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Charge State Distributions from Highly Charged Ions Channeled at a Metal Surface

L. Folkerts, S. Schippers,* and F. W. Meyer
Physics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831 U.S.A.

**ORNL and University of Osnabrück, D-49069 Osnabrück, Germany*

Introduction

The vast majority of the experimental work in the field of multicharged ion-surface interactions, to date, has focused on x-ray and particularly on electron emission. These experiments include measurements of the total electron yield, the emission statistics of the electrons, and, most of all, the electron energy distributions [1-4].

So far, little attention has been paid to the fate of the multicharged projectile ions after the scattering. To our knowledge, the only measurement of the charge state distribution of the scattered ions is the pioneering experiment of de Zwart et al.[5], who measured the total yield of scattered 1+, 2+, and 3+ ions as a function of the primary charge state q (q = 1 - 11) for 20 keV Ne, Ar, and Kr ions after reflection from a polycrystalline tungsten target. Their main finding is the sudden onset of scattered 3+ ions when inner-shell vacancies are present in the primary particles. This suggests that a certain fraction of the inner-shell vacancies survives the entire collision event, and decays via autoionization on the outgoing path. Since the projectiles scattered in the neutral charge state could not be detected in the experiment of de Zwart et al., they were not able to provide absolute charge state fractions.

Recently, H. Winter et al.[6] directed the attention to the scattered particles, measuring the angular distributions of the scattered ions, and found characteristic angular shifts as a function of the incident charge state. These results are attributed to an acceleration toward the surface of the incoming ion due to the attractive image charge force.

In our present experiment, we focus on the scattered projectiles, measuring both the final charge state and the total scattering angle with a single 2D position sensitive detector (PSD). This method gives us the number of positive, as well as neutral and negative, scattered ions, thus allowing us to extract absolute charge state fractions. Using a well-prepared single Au(110) crystal and a grazing incidence geometry, we were able to observe surface channeling along the [001] channels.

Experimental Setup

The experimental setup is schematically shown in Fig. 1. The multicharged ion beam is produced by the CAPRICE ECR ion source at the ORNL Multicharged Ion Research Facility. After collimation by two 0.5-mm diaphragms, the beam is scattered from a clean Au(110) surface in the [001] direction. The preparation of the target is performed by cycles of surface sputter cleaning with 1-keV Ar^+ ions incident at 20° and crystal annealing at about 700°C. The UHV scattering chamber is equipped with an Auger diagnostic system that is used to verify surface cleanliness.

The reflected projectiles are detected with a 2D position sensitive detector (PSD) (Quantar Technology, Model 3394A), which has a 40-mm-diameter active area. The distance between the target and the PSD is about 560 mm. The PSD is mounted on an x-y-z manipulator that enables us to cover total scattering angles Φ_s ranging from -0.8° to +5.6°. This range includes the possibility to measure the direct beams to determine the precise Φ_s = 0° position and the angular spread of the primary beam. The latter is found to be about 0.1° FWHM, depending on the beam parameters.

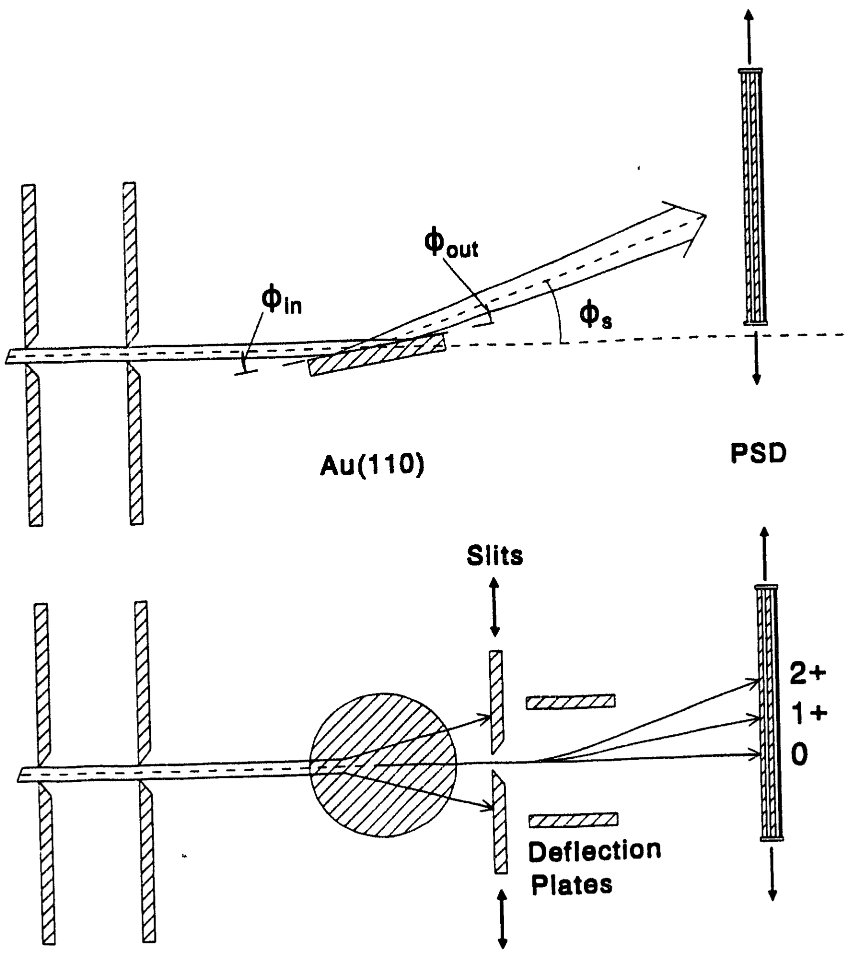

Figure 1: Schematic side and top view of the collision geometry and experimental setup.

A pair of slits between the target and the PSD (see Fig. 1) allows us to take a vertical slice from the scattered beam. By applying a voltage to a pair of deflection plates immediately downstream from the slits, the different charge states are spatially separated, resulting in a well defined charge state distribution on the PSD. In our range of incident energies the detection efficiency of the channel plates is thought to be largely insensitive to the charge state of the scattered particles. In order not to saturate the PSD, during the scattered ion measurements, we limit beam intensities to currents in the order of several 100 pA.

Results

Figure 2 shows the intensity distribution on the PSD from an 80-keV Ar^{11+} beam scattered from the Au(110) crystal in the [001] direction. The angle of incidence is a glancing 1.5°. The larger channel numbers in the vertical direction correspond to smaller total scattering angles. The "banana" shape of Fig. 2a is characteristic for surface channeling [7]. However, the strong intensity of the central spot reveals that in this case a significant fraction of the beam is merely specularly reflected and not guided by the [001] channels.

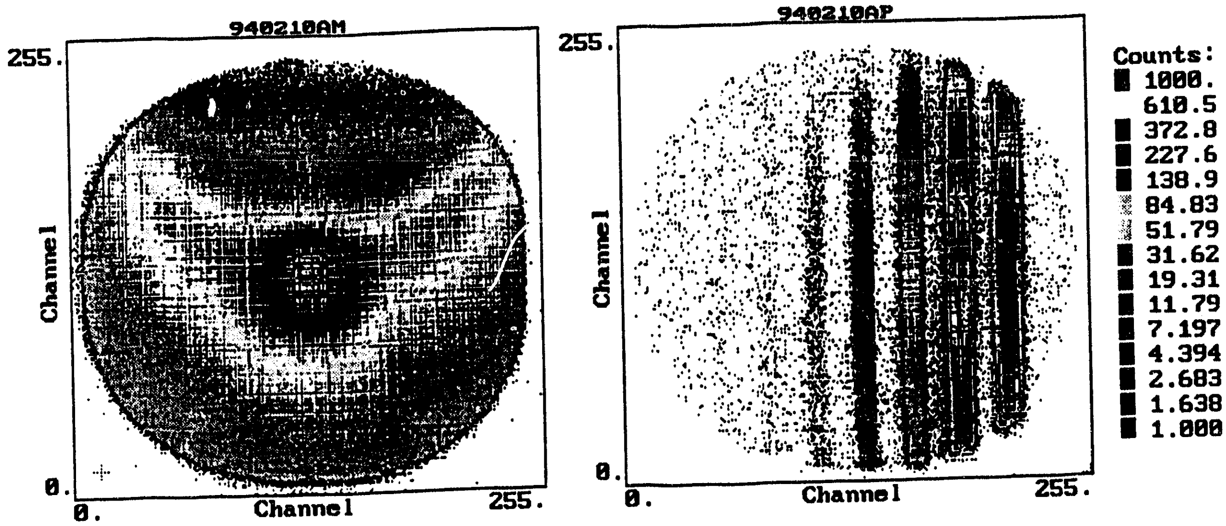

Figure 2: Intensity distribution on the PSD for 2.0 keV/amu Ar^{11+} scattered by a Au(110) crystal in the [001] direction, with an incident angle of 1.5°, (a) with the slits wide open - this picture shows the banana-shaped angular scattering distribution, which is characteristic for surface channeling; (b) with a narrow slit opening and the deflection voltage switched on - charge states from 0 to +5 can be discerned. Note that the larger channel numbers on the vertical axis correspond to smaller total scattering angles.

Figure 2b shows the corresponding charge state distribution on the PSD, after narrowing the slits (see Fig. 1). Thereby a vertical slice is taken from the center of the reflected beam, while the PSD was shifted horizontally in order to maximize the utilization of the active area of the PSD. Without any further analysis one can already discern vertical bands corresponding to charge states from 0 up to +5. Projecting the spectrum onto the horizontal detector axis also reveals small fractions of 6+ and even 7+ ions in the scattered beam. This is shown in Fig. 3, which results from integrating the total scattering angle Φ_s from 1.5° (channel 200) to 4.0° (channel 50).

We have measured a complete set of charge state distributions for 3.75 keV/amu O^{q+} ions incident on the Au(110) crystal in the [001] direction, with an incident angle of 2.0°. Figure 4 shows the results for O^{8+}, in which the total scattering angle is integrated from 2.5° to 5.0°. The most striking difference with the Ar measurement is the presence of a negative ion peak, which is equally intense as the +1 contribution.

In Fig. 5 we have plotted each of the measured charge state fractions in the scattered beam versus the incoming charge state. The contribution of the neutral particles (87 ± 1%) is virtually independent of the initial charge state. The same counts for the +1 and -1 charge states (5.8 ± 0.2%), though there is a rise of about 1% in the +1 fraction when going from O^{6+} to O^{7+}. A more pronounced jump in relative intensity once the K-shell is opened is observed for the +2 and +3 fractions, whereas the +4 and +5 contribution rise above the picture results from integrating (collapse to the x-axis) Fig. 2b from channel 50 (Φ_s = 4.0°) to 200 (Φ_s = 1.5°).

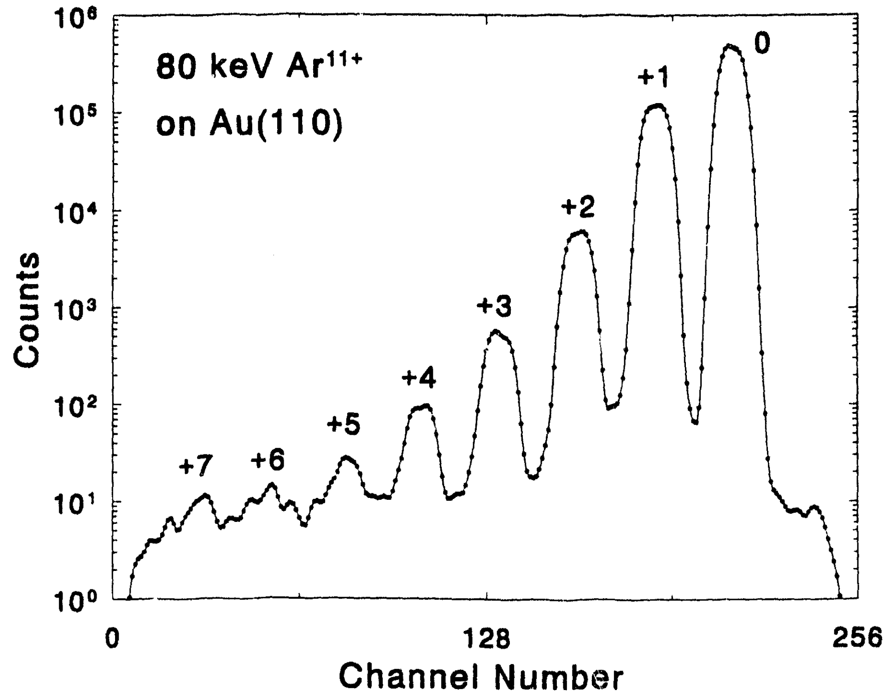

Figure 3: Charge state distribution of 2.0 keV/amu Ar^{11+} scattered on a Au(110) crystal in the [001] direction, with an incident angle of 1.5°. This picture results from integrating (collapse to the x-axis) figure 2b from channel 50 (Φ_s = 4.0°) to 200 (Φ_s = 1.5°).

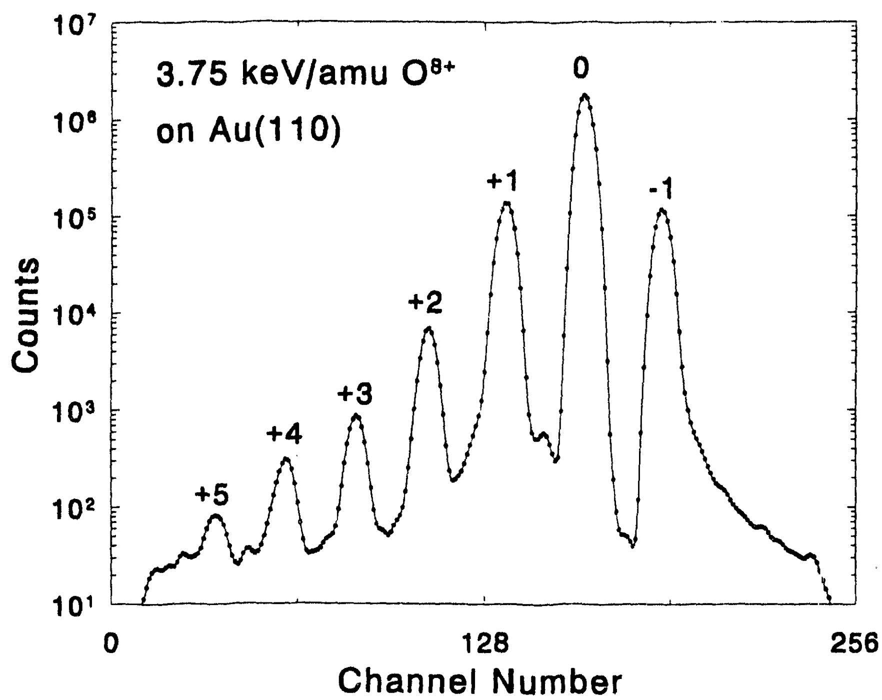

Figure 4: Charge state distribution of 3.75 keV/amu O^{8+} scattered on a Au(110) crystal in the [001] direction, with an incident angle of 2.0°. The range of integrated total scattering angles goes from 2.5° to 5.0°. Note the significant intensity of the negative ions.

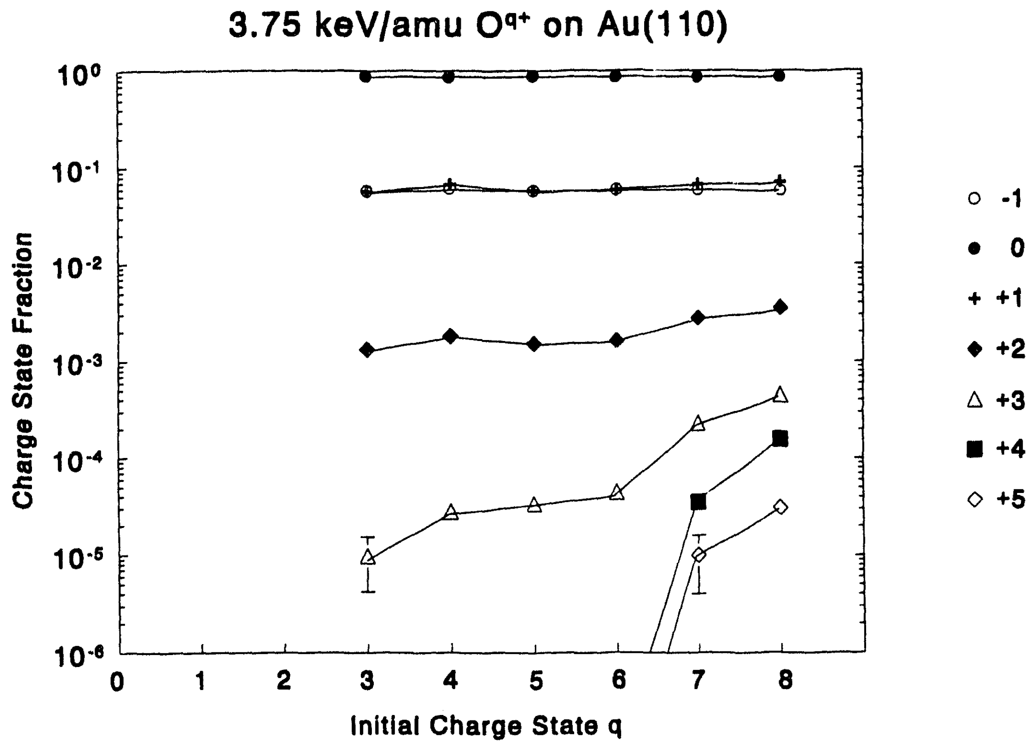

Figure 5: The fraction of each of the measured charge states in the scattered beam plotted against the incoming charge state for 3.75 keV/amu O^{8+} scattered on a Au(110) crystal in the [001] direction, with an incident angle of 2.0°.

detection limit only when the incoming projectile carries a K-vacancy. However, even in the O^{8+} case, the reflected charge states higher than +1 make up less than 1% of the total reflected beam.

Discussion

The most remarkable finding from this experiment is the fact that under the present experimental conditions the final charge state of the scattered projectiles does not depend significantly on the incident charge state. We find that the charge states are almost evenly distributed around reflected charge state 0. This shows that due to various neutralization processes at the surface, the memory of the initial charge state is almost completely lost and a mean equilibrium charge state is reached.

Following the reasoning brought forward by de Zwart et al. [5], we explain the increase in positive reflected charge states when using projectiles with K-vacancies by attributing it to a certain fraction of the K-vacancies surviving the deflection from the surface. The relaxation of these projectiles to the ground state then occurs on the outgoing path of their trajectory by an Auger process. If this relaxation takes place at a large enough distance from the surface such that no subsequent neutralization by, e.g., resonant charge transfer from surface states occurs, this would result in an increase of the charge state by one.

Consequently, when going from O^{6+} to O^{7+}, one would expect the increase in the intensity of a certain final charge state r, in first order approximation, to be proportional to the (r-1) intensity from the O^{6+} measurement. The proportionality factor should then correspond to the fraction of surviving K-vacancies. However, this simple idea doesn't work. The increase in the +1 intensity corresponds to about 2% of the neutral intensity and the +2 fraction increases with almost 3% of the +1 fraction. However, the increase in the +3 intensity is a substantial 13% of the +2 intensity in the O^{6+} measurements, and going to the +4 and +5 fractions this number further increases, with the +4 fraction resulting from initial O^{7+} just below to the fraction of +3 ions in the O^{6+} measurement, and the +5 jumping above the detection limit, whereas no +4 ions could be detected when starting with O^{6+}.

In conclusion from our measurements of charge states of $O^{3\text{-}8+}$ ions reflected at a Au(110) surface under surface channeling conditions, we find that almost independently of the initial charge state the ions are reflected with a charge state distribution that corresponds to a mean charge state acquired when traveling along the surface. A slight increase of positive charge states with projectiles carrying inner-shell vacancies is most likely due to the deexcitation of projectiles on the outgoing path of their trajectory.

Acknowledgement

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