Collisions of highly charged ions with 2D materials
- What we learn from ion transmission spectroscopy -

R.A. Wilhelm[1,2], S. Creutzburg[2], J. Schwestka[1], A. Niggas[1], L. Madauß[3], H. Inani[4], M. Tripathi[4], C. Mangler[4], R. Heller[2], S. Facsko[2], J. Kotakoski[4], P.L. Grande[5], M. Schleberger[3], and F. Aumayr[1]

[1]*TU Wien, Institute of Applied Physics, Vienna, Austria, EU;* [2]*Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Dresden, Germany, EU;* [3]*University Duisburg-Essen, Faculty of Physics and CENIDE, Duisburg, Germany, EU;* [4]*University Vienna, Faculty of Physics, Vienna, Austria, EU;*[5]*Federal University of Rio Grande do Sul, Institute of Physics, Ion Implantation Laboratory, Porto Alegre, Brazil*

Slow ions in high charge states impacting a solid surface represent a far-from-equilibrium system. Upon impact, the ions capture dozens of electrons and these electrons decay into the atomic ground state already during the collision driven by non-radiative de-excitation processes such as Interatomic Coulombic Decay [1]. The neutralization and electronic decay of the ion leads to the release of its potential energy, which amounts up to several 10 keV facilitating nanostructure formation in susceptible materials (mainly insulators with strong electron-phonon coupling).

When a freestanding 2D material is used as a solid target, the ions are still available for spectroscopic measurements after the ion-surface interaction. We performed charge state and kinetic energy analysis of ions transmitted through freestanding single layer graphene (SLG) [2], amorphous 1 nm thick Carbon Nanomembranes (CNM) [3], freestanding single layer MoS_2, SLG/MoS_2 heterostructures and others. As a first result we found an ultrafast (sub-10 fs) neutralization taking place, much faster than established models would have anticipated. Further, kinetic energy loss is significantly enhanced over the expected value from singly charged ions under the same conditions. We are able to find charge exchange patterns, utilizing angle-resolved charge exchange spectroscopy [4]. To facilitate a comprehensive understanding of the plethora of observed phenomena and their interplay, we developed an atomistic model for ion stopping, charge exchange and electronic decay taking the time-dependent ion charge state explicitly into account [5].

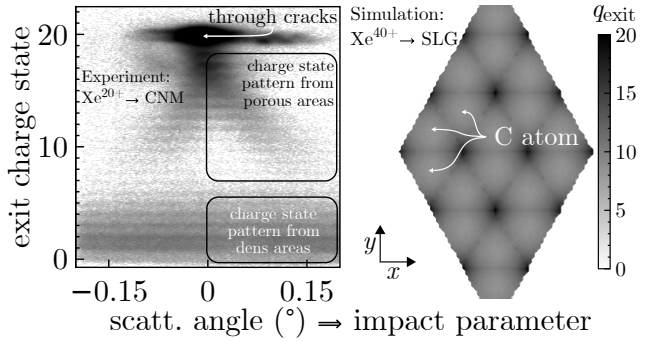

Figure 1: Left: Experimental exit charge state pattern from Xe^{20+} ions transmitted through a CNM. Right: Atomistic model result for the impact parameter dependent exit charge state distribution of Xe^{40+} transmitted through SLG. The scattering angle is related to the impact parameter by the (time-dependent) scattering potential.

In this contribution I will show that charge exchange pattern together with an atomistic and local model for charge exchange can be used to determine the structure of 2D materials on a sub-nm level, especially important for amorphous materials where atomically-resolved microscopy is hard to perform.

[1] Wilhelm R.A. *et al.* 2017 *Phys. Rev. Lett* **119** 103401
[2] Gruber E, Wilhelm R.A. *et al.* 2016 *Nat. Commun.* **12** 126101
[3] Wilhelm R.A. *et al.* 2014 *Phys. Rev. Lett* **112** 153201
[4] Schwestka J., *et al.* 2018 *Rev. Sci. Instrum* **89** 085101
[5] Wilhelm R.A., Grande P.L. 2019 *Commun. Phys.* **under review**