Transverse Cooling or Heating of Channeled Ions by Electron Capture and Loss

W. Assmann, He. Huber, S.A. Karamian [a], H.D. Mieskes, J.U. Andersen [b], M. Posselt [c], and B. Schmidt [c]

[b] ACAP, Aarhus University, Denmark [a] FLNR JINR Dubna, Russia
[c] Forschungszentrum Rossendorf, Dresden

Energetic charged particles entering a crystal nearly parallel to an axis or plane become channeled; their motion is guided by correlated collisions with atoms on atomic rows or in atomic planes. For incidence outside a critical angle, the particles move nearly as in a random medium. During penetration of a thick crystal there will be transitions due to multiple scattering. Scattering from the channeled to the random beam is suppressed by the channeling effect and the opposite transition is hampered by blocking but, according to a general principle of reversibility, the two transition rates are equal if energy loss can be neglected. Hence, an initially isotropic angular distribution is expected to be stable under transmission through a crystal. A small deviation from reversibility, for example due to energy loss or related effects, would be easy to detect under these conditions.

For this purpose we have performed experiments using our large–area position sensitive ionization detector and the ERDA setup [1]. A beam of 210 MeV I or 230 MeV Au ions was incident on a scattering target and the recoils (or scattered ions) were detected after transmission through a thin Si crystal of 2.9 to 8.7 μm thickness, prepared by electrochemical etching with an ion–implanted etch stop. Results of these measurements are presented in fig. 1 exhibiting a strong redistribution of the particle flux from an initially isotropic angular distribution. Recoil atoms and scattered projectiles were separated in the detector but no selection on energy was applied. The particle density is represented by the pixel gray level with darker gray indicating higher density. An increase as well as a decrease of the particle flux in the direction of axes or planes can be seen, depending on the experimental conditions. Enhancement of the particle flux in channeling directions was also observed for p and α particles at energies of 200 to 500 keV/u after transmission through similar thin Si crystals with a nuclear track detector. Such behavior was not predicted by the existing theory and could not be reproduced by computer simulations. The effect is not related to the well known flux peaking of channeled particles which is flux enhancement in space, not in angle.

We propose a new mechanism to be responsible for the observed effects, related to the special properties of charge exchange processes along an ion trajectory. If an electron is captured at distance r_c and lost at a larger distance r_l, the ion experiences a net loss in transverse energy due to the changing potential energy. The electron is carried away from the atomic row, up a potential hill for the electron, and then lost. This effect is analogous to Sisyphus cooling of very cold, trapped atoms in strong laser fields. If, on the average, $r_l > r_c$, capture and loss will lead to an increase in the density of ions at small $E_\perp$ and therefore to an enhancement of the flux of ions exiting the crystal nearly parallel to the axis. The effect is strongly depending on the mean electron loss and capture distance and could be reversed for the case of very heavy ions resulting in transverse heating.

In conclusion, our experiments have shed new light on the basic symmetry of ion scattering in crystals. The observed effects are strong and must be taken into account in calculations of dechanneling or computer simulations.

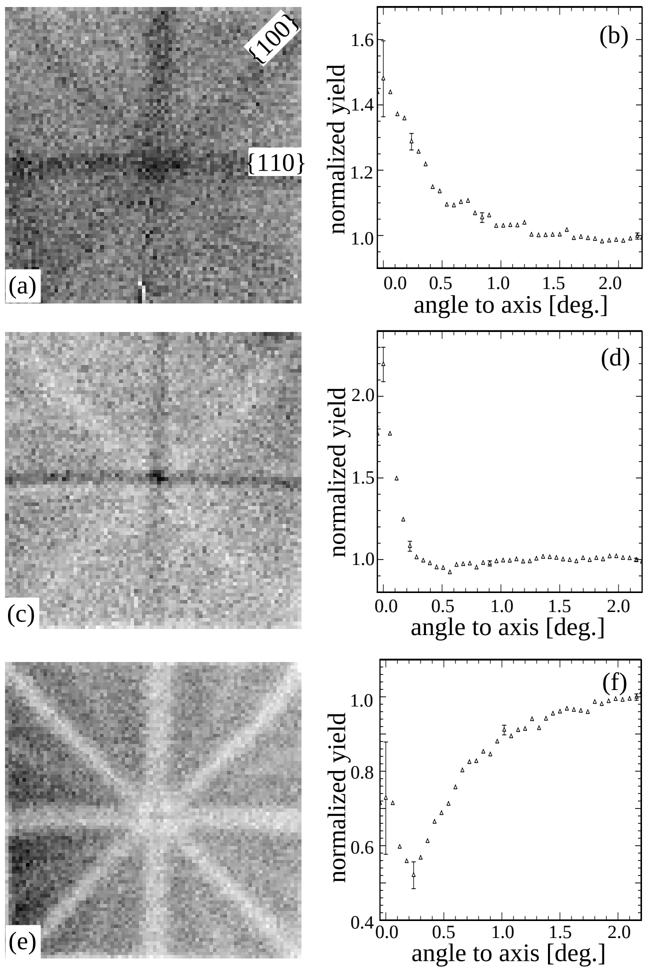

Fig. 1: Flux distributions of heavy ions after transmission of (001) Si foils, and corresponding circular averages around the $\langle 100 \rangle$ axis at varying polar angle: (a,b) C recoils at 18 MeV after 8.7 μm Si, (c,d) Cu recoils at 53 MeV after 8.7 μm Si, (e,f) scattered I ions at 131 MeV after 2.9 μm Si. Planar directions are indicated in (a).

References

[1] W. Assmann *et al.*, Nucl. Instr. Meth. **B89** (1994) 131