Transition from Transverse Cooling to Heating ◊

F. Grüner, W. Assmann, M.Schubert, and S.A. Karamian [a]
[a] FLNR JINR Dubna, Russia

Swift ions that enter a crystal below a critical angle relative to crystallographic directions are channeled due to correlated collisions with the target atoms. Non channeled ions move nearly like in an amorphous material. All ions undergo scatter events with the electron gas and the thermally vibrating target atoms. Due to this scattering there is a transition from channeled ions to non channeled ones, and vice versa. According to a rule of reversibility the transition rates are equal, if energy loss can be neglected. Thus an isotropic ion beam should remain isotropic after transmission of a thin crystal. However, a strong redistribution of the ion flux behind thin crystal foils was recently discovered [1,2,3]. For not fully stripped ions we have seen either a strong enhancement or strong decrease along crystal directions.
Computer simulations (CRYSTAL-TRIM) that entail all known scatter and stopping processes (hence including considerable energy loss) cannot reproduce these redistributions. Therefore, a new mechanism was introduced: cooling or heating of the transverse motion by correlated charge exchange processes [1]. The key point is a different impact parameter dependence for electron capture and loss, yielding a net loss or gain of the transverse ion energy.
The experimental setup consists of a high vacuum scatter chamber, and a position sensitive ionization chamber or a simple plastic track detector (CR-39). The ion beam from the accelerator is scattered on a thin ($150\mu g/cm^2$) W-target, which leads to a quasi-isotropic angular distribution. The energy of the scattered ions is decreased by Al-foils that are mounted just in front of the (100)-Si-,-Ni-, and -Pt- foils.

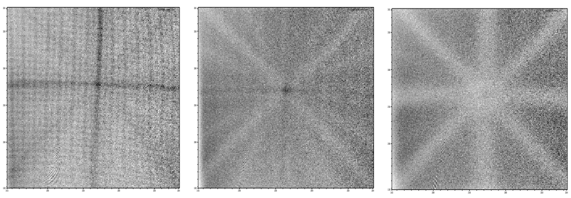

Fig. 1: Flux distributions of Y-ions after transmission of a (100)-Si-foil at 170, 120, and 60 MeV. The left case shows an enhancement of the flux along crystal directions, thus denoted as cooling, whereas the right case displays a decrease, called heating. The grid pattern in the left case is due to electronic artefacts in the ionisation chamber.

Fig. 1 shows the flux distributions of Y-ions at three different energies. The top case at 170 MeV shows what we refer to as cooling, i.e. an enhancement of the flux along crystal planes due to significant transverse energy loss. The bottom case at 60 MeV is the reversed situation, namely heating. The middle case at 120 MeV shows a somewhat intermediate stage. This transition from cooling to heating is one characteristic feature of our effect.
The exit energy of the intermediate stage defines a transition energy at which cooling is transferred into heating. We have measured these transition energies of different ions after 3.0 μm Si-, 0.85 μm Ni-, and 1.08 μm Pt-crystals. The results are displayed in fig. 2.

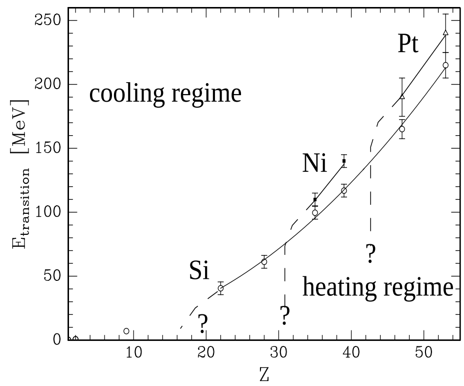

Fig. 2: Transition energies of all measured ions in the case of Si (open circles, fit), Ni (filled triangles), and Pt (open triangles). Ions with exit energies above the transition energy are cooled, and below heated. It is indicated that there is no transition below certain "critical" Z's.

The fit in the Si case yields a Z^2-dependence, with Z being the nuclear charge of the ion. In the cases of Ni-, and Pt-crystals, and probably also of Si-crystals, there is a specific "critical" Z below which there is no such transition from cooling to heating. In these cases only cooling appears. For instance, Ag-ions do show the transition after transmission of a Pt-crystal, but Y-ions do not. For Ni-crystals the critical Z is somewhere between Ni and Br. The critical Z for the Si case, if at all, is not known yet (e.g. protons with 120 keV, alphas with 600 keV, and F-ions with only 7 MeV exit energy still show cooling).
According to our working hypothesis, for understanding the observed effect of cooling and heating it is essential to study the energy dependence of the mean capture and loss radii. First simple estimates of capture cross sections (such as the well known OBK approximation or estimates from a Thomas-Fermi approach) cannot reproduce the relatively narrow energy region (of about 30 %) in which the transition takes place, let alone the values of the transition energies. A satisfying complete model is still not at hand. Future experiments will concentrate especially on the critical Z's.
Further measurements with the Q3D detector will be performed to study the charge state distributions in dependence of the exit angle, and thus of the region of the impact parameters that the ions have tested during their transmission. This could be a direct test of our working hypothesis about the different impact parameter dependence of electron capture and loss.

References

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[2] R. Scharf, Phys. Blätter **55,17** (1999)
[3] W. Assmann, F. Grüner in "Einsichten, Forschung an der LMU **2**, 2000"

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