# Two-electron processes in relaxation of hollow atoms

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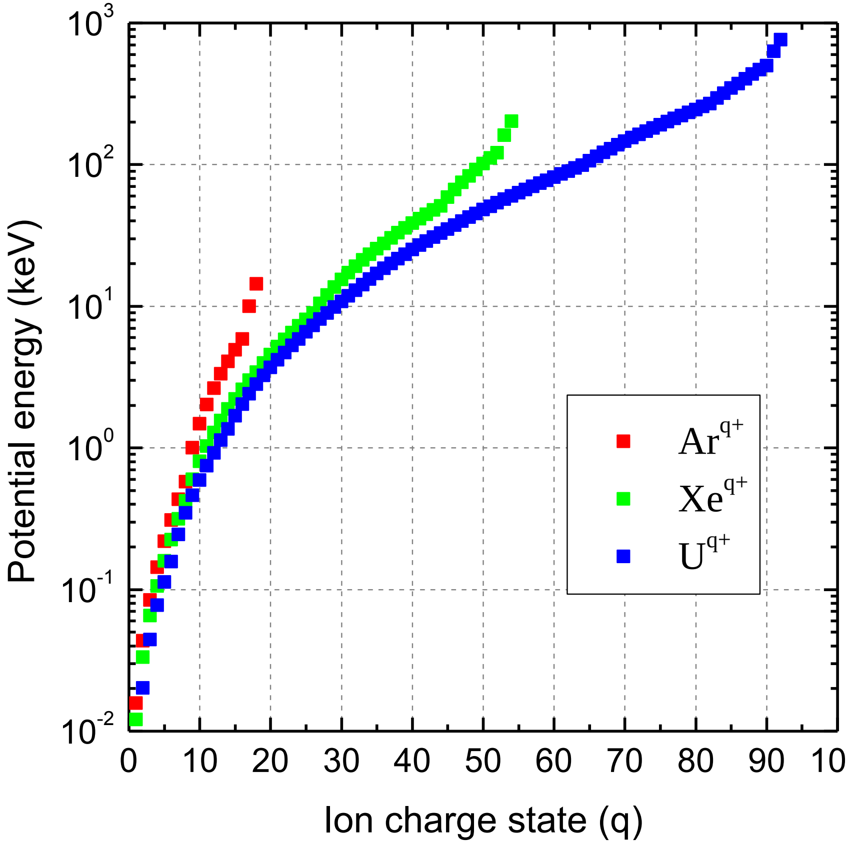
# Slow highly charged ions

- The term slow HCI usually refers to impact velocities ≤1 a.u. or 25 keV/amu

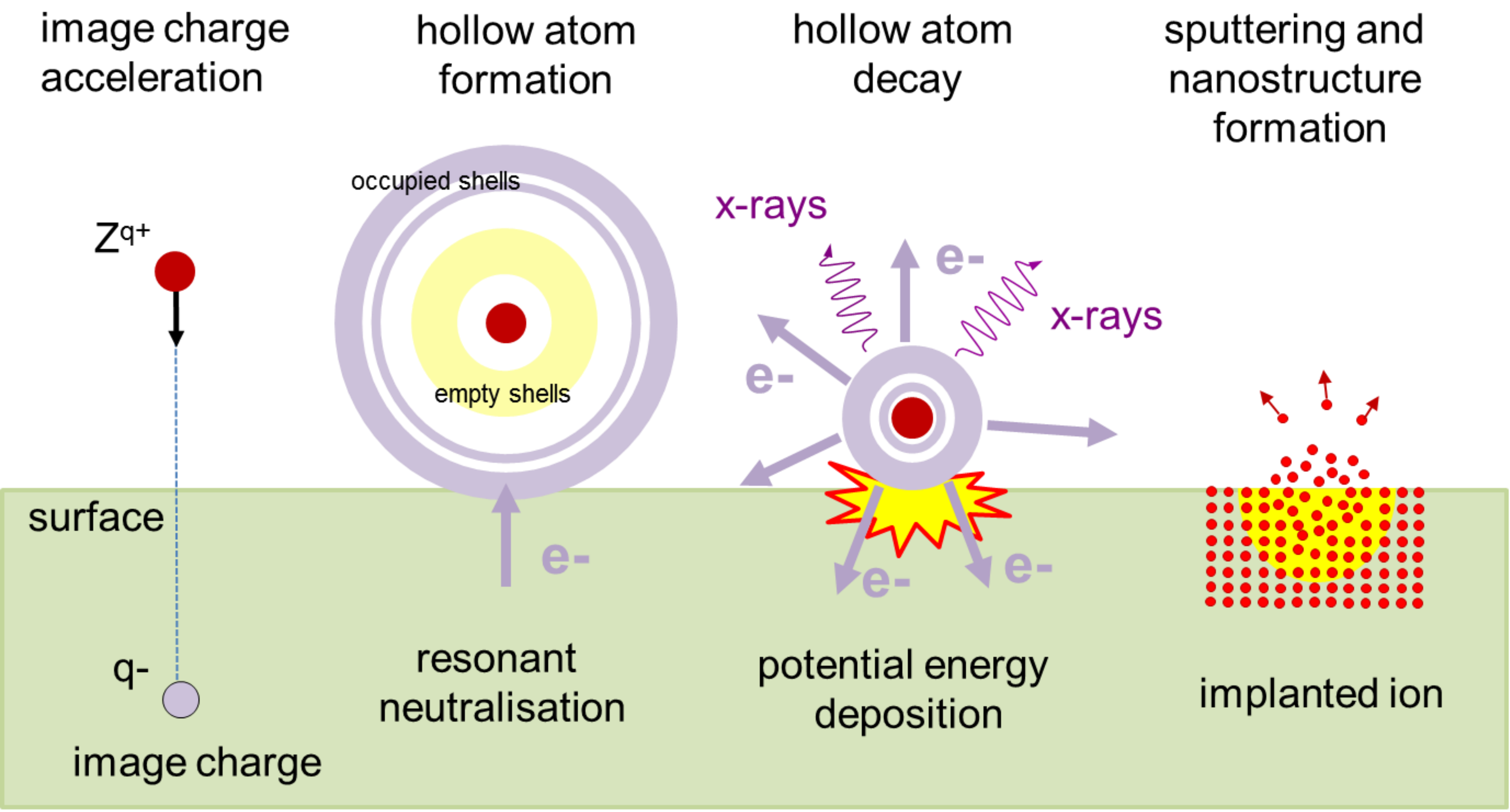
- At such low impact velocity, electronic transitions between the HCI and a solid surface are generally much faster than significant changes of the projectile - surface distance

- **Slow HCI are characterized by relatively high potential energy (e.g. for $Xe^{50+}$~100 keV, i.e. ~8400 higher than that of $Xe^{1+}$)**

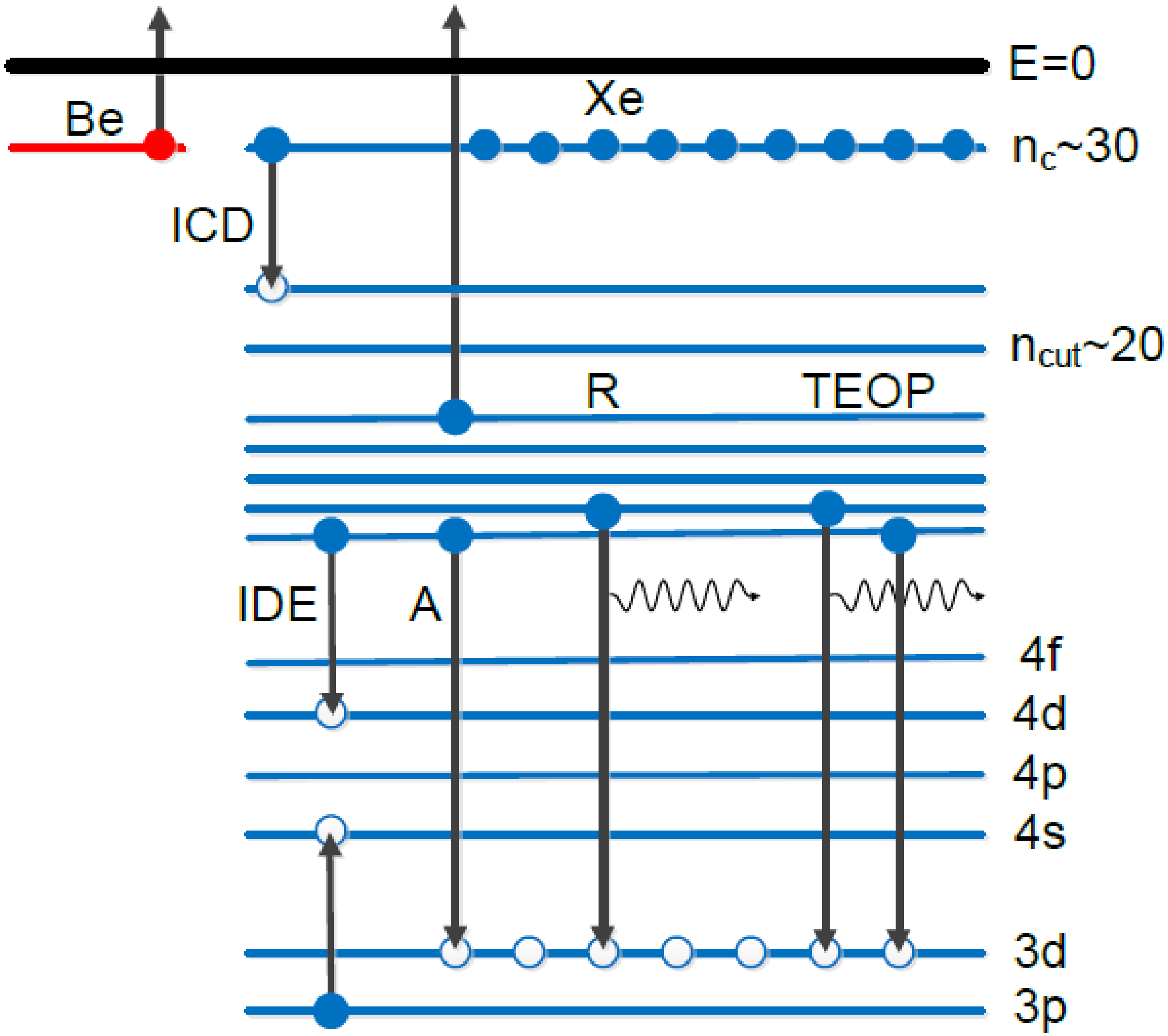


Total potential energy of highly charged $Ar^{q+}$, $Xe^{q+}$ and $U^{q+}$ ions versus charge state q (based on MCDF calculations)

# Interaction of HCI with surface

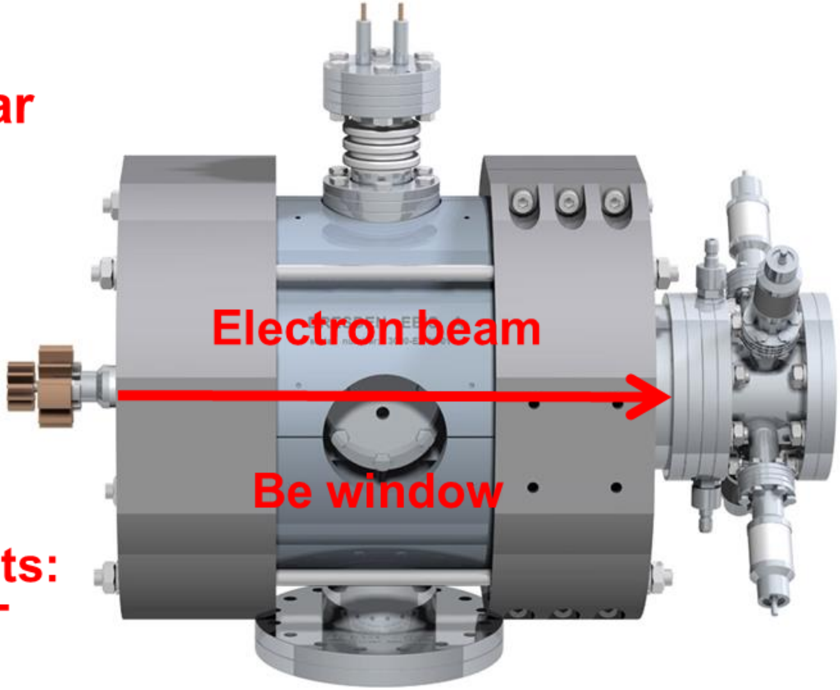


# Ralaxation of RHA



# Electron Beam Ion Trap (EBIT)

- EBIT trap length (6 cm), electron beam energy (25 keV) and current (200 mA), electron beam diameter (200μm), magnetic field strength (600 mT)
- typical ions: $Ar^{18+}$(fully ionized), $Kr^{34+}$(He-like), $Xe^{44+}$(Ne-like)



**UHV: $10^{-9}$ mbar**

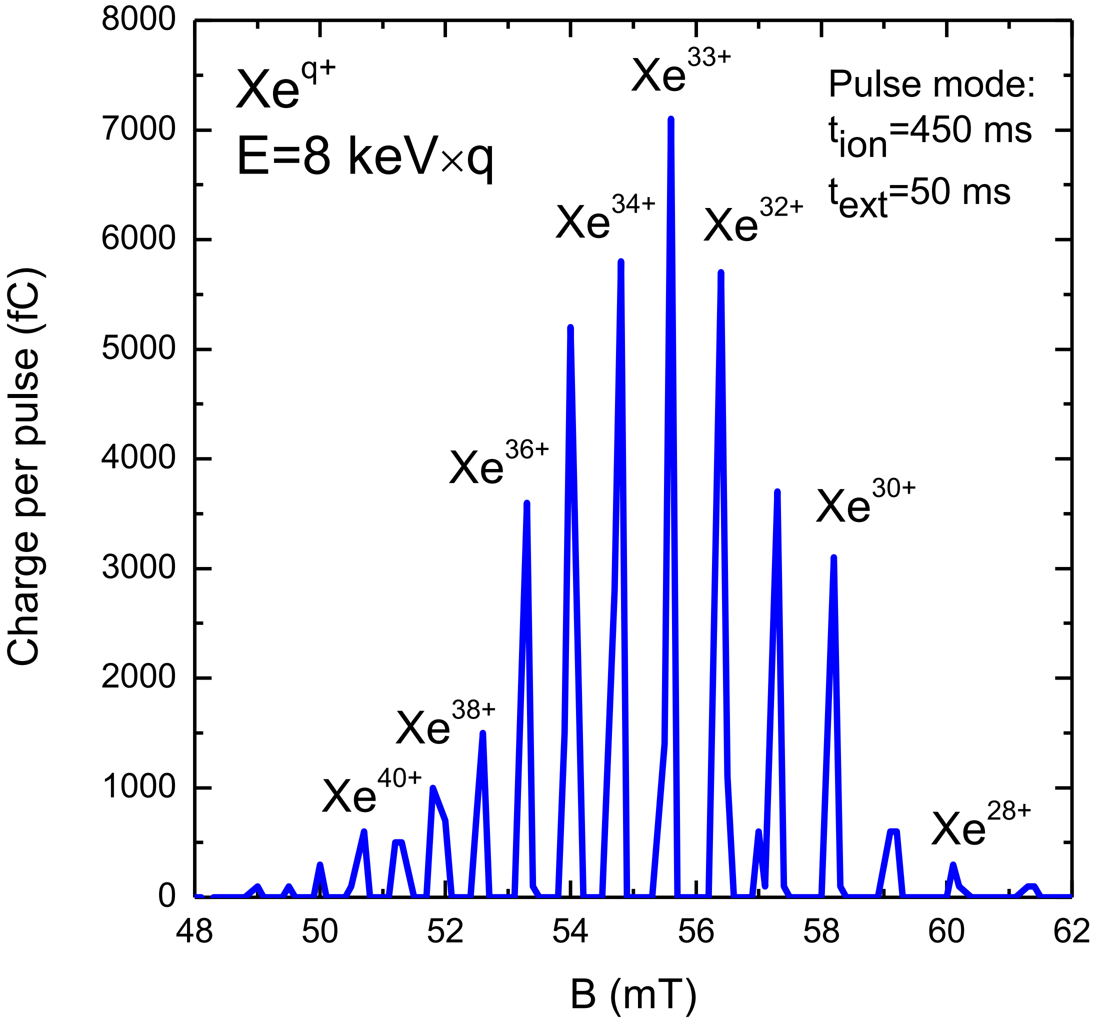
**electron-gun:**
**25 keV, 200 mA**

**permanent magnets:**
**NdFeB, B=600 mT**

**Extraction potential**
**up to 20kV**

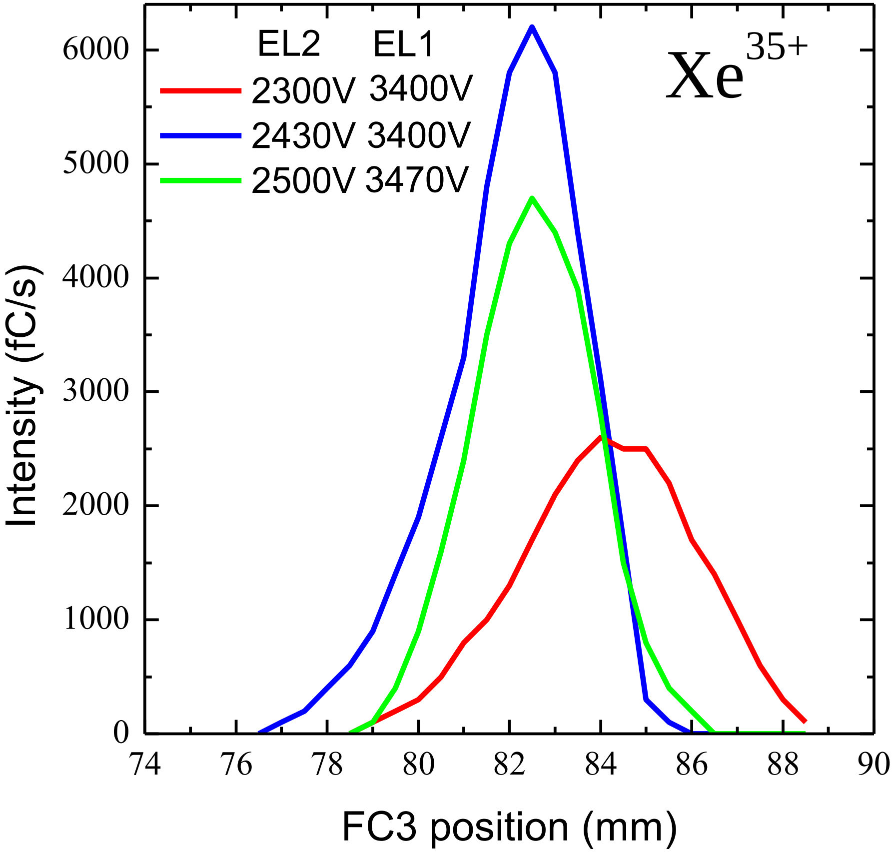
# Charge state selection

Charge state selection on doubly focusing analyzing magnet



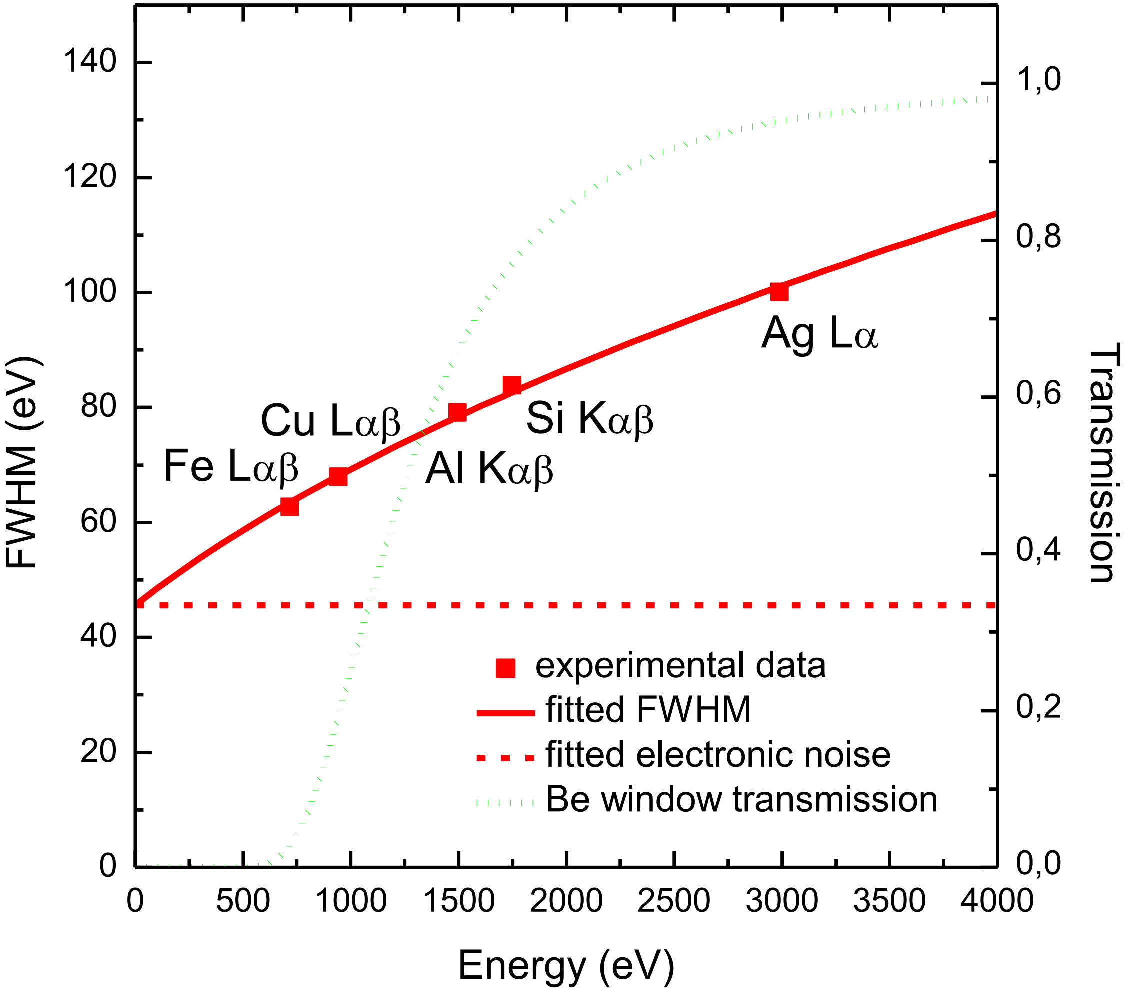
# Beam profile

- Focusing of ion beam on metallic foil mounted on a 5-axis manipulator in experimental chamber
- Stable Xe$^{q+}$ (q = 23 -36)  beams with a beam diameter below one milimeter



# X-ray detector

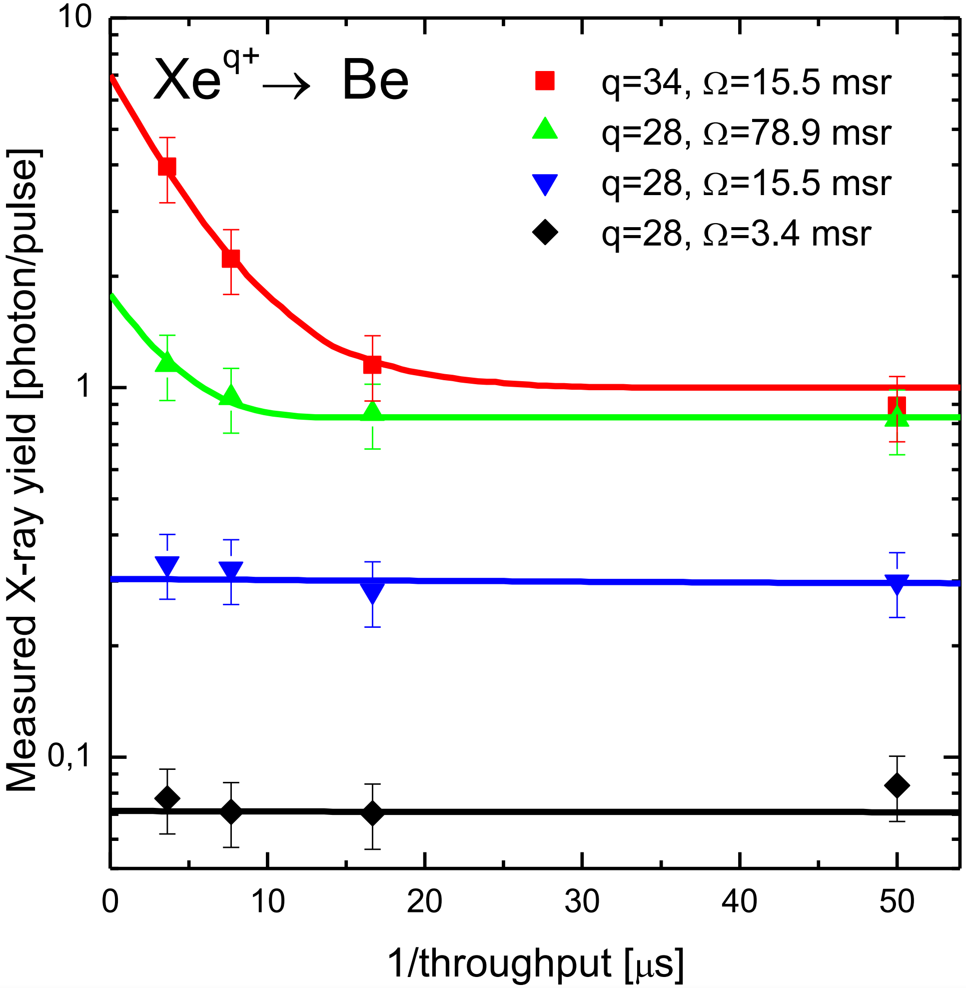
Detector resolution: 60-100 eV for photon energies 0.5 - 3 keV
Detector efficiency: 2-95%



Silicon drift detector (X-Flash 5030) with 12.5 μm thick beryllium window

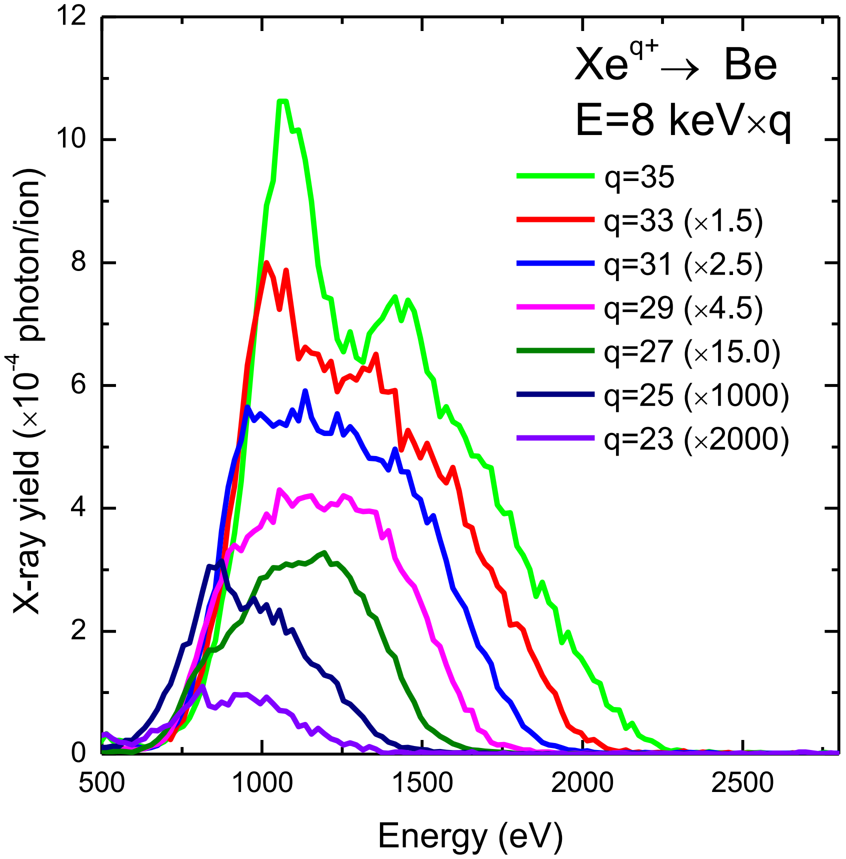
# Event-loss effect

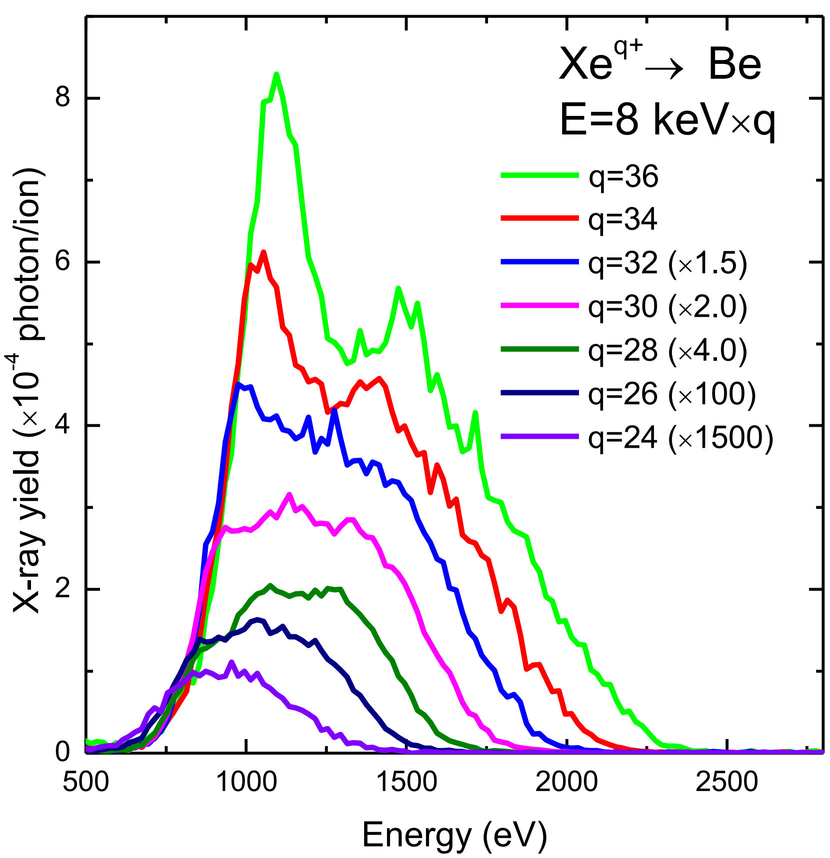
Decrease in the efficiency of the measured x-rays due to the event loss effect for a long signal processing time when more than one photon hits the detector in a pulse



# Measured X-ray spectra

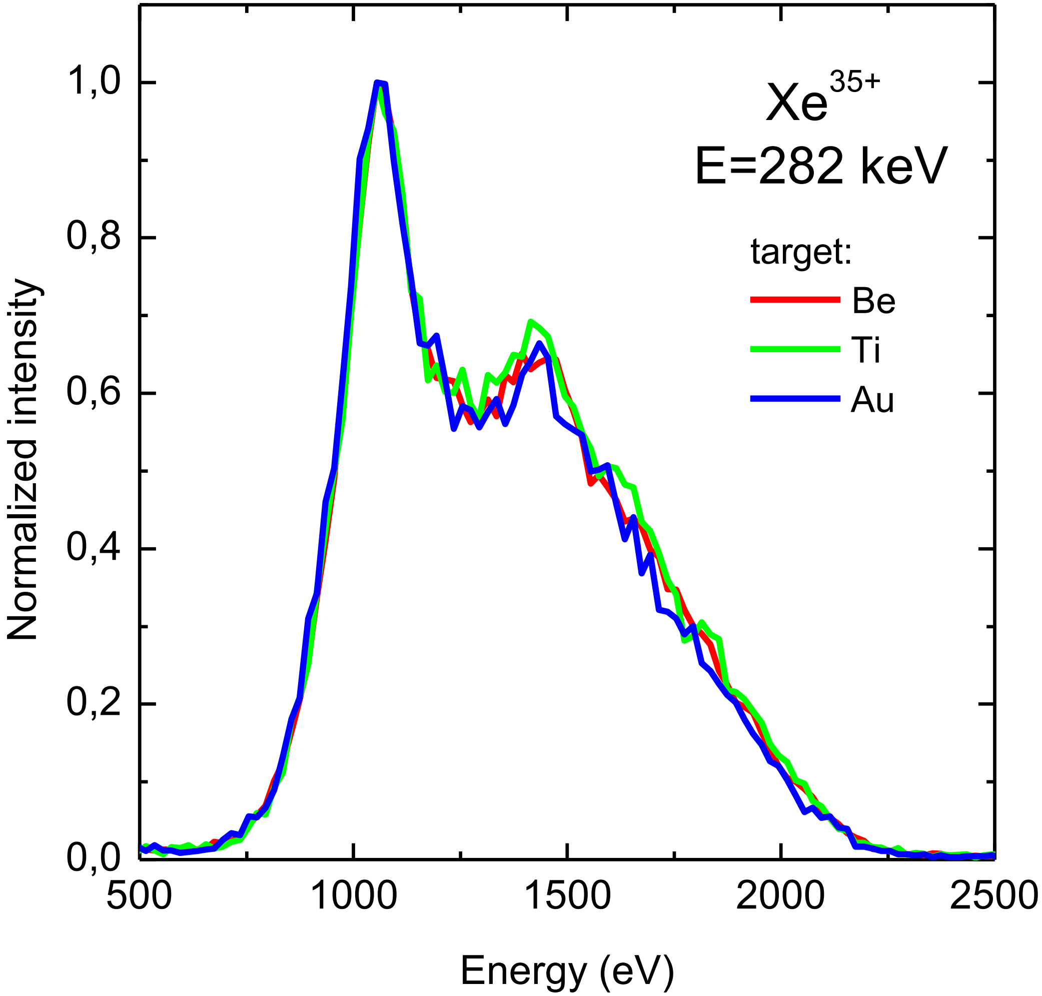
**Strong dependence on ion charge state**





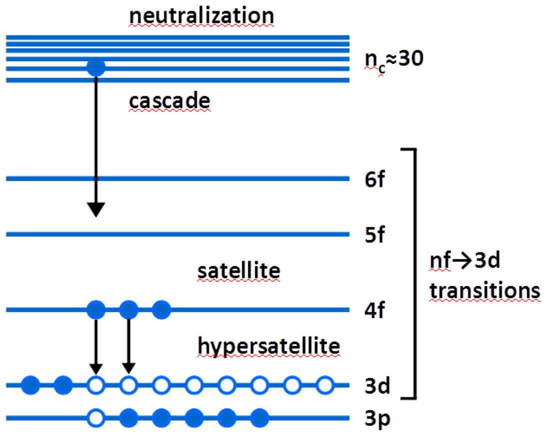
# Measured X-ray spectra

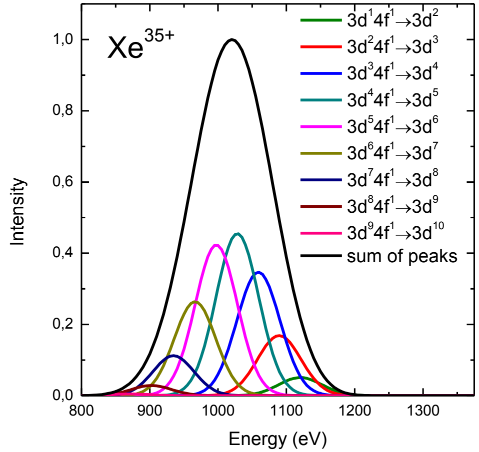
**Independence of a type of metallic foil**

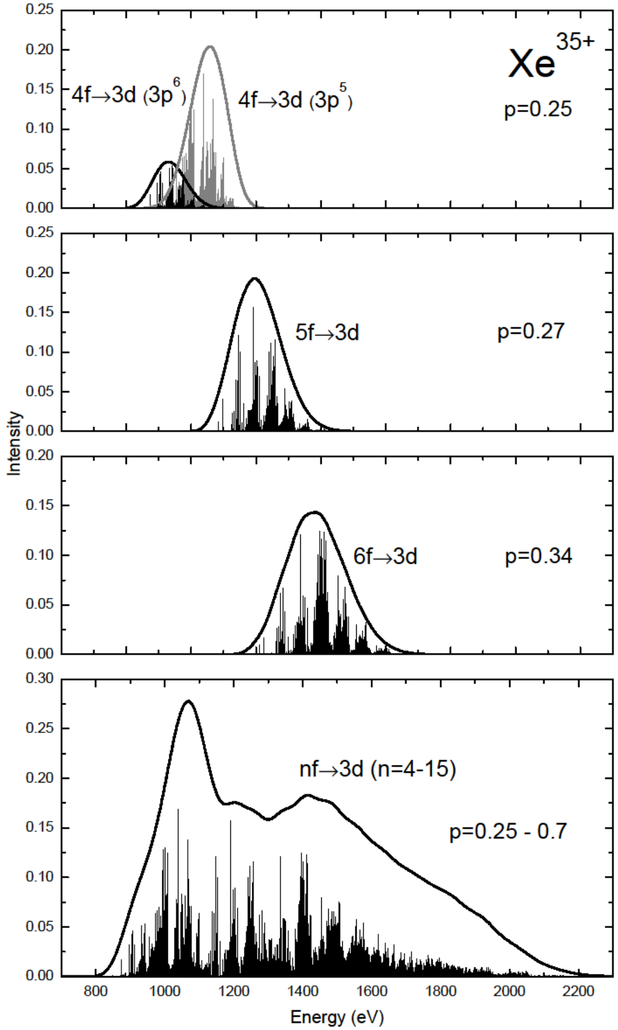


# Calculations and modelling of X-ray spectra

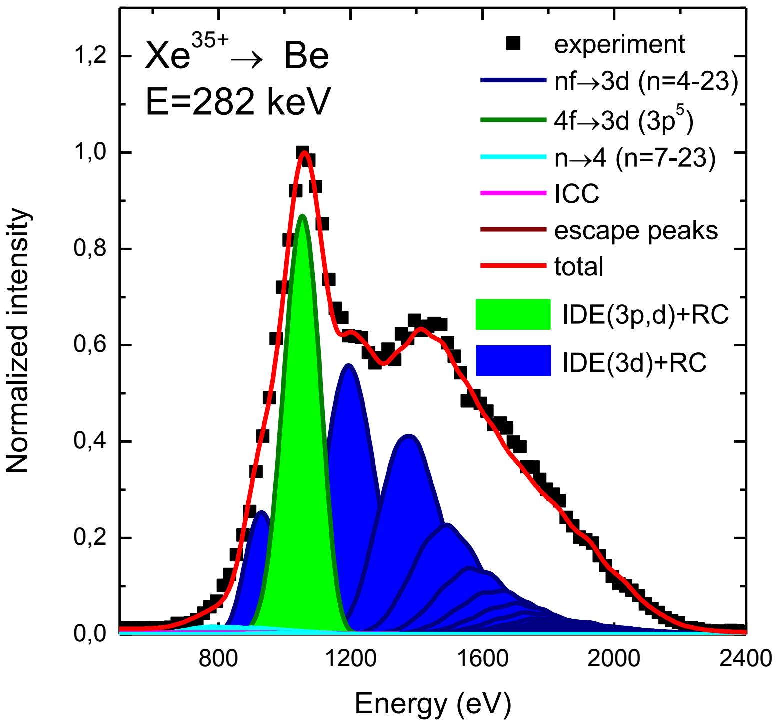
- MCDHF atomic structure calculations were performed using GRASP2K code
- The strongest nf-3d electric dipole transitions were assumed
- X-ray spectra are dominated by X-ray hypersatellites having approximately binomial distribution
- 426670 lines calculated for $Xe^{35+}$ spectrum
- X-ray line profiles, including Gaussian experimental broadening, Incomplete Charge Collection (ICC) low-energy tails and Si-K$\alpha$ escape, were used

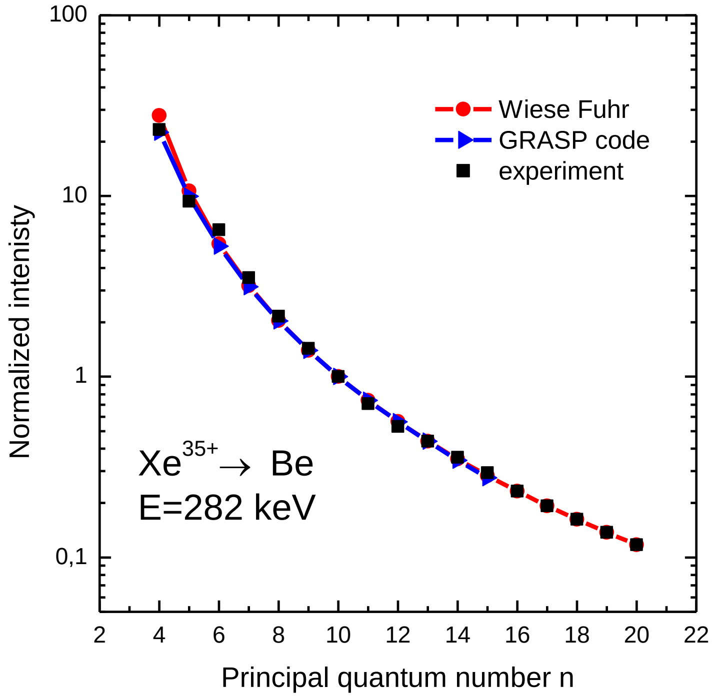






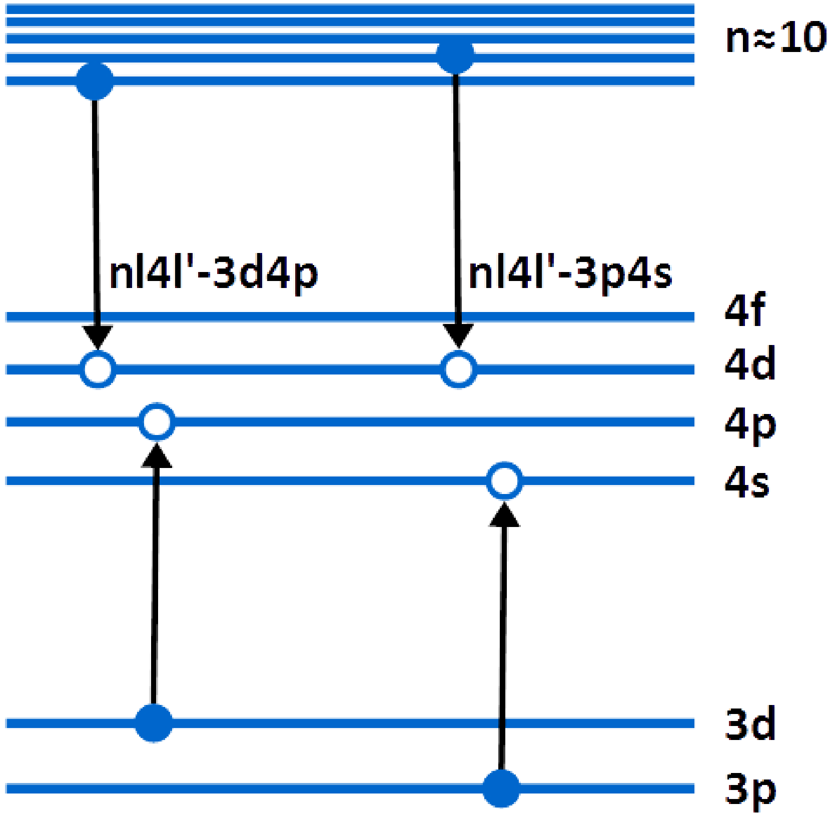
# Interpretation of $Xe^{35+}$ spectrum

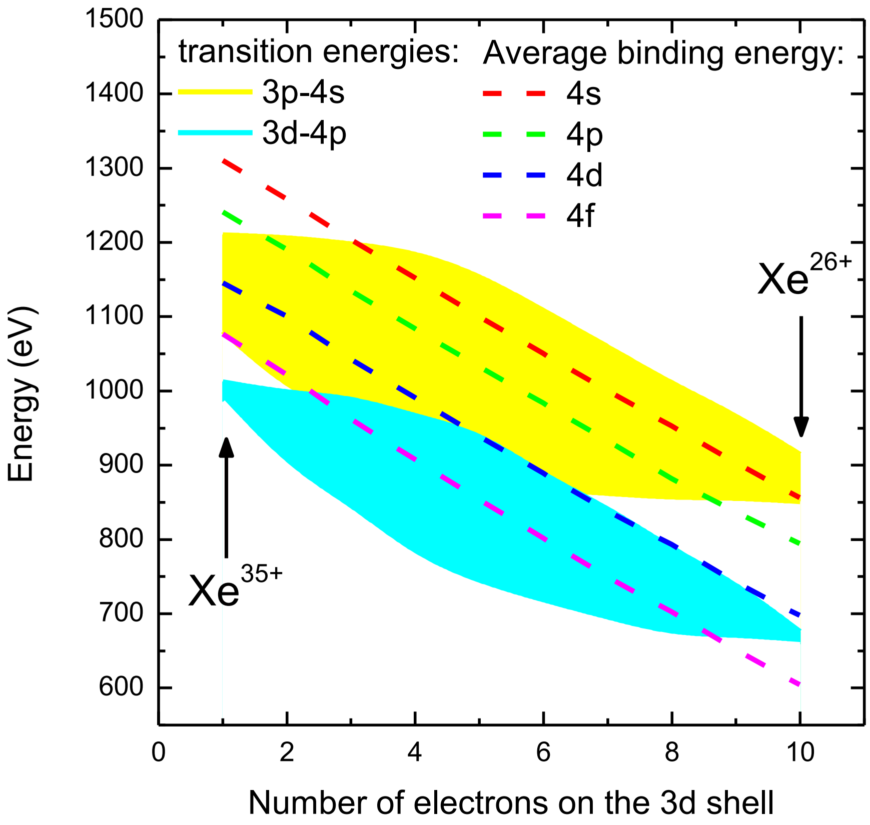




- For $Xe^{35+}$ ions nf-3d M-shell X-ray transitions (Pashen series) were observed for n≤23
- Relative intensities of X-ray lines in the Paschen series support statistical scaling of the electron population in the upper state
- 4f-3d ($3p^5$) hipersatellite X-ray transition excited by IDE is clearly evidenced

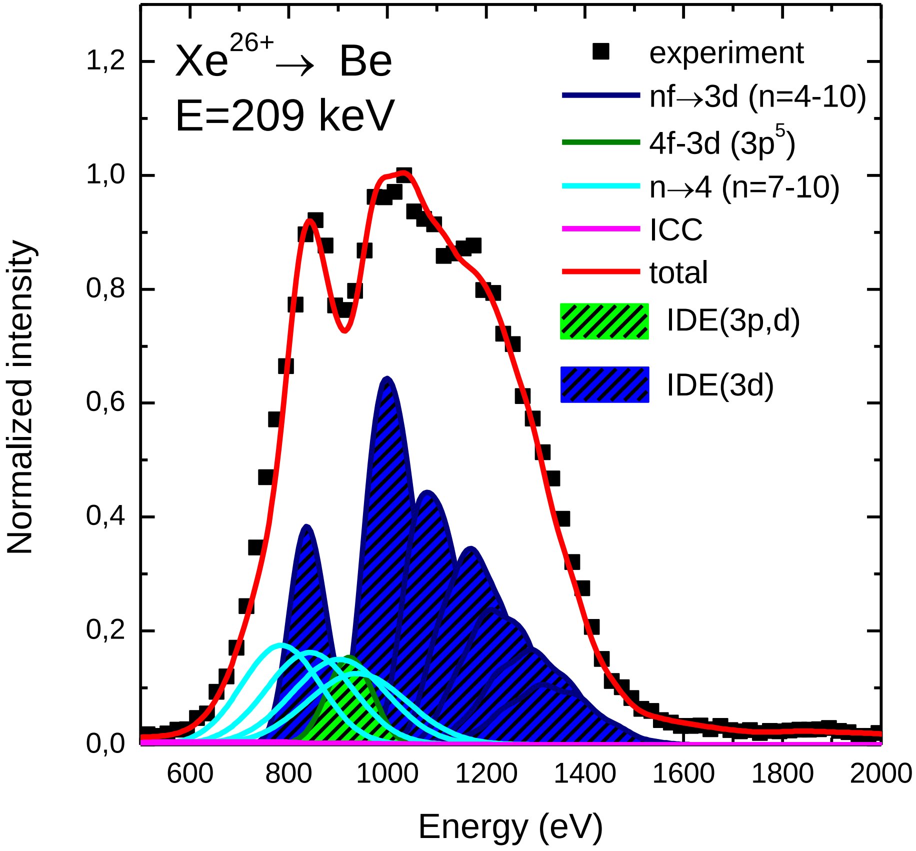
# Internal dielectronic excitation (IDE)





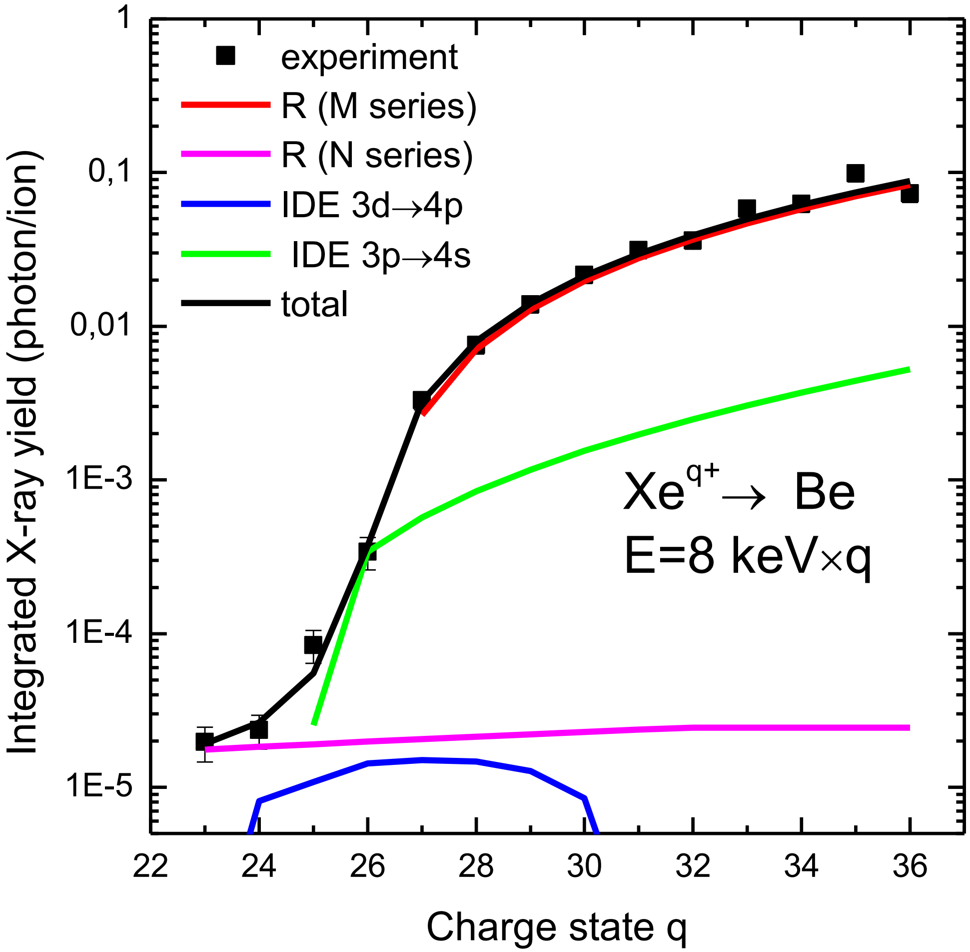
IDE processes leading to 3p-4s and 3d-4p electronic excitations are energeticly allowed for highly charged Xe ions

# Interpretation of $Xe^{26+}$ spectrum



- $Xe^{26+}$ ions have no vacancies in 3d–subshell → the observed M-X-rays are excited exclusively by the IDE
- IDE creates 3d and 3p vacancies via 3d-4p and 3d-4s excitations
- nf-3d M-shell X-ray transitions were observed for n≤10

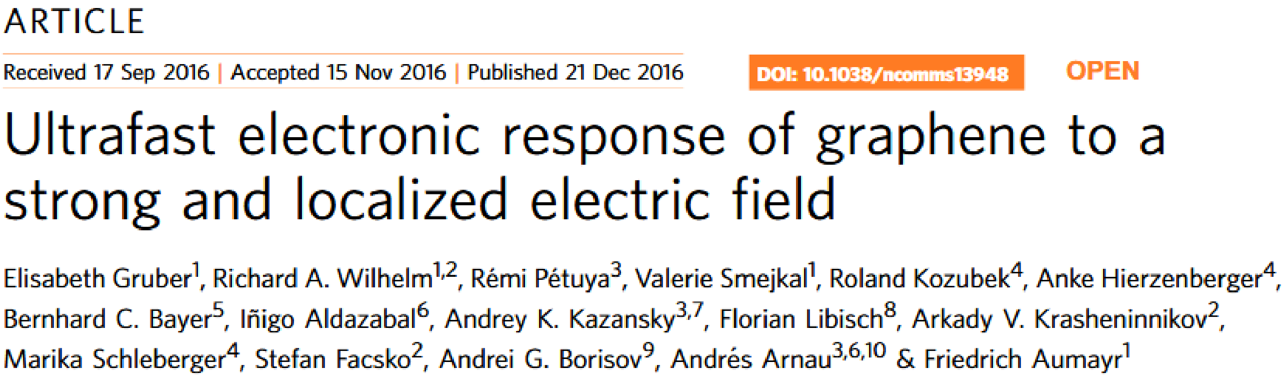
# X-ray yield



- M-X-ray yield for diffrent charge states was measured
- Contributions of initial vacancies and those formed by IDE (3d-4p and 3p-4s) are separeted and extraced using the proposed q-dependent X-ray emission model

$$\omega_x = \frac{\Gamma_x}{\Gamma_x + \Gamma_A} \approx \frac{\Gamma_x}{\Gamma_A} \approx 0.003$$

# Interatomic Coulombic Decay (ICD)



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Ultrafast electronic response of graphene to a strong and localized electric field

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Interatomic Coulombic Decay: The Mechanism for Rapid Deexcitation of Hollow Atoms

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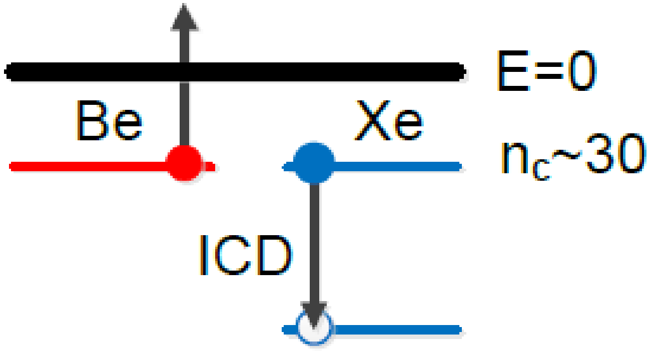
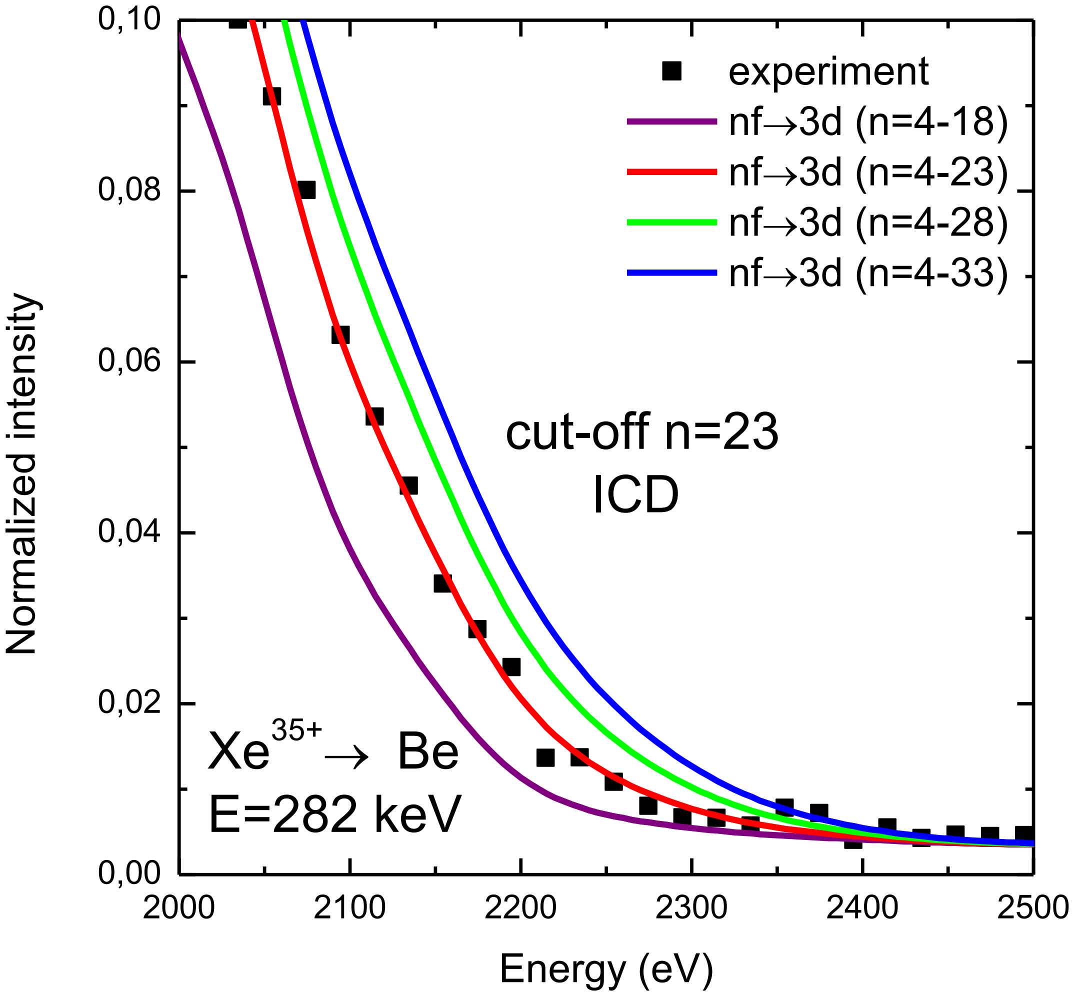
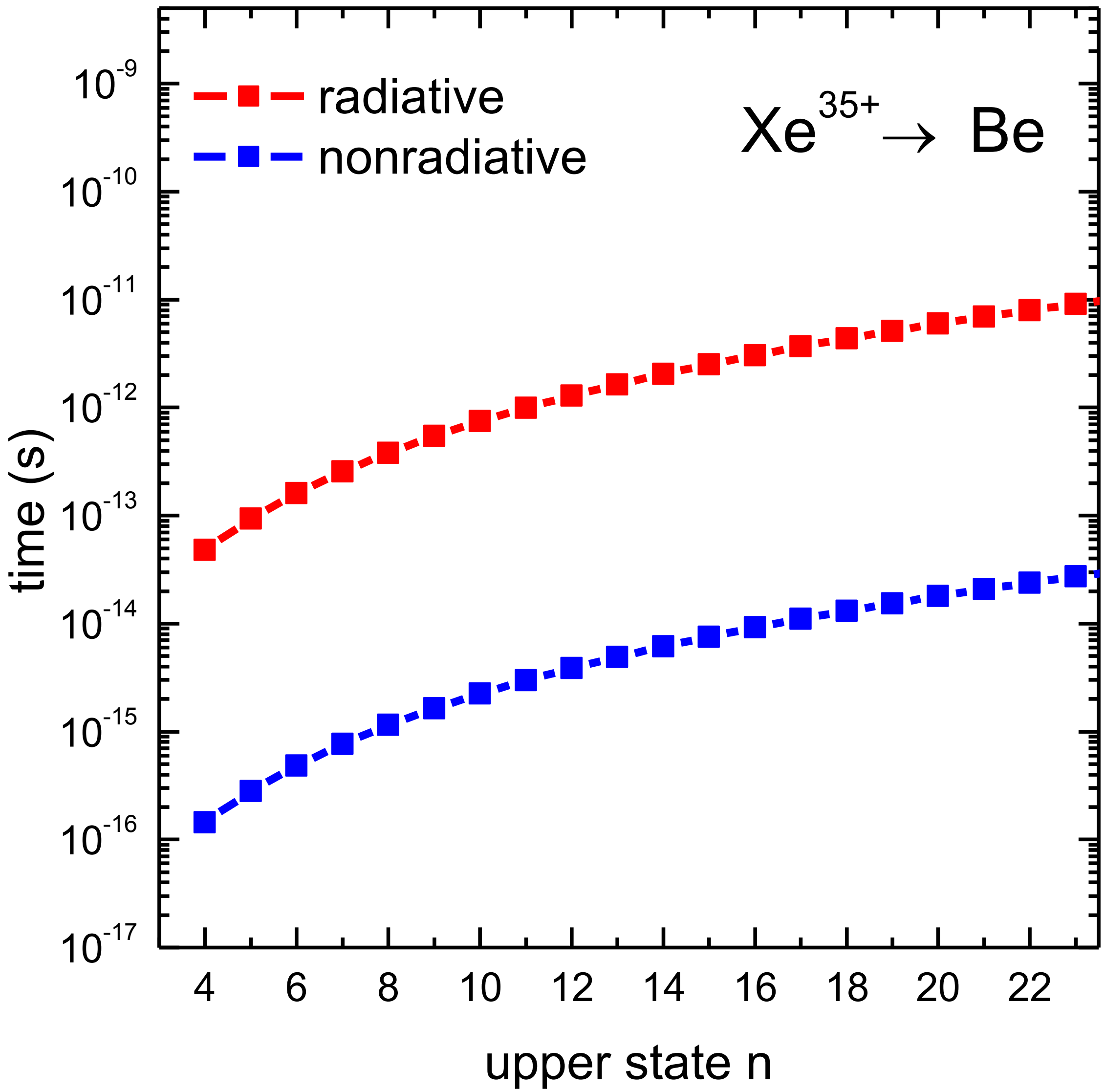


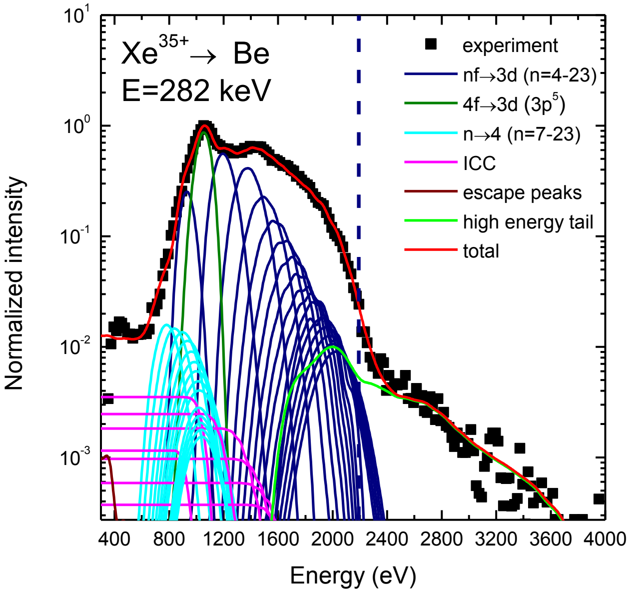
# Experimental evidence of the ICD process

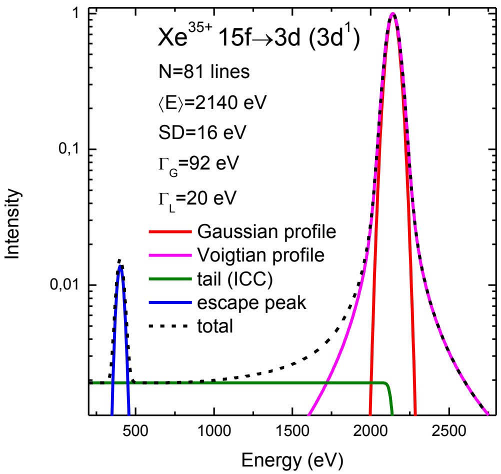


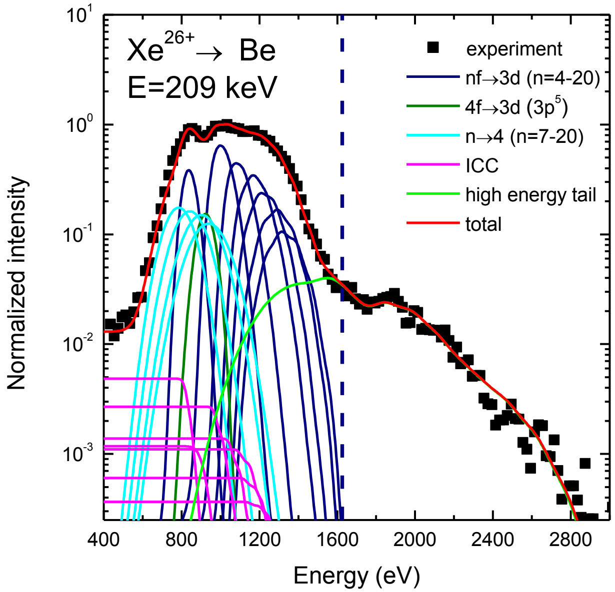
# RHA Relaxation time



# Details of X-ray spectra – high-energy structure



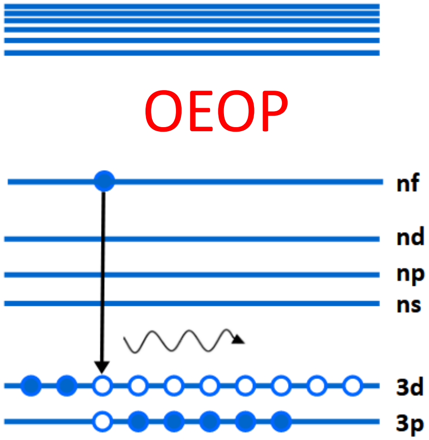


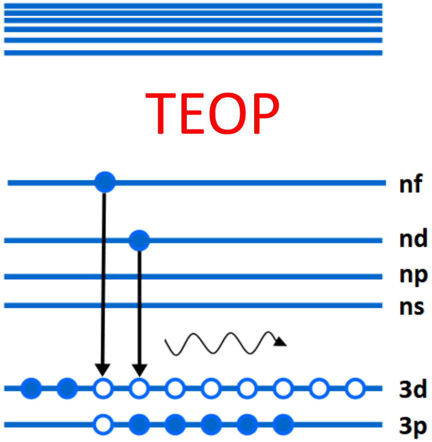


- Observed high-energy structure above the M-series limit
- It cannot be explained by the Lorentzian tail
- High-energy structure could be explained by pile-up events– two transitions are detected as one event having double energy
- High-energy structure could be explained by TEOP transitions

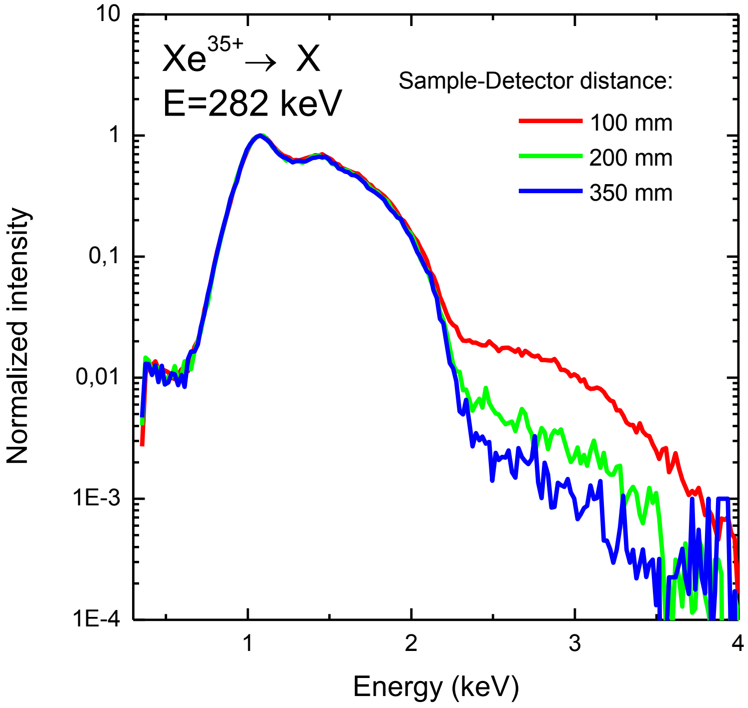
# Two-electron one-photon transition

- TEOP predicted by Heisenberg in 1925
- Observed by Wölfi et. al in 1975 in high energy (MeV) ion-atom collisions
- Selection rules for TEOP: $\Delta l_1 = \pm 1$, $\Delta l_2 = \pm 0$ or 2
- TEOP K-shell branching ratio for low Z ions measured and calculated ~ $10^{-3}$
- Predicted TEOP M-shell branching ratio $< \alpha \approx 1/137$





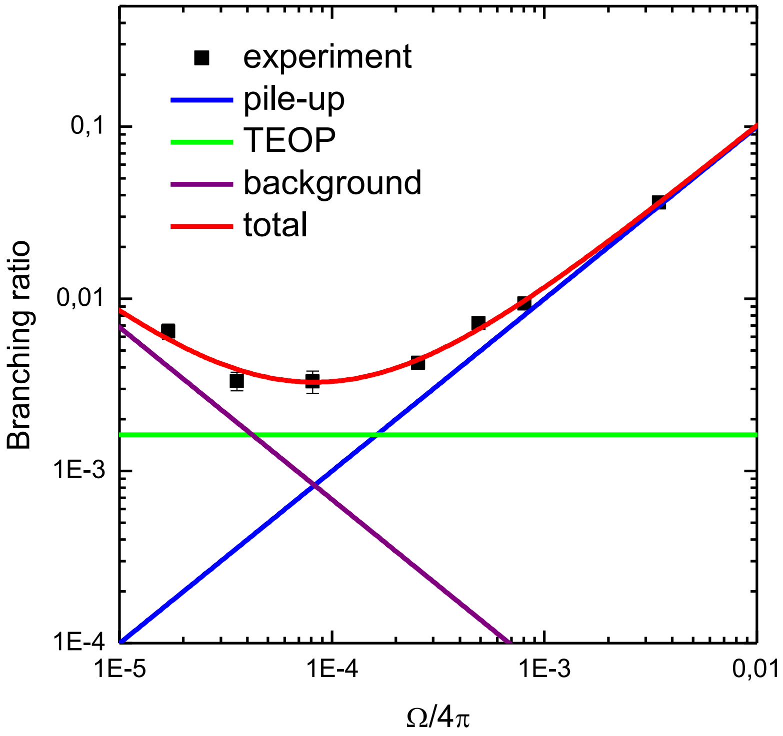
# TEOP – branching ratio measurments



Scaling of branching ratio:

- OEOP ~ Ω
- TEOP ~ Ω → $BR_{TEOP}$ = const
- Pile-up ~ $\Omega^2$ → $Br_{Pile\text{-}up}$ ~ Ω
- Background =const → $BR_{BG}$ ~ 1/Ω

# Separation of TEOP and pile-up



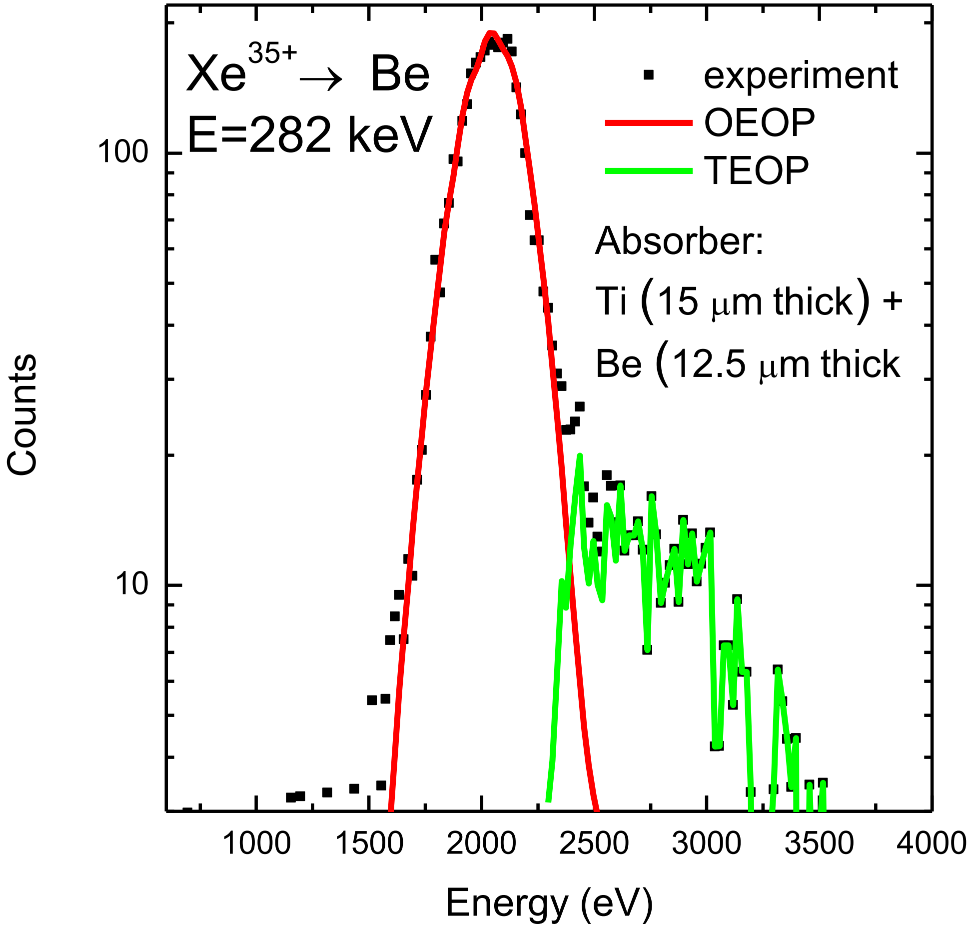
- In order to extract the TEOP branching ratio a series of measuremants for decreasing detector solid angle Ω was performed

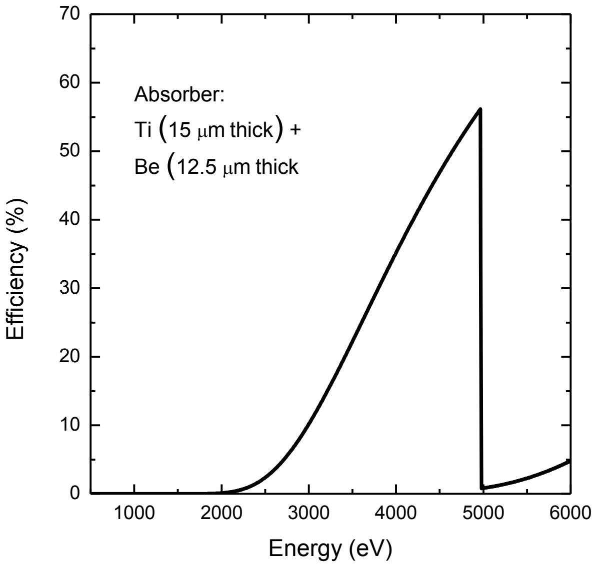
- to separate contribution of different processes results were fitted by the function **$BR(\Omega)=\alpha\cdot(\Omega/4\pi)+\beta+\gamma/(\Omega/4\pi)$**

- Extracted branching ratio:

**$BR=1.6\cdot10^{-3}$ (±20%)**

# TEOP – experiment with titanium absorber





**Branching ratio: $1.4\cdot10^{-3}$ (±25%)**

# Conclusions

- The measured M-X-ray spectra for $Xe^{26+}$ and $Xe^{35+}$ were resolved and interpreted
- The importance of the IDE process was demonstrated
- The observed cut-off terminating the Pashen series can be interpreted as experimental evidence of the ICD process
- TEOP transitions in collisions of slow $Xe^{q+}$ (q=23-40) ions with beryllium surface were observed
- TEOP branching ratio was measured

Thank you for your attention!