Guiding of Argon ions through PET nano capillary foils

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Abstract. The transmission of charge state separated slow ions through nano capillaries with an aspect ratio of 1/100 in insulating polyethylene terephthalate (PET) polymers was investigated on argon ions with different charge states from Ar³⁺ up to Ar₁²⁺. The experiments were performed with a beam line featuring an ion deceleration system. With it the ion guiding of projectiles of different kinetic energies ranging from 600eV up to 9.6 keV has been studied. The guiding power as well as the divergence angle of the transmitted ion beam have been investigated in dependence on the initial ion charge state and the ion energy. A scaling of the profile width \( \tan \sigma \phi \sim \sqrt{q} \) at a constant ion energy was found. Furthermore, the guiding angle was measured as independent on the ion charge state at an ion energy scaling with the ion charge state.

1. Introduction

The interaction of highly charged ions (HCI) with solid surfaces is described by the classical over the barrier model (COB) [1]. Using metallic microcapillaries as a target for a beam of slow HCI is a possibility to observe the decay of the hollow atoms that passed the capillaries [2]. Motivated by the extension of the COB to insulating surfaces [3] first measurements of the transmission of HCI through microcapillary targets in insulating materials were done [4].

In metallic materials the HCI can pass through the capillaries only when their axes are parallel to the incident beam direction. For insulating microcapillaries a transmission of HCI was also measured when the capillary axes are tilted in respect to the direction of the incident ion beam. The creation of charge patches on the inner walls of the capillaries and the deflection of the HCI enables the transmission of ions at tilt angles larger than the capillary aspect ratio. Since the first measurements in 2002 by N. Stolterfoht et al. several investigations have been done using different ion energies[5], ion charge states[6] target materials [7, 8] and different types of ions [9] but also electrons [10, 11] as projectiles. The aim of the miscellaneous experiments is to improve the theoretical models [12, 13] of the guiding effect. To investigate the influence of the charge state of the HCI we studied the guiding power as defined in [14] and the transmission profile of argon ions with different charge states from Ar³⁺ up to Ar₁²⁺ and with different kinetic energies ranging from 600 eV up to 9.6 keV.

2. Experimental techniques

The present experiments were performed at the micro beam facility of the TU Dresden at the Forschungszentrum Dresden-Rossendorf [15]. The ions are produced with an electron beam ion
The capillary foils are mounted on a target holder (Fig. 1) in the target chamber at a base pressure of $10^{-9}$ mbar. The target holder can be tilted with high precision relative to the direction of the incident ion beam to realise different tilt angles ($\Psi$) up to $\pm 10^\circ$. The ion beam is focused and collimated to a diameter of 1 mm with a current of typically 30 – 800 pA. The divergence of the beam is better than $0.5^\circ$ full width at half maximum (FWHM). The transmitted ion beam is collimated and deflected by a condenser perpendicular to the tilt direction so that different charged ions are detected at different positions in x-direction. The collimator can be removed to measure the transmission profile in the x-direction.

**Figure 1.** The Experimental setup is mounted a rotatable stage behind a deceleration lens in an ultrahigh vacuum chamber. Different ion energies in the range from several eV up to 20 keV times $q$ can be realised. A multi-channel-plate with a delay-line-anode is used as a position sensitive ion detector.

The PET capillary samples used for the experiments were produced by the irradiation of the foils with fast ions and etching the ion tracks. The capillaries have a diameter of about $130 \pm 20$ nm at a length of 10 $\mu$m. The front and the back of the PET foil is evaporated with Au forming a film of 10 nm thickness. The used capillary density of $10^7$ mm$^{-2}$ implies a geometric opening of about 13%.

3. Experimental results

3.1. Guiding power

The first investigations were concentrated on the dependence of the guiding power[14] on the charge state of the incident ion beam. The guiding power, as a capability of the capillaries to guide ions, can be quantized by the tilt angle $\Psi_c$ for which the normalized transmission fraction drops as $f(\Psi_c)/f(0) = 1/e$. $\Psi_c$ is called the guiding angle.

First, we determined the fraction of transmitted ions by integration of the transmission profiles in $\theta$-direction. This intensity profile (Fig. 3, left graph) in dependence on $\phi$ is fitted by the Gaussian-like function

$$f(\phi) = f_0 + a \cdot \exp \left[ -\left( \frac{\phi - \phi_0}{\sigma_\phi} \right)^2 \right]$$

(1)

with the additional fitting parameter $f_0$. For calculating the guiding angle Eq. 1 is integrated neglecting the parameter $f_0$, that represents the background of the measurements. The
transmission intensity calculated for different tilt angles is plotted in dependence on the tilt angle and fitted by

\[ f(\Psi) = f(0) \cdot \exp \left[ -\frac{\sin^2 \Psi}{\sin^2 \Psi_c} \right]. \]  

(2)

Figure 2. Guiding power of the transmission of Argon ions. The graph at the left shows the transmission of Ar\(^{8+}\) in dependence on the tilt angle \(\psi\) (dots) with the fit (black line) to calculate the guiding angle \(\Psi_c\). The graph at the right shows the guiding angle in dependence on the charge state of the incident ion beam. The energy of the incident ions is 600 eV \(\cdot q\).

In Fig. 2 the measurement of the guiding angle for Ar\(^{8+}\) and the dependence of the guiding angle on the ion charge state at an ion energy scaling linearly with the ion charge state are shown.

3.2. Transmission profile

The relationship between the guiding power and the profile of the transmitted ion beam was measured. Hence, the dependence of the transmission profile on the charge state is analyzed in the following. The opening, defined as the width \(\sigma_\phi\) in the \(\phi\)-direction of the transmitted ion beam is determined by the ion velocity in \(y\)- and \(z\)-direction:

\[ \tan \sigma_\phi \sim \frac{v_y}{v_z}. \]  

(3)

The velocity in \(z\)-direction, depending on the ion energy, is chosen as a constant. The ion velocity in \(y\)-direction depends on the ion charge state \(q\) and on the deflecting potential \(E_y\) of the capillaries (\(v_y \sim \sqrt{q \cdot E_y}\)). Hence, if \(E_y\) is independent on the ion charge that it is created by, Eq. 3 can be written as:

\[ \tan \sigma_\phi = K(E_y) \cdot \sqrt{q}. \]  

(4)

In Fig. 3 the measurement of the transmission profile and the dependence of the transmission profile and the parameter \(K(E_y)\) on the ion charge state at a constant kinetic energy are plotted. The width \(\sigma_\phi\) is averaged over different tilt angles because no significant dependence of the width on the tilt angle was measured.
Figure 3. The graph on the left side shows the transmission profile of Ar$_{12}^{12+}$ ions. The dots represent the measurement and the solid line the Gaussian fit. In the graph on the right side the width of the transmission profile $\sigma_\phi$ (dots) and the parameter $K(E_y)$ (crosses) in dependence on the ion charge state are plotted. The energy of the incident ions is 6.0 keV.

4. Conclusion
The scaling of the transmission profile $\tan \sigma_\phi \sim \sqrt{q}$ and the independence of the parameter $K(E_y)$ on the charge state at a constant ion energy give evidences, that the deflecting potential of the capillaries depends only on the target properties such as surface and bulk conductivity. Furthermore, the independence of the guiding angle on the ion charge state at an ion energy scaling with the ion charge state shows, that the deflecting fields on the capillary walls are independent on the charge state of the initial ion beam.

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