# Atomic Processes and Beam Lifetimes

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- AP experiments at the ESR
  - the electron cooler
  - the internal jet-target

- charge exchange processes
(cross sections and beam lifetimes)

  - at the electron cooler
    - recombination

  - at the jet-target
    - electron capture
    - ionization

- beam lifetime estimates

# Charge exchange rates and beam lifetimes in storage rings

$$1/\tau = \lambda = \lambda_{target} + \lambda_{cooler} + \lambda_{residual\ gas}$$

the beam lifetime ($\tau$) is connected to the charge-exchange cross-section ($\sigma$) by the relation

$$\lambda = \frac{1}{\tau} = \rho \times \sigma \times f$$

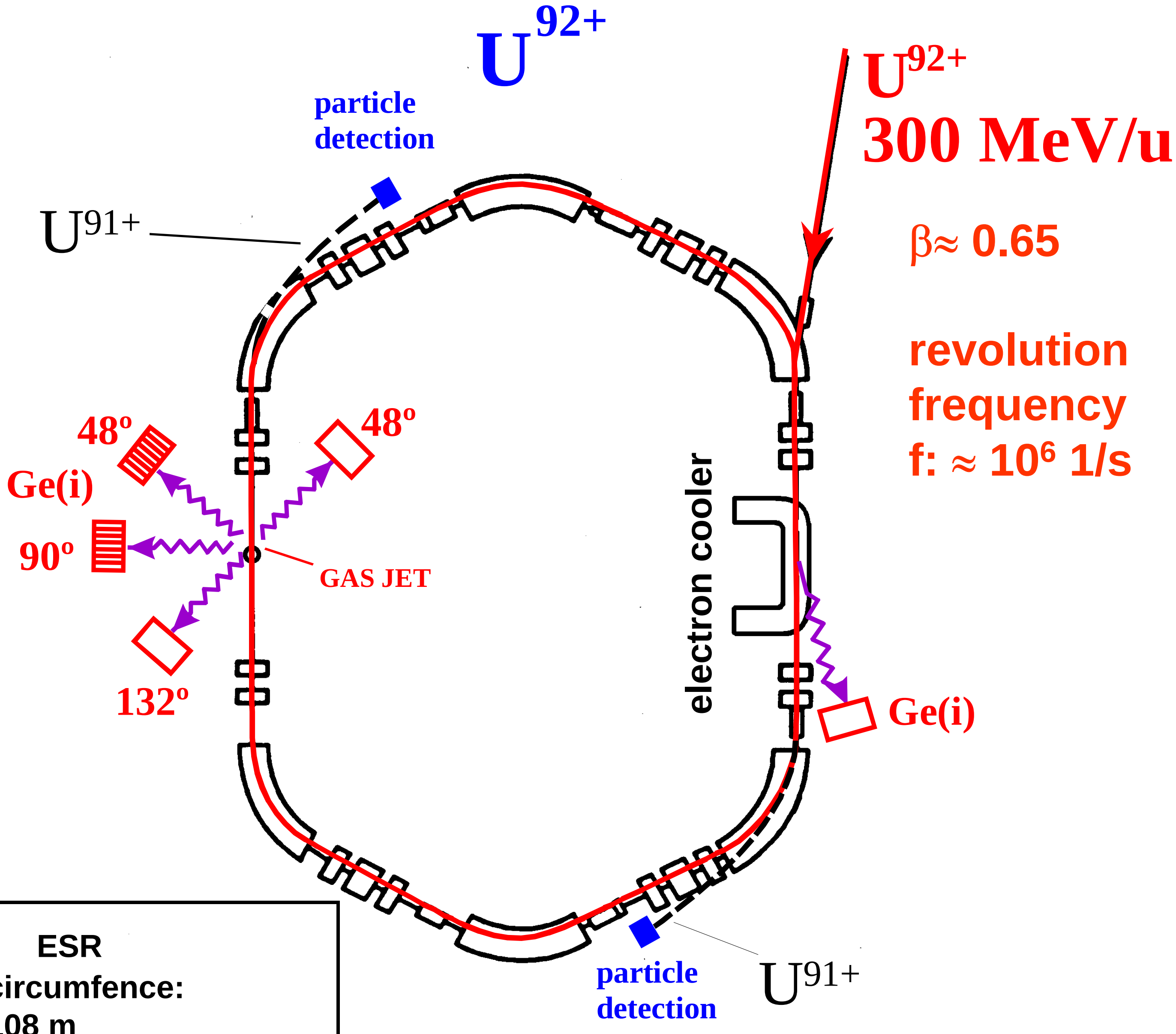
$\lambda$ denotes the charge exchange rate
$\rho$ the effective target thickness ($1/\mathrm{cm}^2$)
$f$ the revolution frequency of the circulating ion beam

***Like in the jet-target, collisions with residual Gas atoms or moleculs may lead to beam losses***

**For the ESR the assumed composition of the residual is**

**79% $H_2$ 20% $N_2$ 1% Ar**

# Lamb-Shift Studies for High-Z Ions: X-ray Spectroscopy at the ESR Storage Rings

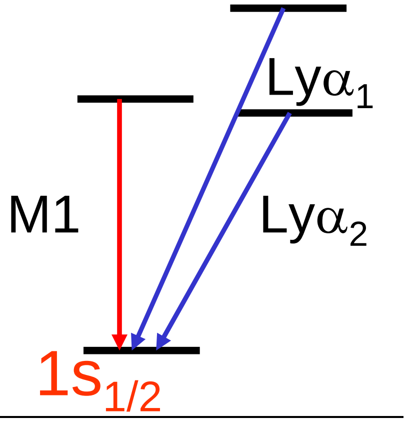


$\beta \approx 0.65$

**revolution frequency**
**f: ≈ $10^6$ 1/s**

**ESR**
**circumfence:**
**108 m**
**number of Ions:**
**$10^8$**

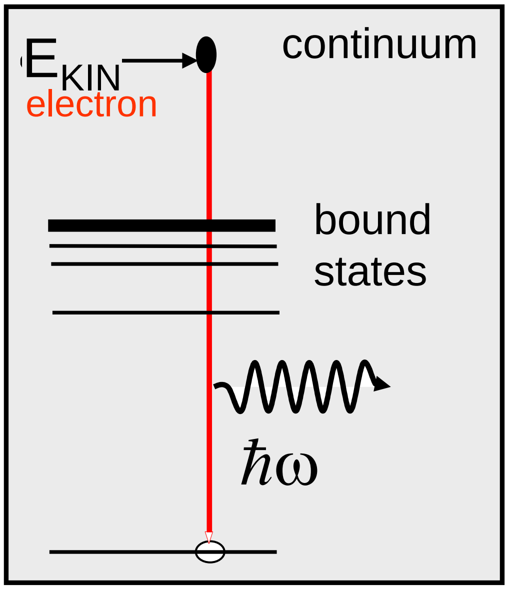
*At the ESR, production of characteristic x-rays by electron capture into the bare Ions (electron cooler or jet-target)*



# Electron Pickup Processes of HCI in Collisions with Electrons (Dynamic Processes)

## Radiative Recombination/Electron Capture

$$A^{Z+} + e^{-} \Rightarrow A^{(Z-1)+} + \hbar\omega$$

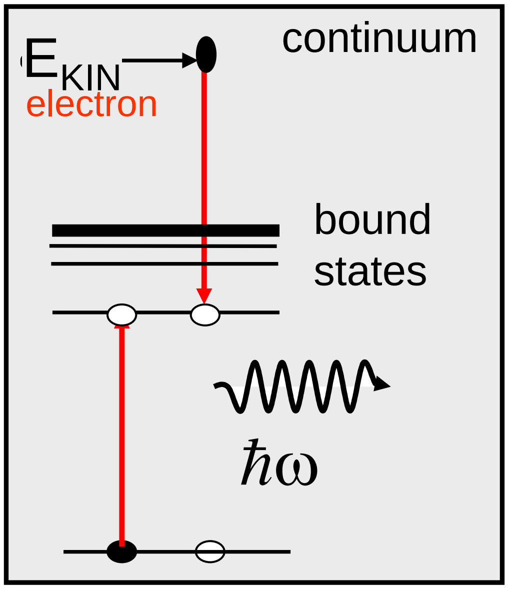


- *•Electron capture into a bound ionic state by emission of a photon*

$$\hbar\omega = E_B + E_{KIN}$$

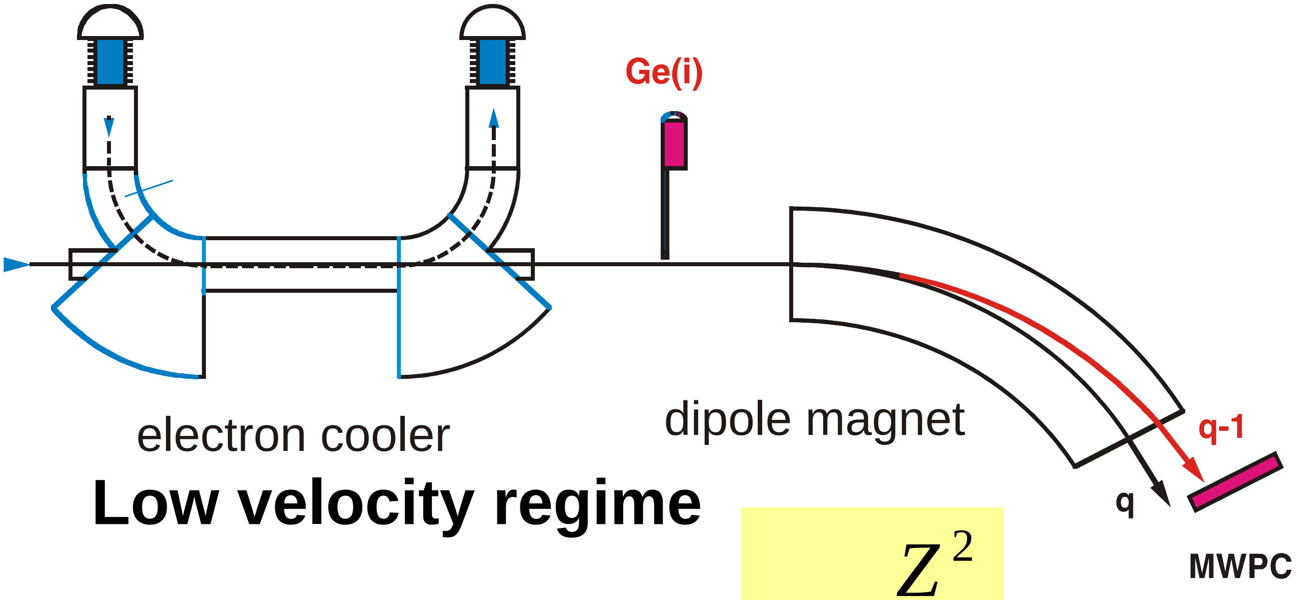
- *•Time-reversed photionization*
- *•Only possible capture/recombination process for bare ions colliding with electrons*

## Dielectron Recombination/Electron Capture



- *•Resonant (non-radiative) capture of an electron into a bound state*
- *•Time-reversed Auger process*
- *•Important charge exchange process for multi-electron ions*

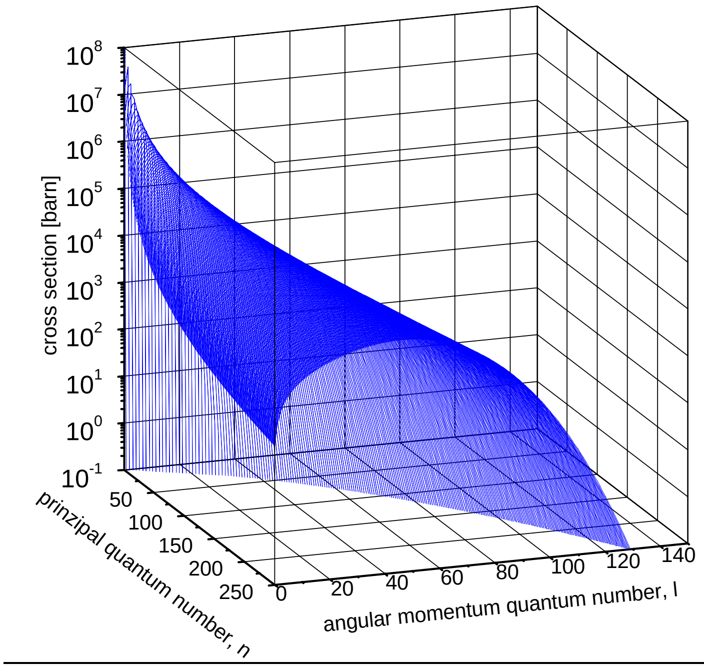
# Radiative Recombination / Electron Capture at Electron Coolers

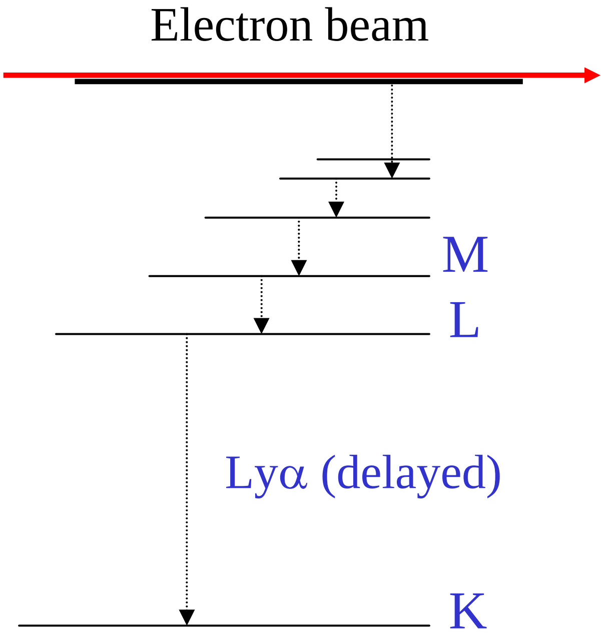


## Low velocity regime

$$\sigma \propto \frac{Z^2}{n}$$

## At low velocities RR populates high n,l states but no s-levels

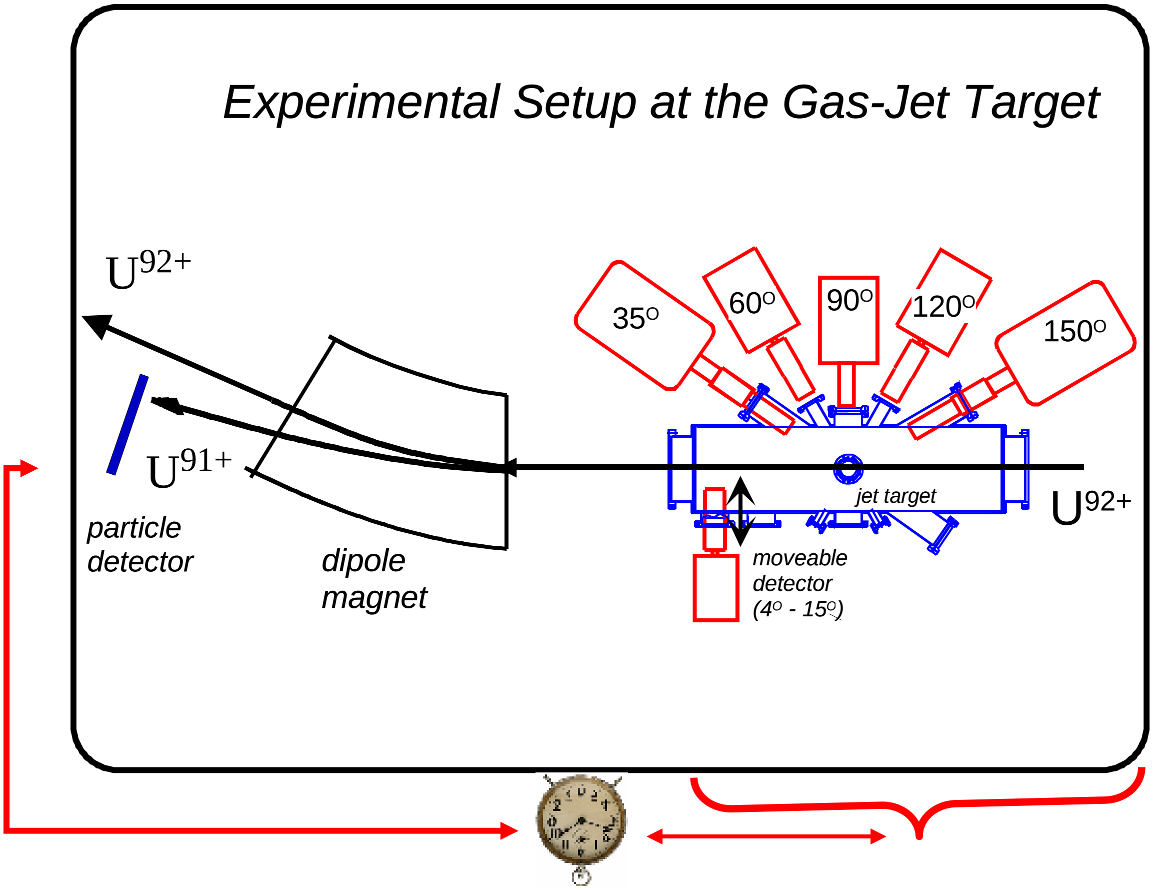




# AP experiments at the Jet-Target

Beam energies: 10 to 400 MeV/u
Charge states: bare to Li-like ions
Photon detection: $\varepsilon \approx 10^{-3}$-$10^{-2}$
Photon energies: 2 keV – 1 MeV

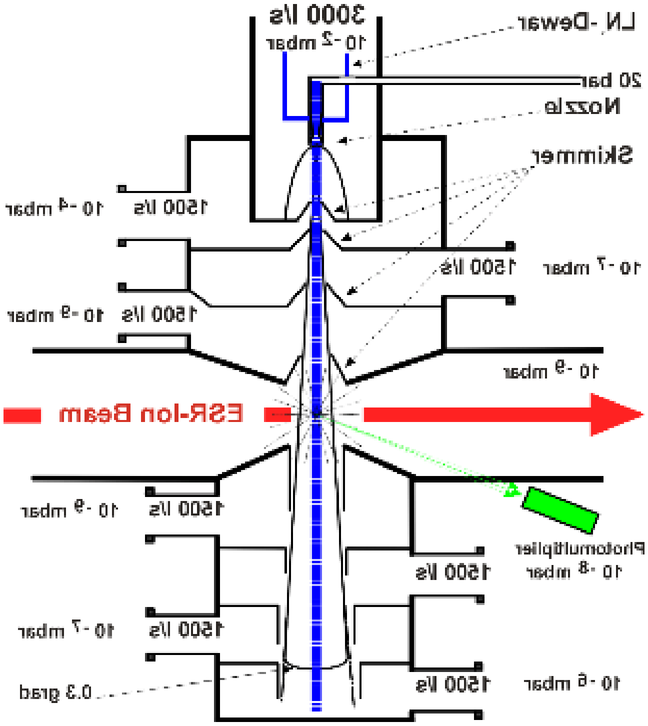
- **Photon angular correlation studies**
- **0-deg photon spectroscopy**
- **X-X coincidence experiments**
- **photon polarization experiments**
- **precision photon spectroscopy**


*Experimental Setup at the Gas-Jet Target*

**x-ray/particle coincidences**

# The Jet-Target

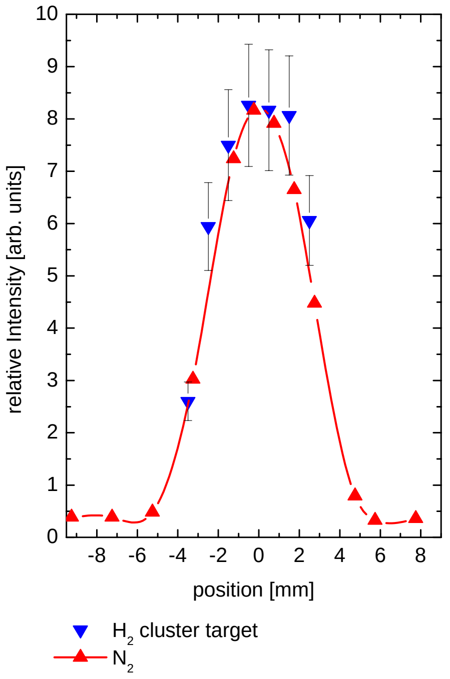
## Supersonic jet, operates in ultra high vacuum enviroment ($10^{-11}$ mbar)



**Target densities**

**$10^{12}$ – $10^{14}$ p/cm$^3$**

**Single collision conditions**

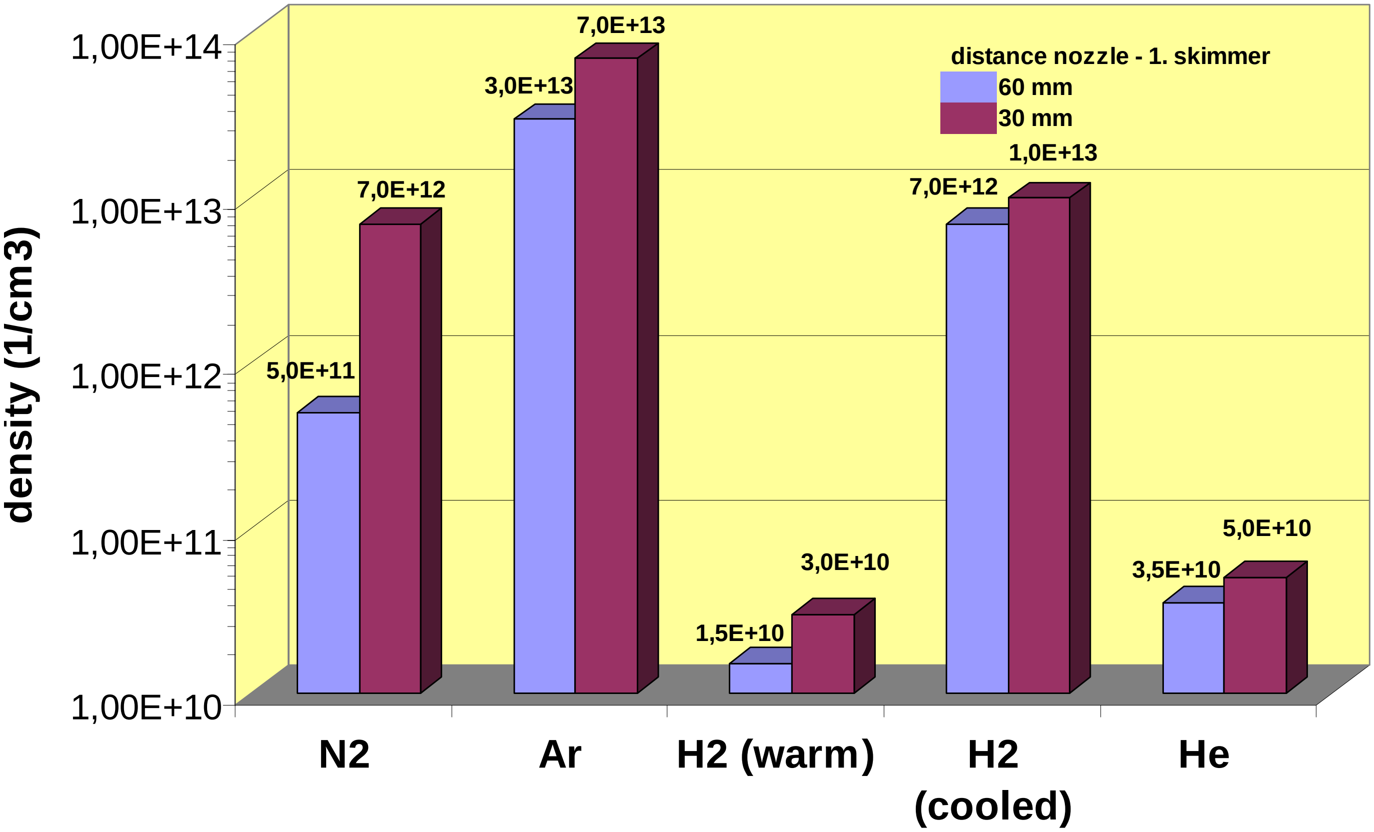


Target profile:

**FWHM: 5 mm**

**A. Krämer et al., NIM B174, 205 (2001)**

# Target densities



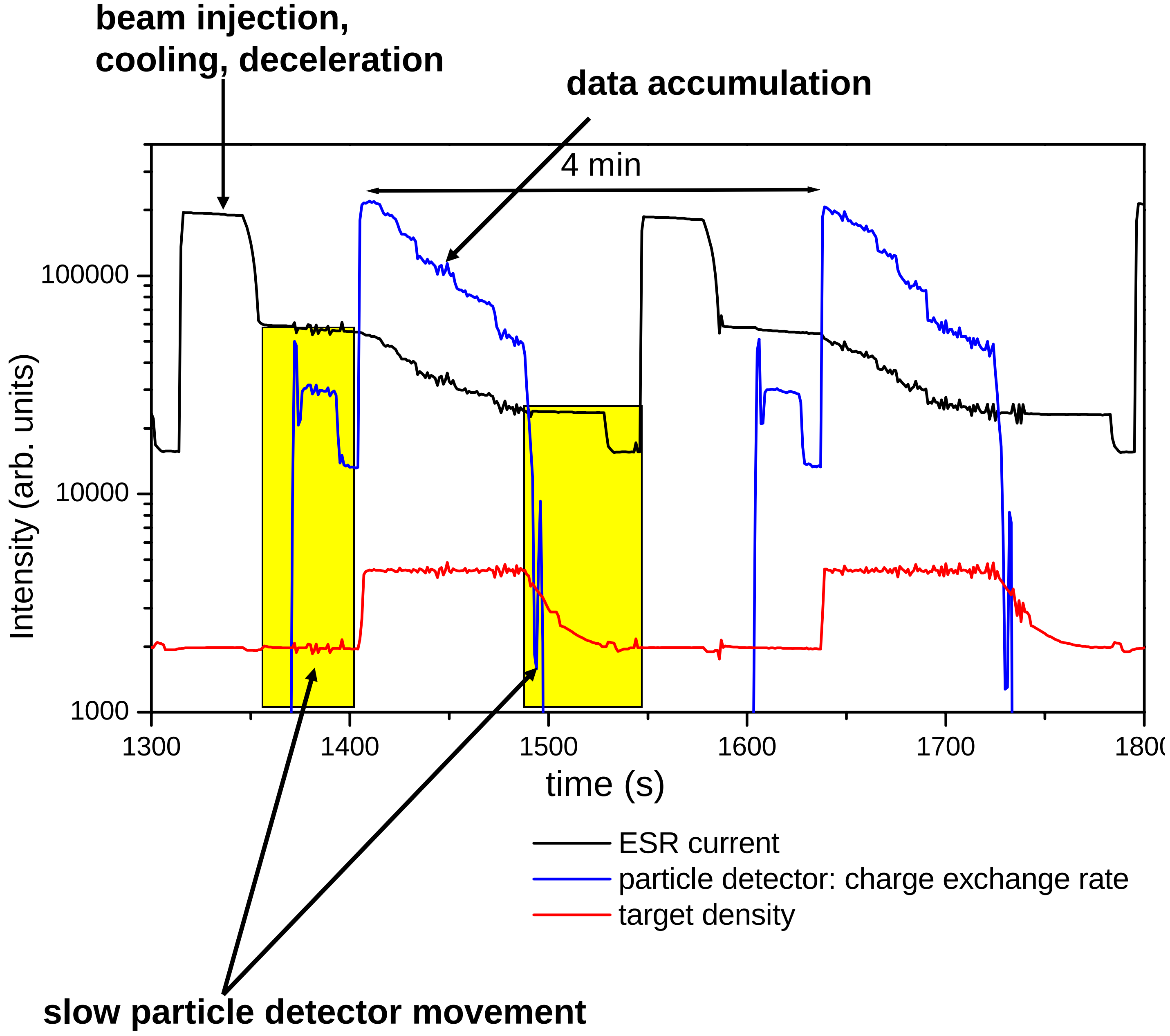
***by cooling to LN2 temperatures a density increase from ≈$10^{10}$ p/$cm^3$ to ≈$10^{13}$ p/$cm^3$ has been achieved for $H_2$***

**A. Krämer et al., NIM B174, 205 (2001)**

## Future modifications

- **Lower temperatures**
- **Variable/smaller jet-beam diameter (5mm to 1mm)**

# experiment cycle at the target



**beam injection, cooling, deceleration**

**data accumulation**

**slow particle detector movement**

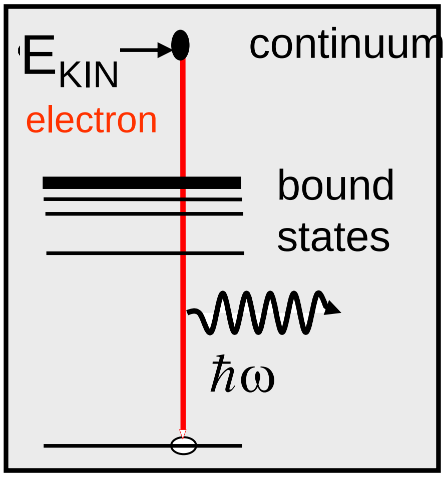
***By fast particle detector movement, the overall efficiency has now been improved by up to a factor of two.***

# Charge Exchange Processes for Bare Ions

## (High energy domain)

**REC:** Radiative Electron Capture (time reversed photoionization)

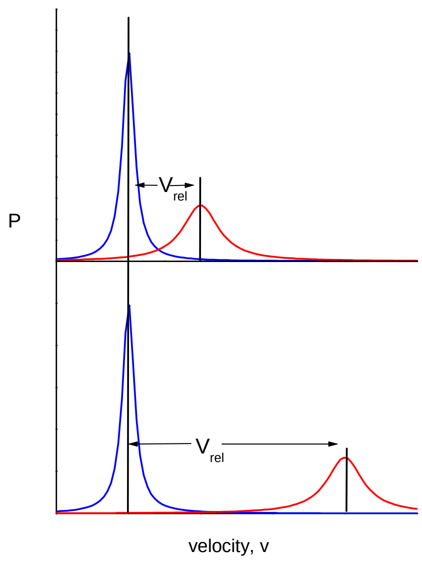
$$\sigma_{REC} \propto \frac{\left(Z_T \times Z_P\right)^5}{V^{5/2}}$$



**NRC:** Kinematic or Non-Radiative Electron Capture (three body interaction where momentum and energy is shared between the collision partner)

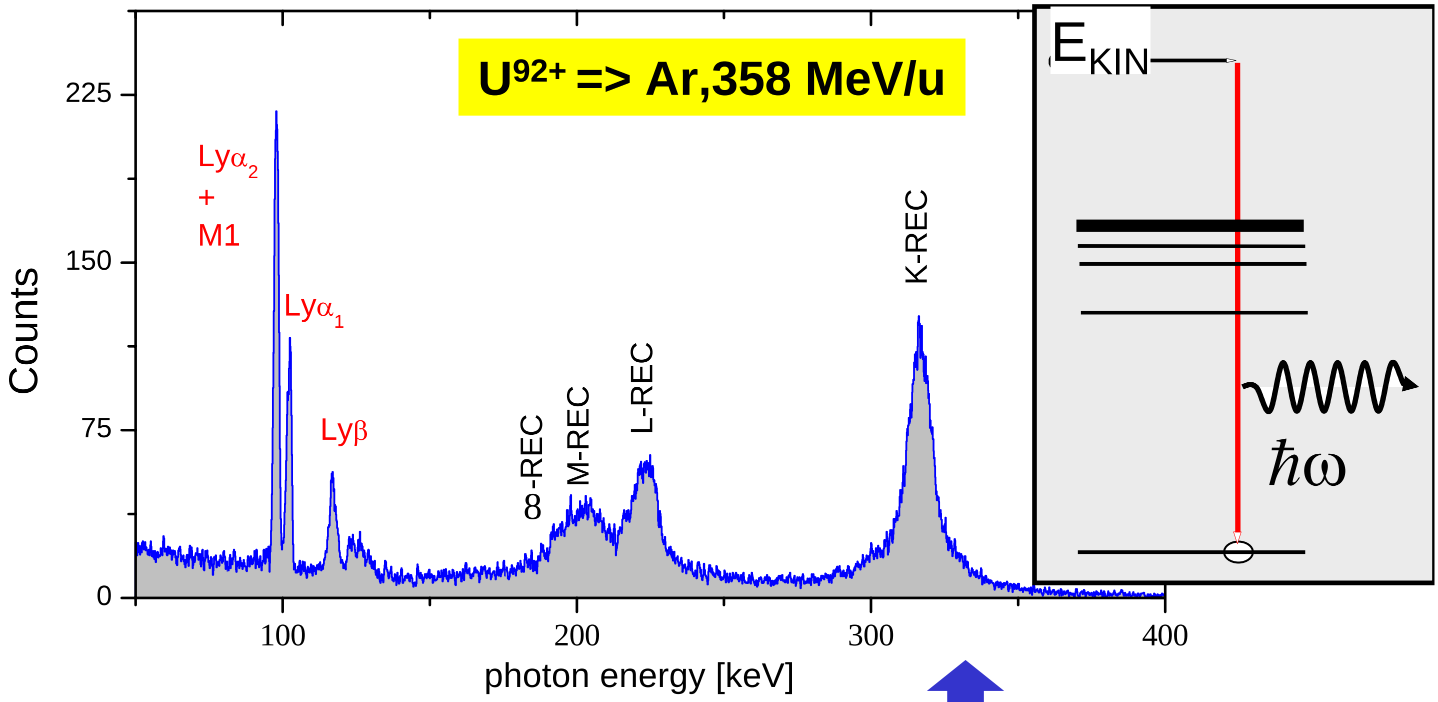
$$\sigma_{NRC} \propto \frac{Z_T^{\,5} \times Z_P^{\,5}}{V^{11}}$$

(NRC, Non-Radiative Electron Capture)



$Z_T$ : Nuclear charge of the target
$Z_P$ : Nuclear charge of the projectile
V : Relative velocity between target electron and projectile

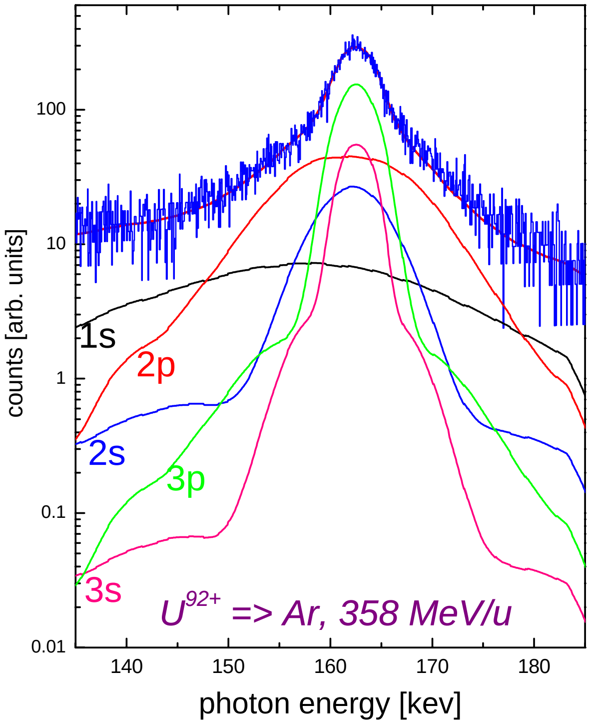
# Radiative Electron Capture
## Capture of Quasifree Targetelectrons



REC photon energy

$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$

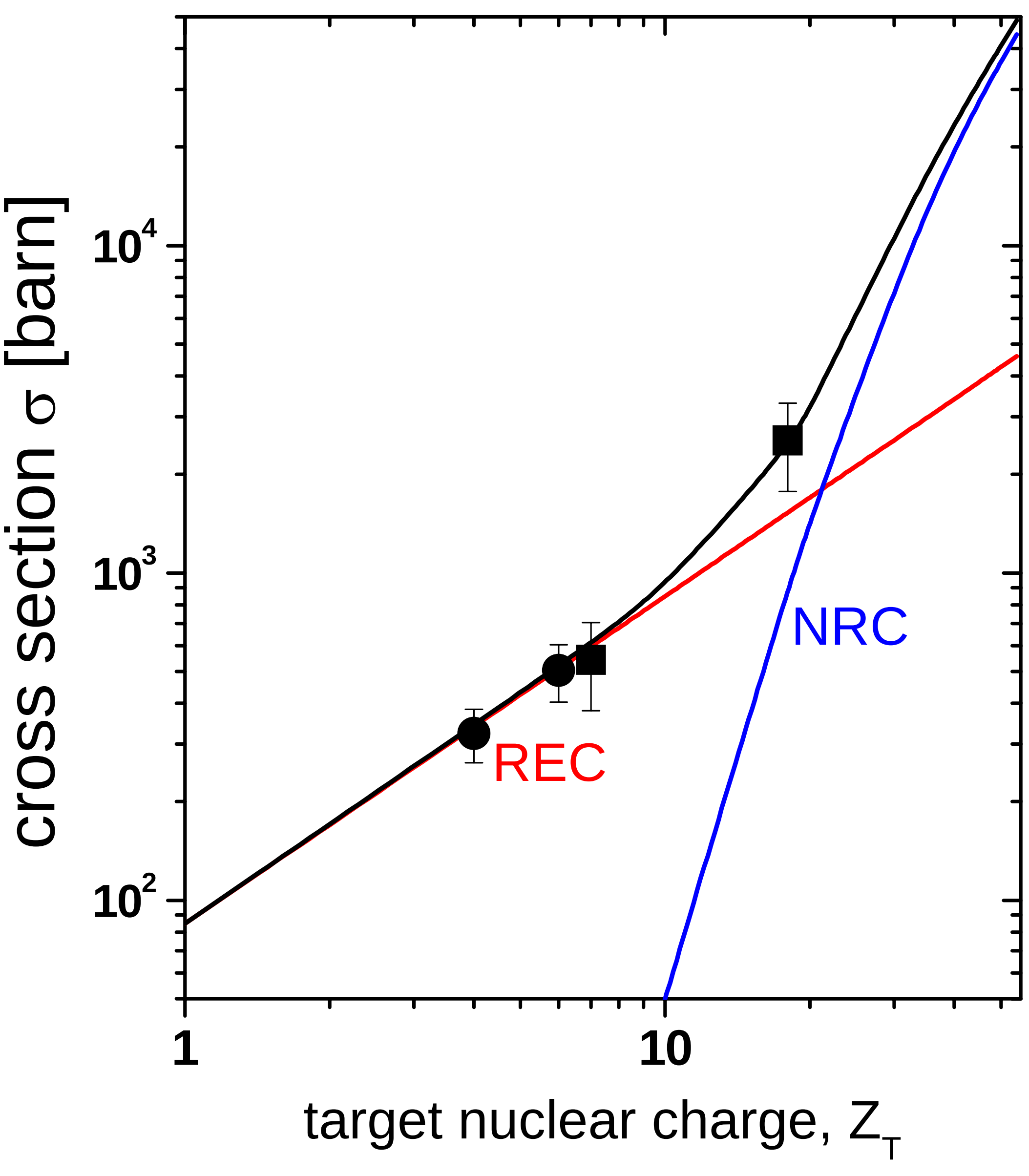
**Shape and width of REC lines are determined by the momentum distribution of the target electrons**



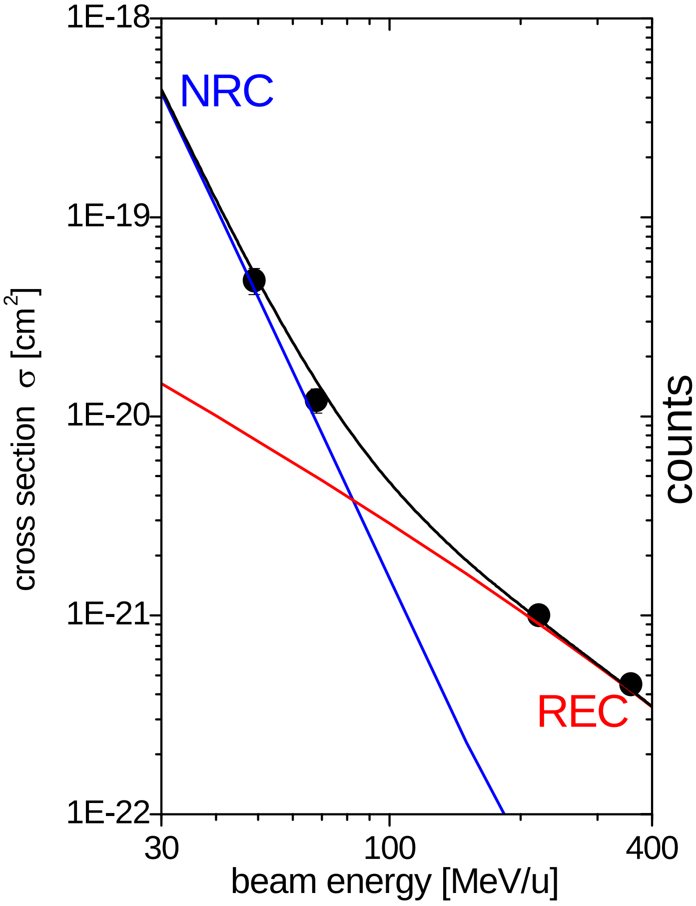
# $Z_T$ scaling of cross sections

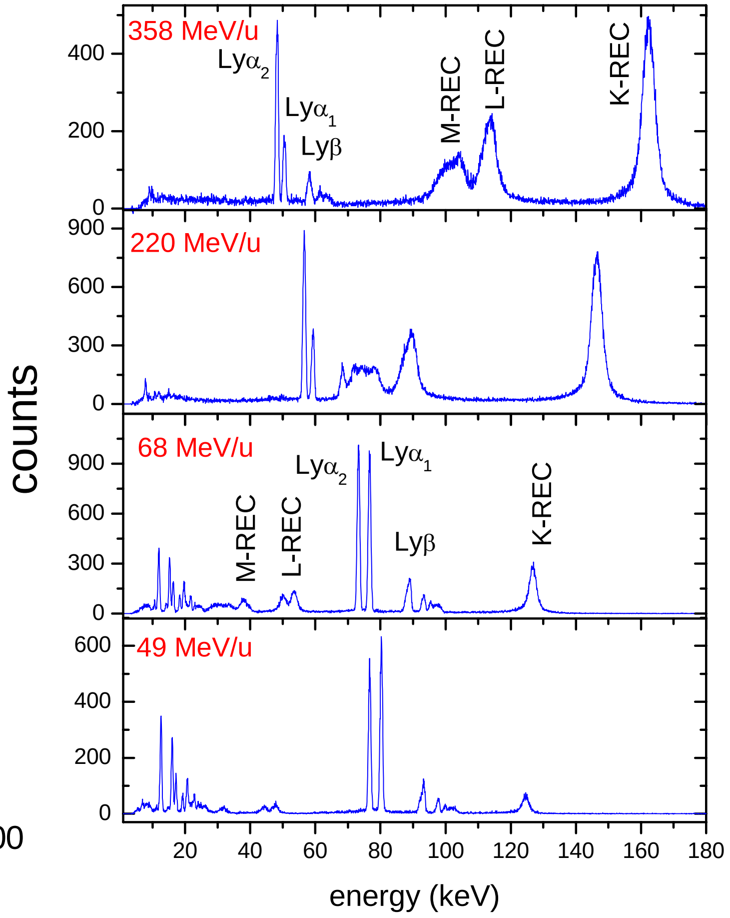
$$\sigma_{\mathrm{REC}} \propto Z_T \cdot Z_P^{\,5}$$

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



# REC Cross Sections



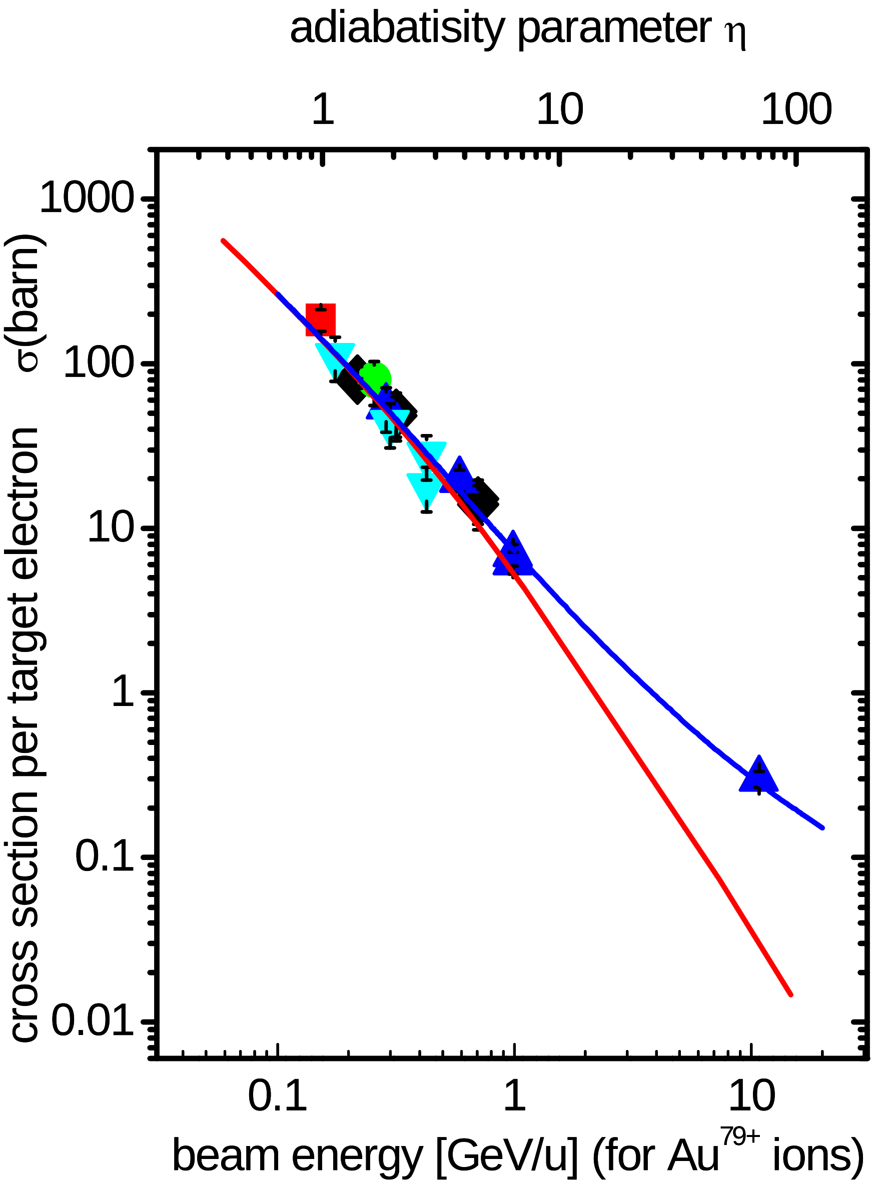


REC: dipole approximation
NRC: eikonal approach

For high-Z ions and high energies, REC is the most important charge exchange process for collisions with low-Z targets

REC populates predominately s-states and in particular the 1s ground state (80%)

# Total REC cross sections for bare ions



$$\eta = \frac{E_{KIN}}{E_K}$$

$E_K$:
K-shell binding energy

$E_{KIN}$ :
kinetic projectile energy

**Data cover the Z range between Z=54 to 92**

**(BEVALAC, SIS/FRS/ESR, BROOKHAVEN)**

━━ **complete relativistic calculations for Au $^{79+}$ (Eichler et. al)**

━━ **dipole approximation**

***The simple non-relativistic dipole approximation provides an accurate tool for cross section preditions (below 1 GeV/u)***

# Beam life times with the gasjet target

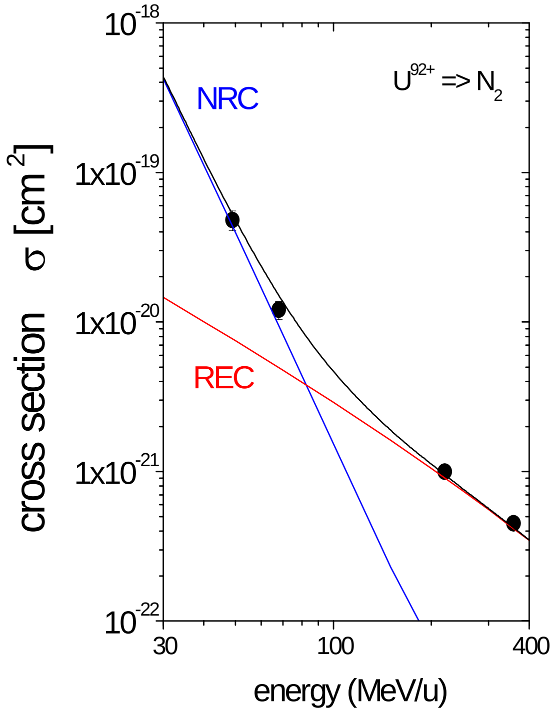
the beam lifetime ($\tau$) is connected to the charge-exchange cross-section ($\sigma$) by the relation

$$\boxed{\lambda = \frac{1}{\tau} = \rho \times \sigma \times f}$$

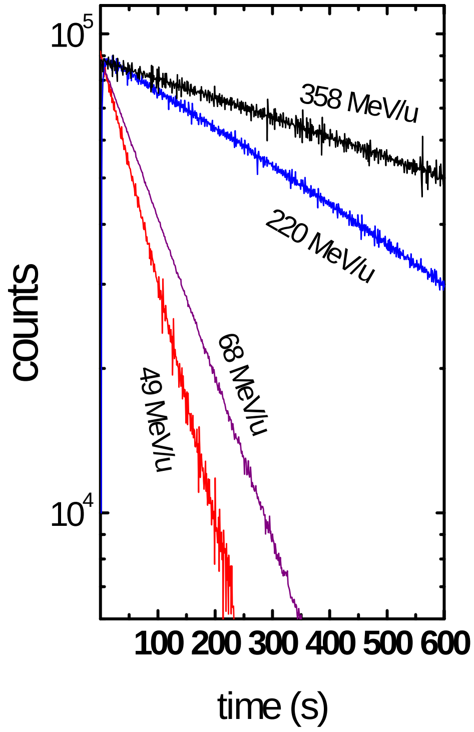
$\lambda$ denotes the charge exchange rate
$\rho$ the effective target thickness ($1/cm^2$)
$f$ the revolution frequency of the circulating ion beam

$U^{92+} \Rightarrow N_2$

cross sections



beam lifetimes



**Th. Stöhlker et al., Phys. Rev. A58, 2043 (1998)**

# Beam life times with the gasjet target

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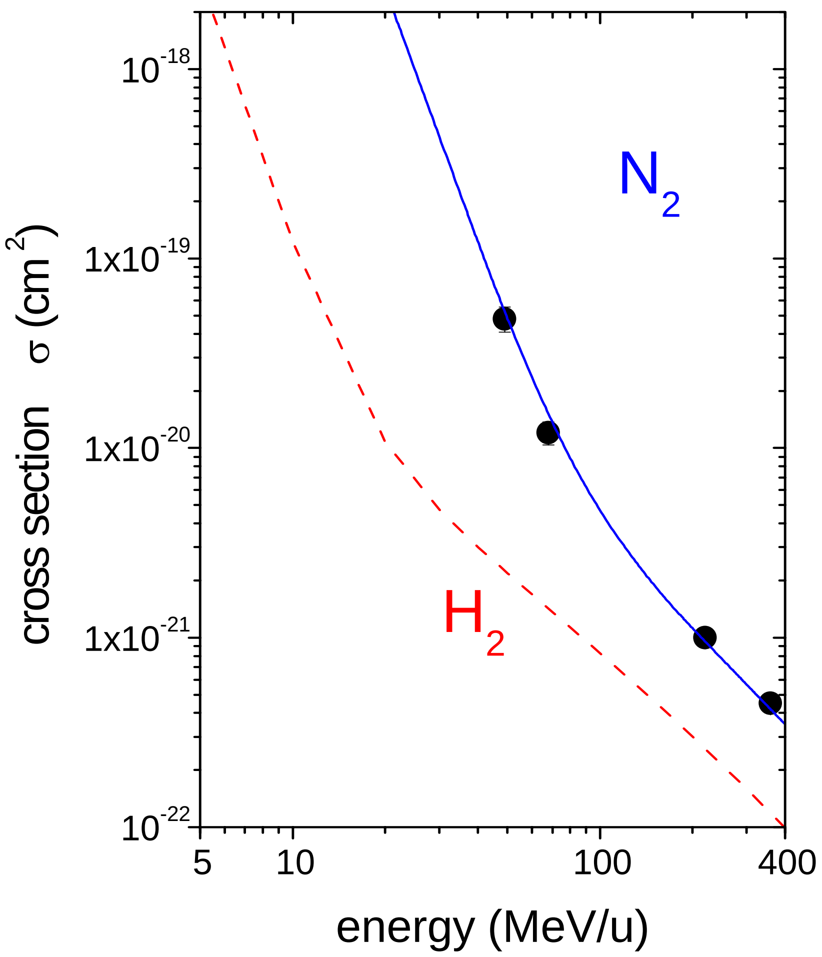
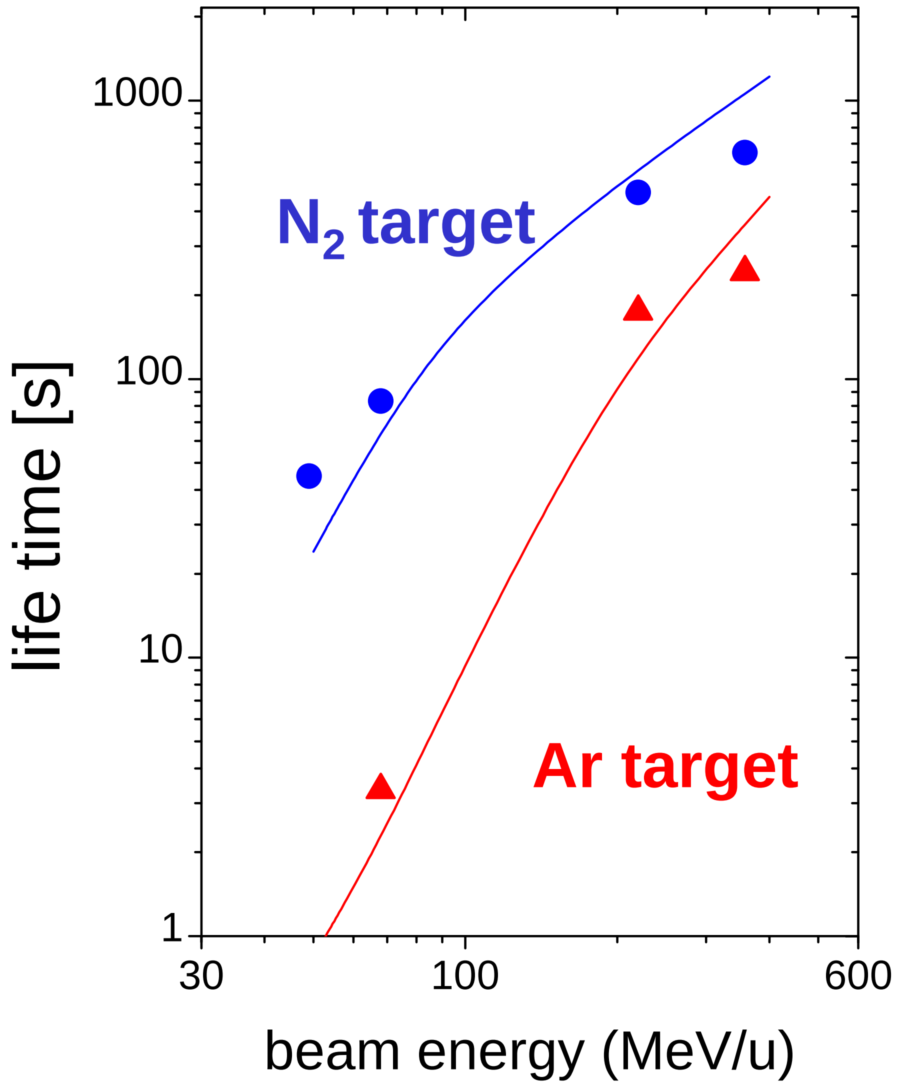
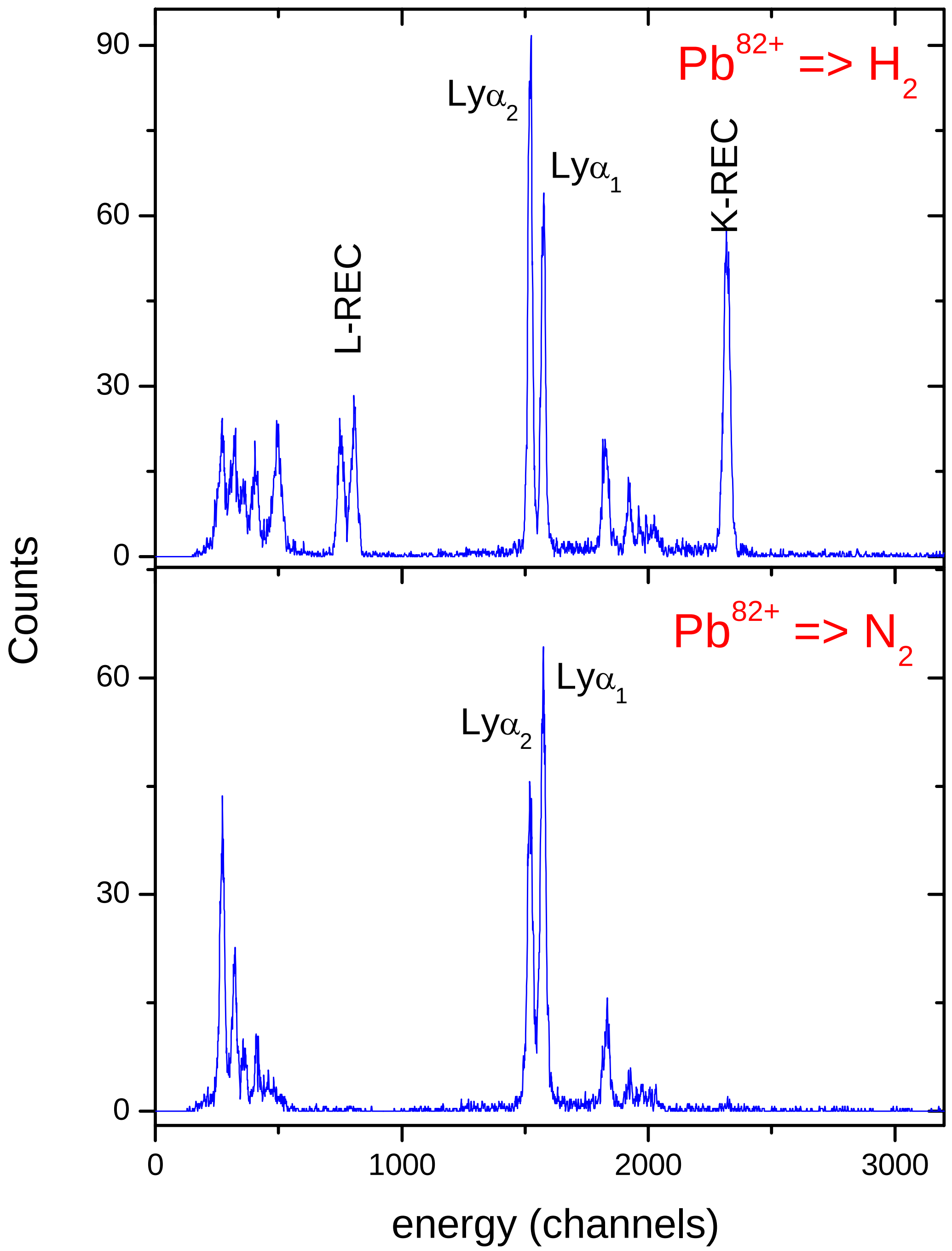


# Lifetimes for bare uranium beams



$10^{12}$ p/cm$^2$
cooler: 100 mA

# First test experiment with an $H_2$-target: bare Pb ions at 25 MeV/u



$\theta_{LAB}$ =150 deg

# Beam lifetimes for ion beams in the NESR for a $H_2$ target at 740 MeV/u

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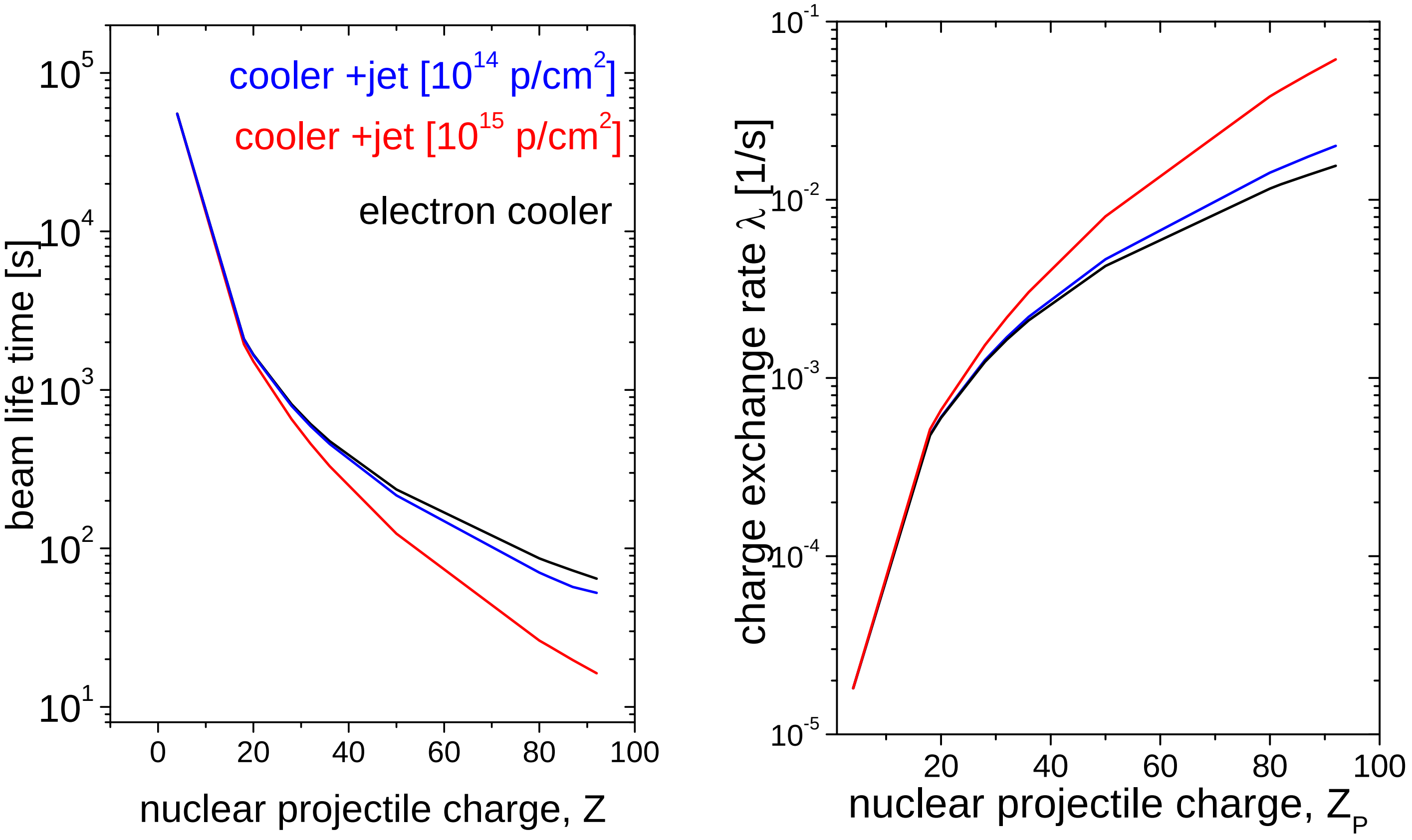
## 500 mA cooler current; T=0.1 eV



# Beam lifetimes for ion beams in the NESR for a Xe target at 500 MeV/u

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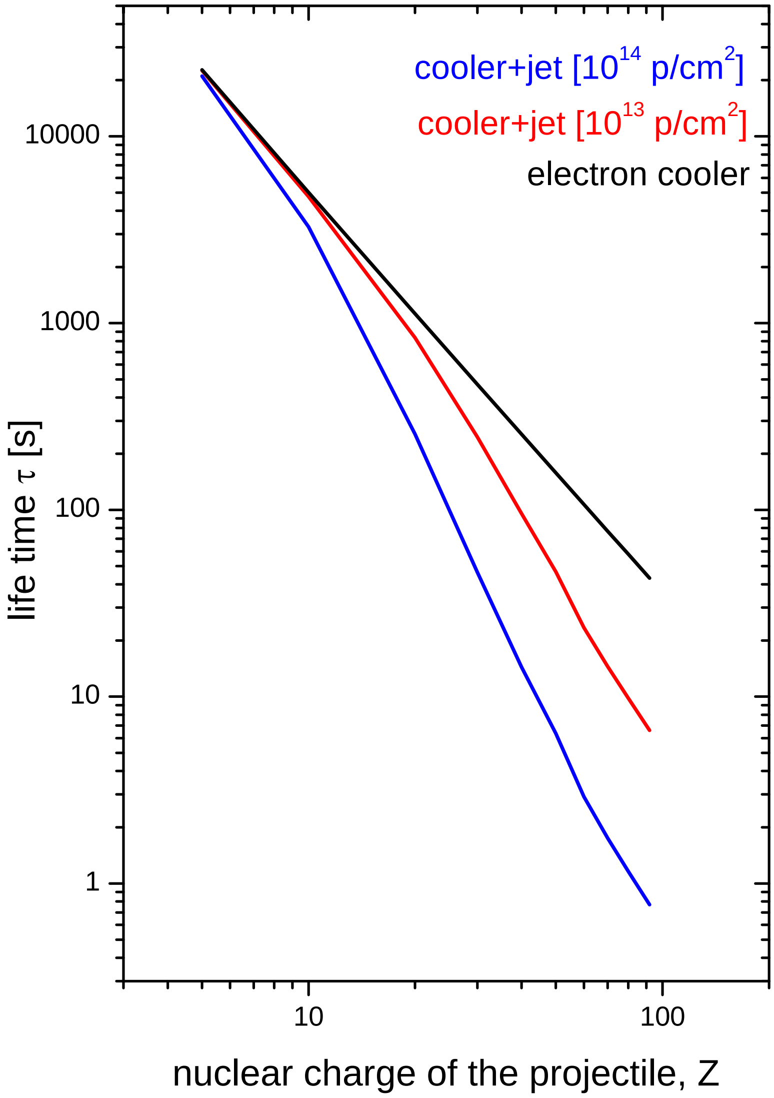
**500 mA cooler current; T=0.1 eV**



***With a Xe target and for heavy projectiles, the beam life time is entirely dominated by charge exchange in the target***

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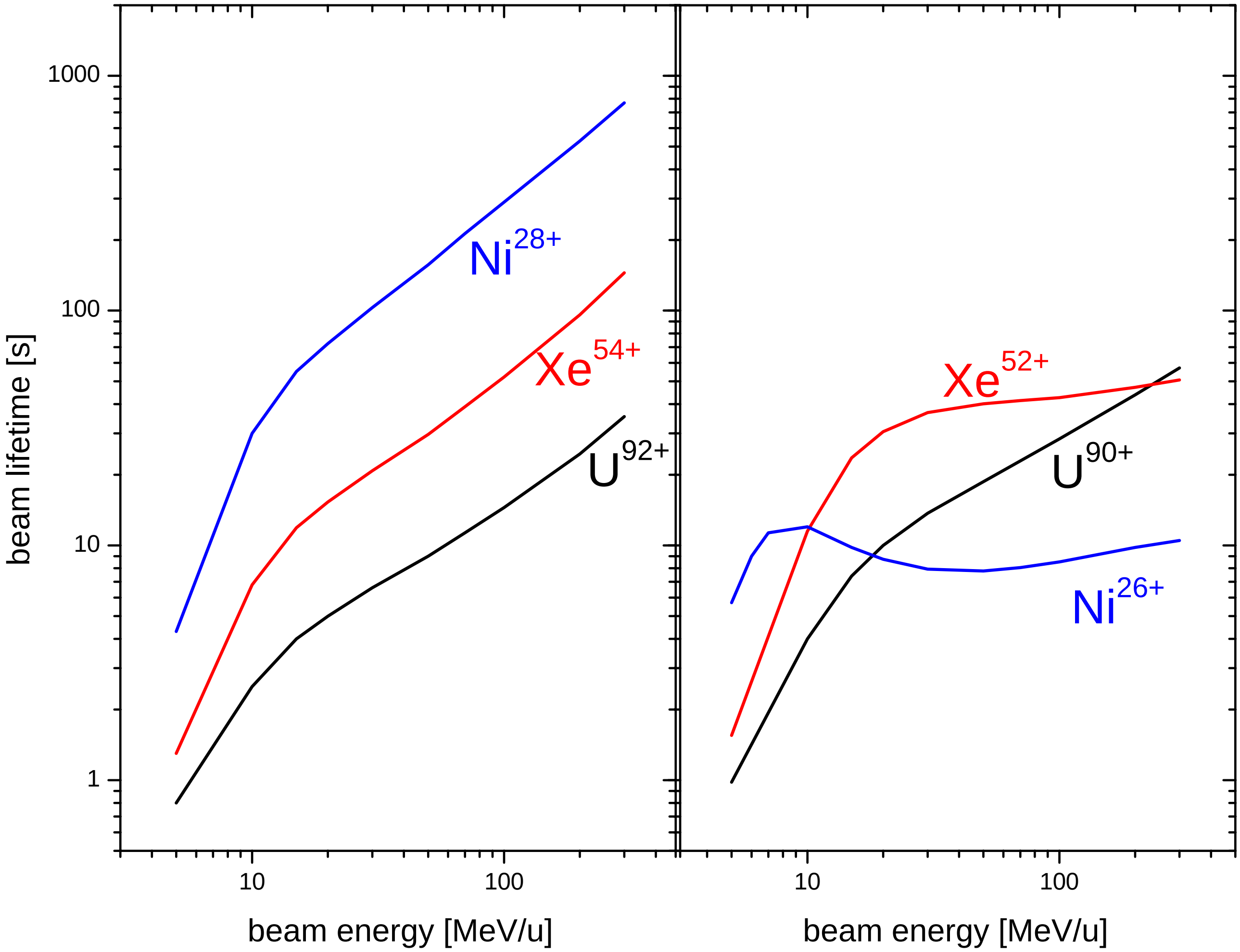
# Beam life times for few-electron ions in the NESR

interplay between ionization and capture

ionization $\sigma_{\text{ionis}} \propto \frac{Z_T^{\,2}}{Z_P^{\,4}}$

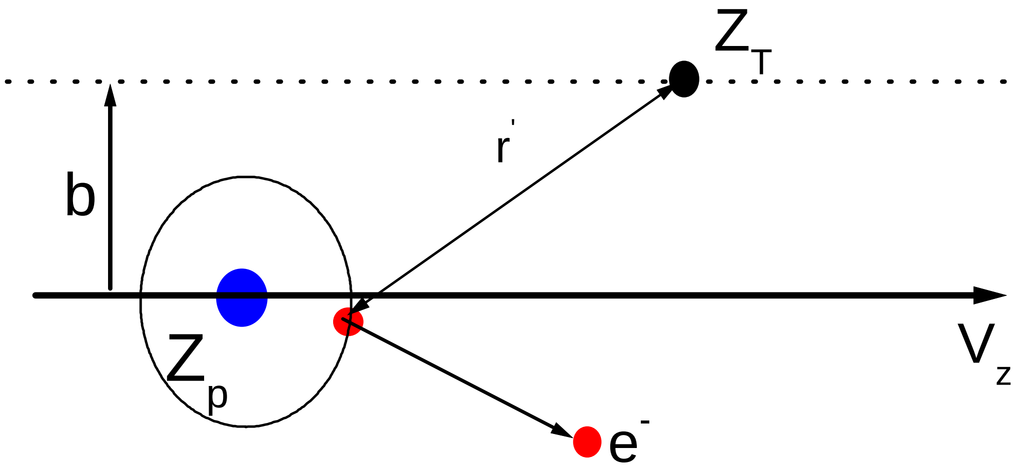
capture
$$\begin{cases} \sigma_{\text{REC}} \propto Z_T \cdot Z_P^{\,5} \\ \sigma_{\text{NRC}} \propto Z_T^{\,5} \cdot Z_P^{\,5} \end{cases}$$



***for heavy elements, a closed K-shell results in an increase of beam lifetime by a factor of two***

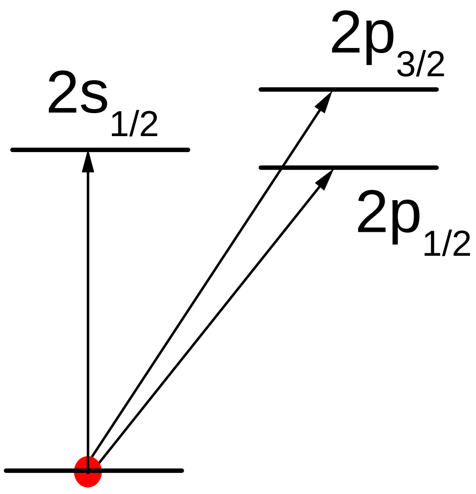
# **Charge exchange for few-electron ions**

## *Projectile excitation and ionization of high-Z one-electron ions*



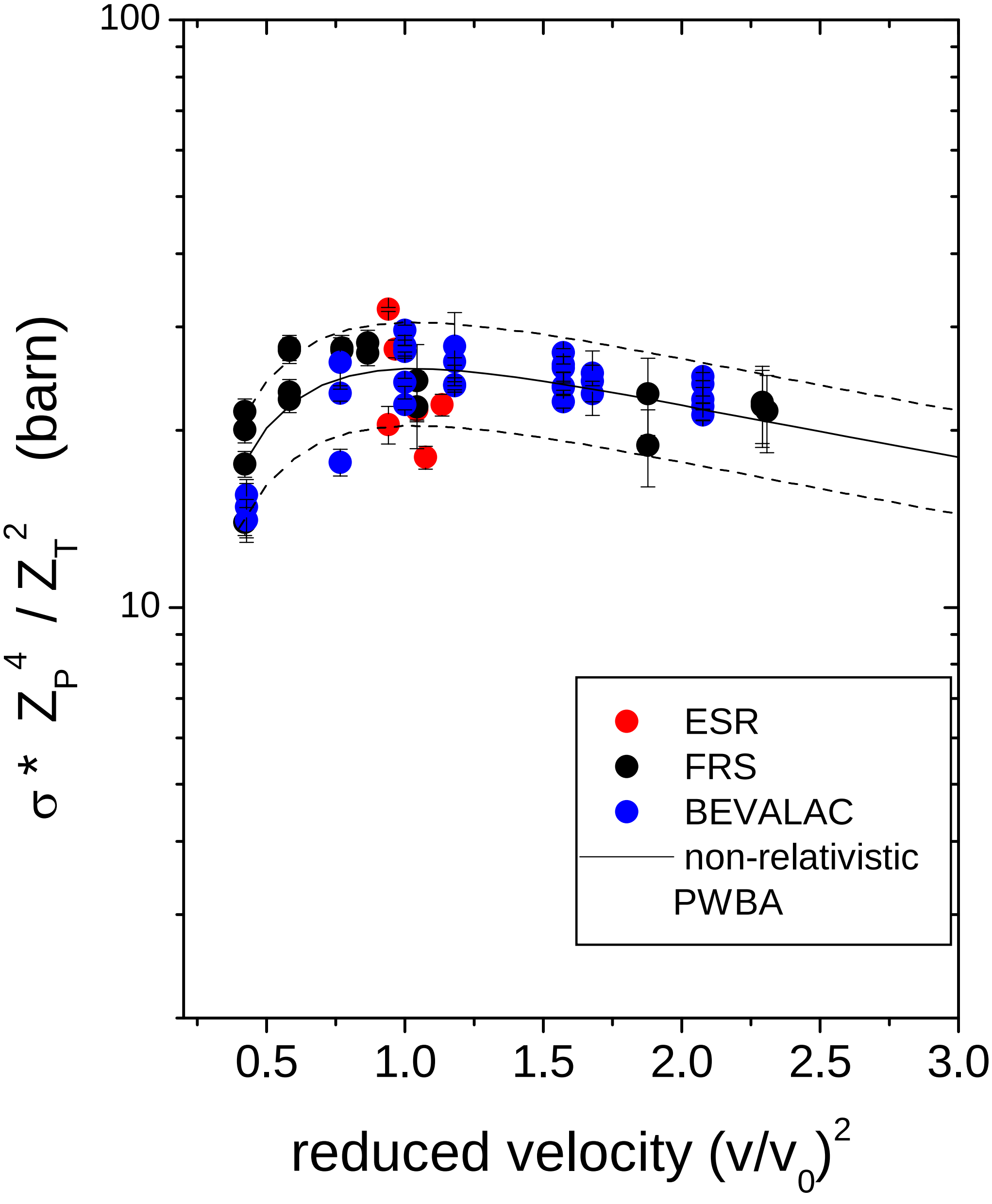
## *Cross sections*

Excitation

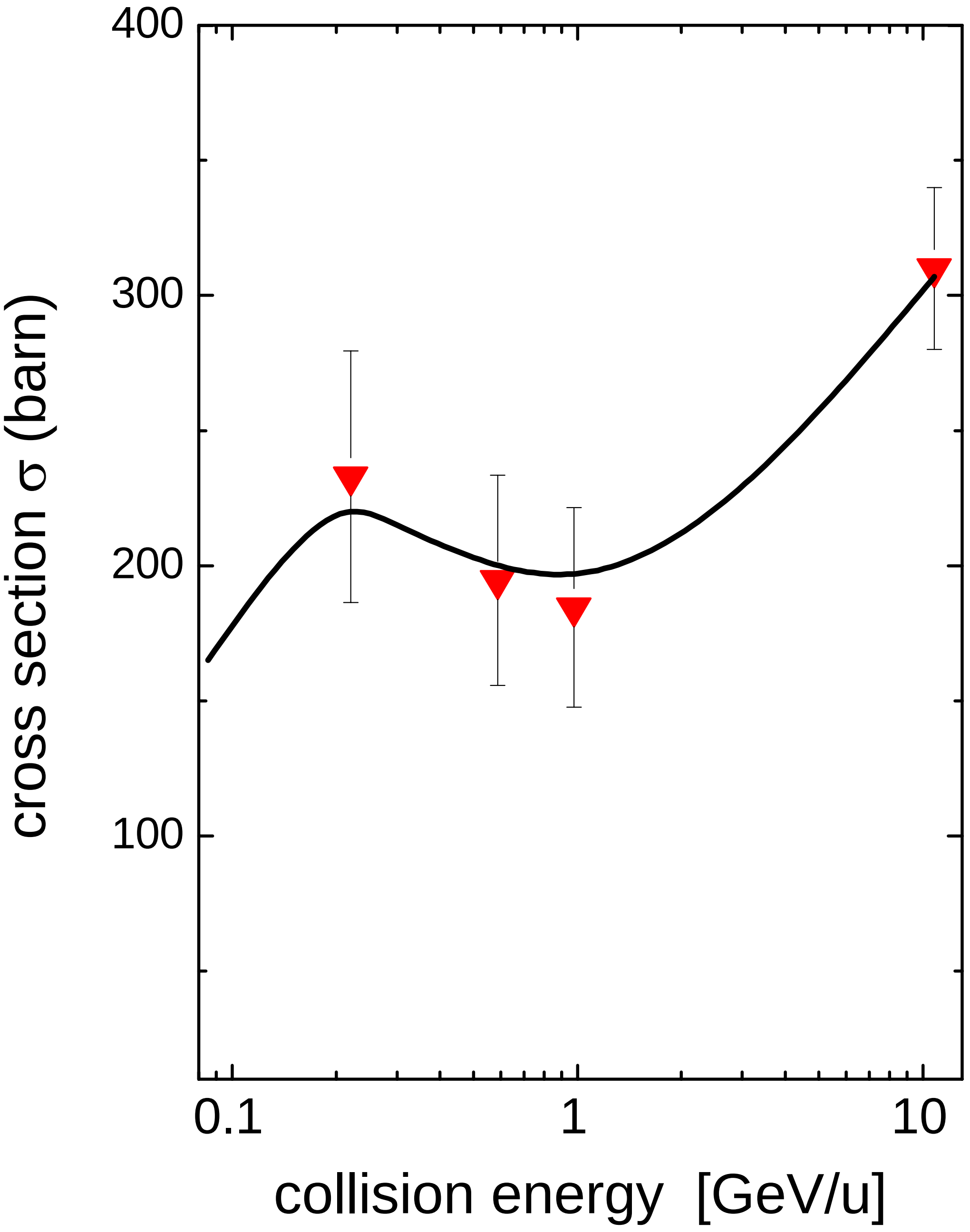


$$\boxed{\sigma = const \times \frac{Z_T^{\;2}}{Z_P^{\;4}} \times f\left(\frac{v}{v_k}\right)}$$

# K-shell ionization of one- and two-electron high-Z ions ( xenon => uranium )



# K-shell ionization of H-like Au ions (collisions with carbon atoms)



# Accuracy of total cross section data

General experimental accuracy: 10 to 30%

## Theory

### Asymmetric collisions $Z_P >> Z_T$ and bare, H-, He-like ions

**REC:** rigorous relativistic calculations
(very accurate)
**NRC**: very difficult, general agreement with experiment
a factor 2 to 3 (relativistic eikonal approximation)
At low energies empirical scaling laws available.

Ionization: deviations between experiment and theory
typically on the 20% level (PWBA, SCA)

### Symmetric collisions $Z_P \approx Z_T$ and bare, H-, He-like ions

Ionization/Capture: coupled channel calculations
required (almost not available)

### Low-projectile charge states

Almost no data available

Almost no theory available since perturbation theory not valid

Energy and $Z_T$ scaling unknown