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Guided transmission of oxygen ions through Al_2O_3 nanocapillaries*

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The transmissions of oxygen ions through Al_2O_3 nanocapillaries each 50 nm in diameter and 10 μm in length at a series of different tilt angles are measured, where the ions with energies ranging from 10 to 60 keV and charge states from 1 up to 6 are involved. The angular distribution and the transmission yields of transported ions are investigated. Our results indicate both the existence of a guiding effect when ions pass through the capillary and a significant dependence of the ion transmission on the energy and the charge state of the ions. The guiding effects are observed to be enhanced at lower projectile energies and higher charge states. Meanwhile, the results also exhibit that the transmission yields increase as the tilt angle decreases at a given energy and charge state.

Keywords: capillary guiding, tilt angle, energy dependence, charge state dependence
PACC: 3450H, 3450D

1. Introduction

The interaction of slow highly charged ions (HCIs) with surfaces has been widely investigated in the last two decades.[1−4] When ions approach a solid surface, a target electron can be resonantly transported to the empty outer shells. As a result, a so-called hollow atom of the first generation is created. When the ions approach the under surface, the inner electrons of the surface atoms resonantly transfer to incident ions. Such a hollow atom below the surface is called a hollow atom of the second generation. To achieve an understanding of the above-surface interaction, studies for different targets and ions have been carried out.[5−7]

In the late 90s, metallic capillaries were fabricated and used to understand the behaviour of HCIs moving close to the surface, without having a hard collision with surface atoms.[8,9] The transmission of HCIs through capillaries with metal surfaces was described successfully in theory.[10,11] Recently, Stolterfoht *et al* [12−16] used polyethylene terephthalate (PET) capillaries to study the charging up effects inside the walls of the capillaries. It was found that a considerable fraction of ions was guided through the capillary and the distribution of transmitted ions was homogeneous; in addition, the centroid of transmitted ion angle distribution shifted with the increase of the related tilt angle. Since a large number of highly charged ions were transmitted through the capillary, close contact with the inner walls seemed to be inevitable. To explain the capillary guiding, it was proposed that the incident ions deposit on the inner wall and form an electrical field which guides the further projectiles through the capillaries.[12−17] The modeling of the guiding effect due to the charging up of the inner capillary walls is not well understood in detail. Therefore, it is still necessary to further investigate the capillary guiding. Our goal in this work is to investigate the guiding effect of oxygen ions with different energies and charge states through Al_2O_3 capillaries.

2. Experiment

The experiments were performed at the electron cyclotron resonance (ECR) ion source at the National Laboratory of Heavy Ion Research Facility in Lanzhou, China. The experimental setup is schematically shown in Fig.1. A 90° bending magnet is used to select a particular charge state according to its mass-to-charge ratio. The beam is then collimated with a

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system of two step slits (S_1, S_2). The entrance slit is kept at less than 2 mm in width and 2 mm in height.

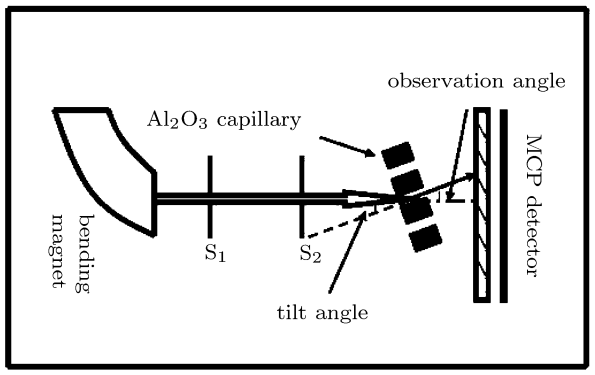


Fig.1. Schematic diagram of the experimental setup.

The divergence of the beam is better than 0.4° full width at half maximum (FWHM). A stepper motor controller is used to tilt the angle of beams with respect to the target. The ions are transmitted through the Al_2O_3 capillary at a fixed incident angle. A position sensitive microchannel plate detector with a resistive anode, placed 50 cm away from the target, is used for detecting transmitted projectiles. The vacuum in the chamber is below 1.3×10^{-6} Pa. In the experiment, the measurements involve the angular distributions of ions with different energies and charge states transmitted through the capillaries.

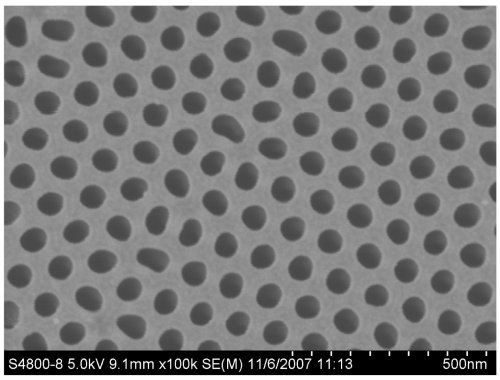


Fig.2. SEM image of the Al_2O_3 capillaries each with a diameter of 50 nm.

Al_2O_3 capillaries each with a 50 nm diameter opening and 10 μm length are used, which have been prepared at Kunming University of Science and Technology, China. The capillary production is described in detail in Ref.[18]. The scanning electron microscope (SEM) image of the capillary is shown in Fig.2. It can be seen that the capillary possesses homogeneous pores of about 50 nm in diameter and is consistent with the experiment.

3. Results and discussion

The angular distribution of 60 keV O^+ ions through the Al_2O_3 capillary is presented in Fig.3. The data are acquired for tilt angles varying from –2° to 3° in steps of 1°. At the 0° tilt angle, the integrated intensity of the transmitted ions reaches a maximum. As the tilt angle increases, the integrated intensity of transmitted ions obviously declines. The angular distributions present Gaussian distribution. Furthermore, it is recalled that the aspect ratio of the capillary is equal to 200 which corresponds to an angular width of 0.3°. However, Fig.3 indicates that the angular distribution of transmitted ions is far greater than 0.6°. These values are much larger than expected from the aspect ratio. This enlargement is likely to be caused by deflections near the capillary exit.

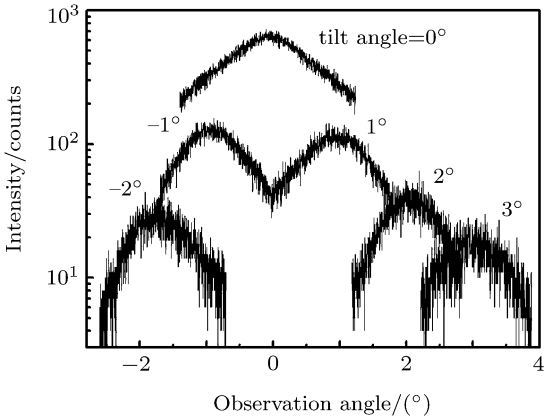


Fig.3. Angular distribution of 60 keV O^+ ions through Al_2O_3 capillaries each with a diameter of 50 nm for tilt angles varying from –2° to 3° in steps of 1°.

Moreover, it is found that the centroids of the angular distributions are significantly shifted with respect to the 0° data when the tilt angle is changed, and each centroid angle nearly coincides with the relevant tilt angle. For instance, when the tilt angle is 1°, the centroid of the corresponding angular distribution is observed to be 1°. The shifts of angular distribution indicate that the ions appear to be guided through the capillary. As a close wall interaction changes the ionic charge state, the transmitted ions would be neutral if there was a close contact, then the integrated intensity of transmitted ions should be zero for tilting the angle. But it can be seen from Fig.3 that the integrated intensity of transmitted ions is still large when the tilt angle is 3°. The phenomenon indicates that the transmitted ions remain charged. These results indicate the guiding of 60 keV O^+ ions through the Al_2O_3 capillaries.

To obtain more information about the capillary guiding we investigate the transmission as a function of the charge state and the energy of the incident ions. Figure 4 shows the values of normalized transmission yield I for O^+ in an energy range from 10 to 60 keV and for 60 keV oxygen ion in a charge state range from 1 to 6 with tilt angles varying from 0° to 3° in steps of 1°. The normalized transmission yield is defined as

$$I = N/N_0,$$

where N is the number of transmitted ions through the capillaries at the 0° tilt angle and N is the number of transmitted ions at an arbitrary tilt angle.

It is found that the trends of transmission yield are falling off with the increase of the tilt angle. For each tilt angle, the guiding efficiency is measured to be higher for a lower energy with a given charge state and the transmission yield is measured to be higher at a higher charge state with a given energy.

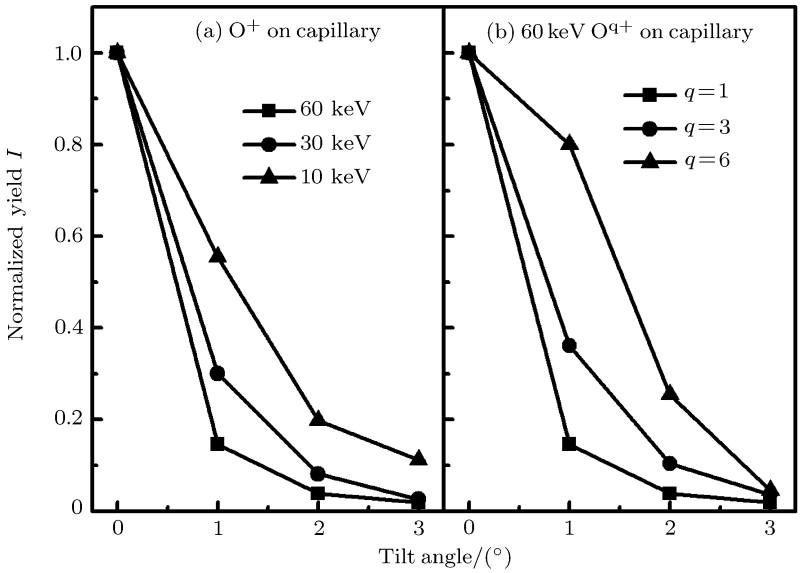


Fig.4. Values of normalized transmission yield I for O^+ in an energy range from 10 to 60 keV (a) and for a 60 keV oxygen ion in a charge state range from 1 to 6 (b) with tilt angles varying from 0° to 3° in steps of 1°.

According to the theory,[12−17] projectile ions approaching the inner wall of the capillary will deposit charges on one side of the capillary wall and this is the charging-up process. At the same time, the ions depositing on the wall diffuse to the periphery, this is the discharging process. When the charging and the discharging processes achieve balance, the quantity of charge on the inner wall is a constant. The charge deposited on the wall forms an electrical field, thereby changing the orientation of the ion velocity and preventing a close wall interaction with the projectile ions. It is assumed that the ions keep some memory of the tilt direction at the beginning. After a few scatterings the ions will lose this memory. As a close wall interaction changes the ionic charge state, the integrated intensity of the transmitted ions should be zero. The result of Fig.4 can be explained as follows: the orientation of the projectile ion with higher energy and lower charge state cannot be shifted by the electrical field easily, resulting in a close interaction with the wall of the capillary. Therefore, it could not be guided through the capillary.

The relation between normalized transmission yield (I) and projectile ion energy (E) and charge state (q) is adopted as

$$I \propto \exp(q/E). \tag{2}$$

In Fig.5, the value of $\ln I$ is plotted as a function of the ratio q/E between projectile charge and energy. From the data in Fig.5, we observe the expected monotonic increase of normalized transmission yield with ratio q/E at a given tilt angle and we also

observe that the values of $\ln I$ for different energies and charge states of the ions are equal within the experimental uncertainties when the ratio $q/E = 1$. The results are in good agreement with those in expression (2).

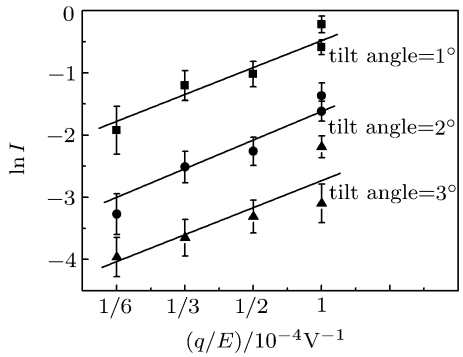


Fig.5. Values of $\ln I$ linearly depending on ratio q/E, where the straight lines are guides for the eye.

The relation between normalized transmission yield (I) and tilt angle (α) is adopted as

$$I \propto \exp\left(-\sin\alpha\right). \tag{3}$$

This leads to the normalized transmission yield $I(q, E, \alpha)$ as follows:

$$I\left(q, E, \alpha\right) = \exp(A \cdot E \cdot \sin\alpha/q) \tag{4}$$

where A is a constant.

In Fig.6, the results for $-\ln I/\sin\alpha$ from the measurements in an O^+ energy range of 10 to 60 keV and the charge state range of 1–6 for 60 keV oxygen ions are plotted against E/q. The plot shows that the results for $-\ln I/\sin\alpha$ fall on a straight line and the values for different tilt angles at a given ratio of E/q are equal within the experimental uncertainties.

It can be seen from Fig.6 that the transmission yield strongly depends on the tilt angle and ion energy and charge state. The results reveal that Eq.(4) can be used as a scaling law for a single capillary to predict the guiding power for different charge states and projectile energies. The representation of the data over a wide range of projectile energy and charge state by a straight line is an implicit confirmation that the charge deposited on the wall, and therefore, the deflecting potential keeps practically constant.

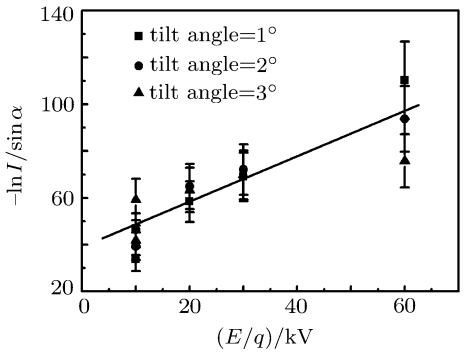


Fig.6. Values of $-\ln I/\sin\alpha$ linearly depending on ratio E/q, where the straight line is a guide for the eye.

4. Conclusion

We investigate the guiding effect over an energy range from 1 to 60 keV and a charge state range from 1 up to 6. We obtaine a charge state dependence as well as energy dependence on the yield of the transmitted ions. The guiding effects are observed to be enhanced at lower projectile energies and higher charge states. In addition, the transmission yield becomes larger with the tilt angle decreasing at a given energy and charge state.

Experimental guiding powers are determined from the transmission profiles for all investigated charge states, projectile energies and tilt angles within the uncertainties of the measurements. They present a confirmation of the model assumptions by comparing the results. This result is in good agreement with the assumption of a constancy of the charge deposited in the deflecting patch under equilibrium conditions for different beam intensities, and therefore, predicting the constancy for different charge states and projectile energies.

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