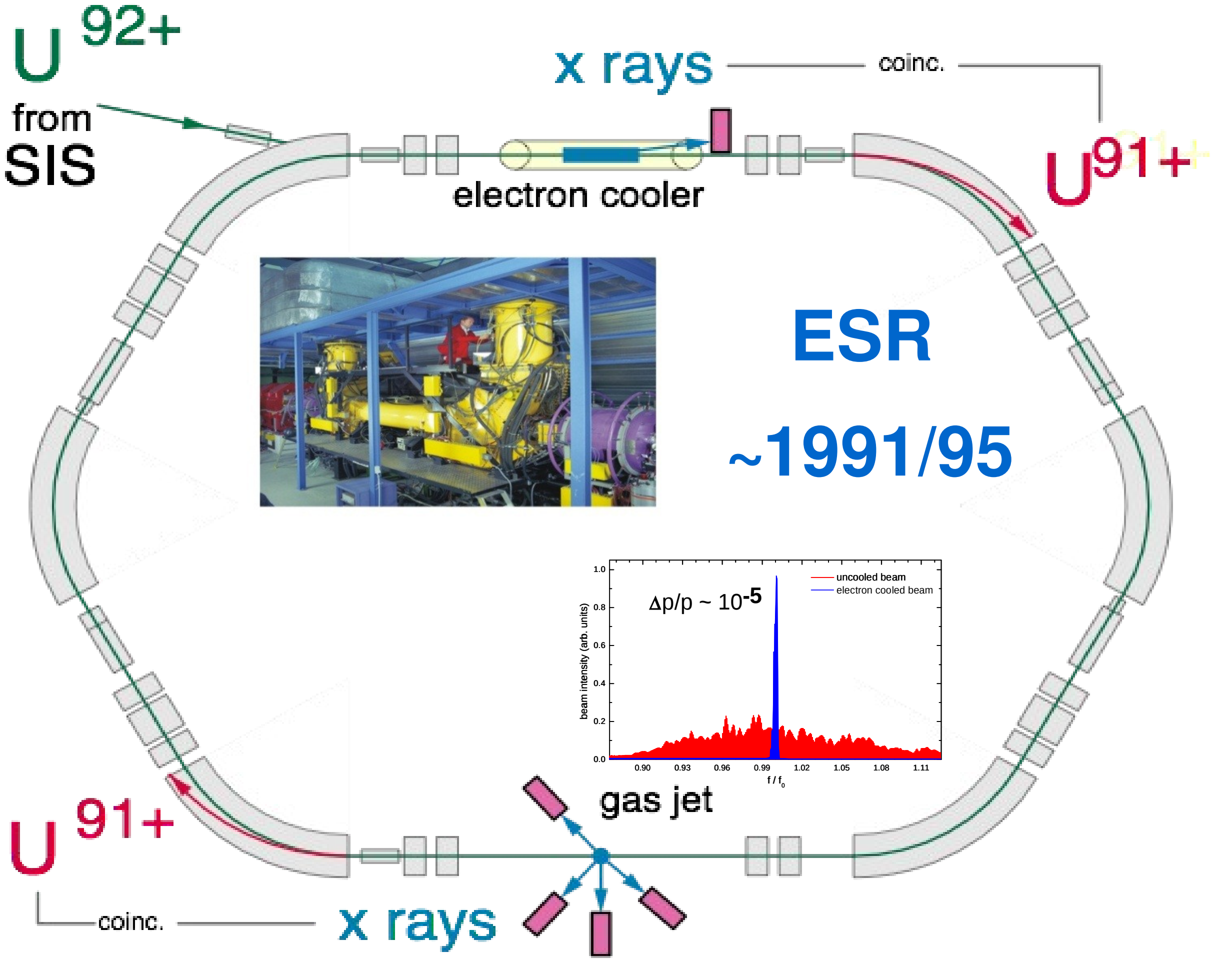
Photon angular distribution for REC into the K-shelll ($U^{92+}$, 310 MeV/u)



Identification of spin-flip transitions.



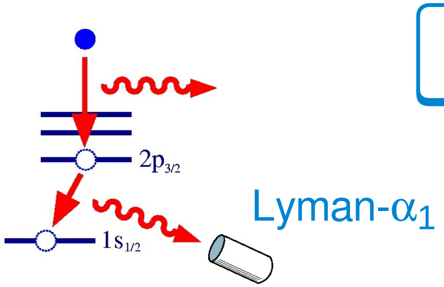
photoionization recombination

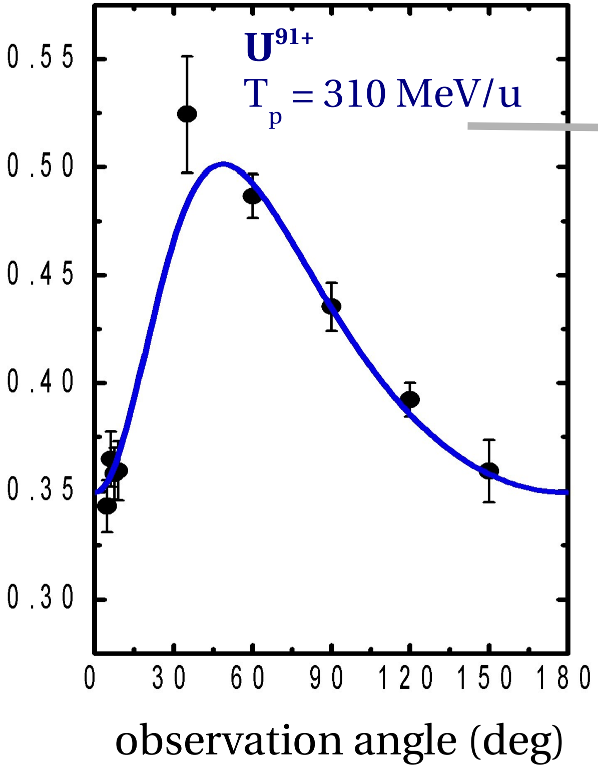


T. Stöhlker et al., PRL 79 (1997) 3270.
J. Eichler and T. Stöhlker, Phys. Reports 439 (2007) .

# Atomic excitations in relativistic heavy-ion collisions

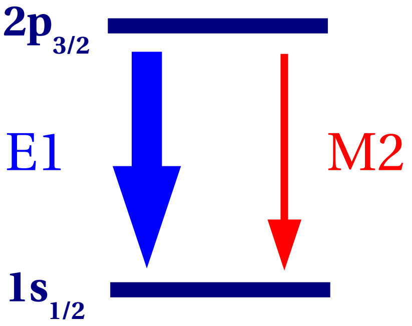
**1** Alignment of the $2p_{3/2}$ state

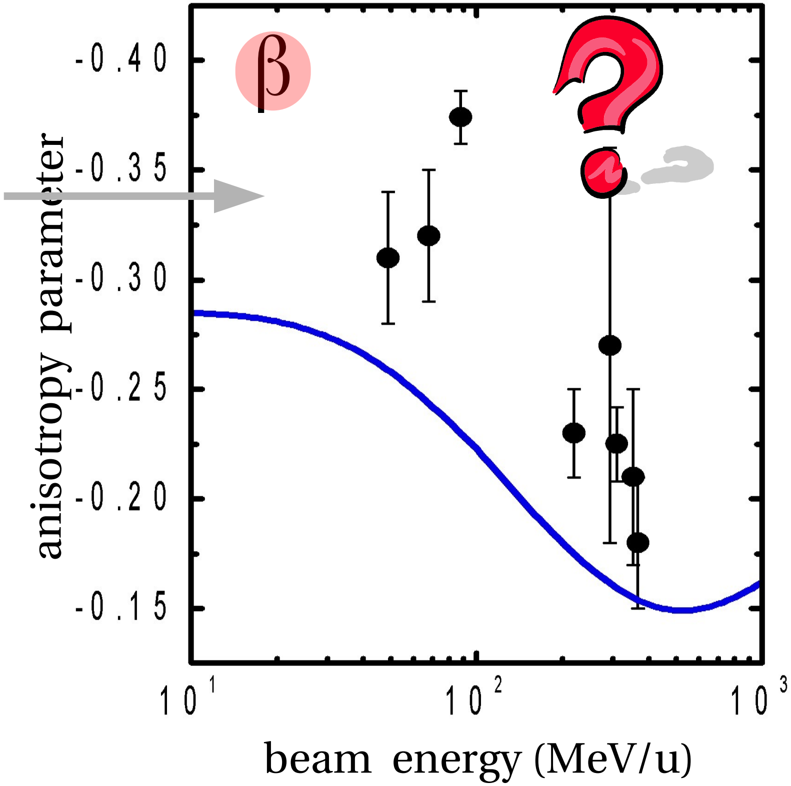




Th. Stöhlker et al., PRL 79 (1997) 3270.

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



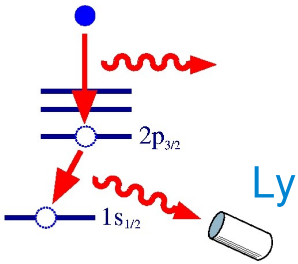


J. Eichler et al., PRA 58 (1998) 2128.

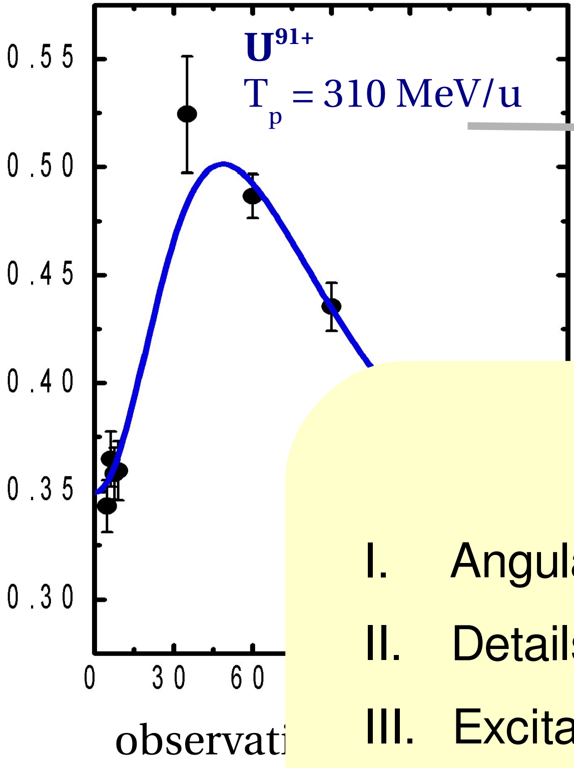
- Fundamental (relativistic) interactions in strong Coulomb field ?
- Virtual vs. real photon fields ?

# Atomic excitations in relativistic heavy-ion collisions

**1** Alignment of the $2p_{3/2}$ state



Lyman-$\alpha_1$



Th. Stöhlker et al.

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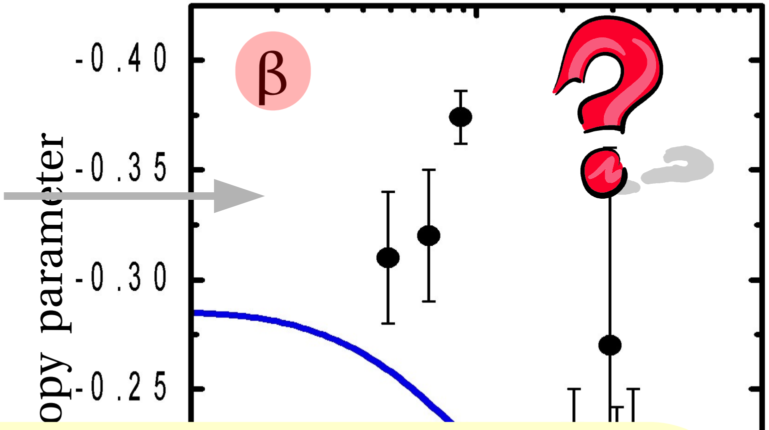


## Plan of this talk

I. Angular distributions & polarization: Making the alignment of ions visible

II. Details matter: One electron more ?

III. Excitations in relativistic collisions: Taking a theoretial viewpoint.

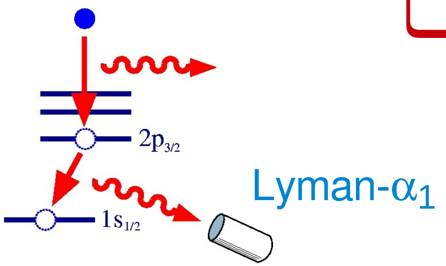
IV. Excitations: A successful route into strong-field physics

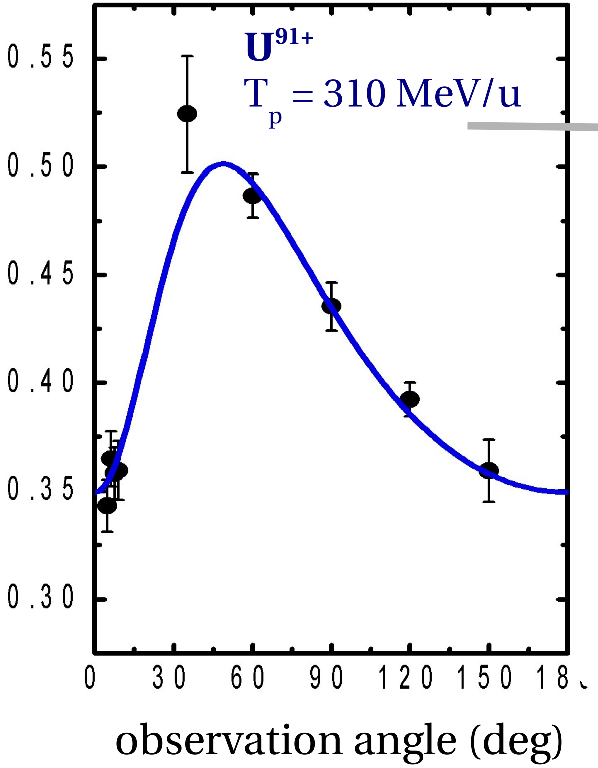
V. Non-linear ($e^-$-$\gamma$) processes at relativistic energies

VI. Summary & outlook

# E1- M2 multipole mixing of high-Z hydrogen-like ions

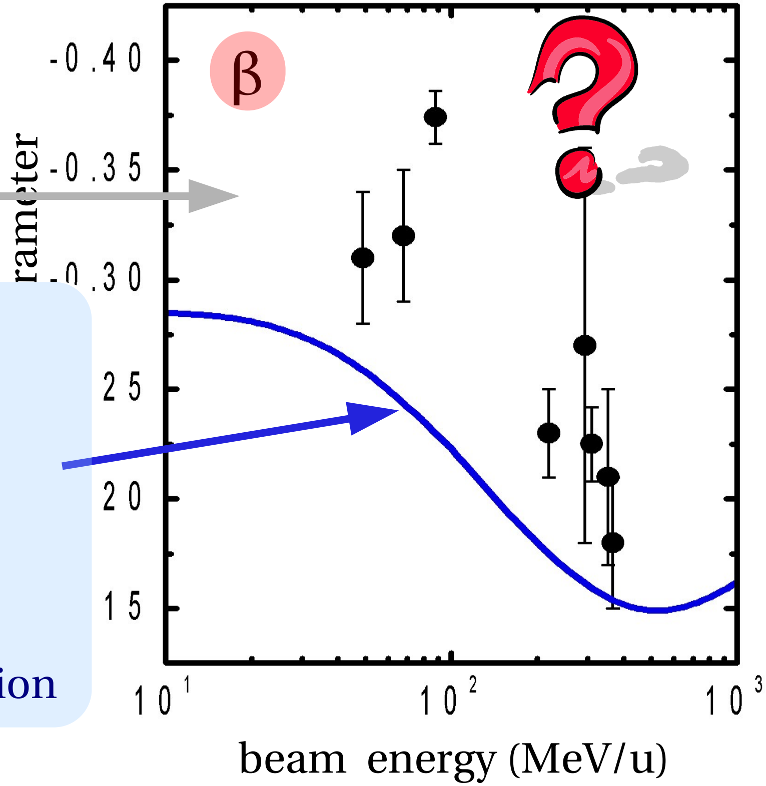
## 1 Alignment of the $2p_{3/2}$ state





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

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



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

**Theory:**

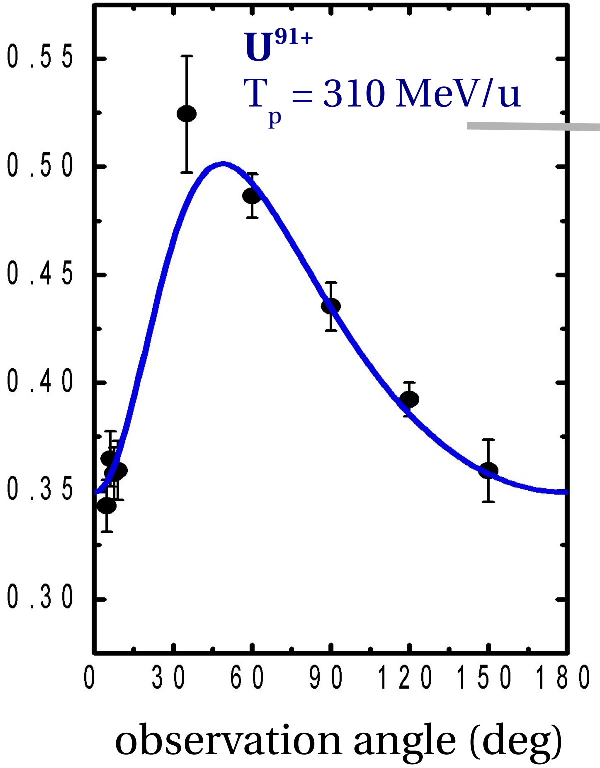
$$\beta = \frac{1}{2}\,\frac{\sigma_{\mu_b=\pm 3/2} - \sigma_{\mu_b=\pm 1/2}}{\underbrace{\sigma_{\mu_b=\pm 3/2} + \sigma_{\mu_b=\pm 1/2}}}$$

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

- Magnetic sublevel population cannot be measured directly.
- Detailed population of excited states may be derived from subsequent x-ray emission.

# E1- M2 multipole mixing of high-Z hydrogen-like ions

**1** Alignment of the $2p_{3/2}$ state



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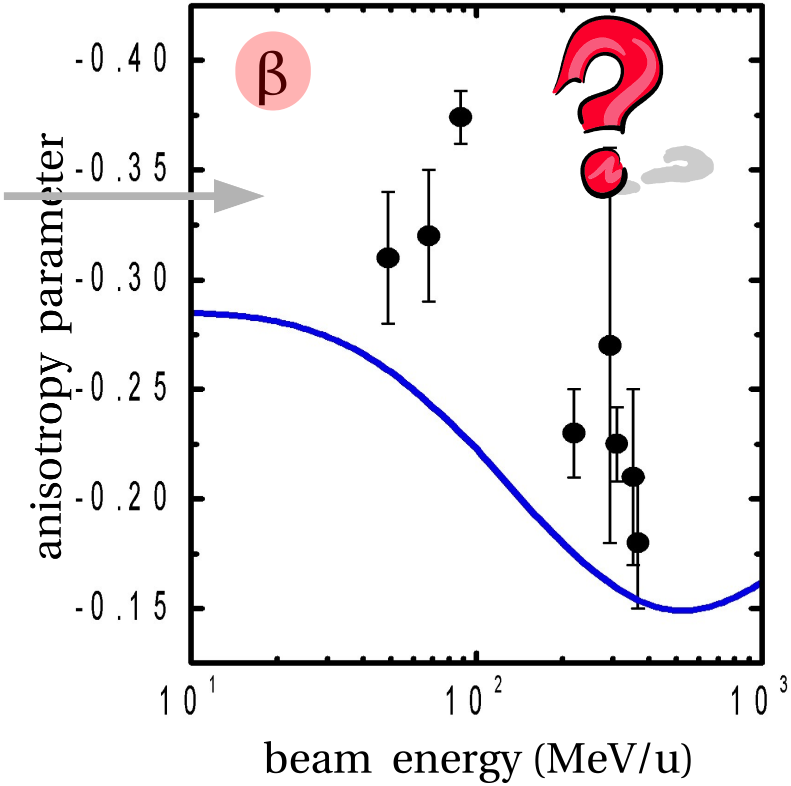

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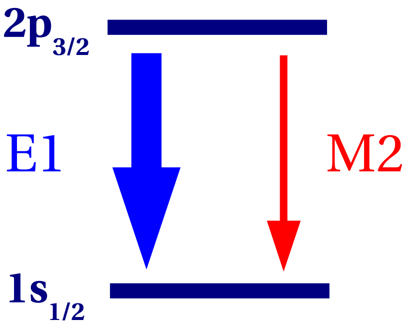
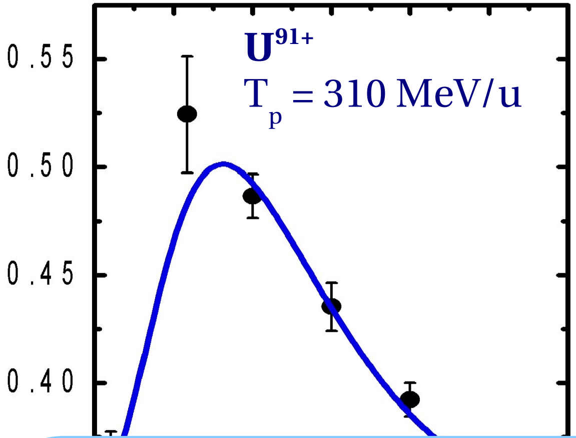


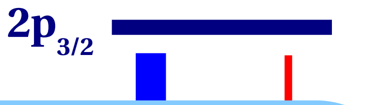
$$\beta_{eff} = \frac{1}{2}\underbrace{\frac{\sigma(\pm 3/2) - \sigma(\pm 1/2)}{\sigma(\pm 3/2) + \sigma(\pm 1/2)}}_{\text{alignment parameter (capture)}} * \underbrace{f(E1, M2)}_{\text{structure function (ion)}}$$

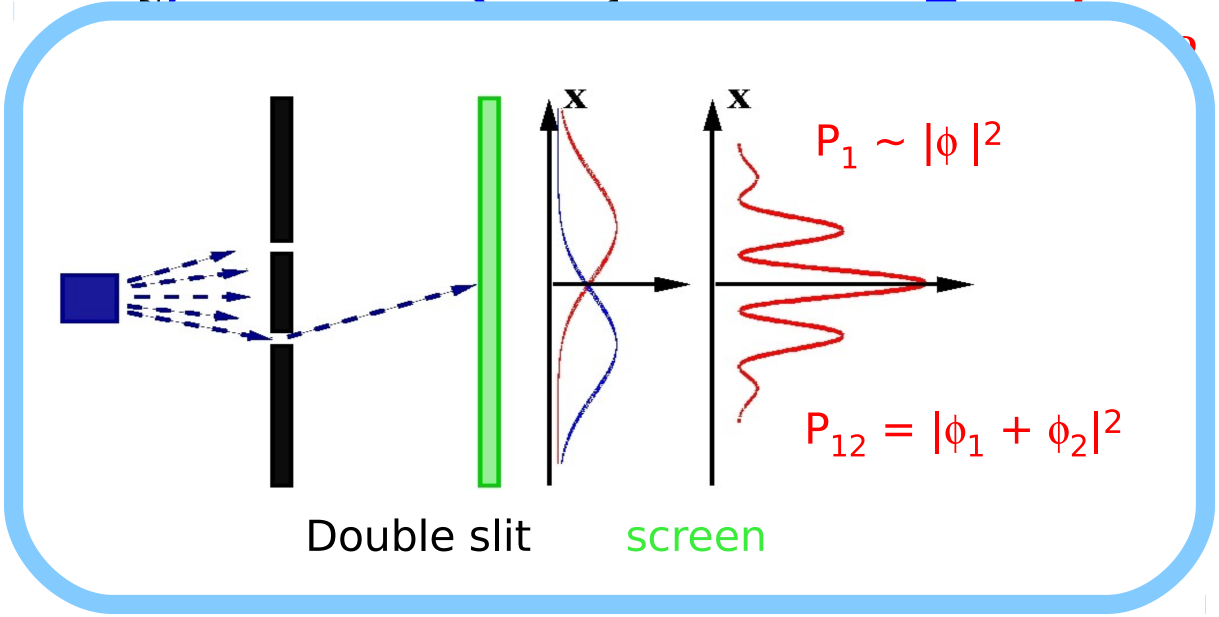
$$f(E1, M2) \propto 1 + 2\sqrt{3}\,\frac{\langle|M2|\rangle}{\langle|E1|\rangle}$$

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

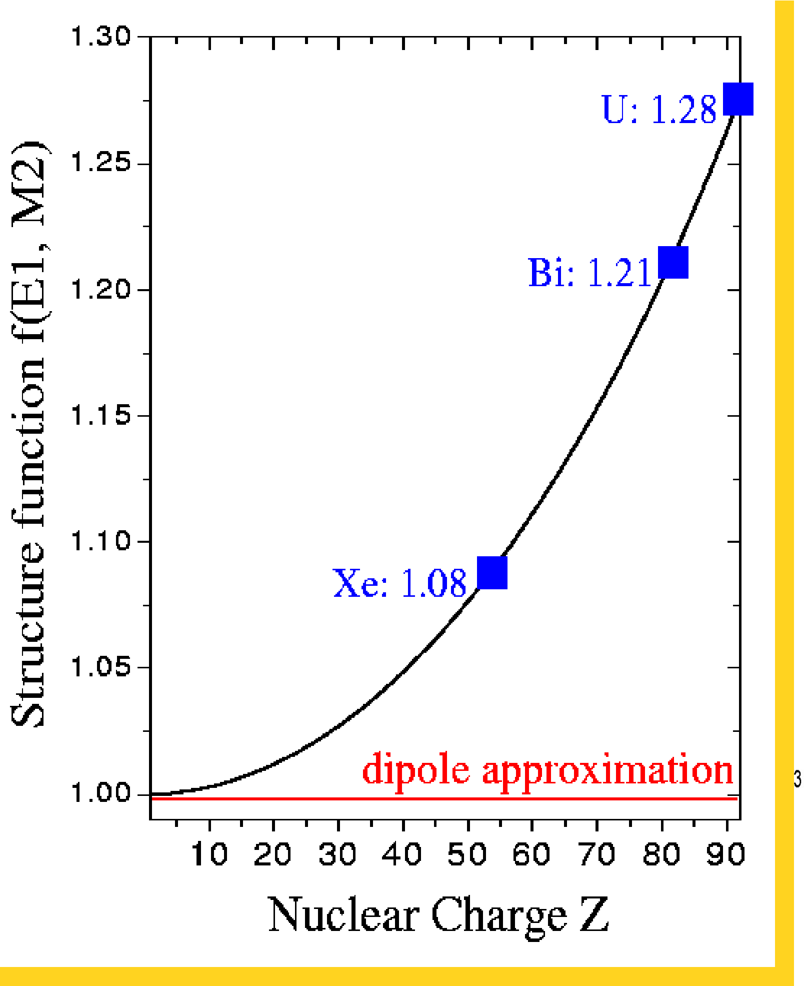
# E1- M2 multipole mixing of high-Z hydrogen-like ions







## 1 Alignment of the $2p_{3/2}$ state



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

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# E1- M2 multipole mixing of high-Z hydrogen-like ions

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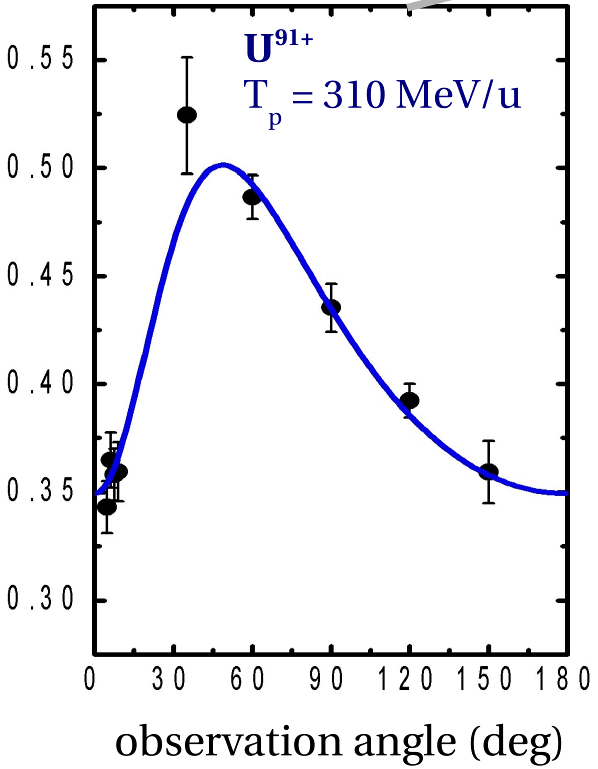
$$W(\theta) \propto 1 + \beta_{eff} P_2(\cos\theta)$$



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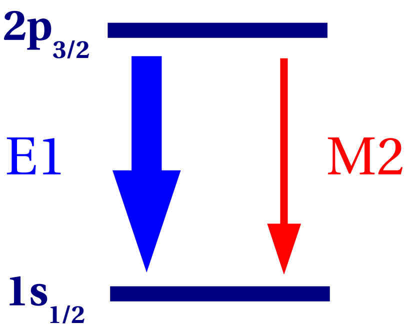

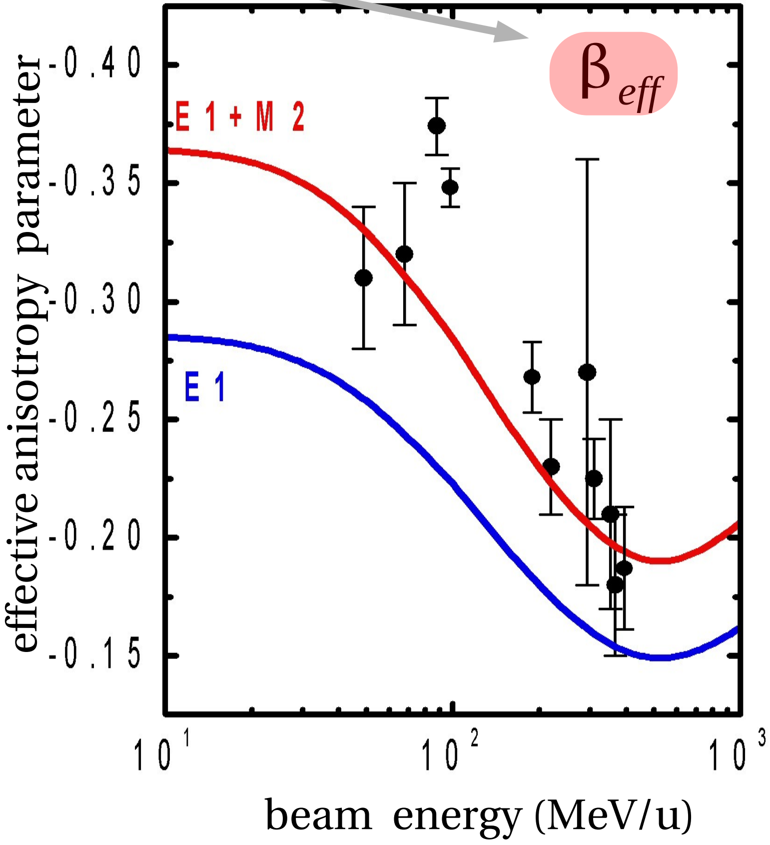

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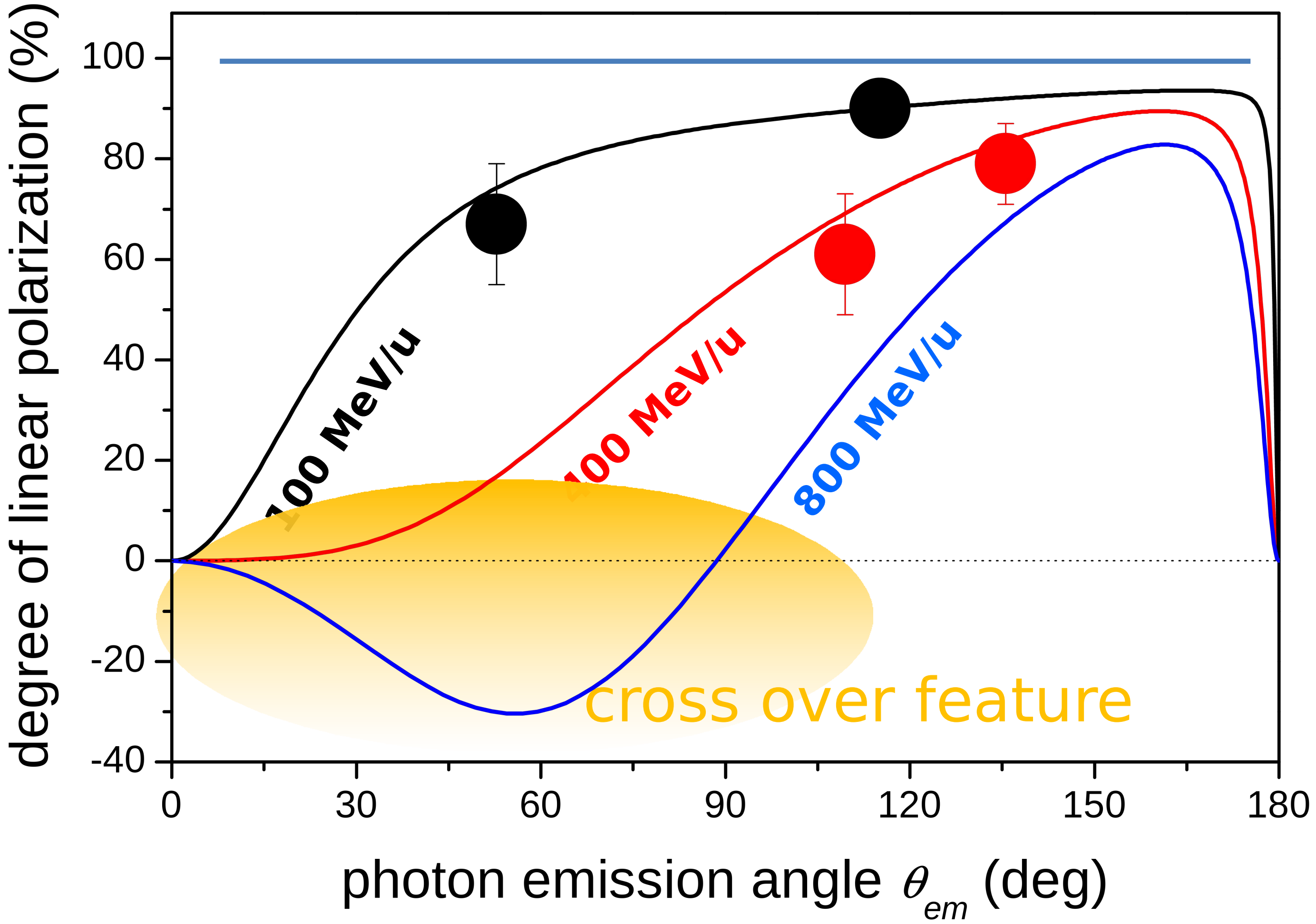
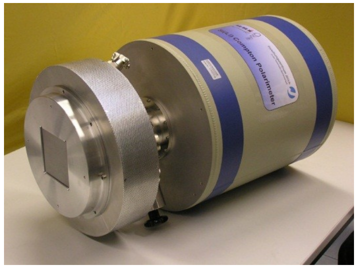
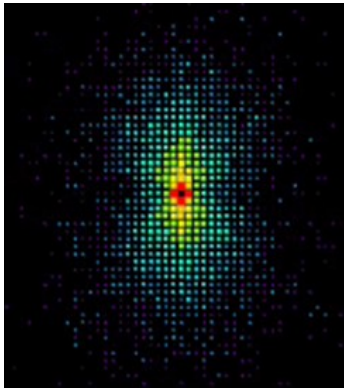
- Dynamical alignment studies enables one to explore magnetic interactions in the bound-bound transitions in H-like ions !

# Linear polarization of x-rays following K-shell REC

$\boxed{2}$ Sensitive probe for high-multipole components





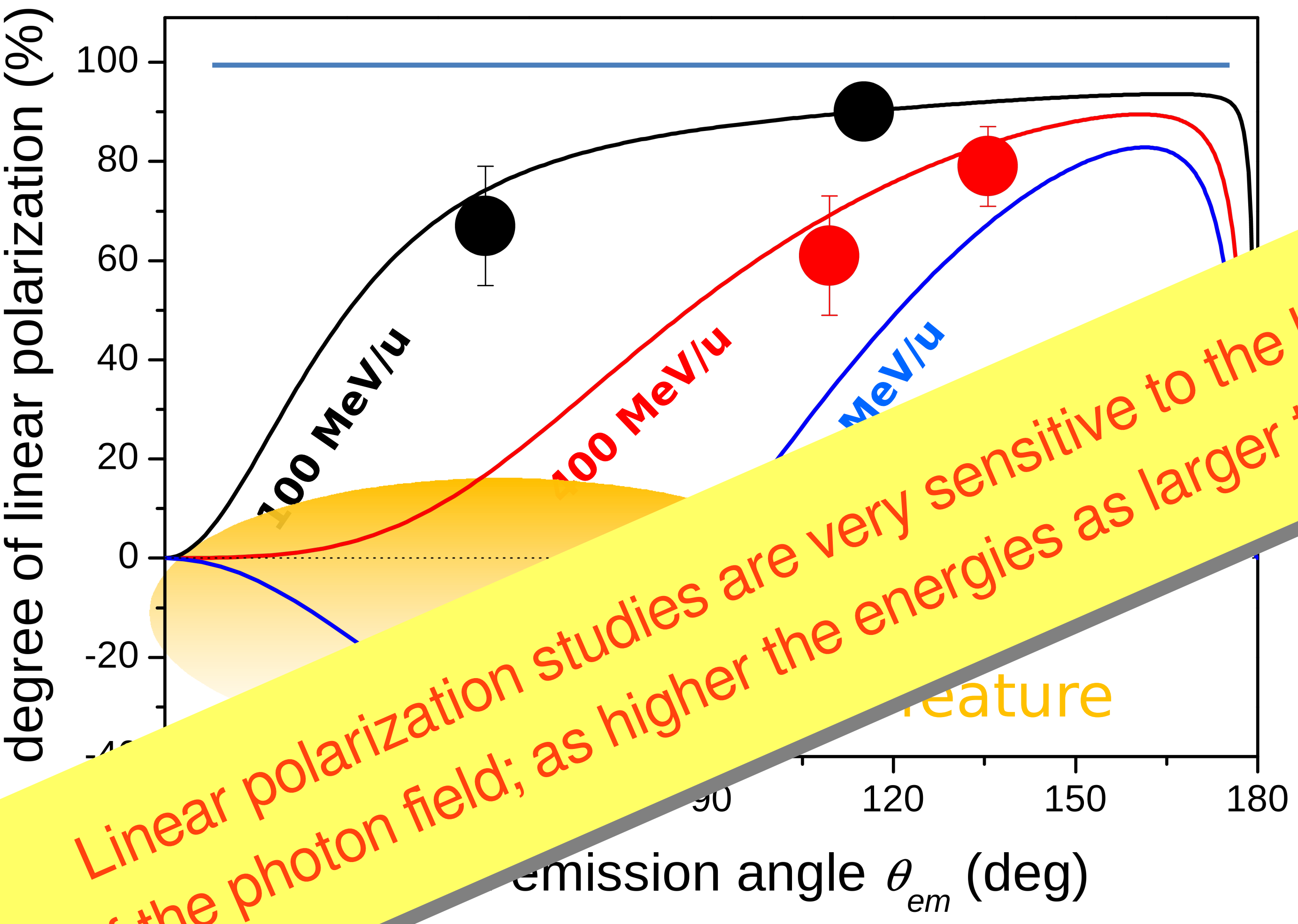


T. Stöhlker &AP @ GSI

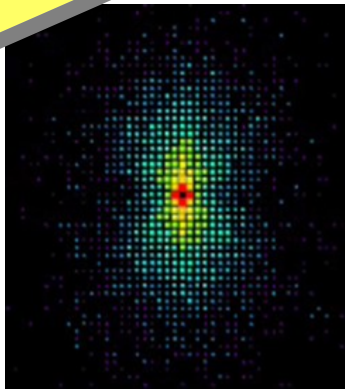
S. Tashenov et al., PRL 97 (2006) 223202.
J. Eichler and A. Ichihara, PRA 65 (2002) 052716.
A. Surzhykov et al., PRA 68 (2003) 022710.

# Linear polarization of x-rays following K-shell REC

**2** Sensitive probe for high-multipole components



Linear polarization studies are very sensitive to the high multipoles of the photon field; as higher the energies as larger the depolarization.



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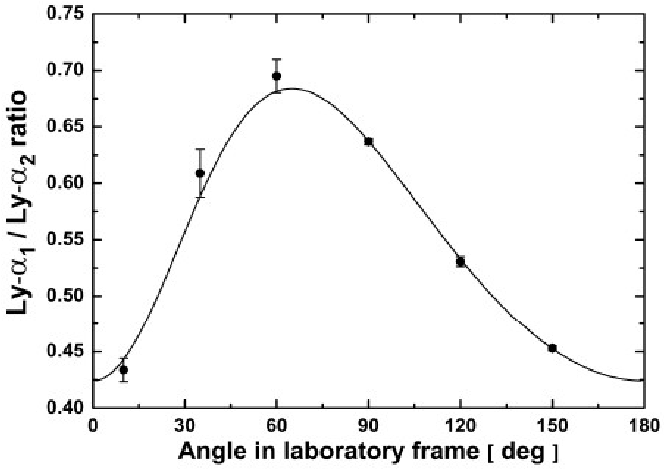
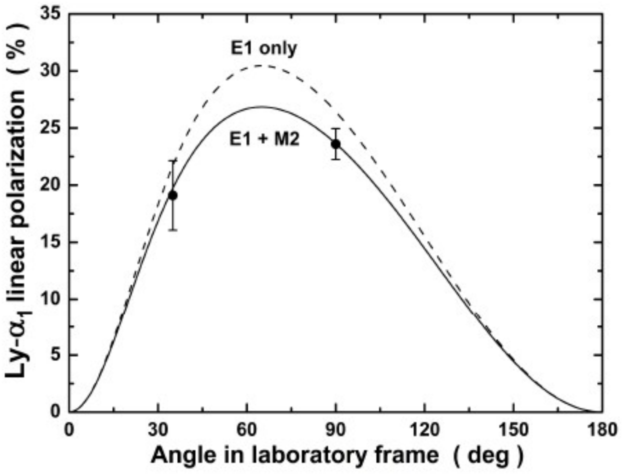
# Electron-photon interactions in strong Coulomb fields

## 3 Can one directly ``measure'' multipole fields ?

Lyman-$\alpha_1$ ($2p_{3/2}$ --> $1s_{1/2}$) for H-like $U^{91+}$ ions:

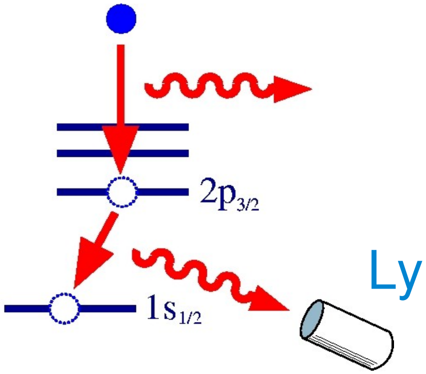


Angular distribution



Linear polarization

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



Lyman-$\alpha_1$

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

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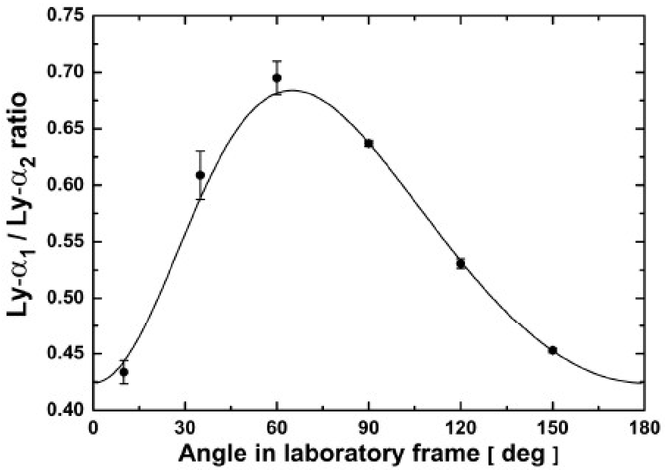
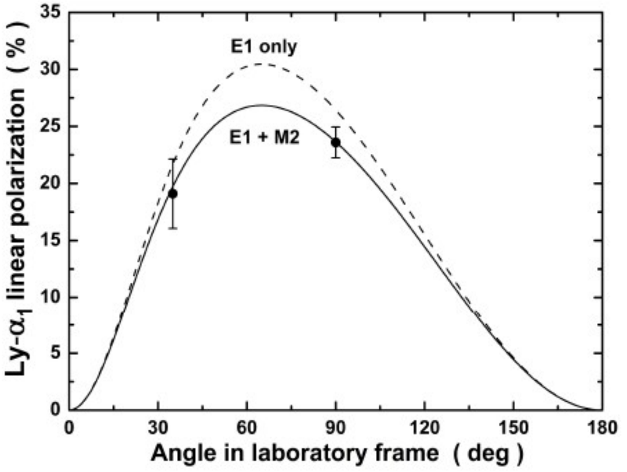


Angular distribution



Linear polarization

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

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

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

| 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.

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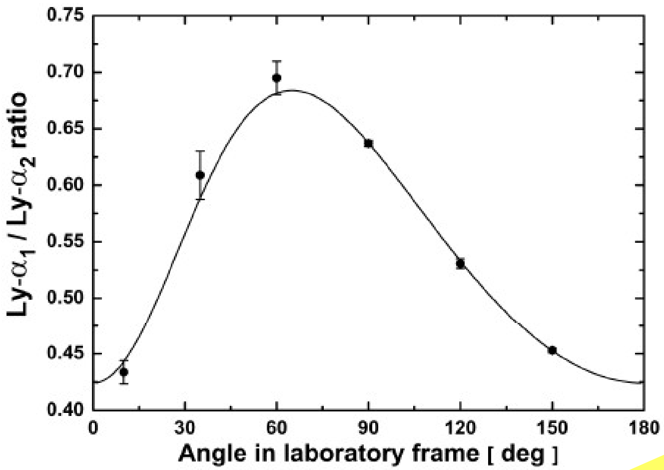
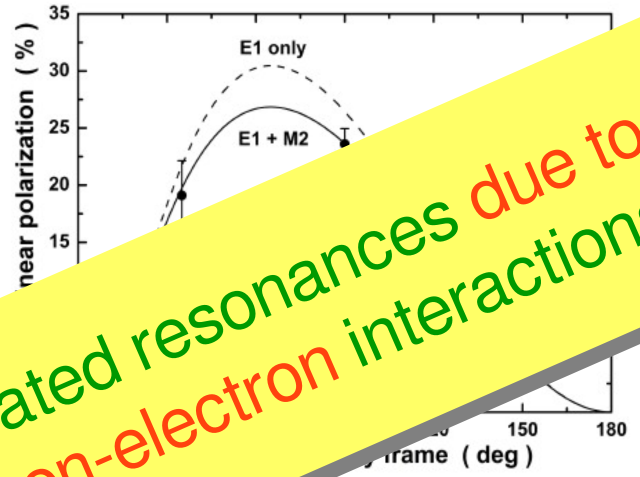


Angular distributi



polarization

Modified angular distributions for isolated resonances due to relativistic electron-photon and electron-electron interactions.

$W(\theta) \propto 1 + \beta^{\mathrm{eff}}$

$a_{M2}/a_{E1}$)

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

|  |  | Amplitude ratio $a_{M2}/a_{E1}$ |  |
|---|---|---|---|
| Ex | y | Experiment | Theory |
| -0.45 | -0.457 | 0.083 ± 0.014 | 0.0844 |

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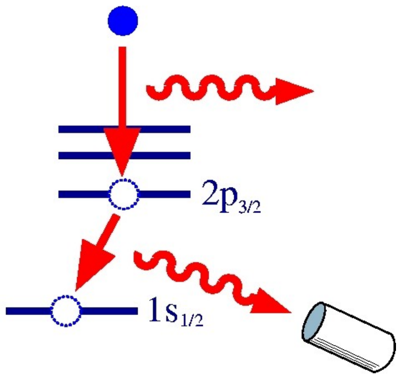
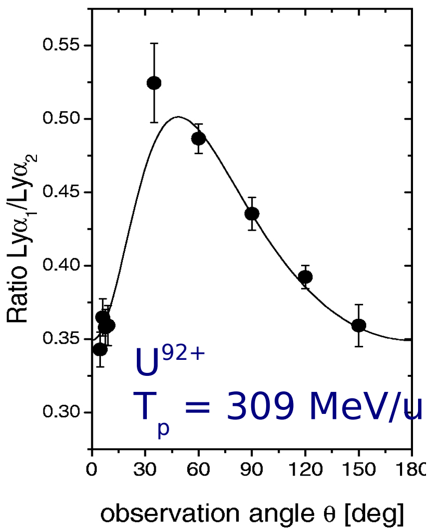
# Details matter: Adding a single electron to the ions

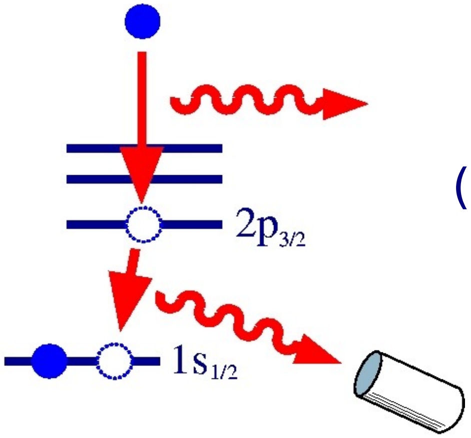
## 4 Lyman-$\alpha$ vs. K-$\alpha$ emission from high-Z ions



(initially) bare ion

Ly-$\alpha_1$ is strongly anisotropic





(initially) H-like ion

K-$\alpha_1$ is isotropic

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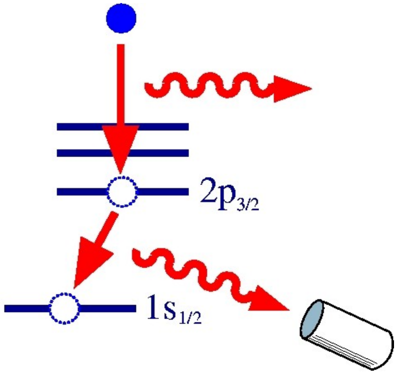

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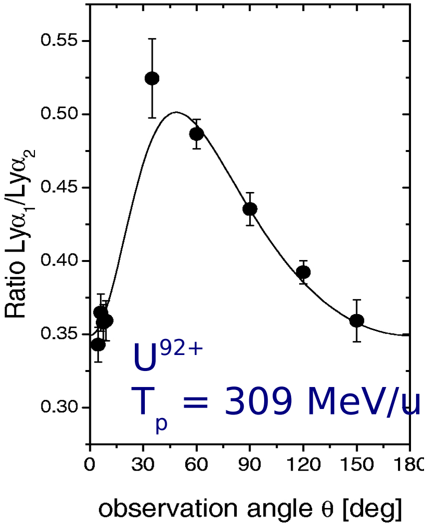
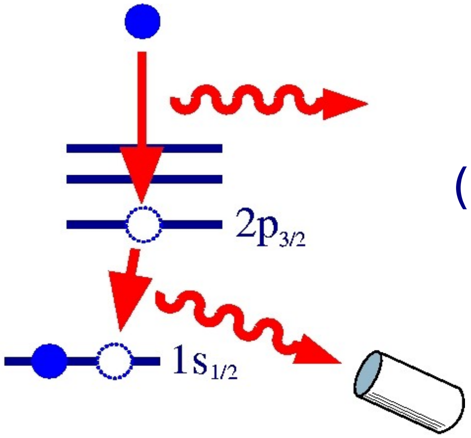


$U^{92+}$

$T_p$ = 309 MeV/u



(initially) H-like ion

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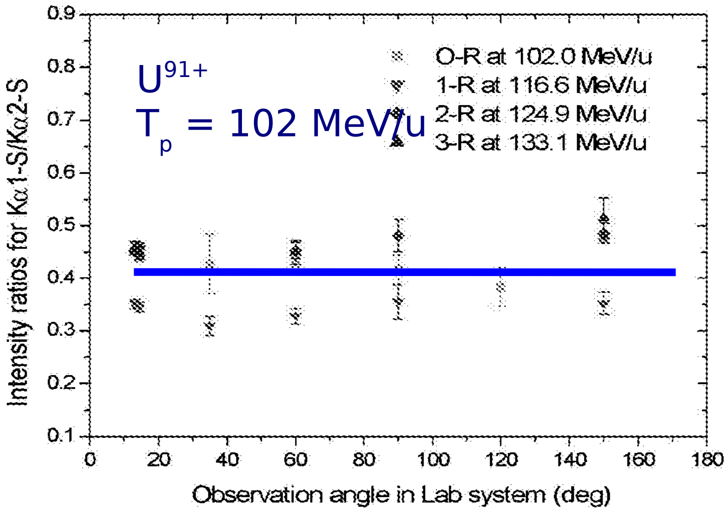

$U^{91+}$

$T_p$ = 102 MeV/u

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

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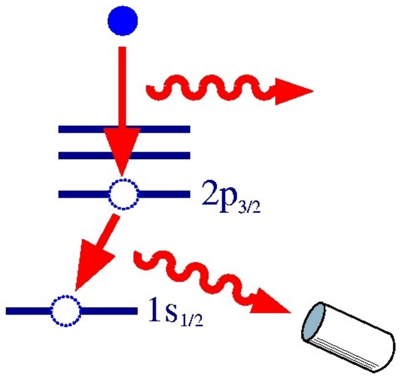
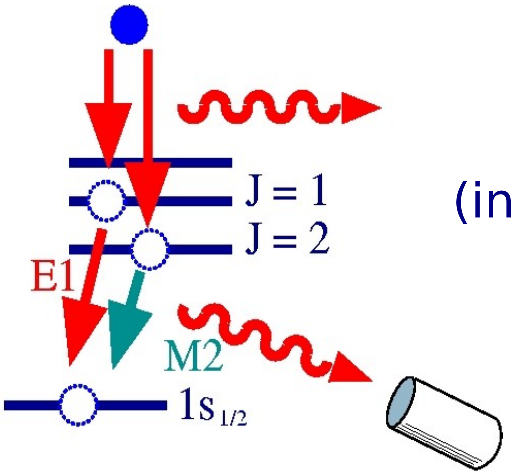


(initially) bare ion



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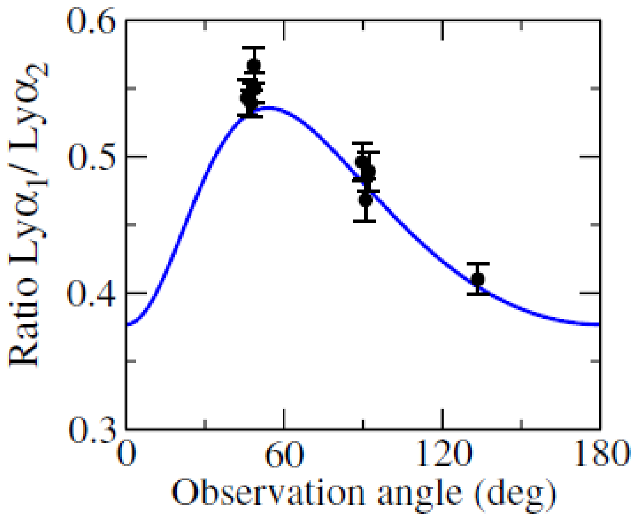

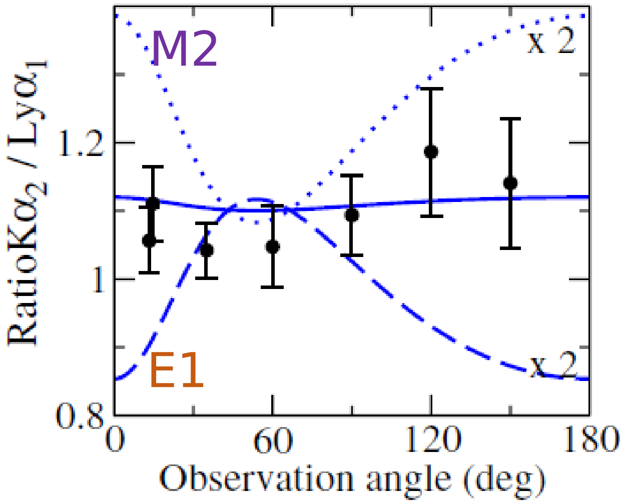

No interference of the various multipoles of the radiation field !

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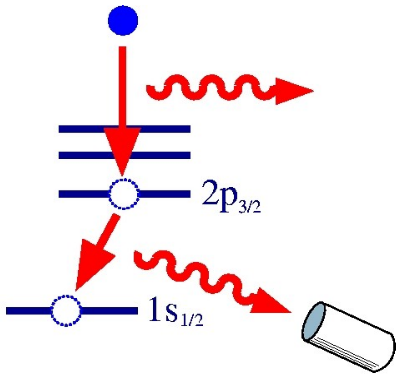
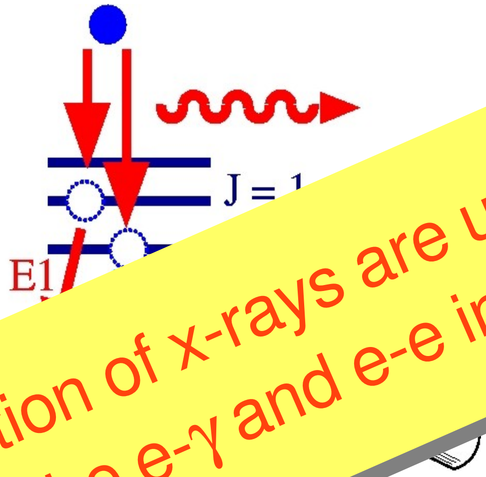
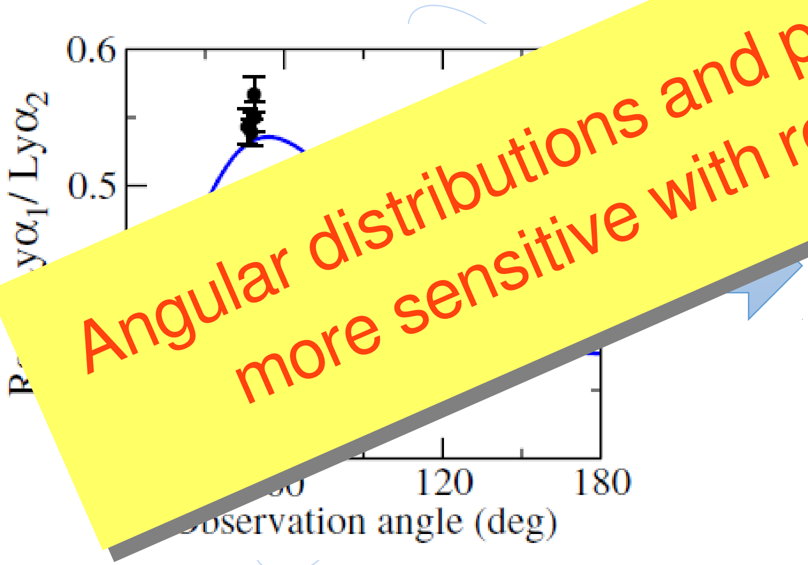


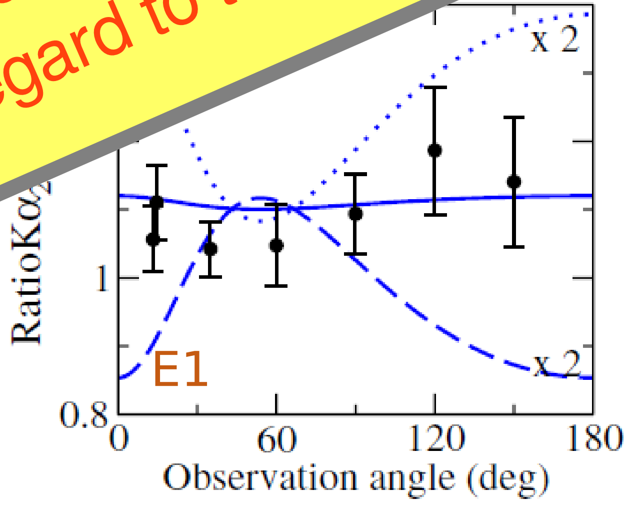
(initially) bare ion



K-α$_1$ is isotropic

Angular distributions and polarization of x-rays are usually (much) more sensitive with regard to the e-γ and e-e interactions.



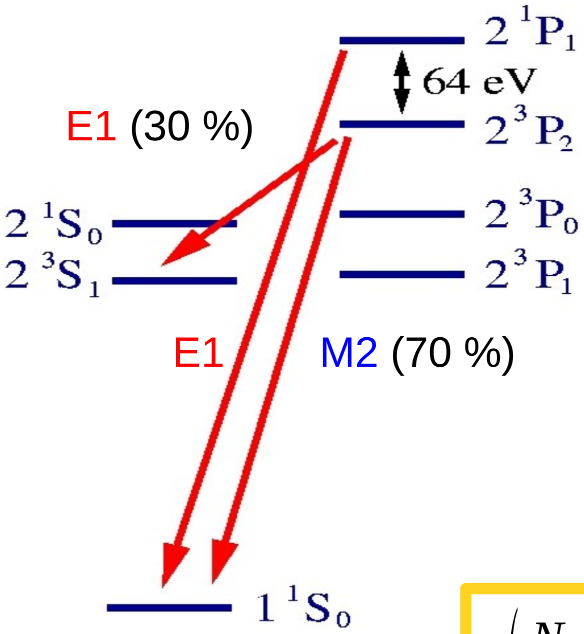


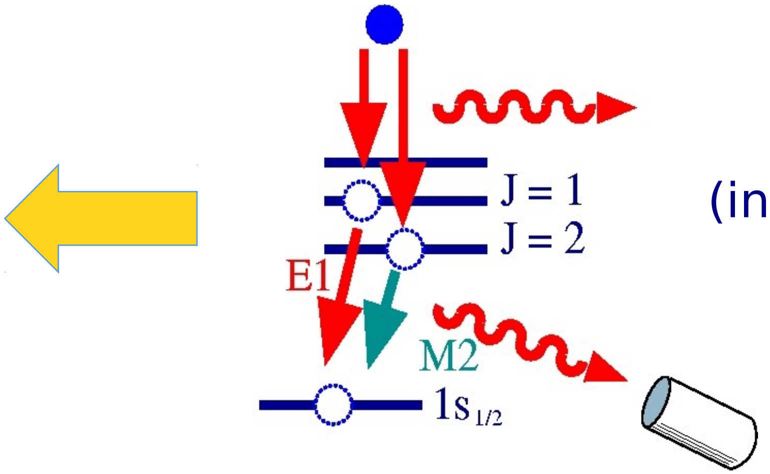
No interference of the various multipoles of the radiation field !

# Details matter: Adding a single electron to the ions

## 4 Lyman-α vs. K-α emission from high-Z ions

K-α decay for 220 MeV/u $U^{90+}$ ions **following REC.**





(initially) H-like ion

K-$\alpha_1$ is isotropic

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

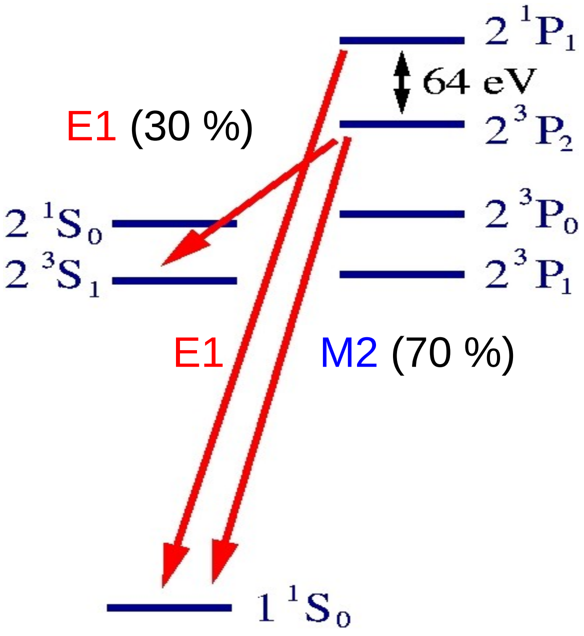
$$W(\theta)_{K\alpha_1} \sim N_{J=1} W_{E1}(\theta) + N_{J=2} W_{M2}(\theta)$$

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

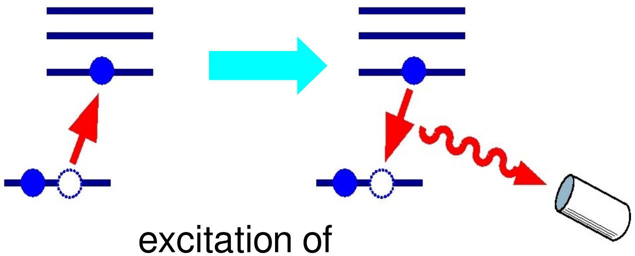
A. Surzhykov et al., PRA 73 (2006) 032716.

# Details matter: Role of excitation process

## 5 K-α emission following Coulomb excitations

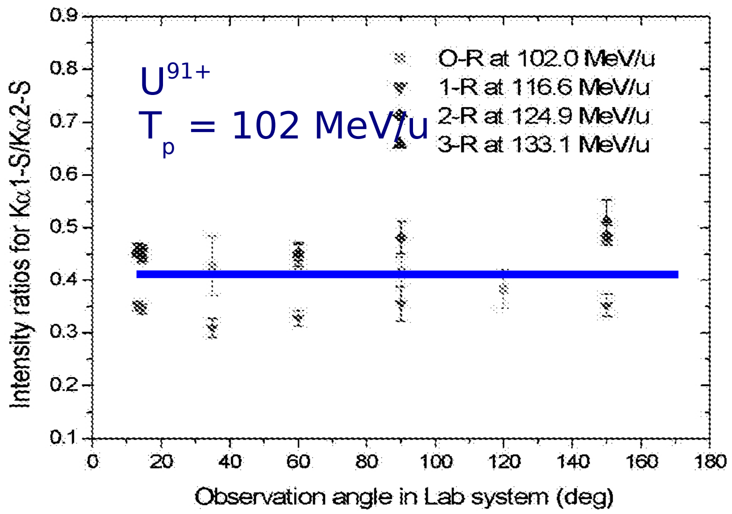


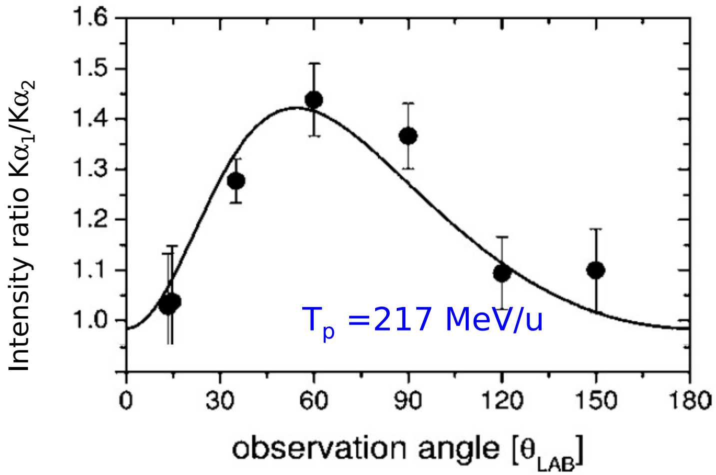
(initially) He-like ion



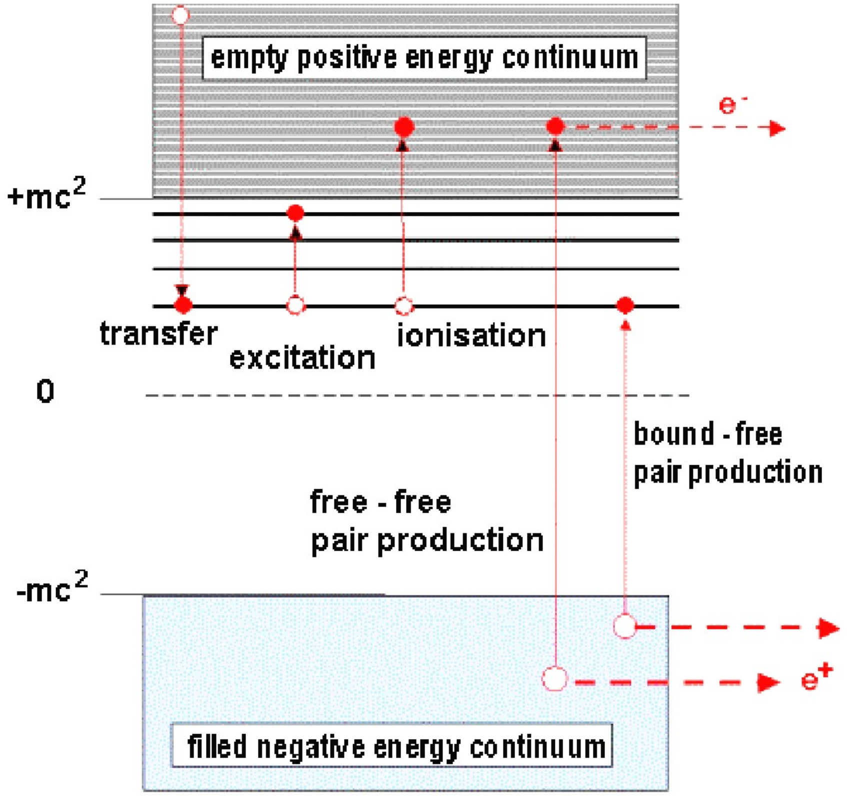
excitation of
He-like $U^{90+}$ ion

K-$\alpha_1$ is anisotropic

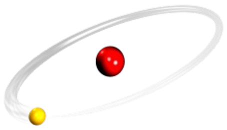




# Atomic excitations in relativistic heavy-ion collisions



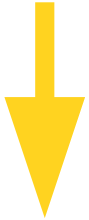
**hydrogen**



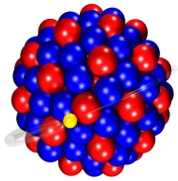
Z=1

$E_b$ = 13.6 eV

Z·α « 1



**uranium ion**



Z=92

$E_b$ =  132 keV

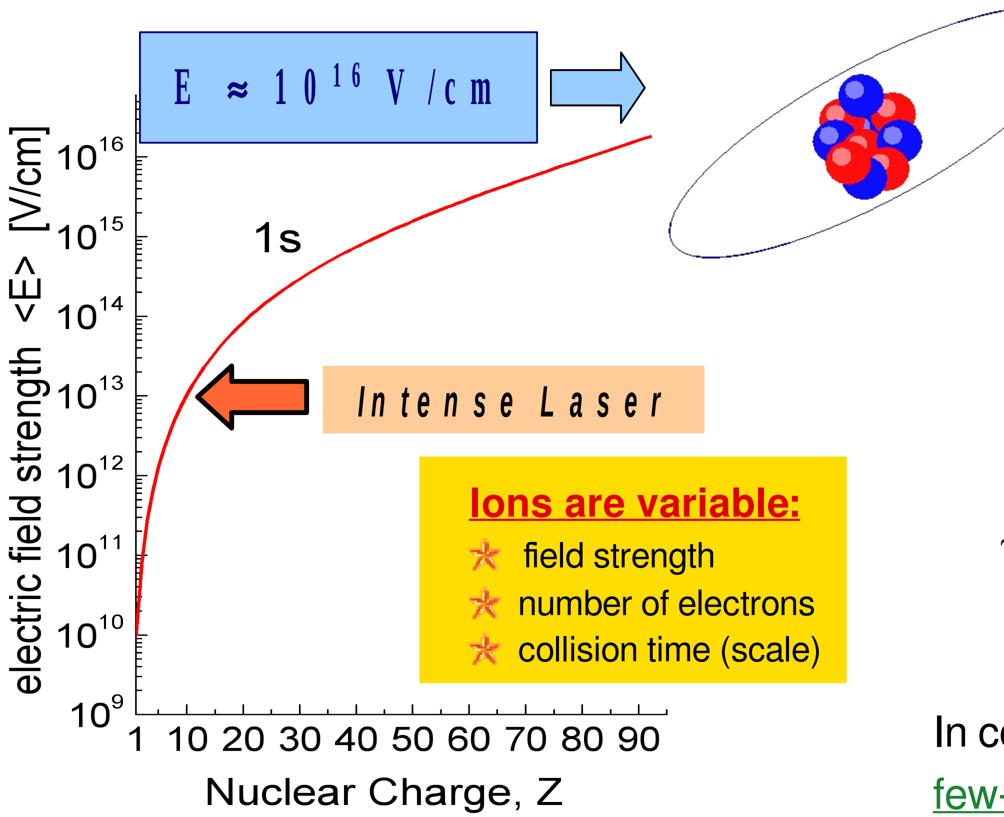
Z·α  ≈  1

Unique features of heavy-ion collisions:

- Tunable field strength.
- Correlated vs. relativistic quantum dynamics.
- Non-perturbative particle production.
- (Sub-) attosecond time scale.
- Inherent coupling to radiation field (“tests” of QED)

# Atomic excitations in relativistic heavy-ion collisions

ultra-strong



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

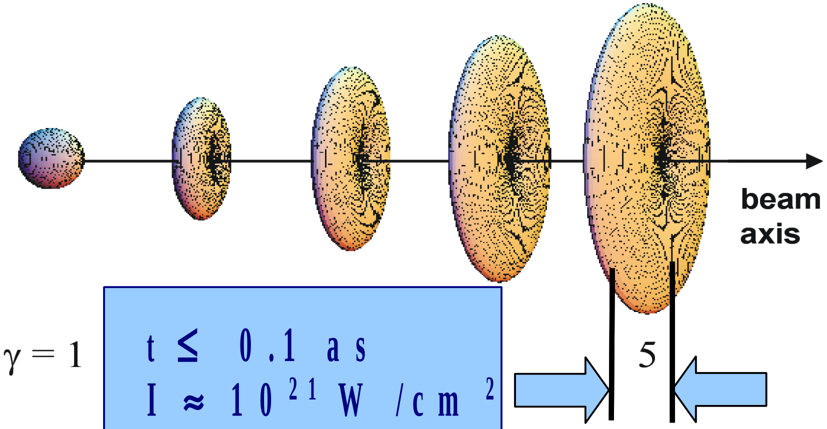
Intense Laser

**Ions are variable:**

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

ultra-short

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

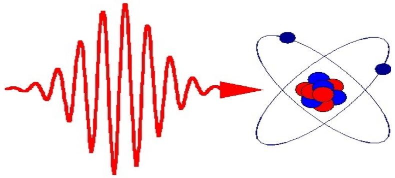


$\gamma = 1$

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

In contrast to:

few-cycle laser pulses



## Unique features of heavy-ion collisions:

- Tunable field strength.
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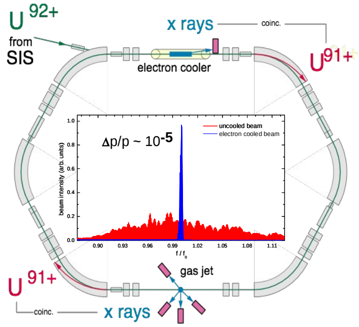
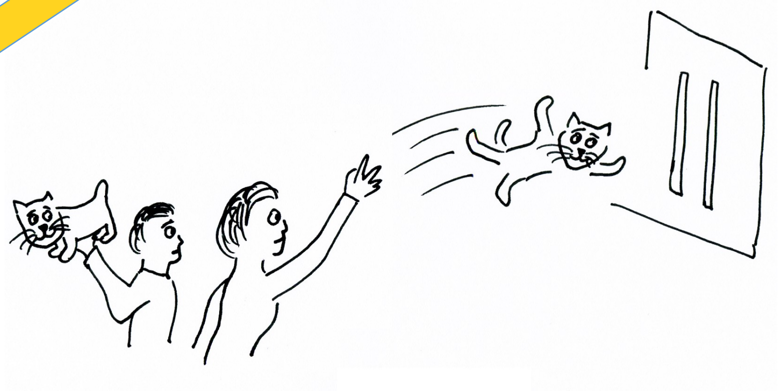
- Non-perturbative particle production.
- (Sub-) attosecond time scale.
- Inherent coupling to radiation field ("tests" of QED)



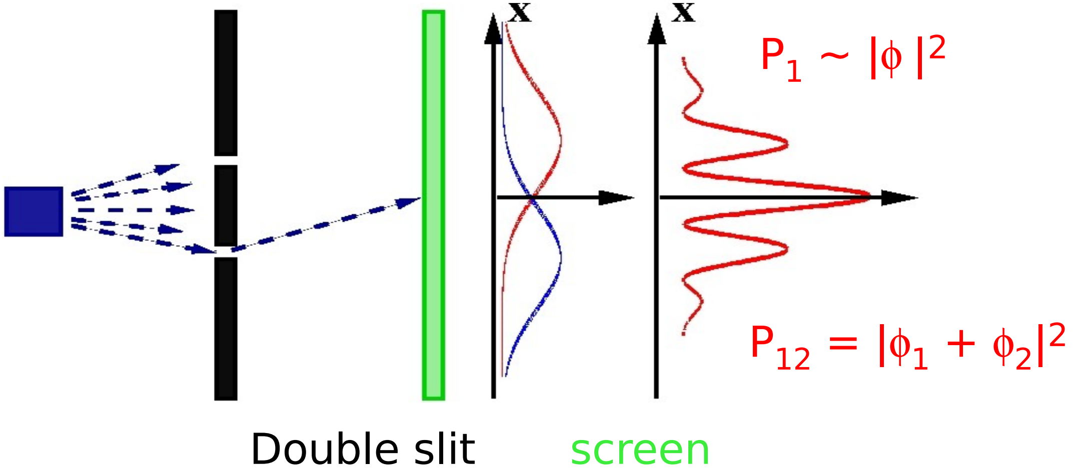
# Atomic excitations in relativistic heavy-ion collisions

## – How to deal with them theoretically ?

$$H(t)|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$



http://scienceblogs.de/naklar/wp-content/blogs.dir/



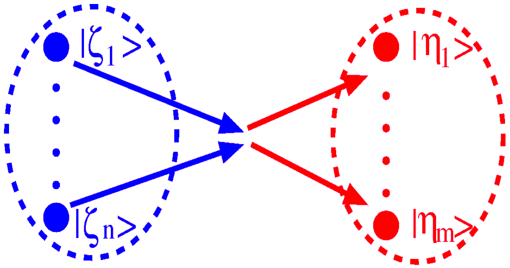
# Atomic excitations in relativistic heavy-ion collisions

## – How to deal with them theoretically ?

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



Final state

$(t \to +\infty)$

$\hat{\rho}_f$

$$H(t)|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle$$

$\rho$ = ($\mu_S$, J, J'; E; I, $\mu_I$; t ... density matrix)

Ensemble of collision systems: requires statistical description

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

$\hat{S}$ - scattering operator

Measurement of physical properties:

'detector operator' describes the experimental setup: $\hat{P} = |\epsilon><\epsilon|$

probability to get a 'click' at the detectors:

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

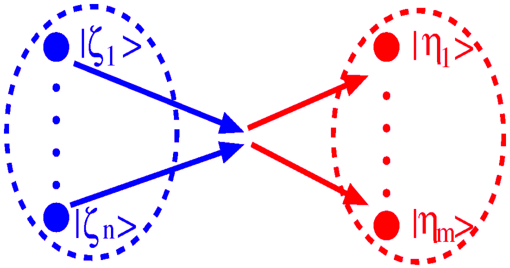
# Atomic excitations in relativistic heavy-ion collisions

## – How to deal with them theoretically ?

Initial state

$(t \rightarrow -\infty)$

$\hat{\rho}_i$



Final state

$(t \rightarrow +\infty)$

$\hat{\rho}_f$

$H(t)|\psi(t)\rangle = i$

$\rho$ = ($\mu_S$, J, J'; E; I

Ensemble of collision

escription

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

$\hat{S}$ - scattering operator

Measurem

mental setup: $\hat{P} = |\epsilon><\epsilon|$

e 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 to “follow” the system through several (and time-dependent) interactions, including the capture or emission of photons, electrons, etc. !

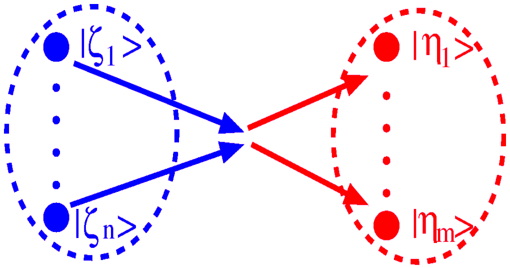
# Atomic excitations in relativistic heavy-ion collisions

## – How to deal with them theoretically ?

Initial state

$(t \rightarrow -\infty)$

$\hat{\rho}_i$



Final state

$(t \rightarrow +\infty)$

$\hat{\rho}_f$

$$H(t)|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle$$

$\rho$ = ($\mu_S$, J, J'; E; I, $\mu_I$; t ... 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 distributions

$$\sim |M|^2$$

No summation over polarization states !

polarization & alignment

Examples from this talk:

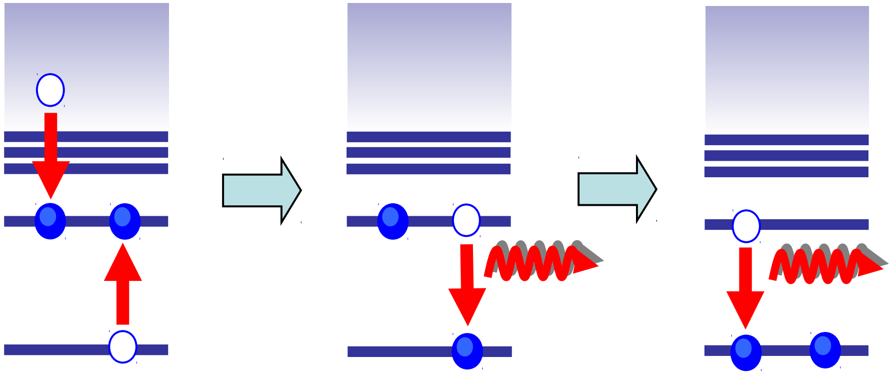
- Radiative electon capture: Exploring the electron-photon interaction
- Projectile excitation: Testing the Lorentz-transformed „Coulomb field“
- Dielectronic recombination of high-Z ions: A detailed view on the electron-electron interaction
- Radiative cacacdes & level splitting, ...

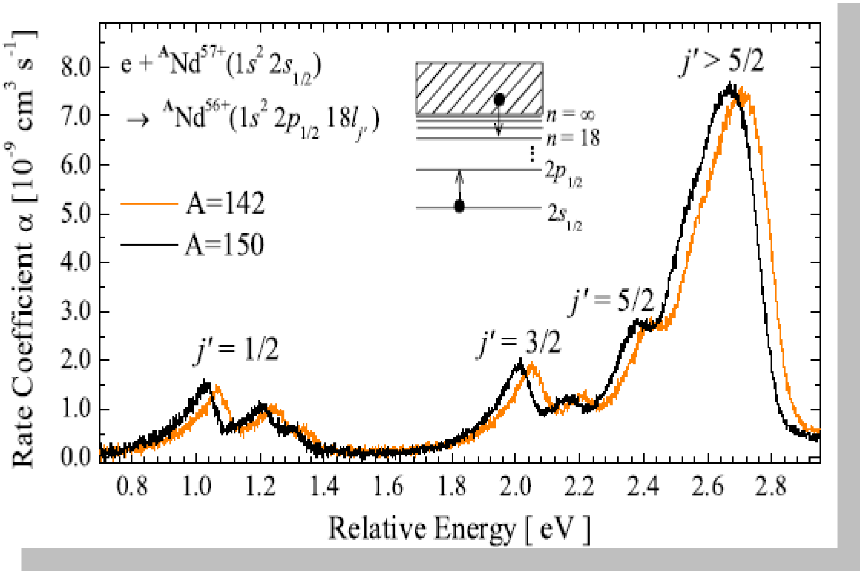
# Electron-electron interactions in strong Coulomb fields

## $\boxed{6}$ signatures of magnetic and retarded 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

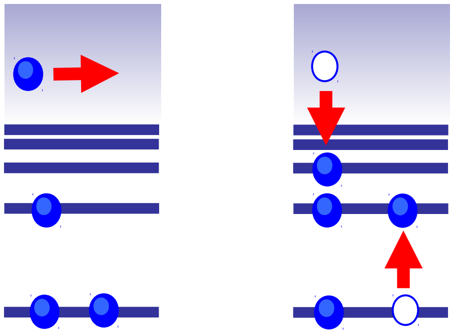
- Dielectronic recombination (DR) process provides a unique tool for precise spectroscopy of HCI and, especially, doubly excited ionic states.
- accurate QED and isotope studies
- finger print upon nuclear properties (nuclear spins and moment, isomeric states)

→ Great importance for astro and plasma physics.

# Electron-electron interactions in strong Coulomb fields

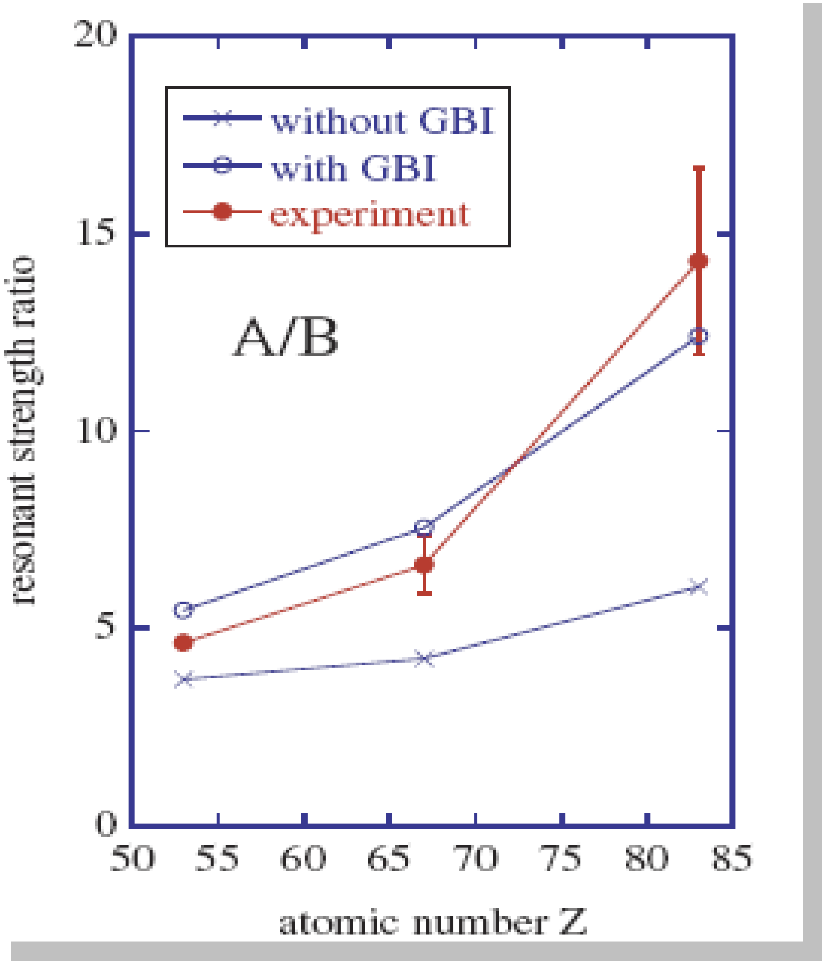
## $\boxed{6}$ signatures of magnetic and retarded interactions

K-LL DR into initially lithium-like ions:



$$[1s^2\,2s]_{1/2} + e^- \rightarrow [1s\,2s^2\,2p]_1$$

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



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

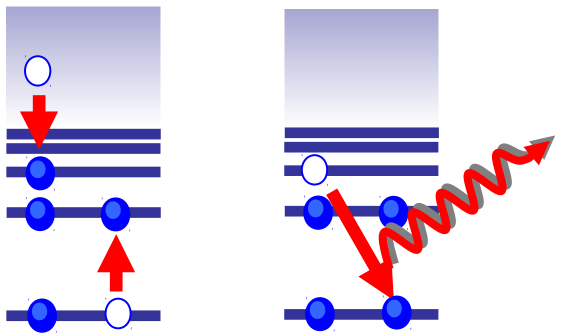
Breit interaction

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

# Electron-electron interactions in strong Coulomb fields

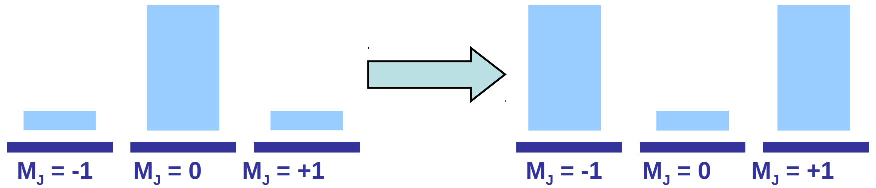
## $\boxed{6}$ signatures of magnetic and retarded interactions

K-LL DR into initially lithium-like ions:



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

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



only Coulomb

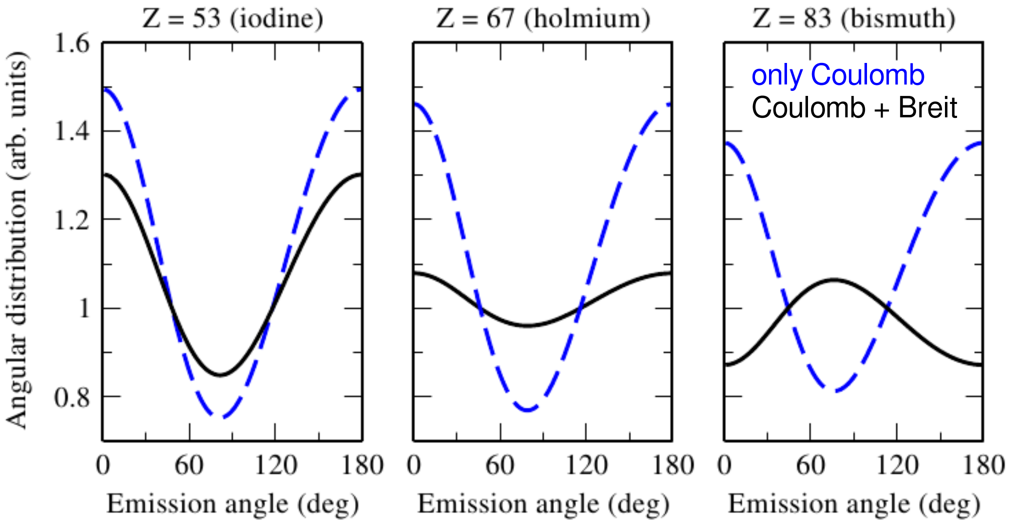
$A_2 = -0.516$

Coulom + Breit

$A_2 = +0.374$

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

Angular distribution of emitted photons

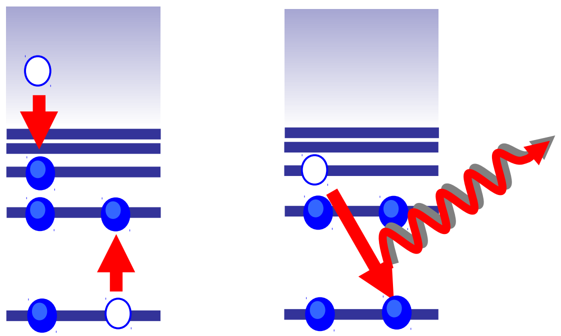


S. Fritzsche et al., PRL 103 (2009) 113001.

# Electron-electron interactions in strong Coulomb fields

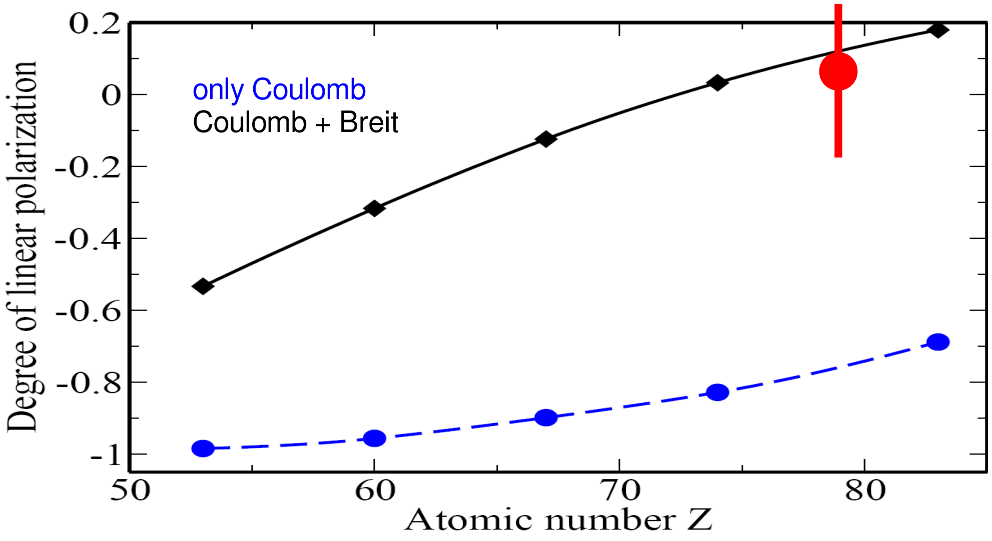
## $\boxed{6}$ signatures of magnetic and retarded interactions

K-LL DR into initially lithium-like ions:



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

Linear polarization of emitted photons



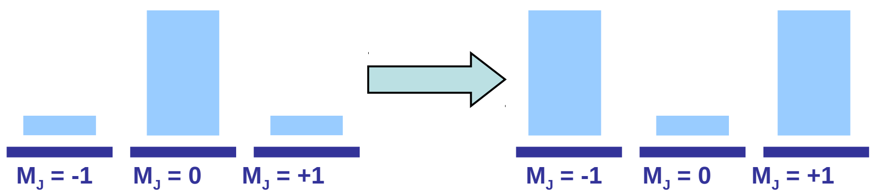
S. Fritzsche et al., PRL 103 (2009) 113001.

$$V_{ee} = V^C + V^B = \frac{1}{r_{12}}$$

$$+ \left( -\alpha_1 \alpha_2 \frac{\cos \omega r_{12}}{r_{12}} + \left(\alpha_1 \nabla_1\right)\left(\alpha_2 \nabla_2\right) \frac{\cos \omega r_{12}}{\omega^2 r_{12}} \right)$$

only Coulomb

Coulom + Breit



$A_2$ = -0.516

$A_2$ = +0.374

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

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

# Atomic excitations in relativistic heavy-ion collisions

## – a successful route to strong-fields physics

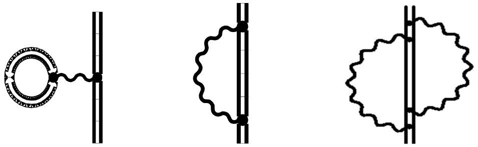
Both, highly-charged ions and atoms in intense laser fields support tests for our understanding of the fundamental interactions in strong fields:

- X-ray emission from highly and multiply-charged ions

  (e-γ interaction; diagnostics of laboratory and astrophysical plasma)

- Bound-state QED and correlated electron dynamics for $\alpha Z \sim 1$

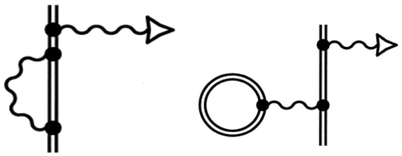
Electric Sector of QED



$\Delta E_{QED} \sim (\alpha Z)^4 F(\alpha Z)$

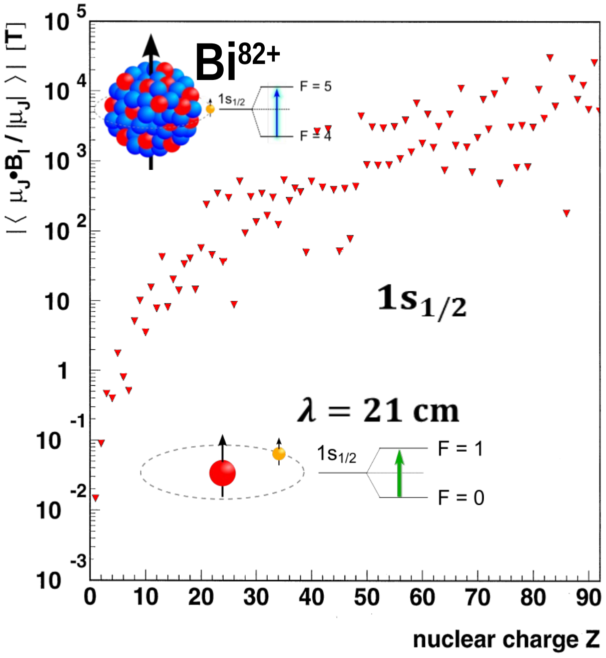
A. Gumberidze et al., PRL 94 (2005) 223001.

Magnetic Sector of QED



$\Delta E_{HFS} \sim Z^3$

M. Lochmann et al., PRA 90 (2014) 030501.



T. Beier, Phys. Reports 339 (2000) 79.

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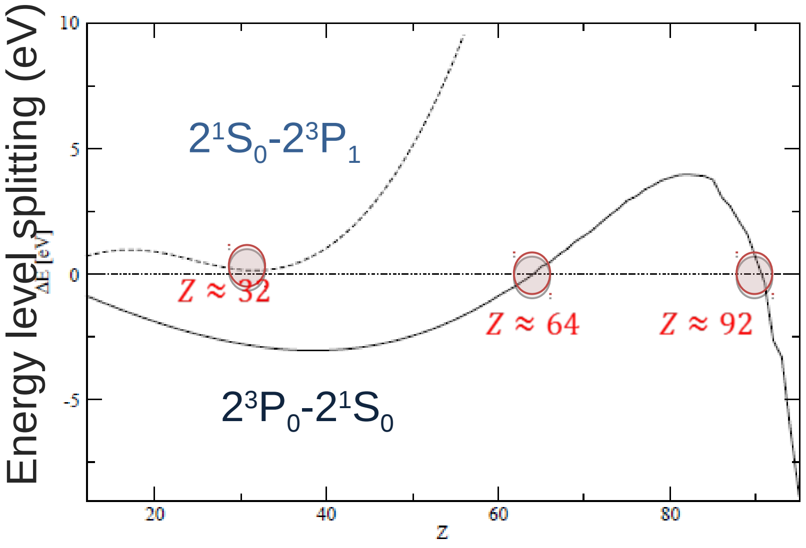
  (e-γ interaction; diagnostics of laboratory and astrophysical plasma)
- Bound-state QED and correlated electron dynamics for $\alpha Z \sim 1$
- Parity and time-reversal violating interactions

How to resolve such small level splittings in the excitation energies of HCI ?



F. Ferro et al., PRA **81** (2010) 062503.

# Atomic excitations in relativistic heavy-ion collisions

## – a successful route to strong-fields physics

Both, highly-charged ions and atoms in intense laser fields support tests for our understanding of the fundamental interactions in strong fields:

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  (e-p interaction; diagnostics of laboratory and astrophysical plasma)
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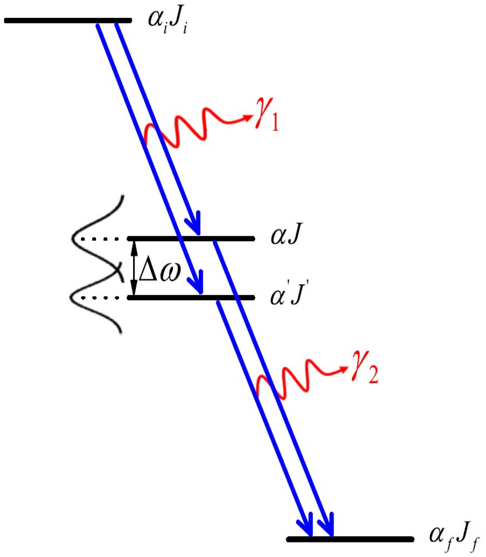


In typical x-ray spectra from HCI, neither the hyperfine nor fine-structure can be resolved:

## Strategies:

- Explore the (2nd-step) angular distributions.
- Study the photon-photon correlation functions.

# How to resolve small level splittings of HCI ?

$\boxed{7}$ Exploring the 2nd-step angular distribution

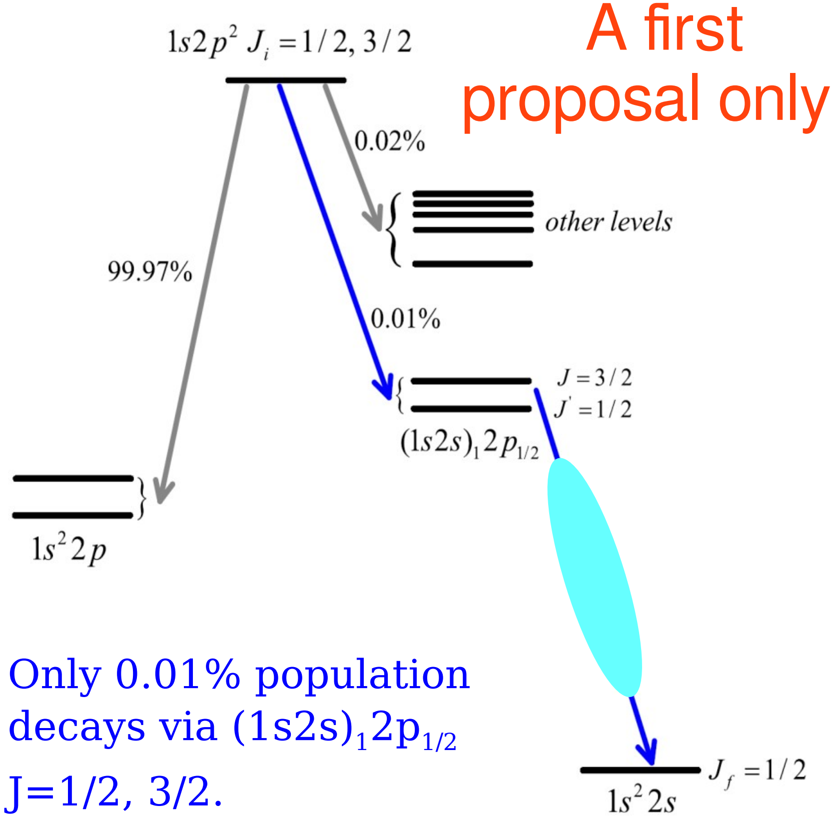
Decay via the two 1s 2s $2p_{1/2}$ J=1/2, 3/2 intermediate resonances

$$
\begin{aligned}
&1s2p^2\ J_i = 1/2, 3/2\\
&\quad \rightarrow \gamma_1 + \begin{Bmatrix} 1s2s2p\ J = 1/2 \\ 1s2s2p\ J' = 3/2 \end{Bmatrix}\\
&\quad \rightarrow \gamma_1 + \gamma_2 + 1s^2 2s\ J_f = 1/2
\end{aligned}
$$

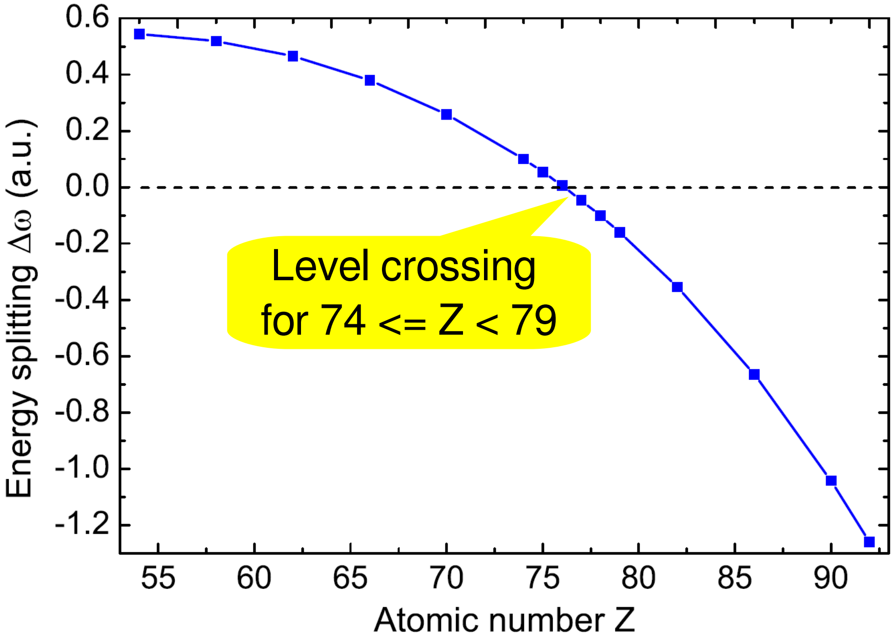
$\rho = (\mu_S, J, J'; E; I, \mu_I$ ... density matrix$)$

Depolarization factors & detector functions

A first proposal only !



Only 0.01% population decays via $(1s2s)_1 2p_{1/2}$ J=1/2, 3/2.



Z.W. Wu et al, PRA 90 (2015) 052515.

# How to resolve small level splittings of HCI ?

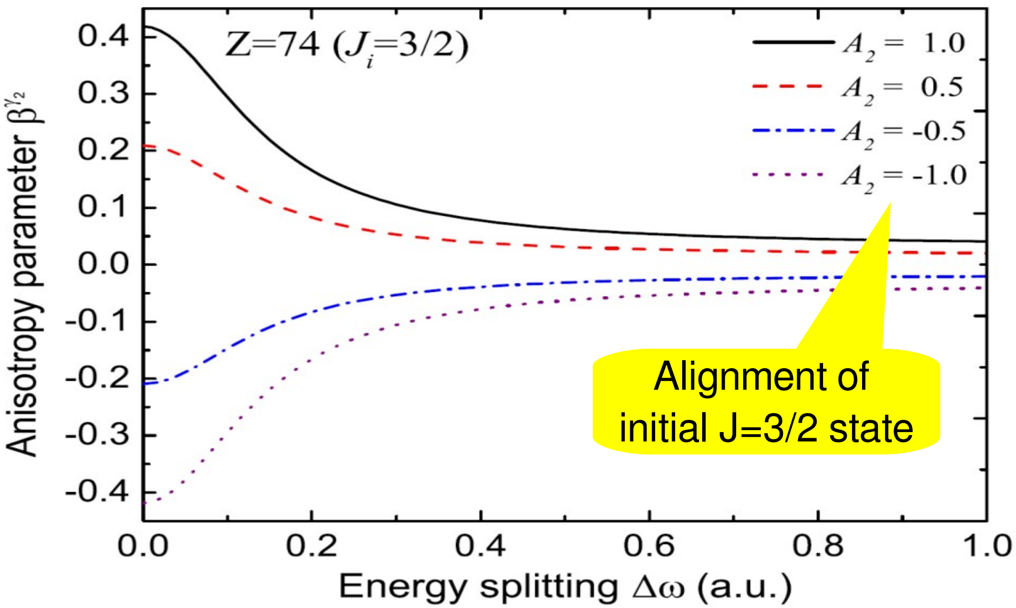
## 7 Exploring the 2nd-step angular distribution

Decay via the two 1s 2s $2p_{1/2}$ J=1/2, 3/2 intermediate resonances

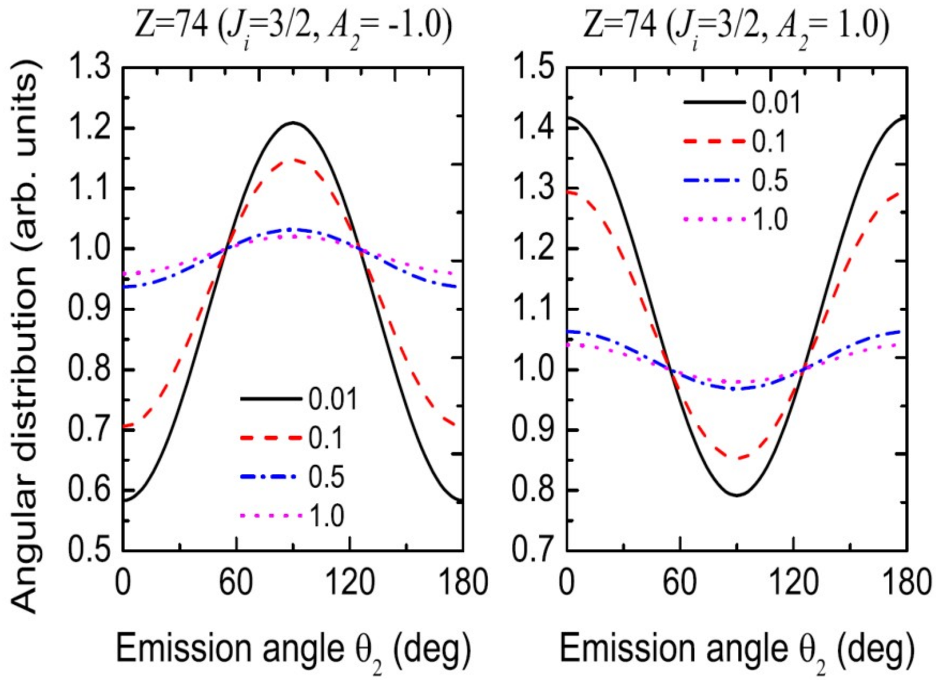
$$\begin{aligned} &1s2p^2\ J_i = 1/2, 3/2 \\ &\qquad \to \gamma_1 + \begin{Bmatrix} 1s2s2p\ J = 1/2 \\ 1s2s2p\ J' = 3/2 \end{Bmatrix} \\ &\qquad \to \gamma_1 + \gamma_2 + 1s^2 2s\ J_f = 1/2 \end{aligned}$$

$$W^{\gamma_2}_{J_i=3/2}(\theta_2) \propto 1 + \beta^{\gamma_2}_{J_i=3/2} P_2(\cos\theta_2)$$

Anisotropy proportional to the initial alignment $A_2$ (=$\rho_{20}/\rho_{00}$).



Alignment of initial J=3/2 state



Anisotropy is particularly sensitive to small level splittings < 0.2 a.u. ≈ 5.4 eV.

Z.W. Wu et al, PRA 90 (2015) 052515.

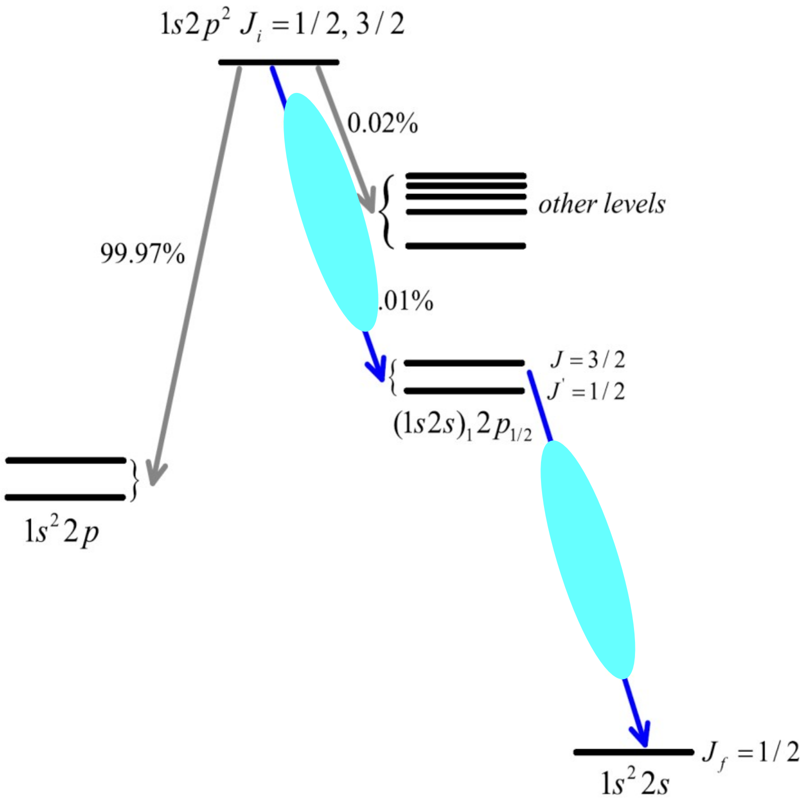
# How to resolve small level splittings of HCI ?

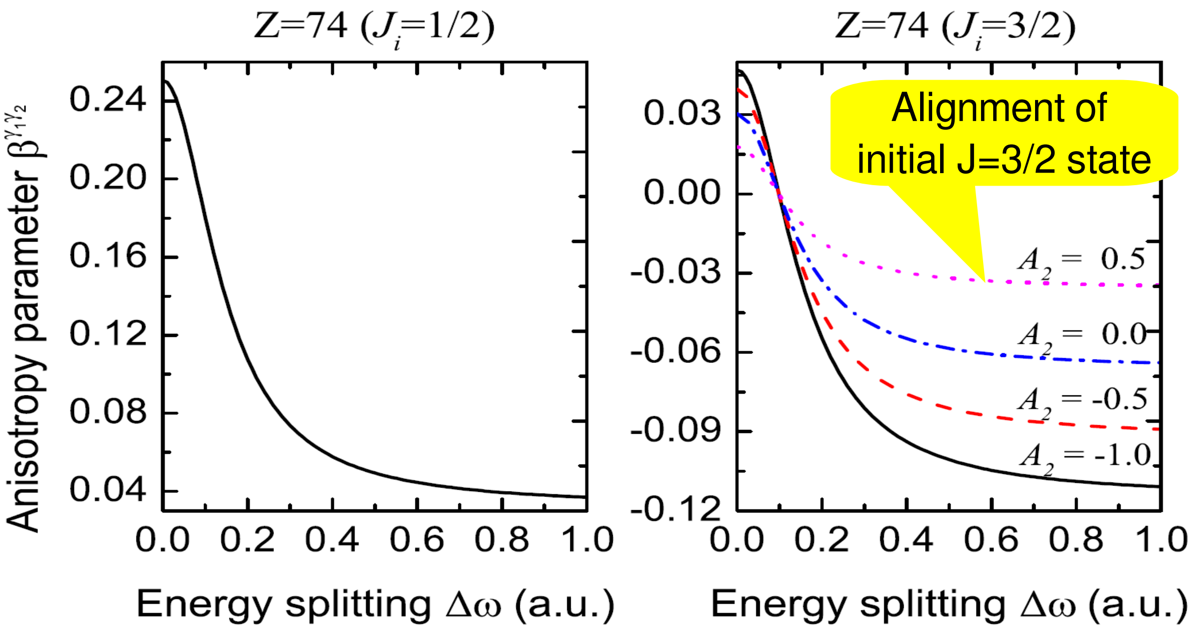
$\boxed{7}$ ... or the photon-photon correlation function

Decay via the two 1s 2s $2p_{1/2}$ J=1/2, 3/2 intermediate resonances

$$\begin{aligned} &1s2p^2\ J_i = 1/2,3/2 \\ &\qquad \rightarrow \gamma_1 + \begin{Bmatrix} 1s2s2p\ J = 1/2 \\ 1s2s2p\ J' = 3/2 \end{Bmatrix} \\ &\qquad \rightarrow \gamma_1 + \gamma_2 + 1s^22s\ J_f = 1/2 \end{aligned}$$

$$W^{\gamma_1\gamma_2}_{J_i=1/2}(\Omega_{12}) \propto 1 + \beta^{\gamma_1\gamma_2}_{J_i=1/2} P_2(\cos\Omega_{12})$$





Z.W. Wu et al, PRA 90 (2015) 052515.

# How to resolve small level splittings of HCI ?

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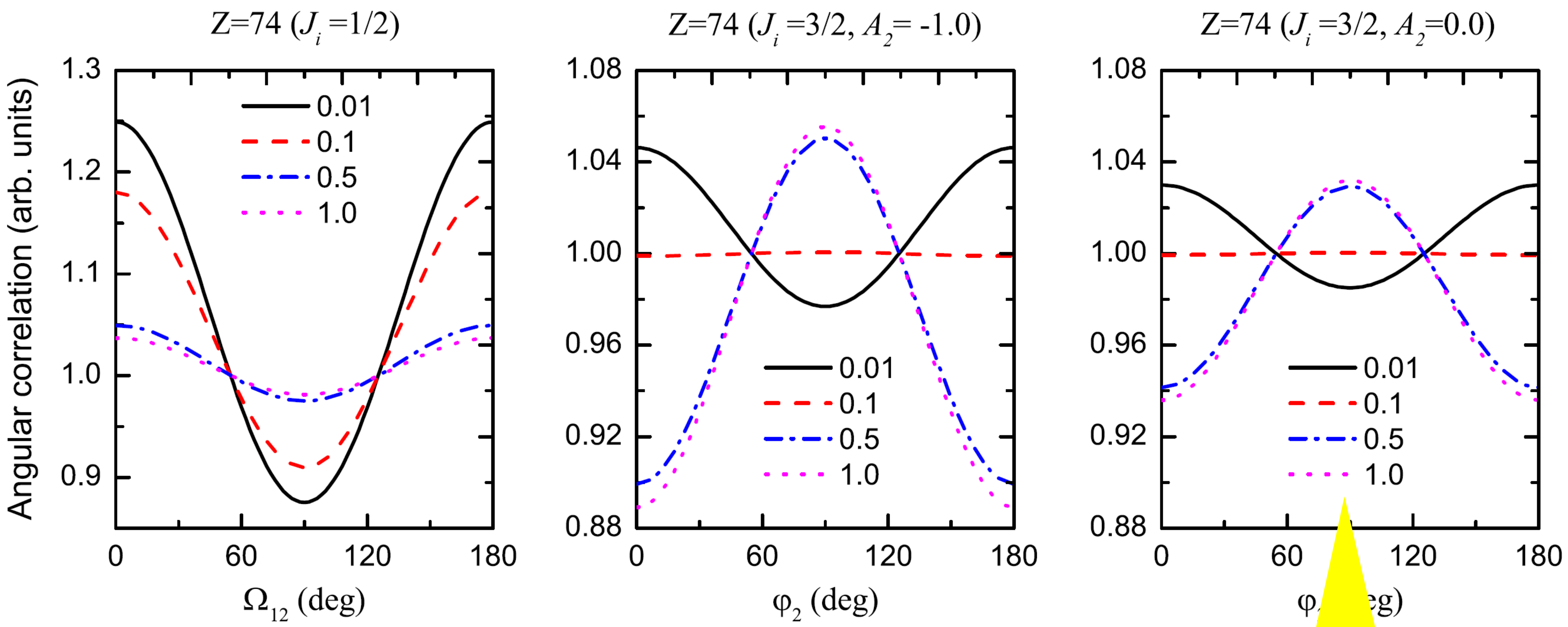

$J_i$=1/2: Strong anisotropic behavior, especially for small level splittings.

$J_i$=3/2: Quite different behavior for different level splittings.

Level splitting
in a.u (=27.21 eV)

Z.W. Wu et al, PRA 90 (2015) 052515.

# How to resolve small level splittings of HCI ?

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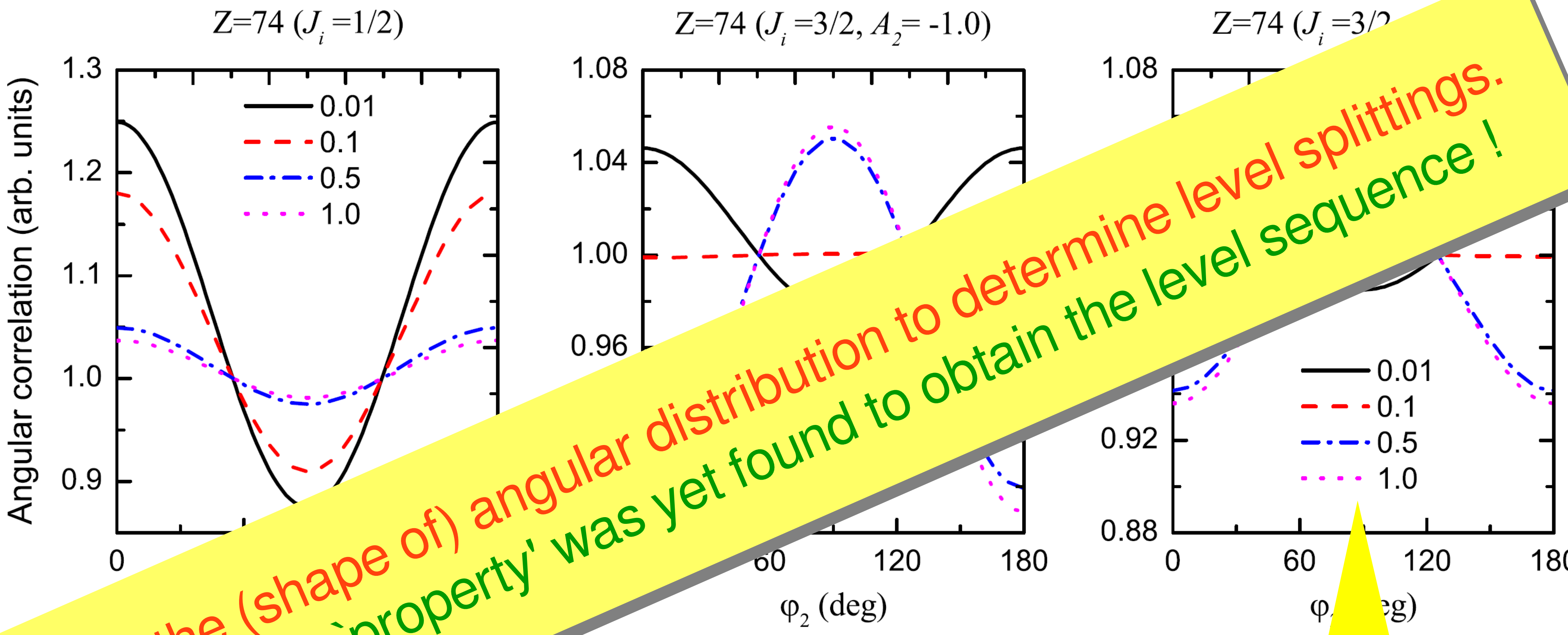
Decay via the two 1s 2s $2p_{1/2}$ J=1/2, 3/2 intermediate resonances



Use the (shape of) angular distribution to determine level splittings.

No simple `property' was yet found to obtain the level sequence !

havior, especially for small level splittings.

t behavior for different level splittings.

Level splitting

in a.u (=27.21 eV)

Z.W. Wu et al, PRA 90 (2015) 052515.

# Atomic excitations in relativistic heavy-ion collisions

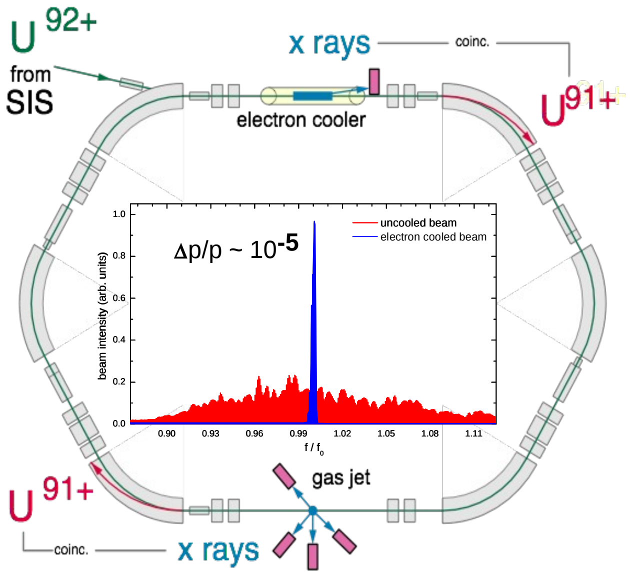
## – a successful route to strong-fields physics

Both, highly-charged ions and atoms in intense laser fields support tests for our understanding of the fundamental interactions in strong fields:

- X-ray emission from highly and multiply-charged ions
  (e-p interaction; diagnostics of laboratory and astrophysical plasma)
- Bound-state QED and correlated electron dynamics for $\alpha Z \sim 1$
- Parity and time-reversal violating interactions
- Super-critical field phenomena (low-energy and ultra-relativistic ion collisions)
- Laser-induced multi-photon processes & non-linear x-ray optics
- ...

# Atomic excitations in relativistic heavy-ion collisions

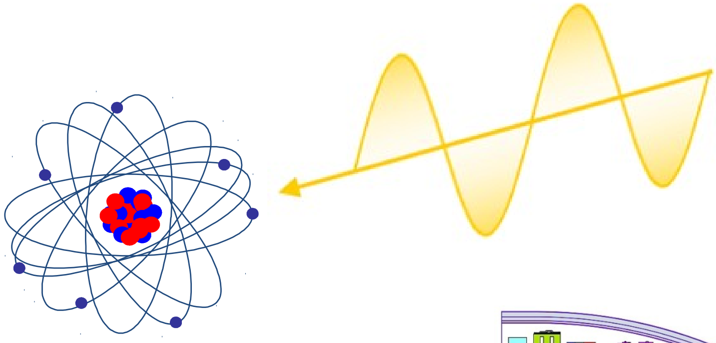
## – a successful route to strong-fields physics

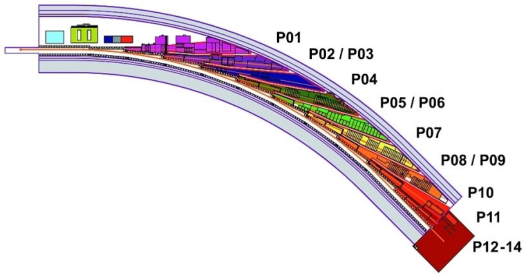


http://photon-science.desy.de/

Completely linearly polarized light with energy of about 100 keV.

What is the polarization of the scattered light, elastically & inelastically ?





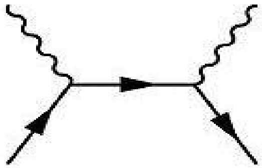
# Atomic excitations in relativistic heavy-ion collisions

## – Non-linear ($e^-$-$\gamma$) processes at relativistic energies

http://photon-science.desy.de/

## Photoabsorption & ionization:

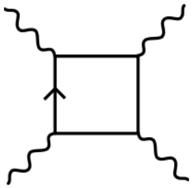
- Two-photon (2-color) absorption: $\gamma + \gamma' + A \;\rightarrow\; A^*$
- Two- or multi-photon ionization: $\gamma + \gamma + A \;\rightarrow\; A^+ + e^-$
- Photon cascades: $A^* \;\rightarrow\; A + \gamma + \gamma'$



Rayleigh scattering

## Photon scattering:

- Thompson & Rayleigh scattering: $\gamma + A \;\rightarrow\; \gamma + A$
- Inelastic Compton scattering: $\gamma + A \;\rightarrow\; \gamma' + A + e^-$
- Delbrück & photon-photon scattering (via virtual $e^+ + e^-$ pairs).
- ...

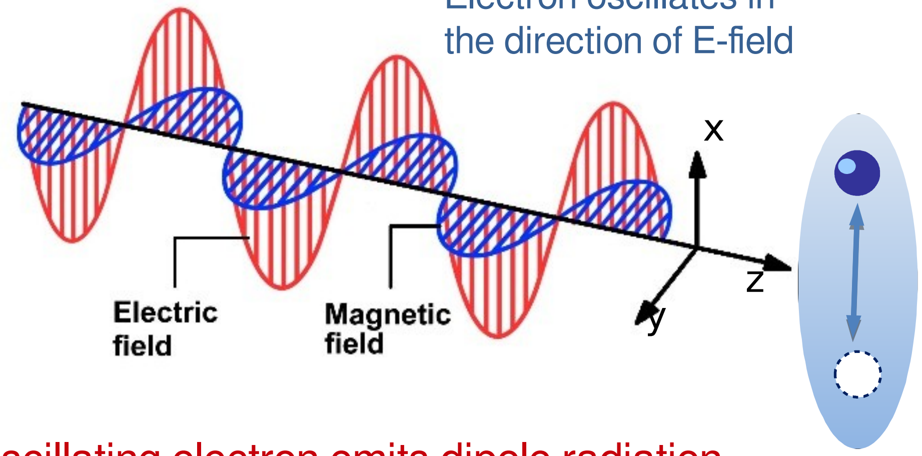


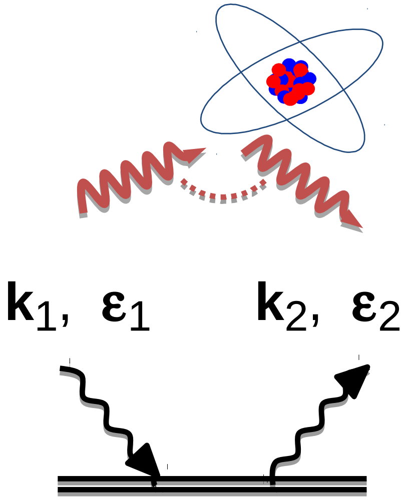
Delbrück scattering

# Non-linear (e$^-$-$\gamma$) processes at relativistic energies

$\boxed{8}$ Rayleigh scattering of hard x-rays

Electron oscillates in
the direction of E-field

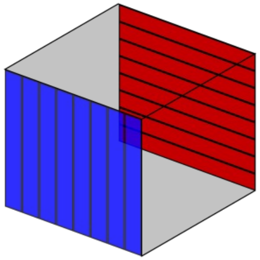


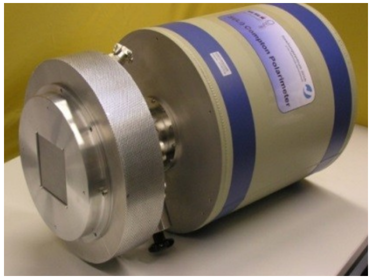


Rayleigh scattering

Oscillating electron emits dipole radiation.

$$\sigma(\hat{k}_1, \epsilon_1; \hat{k}_2, \epsilon_2) \propto |(\epsilon_1 \cdot \epsilon_2)|^2$$

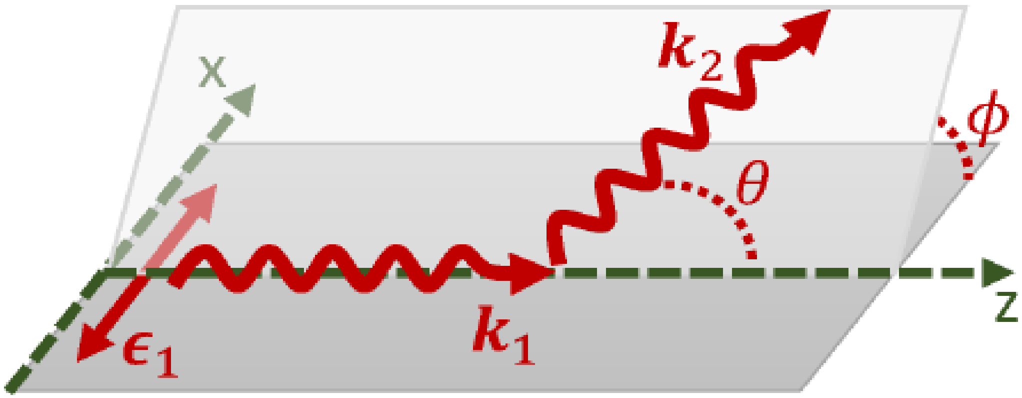


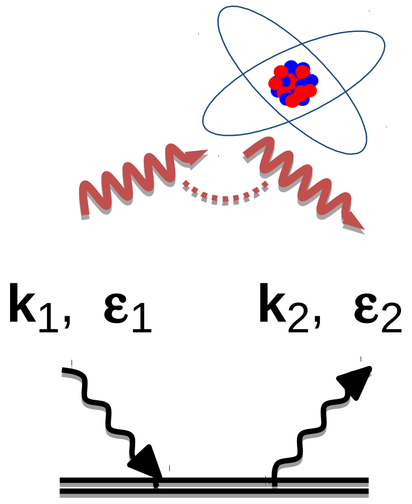


T. Stöhlker &AP @ GSI

# Non-linear ($e^-$-$\gamma$) processes at relativistic energies

## 8 Rayleigh scattering of hard x-rays





Rayleigh scattering

$$\sigma(\hat{k}_1, \epsilon_1; \hat{k}_2, \epsilon_2) \propto \left|(\epsilon_1 \cdot \epsilon_2)\right|^2$$

$$\sigma_0(\theta, \phi) \propto \sin^2\phi + \cos^2\theta \cos^2\phi$$

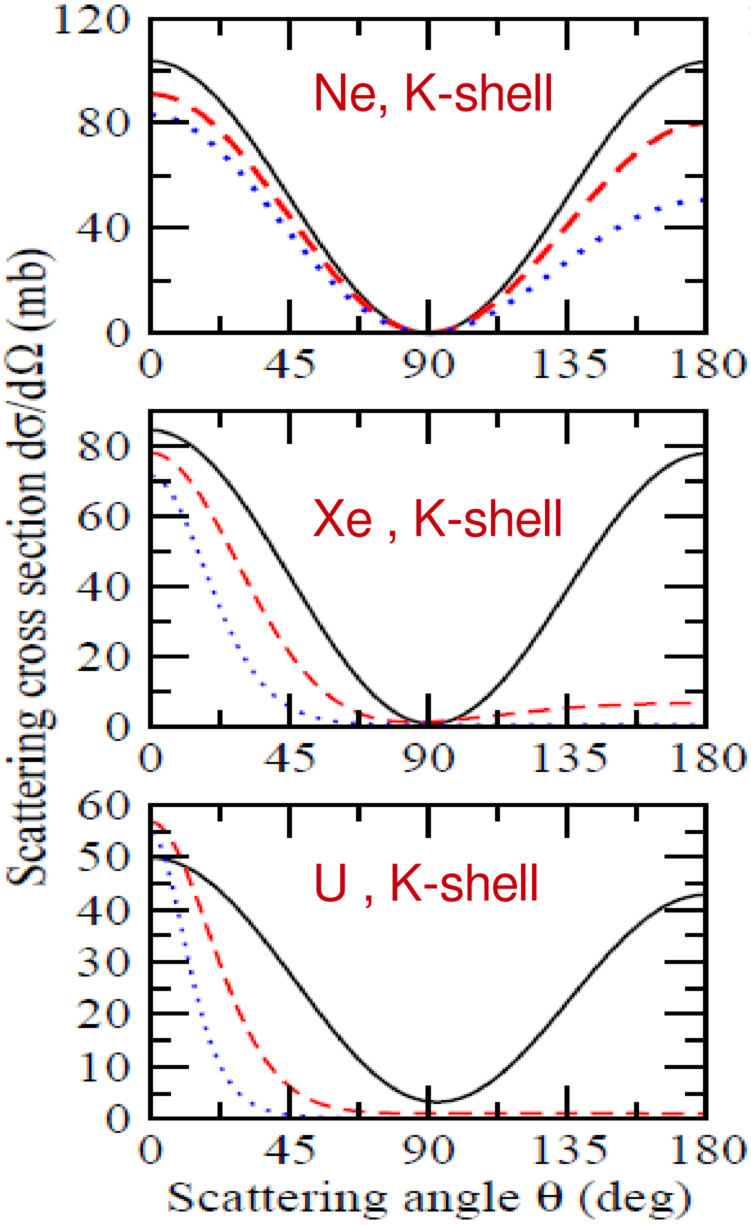
$$P_1(\theta, \phi) = \frac{-\sin^2\phi + \cos^2\phi \cos^2\theta}{\sin^2\phi + \cos^2\phi \cos^2\theta}$$

$$P_2(\theta, \phi) = \frac{2 \sin\phi \cos\phi \cos\theta}{\sin^2\phi + \cos^2\phi \cos^2\theta}.$$

## Consequences:

- For $\phi = 0$, $P_1 = 1$ & within scattering plane
- $P_2 = 0$ if photons are emitted within the scattering plane

# Non-linear ($e^-$-γ) processes at relativistic energies



## 8 K-shell Rayleigh scattering of hard x-rays

- For light targets and low energies, the photon emission pattern follows the non-relativistic prediction:

$$\frac{d\sigma}{d\Omega} \propto \cos^2\theta$$

- Forward photon emission becomes pronounced with increasing energy & charge.

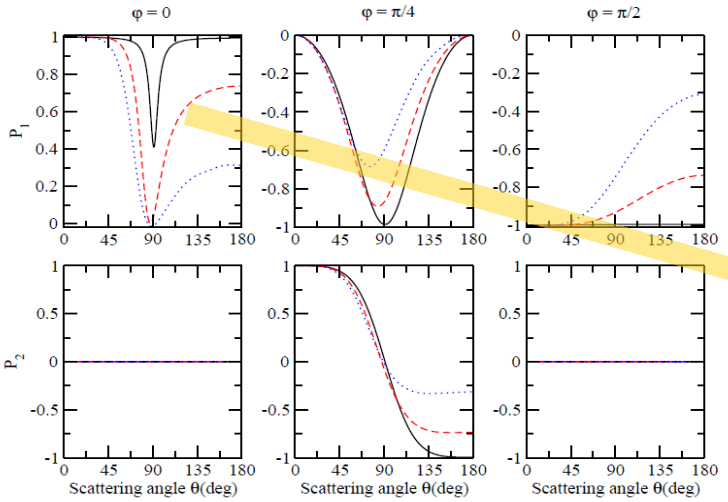
$$\frac{d\sigma}{d\Omega} \propto \cos^2\theta + \underbrace{4\frac{a_{M1M1}}{a_{E1E1}}\cos\theta + \frac{20}{5}\frac{a_{E2E2}}{a_{E1E1}}\cos^3\theta + \cdots}_{\text{non-dipole contributions}}$$

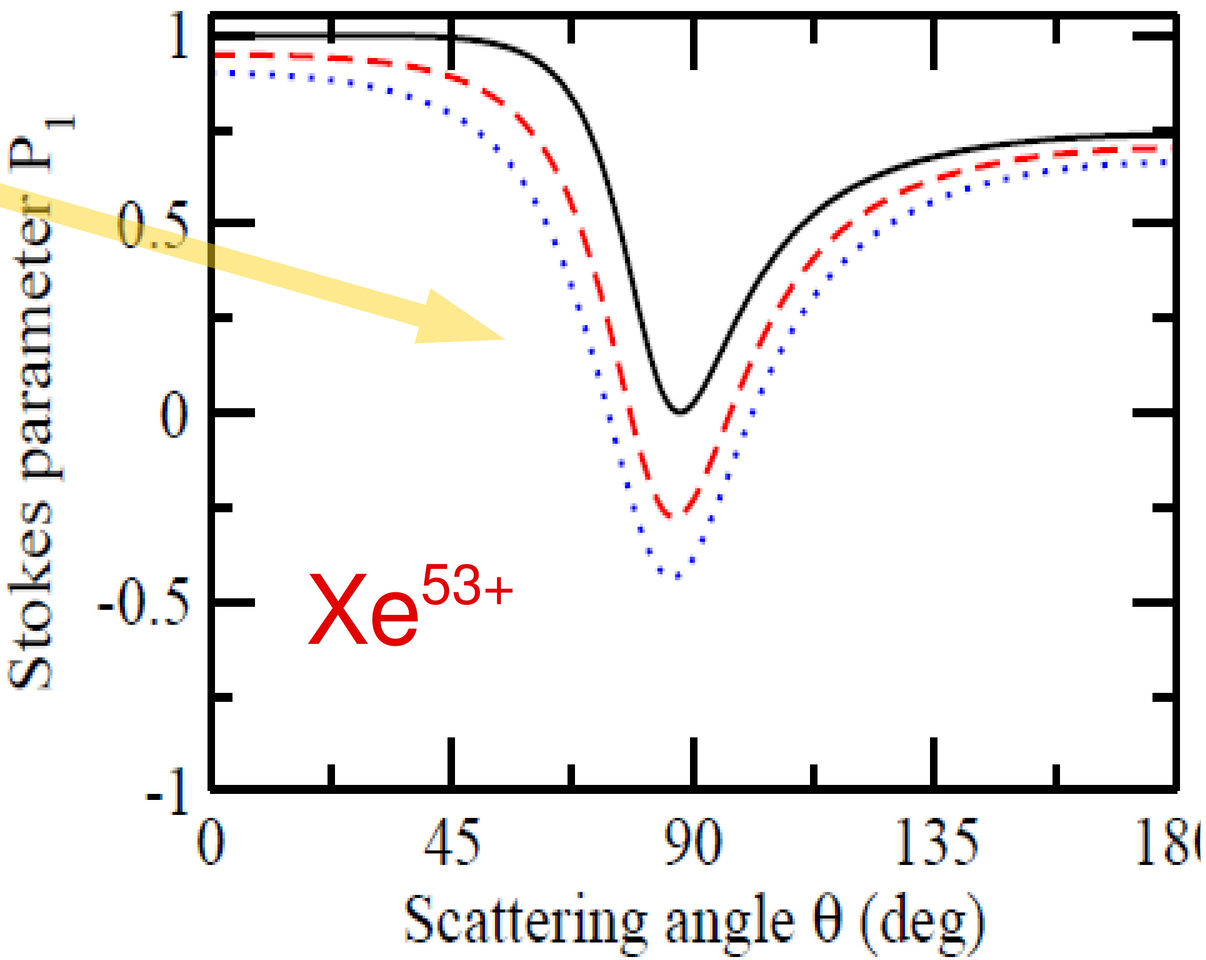
Calculations are performed for the coplanar geometry and three photon energies: 1.1 $I_{\text{th}}$, 5 $I_{\text{th}}$, and 10 $I_{\text{th}}$

A. Surzhykov *et al.*, Phys. Rev. A **88**, 062515 (2013).

# Non-linear ($e^-$-$\gamma$) processes at relativistic energies

## 8 K-shell Rayleigh scattering of hard x-rays





Polarization of incoming light ($\hbar\omega = 5\ I_p$)

----- P = 1.0

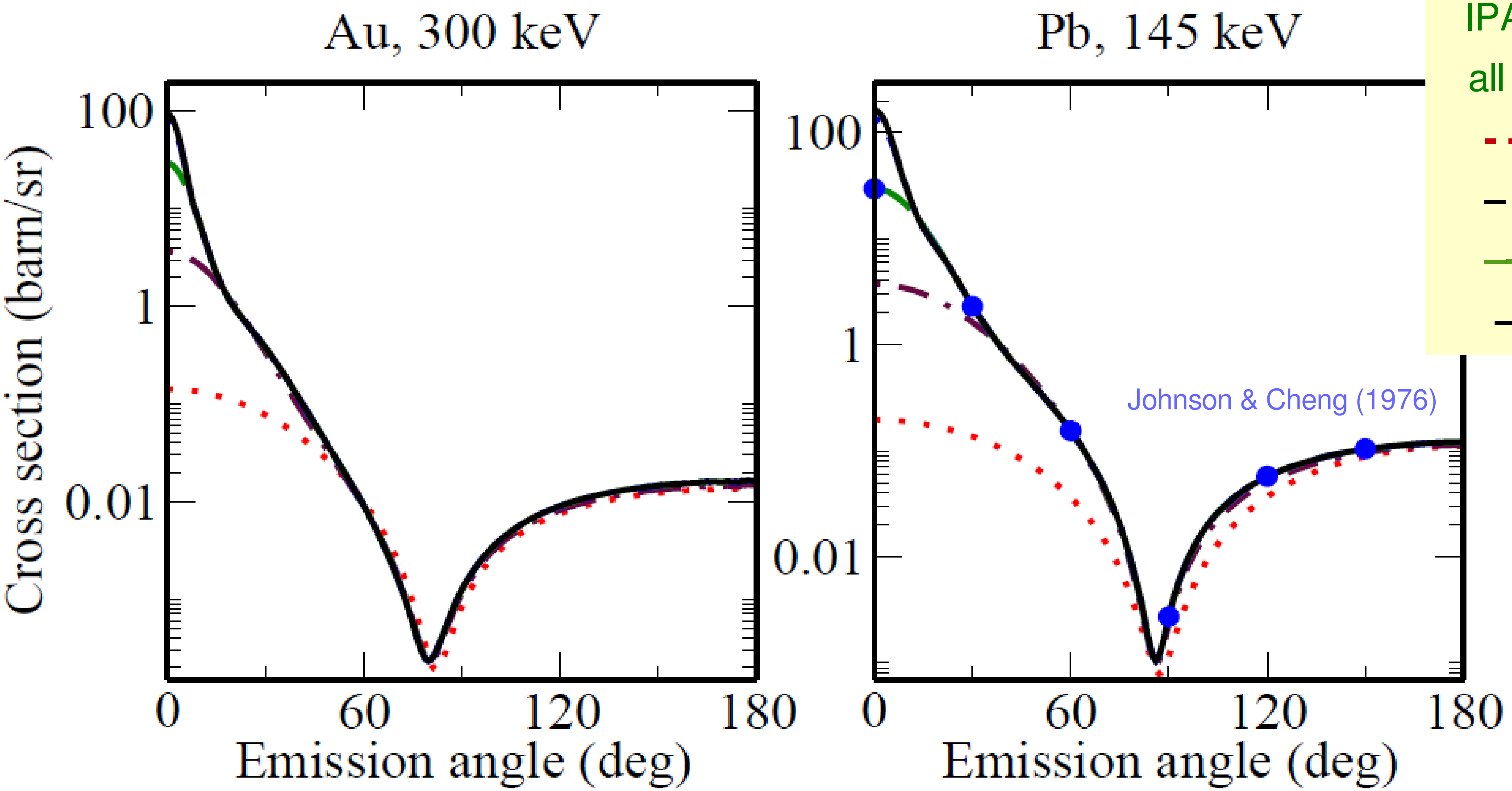
- - - P = 0.95

..... P = 0.9

Polarization of the scattered photons occurs rather sensitive to the polarization of the incident light !

# Non-linear ($e^-$-$\gamma$) processes at relativistic energies

## 8 Rayleigh scattering of hard x-rays by many-electron atoms



IPA calculations for all occupied shells:

- - - K-shell
– . -- KL shells
–---- KLM
–--- all shells

Contributions of (sub-) valence shells to the angular distribution of the Rayleigh scattered photons is large, especially in forward direction !

W. R. Johnson and K. Cheng, PRA 13 (1976) 692
A. Surzhykov *et al.*, J. Phys. B48 (2015) 144015.

# Non-linear ($e^-$-$\gamma$) processes at relativistic energies

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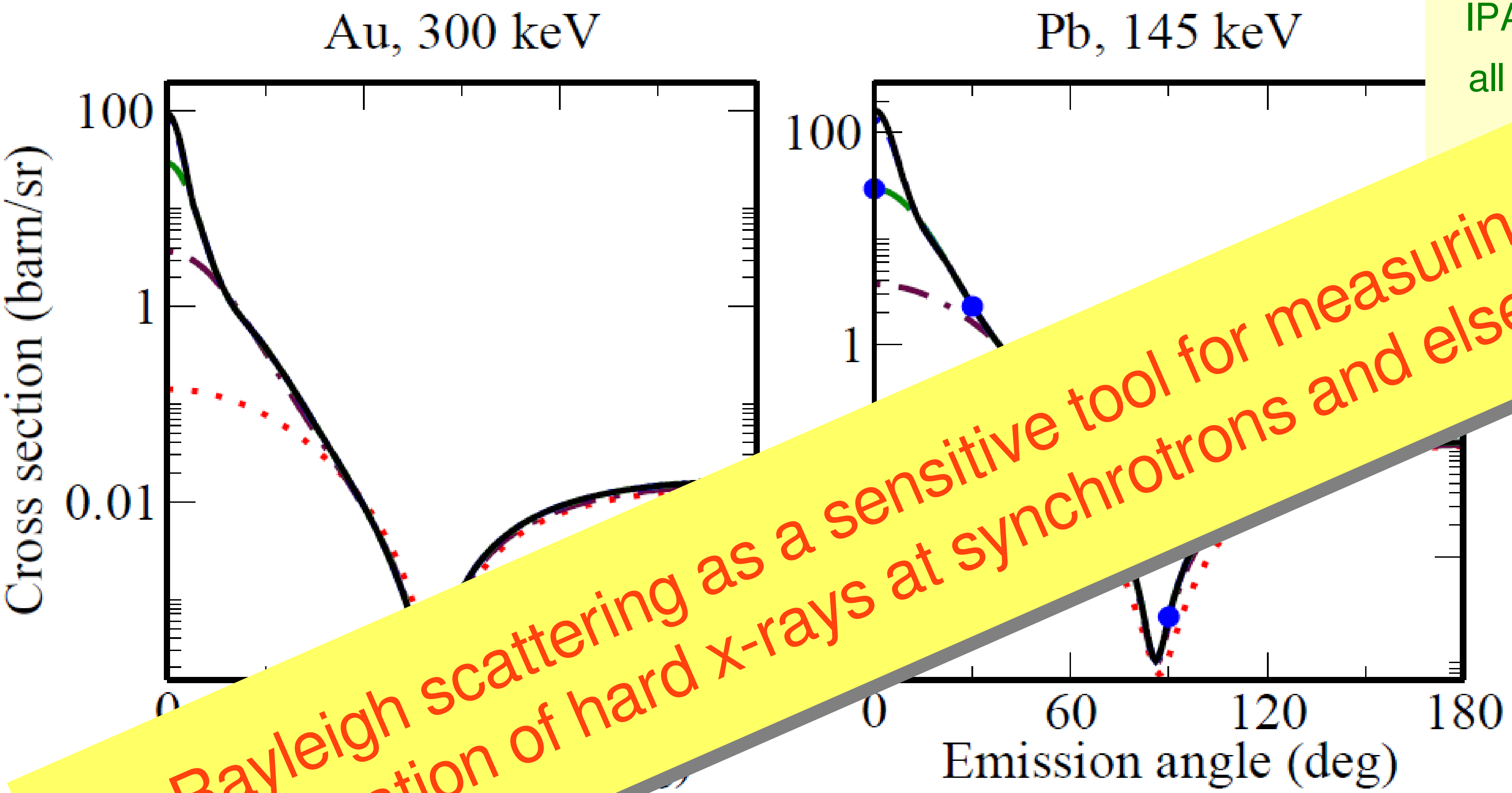


IPA calculations for
all occupi

Rayleigh scattering as a sensitive tool for measuring the polarization of hard x-rays at synchrotrons and elsewhere.

) valence shells to the angular distribution of the
ayleigh scattered photons is large, especially in forward direction !

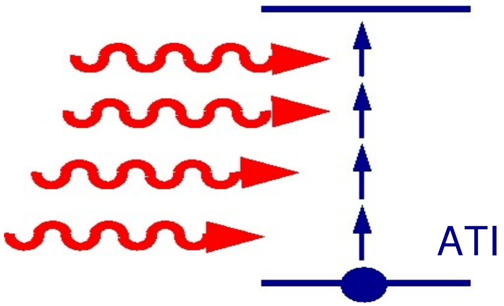
K. Blumenhagen, T. Stöhlker *et al.*,
to be published (2015).

W. R. Johnson and K. Cheng, PRA 13 (1976) 692
A. Surzhykov *et al.*, J. Phys. B48 (2015) 144015.

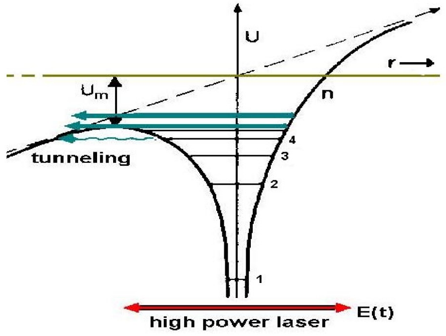
# Non-linear light-matter interactions in intense (FEL) fields

## – from weak- to strong-field ionization

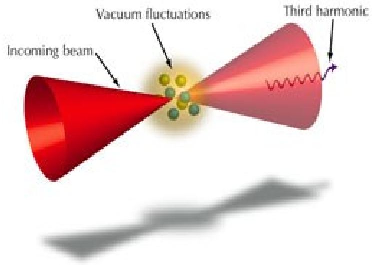
increasing field strength (intensity)



Multiphoton ionization



tunnel ionization



HH and pairs from vacuum

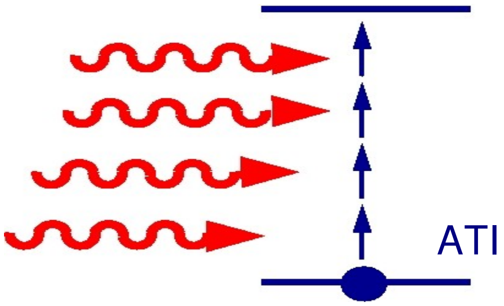
increasing frequency (photon energy)

- Excitation & ionization at (ultra-) fast time scales & relativistic photon energies.
- Electron dynamics in intense FEL radiation (multi-photon & multi-color ionization; coherent dynamics of inner-shell excitations; sidebands; quantum beats, …).
- Creation and dynamics of warm dense matter.

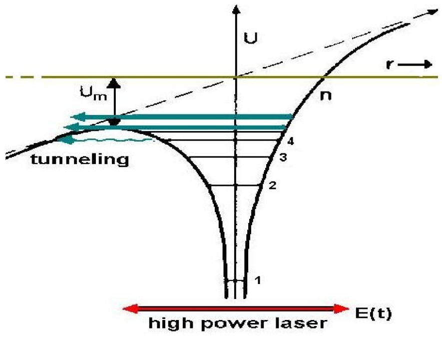
# Non-linear light-matter interactions in intense (FEL) fields

## – (time-) evolution “through” the density matrix

increasing field strength (intensity)



Multiphoton ionization



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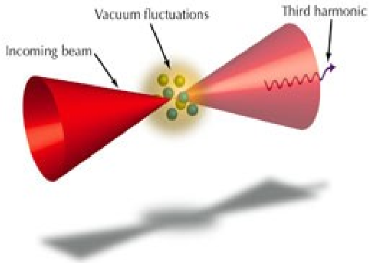


HH and pairs from vacuum

increasing frequency (photon energy)

### Density matrix

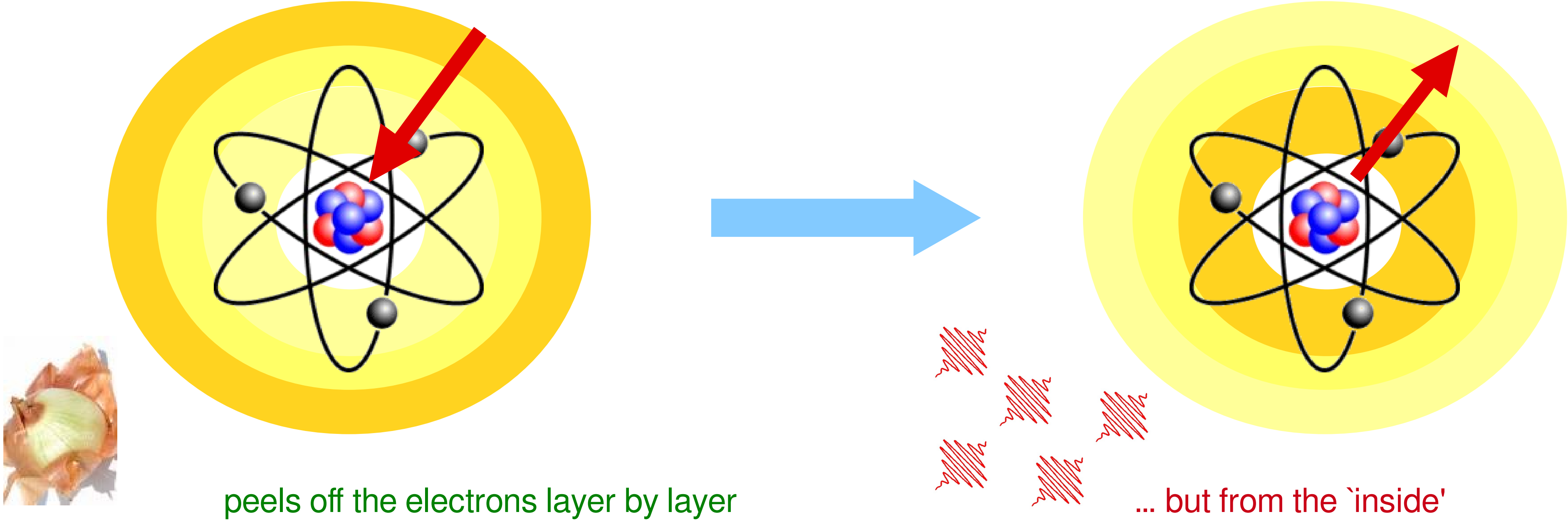
$$\rho = \rho(r,t;\, r',t')$$

$$= \rho(\mu_S,\, J,\, J';\, E;\, I,\, \mu_I;\, t)$$

time-dependent

# Non-linear light-matter interactions in intense (FEL) fields

## – (time-) evolution “through” the density matrix



Intense optical and VUV laser

intense FEL radiation

peels off the electrons layer by layer

... but from the `inside'

**Density matrix**

$$\rho \; = \; \rho(r,t;\, r',t')$$

$$= \; \rho(\mu_S,\, J,\, J';\, E;\, l,\, \mu_{l;}\; t)$$

time-dependent

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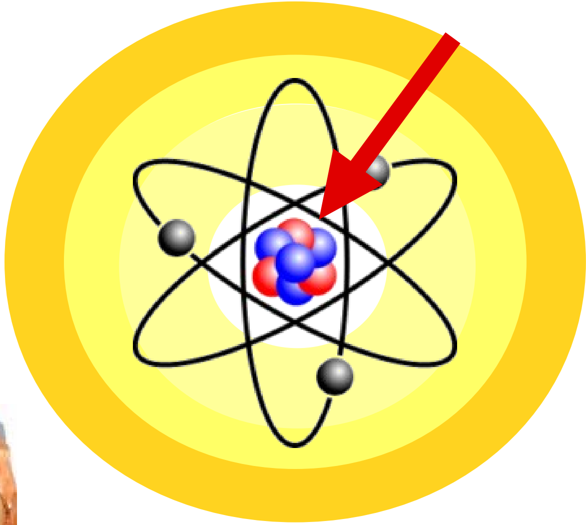

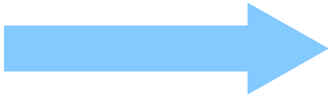

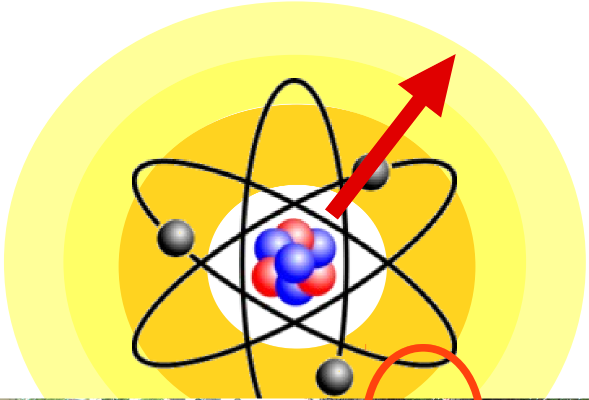

peels off the electrons layer by laye

$\rho =$

Special thanks to A. Surzhykov & Z.W. Wu

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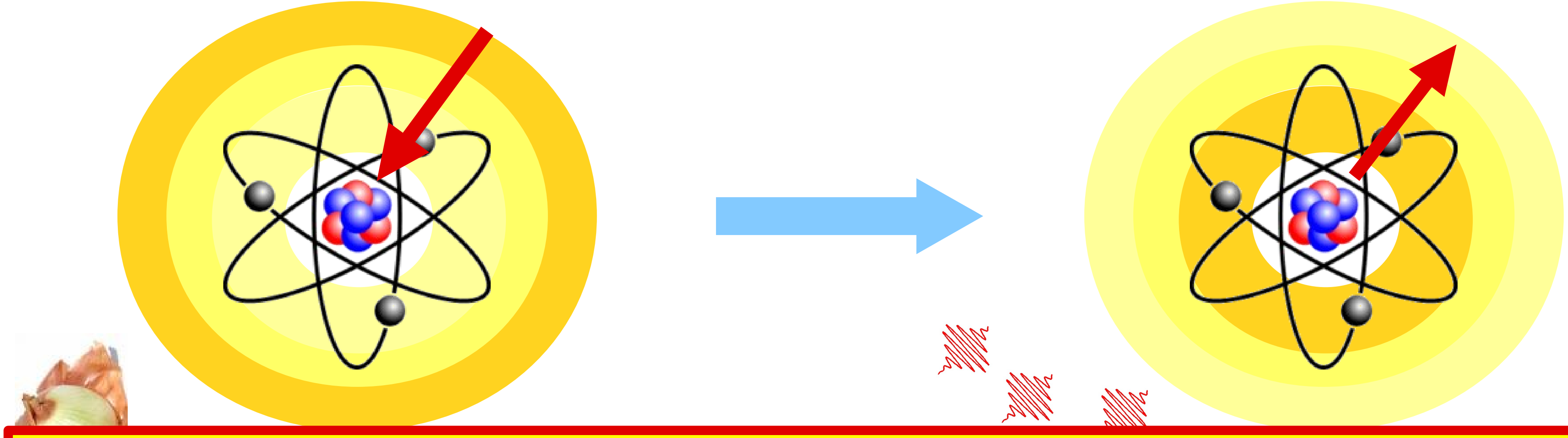
## – (time-) evolution “through” the density matrix



Intense optical and VUV laser

intense FEL radiation

## **In the end**

- Ion-electron collisions: very suitable to explore fundamental interactions.
- Strong and intense fields are indeed fundamental for discovering new phenomena and for obtaining a quantitative understanding of light-matter interactions; they are essential for a better spectroscopy and diagnostics.