Heavy Ion channeling in Cave A

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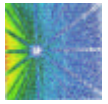
S003-E027 collaboration:

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



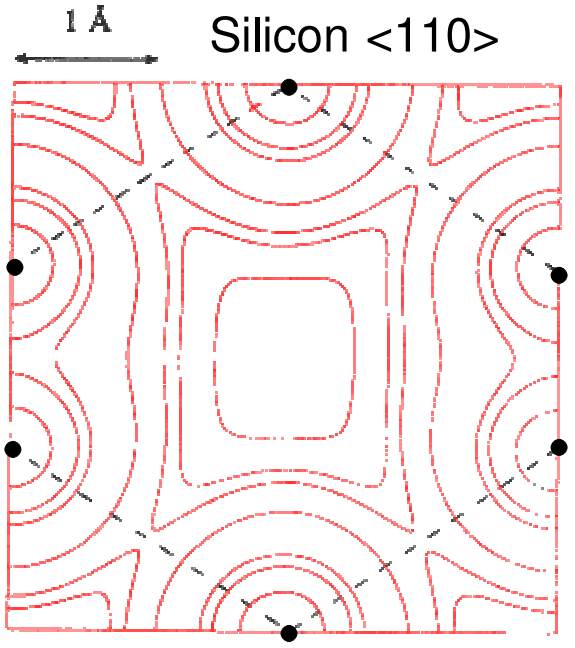
Continuum potential approximation

Continuum potential $V(r_\perp)$

Transverse energy

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

$A(E_\perp)$ = accessible transverse space



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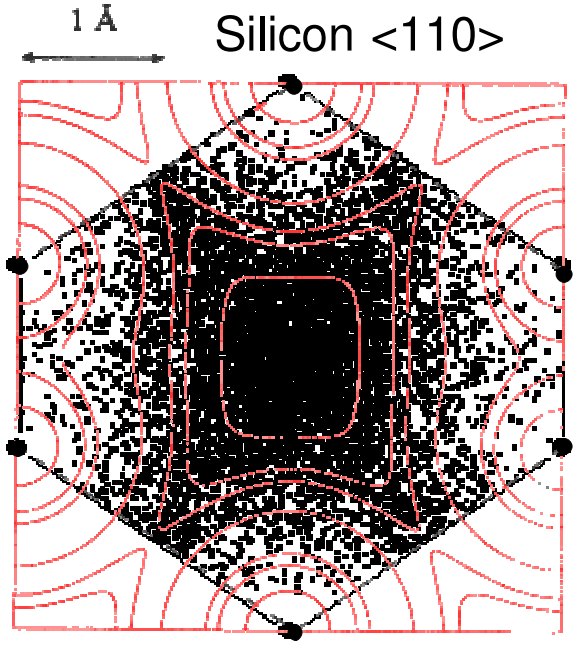
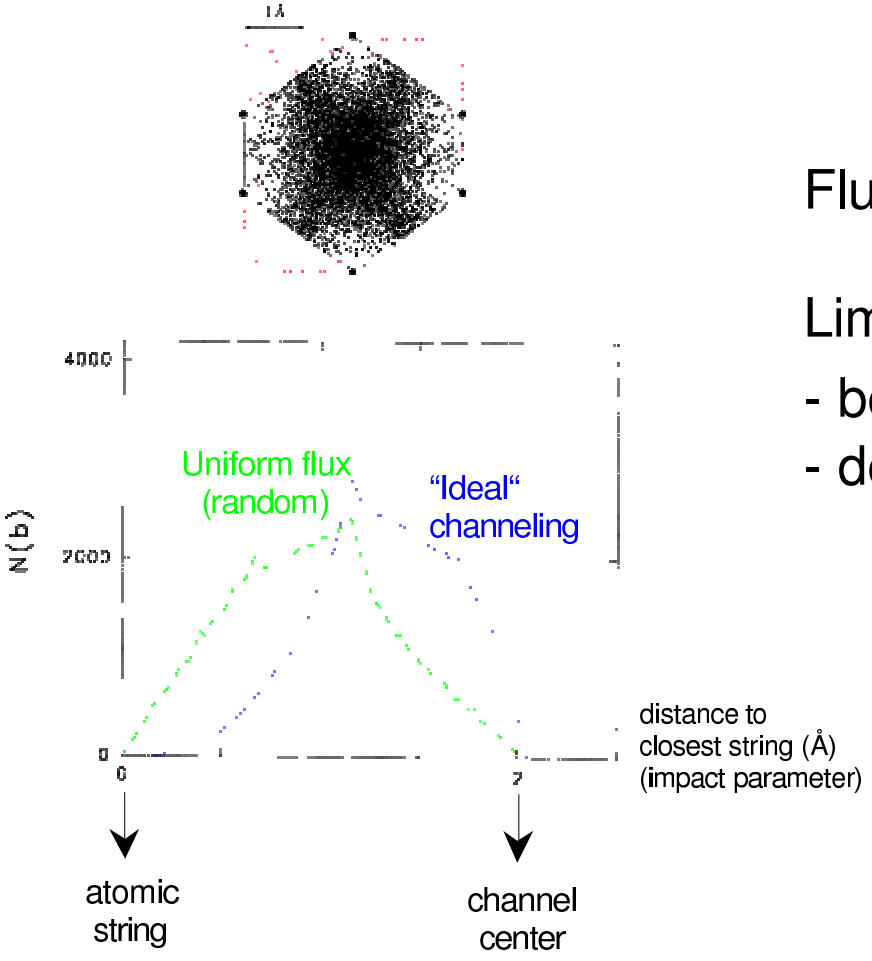


$E_\perp$ distribution $\Rightarrow$ flux distribution

Ion flux distribution inside a crystal channel

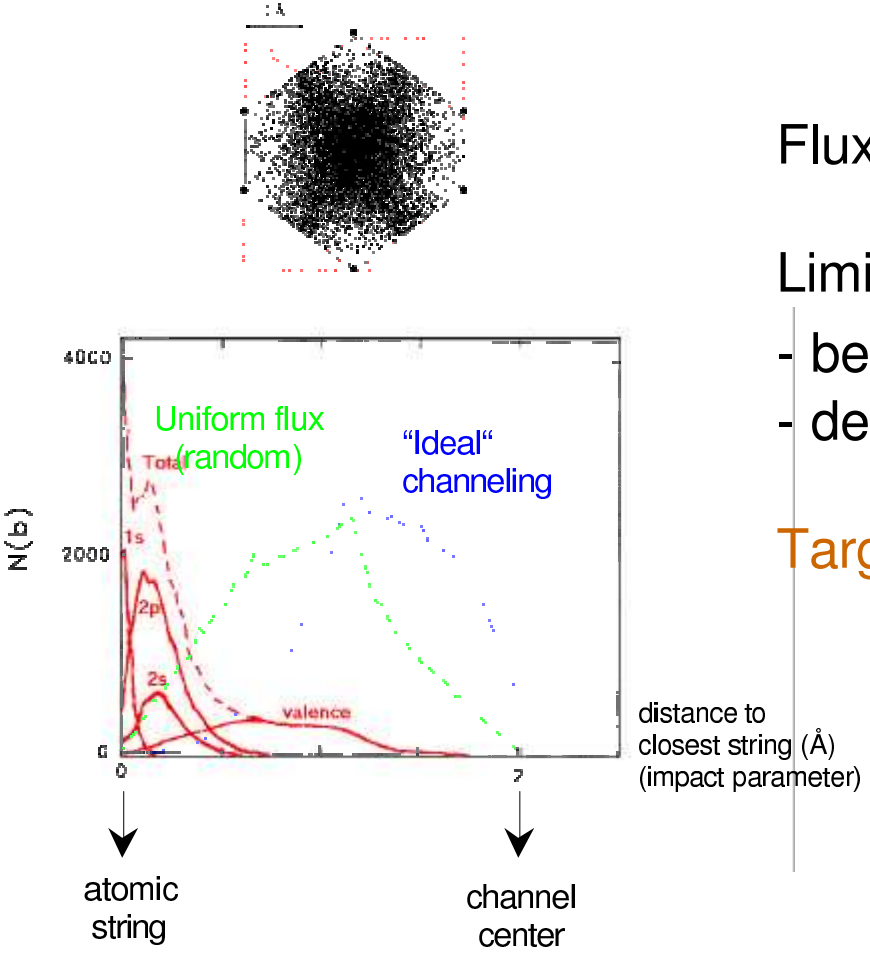


Flux peaking

Limited by :

- beam angular divergence
- dechanneling

Ion flux distribution inside a crystal channel



Flux peaking

Limited by :

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Target electron distribution

Main channeling features

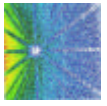
- Extinction of close collisions with target nuclei and core electrons
- Interaction with quasi-free valence/conduction electrons
- (periodic crystal field ⇒ projectile Resonant Coherent Excitation)

  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



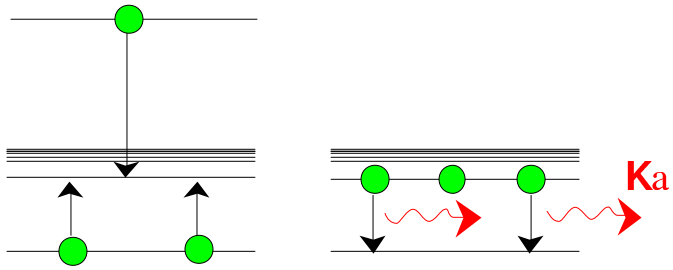
Application: crystal = thick electron target

Observation of “exotic” processes

- Trielectronic recombination at GANIL

  s **< 2 mbarn/e-** for Kr^{34+} ions

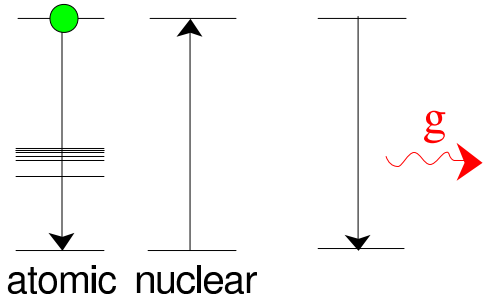
  (M.Chevallier et al., Phys. Rev. A61 (2000) 0022724)

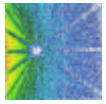


- NEEC at GSI (S003 proposal) σ ~ mbarn/e-

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

needs | high intensity (~10^7 ions/s during 3 days)
small emittance (<0.3 π.mm.mrad)
charge state selection
transverse energy selection





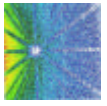
Detailed channeling studies require the knowledge of $A(E_{\perp})$ for each ion

- **Precise ΔE measurements**
  $\Rightarrow$ high resolution spectrometer (FRS-GSI, SPEG-GANIL)

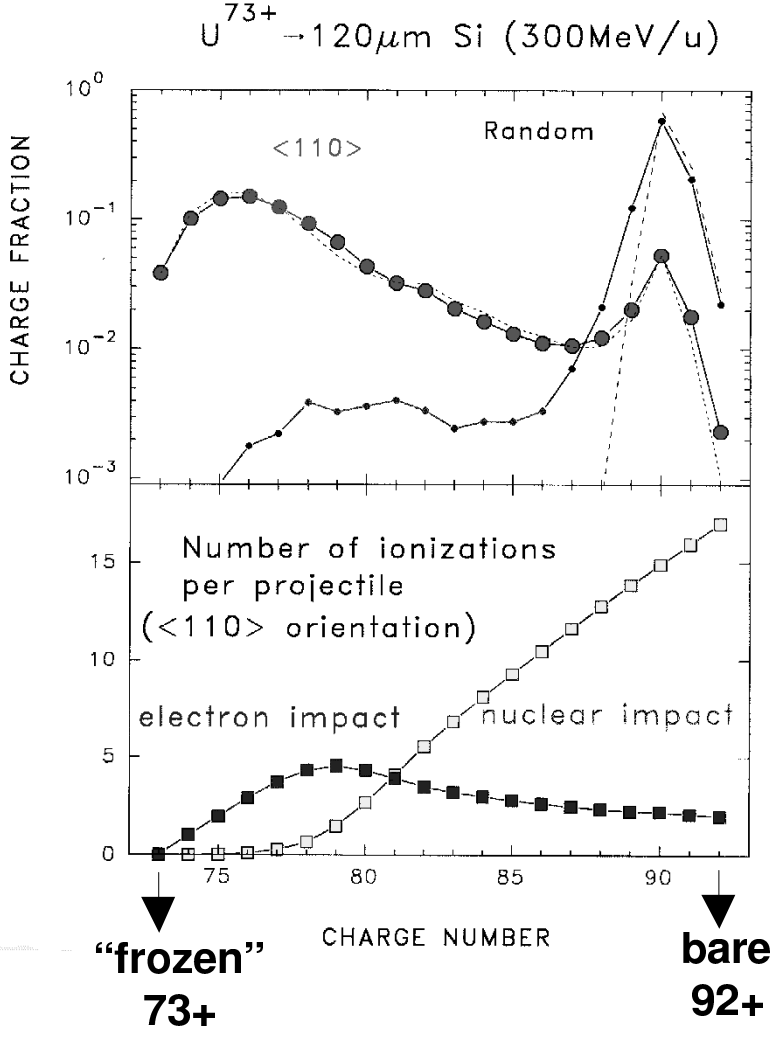
- **Broad charge state distribution** F(Q) at crystal emergence with Q_{in} far from mean Q_{out} in random orientation conditions

- **Electron emission yields** from entrance/exit surfaces

- Trajectories inside the crystal (exit angle)
  $\Rightarrow$ very thin crystals



Selection of transverse energy



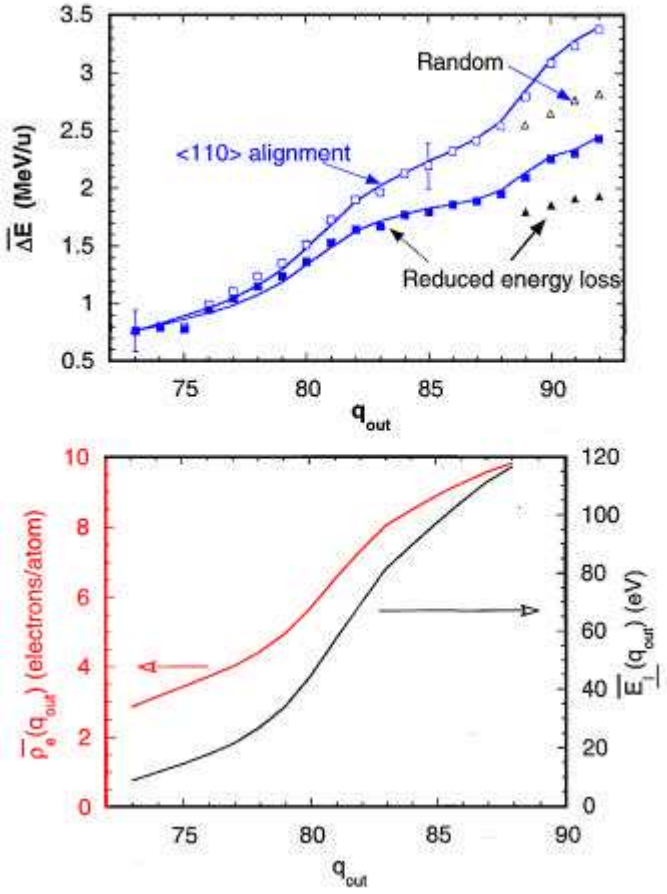
Energy loss and $Q_{out}=f(E\perp)$

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

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

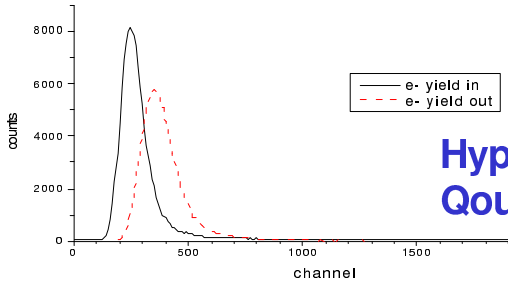
Relation between Q_{out}, $E_{\perp}$, electron density and mean energy loss

$U^{73+} \rightarrow$ 120 µm Si <110>

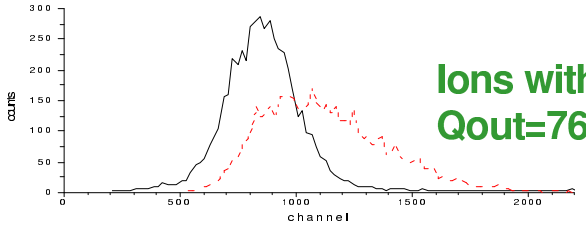


Relation between transverse energy and electron emission yield from surfaces

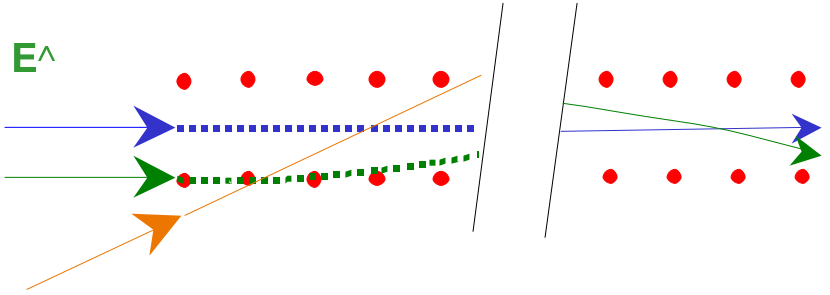
$Pb^{56+} \rightarrow$ 1.4 µm thick Si <110> 29 MeV/u
(GANIL nov.2000)

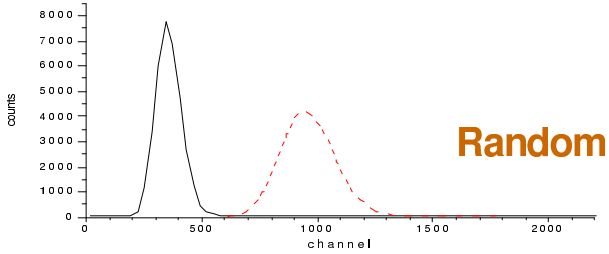


Hyperchanneled ions
Qout=56+



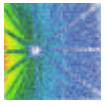
Ions with critical E^
Qout=76-79+



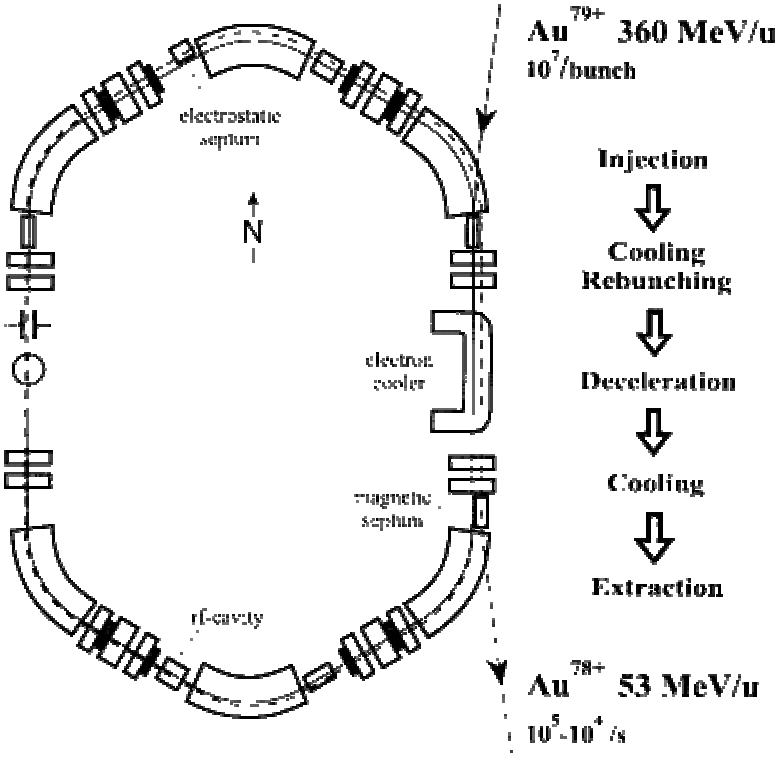


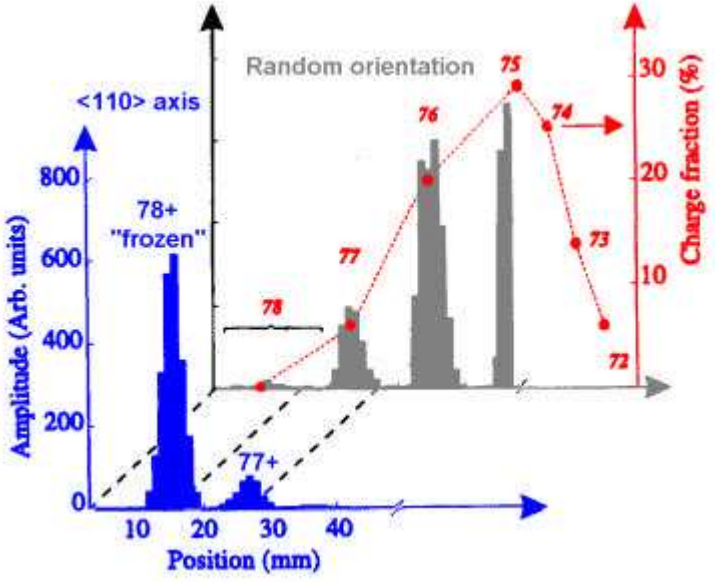
Random orientation

Electron yield distribution



First channeling experiment in cave A (1995)





Axial orientation: $\langle Q_{out} \rangle = Q_{in}$

Random orientation: $\langle Q_{out} \rangle < Q_{in}$

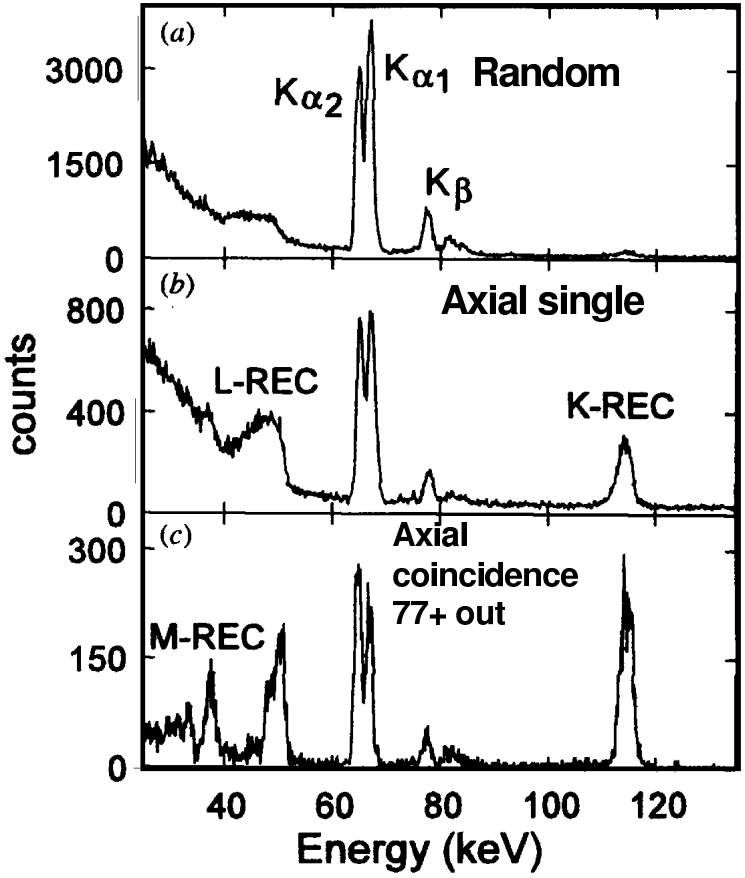
Calculation (ETACHA): $\langle Q_{out} \rangle = 75+$

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 → 17 µm Si



- **Random orientation**:
  - Kα,β =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-
    - Kα2 > Kα1 (L-REC decay)
- Kα extinction with tilt angle:

  ⇒ measurement of the beam angular divergence

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

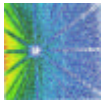
U^{91+} E<25 MeV/u

- Q_{in} » $<Q_{random}>$ ⇒ **detailed study of capture in channeling**
  - low E⊥ : single-capture regime (K, L-REC)
  - high E⊥ : multi-capture { REC
    MEC ($\sigma \propto E^{-5.5}$!)

K-REC for very well channeled ions : line shape study
{ Compton profile
polarization of the valence electron gas

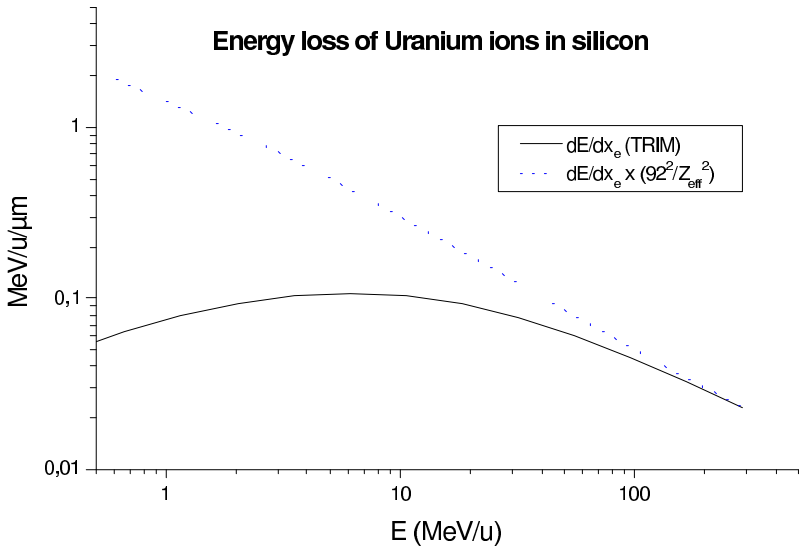
Competition between REC and MEC vs impact parameter

- **Energy loss of frozen ions**

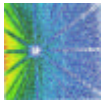


Can hyperchanneled ions lose more energy than unchanneled ions?

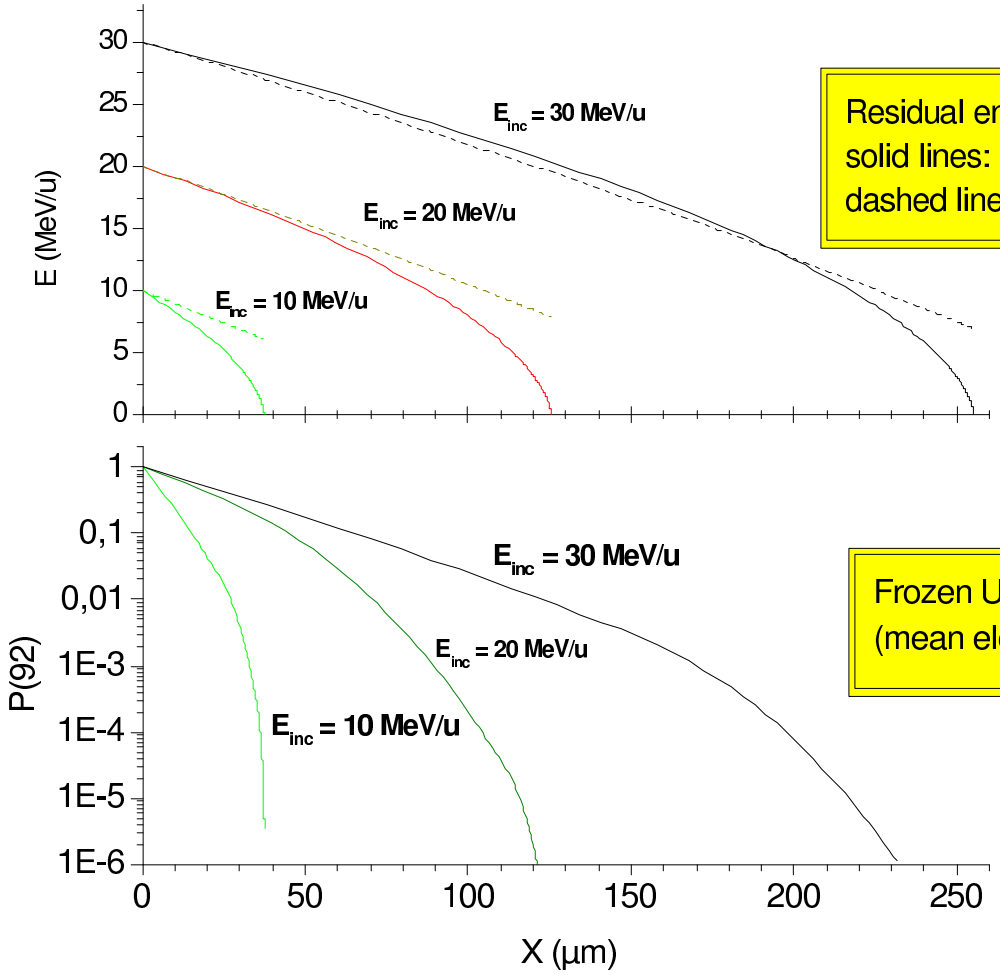
- $dE/dx \propto Q^2$



- Channeling : suppression of close collisions with electrons
  reduced energy loss (factor ~ 2)
- REC cross sections are “small” ($4.10^{-21} cm^2$ for U^{92+} at 20 MeV/u)



Crystal decelerator for bare uranium ions

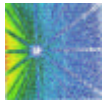


Residual energy:
solid lines: frozen U^{92+} hyperchanneled
dashed lines: unchanneled U^{q+} using Zeff (Ziegler)

Frozen U^{92+} fraction for hyperchanneled ions
(mean electron density ρ_e=0.1e-/Å^3)

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!