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ЯРОСЛАВСКИЙ ФИЛИАЛ ФИЗИКО-ТЕХНОЛОГИЧЕСКОГО ИНСТИТУТА РАН
НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ ЯДЕРНЫЙ УНИВЕРСИТЕТ «МИФИ»
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Том 2

THE INTERACTION OF HIGHLY CHARGED IONS WITH FREE-STANDING 2D MATERIALS

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In the last decade, free-standing atomically thin materials have proven to be excellent candidates to study ion-solid interaction on a fundamental basis. Not only do they allow for direct observation of the projectiles after the interaction, they also offer the opportunity to study target characteristics while showing pure surface effects, i.e., no sub-surface effects need to be considered. Thereby, we were able to discuss the ultrafast response of suspended semi-metallic single-layer graphene sheets upon excitation via highly charged Xe impact: while the ions were found to neutralise within a few fs only and thus extracting a high number of electrons from the target at the same time, no pore formation could be determined via transmission electron microscopy proposing ultrahigh local current densities [1]. For free-standing semi-conducting molybdenum disulfide (MoS_2), however, pore formation via highly charged ion impact under similar conditions was shown recently [2]. Still, the neutralisation of the projectile is comparable to the case of single-layer graphene when taking an increased interaction time into account, following from the three-layered nature of MoS_2, where Mo atoms are sandwiched in-between two layers of S atoms (cf. figure 1) [3]. In this contribution we will focus on the electron emission from both materials induced by highly charged ion impact. For single-layer graphene, Schwestka *et al.* presented a high number of emitted low-energy electrons lately [4], being in accordance with the predictions of Wilhelm *et al.* proposing a two-center Auger process – the interatomic Coulombic decay – as dominant mechanism in the de-excitation of these highly charged projectiles [5]. As MoS_2 and single-layer graphene are comparable in their hexagonal structure (cf. top view of graphene and MoS_2 sheets in figure 1), any discrepancies in the electron emission may be retraced to their significantly different electronic properties, i.e., zero vs. non-zero bandgaps.

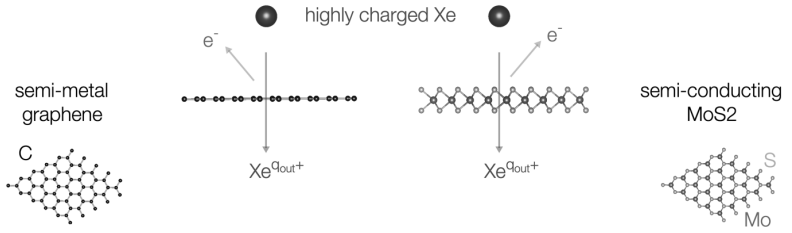

Figure 1 - Highly charged ion transmission through atomically thin materials [6]. We discuss the difference of single-layer graphene and MoS_2 as samples in regard to the ion neutralisation, the number of emitted electrons and the response of the target itself. Since both samples have a similar structure (see top view left and right, respectively) differences may be attributed to the semi-metallic and semi-conducting electronic properties of the materials themselves.

For our studies, we use the ion beam spectrometer at TU Wien enabling us to produce highly charged Xe ions with charge states up to 40 and acceleration voltages up to 10kV [7]. We further employ a coincidence technique including two detectors, a solid-state (PIPS) detector for electron number statistics and a microchannel plate (MCP) detector behind a pair of deflection plates for exit charge state analysis of the projectiles. The combination of both additionally provides the time of flight (TOF) of projectiles from target to MCP position (cf. figure 2). We record all data in a listmode and are thus able to perform post-measurement data analysis to filter signals from target and support materials as well as contaminated regions [8].

Exemplary spectra of 130 keV Xe^{40+} transmitted through single-layer graphene are given in figure 2: an unfiltered exit charge state spectrum for the appropriate TOF region is shown in the lower right corner (orange). We find a distribution of neutral particles (blue) arising from the transmission through the amorphous carbon Quantifoil support of the sample (10-20 nm thick) and a distribution with an exit charge state of ~25 (red) from projectiles transmitted through graphene only. Filtered TOF spectra corresponding to the blue and red region are presented in the upper right corner (violet) and show distinctive graphene at lower and Quantifoil distributions at higher TOF values. Thereby, we can unambiguously separate electron yields for graphene and Quantifoil support which then amount to 96 and 78 electrons per impinging ion, respectively. Exit charge state and TOF filtered electron statistics spectra including Gaussian fits to determine the electron yields are presented in the upper left corner (green). The lower left corner shows a schematic of our setup to point out the relations of the discussed spectra.

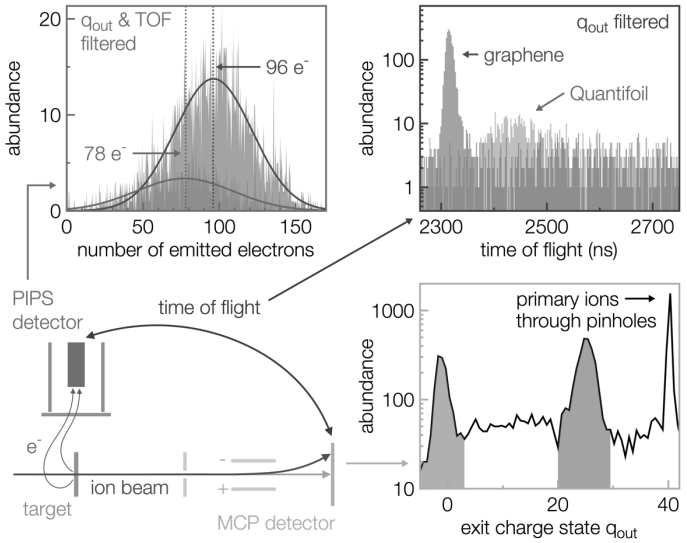

Figure 2 - Ion spectroscopy setup at TU Wien [7]. We employ a PIPS detector (for electrons) and an MCP detector (for ions) in coincidence to study the interaction of highly charged ions with atomically thin materials. A schematic of our setup is depicted in the lower left corner. The MCP detector serves for exit charge state analysis of projectiles after transmission through a target (lower right), whereas the PIPS detector allows for electron emission statistics analysis (upper left). Combining both, we are also able to record the time of flight of the projectiles from target to MCP position (upper right). Our measurement recordings in a listmode enable complex filtering of target and support signals as shown in the figure for single-layer graphene and its thicker Quantifoil support for 130 keV Xe^{40+} projectiles.

When we repeat these measurements for semiconducting MoS2 we find that the electron emission yield for single-layer graphene is six times higher than in MoS_2, while the amorphous carbon Quantifoil support contributes an electron yield approximately midway in-between graphene and MoS_2. In addition, we compare the kinetic and potential energy loss of ions transmitted through both samples. In order to understand the resulting differences between graphene and MoS_2 we then discuss our results in regard to the samples' electronic properties both in their bulk counterparts and in particular in their two-dimensional form.

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