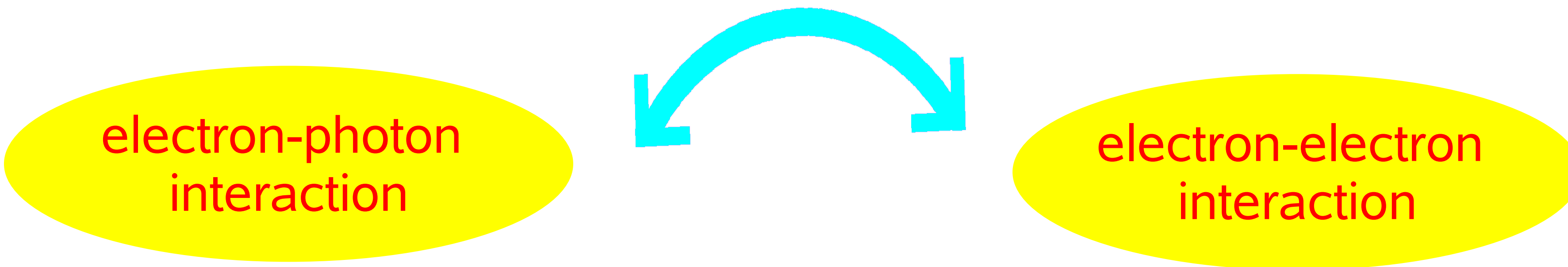
Relativistic dynamics of (slow) highly-charged ions

Stephan Fritzsche
GSI Darmstadt & Oulu University
Eisenach, 28th June 2010



Thanks to: N.M. Kabachnik, A. Surzhykov, T. Stöhlker and GSI Atomic Physics Group

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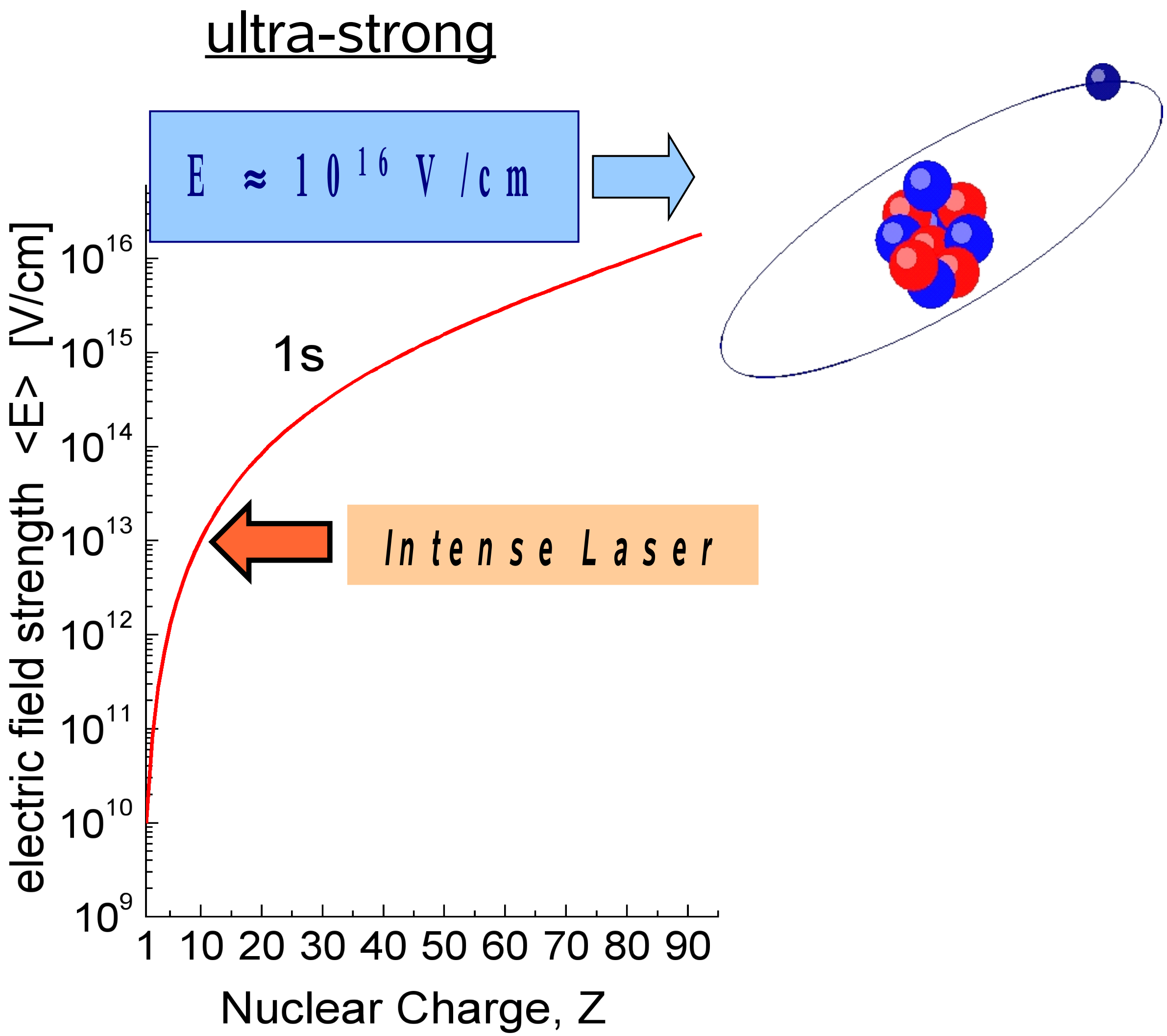
GSI

SUOMALAINEN TIEDEAKATEMIA * 1908 *

Highly-charged ions provide a unique tool

-- for probing strong electro-magnetic fields



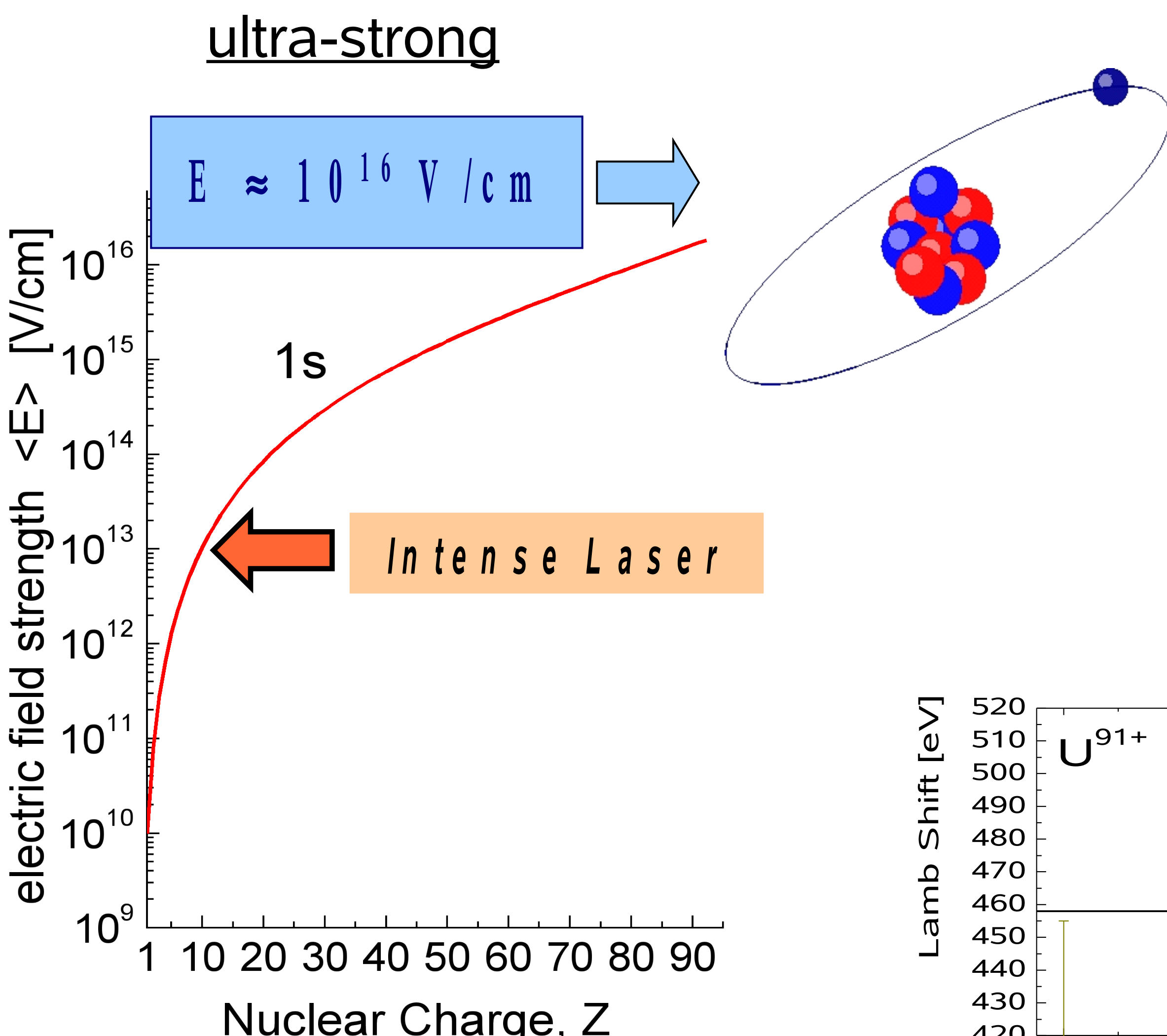
Highly-charged ions provide a unique tool

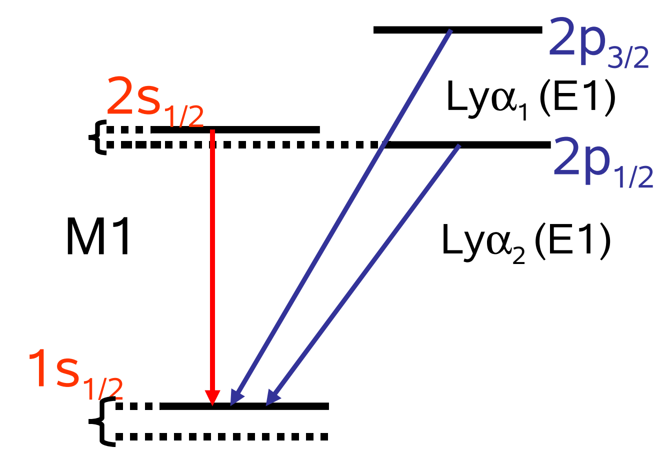
-- for probing strong electro-magnetic fields

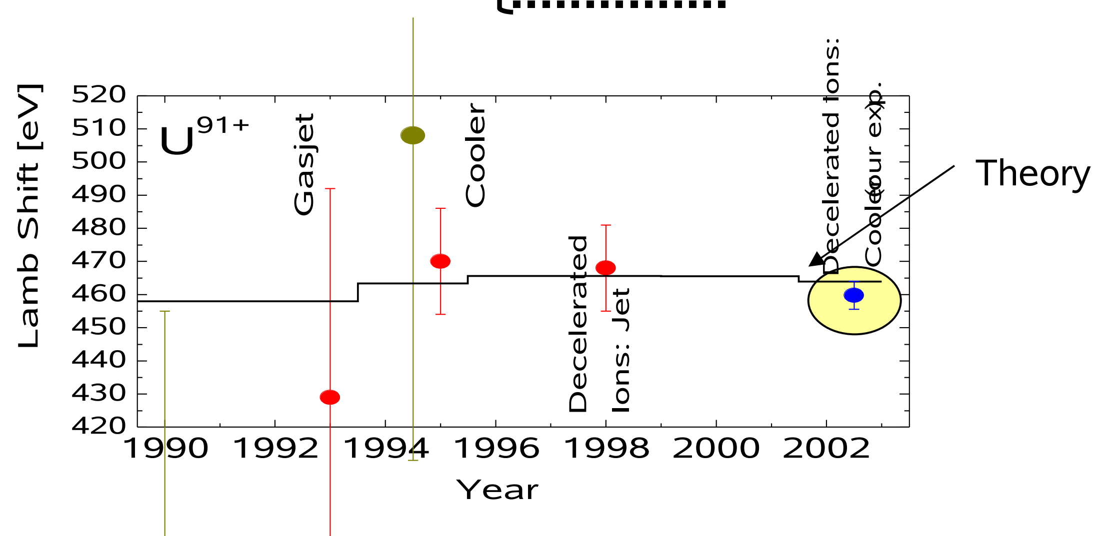
1s-Lamb Shift

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV







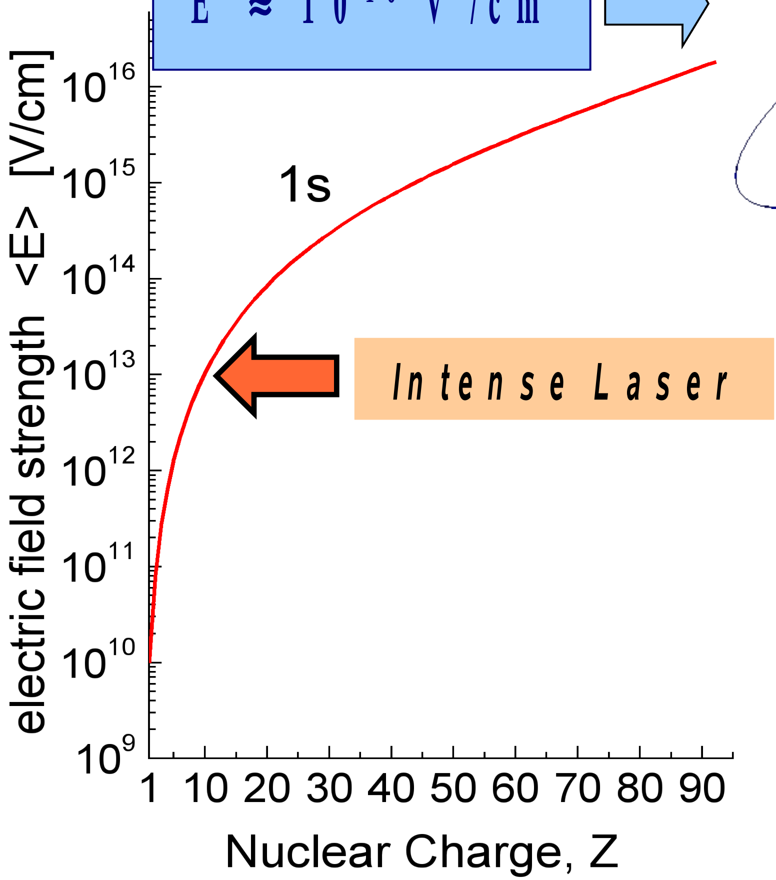
A. Gumberidze et al., PRL 94 (2005) 223001

Highly-charged ions provide a unique tool

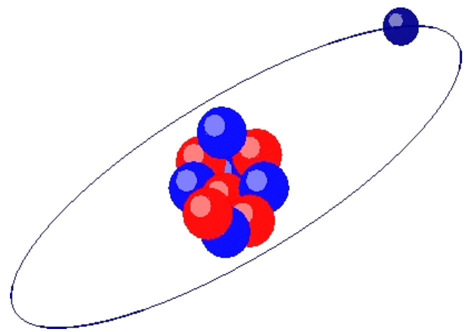
-- for probing strong electro-magnetic fields

<u>ultra-strong</u>

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

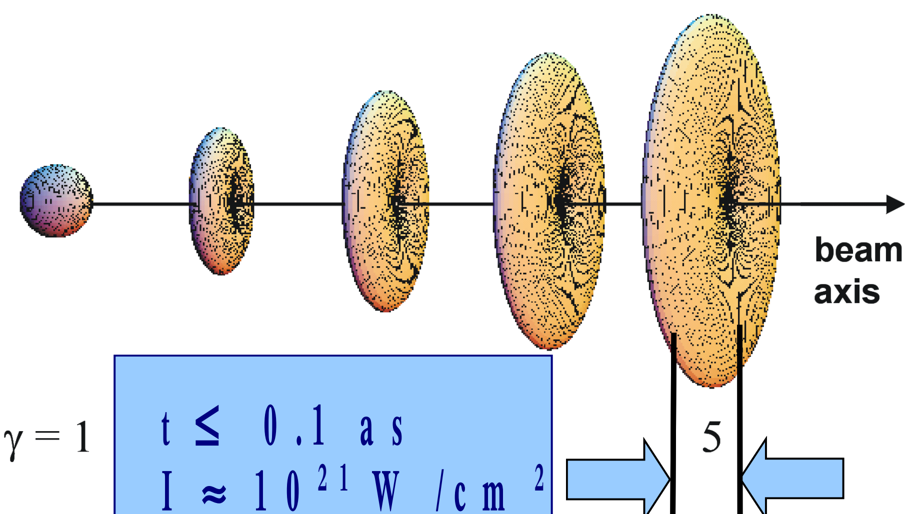


Intense Laser



<u>ultra-short</u>

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



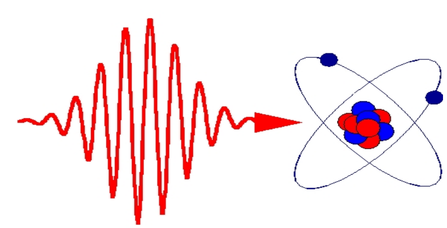
$\gamma = 1$

$t \leq 0.1$ as

$I \approx 10^{21}$ W/cm^2

In contrast to:

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



decelerated ion beams, HITRAP

Relativistic dynamics of (slow) highly-charged ions

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electron-photon interaction

electron-electron interaction

Plan of this talk

- Electron capture: angular correlations & polarization
- Multipole mixing in strong fields
- Two-step processes: Capture vs. excitation
- Atomic PNC: Two-photon processes
- Spectroscopy of (super-) heavy elements
- Conclusions

Thanks to: N.M. Kaba

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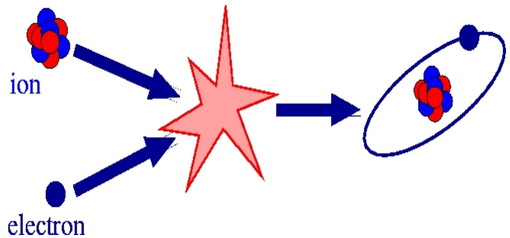
Electron capture by bare ions

-- angular correlation and polarization studies

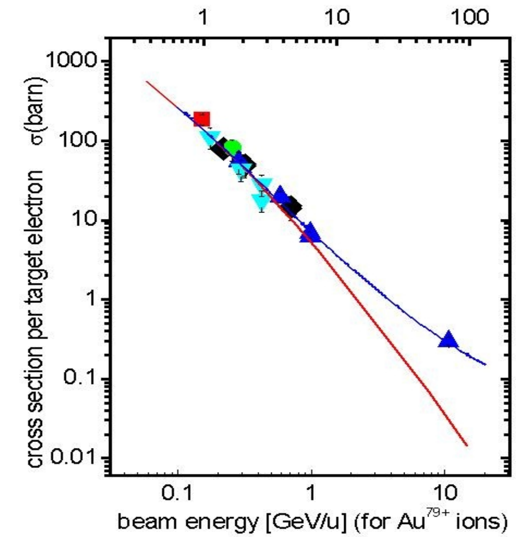
Electron capture into bare high-Z ions

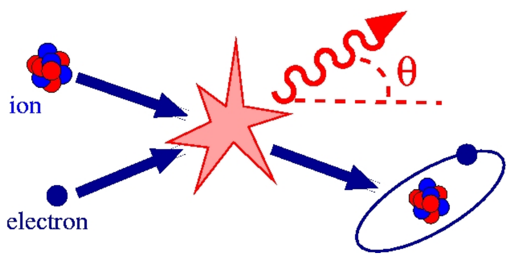
So far...



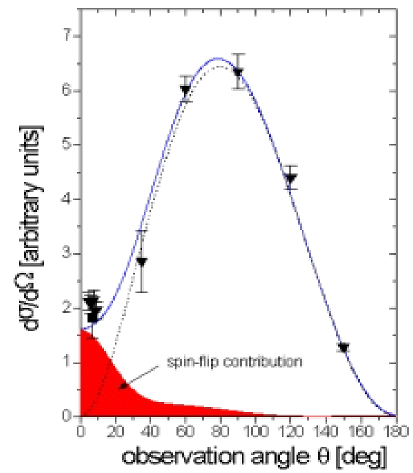
total cross sections

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





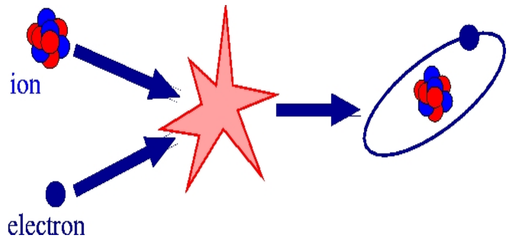
angular distributions



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

Electron capture into bare high-Z ions

So far…



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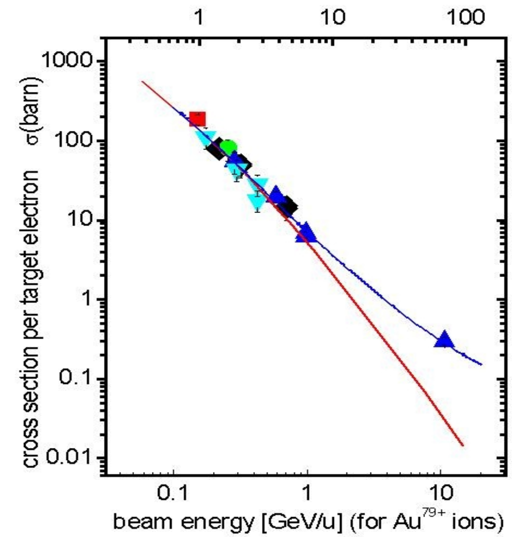

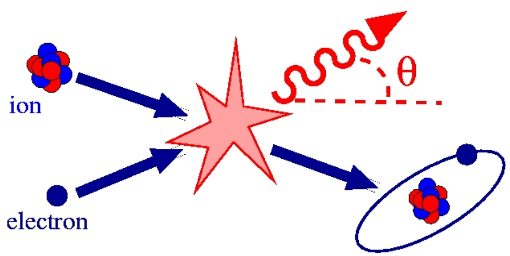

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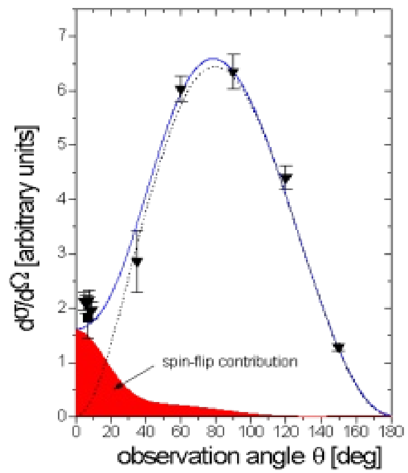
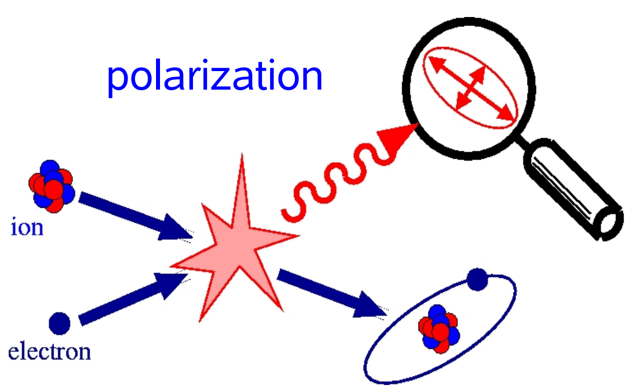
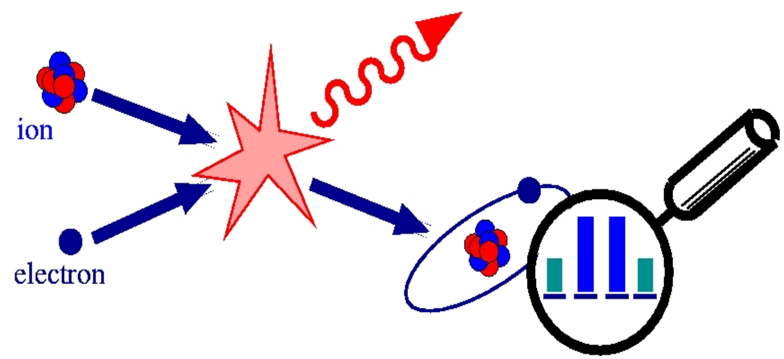


$$\frac{d\sigma}{d\Omega}(\theta) \sim \sum_{polarization} |M|^2$$

New directions …

polarization





Alignment studies

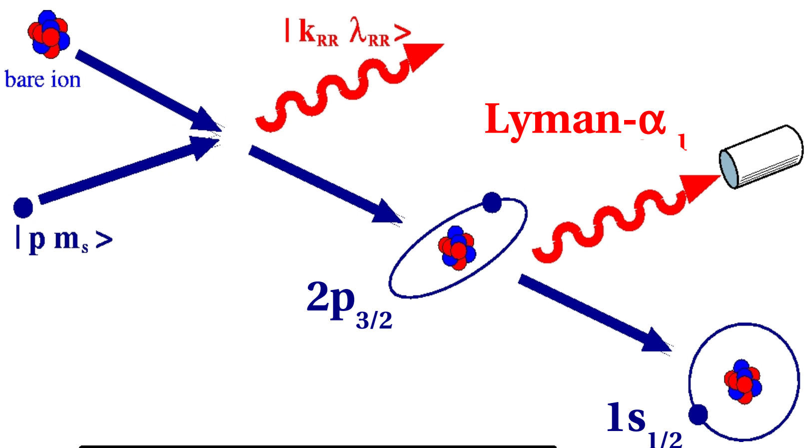
$$\sim |M|^2$$

No summation over polarization states !

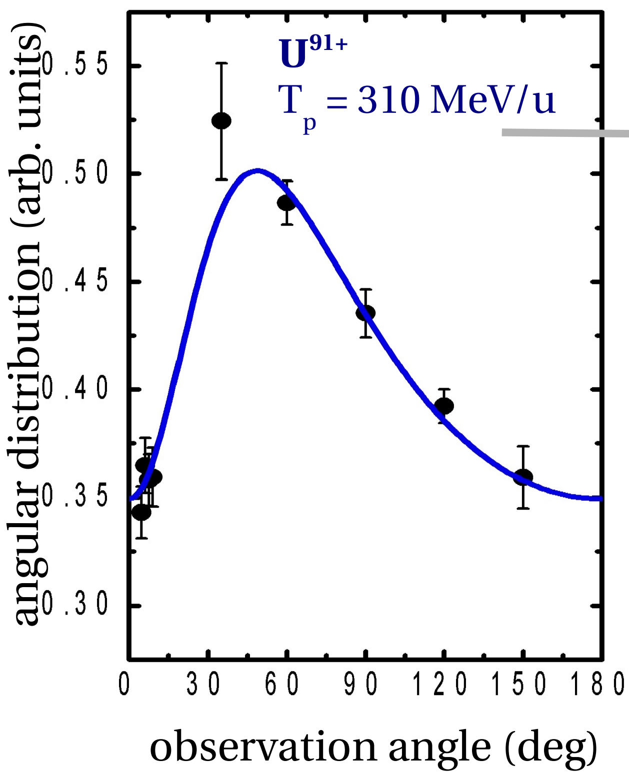
Multipole mixing of the radiation field

-- in the capture and decay of highly-charged ions

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

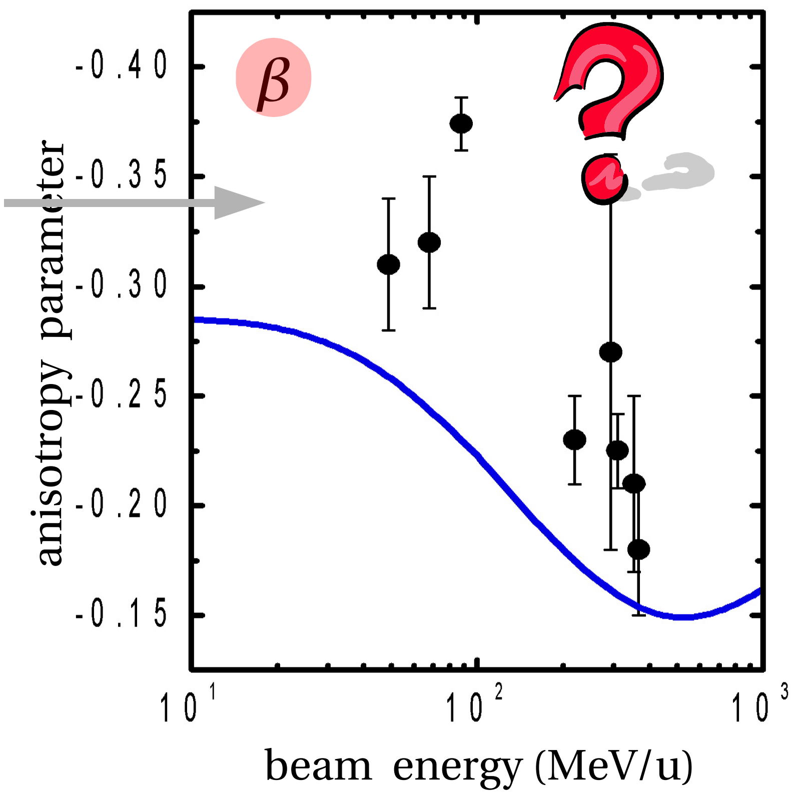


- Magnetic sublevel population of the residual ion can not be measured **directly**
- **But:** knowledge on population of excited ion state may be derived from the properties of subsequent decay



fitting

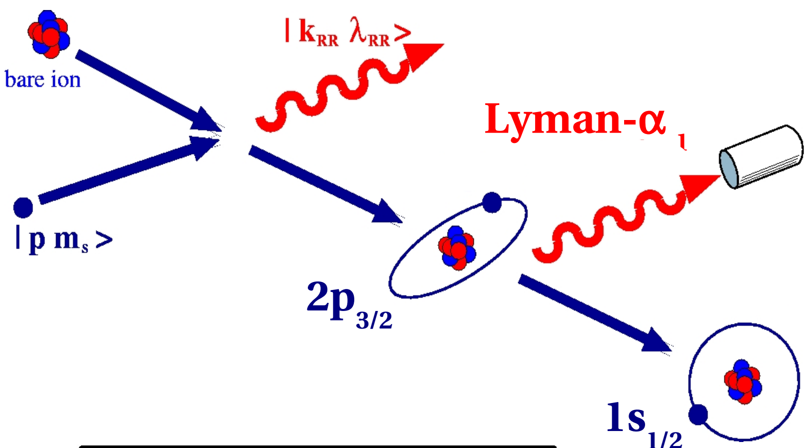
$$W(\theta) \propto 1 + \beta P_2(\cos\theta)$$



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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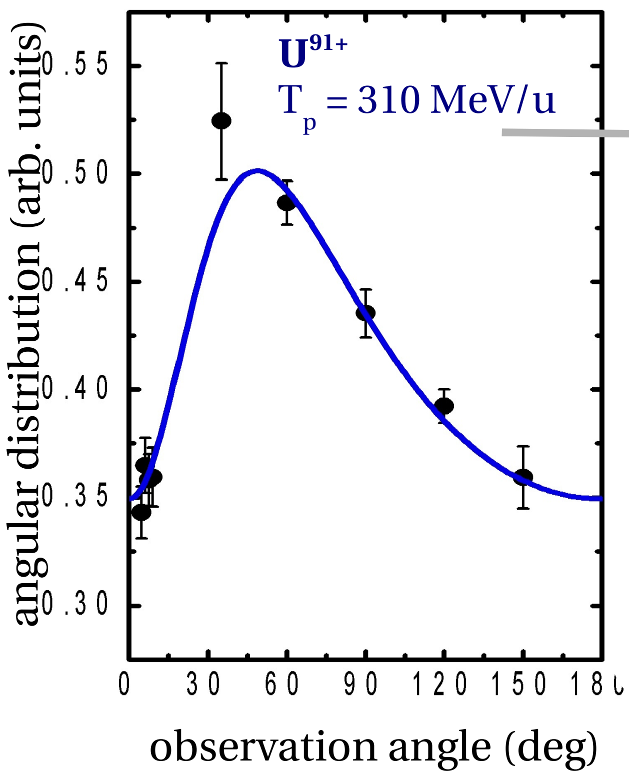

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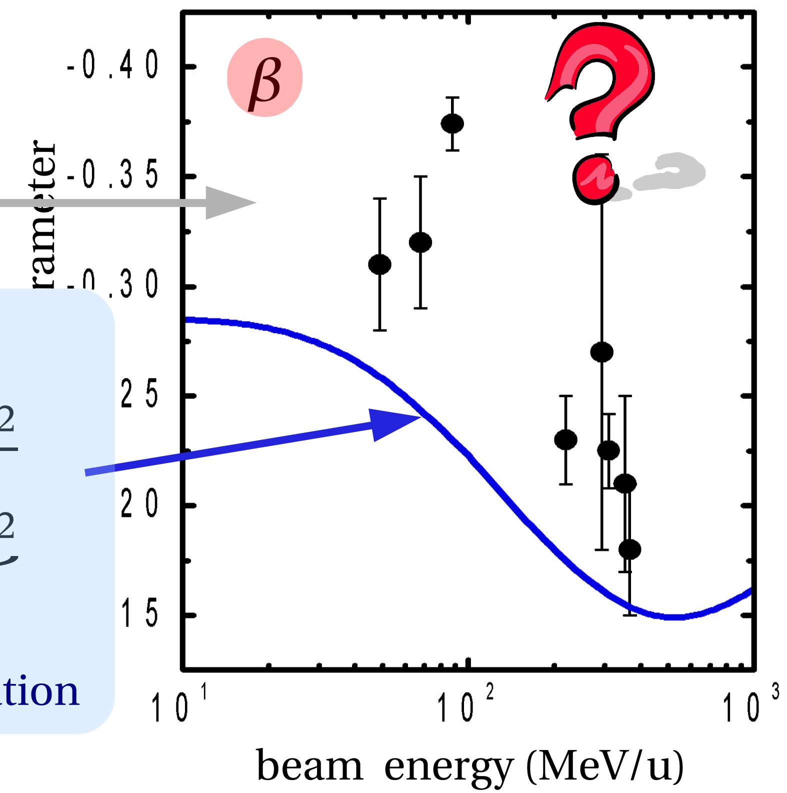


Theory:

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

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

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

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

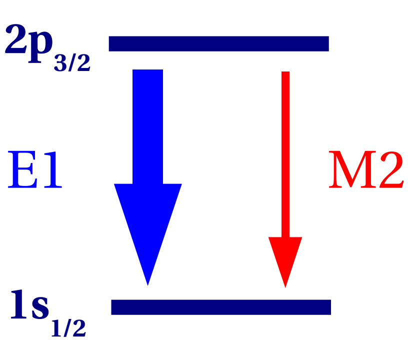
Effective anisotropy parameter: Multipole contributions

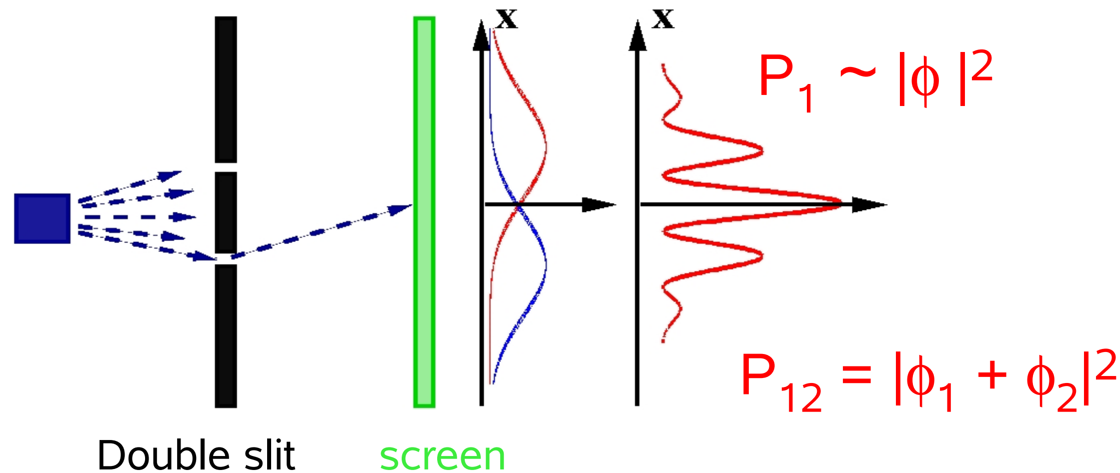
$$W(\theta) \propto 1 + \beta_{eff} P_2(\cos\theta)$$

effective anisotropy parameter

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

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





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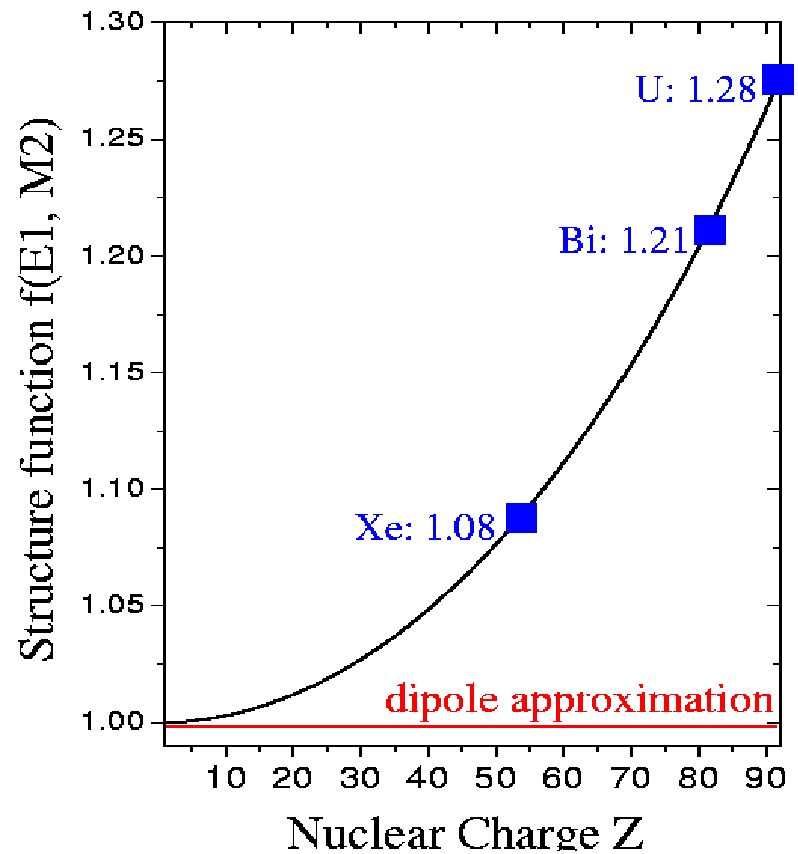

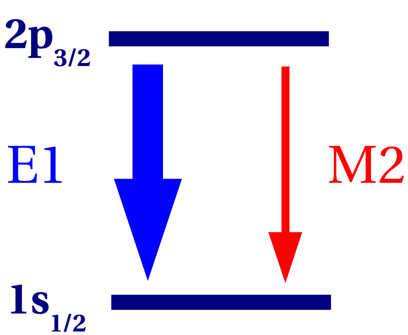

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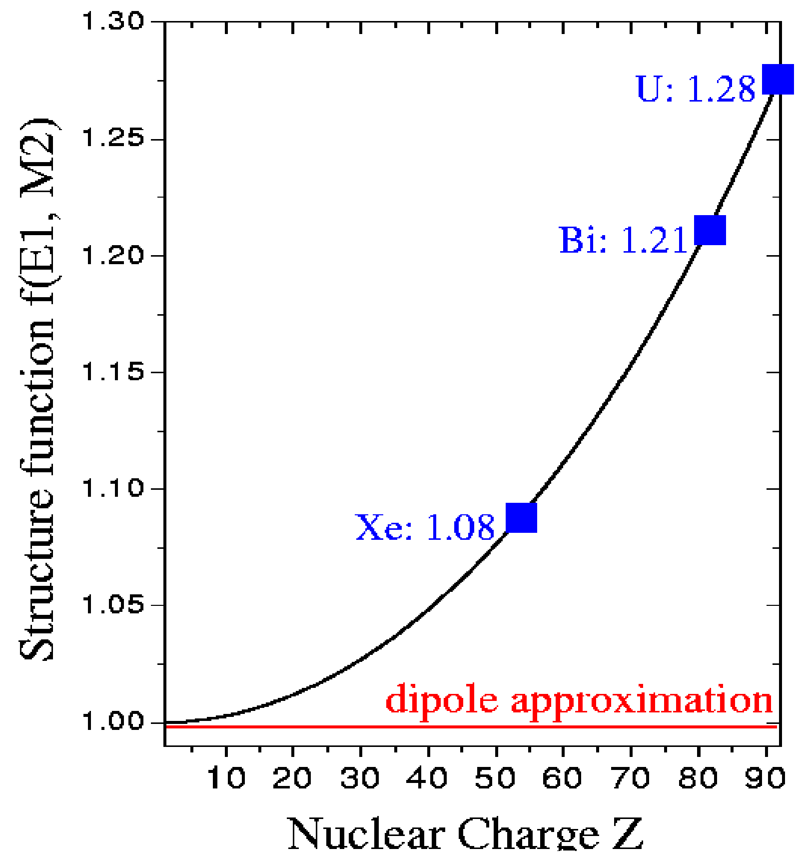
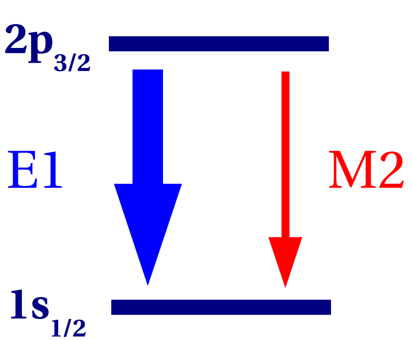




In contrast, contributions to decay rates appear additive:

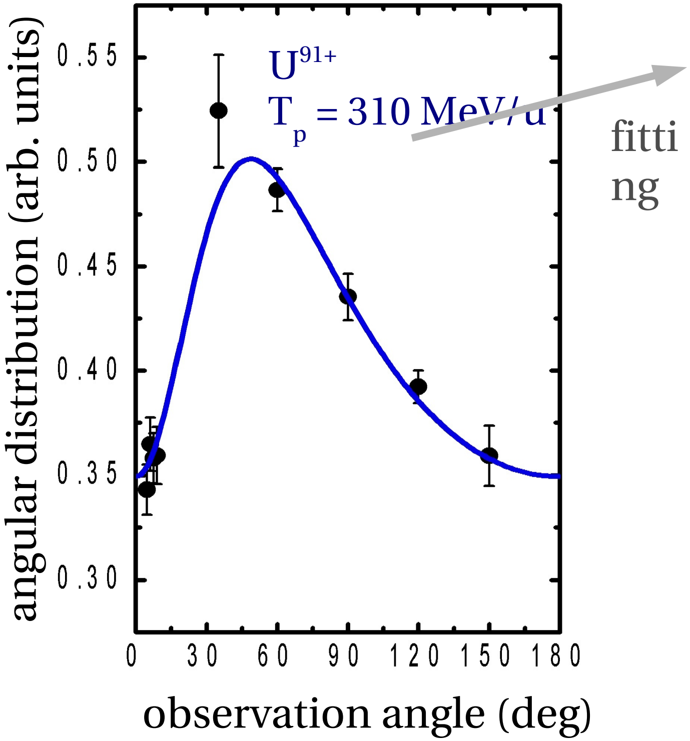
$$\frac{\Gamma_{M2}}{\Gamma_{tot}} \propto \frac{|\langle |M2| \rangle|^2}{|\langle |E1| \rangle|^2} \propto 0.008$$

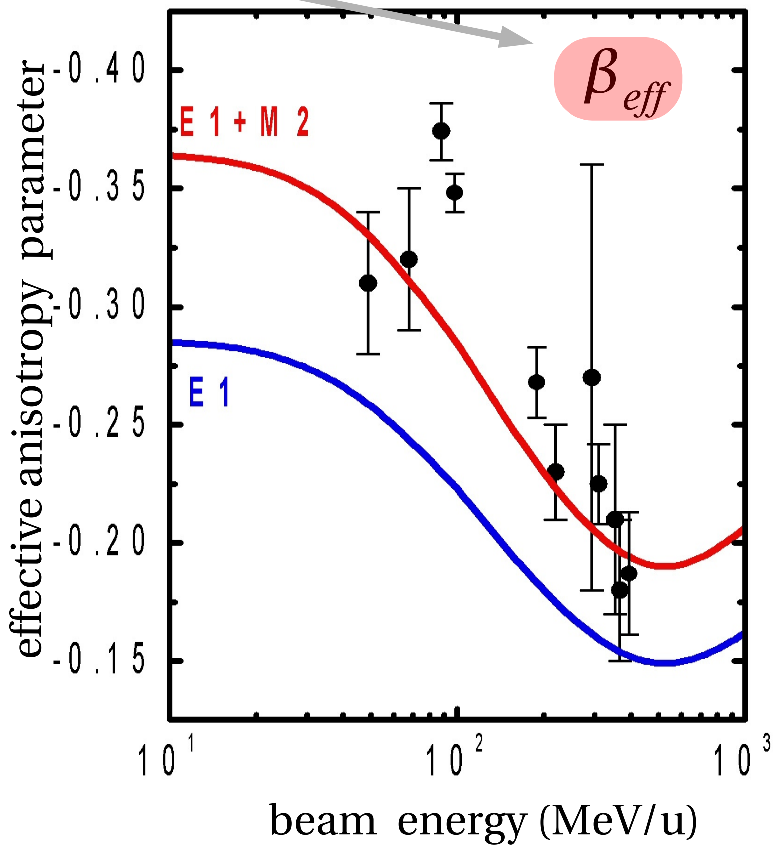
even for U^{91+}

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

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

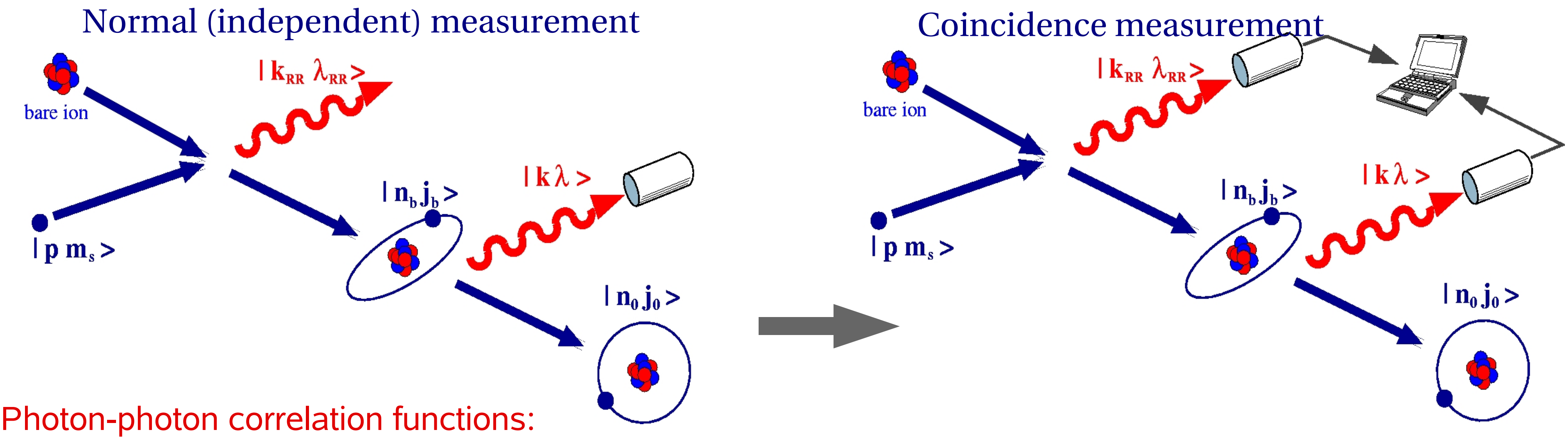
$$W(\theta) \propto 1 + \beta_{eff} P_2(\cos\theta)$$





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

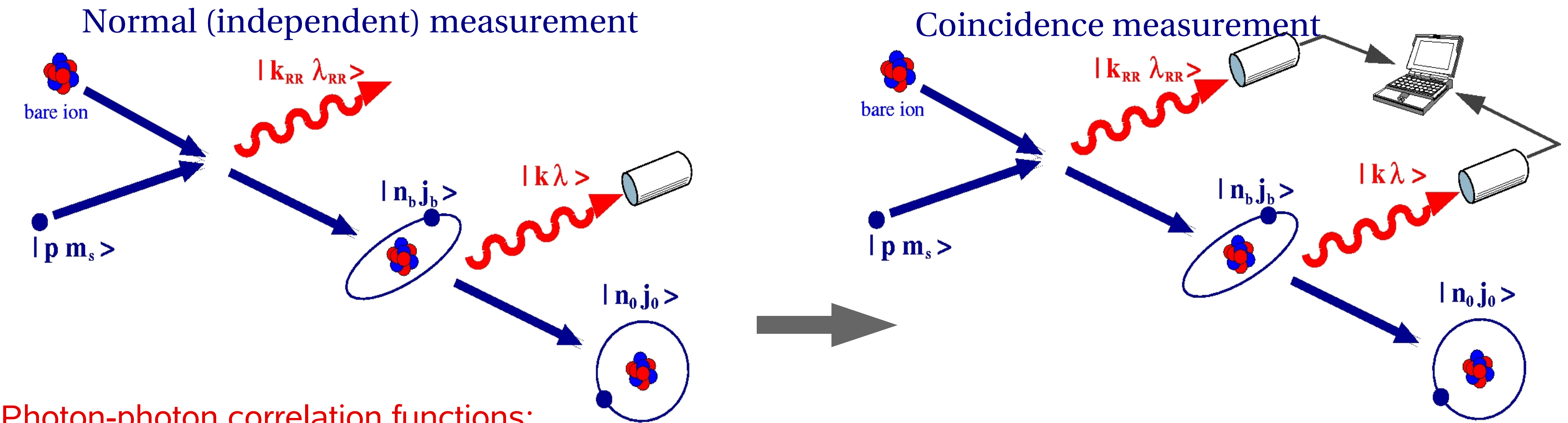
Two-photon coincidence studies



Photon-photon correlation functions:

$$W(\theta_{RR}, \theta) = ?$$

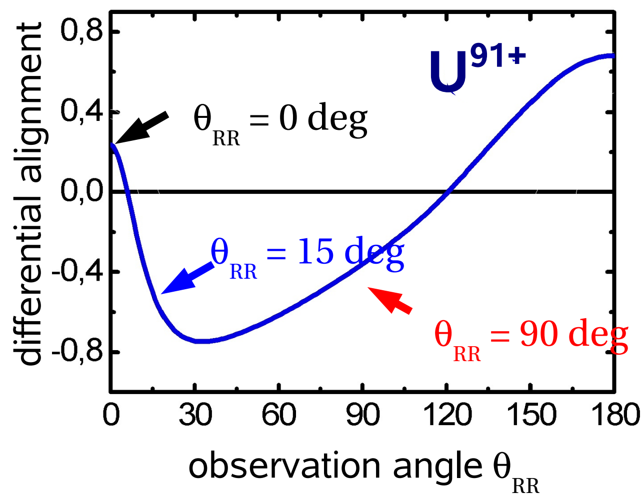
Two-photon coincidence studies

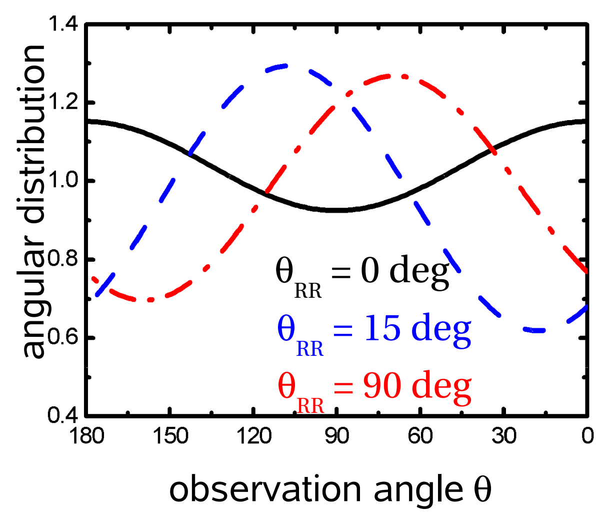


Photon-photon correlation functions:

$$W(\theta_{RR},\theta) \propto 1+\sqrt{\frac{4\pi}{5}}\sum_q A_{2q}(\theta_{RR})\,Y_{2q}(\theta)$$

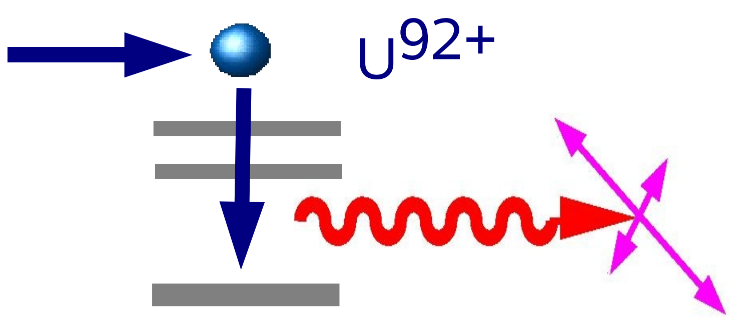
Lengthy derivation in the framework of the density matrix theory.



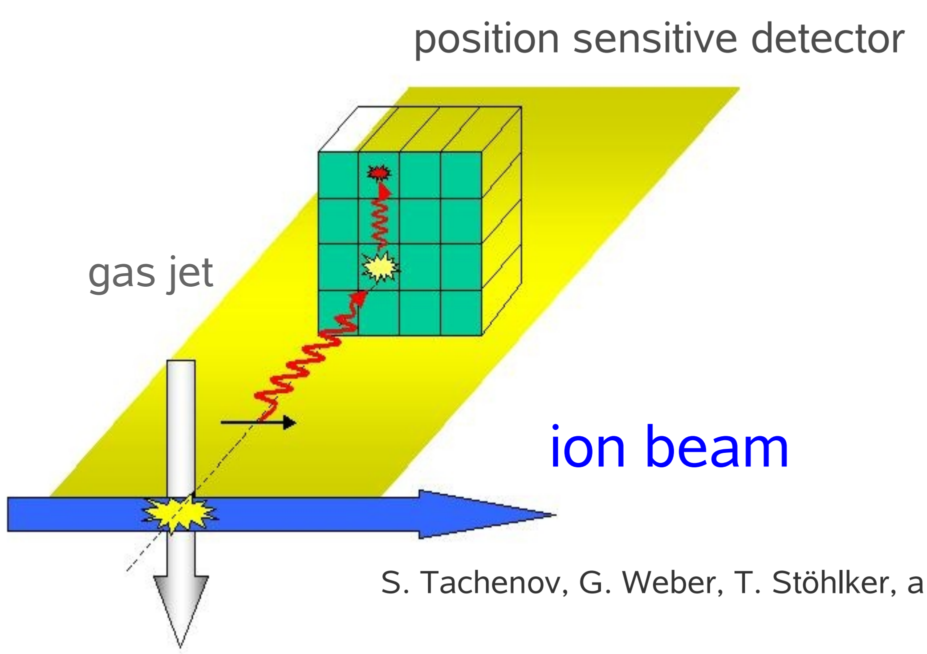


X-ray polarimetry for HCI

-- exploring a new `dimension' in the electron-photon interaction



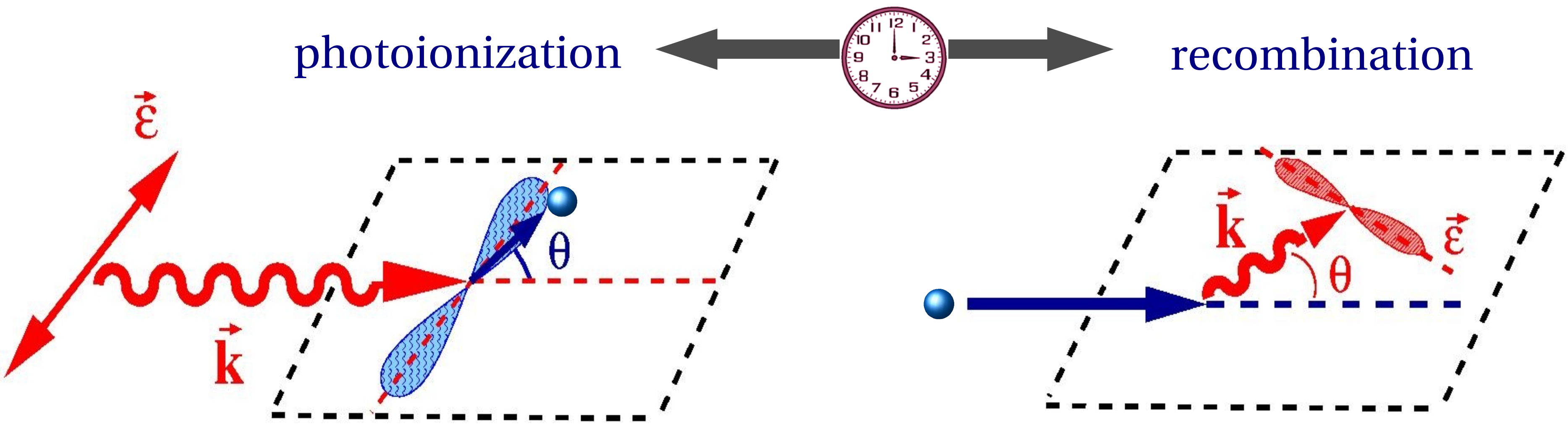
K-shell capture or
subsequent decay



S. Tachenov, G. Weber, T. Stöhlker, a.o.

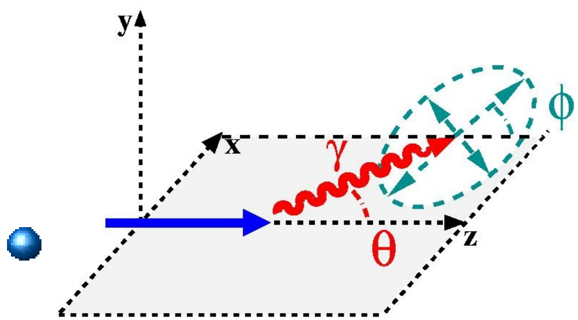
Linear polarization of emitted x-ray photons

-- theoretical expectation



electric dipole approximation

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

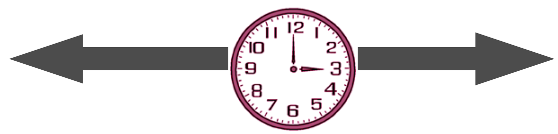


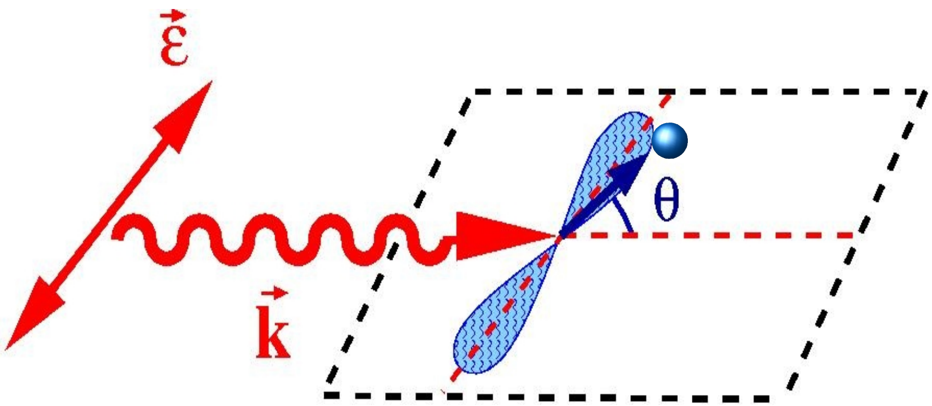
only 2 (Stokes) parameters are required !

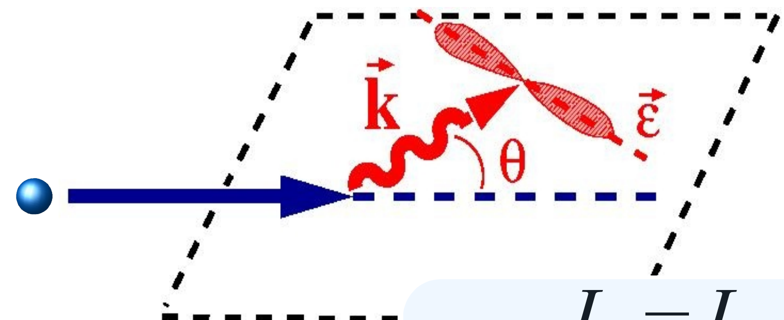
$$P_L = \sqrt{P_1^2 + P_2^2} \qquad \cos(2\phi) = \frac{P_1}{P_L}$$

Linear polarization of emitted x-ray photons

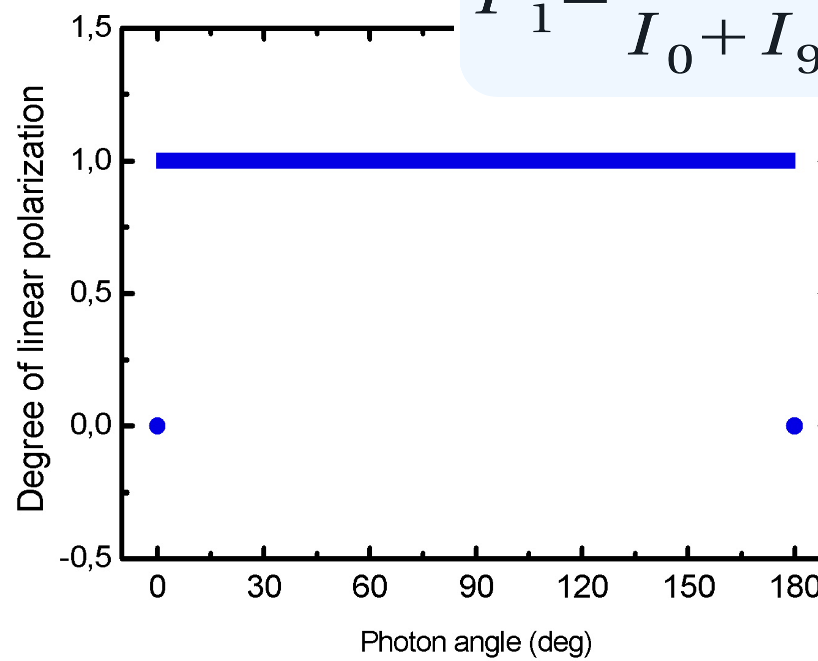
-- Statistical characteristics for photon ensembles

photoionization  recombination





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



electric dipole approximation

photoelectron angular distribution:

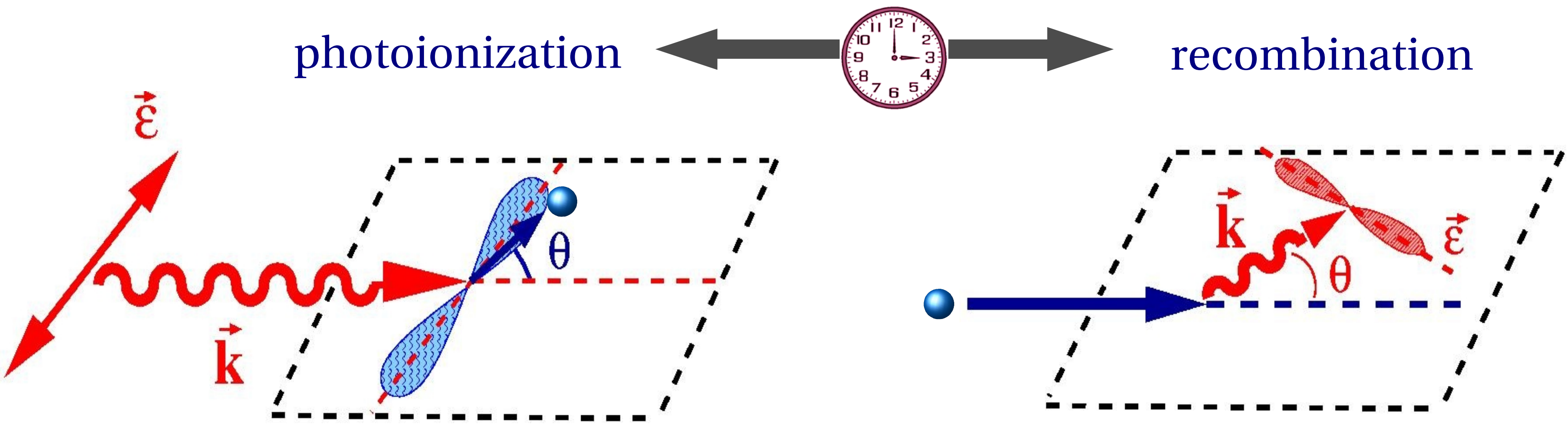
$$W_{PI} \propto \sin^2\theta \ \cos^2\phi$$

photoelectrons are emitted predominantly within the plane of the electric field

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

Linear polarization of emitted x-ray photons

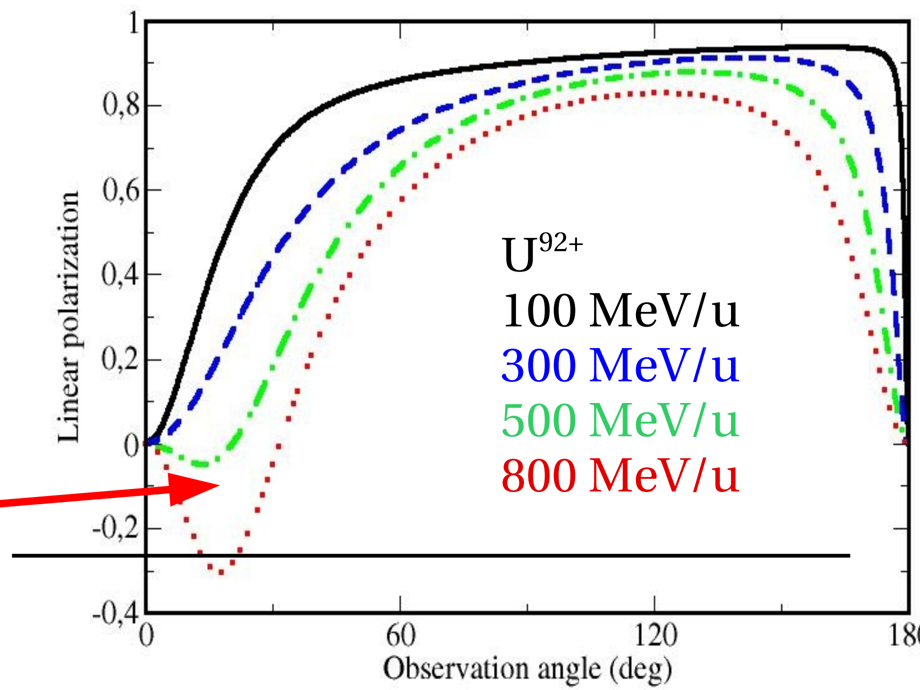
-- Statistical characteristics for photon ensembles



electric dipole approximation

- Relativistic effects decrease the linear polarization !
- Cross-over behaviour !!

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

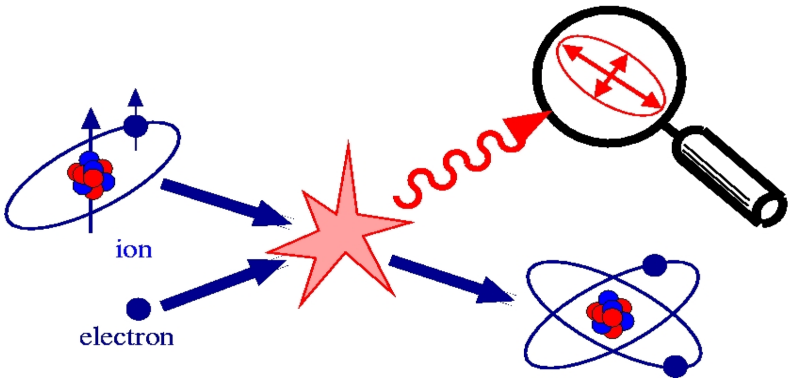


A. Surzhykov *et al*, PLA 289 (2001) 213
J. Eichler *et al*, PRA 65 (2002) 052716

Linear polarization of emitted x-ray photons: Applications

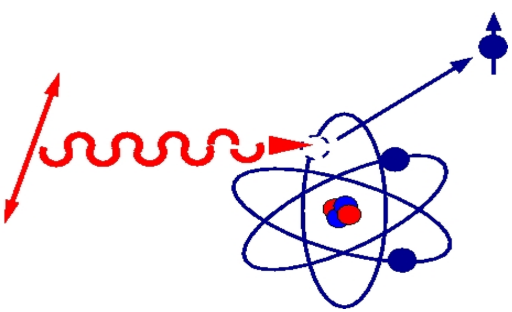
-- Diagnostics of highly-charged ion beams

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



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

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



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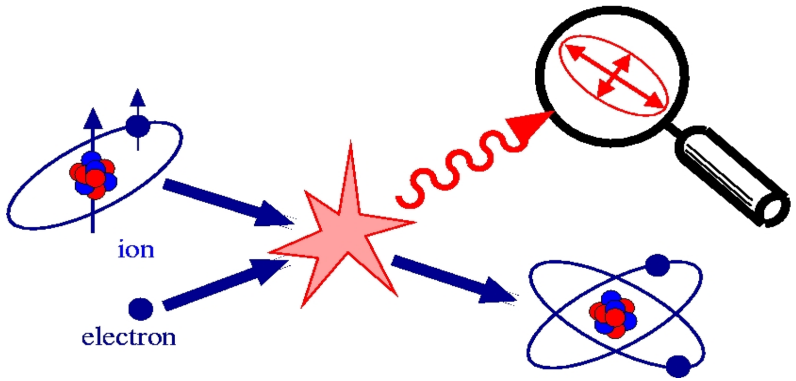

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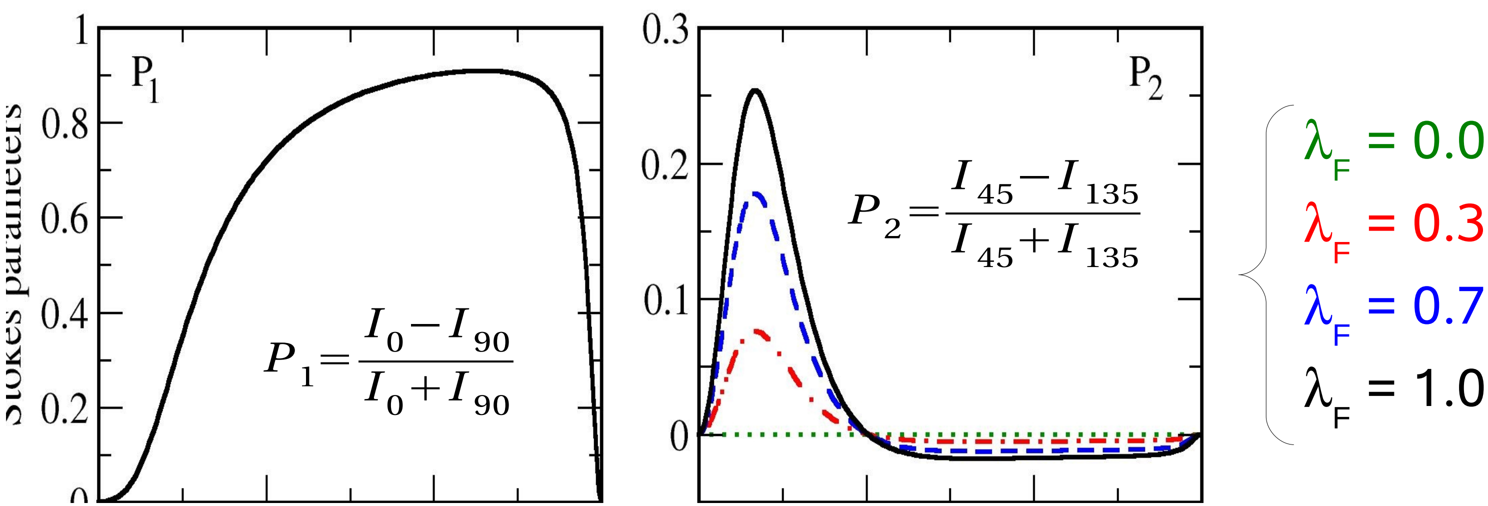
- Calculations performed for the REC into (initially) hydrogen-like bismuth Bi^{82+} ions (***I*** = 9/2) for the energy T_p = 420 MeV/u.



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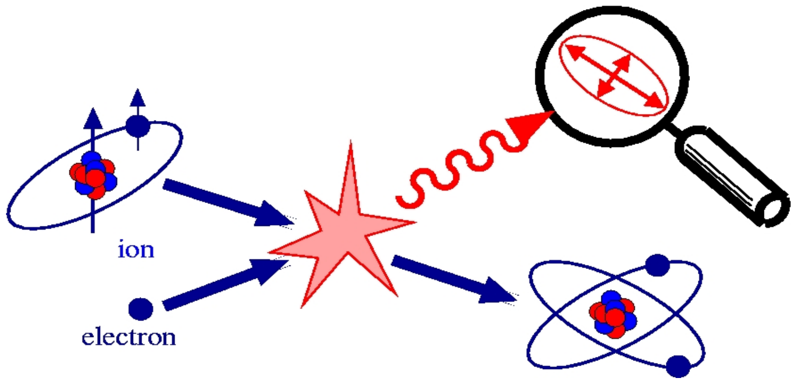

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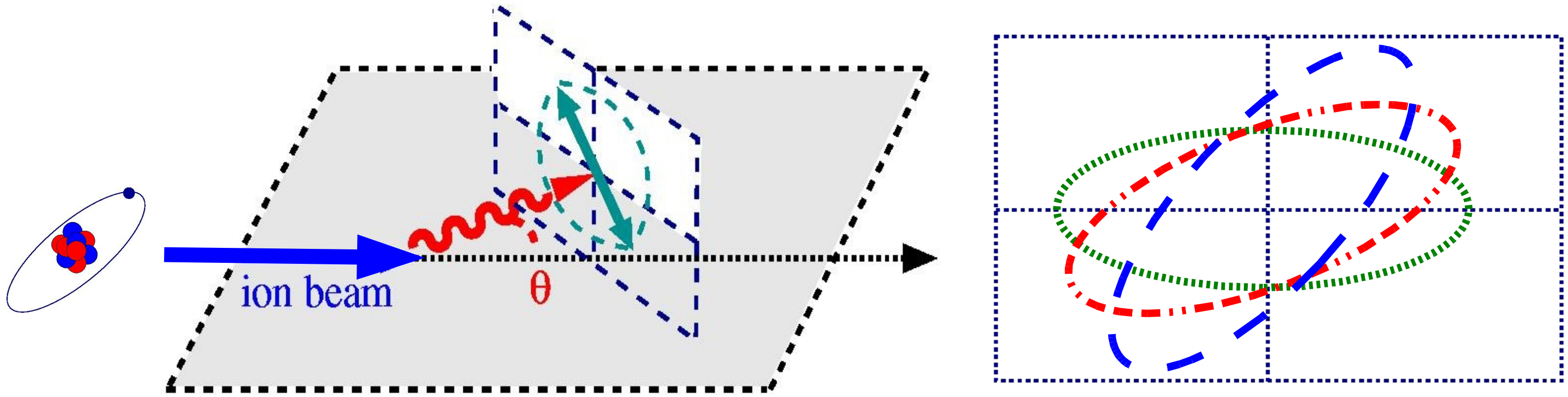

$$\tan(2\phi) = \frac{P_2}{P_1}$$

direction of polarization

A. Surzhykov *et al.*, Phys. Rev. Lett. **94** (2005) 203202

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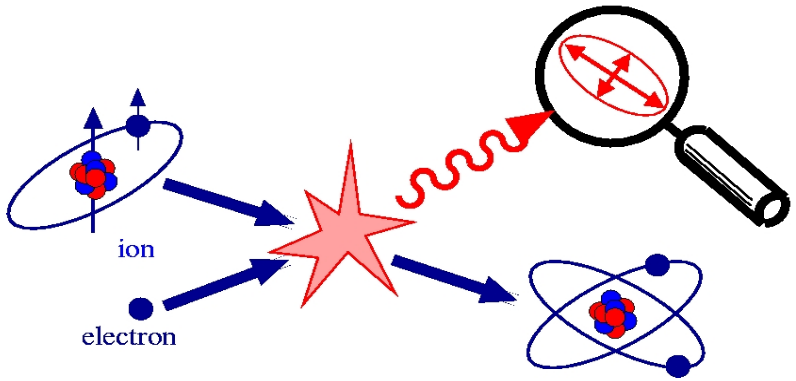
-- Diagnostics of highly-charged ion beams

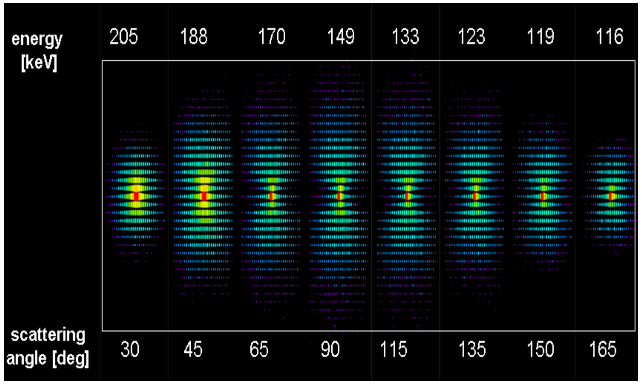
- Proposal: to use REC linear polarization as a probe for ion spin polarization.



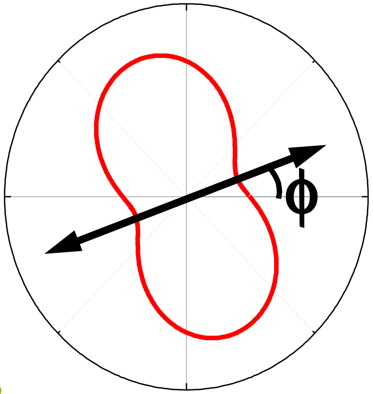
- Established theory from the "polarization transfer" in atomic photoionization.

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.



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

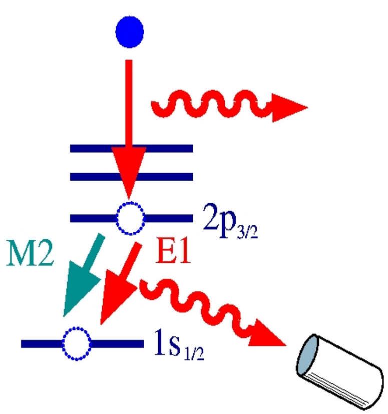


S. Tashenov *et al.*, PRL **97** (2006) 223202;
A. Surzhykov *et al.*, PRL **94** (2005) 203202.

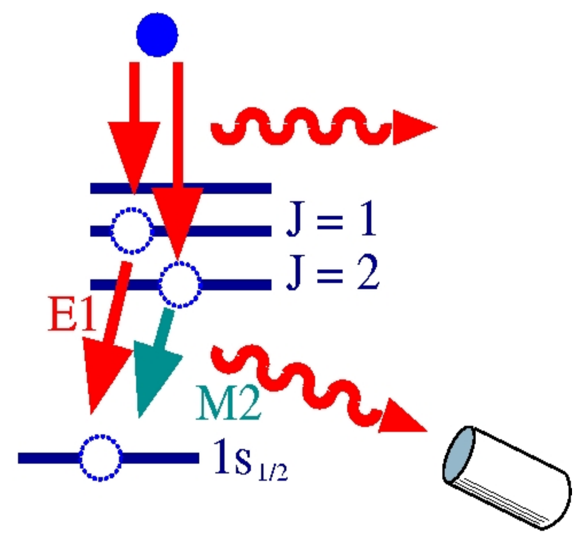
Rotation angle ϕ provides information on the <u>degree</u> of ion polarization !

Two-step processes: Capture vs. excitation

-- Do we get more by following the dynamics of the ions ?

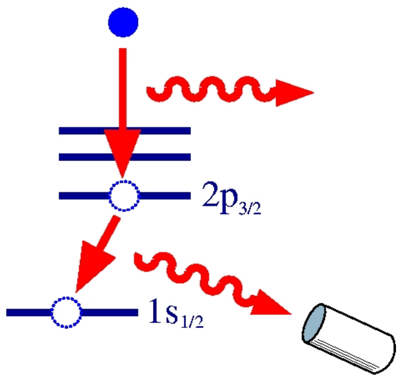


(initially) bare ion

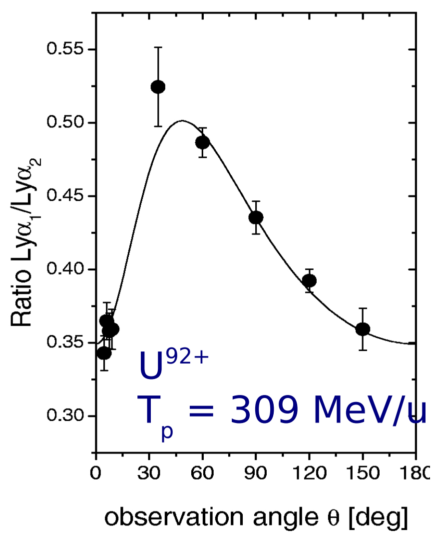


(initially) H-like ion

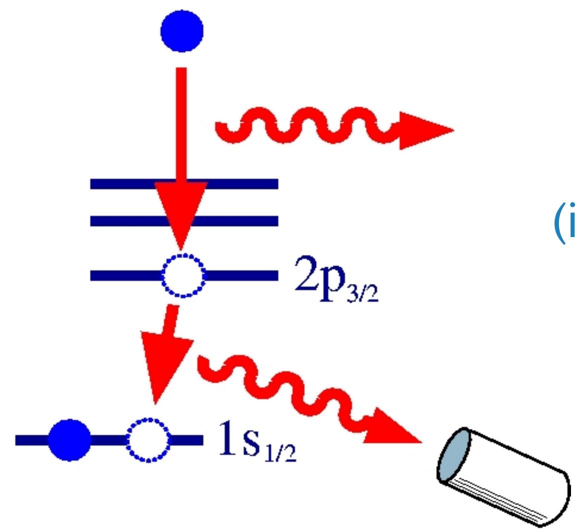
Lyman-α vs. K-α emission from high-Z ions



(initially) bare ion

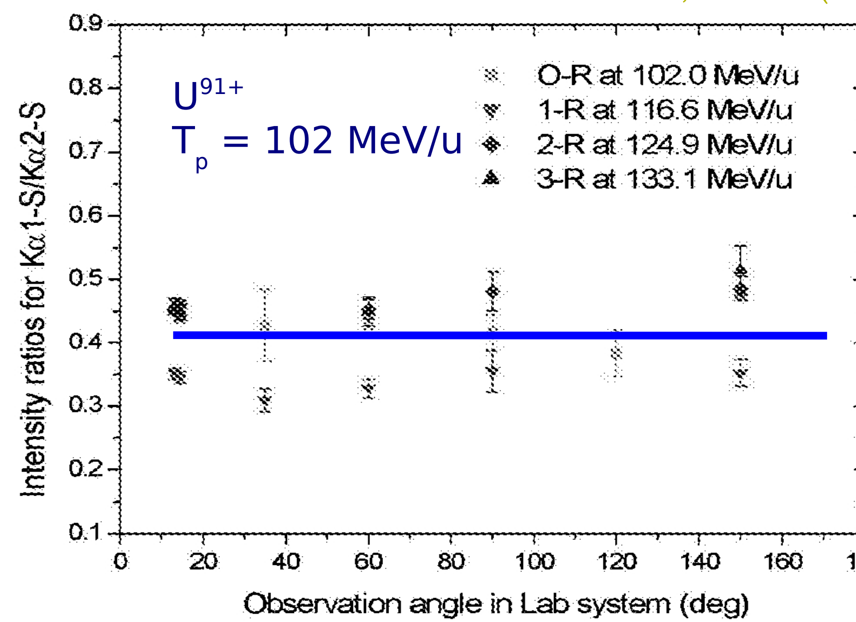


Ly-α_1 is strongly anisotropic



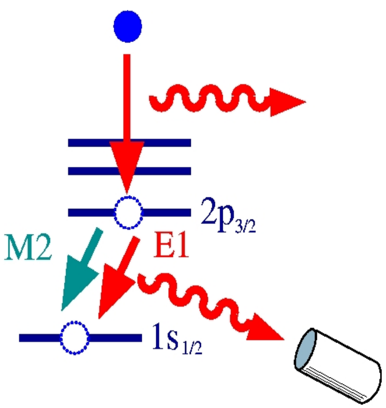
(initially) H-like ion

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

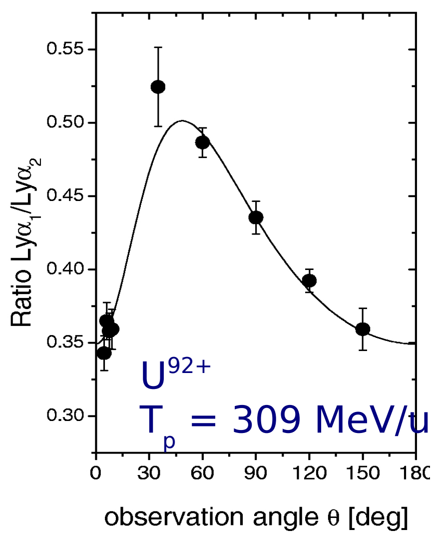


K-α_1 is isotropic

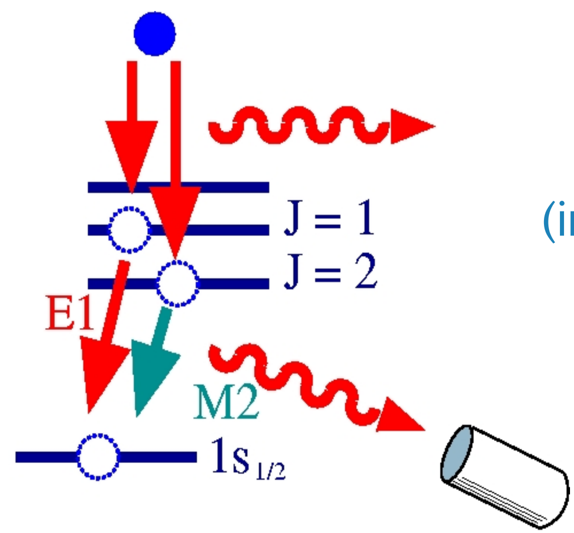
Lyman-α vs. K-α emission from high-Z ions



(initially) bare ion

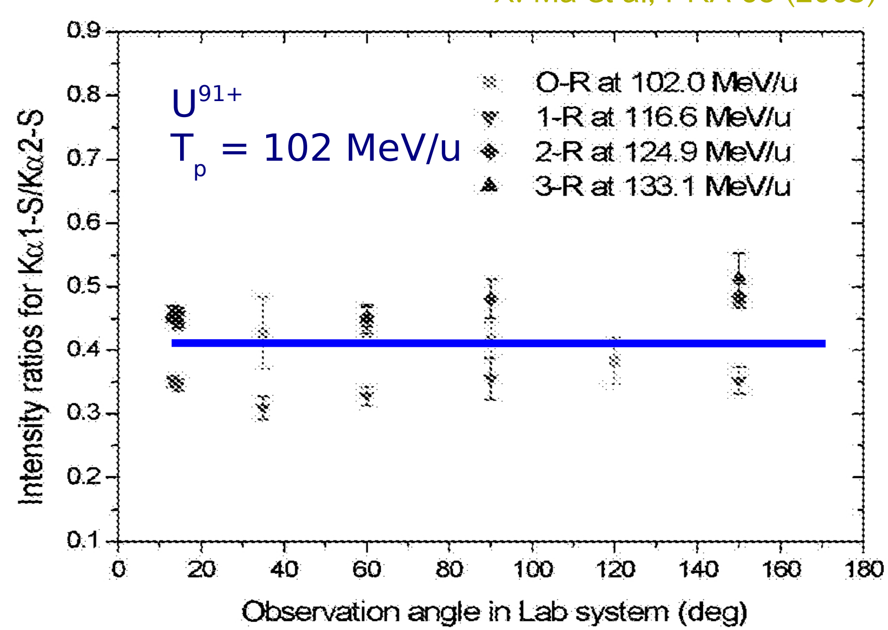


Ly-a$_1$ is strongly anisotropic



(initially) H-like ion

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-α decay of highly-charged ions

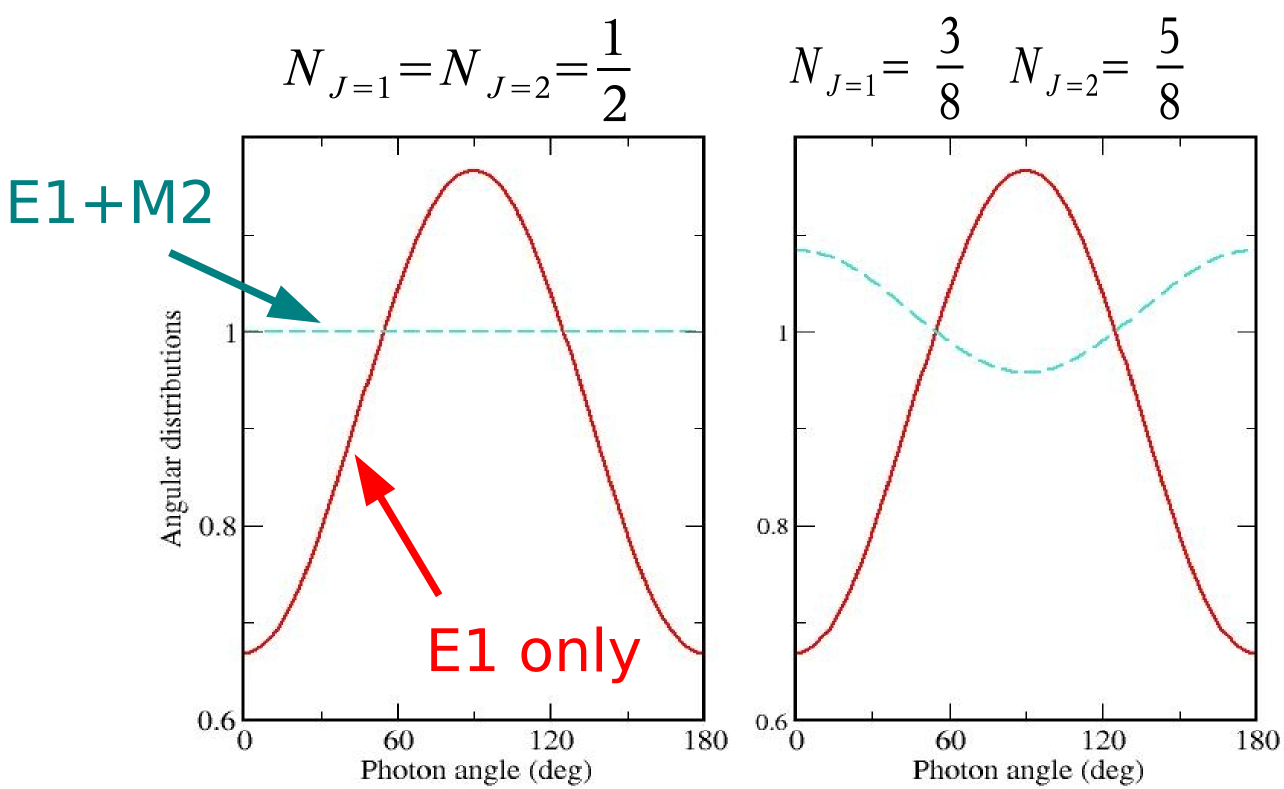
-- angular distribution as „observed" in experiment

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

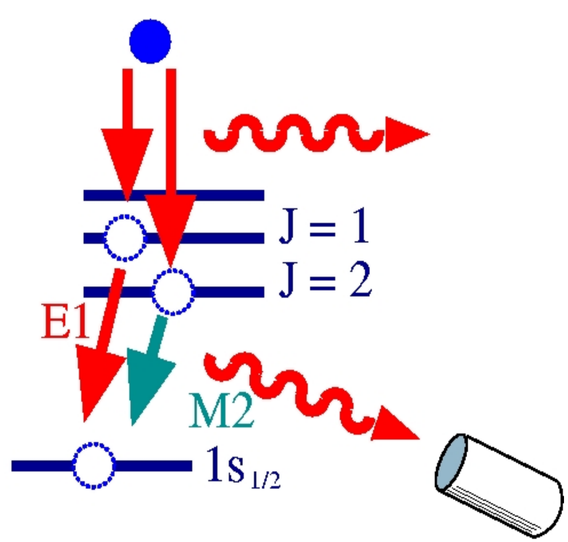
A. Surzhykov et al., PRA 73 (2006) 032716.

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

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



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.

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

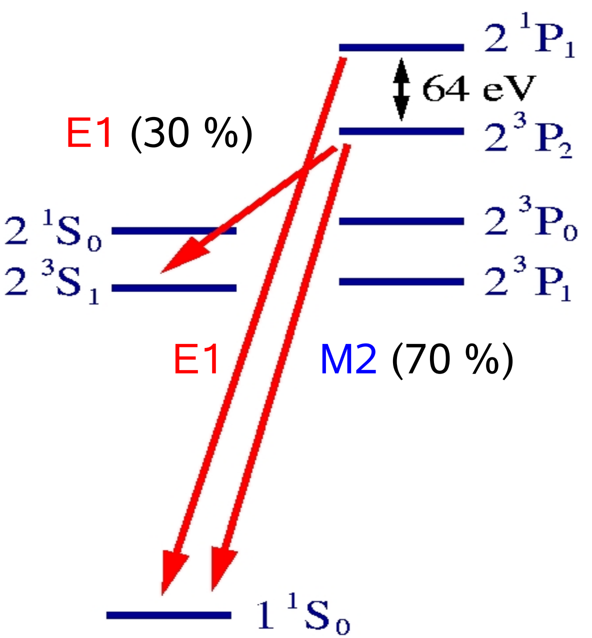
- Relative populations of the J = 1, 2 levels following REC (IPM model):

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

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

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

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



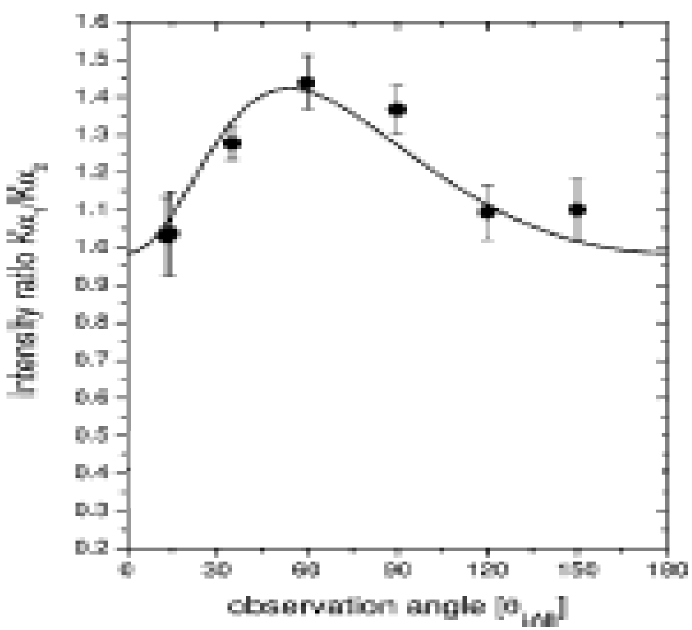
K-α decay of highly-charged ions

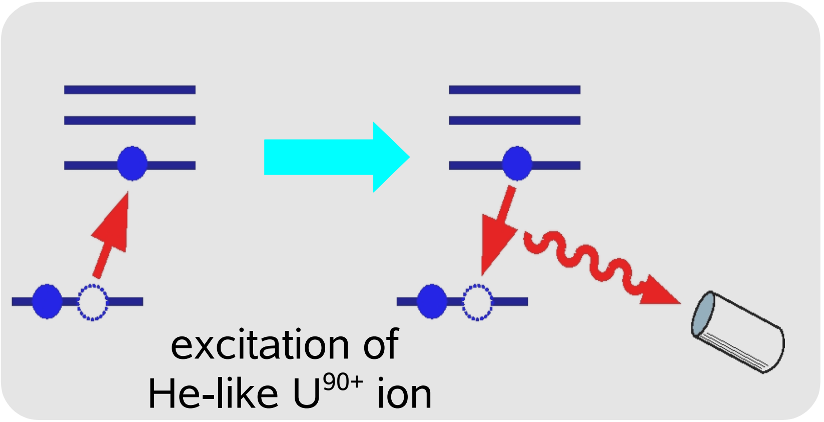
-- following the Coulomb excitation of the projectiles

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

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

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





- Excited states of He-like heavy ions can be produced also by the Coulomb excitation of the projectile in the field of target atoms.

- Experiments were already performed at the GSI storage ring for He-like uranium ions U^{90+}.

- Strong anisotropy of the subsequent $K\alpha_1$ radiation has been observed!

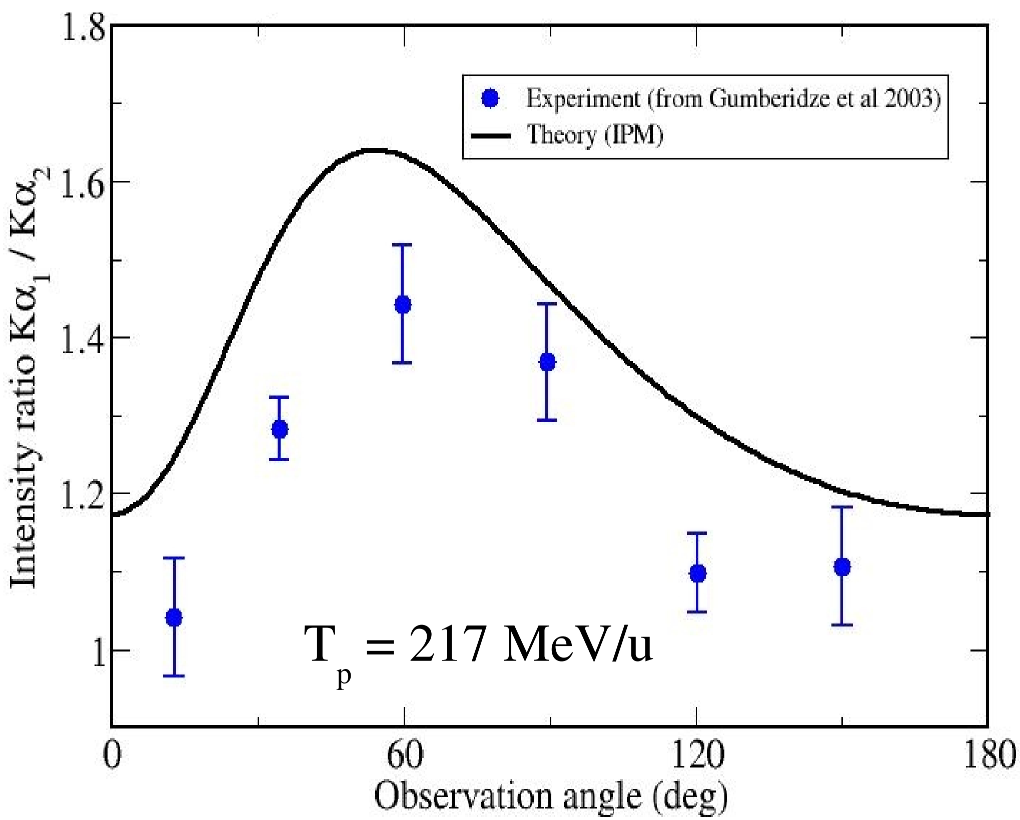
K-α decay of highly-charged ions

-- following the Coulomb excitation of the projectiles

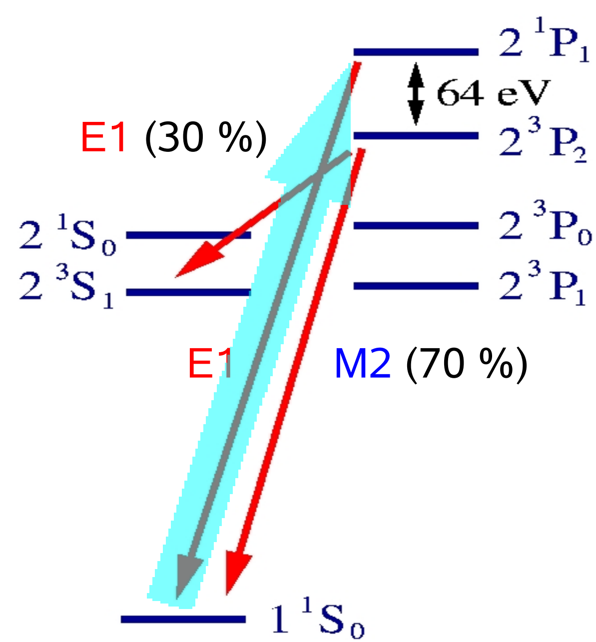
$$W(\theta)_{K\alpha_1} \sim N_{J=1} W_{E1}(\theta) + N_{J=2} W_{M2}(\theta)$$

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

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

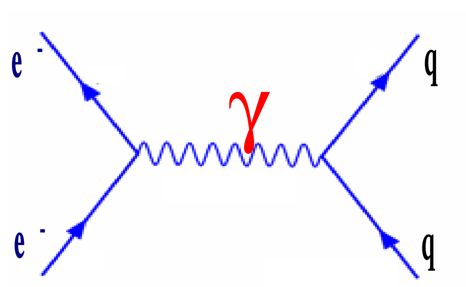


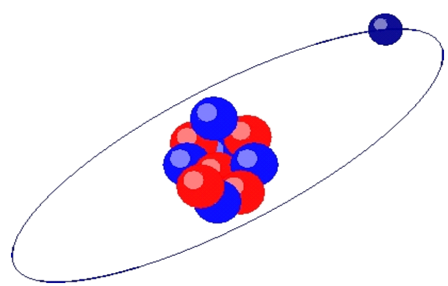
- Angular distribution results dominantly from the decay of the J=1 level.
- Role of electron-electron interactions still unexplored.

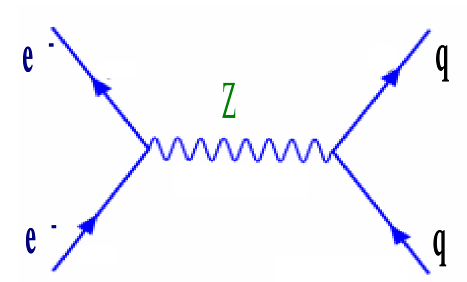


Atomic parity non-conservation processes

-- Two-photon processes for HCI

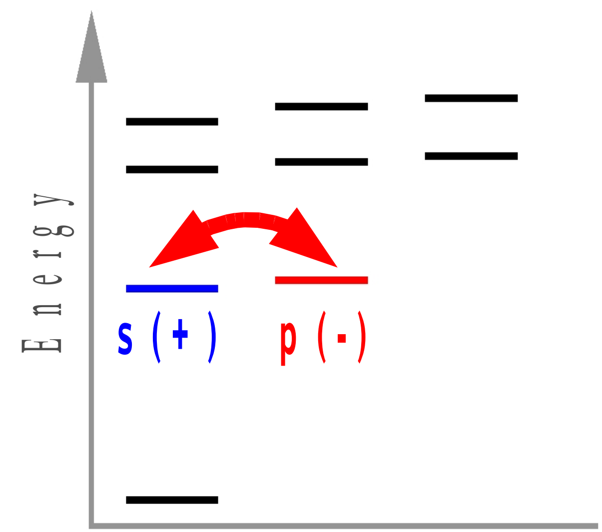






- Exchange of Z-boson leads to the mixing of atomic levels with different parities.

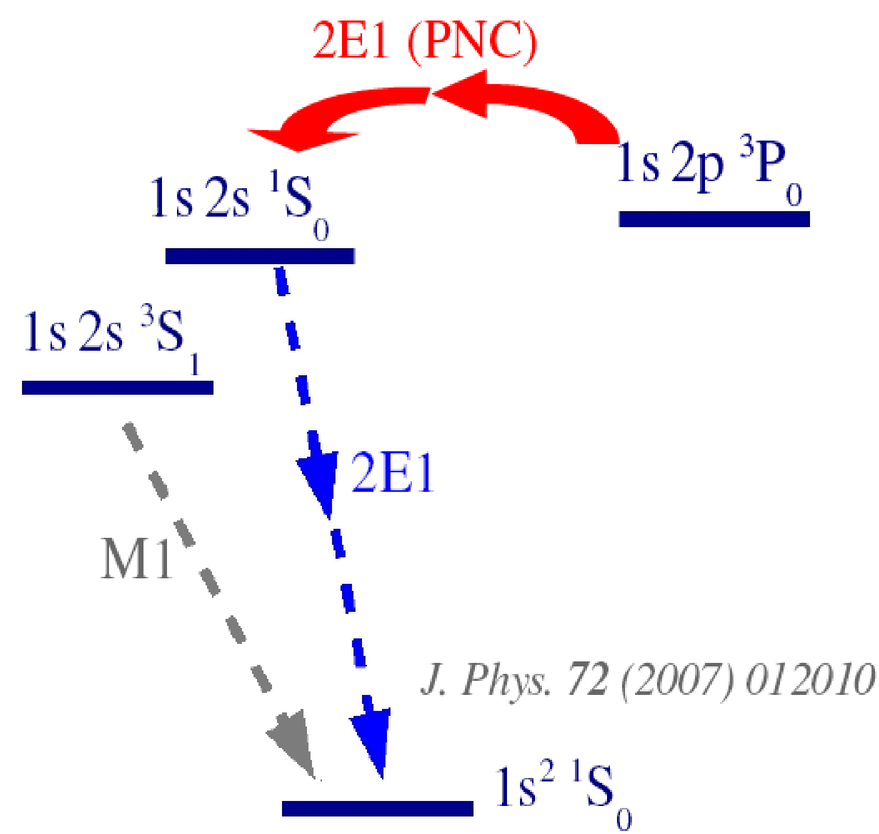
$$\eta = \frac{\langle \Psi_s | G_F / 2\sqrt{2} \ (1 - 4\sin^2\theta_w - N/Z)\rho_{el}\gamma_5 | \Psi_p \rangle}{E_s - E_p}$$

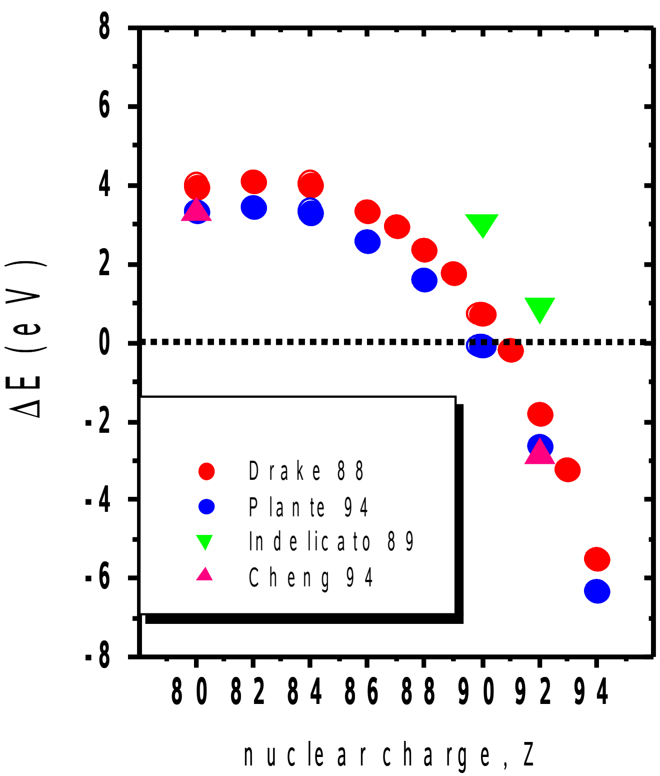


PNC studies with heavy, few-electron ions

-- enhancement of parity and time-reversal violating interactions

- Helium-like uranium U^{90+} is a perfect candidate for PNC studies:
  - Simple system (only 2 electrons)
  - Large electron-nucleus overlap
  - Small 2^1S_0-2^3P_0 energy splitting



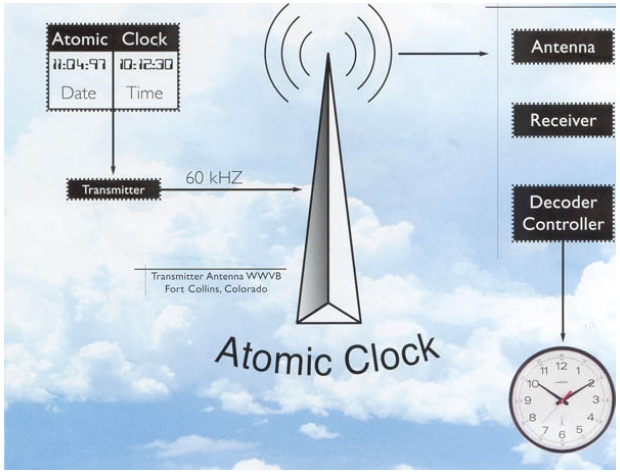


- Still many open questions:
  - How big is the 2^1S_0-2^3P_0 energy splitting?
  - How strong laser fields do we need?
  - What is the role of e-e interactions?

There is a need for accurate many-electron calculations !

- Analysis and interpretation of optical and x-ray spectra (astro physics)
- Diagnostics of astro physical and laboratory plasmas
- Development of UV/EUV light sources and lithograhpy
- Frequency standards and atomic clocks
- Spectroscopy on heavy and superheavy elements (actinides, transactinides)
- Isotope shifts and hyperfine structures
- Nonradiative (inner-shell) transitions and autoionization
- Ion recombination and photon emission
- Multi-photon processes
- …
- „Complete experiments"
- Parity nonconservation (PNC)
- Search for electric dipole moments

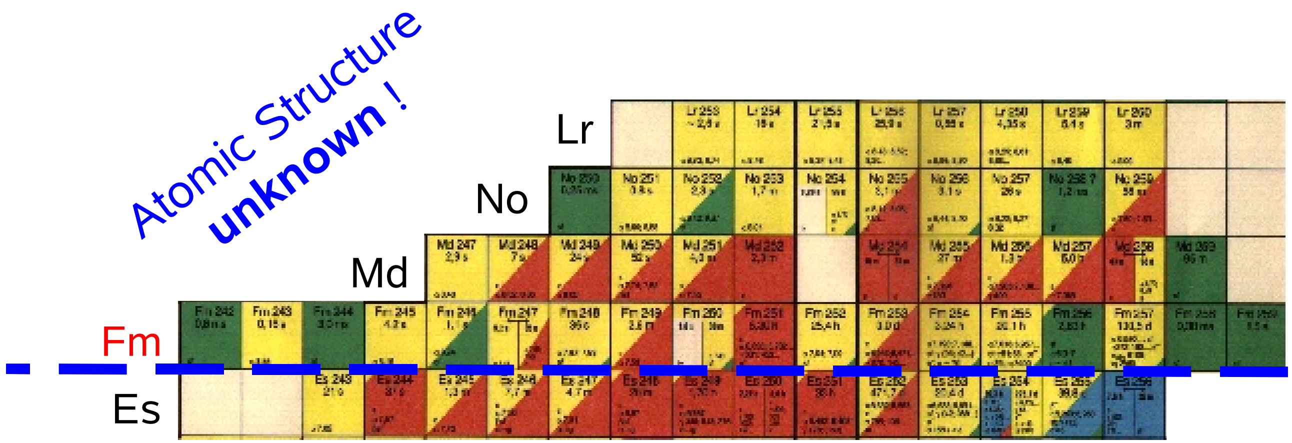
„many but not so accurate"



Spectroscopy of heavy and super-heavy elements

Atomic Levels → Atomic Physics : Atomic Structure, Ionization Potentials

Nuclear Physics : Nuclear Spins, Moments



Backe, Lauth, Sewtz (Mainz)

Theoretical challenges:

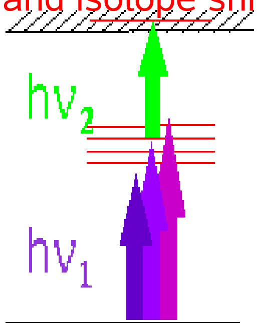
- strong relativistic and QED effects
- systems with open d- and f-shells
- many overlapping and nearly degenerate configurations
- large number of electron

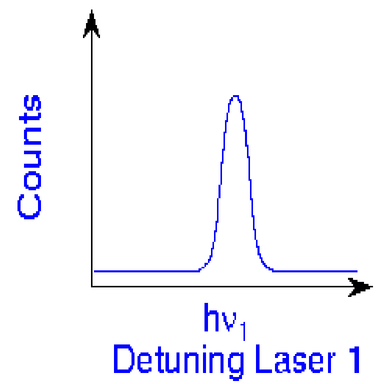
M. Sewtz et al., Phys. Rev. Lett. 90 (2003) 163002

Optical spectroscopy of atomic Fermium (Z = 100)

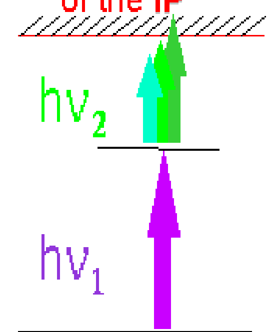
First observation and classification of atomic levels

Determination of hfs and isotope shifts





Determination of the IP



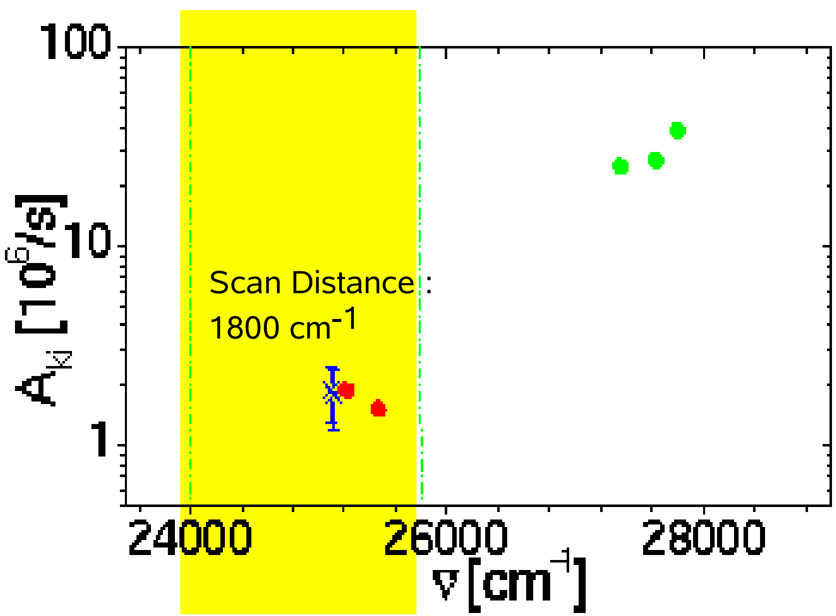
Atomic Physics:

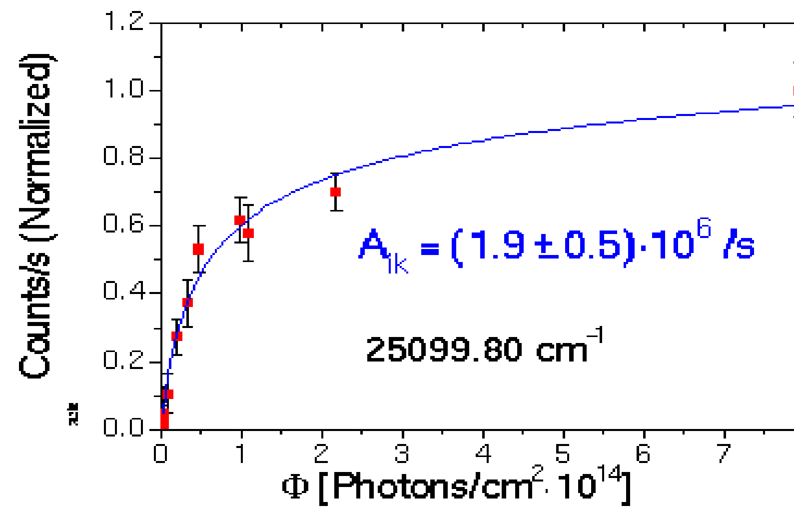
- Atomic Structure
- Ionization potentials

Nuclear Physics:

- Nuclear spins
- Moments
- Changes of charge radii

Theoretical request: Energies, lifetimes, transition rates





$5f^{12}$ 7s 7p, $J^P = 6^-, 5$ $\quad$ $^5G_{6,5}{}^o$

ES : $5f^{12}$ 7s 7p, $J^P = 6^-, 5^-, 7^-$ $\quad$ $^3H_{6,5,7}{}^o$ (?)

Breeding in High Flux Reactors

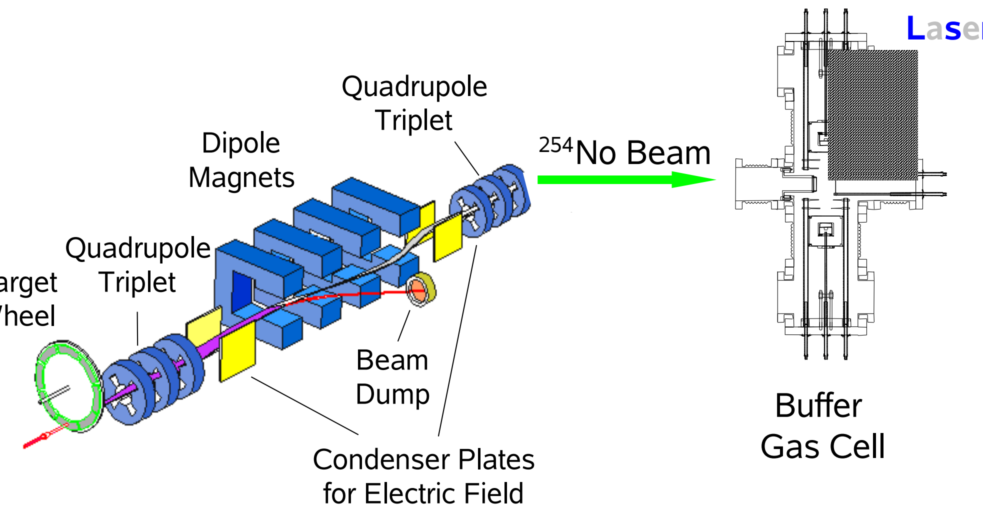
$N_{Fm} < 10^{12}$; ^{255}Fm; $t_{1/2} = 20.1$ h

M. Sewtz, W. Lauth et al., private commun. (2005)

Experimental proposal: Optical spectroscopy of nobelium (Z=102)

Ground-state configuration:

[Rn] $5f^{14}\,7s^2$



Low-lying excitations:

[Rn] $5f^{14}\,7s\,7p$

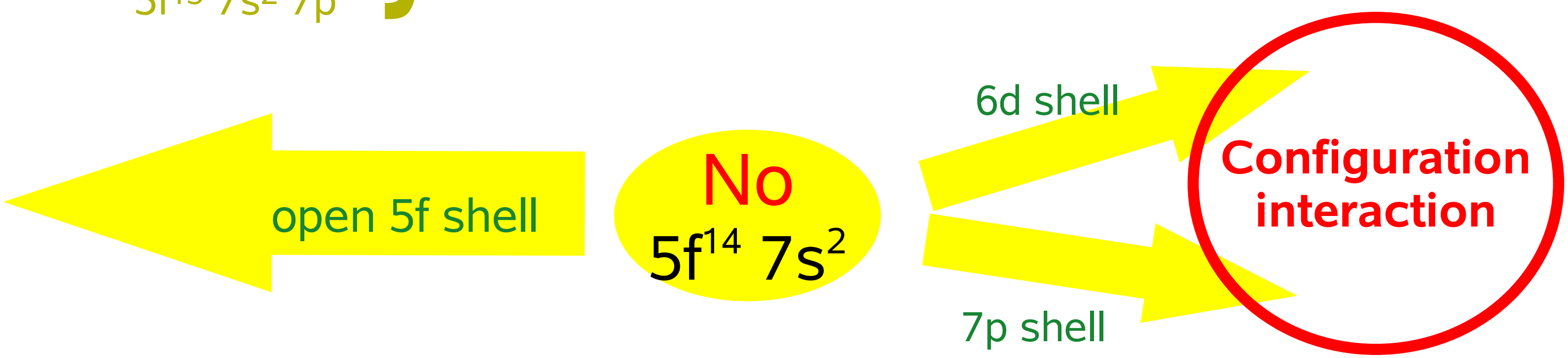
$5f^{13}\,6d\,7s^2$

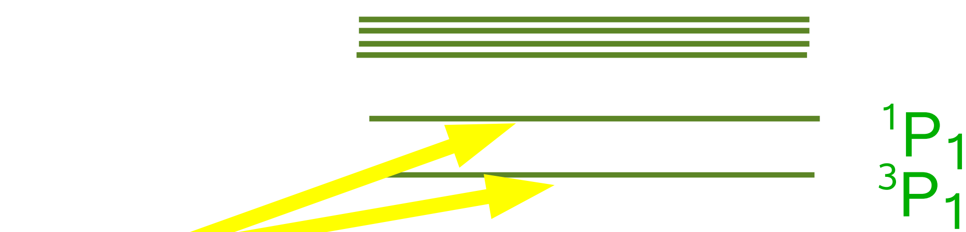
$5f^{14}\,6d\,7s$

$5f^{14}\,7s\,8s$

$5f^{13}\,7s^2\,7p$

} 2 ... 5 eV





	Level	$^{2S+1}L_J$	Excitation energy (eV) Model I	Model II
No	$5f^{14}7s7p$	$^3P_1$	2.34	2.60
	$5f^{14}7s7p$	$^1P_1$	3.49	3.36

S. Fritzsche, EJP D33, 15 (2005)

Zhou & Froese Fischer., Phys. Rev. Lett. 88 (2002) 183001.

Low-lying resonances of (super-) heavy elements

… for lutetium (Z=71) and lawrencium (Z=103)

TABLE I. The transition energies in cm^{-1} of $nd\ ^2D_{3/2} - (n+1)p\ ^2P^o_{1/2,3/2}$ and the size of CSF expansions for Lu ($n = 5$) and Lr ($n = 6$).

Expansion	$^2D_{3/2} - ^2P^o_{1/2}$	$^2D_{3/2} - ^2P^o_{3/2}$	CSF ($^2D_{3/2}/^2P^o_{1/2}/^2P^o_{3/2}$)
	Lu		
VV + CV($4f^{14}$)	3989	7276	4354/2071/3813
VV + CV($5p^64f^{14}$)	8004	11 483	5600/2764/5073
VV + [(CV + CC)($5p^64f^{14}$)]	3857	7130	128 763/36 974/100 277
VV + [(CV + CC)($4d^{10}5s^25p^64f^{14}$)]	4186	7462	305 717/87 241/236 554
RCC [7]	3828	7140	
DFT [10]	3862		
Exp.	4136	7476	
DHF Breit Correction	87	53	
DHF Breit & QED Correction	76	43	
	Lr		
VV + CV($5f^{14}$)	−1298	9137	3659/1842/3338
VV + CV($6p^65f^{14}$)	1339	12 761	4708/2495/4495
VV + [(CV + CC)($6p^65f^{14}$)]	−1953	6469	125 325/37 333/97 500
VV + [(CV + CC)($5d^{10}6s^26p^65f^{14}$)]	−1127	7807	330 252/95 969/246 376
RCC	−1388	6960	
RCC with Breit	−1263	7010	
DHF Breit Correction	97	4	
DHF Breit & QED Correction	59	−26	

RCC: Eliav et al.., Phys. Rev. A52 (1995) 291; DFT: Vosko & Chevary, J. Phys. B26 (1993) 873

Zhou & Froese Fischer., Phys. Rev. Lett. 88 (2002) 183001

Low-lying resonances of (super-) heavy elements

… oscillator strengths in different gauges

TABLE II. The oscillator strengths of $nd\ ^2D_{3/2} - (n+1)p\ ^2P^o_{1/2,3/2}$ for Lu ($n = 5$) and Lr ($n = 6$).

	$^2D_{3/2} - {}^2P^o_{1/2}$			$^2D_{3/2} - {}^2P^o_{3/2}$		
Expansion	gf_L	gf_V	Scaled gf_L	gf_L	gf_V	Scaled gf_L
Lu						
VV + CV($4f^{14}$)	0.0304	0.0582	0.0315	0.0111	0.0219	0.0114
VV + CV($5p^6 4f^{14}$)	0.0511	0.1552	0.0264	0.0144	0.0467	0.0094
VV + [(CV + CC)($5p^6 4f^{14}$)]	0.0908	0.3835	0.0974	0.0322	0.0856	0.0337
VV + [(CV + CC)($4d^{10} 5s^2 5p^6 4f^{14}$)]	0.1043	0.3345	0.1031	0.0354	0.0742	0.0355
Lr						
VV + CV($5f^{14}$)	−0.0162	−0.0076		0.0210	0.0313	
VV + CV($6p^6 5f^{14}$)	0.0144	0.2359		0.0227	0.0839	
VV + [(CV + CC)($6p^6 5f^{14}$)]	−0.0624	−0.0002		0.0414	0.0867	
VV + [(CV + CC)($5d^{10} 6s^2 6p^6 5f^{14}$)]	−0.0378	−0.0024		0.0519	0.0685	

Good accuracy of the (atomic) energies is a necessary, but not a sufficient criterion !

S. Fritzsche, JESRP 114-116 (2001) 1155; Phys. Scr. T100 (2002) 46

RATIP

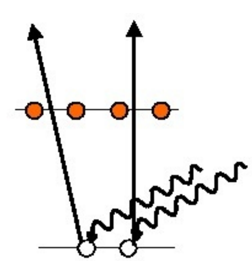
Relativistic Atomic Transition and Ionization Properties

(CPC library)

$$\psi_{\alpha}(P\,J\,M) = \sum_{r}^{n_c} c_r(\alpha)\, \left|\gamma_r\, P\,J\,M\right\rangle$$

Many-electron basis (wave function expansions)

- Construction and classification of N-particle Hilbert spaces
- Shell model: Systematically enlarged CSF basis
- Interactions
  - Dirac-Coulomb Hamiltonian
  - Breit interactions + QED
  - Electron continuum; scattering phases
- Coherence transfer and Rydberg dynamics



Relativistic CI wave functions including QED estimates and mass polarization

RELCI, CPC 148 (2002) 103

LSJ spectroscopic notation from jj-coupled computations

LSJ, CPC 157 (2003) 239

Auger rates, angular distributions and spin polarization; level widths

AUGER

Photoionization cross sections and (non-dipole) angular parameters

PHOTO

Radiative and dielectronic recombination; angle-angle correlations

...

S. Fritzsche, JESRP 114-116 (2001) 1155; Phys. Scr. T100 (2002) 46

RATIP

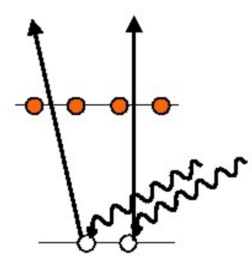
Relativistic Atomic Transition and Ionization Properties

(CPC library)

$$\psi_\alpha(PJM) = \sum_r^{n_c} c_r(\alpha) \left|\gamma_r P \right.$$

Many-electron basis ... nsions)

- Construction a... rticle Hilbert spaces
- Shell ... larged CSF basis
- In...
  - ... Hamiltonian
  - ... ctions + QED
  - E... on continuum; scattering phases
- Coherence transfer and Rydberg dynamics



Relativistic C... functions including ... tes and mass ...

R...

... pic notation ... ed ... ions

CPC 157 (2003) 239

Auger rates, angular distributions and spin polarization; level widths

AUGER

Photoionization cross sections and (non-dipole) angular parameters

PHOTO

Radiative and dielectronic recombination; angle-angle correlations

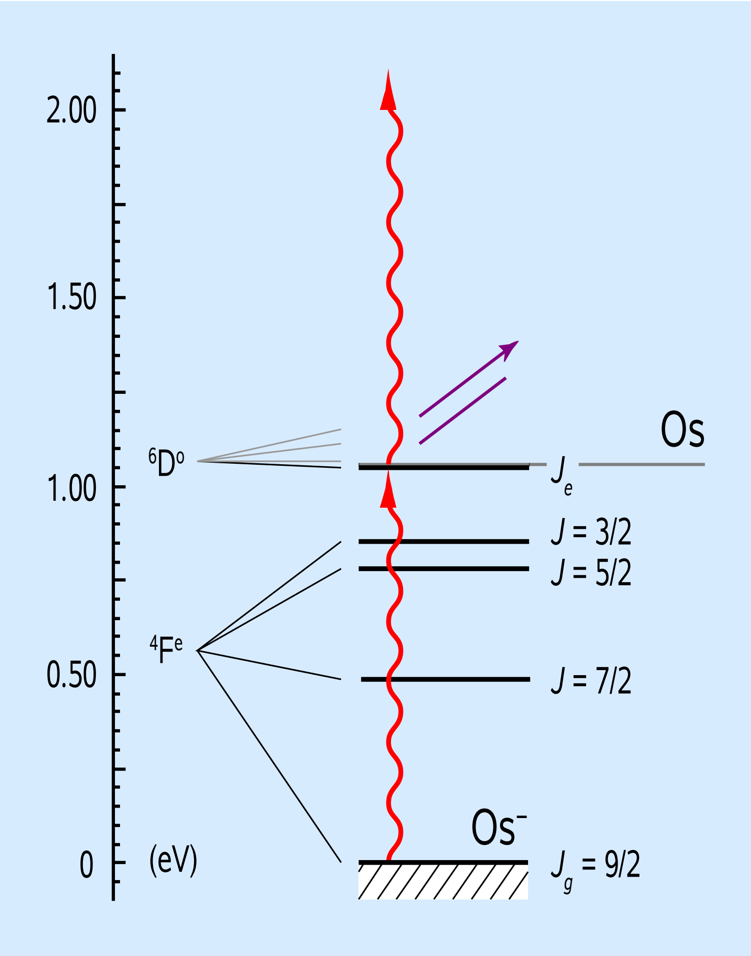
...

Utilized in more than 130 case studies during the last decade;

the offer to consider other systems ... and properties

AG A. Kellerbauer *et al.*
MPIK Heidelberg

HFS & Isotope shift measurements for Os⁻



Typical spectrum $^{192}Os^-$:

Signal: Neutral atoms as function of laser frequency

$\Rightarrow$ ν = 257.831190(30) THz
λ = 1162.74706(14) nm

U. Warring *et al.*, Phys. Rev. Lett. **102** (2009) 043001

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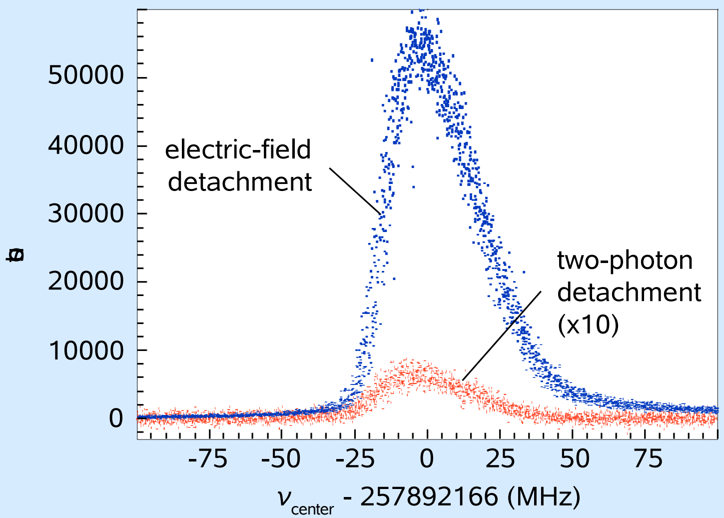

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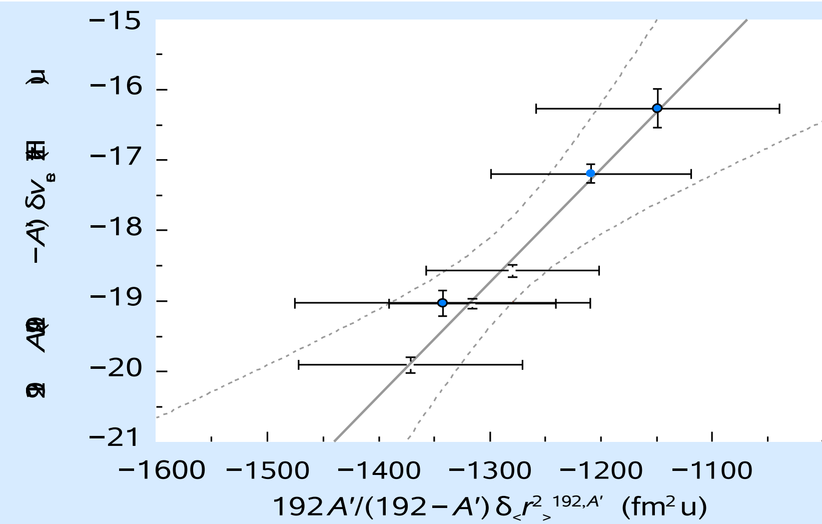
$$M_{\mathrm{NMS}} = \nu_0 \frac{m_e}{1\mathrm{u}} = 0.14\ \mathrm{THz\ u}$$

Transition for all stable isotopes:



Experiment: M_{SMS} = 2(11) THz u
F = 16(9) GHz fm⁻²

preliminary

Theory: M_{SMS} = 4.9 THz u
F = 12.4 GHz fm⁻²

A. Fischer *et al.*, Phys. Rev. Lett. **104** (2010) 073004

Atomic and heavy-ion theory @ SPARC collaboration

-- Recent developments and progress

Key topics of this collaboration:

- Test of quantum electrodynamics in strong fields for light and high-Z ions

  ... two-times Green's functions; 2-photon, 3-photon (??) diagrams; differences with experiment especially for the HFS; systematic QED approach in the MBPT framework
- Collision & capture dynamics in strong fields at relativistic energies

  ... U28+ electron loss; few-body dynamics; polarization effects; multi-electron processes
- Atomic physics techniques applied to nuclear physics
- Multi-photon processes
- Antiproton physics
- Test of fundamental interactions and symmetries beside of QED
- Interaction of ions with intensive (laser) light

  ... dynamics in strong fields, high-harmonics generation

Atomic and heavy-ion theory @ SPARC collaboration

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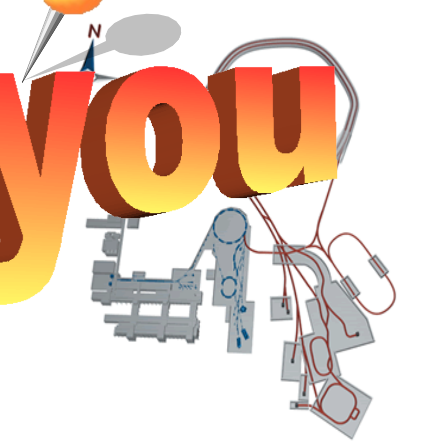
- Interaction of ions with i... nsiv... r) ...
  ... dynamics in strong fields ... h-ha... on... ge... n...

Thank you

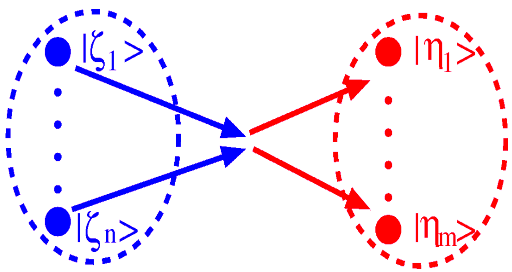


Time-independent density matrix theory

Initial state

$(t \to -\infty)$

$\hat{\rho}_i$



Final state

$(t \to +\infty)$

$\hat{\rho}_f$

$\hat{S}$ - scattering operator

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

initial-state density matrix

transition amplitudes

$$\langle \eta_1 \ldots \eta_m | \hat{\rho}_f | \eta'_1 \ldots \eta'_m \rangle = \sum_{\xi_1, \xi_2 \ldots} \langle \xi_1 \ldots \xi_n | \hat{\rho}_i | \xi'_1 \ldots \xi'_n \rangle \langle \eta_1 \ldots \eta_n | \hat{R} | \xi_1 \ldots \xi_n \rangle \langle \eta'_1 \ldots \eta'_n | \hat{R} | \xi'_1 \ldots \xi'_n \rangle^+$$

Measurement of physical properties:

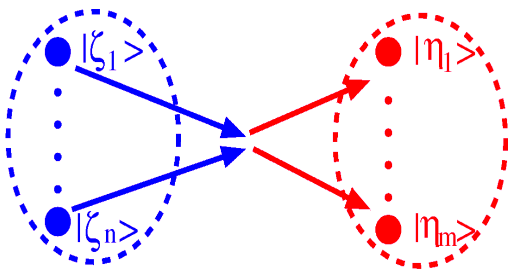
- 'detector operator' describes the experimental setup: $\hat{P} = |\epsilon><\epsilon|$
- probability to get a 'click' at the detectors:

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

Time-independent density matrix theory

$\hat{S}$ - scattering operator

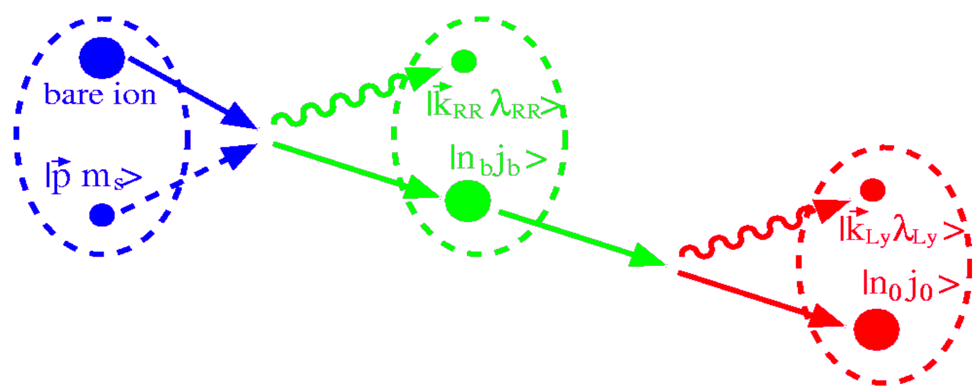
Initial state $(t \rightarrow -\infty)$ $\hat{\rho}_i$



Final state $(t \rightarrow +\infty)$ $\hat{\rho}_f$

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

Great advantage !



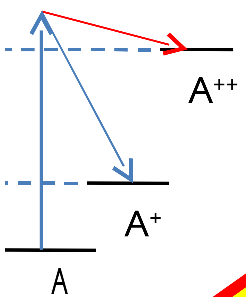
Using the density matrix, the system can be accompanied through several steps of the interaction which may lead to the emission of photons, electrons, ...

Weak- vs. strong-field (light-matt… nteractions

Weak-field photoexcitation and ioniz…

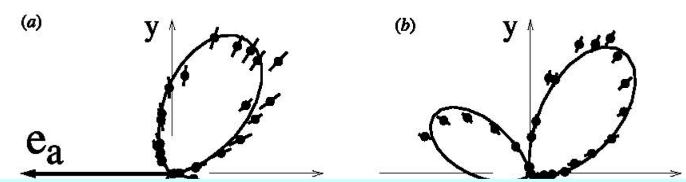
cross sections, angular distributions … eriments', …;

for example: single-photon d…



He…

He (Briggs and Schmidt, 2000)



excess e…

Different mechanisms: shal…

Domain of precision physics

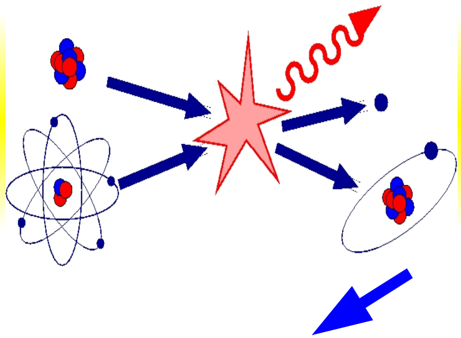
Role of e-e correlations;

parity and … reversal violating interactions.

Current interests and challenges

- Atomic processes and multipole mixing in strong fields
- Multi-electron coincidences (magnetic bottle)
- Second-order emission processes
- Creation and control of entangled photon pairs
- Parity non-conservation and time-reversal violation
- Studying fundamental constants (time variations, ...)

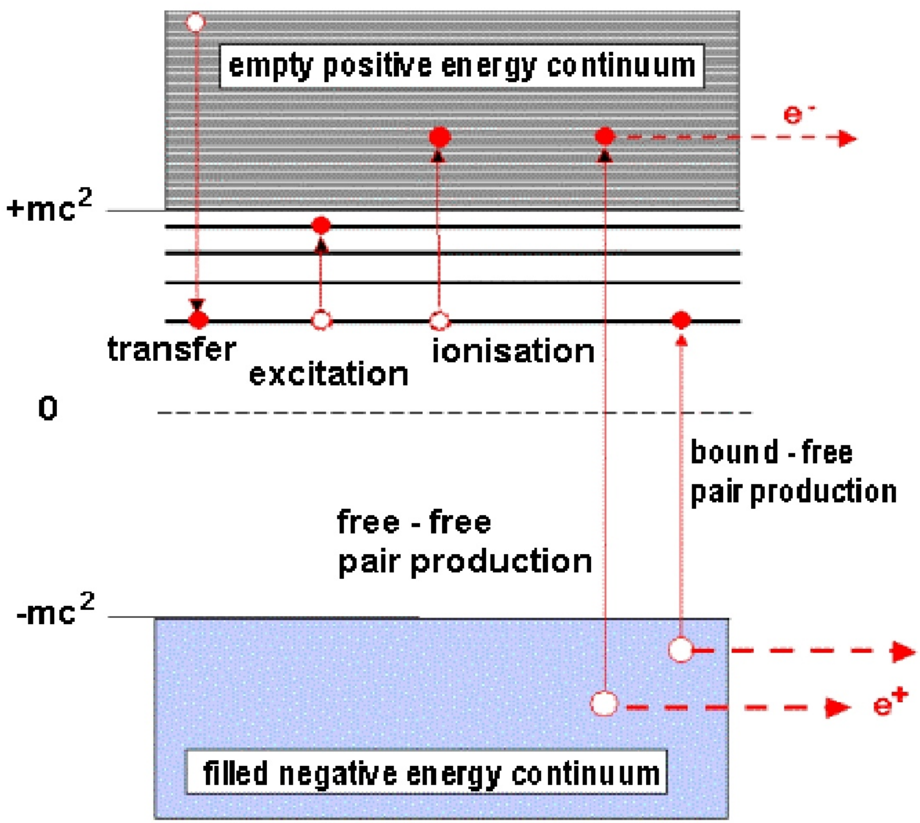
Ion-Atom Stöße



schnelle Stöße

„Einteilchenbild“

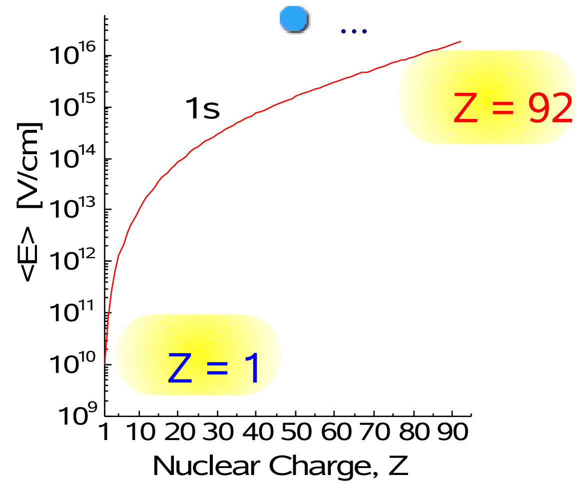
- Hochgeladene Ionen sind sehr gut geeignet, um die elementaren Prozesse in (extrem) starken Feldern zu verstehen.



langsame Stöße

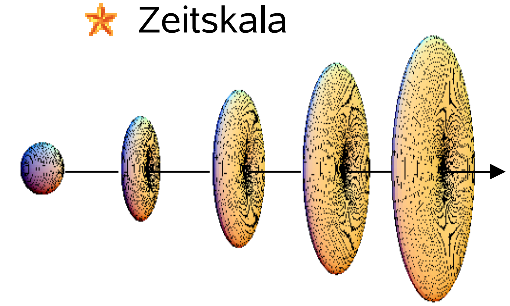
„Vielteilchenbild“

- Besseres Verständnis der Vielteilchendynamik erforderlich.
  - Verstärkung des REC bei langsamen Ionen (!)
  - Resonante (dielektronische) Rekombination.
  - Abbremsen und Einfang in Fallen.
  - Wichtig für Ionen-Oberflächen Prozesse.
  - ...

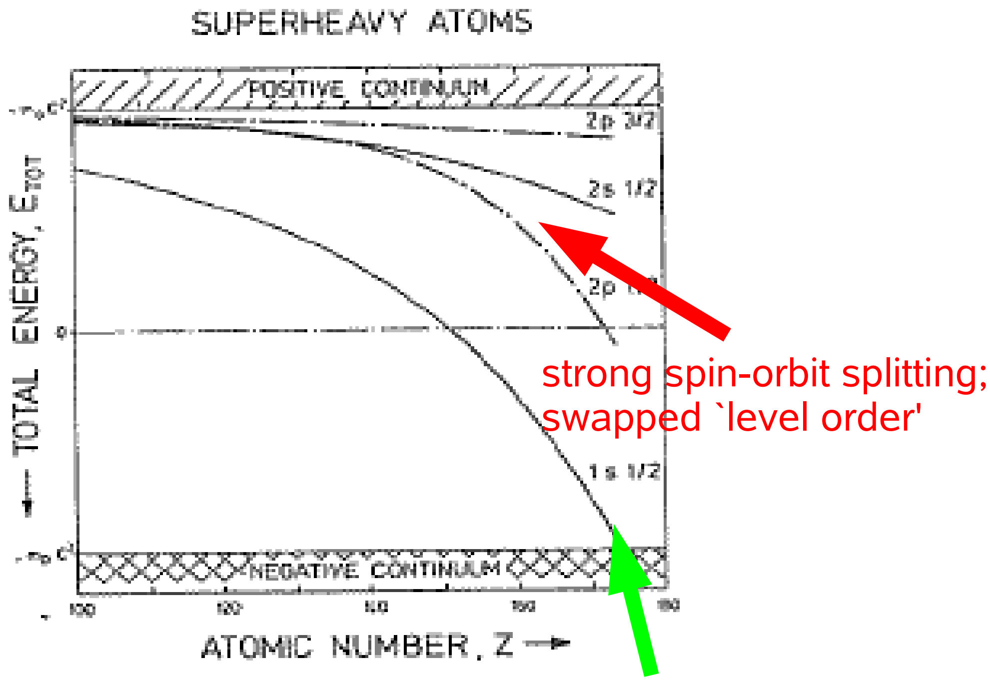


Ionen sind variabel:

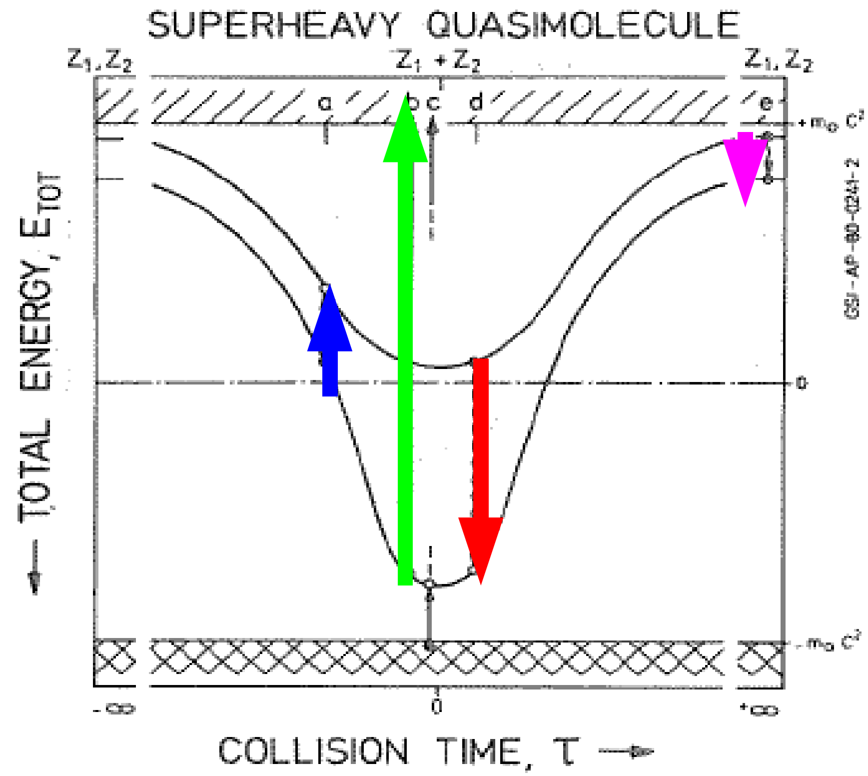
- Feldstärke
- Zahl der Elektronen
- Zeitskala



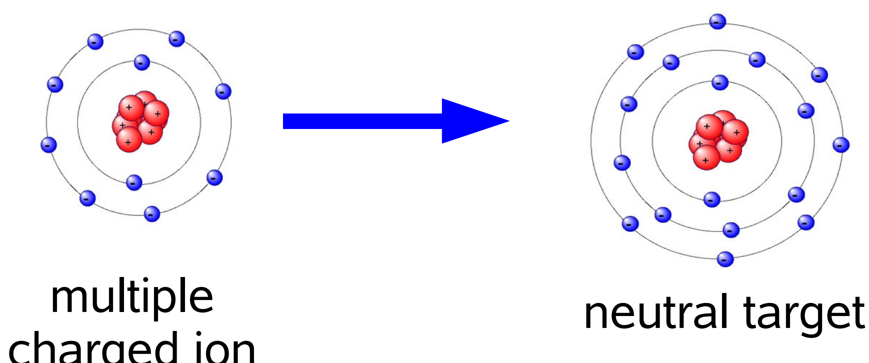
Supercritical fields in ion-atom collisions



Fricke & Soff (1977)



Mokler & Liesen (1982)

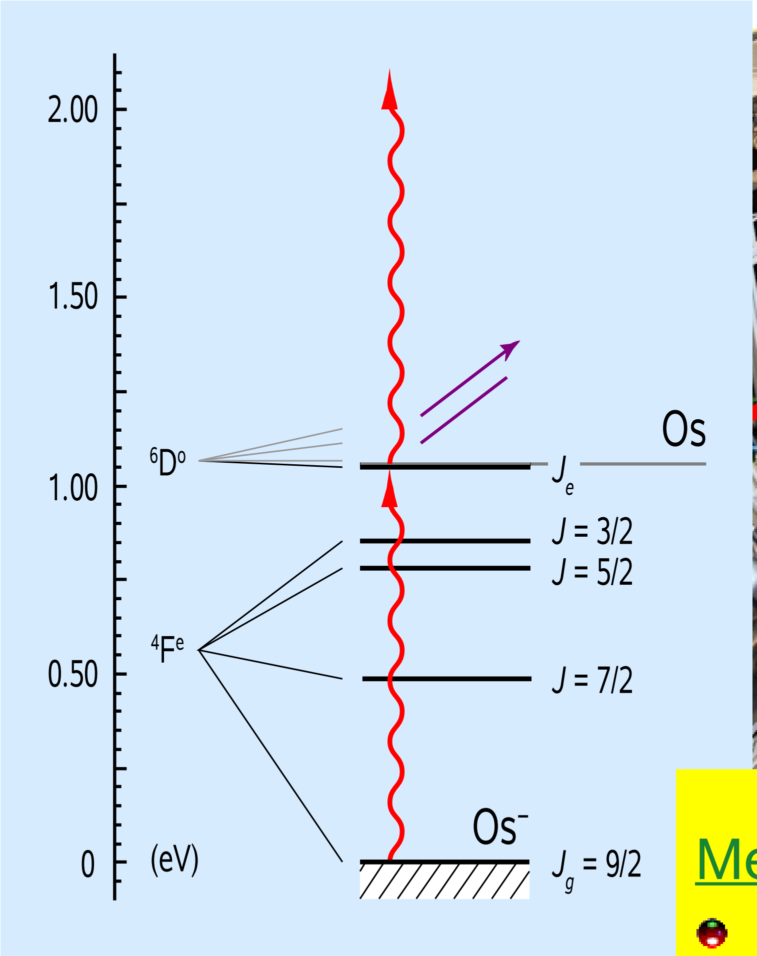


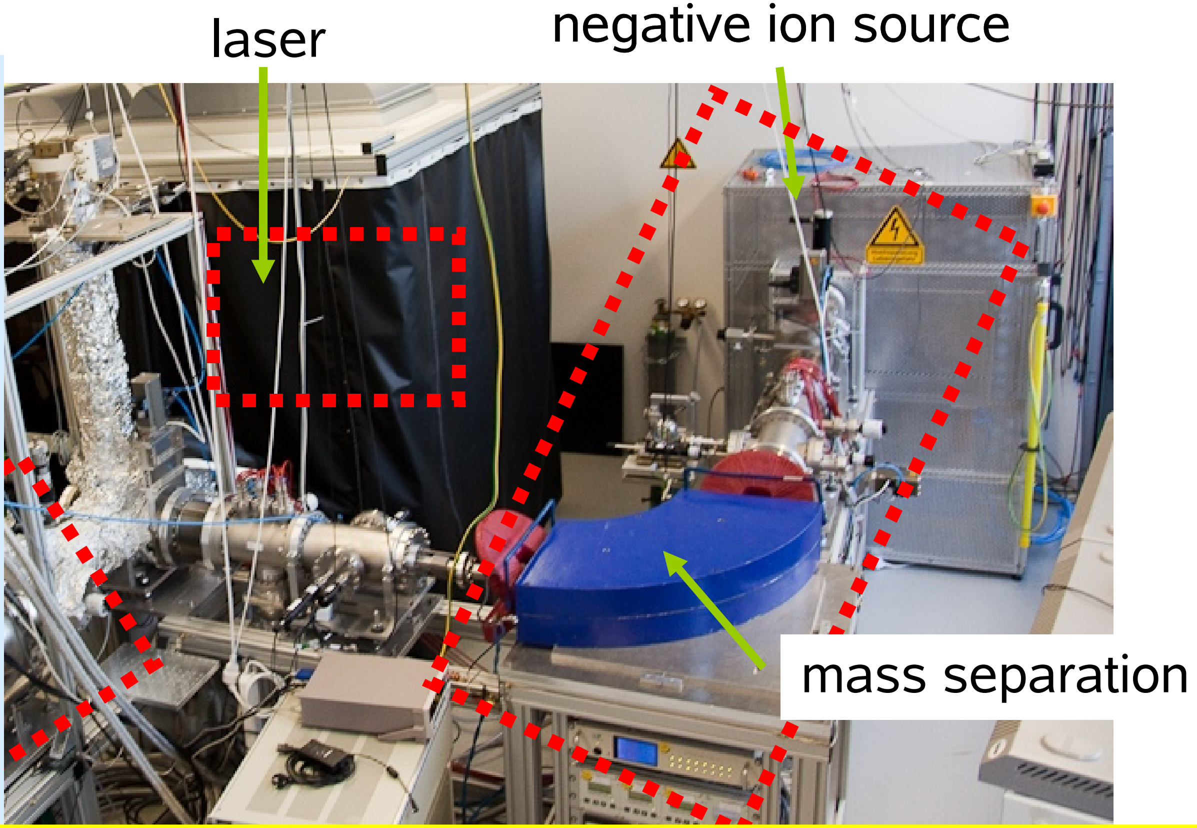
Processes during the collision:

- excitation into higher shells
- ionization (δ-electrons)
- MO radiation
- characteristic x-rays

Laser spectroscopy of Os⁻

@ MPI-K in Heidelberg (A. Kellerbauer *et al.*)





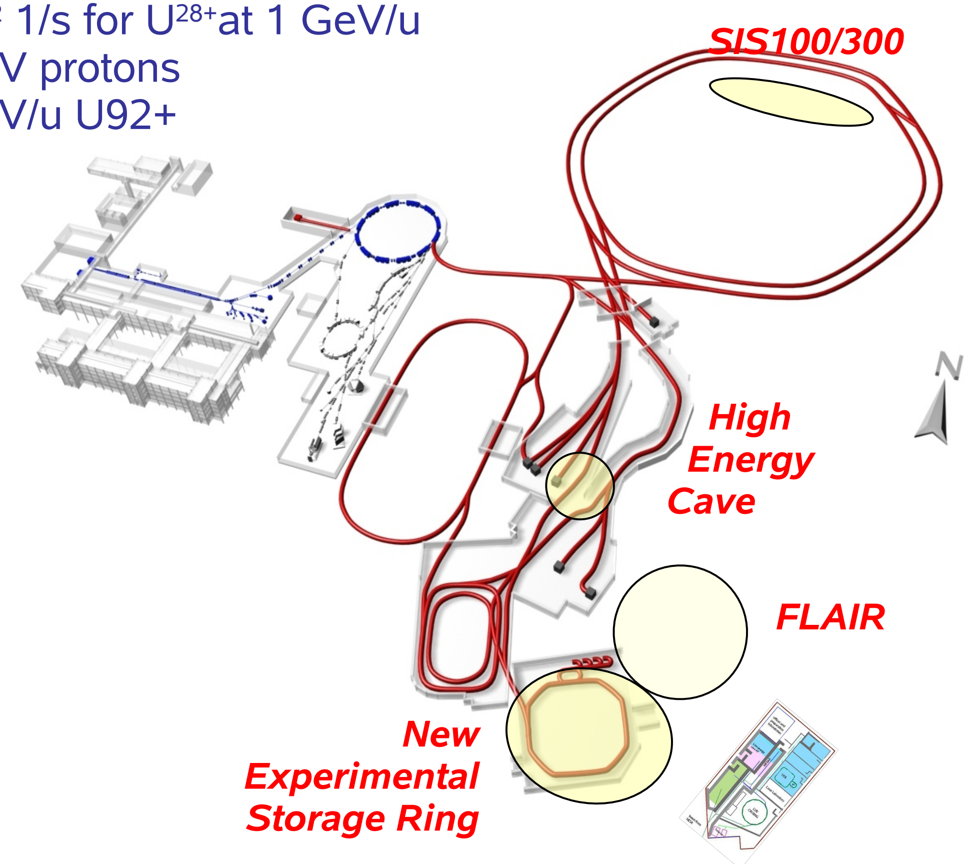
Measurement principle:

- Laser frequency is scanned around transition frequency
- Excited state is detached by electric field

Neutrals detected on forward MCP

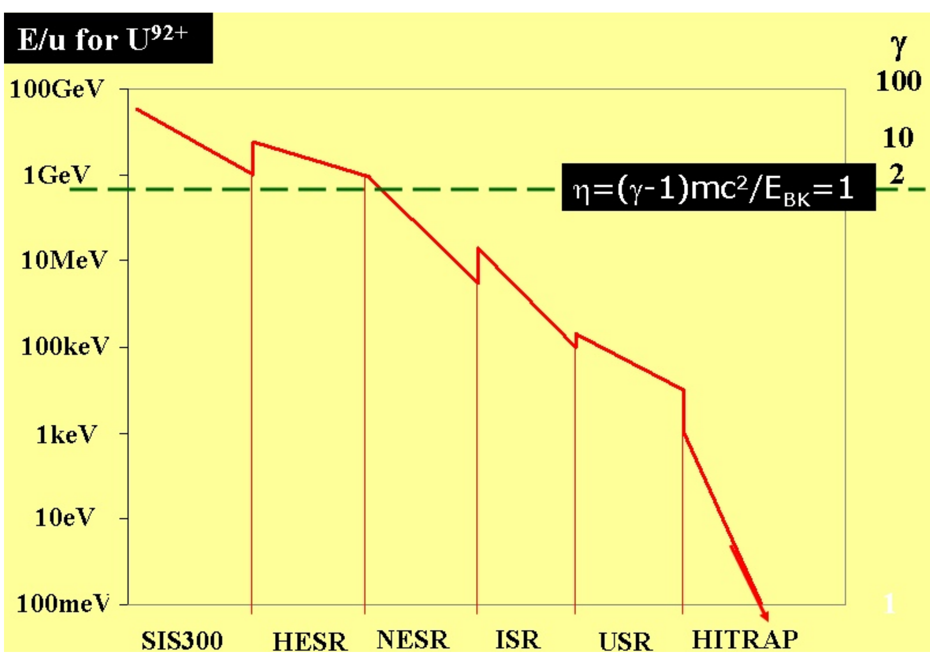
SPARC-Collaboration @ FAIR

1×10^{12} 1/s for U^{28+} at 1 GeV/u
90 GeV protons
34 GeV/u U92+



Stored and Cooled

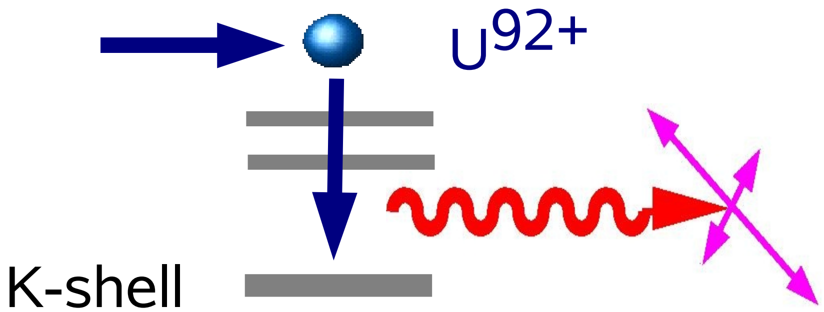
- Highly-Charged Ions and Exotic Nuclei from Rest to Relativistic Energies
- Intense Beams of Radioactive Isotopes
- Virtual Photon Sources at X- and γ-Ray Energies
- XUV Energies via Lorentz Boost of optical wavelengths

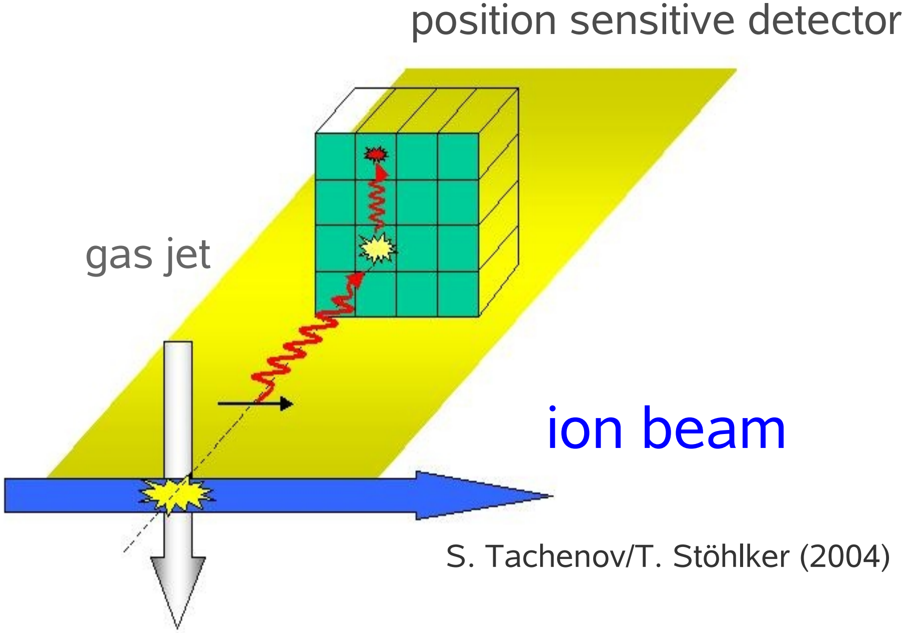


... with Novel Instrumentation

- Ultracold Electron-Beam Target
- High Resolution X-Ray and Electron Spectrometers
- In-Ring Recoil Momentum Microscope
- Highly Intense Laser Beams
- Traps

Polarization of the K-shell REC photons





S. Tachenov/T. Stöhlker (2004)

- Compton effect: Klein-Nishina formula

$$\frac{d\sigma}{d\Omega} \propto \frac{\hbar\omega}{\hbar\omega'} + \frac{\hbar\omega'}{\hbar\omega} - 2\sin^2\theta\cos^2\phi$$

polarization dependence