Angular distributions of x-ray photons from excited ionic states with unresolved fine structure

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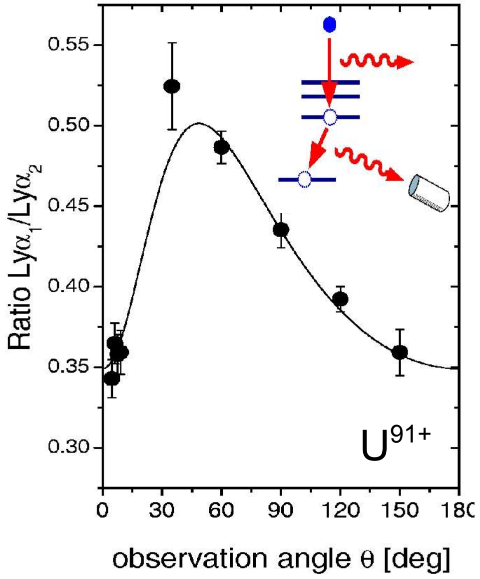
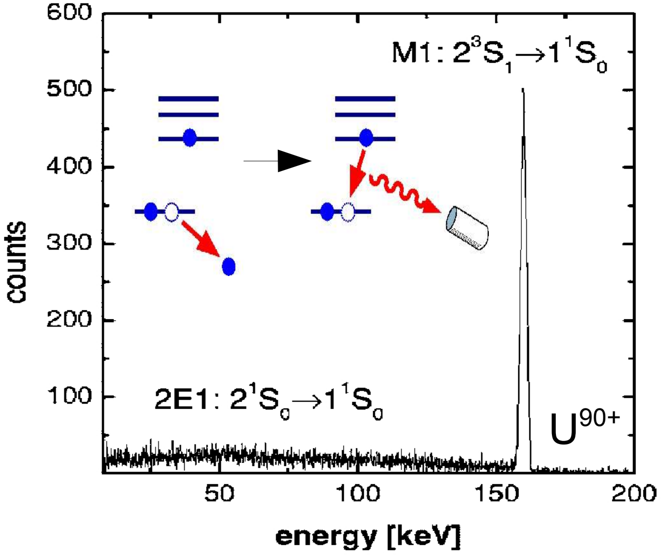
X-ray spectroscopy of highly-charged ions

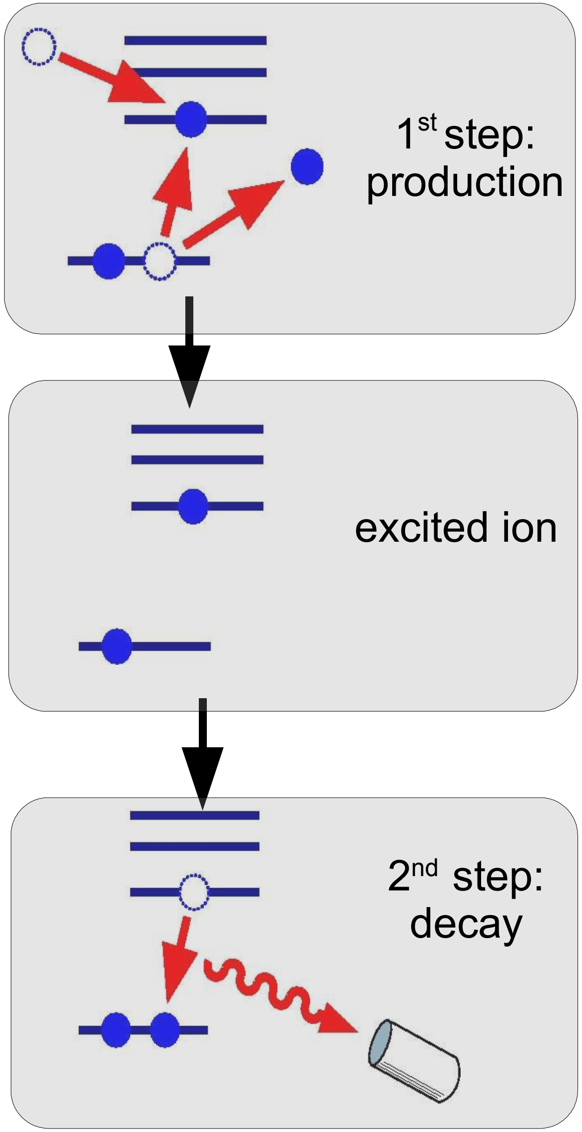
- A large number of studies have been performed at the GSI facility to explore projectile x-ray emission following ion-atom collisions.
- Analysis of the subsequent x-ray emission provides important information on the structure and dynamics of highly-charged ions.



$Ly\alpha_1$ emission following REC
(multipole mixing in HCI)



Kα emission following K-shell ionization
(selective population of 1s2s states)



1st step: production

excited ion

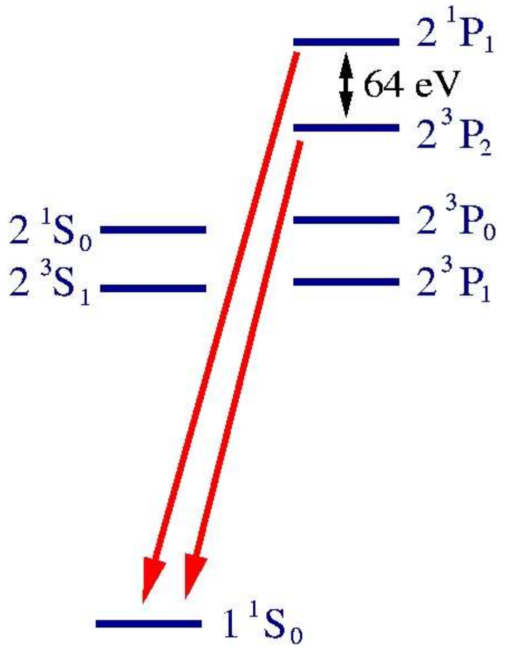
2nd step: decay

Th. Stöhlker *et al.*, PRL **79** (1997) 3270
A.S. *et al.*, PRL **88** (2002) 153001

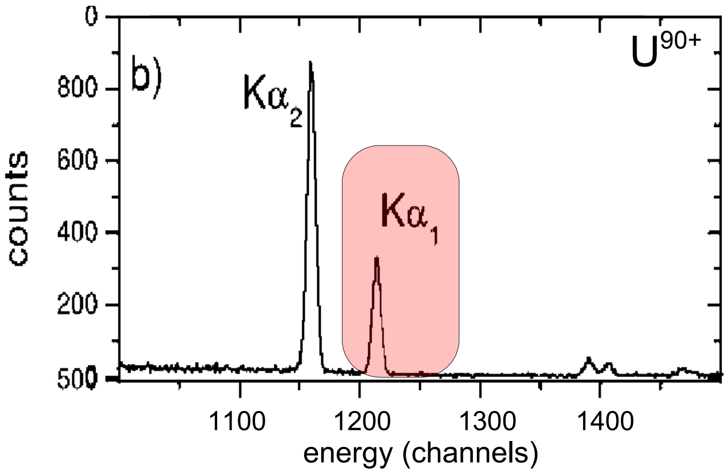
J. Rzadkiewicz *et al.*, PRA **74** (2006) 012511

X-ray spectroscopy of unresolved lines

- Ideal situation for x-ray spectroscopy is when we can resolve individual transitions.
- Quite often, however, two (or more) characteristic lines can not be resolved by available x-ray detectors.
- Only “averaged” information about the subsequent decay is available.



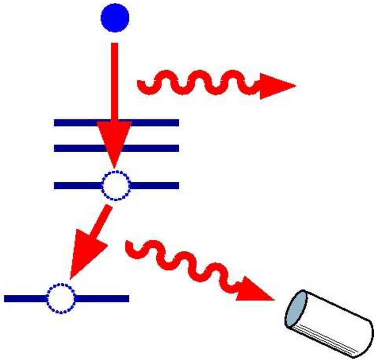
- How the results of the measurements are affected by such an “averaging”?
- Can we still learn some information from the “averaged” properties (intensities, <u>angular distributions</u>, polarization....)?



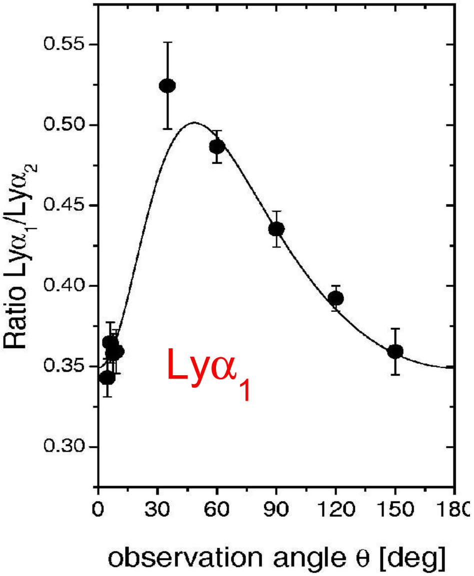
Characteristic x-ray emission following REC

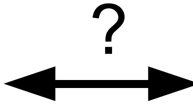
- Most pronounced example: angular analysis of the $K\alpha_1$ radiation following REC into 1s $2p_{3/2}$: J=1,2 states of uranium projectiles.

- Qualitatively different angular behaviour of the $K\alpha_1$ and $Ly\alpha_1$ transitions has been found.

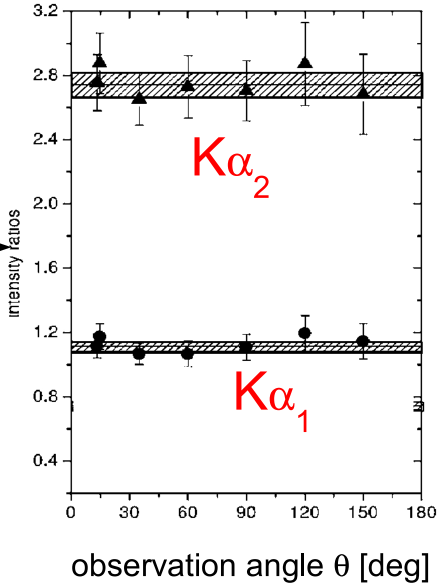


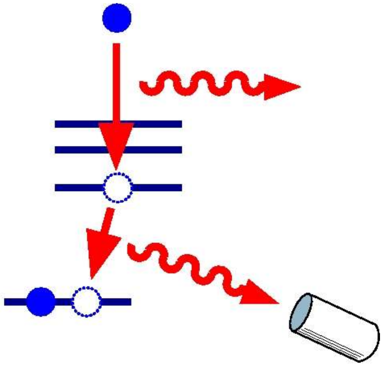
$Ly\alpha_1$ radiation is strongly anisotropic





$K\alpha_1$ radiation is almost isotropic





Th. Stöhlker *et al.*, PRL **79** (1997) 3270
A. Gumberidze *et al.*, Hyperfine Int. **146** (2003) 133
X. Ma *et al.*, PRA **68** (2003) 042712

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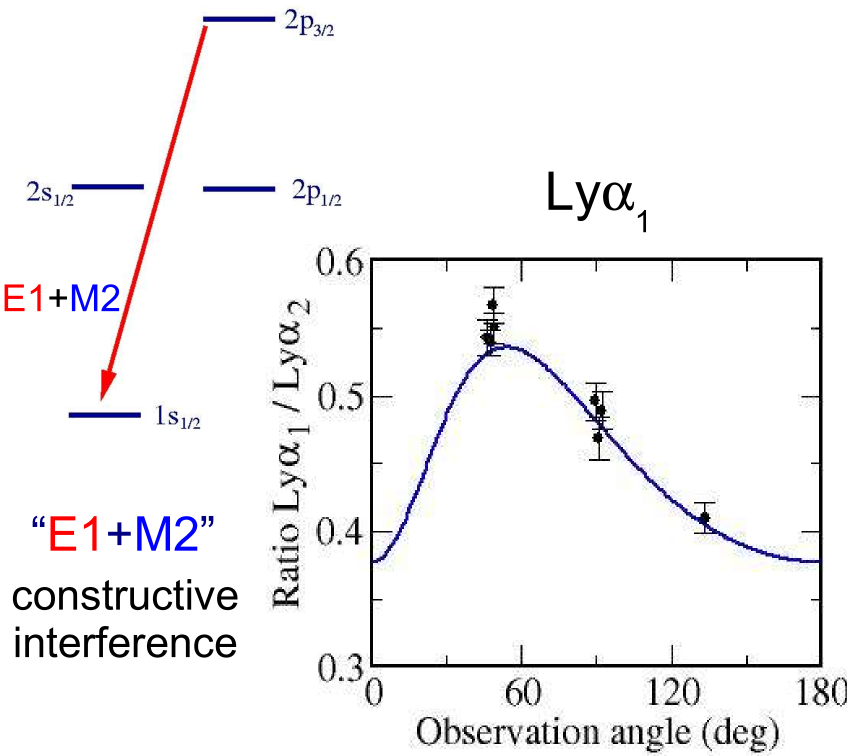
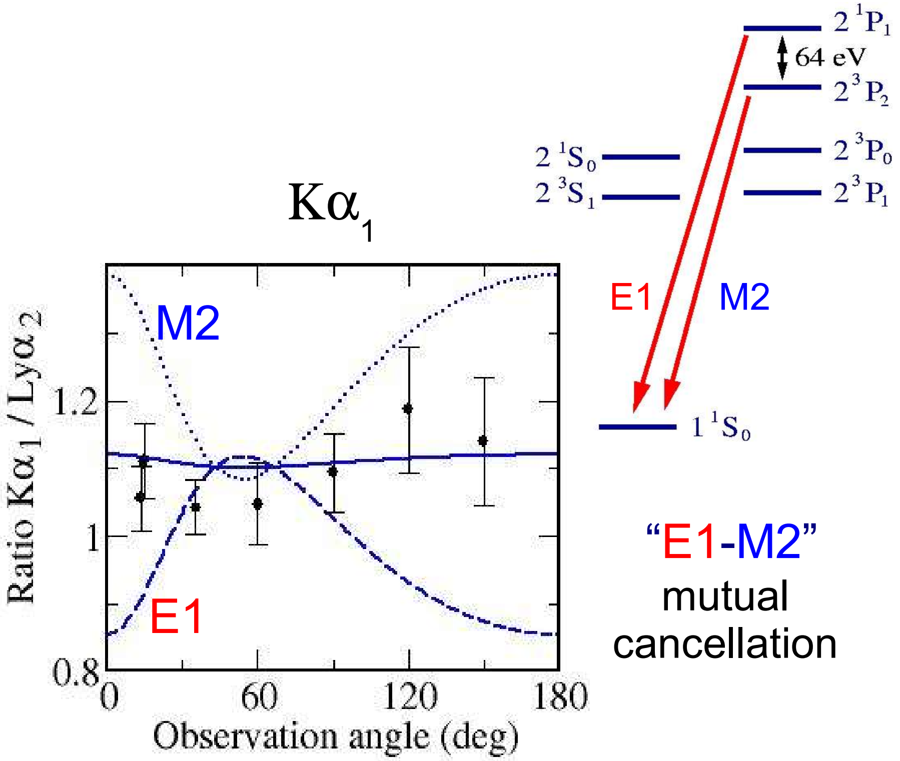
Lyα_1 vs. Kα_1: theoretical analysis

- Angular distribution of the Lyα_1 as well as the Kα_1 decay: $W(\theta) \sim 1 + \beta_2 P_2(\cos\theta)$



"E1+M2"
constructive interference

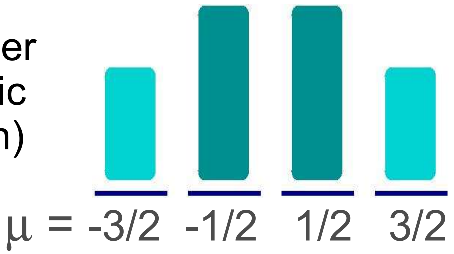


"E1-M2"
mutual cancellation

$$\beta_2 = \frac{1}{2} A_2(j=3/2)\, f(E1, M2)$$

$$\beta_2 = N_{J=1} \frac{1}{\sqrt{2}} A_2(J=1) - N_{J=2} \sqrt{\frac{5}{14}} A_2(J=2)$$

alignment parameter
(describes magnetic
sublevel population)



weights

E. Drukarev *et al.*, PRA **74** (2006) 022717
A. S. *et al.*, PRA **74** (2006) 052710

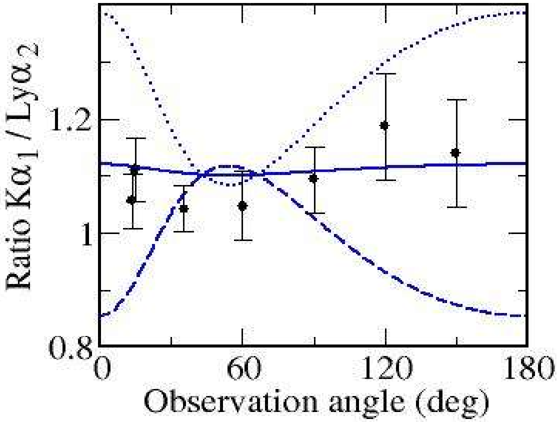
Kα_1 angular distribution: Independent Particle Model

- Anisotropy parameter of the Kα_1 radiation:

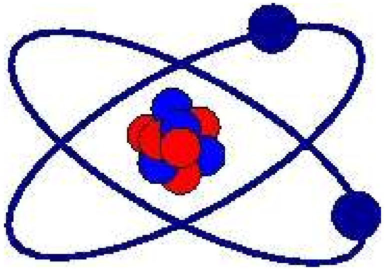
$$\beta_2 = N_{J=1}\frac{1}{\sqrt{2}}A_2(J=1) - N_{J=2}\sqrt{\frac{5}{14}}A_2(J=2)$$

- ... but: too many parameters! It is difficult to extract information from the Kα_1 measurements.

$$W(\theta) \sim 1 + \beta_2 P_2(\cos\theta)$$



- To simplify angular analysis of the Kα_1 radiation one may consider theoretical treatment with the framework of Independent Particle Model (IPM).

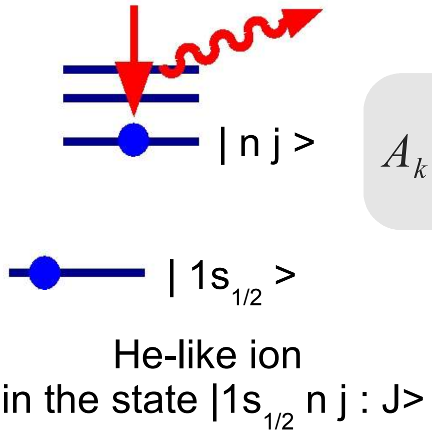


$$<\boldsymbol{r}|\alpha P J M> = \frac{1}{\sqrt{2}}\sum_{\mu_1\mu_2}\langle j_1\mu_1 j_2\mu_2|J M\rangle \begin{vmatrix}\phi_{j_1\mu_1}(\boldsymbol{r}_1) & \phi_{j_2\mu_2}(\boldsymbol{r}_1)\\ \phi_{j_1\mu_1}(\boldsymbol{r}_2) & \phi_{j_2\mu_2}(\boldsymbol{r}_2)\end{vmatrix}$$

- We assume electron-electron interaction to be much weaker when compared with electron-nuclear one.

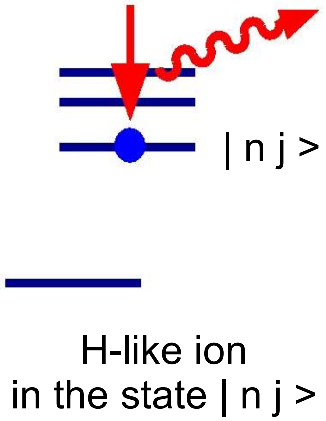
Alignment parameters and relative populations of He-like ions

- By making use of IPM and after some angular momentum algebra we may find a relation between alignment of one-electron and many-electron ions:



He-like ion
in the state $|1s_{1/2}\ n\ j : J>$

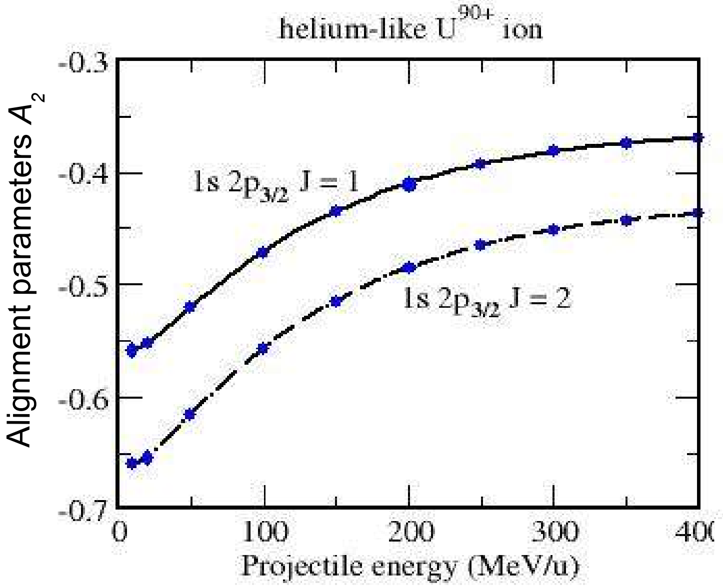
$$A_k(J)=\sqrt{(2j+1)(2J+1)}(-1)^{J+j+1/2}\begin{Bmatrix} J & J & k \\ j & j & 1/2 \end{Bmatrix} A_k(j)$$



H-like ion
in the state | n j >

- Extensive calculations have been performed to test such a IPM approach:

- IPM works well for $1s\ 2p_{3/2} : J = 1,2$ but fails for higher excited states.



MCDF calculations
IPM

A. S. *et al.*, work in progress
S. Fritzsche *et al.*, PRA **72** (2005) 012704

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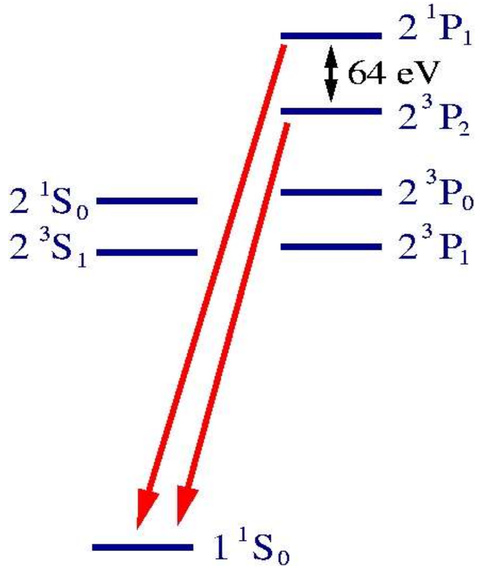
$K\alpha_1$ angular distribution: Independent Particle Model



- The angular distribution of the $K\alpha_1$ radiation:

$$W_{K\alpha_1}(\theta) \sim 1 + \beta_2^{K\alpha_1} P_2(\cos\theta)$$

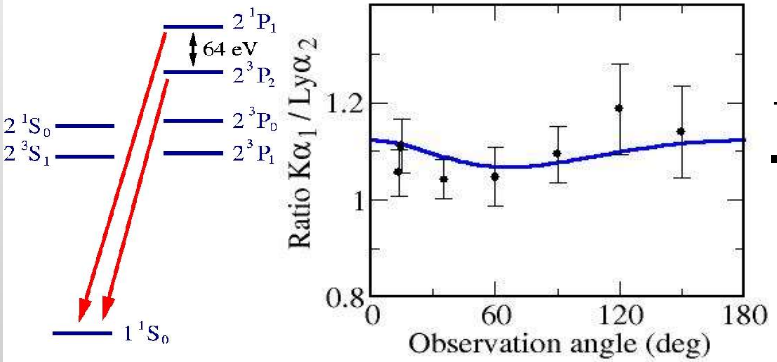
- ... where: $\beta_2 = N_{J=1}\frac{1}{\sqrt{2}}A_2(J=1) - N_{J=2}\sqrt{\frac{5}{14}}A_2(J=2)$
- reads within the framework of IPM:

$$\beta_2^{K\alpha_1} = \frac{1}{2}A_2(j=3/2)\times(N_{J=1}-N_{J=2}) = \beta_2^{Ly\alpha_1}(E1)\times(N_{J=1}-N_{J=2})$$

- We reduce the number of parameters required for analysis of the $K\alpha_1$ decay!
- $K\alpha_1$ measurements give us access to the population **dynamics** as well as to the **structure** properties of few-electron heavy ions.

Example: Kα_1 radiation from 220 MeV/u U^{90+} ions [1]

- We may extract the anisotropy parameter for the Kα_1 radiation in U^{90+} @ T$_p$ = 220MeV/u:

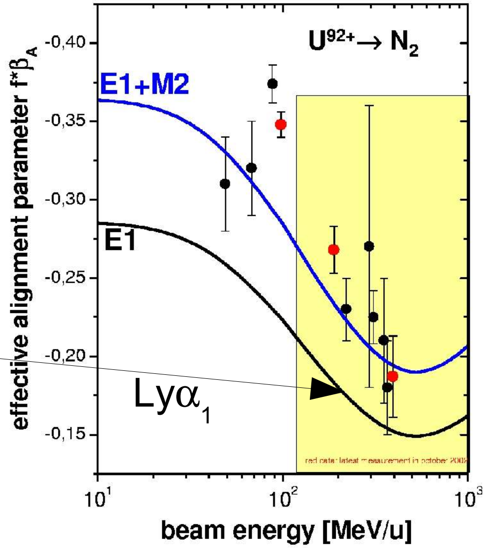


fitting

$$\longrightarrow W_{K\alpha_1}(\theta) \sim 1 + \beta_2^{K\alpha_1} P_2(\cos\theta) \longrightarrow \beta_2^{K\alpha_1} \approx 0.018$$

- Within the IPM: $\beta_2^{K\alpha_1} = \beta_2^{Ly\alpha_1}(E1) \times (N_{J=1} - N_{J=2})$

- Anisotropy of Lyα_1 radiation is known: $\beta_2^{Ly\alpha_1}(E1) \approx -0.17$



- This implies that: $\dfrac{N_{J=1} - N_{J=2}}{N_{J=1} + N_{J=2}} \approx -0.1$

- ... i.e. both E1 ($^1P_1$ -> $^1S_0$) and M2 ($^3P_2$ -> $^1S_0$) decay channels contribute to the Kα_1 decay with (almost) the same weights.

Example: Kα_1 radiation from 220 MeV/u U^{90+} ions [2]

- This implies that: $$\left(\frac{N_{J=1}-N_{J=2}}{N_{J=1}+N_{J=2}}\right)_{\exp}\approx -0.1$$

- ... i.e. both E1 ($^1P_1$ -> $^1S_0$) and M2 ($^3P_2$ -> $^1S_0$) decay channels contribute to the Kα_1 decay with (almost) the same weights.

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

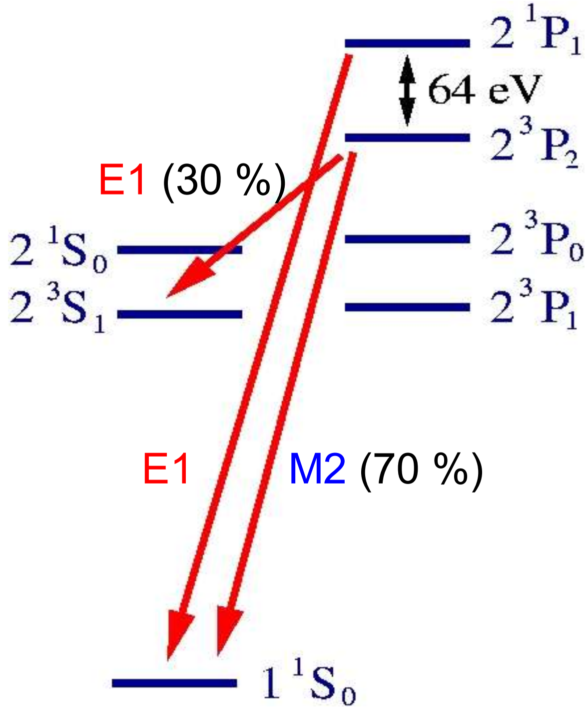
$$\frac{N_{J=1}}{N_{J=2}}=\frac{3}{5}$$

- By taking into account $^3P_2$ -> $^3S_1$ channel:

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

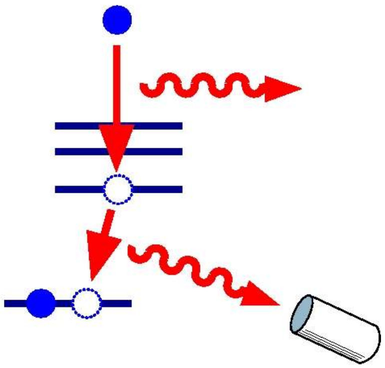
$$\downarrow$$

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



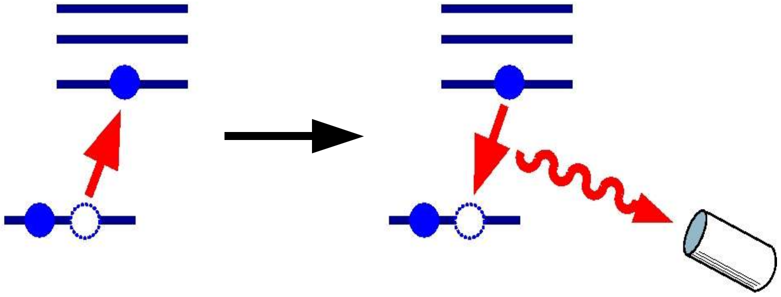
Summary and outlook

- “Averaging” over few unresolved lines in the subsequent x-ray decay of excited HCI may strongly affect the outcome of experiments.



- Theoretical analysis based on IPM may help to “understand” and to interpret the experimental data (Example: Kα_1 decay following REC).

- Indeed, IPM analysis may be applied to other processes. Our next goal is to analyze projectile excitation process.



Thank you for your attention!