Ion channeling at intermediate energies:

- Experiments at GANIL and GSI
- Beam bending simulations

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Summary

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2. Heavy ion experiments

3. Proton and C ion bending simulations

4. Conclusion
Introduction

Ion channeling at intermediate energies

- Ions: protons to uranium
- Energies: from 10 to 400 MeV/u
  - No or little relativistic effects
  - Fast ions: \( v \gg v_0 \), but \( v \sim v_0 Z^{1/3} \): Charge exchange
- Channeling: effects related to ion-electron interaction:
  - Energy loss
  - Impact parameter dependent charge exchange
  - Blocking: lifetime during nuclear reactions
- Critical angles \( \sim 1 \) mrad
  - Large bending radii: large angle deflection with bent crystals
GANIL (Caen)

High energy
Ar: 95 MeV/u
Kr: 60 MeV/u
Pb$^{56+}$: 29 MeV/u

Stripping before last acceleration stage: ions with electrons in excess
**SIS - ESR at GSI (Darmstadt)**

**H-like ion beams:**
- \( \text{U}^{91+} 20 \text{ MeV/u:} \quad \eta_K = \left( \frac{v}{v_K} \right)^2 \approx 0.085, \eta_L \approx 0.35, \eta_M \approx 0.8 \)
- \( \text{U}^{91+} 12 \text{ MeV/u:} \quad \eta_K \approx 0.051, \eta_L \approx 0.21, \eta_M \approx 0.48 \)

**Stripping before deceleration:** ions lacking of electrons
Ion channeling
interaction with the non-uniform electron gas

Flux redistribution simulation

Silicon <110>

Uniform flux (random)  “Ideal“ channeling

N(b)

atomic string  channel center
Energy loss

Pb 29 MeV/u on Si <110> 1.1 µm (GANIL: SPEG spectrometer)

L’Hoir et al., NIMB 245(2006)1

High Et ions:
- close collisions along strings at entrance
- Averaged $DE \sim 2 \times DE_{\text{random}}$

Low Et ions $\rightarrow$ Low DE

Locally, $DE \sim 10 \times DE_{\text{random}}$

Low $dE/dx$

Very high $dE/dx$

[110] row

$\sim 4$ Å

$\sim 1$ µm
Charge state distributions (Magnetic spectrometers)

Pb$^{56+}$ 29 MeV/u 1.1 µm Si (GANIL)  

U$^{91+}$ 20 MeV/u 11.7 µm Si (GSI)

Incident ions far from charge equilibrium

- "Random" orientations: 3-body capture (MEC) and Nuclear Impact Ionization Equilibrium
- Axial orientation: $F(Q_{\text{out}})$ linked to $F(E^-)$
  
  Broad distributions, large "frozen" ion fraction

Superdensity effect: $Q_{\text{out}} > Q_{\text{out}}(\text{random})$, enhanced ionization close to strings

Critical incidence: $Y \sim Y_c$ : superdensity effect maximum
Deceleration of highly charged uranium ions in a silicon crystal

$U^{91+}$ 12 MeV/u $\circledR$ 18 $\mu$m Si

Frozen transmitted $U^{91+}$ ions $\sim$ 0.3% for (110) planar channeling
$\sim$1.5 % for <110> axial channeling
Crystal deceleration of heavy ions

- 12 MeV/u $^{91+}$ U deceleration in 18 µm Si
  - Ion transmission $^{91+}$ U ~0.3%; $E_{\text{final}} = 9.4$ MeV/u (110) plane
  - $E(110) = 2.6$ MeV/u > $E(\text{random}) = 1.9$ MeV/u

![Graph showing dE/dx vs. E for $^{91+}$ U in 18 µm Si](image)

*C. Ray et al., Physical Review B 84 (2011) 024119*
Fission time measurement by crystal blocking

- Fission time measurement
  - Long time filling of the blocking dip
  - Simulations long time fraction

\[ r_c = v_r \cdot t_{\text{fiss}} \] : compound nucleus transverse recoil

Experiments
Uranium fission times as a function of excitation energy

\[ x = \text{long time component fraction} \]

\[ 10^{-19} \text{s} \quad 3 \times 10^{-17} \text{s} \]

C. Cohen and D. Dauvergne,

* NIM B 225 (2004) 40

F. Goldenbaum et al.,

Simulations

Full trajectory simulations are needed for:

- Blocking experiments
  - Delayed neutron evaporation by fragments inside crystal
  - Angle at exit is required
- Energy loss or charge exchange when correlated collision dynamics play a role
  - Superdensity effect
- Dechanneling in thick crystals
  - Bent crystals
Planar channeling trajectory simulations

Oscillation between 2 planes

\[ ^{12}\text{C} @ 400 \text{ MeV/u} \rightarrow \text{Si} ; \ L = 5 \ \mu\text{m} \]
First experiments 70’s – and 80’s

- High energies and small deviations
  - Proton 70 GeV, 450 GeV
    q : 80 mrad (4°)
  - Pb\(^{82+}\) : 22 – 33 TeV
    q : 4-9 mrad (0.2-0.5°)
  - Proton 3,5,10 MeV
    q : 1 mrad (0.08°)
  - Proton 7 TeV
    q : 2-20 µrad (0.1-1 x10\(^{-3}\) °)
Ion therapy applications?

- Medical constraints
  - Multi entrance ports
  - No rotation of the patient

- « Gantry »
  - Beam deviation

- Carbon gantry ~ 600t
  - (proton ~ 30t)
  - bent crystal < 1g
    - Large deviations
      - 45° ? 90° ?
    - Ion survival yield

- Curvature influence
  - Critical radius ($R_c$)

$^{12}\text{C} @ 400\text{ MeV/u} \rightarrow \text{Si} ; L = 5\text{ µm}$
Monte Carlo simulations
Monte Carlo simulations

- Thermal vibration

- Electronic local density

- Energy loss

- Multiple scattering on electrons

- Use of the crystal symmetry

- Relativistic speed

\[
\frac{dE}{dx} \propto \frac{1}{v^2}
\]

\[
\langle \frac{d\Omega^2}{dz} \rangle = \frac{m_e}{2 \cdot E \cdot m_t} \langle \frac{dE}{dx} \rangle_{sd} \cdot \frac{\rho(z)}{\rho_{sd}}
\]
Simulation results

Survival: $c < \text{angle} < c$ relative to crystal plane

![Graph showing survival rate against angular deviation for different ions and curvature radii.](image-url)
Simulation results

- Comparison with predictions

$^{12}\text{C} @ 400\text{MeV/u}$

$$T(\theta, R_C / R) = A_s^* \left(1 - \frac{R_C}{R}\right)^2 \exp \left(-\frac{L}{L_D \left(1 - \frac{R_C}{R}\right)^2}\right)$$

$L$ : crystal length
$R$ : bending radius
$q$ : deviation angle
$L_D$ : dechanneling length (from simulation)
$R_C$ : critical bending radius

$L = R \cdot \theta$

$R_C = 0.225\ \text{cm} \\
L_D = 0.087\ \text{cm}$
Simulation results

- Survival rate vs crystal depth

![Graph showing survival rate vs crystal depth](image)
Simulation results

- Influence of crystal type and temperature

![Graph showing deviation at 1% survival rate](image-url)
Simulation results

- Angular distribution of surviving ions
  (C ions at 400 MeV/u in Si 293 K)
Simulation work based on previous work with heavy ions at GANIL and GSI

Deflection angles above 10° achievable in planar channeling conditions
But hardly convenient for demanding applications such as hadrontherapy

Experiments needed to validate simulations (and extrapolation at higher energies)