Stopping power of heavy ions under channeling condition

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Synopsis We present experimental work providing evidence on the mechanisms underlying the observed trajectory dependence of inelastic energy deposition by heavy ions in the keV energy regime.

We present experimental results on the inelastic energy loss of a wide range of ions in the 4-300 keV energy regime in single crystalline matrices. The comparable velocity of ions and electrons in the target's valence and conduction bands renders the underlying interaction highly dynamic and strongly trajectory-dependent. Ion transmission experiments through self-supporting crystalline silicon targets provide an excellent model system to study the trajectory-dependence due to its simple geometry, which allows for an exclusive choice of projectile trajectories [1].

The stopping power of all ions except protons is found to be highly reduced under channeling conditions compared to random incidence [1,2]. However, a reduction in electron-hole pair excitation alone cannot explain the disparity of the electronic excitations in different geometries since the core-shell electrons are no longer accessible. While an influence of different electron densities is expected, the observed dependence of the differences on the atomic number of the ion indicates that additional energy loss processes are involved. We explain our observation by several charge exchange processes, such as electron promotion due to the creation of molecular orbitals occurring in close collisions of ions with target atoms only accessible in random geometry. Additional to direct losses in the electron promotion, these events result in trajectory-dependent mean charge states that heavily affect the energy loss.

The evidence for the altered charge state distribution developed along different trajectories is investigated by discrimination of transmitted projectiles based on their charge state. Considerably larger fractions of higher charge states are emerging from random geometry, while the channeled projectiles tend to remain more neutral.

Furthermore, the large energy-loss events in the promotion events leave a signature in the shape of the energy distribution of transmitted projectiles in the form of energy loss straggling. For projectiles heavier than protons and helium, the velocity scaling of the straggling in random geometry suggests a minimum and increase towards lower projectile velocities [4].

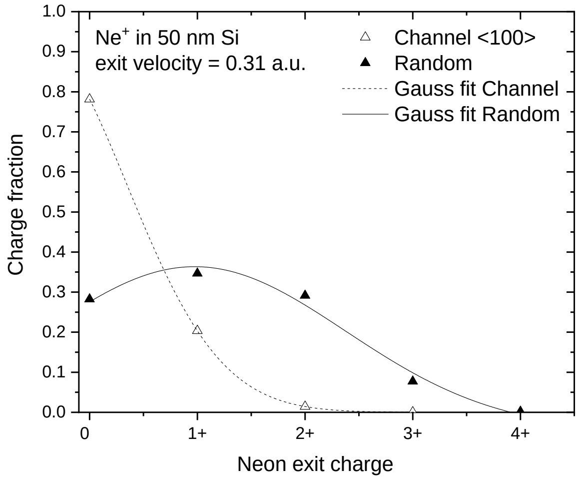

Figure 1. Charge fraction distributions of Neon projectiles at exit velocity 0.31 a.u. after transmission through 50 nm Si crystal.

Ongoing development of our understanding forms the basis for analytical tools based on ion beams, irradiation damage, sputtering and other industrial methods. Above that, the channeling condition being to a large extent not affected by the complex charge exchange processes can yield a well-defined test scenario for theoretical models on ion-electron dynamics, which aim to predict equilibrium [DFT] and non-equilibrium conditions [TD-DFT] in solids [3].

References

[1] Holeňák R et al. 2020 *Ultramicroscopy* **217**
[2] Lohmann S et al. 2020 *PRL* **124** 096601
[3] Lohmann S et al. 2020 *PRA* **102** 062803
[4] Lohmann S et al. 2023 *PRB* **107** 085110

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