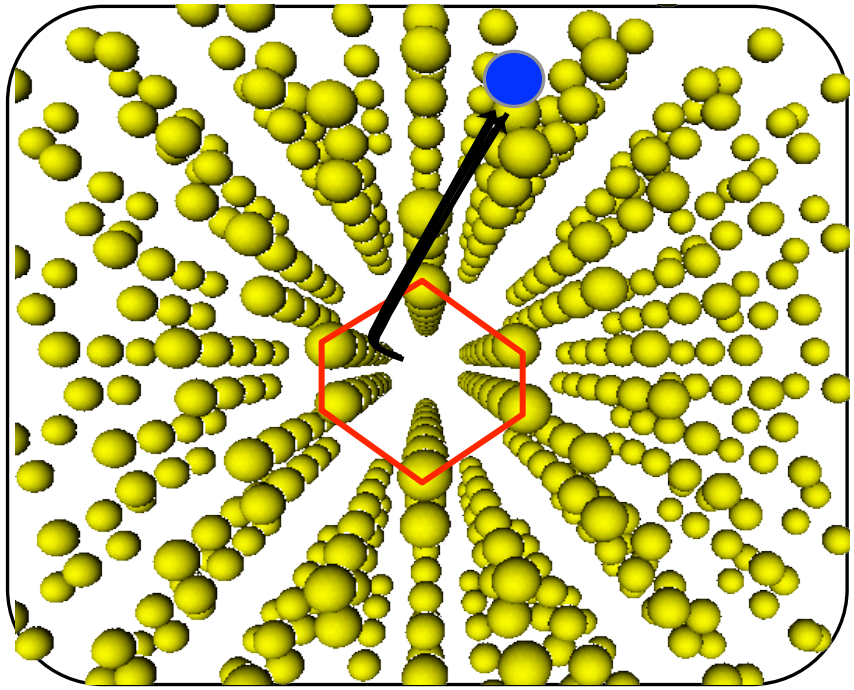
# Original aspects of Heavy-ion interactions in crystals at non relativistic energies



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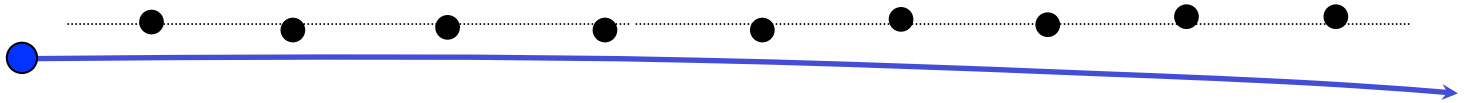
**Channeling 2012, Alghero, 24-28 September 2012**

# Outline

- Flux distribution in channeling
- Energy loss and charge exchange
  - Transmission of highly charged ions in their frozen charge state
  - Superdensity effects
- Nuclear lifetime measurements in inverse kinematics

# Ion channeling in a crystal

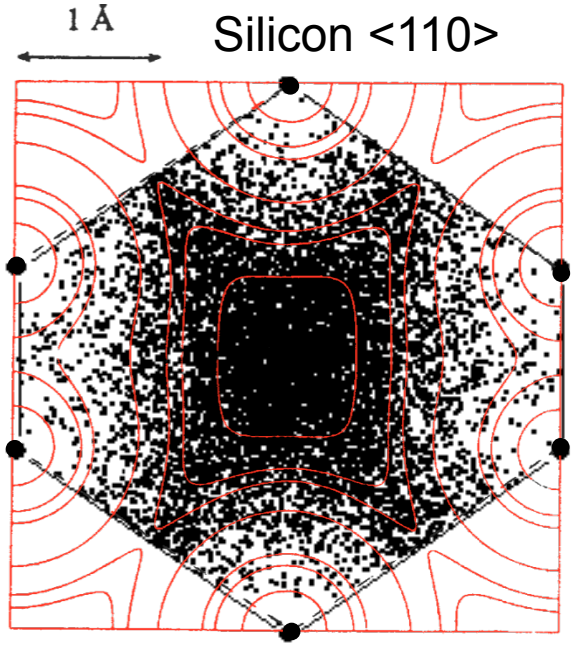


## Continuum potential $V(r_\perp)$

Transverse energy
$E_\perp = QV(r_{init}) + E\Psi_{init}^2$

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

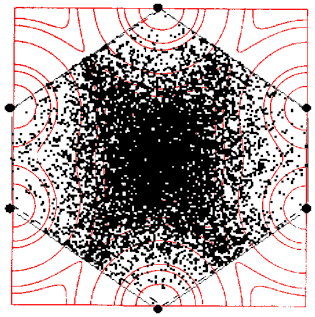
$E_\perp$ distribution $\Rightarrow$ flux distribution



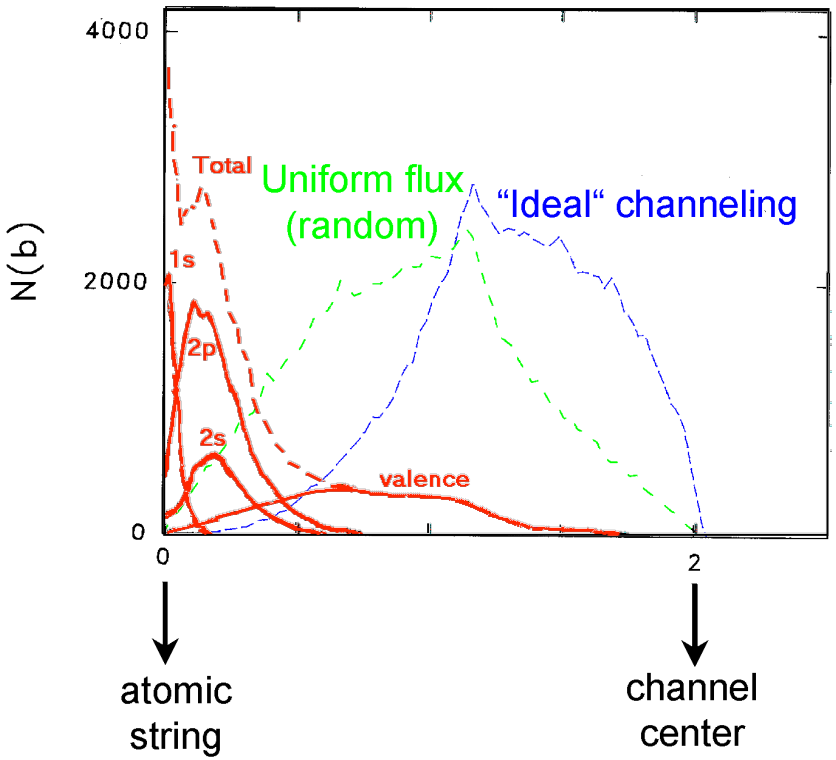

- **Low $E_\perp$** : extinction of close collisions with atomic cores
- **High $E_\perp$** : $A(E_\perp)$ not restricted

*Review:*
*High energy ion channeling, principles and typical applications*
*C.Cohen and D.Dauvergne, NIM B 225 (2004) 40*

# Interaction with a non uniform electron gas

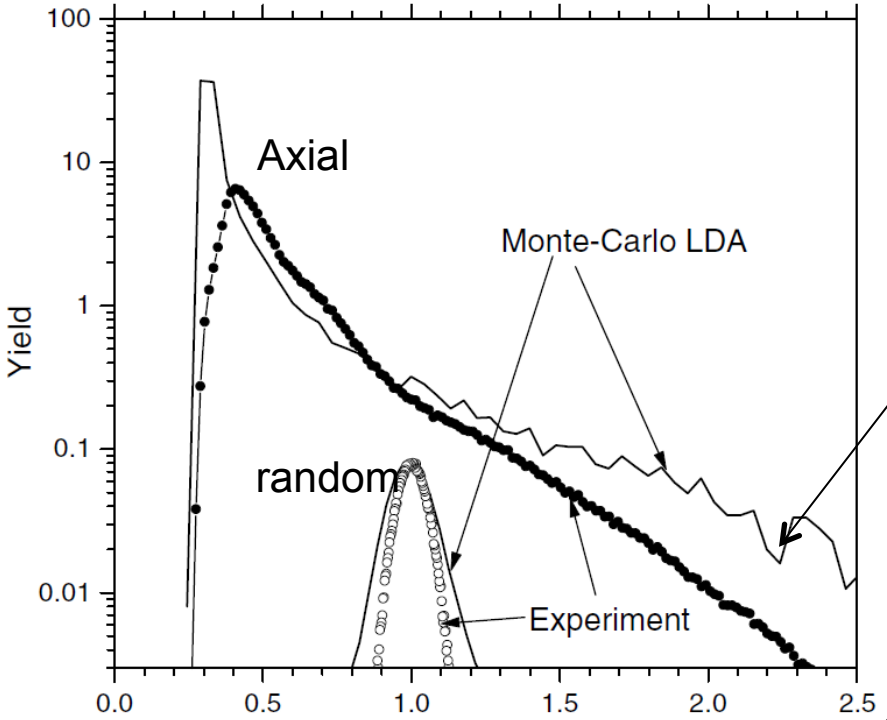


Silicon
<110>



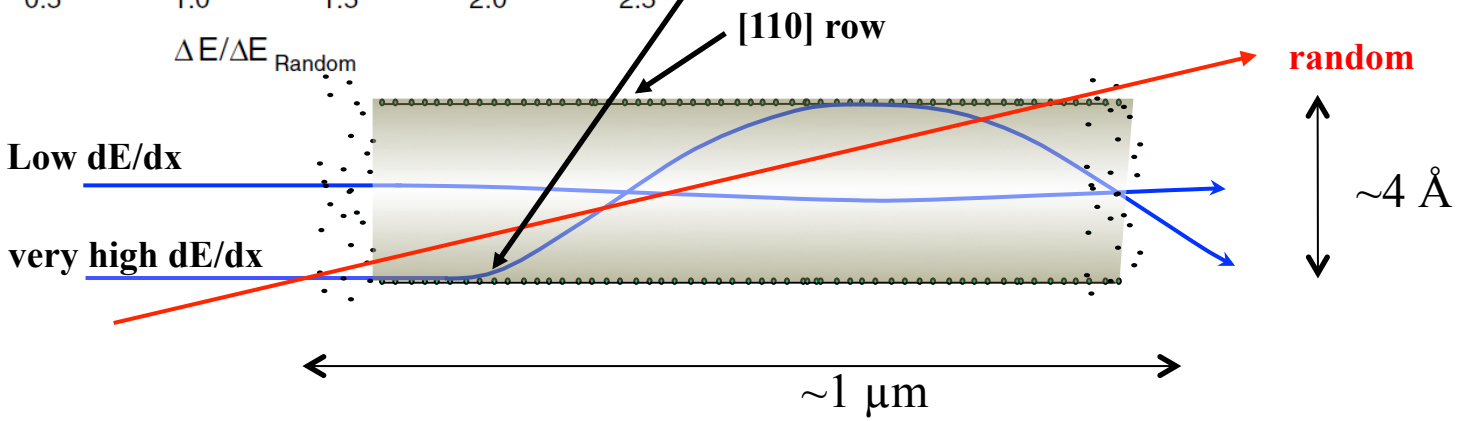
# Energy loss

Pb 29 MeV/u on Si <110> 1.1 μm (GANIL)
L'Hoir et al., NIMB 245(2006)1

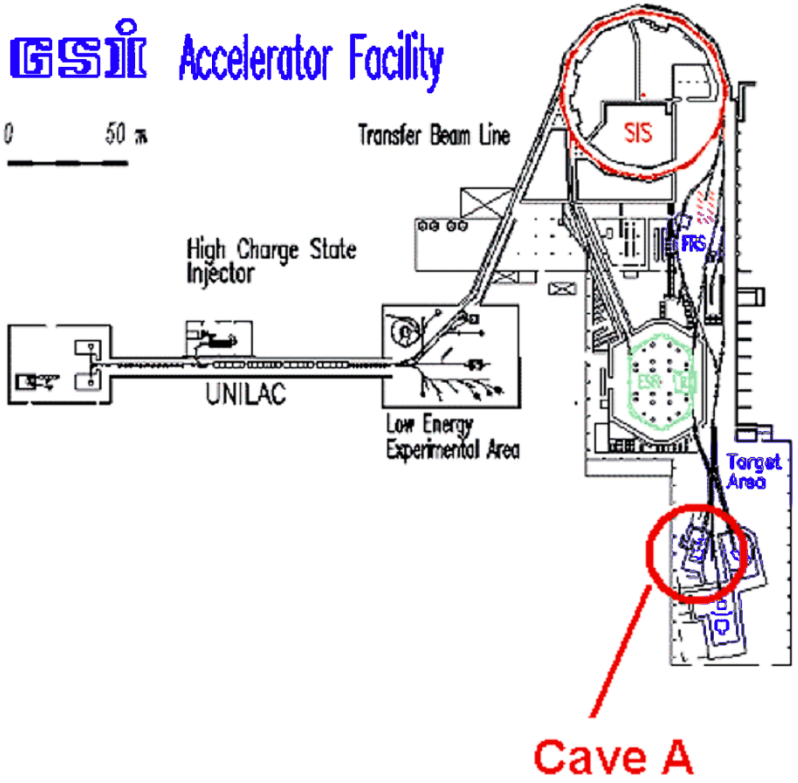


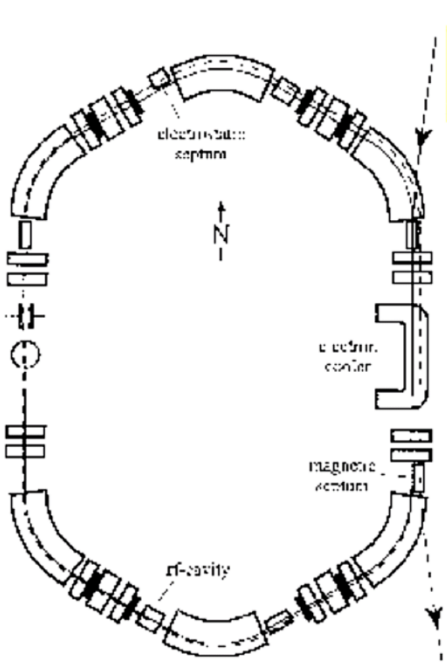

High Et ions:
close collisions along strings at entrance
Averaged energy loss
~2 times $\Delta E_{random}$

**Locally, $\Delta E \sim 10 \times \Delta E_{random}$**



# SIS - ESR at GSI (Darmstadt)



$U^{92+}$ 300 MeV/u

$10^7$ /bunch

Injection

⇩

Cooling
Rebunching

⇩

Deceleration

⇩

Cooling

⇩

Extraction

$U^{91+}$ 12 MeV/u

$10^4$-$10^3$ /s

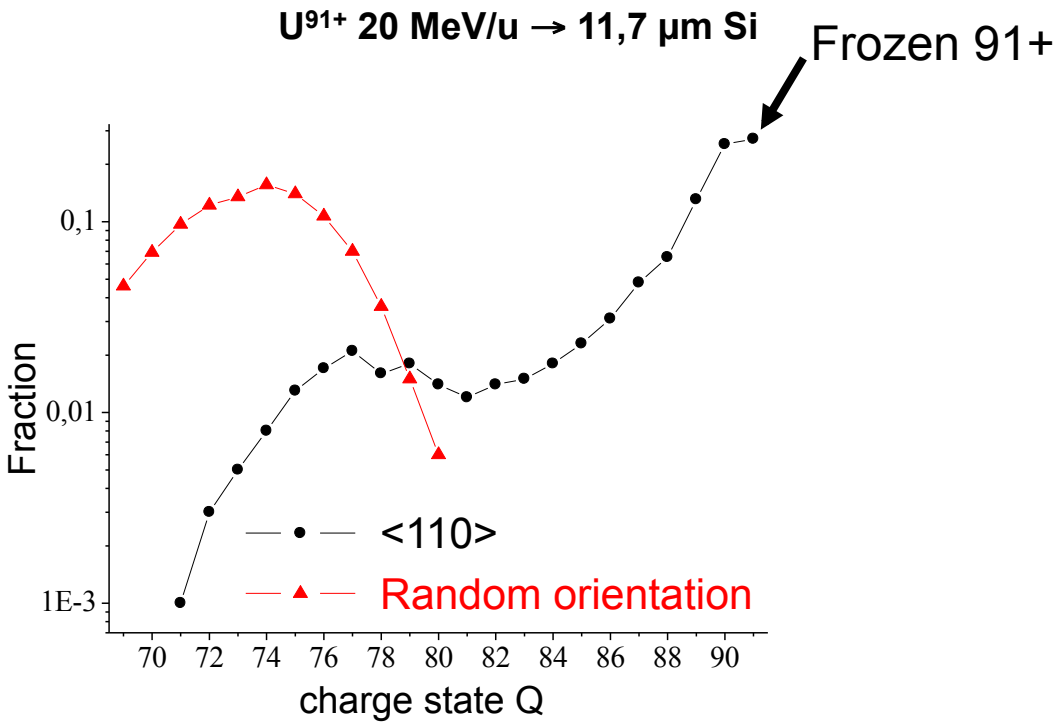
**H-like ion beams**:

$U^{91+}$ 20 MeV/u: $\eta_K = (v/v_K)^2 \approx 0.085$, $\eta_L \approx 0.35$, $\eta_M \approx 0.8$

$U^{91+}$ 12 MeV/u: $\eta_K \approx 0.051$, $\eta_L \approx 0.21$, $\eta_M \approx 0.48$

⇒ **Far from charge equilibrium in matter**

# Charge state distributions



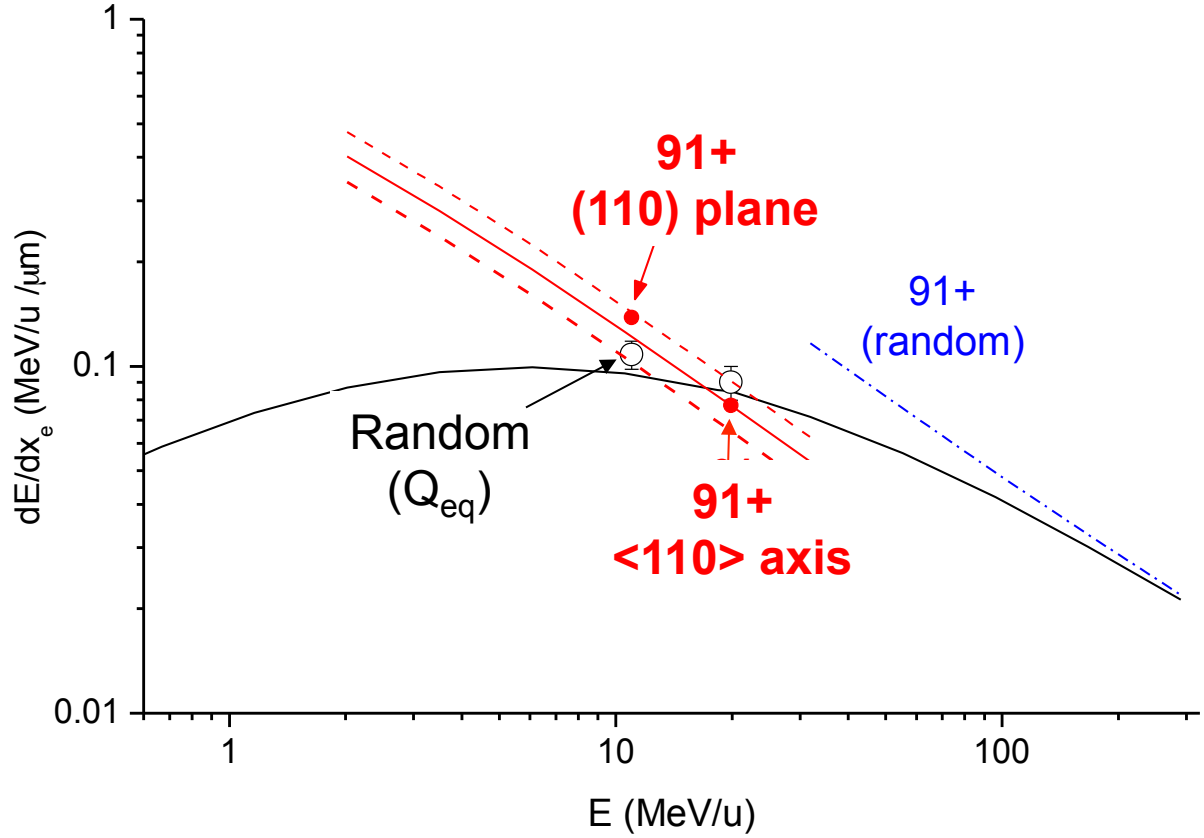

- **Random orientations** : MEC and NII dominate ⇒ charge equilibrium
- **Axial orientations** : $F(Q_{out})$ connected to $F(E_\perp)$

  broad distributions, with large frozen ion fractions

**Superdensity effect for high $E_\perp$ ions:** $Q_{out} > Q_{out}(random)$

enhanced ionization along atomic strings

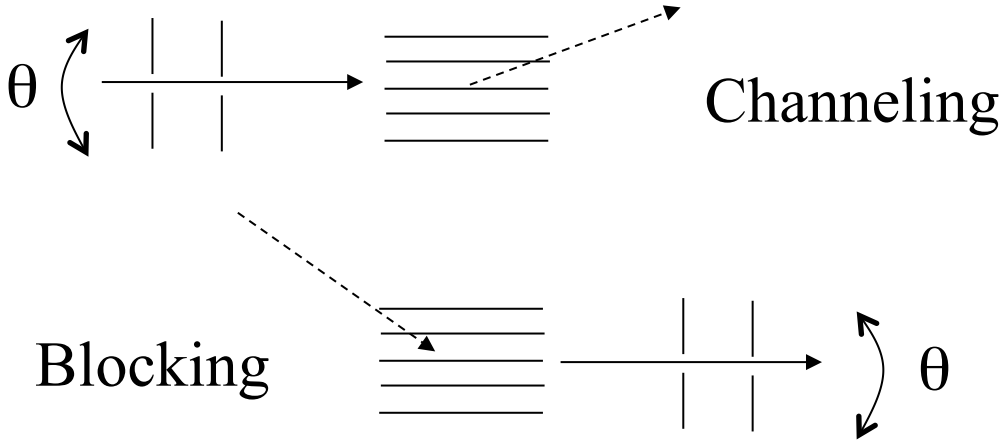
# Deceleration of highly charged uranium ions
## in a silicon crystal



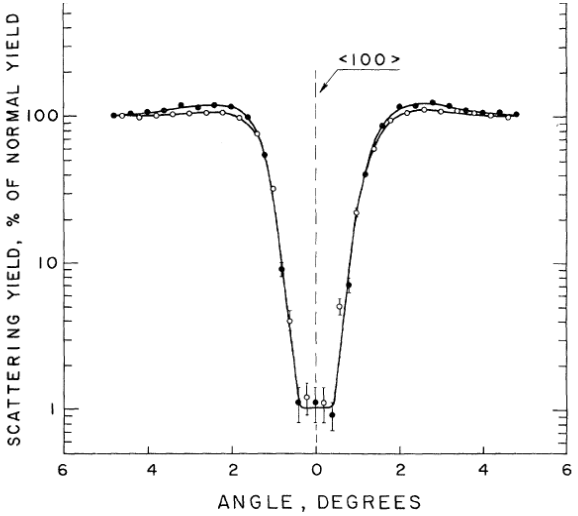

For E< 15 MeV/u : dE/dx (channeled $U^{91+}$ ) > dE/dx (random)

**Deceleration of $U^{91+}$ from 12 to 9.4 MeV/u in a 18 µm thick crystal**
**Frozen 91+ fraction: 0.3% (planar), ~ 1.5% (axial)**
**Lower energy limit not reached** (→ FLAIR-SPARC)

# Blocking

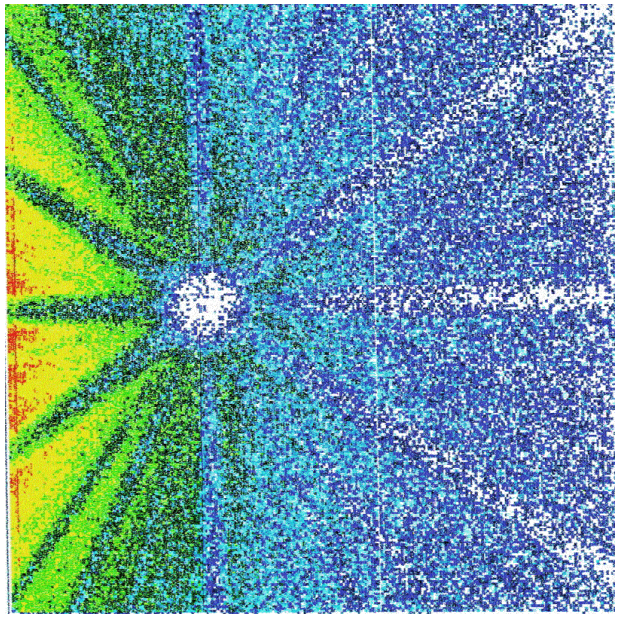



*Bøgh and Whitton (1967)*
1 MeV $H^+ \rightarrow W$

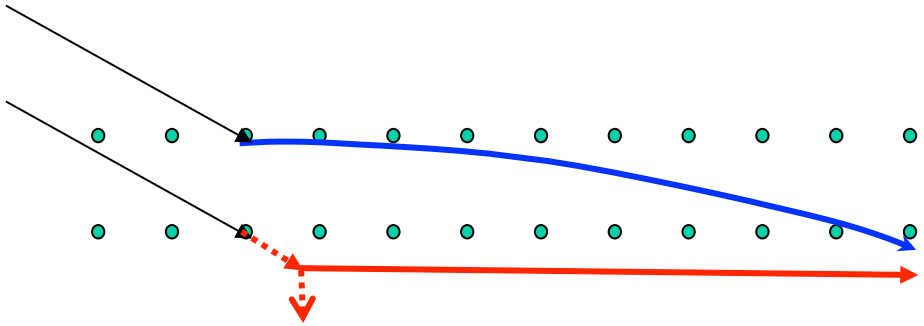



Blocking pattern of elastic scattering around <110> axis of Si

29 MeV/u Pb incident beam



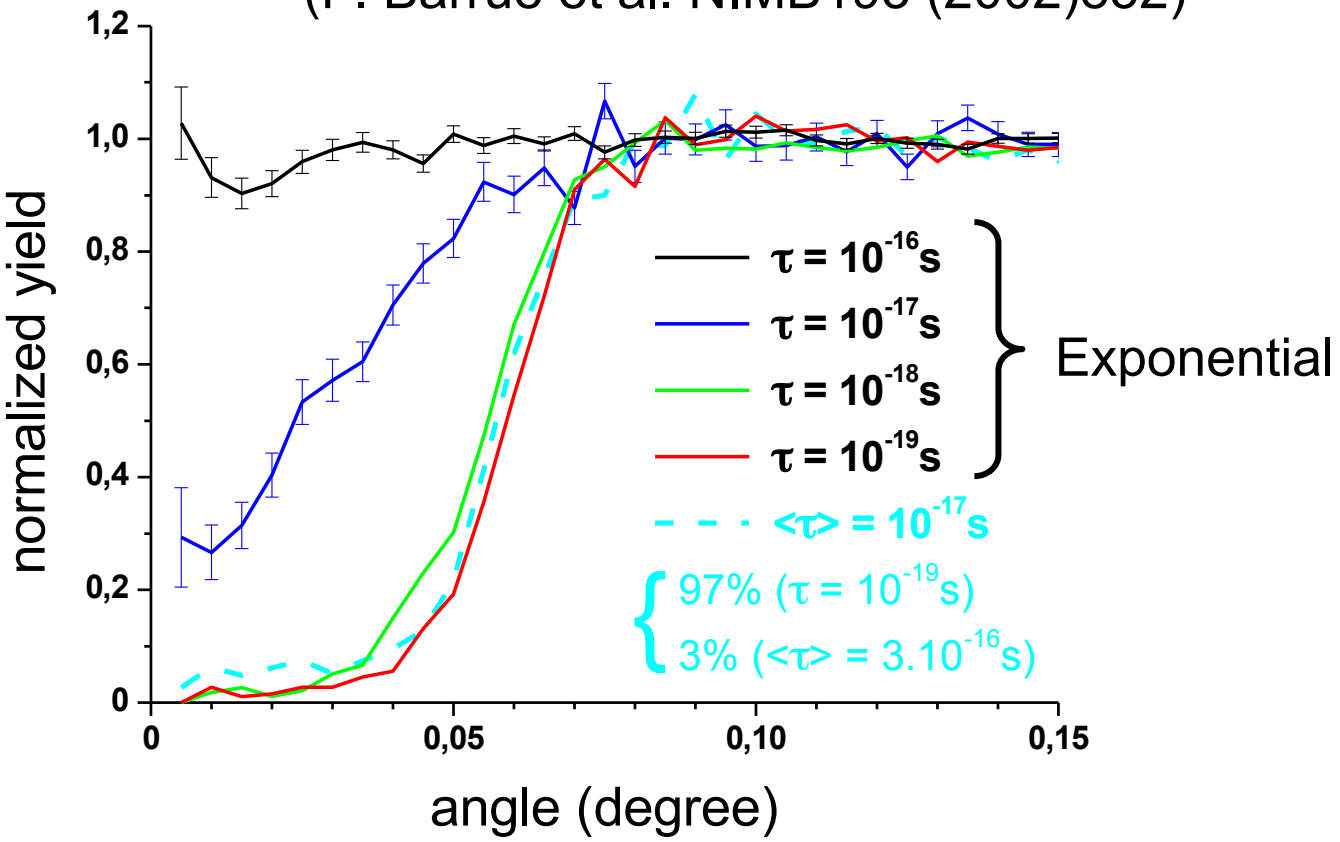
- Damage control
- Reference during an experiment devoted to nuclear lifetime measurements



# Simulations for Pb fission fragments

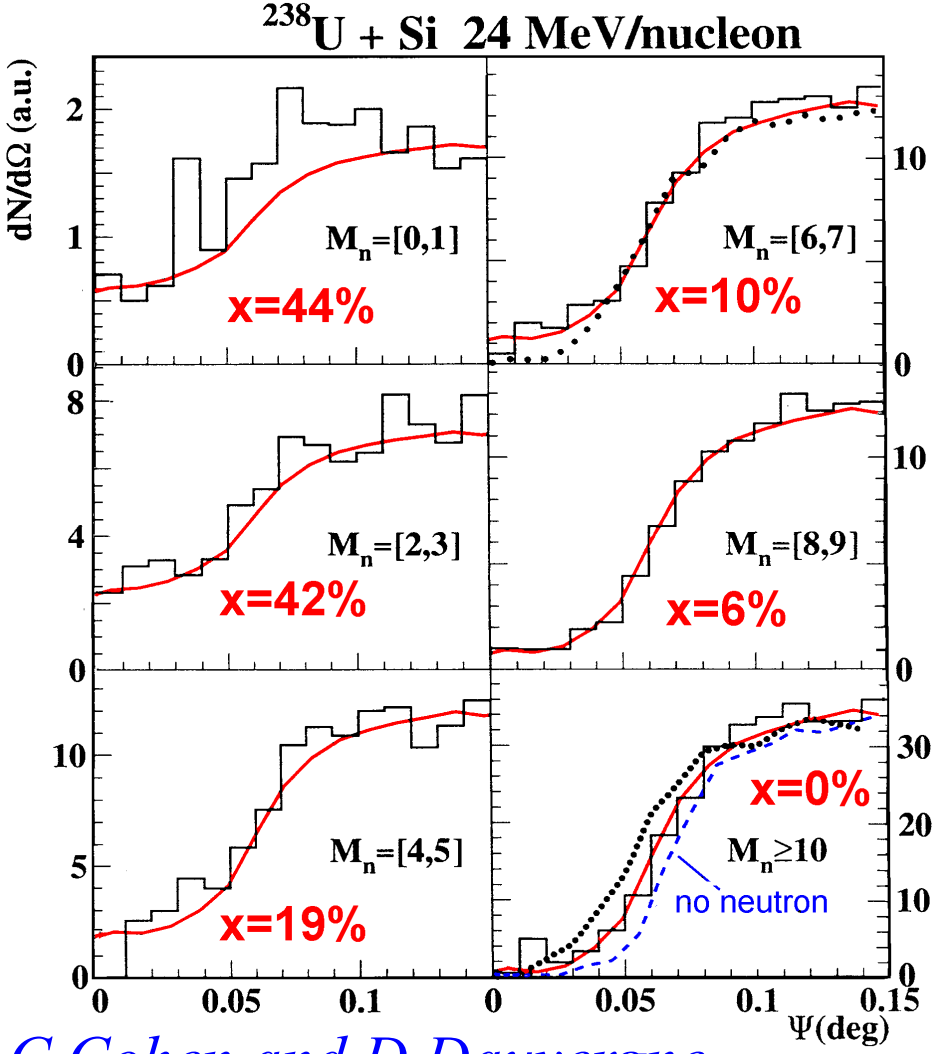
## 29 MeV/u incident Pb ions at 5° from <110> axis of Si

(F. Barrué et al. NIMB193 (2002)852)

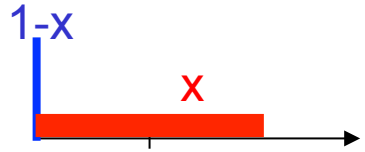



Blocking experiments are sensitive to long-lifetime components

# Uranium fission times as a function of excitation energy

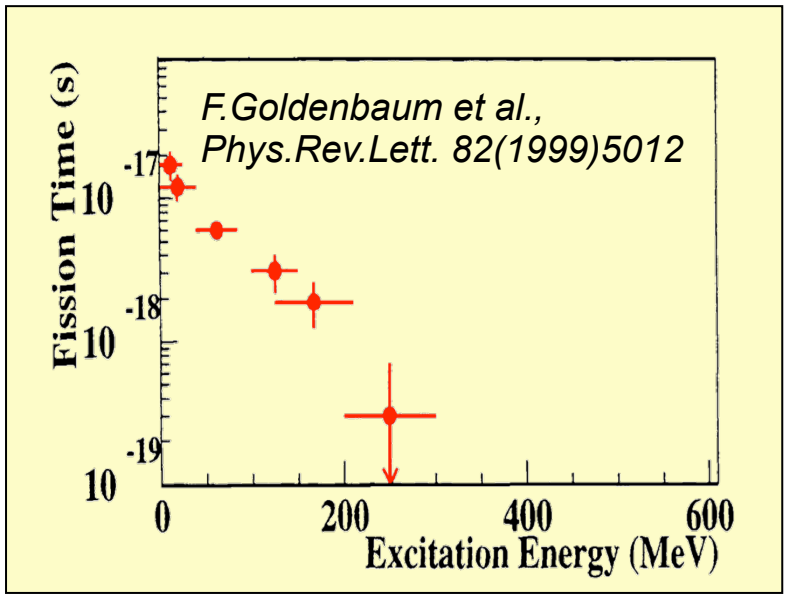



*C.Cohen and D.Dauvergne, NIM B 225 (2004) 40*




**$10^{-19}$s $3.10^{-17}$s**

**x** = long time component fraction deduced from simulated dips



# Super-heavy nuclei fission times

- Goal: observation of the fission-barrier for 114<Z<128 compound nuclei formed during fusion-fission experiments
  - If Bf ~ 0: deep inelastic or quasi-fission
  - If Bf > 0: enhanced fission time (>$10^{-18}$s)

- Two experiments at GANIL ($4\pi$ detector INDRA):

  U+Ni, U+Ge, Pb+Ge

  Long fission times for Z=120 and Z=124

  No evidence at the limit of sensitivity for Z=114

  More conclusive experiment without long fission times would be necessary

M. Morjean et al., Phys Rev. Lett 101 (2008) 072701

# Conclusion

- Some examples of particular aspects of « low » energy heavy ion interaction with crystals

- Applications in:
  - Atomic physics (X-ray spectroscopy, charge exchange)
  - Material modification (very high energy loss rates: surface emissions)
  - Beam optics (ion deceleration)
  - Nuclear physics (fission studies in blocking and channeling)