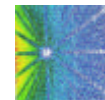


Heavy Ion channeling in Cave A

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S003-E027 collaboration:

- IPN Lyon
- GPS Paris 6-7
- GSI
- Hong Kong UST
- CIRIL Caen



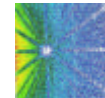
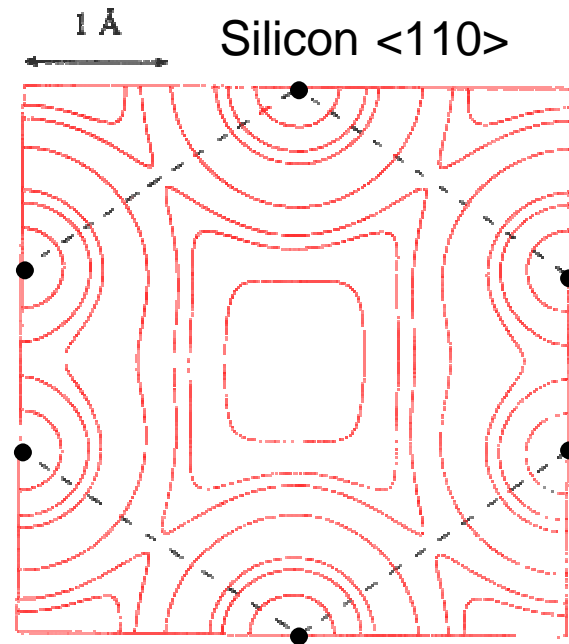
Continuum potential approximation

Continuum potential $V(r_{\perp})$

Transverse energy

$$E_{\perp} = QV(r_{\text{init}}) + p_z v \Psi_{\text{init}}^2 / 2$$

$\mathcal{P} A(E_{\perp}) =$ accessible
transverse space



Continuum potential approximation

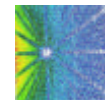
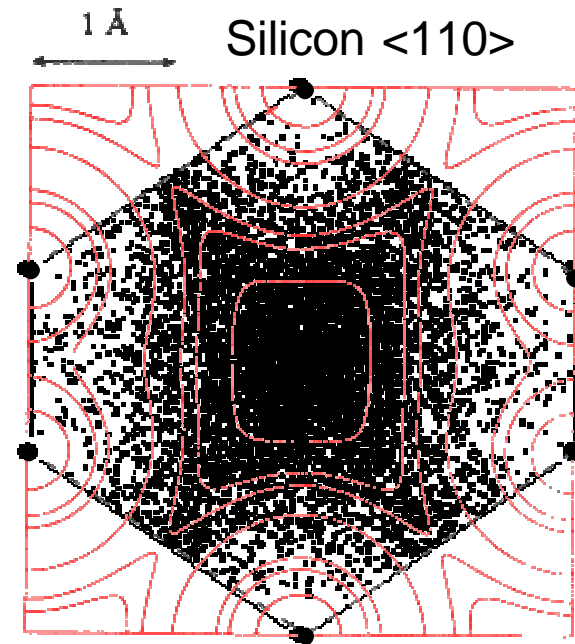
Continuum potential $V(r_{\perp})$

Transverse energy

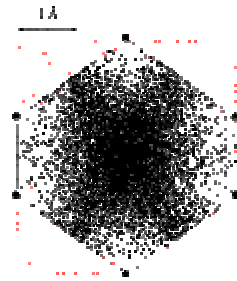
$$E_{\perp} = QV(r_{\text{init}}) + p_z v \Psi_{\text{init}}^2 / 2$$

\mathcal{P} $A(E_{\perp})$ = accessible
transverse space

E_{\perp} distribution \Rightarrow flux distribution



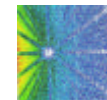
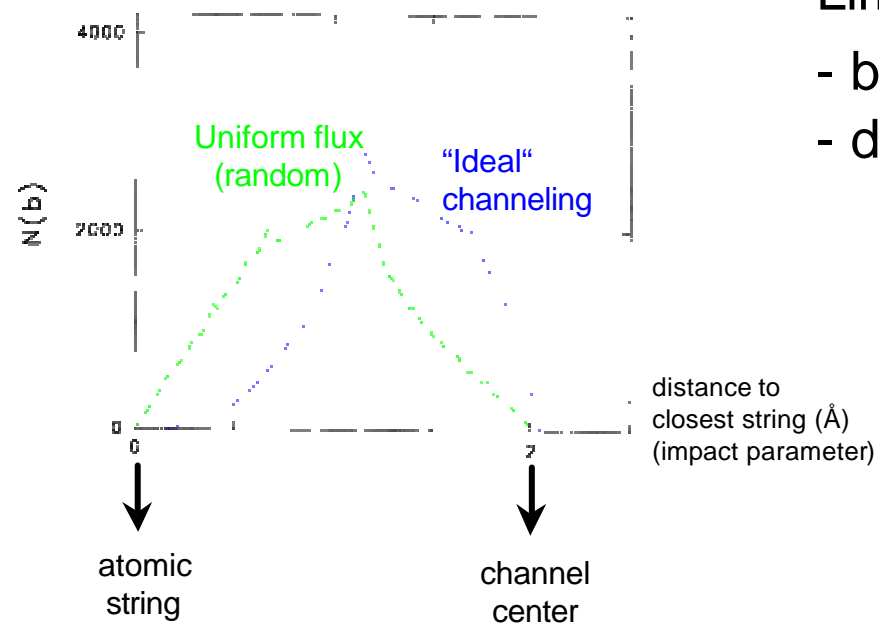
Ion flux distribution inside a crystal channel



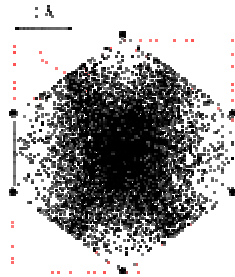
Flux peaking

Limited by :

- beam angular divergence
- dechanneling



Ion flux distribution inside a crystal channel

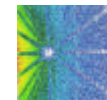
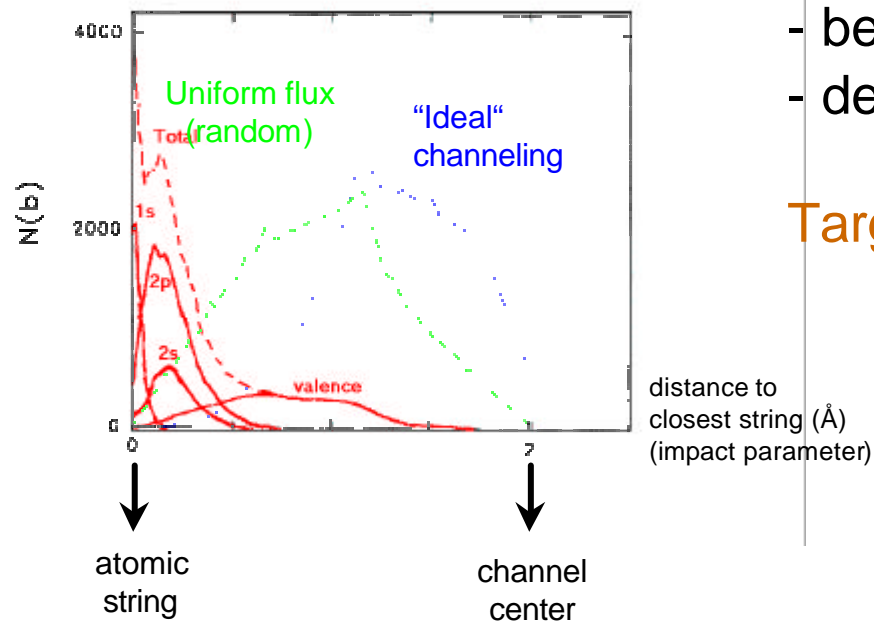


Flux peaking

Limited by :

- beam angular divergence
- dechanneling

Target electron distribution



Main channeling features

- Extinction of close collisions with target nuclei and core electrons
- Interaction with quasi-free valence/conduction electrons
- (periodic crystal field \Rightarrow projectile Resonant Coherent Excitation)

J.U. Andersen et al., Nucl. Inst. Meth B119 (1996) 292

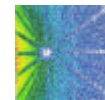
T. Azuma, Physica Scripta T80 (1999) 79

⊢ reduction of energy loss

⊢ charge exchange:

- no target atom recoil
- electron impact ionization/excitation
- capture - resonant (RTE)
- radiative (REC)

Review by H.F. Krause and S. Datz, Adv. At. Mol. Opt. Phys. 37 (1996) 139



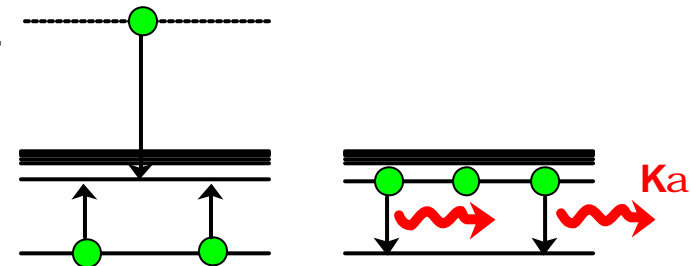
Application: crystal = thick electron target

Observation of “exotic” processes

- Trielectronic recombination at GANIL

$\sigma < 2 \text{ mbarn/e}^-$ for Kr^{34+} ions

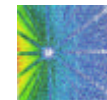
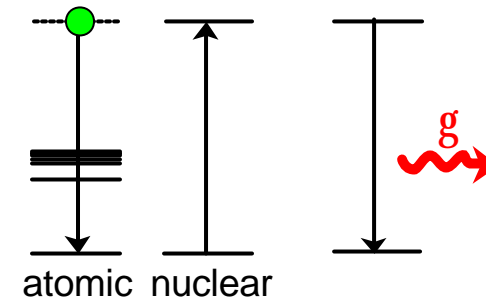
(M.Chevallier et al., Phys. Rev. A61 (2000) 0022724)



- NEEC at GSI (S003 proposal) $\sigma \sim \text{mbarn/e}^-$

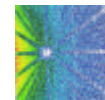
J.C. Kimball et al., Phys. Lett. A152 (1991) 367

needs | **high intensity** ($\sim 10^7$ ions/s during 3 days)
 | **small emittance** ($< 0.3 \pi \cdot \text{mm} \cdot \text{mrad}$)
 | charge state selection
 | transverse energy selection

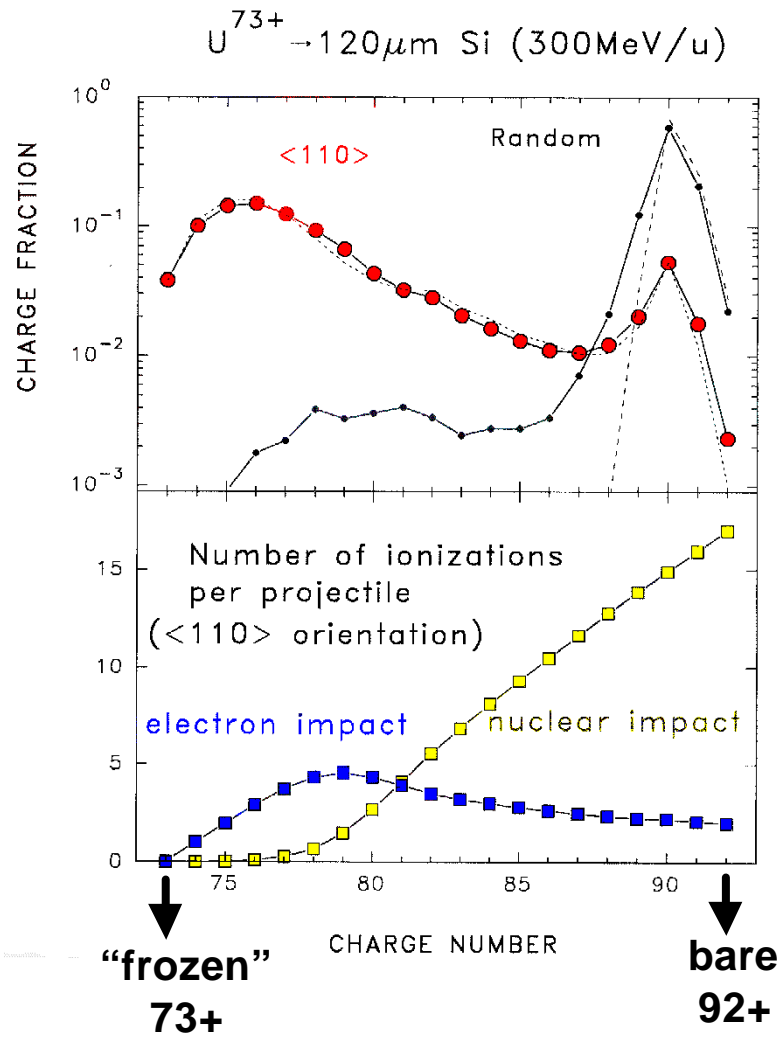


Detailed channeling studies require the knowledge of $A(E_{\perp})$ for each ion

- **Precise DE measurements**
⇒ high resolution spectrometer (FRS-GSI, SPEG-GANIL)
- **Broad charge state distribution** $F(Q)$ at crystal emergence
with Q_{in} far from mean Q_{out} in random orientation conditions
- **Electron emission yields** from entrance/exit surfaces
- Trajectories inside the crystal (exit angle)
⇒ very thin crystals



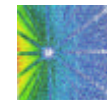
Selection of transverse energy



Energy loss and $Q_{\text{out}}=f(E_{\perp})$

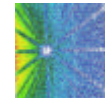
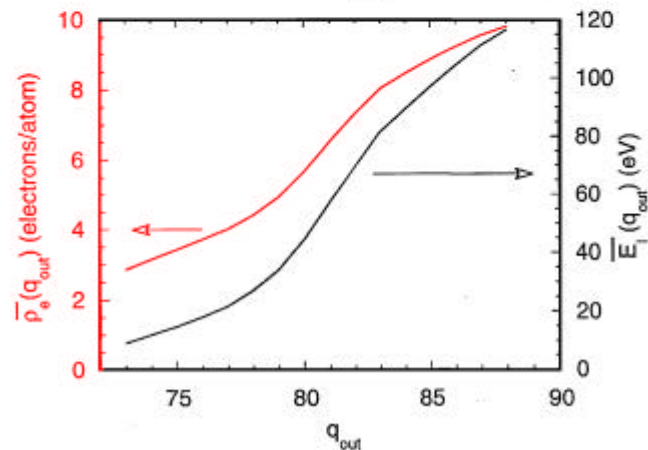
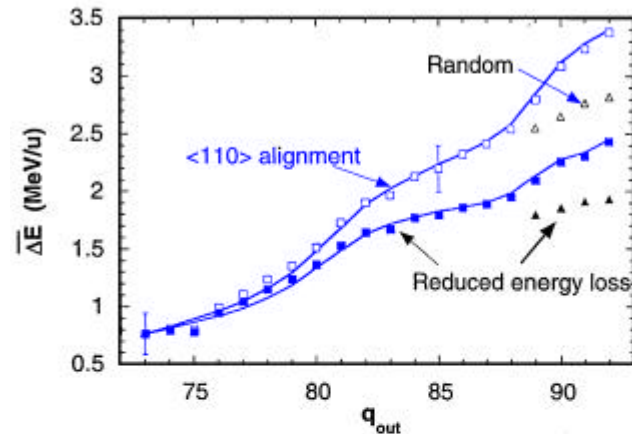
*D.DAUVERGNE et al.,
Phys Rev. A59 (1999) 2813*

Precise EII cross section
measurement ($n=2,3$)



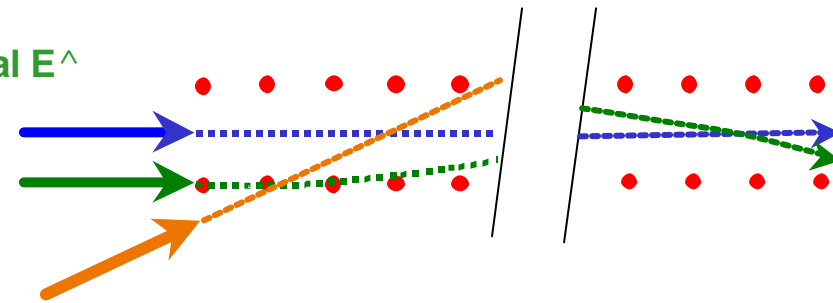
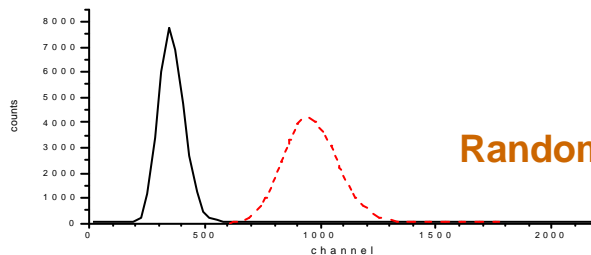
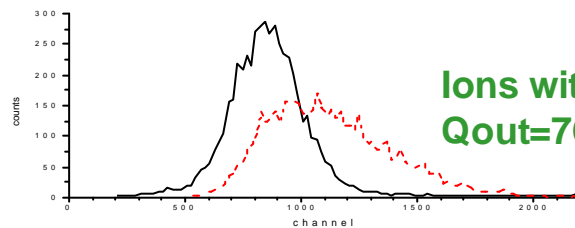
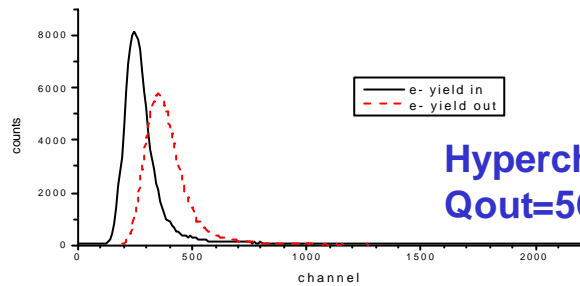
Relation between Q_{out} , E_{\perp} , electron density and mean energy loss

$U^{73+} \rightarrow 120 \mu\text{m Si } \langle 110 \rangle$

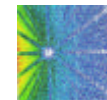


Relation between transverse energy and electron emission yield from surfaces

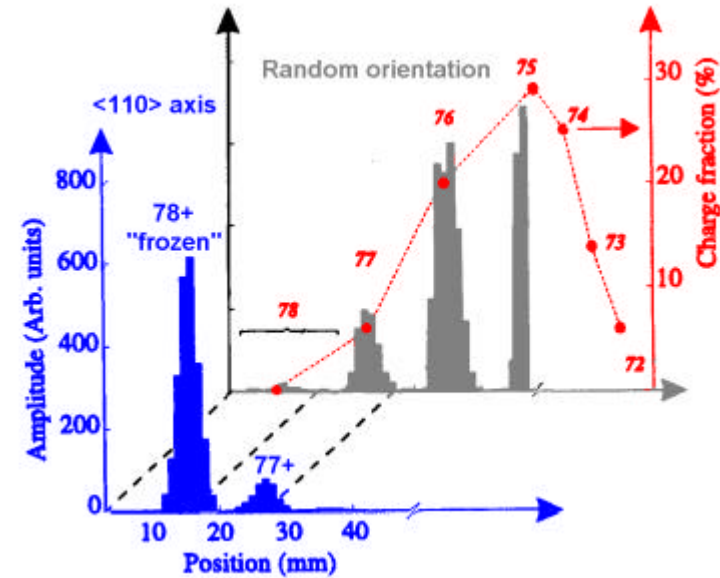
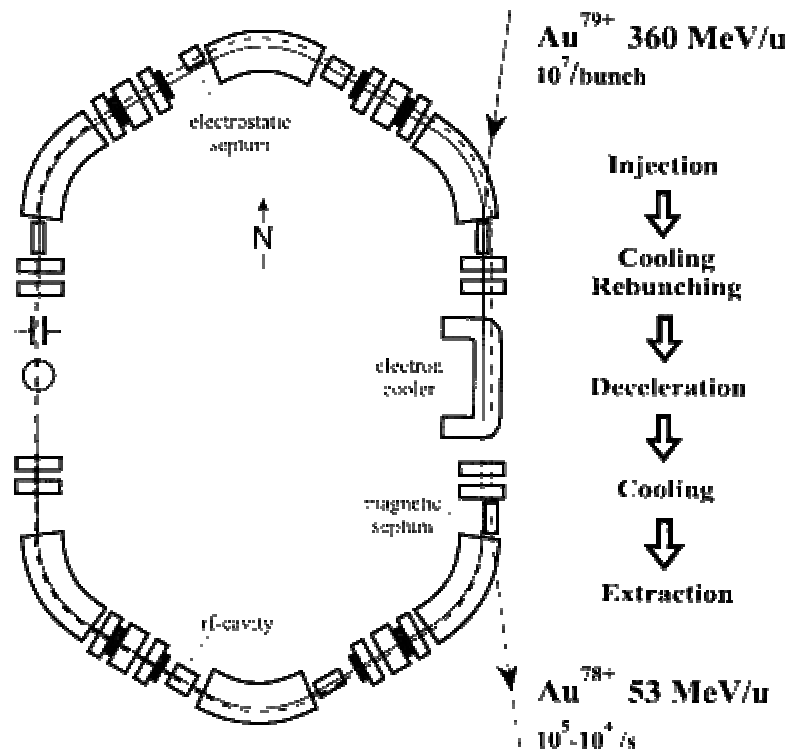
$Pb^{56+} \rightarrow 1.4 \mu\text{m thick Si } \langle 110 \rangle 29 \text{ MeV/u}$
(GANIL nov.2000)



Electron yield distribution

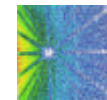


First channeling experiment in cave A (1995)



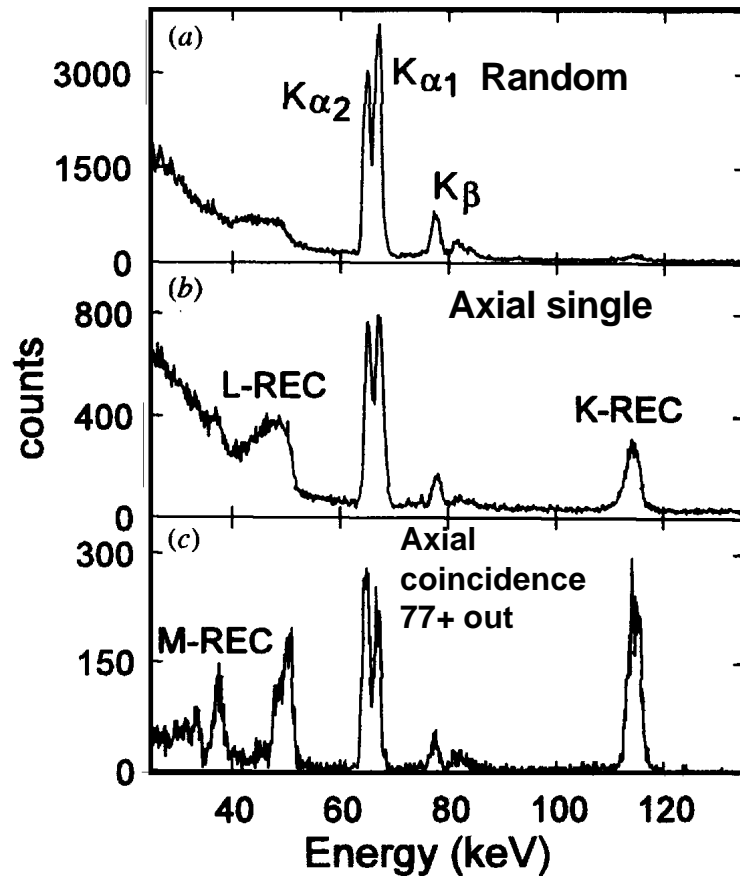
Axial orientation: $\langle Q_{\text{out}} \rangle = Q_{\text{in}}$
 Random orientation: $\langle Q_{\text{out}} \rangle < Q_{\text{in}}$
 Calculation (ETACHA): $\langle Q_{\text{out}} \rangle = 75+$

H.-T. Prinz et al., *Hyp. Int.* 108(1997)325
 S. Andriamonje et al., *J. Phys.* B30(1997)5099

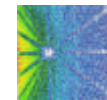


X-ray measurements with slow-heavy ions

Au^{78+} 53 MeV/u \rightarrow 17 μm Si



- **Random orientation:**
 - $K\alpha, \beta$ = radiative decay after MEC
 - No K-REC (K-shell filled by MEC)
- **Axial orientation:**
 - REC observable
 - coincidence with e- capture:
 - narrow K,L,M-REC peaks: capture from valence e-
 - $K\alpha_2 > K\alpha_1$ (L-REC decay)
- $K\alpha$ extinction with tilt angle:
 \Rightarrow measurement of the beam angular divergence

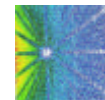


Request for beam time in cave A with the slowest and heaviest H-like ions

U⁹¹⁺ E < 25 MeV/u

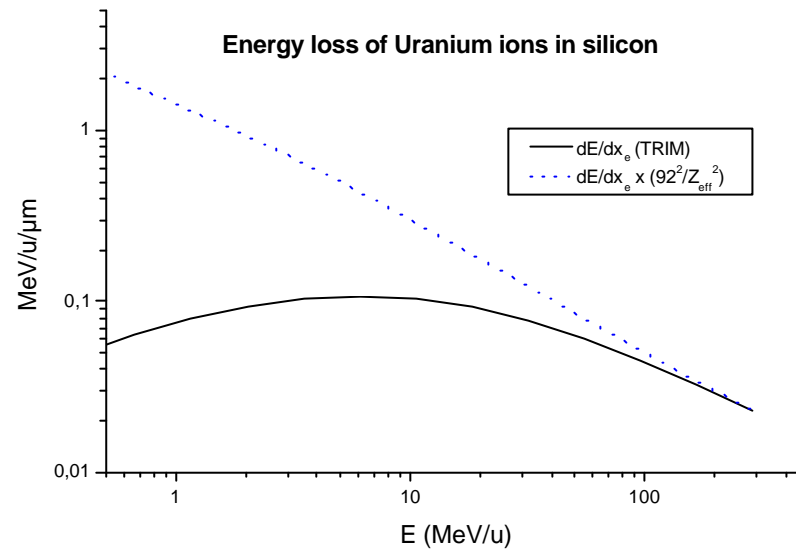
- $Q_{in} \gg \langle Q_{random} \rangle \Rightarrow$ **detailed study of capture in channeling**
 - low E_{\perp} : single-capture regime (K, L-REC)
 - high E_{\perp} : multi-capture $\left\{ \begin{array}{l} \text{REC} \\ \text{MEC } (\sigma \propto E^{-5.5} !) \end{array} \right.$

 - ▷ K-REC for very well channeled ions : line shape study
 - $\left\{ \begin{array}{l} \text{Compton profile} \\ \text{polarization of the valence electron gas} \end{array} \right.$
 - ▷ Competition between REC and MEC vs impact parameter
-
- **Energy loss of frozen ions**

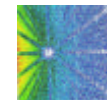


Can hyperchanneled ions lose more energy than unchanneled ions?

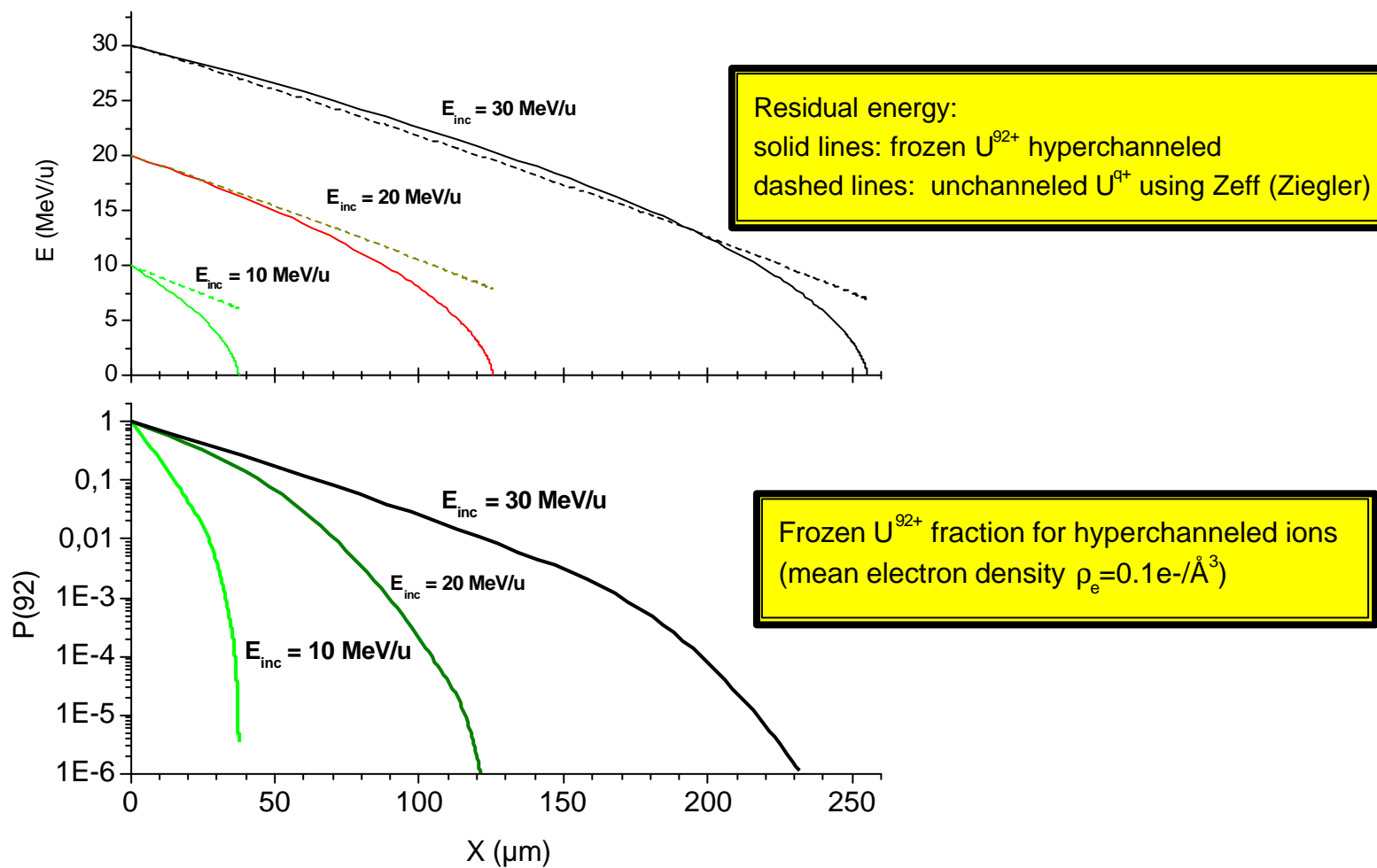
- $dE/dx \propto Q^2$



- Channeling : suppression of close collisions with electrons
↳ reduced energy loss (factor ~ 2)
- REC cross sections are “small” ($4 \cdot 10^{-21} \text{cm}^2$ for U^{92+} at 20 MeV/u)



Crystal decelerator for bare uranium ions



CONCLUSION

- Two channeling experiments performed at GSI
 - U^{73+} 300 MeV/u : Energy loss and Electron Impact Ionization
 - Au^{78+} 53 MeV/u : probe for the extracted beam in cave A
- Channeling = unique tool to study in detail electron capture by slow ions
- Beam time is missing!

