Balmer- and L-shell series of highly charged uranium in the experimental storage ring

Summer student program @ GSI - 2007

Thomas Burschil

Johann Wolfgang von Goethe-University, Frankfurt/Main

09/24/2007

Overview

Overview

Physical basics

- Radiative emission

Experiment

- Research at the ESR

series

- Balmer series in hydrogen-like uranium
- L-shell series in helium- and lithium-like uranium

Overview

Physical basics
Radiative emission

Experiment
Research at the ESR

series
Balmer series in hydrogen-like uranium
L-shell series in helium- and lithium-like uranium

Radiative processes

- transition
- recombination
- electron capture
  - radiative (REC)
    time reverse photo ionization
  - non-radiative (NRC)
    three body interaction where momentum and energy is shared between the collision partner
- bremsstrahlung, etc.

Radiative processes

- transition
- recombination
- electron capture
  - radiative (REC)
    time reverse photo ionization
  - non-radiative (NRC)
    three body interaction where momentum and energy is shared between the collision partner
- bremsstrahlung, etc.

Radiative processes

- transition
- recombination
- electron capture
    - radiative (REC)
      time reverse photo ionization
    - non-radiative (NRC)
      three body interaction where momentum and energy is shared between the collision partner
- bremsstrahlung, etc.

Radiative processes

- transition
- recombination
- electron capture
  - radiative (REC)
    time reverse photo ionization
  - non-radiative (NRC)
    three body interaction where momentum and energy is shared between the collision partner
- bremsstrahlung, etc.

Radiative processes

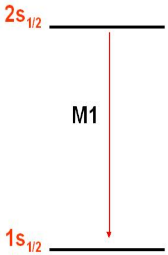
- transition
- recombination
- electron capture
  - radiative (REC)
    time reverse photo ionization
  - non-radiative (NRC)
    three body interaction where momentum and energy is shared between the collision partner
- bremsstrahlung, etc.

Transition

- from energy level to energy level
- energy splitting
- so-called series
  - finite state has the same main quantum number
  - Lyman, Balmer, Paschen, . . . in hydrogen-like ions
  - K-shell, L-shell, M-shell, . . . in other ions

$$\hbar\omega = E_f - E_i$$

For example:

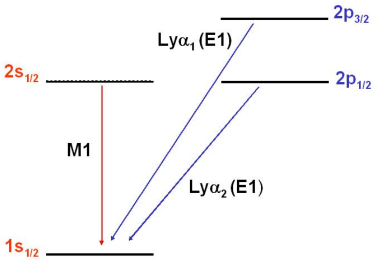


Transition

- from energy level to energy level
- energy splitting
- so-called series
    - finite state has the same main quantum number
    - Lyman, Balmer, Paschen, ... in hydrogen-like ions
    - K-shell, L-shell, M-shell, ... in other ions

$$\hbar\omega = E_f - E_i$$

For example:

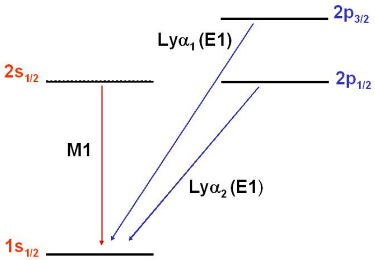


Transition

- from energy level to energy level
- energy splitting
- so-called series
    - finite state has the same main quantum number
    - Lyman, Balmer, Paschen, ... in hydrogen-like ions
    - K-shell, L-shell, M-shell, ... in other ions

$$\hbar\omega = E_f - E_i$$

For example:

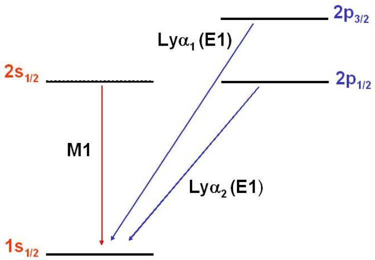


Transition

- from energy level to energy level
- energy splitting
- so-called series
  - finite state has the same main quantum number
  - Lyman, Balmer, Paschen, . . . in hydrogen-like ions
  - K-shell, L-shell, M-shell, . . . in other ions

$$\hbar\omega = E_f - E_i$$

For example:

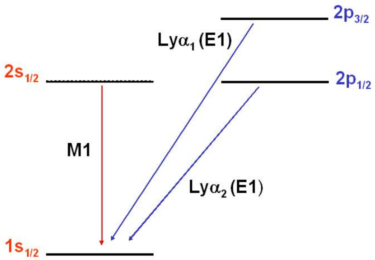


Transition

- from energy level to energy level
- energy splitting
- so-called series
    - finite state has the same main quantum number
    - Lyman, Balmer, Paschen, . . . in hydrogen-like ions
    - K-shell, L-shell, M-shell, . . . in other ions

$$\hbar\omega = E_f - E_i$$

For example:



REC and NRC

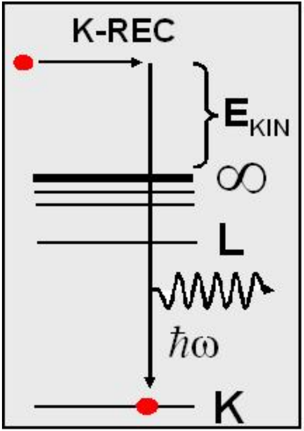
- ion captures electron from a target atom
- two possibilities:
    1. non-radiative electron capture

REC and NRC

- ion captures electron from a target atom
- two possibilities:
  1. non-radiative electron capture

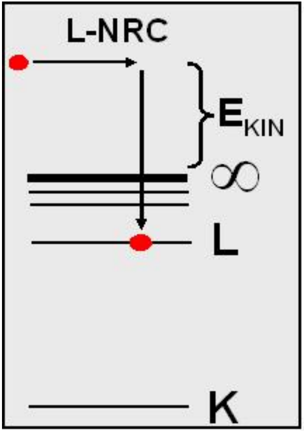
REC and NRC

- ion captures electron from a target atom
- two possibilities:
  1. radiative electron capture
  2. non-radiative electron capture



REC and NRC

- ion captures electron from a target atom
- two possibilities:
  1. radiative electron capture
  2. non-radiative electron capture

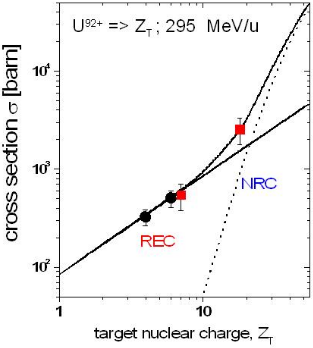


REC and NRC

cross section:

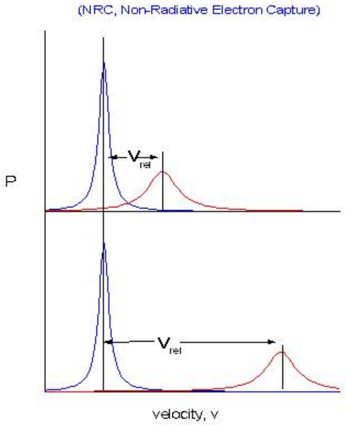
$$\sigma_{REC} \propto Z_T \cdot Z_P^5$$

$$\sigma_{NRC} \propto Z_T^5 \cdot Z_P^5$$



REC and NRC

- ion captures electron from a target atom
- two possibilities:
    1. radiative electron capture
    2. non-radiative electron capture

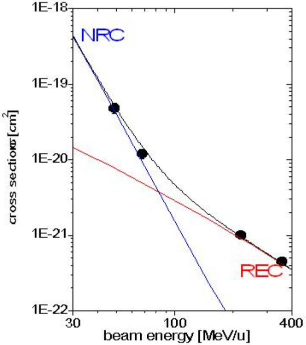


REC and NRC

cross section:

$$\sigma_{REC} \propto \frac{Z_T \cdot Z_P^5}{v^{5/2}}$$

$$\sigma_{NRC} \propto \frac{Z_T^5 \cdot Z_P^5}{v^{11}}$$



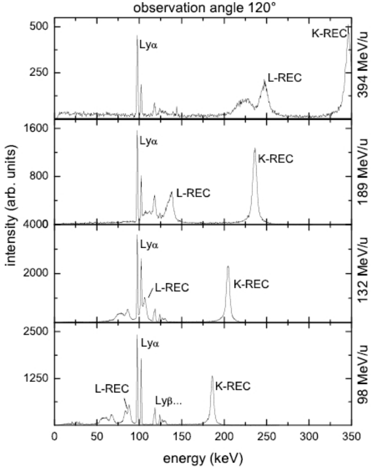
REC: dipole approximation
NRC: eikonal approach

REC and NRC

cross section:

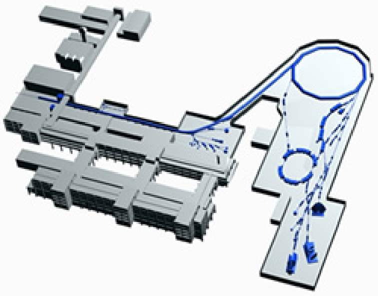
$$\sigma_{REC} \propto \frac{Z_T \cdot Z_P^5}{v^{5/2}}$$

$$\sigma_{NRC} \propto \frac{Z_T^5 \cdot Z_P^5}{v^{11}}$$



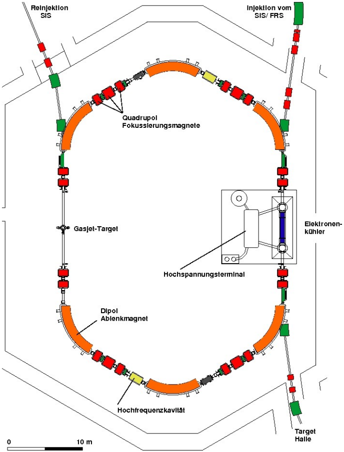
Research facility

- UNILAC → SIS → ESR
- electron cooler
  radiative recombination
  experiments
- gas-jet target
  electron capture
  experiments



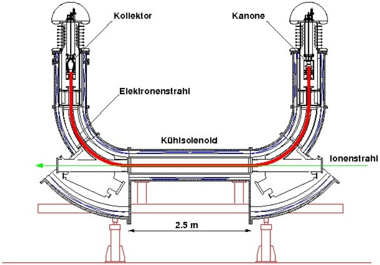
Research facility

- UNILAC → SIS → ESR
- electron cooler
  radiative recombination
  experiments
- gas-jet target
  electron capture
  experiments



Research facility

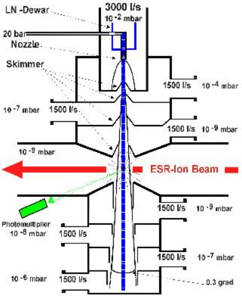
- UNILAC → SIS → ESR
- electron cooler
  radiative recombination experiments
- gas-jet target
  electron capture experiments



Research facility

- UNILAC → SIS → ESR
- electron cooler
  radiative recombination
  experiments
- gas-jet target
  electron capture
  experiments

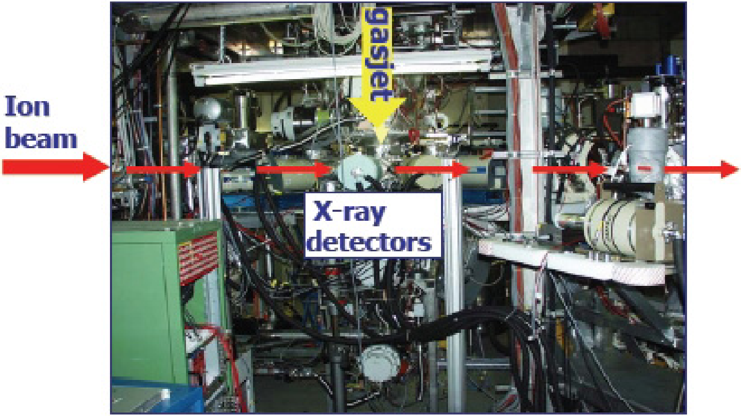
The Jet-Target



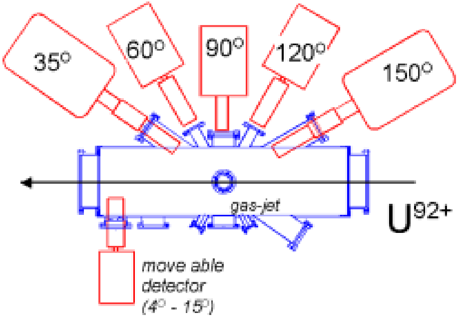
Supersonic jet, operates in ultra high vacuum enviroment (10^{-11} mbar)

A. Krämer et al, NIM B 174. 205 (2001)

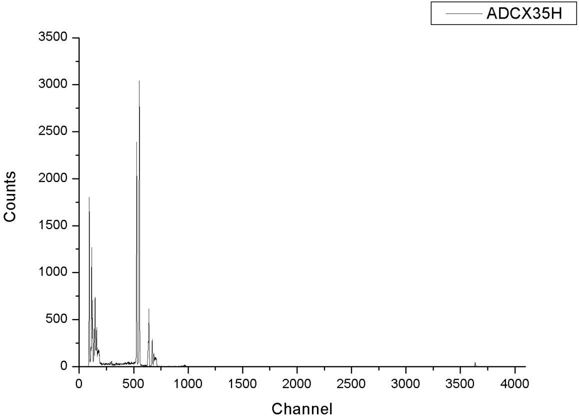
Observation places at the gas-jet target



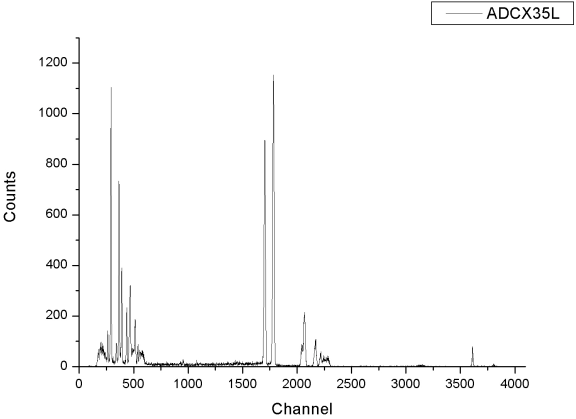
Observation places at the gas-jet target



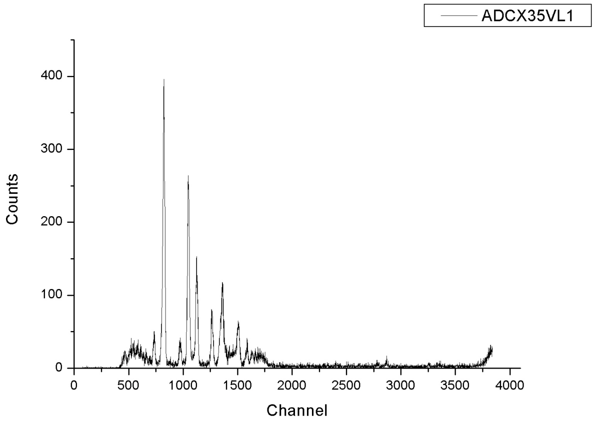
Recorded spectra



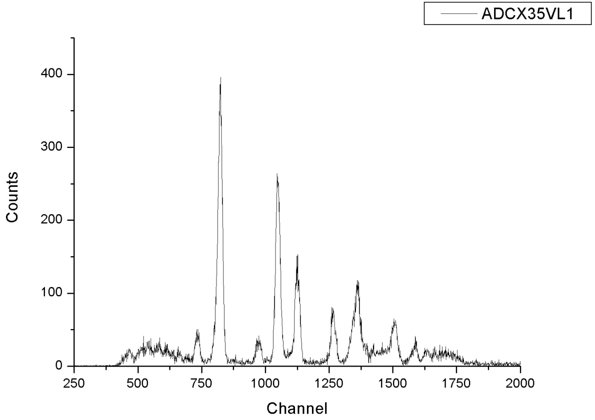
Recorded spectra



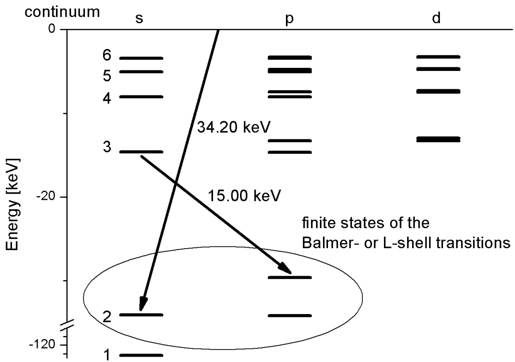
Recorded spectra



Recorded spectra



Calibration



Calibration

system parameters

$U^{92+} \rightarrow Ar$

observation angle: 35°

beam energy: 88 MeV/u

$\Rightarrow \beta = 0.4064$, $\gamma = 1.0945$

transfer factor between the laboratory and the emitter system:

Doppler Shift $= 1.3697$

$$E_{labor\ sys} = \frac{E_{emitter\ sys}}{\gamma\,(1 - \beta\cos\vartheta)}$$

Calibration

system parameters

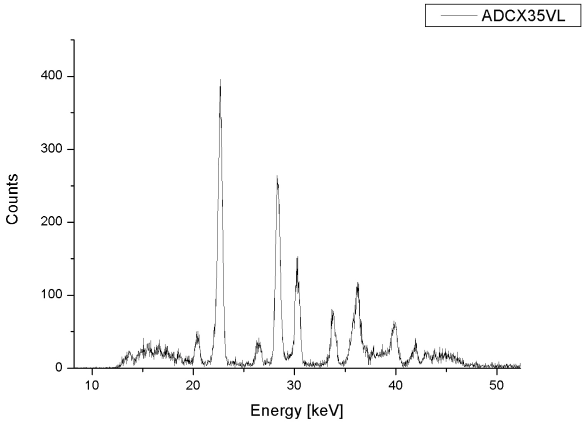
$\mathrm{U}^{92+} \rightarrow \mathrm{Ar}$
observation angle: 35°
beam energy: 88 MeV/u
$\Rightarrow \beta = 0.4064$, $\gamma = 1.0945$
transfer factor between the laboratory and the emitter system:
Doppler Shift = 1.3697

$$E_{labor\ sys} = \frac{E_{emitter\ sys}}{\gamma\,(1-\beta\cos\vartheta)}$$

Calibration

$E_{emitter\ system}$	$E_{labor\ system}$	channel
34.2 keV	46.9 keV	1784 ± 30
15.0 keV	20.4 keV	733 ± 10

Calibration



Comparison

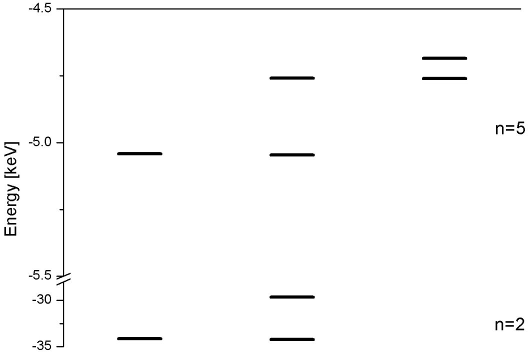
Binding energies associated with transitions in a Balmer series

peak	$E_{labor\ system}$	$E_{emitter\ system}$
1	$20.40\ keV \pm 0.44\ keV$	$14.88\ keV \pm 0.32\ keV$
2	$22.65\ keV \pm 0.43\ keV$	$16.53\ keV \pm 0.32\ keV$
3	$26.45\ keV \pm 0.60\ keV$	$19.30\ keV \pm 0.44\ keV$
4	$28.35\ keV \pm 0.43\ keV$	$20.69\ keV \pm 0.31\ keV$
5	$30.27\ keV \pm 0.49\ keV$	$22.10\ keV \pm 0.36\ keV$
6	$33.82\ keV \pm 0.43\ keV$	$24.69\ keV \pm 0.32\ keV$
7	$36.17\ keV \pm 0.62\ keV$	$26.40\ keV \pm 0.45\ keV$
8	$39.86\ keV \pm 0.60\ keV$	$29.09\ keV \pm 0.44\ keV$
9	$41.90\ keV \pm 0.47\ keV$	$30.58\ keV \pm 0.34\ keV$
end	$46.90\ keV \pm 0.50\ keV$	$34.23\ keV \pm 0.36\ keV$

Comparison

Binding energies associated with transitions in a Balmer series

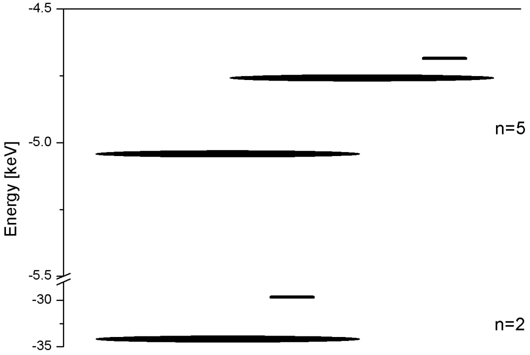
Example for transition energies



Comparison

Binding energies associated with transitions in a Balmer series

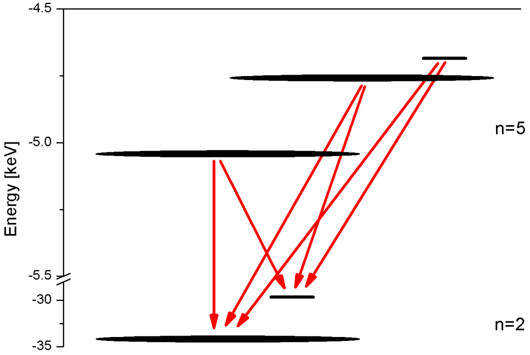
Example for transition energies



Comparison

Binding energies associated with transitions in a Balmer series

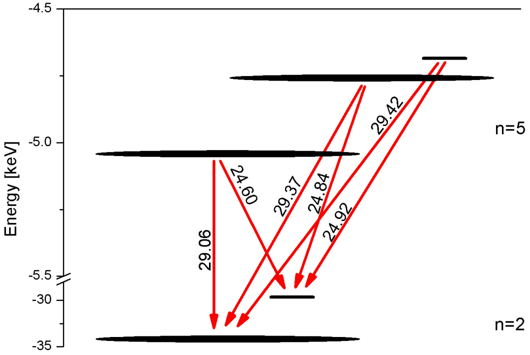
Example for transition energies



Comparison

Binding energies associated with transitions in a Balmer series

Example for transition energies



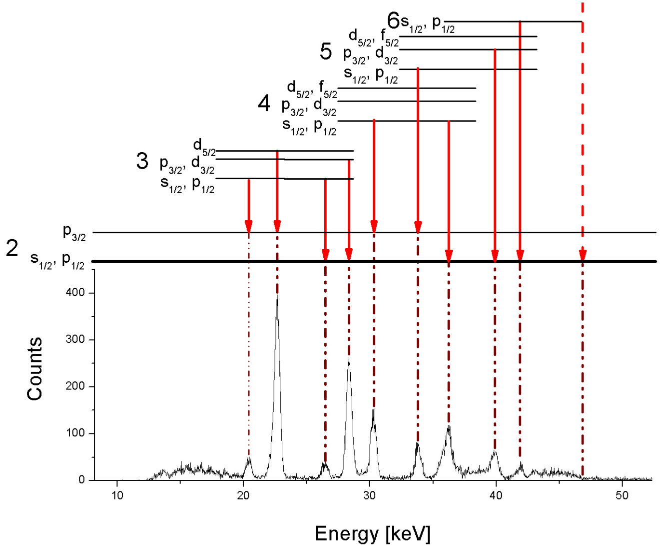
Comparison

Binding energies associated with transitions in a Balmer series

peak	$E_{emitter\ \ system}$	$E_{transition}$	transition
1	$14.88\ keV \pm 0.32\ keV$	$15.00\ keV$	$3s_{1/2} \to 2p_{3/2}$
2	$16.53\ keV \pm 0.32\ keV$	$16.68\ keV$	$3d_{5/2} \to 2p_{3/2}$
3	$19.30\ keV \pm 0.44\ keV$	$19.48\ keV$	$3s_{1/2} \to 2s_{1/2}$
4	$20.69\ keV \pm 0.31\ keV$	$20.82\ keV$	$3p_{3/2} \to 2s_{1/2}$
5	$22.10\ keV \pm 0.36\ keV$	$22.32\ keV$	$4d_{5/2} \to 2p_{3/2}$
6	$24.69\ keV \pm 0.32\ keV$	$24.60\ keV$	$5s_{1/2} \to 2p_{3/2}$
7	$26.40\ keV \pm 0.45\ keV$	$26.66\ keV$	$4p_{3/2} \to 2s_{1/2}$
8	$29.09\ keV \pm 0.44\ keV$	$29.37\ keV$	$5p_{3/2} \to 2s_{1/2}$
9	$30.58\ keV \pm 0.34\ keV$	$30.67\ keV$	$6s_{1/2} \to 2s_{1/2}$
end	$34.23\ keV \pm 0.36\ keV$	$34.20\ keV$	continuum

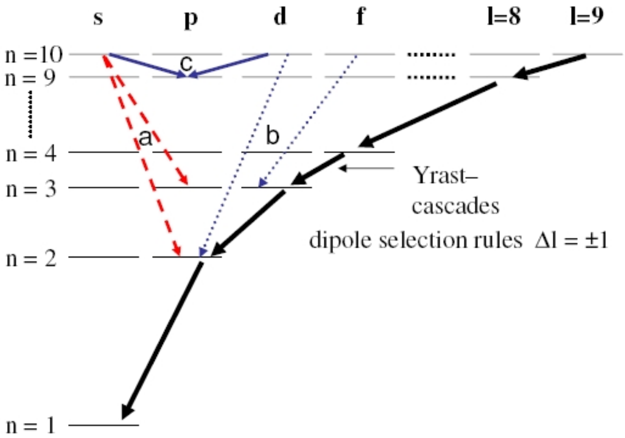
Results and Conclusion

Spectra with associated transitions to the L-shell



Results and Conclusion

Cascade



L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction
  $\longrightarrow$ every electron in the ion shields one proton

L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction
  $\longrightarrow$ every electron in the ion shields one proton

L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction
  $\longrightarrow$ every electron in the ion shields one proton

L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction

  $\longrightarrow$ every electron in the ion shields one proton

L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction
  $\longrightarrow$ every electron in the ion shields one proton

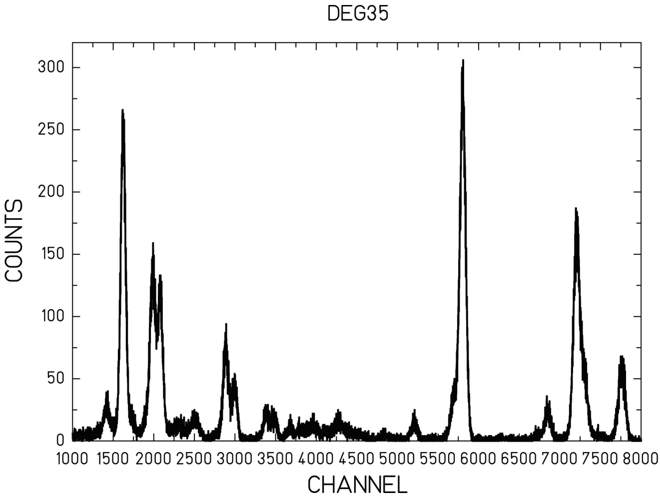
L-shell series in helium- and lithium-like uranium

- experiment in August 2007
- spectra with the first 4 L-shell lines
- data do not fit with the theoretical values
- more corrections: shielding correction
  $\rightarrow$ every electron in the ion shields one proton

$$E_{corr} \propto \left(\frac{92}{90}\right)^2$$

Spectrum of lithium-like uranium

M- and L-shell series



Comparison

Shielding correction

Helium-like uranium in [keV]

peak	$E_{labor\ sys}$	$E_{emitter\ sys}$	$E_{shield\ corr.}$	$E_{theor.}$
11	18.44758	14.63544	14.95887	14.998
12	20.56333	16.31398	16.6745	16.682
13	24.14803	19.15792	19.58129	19.485
14	25.6703	20.36561	20.81567	20.824

Comparison

Shielding correction

Lithium-like uranium in $[keV]$

peak	$E_{labor\ sys}$	$E_{emitter\ sys}$	$E_{shield\ corr.}$	$E_{theor.}$
11	17.53268	14.31346	14.95669	14.998
12	19.54938	15.95987	16.67708	16.682
13	23.08047	18.84261	19.68937	19.485
14	24.33888	19.86996	20.76288	20.824

Conclusions

$$E \propto \left(\frac{92}{90}\right)^2$$

- shielding correction is very rough approximation
- a more precise theory is needed

Conclusions

$$E \propto \left(\frac{92}{90}\right)^2$$

- shielding correction is very rough approximation
- a more precise theory is needed

The end

The end

Questions?