Surface Channeling Experiments at 20 MeV and Resonant Coherent Excitation of N^{6+} Ions

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Surface channeling of 21.8 and 23 MeV N^{6+} ions of a Pt(110) surface is experimentally verified. At 21.8 MeV resonant coherent excitation is observed leading to enhanced ionization when the ions scatter along the $[1\bar{1}0]$ surface half channels. [S0031-9007(97)04307-X]

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Channeling was first observed in a computer simulation [1]. The phenomenon was explained theoretically by a guided motion of the fast ions by the planar or cylindrical potentials formed by the planes or the strings of atoms in a single crystalline solid [2,3]. Experimental verification of the effect was found in high energy ion beam experiments typically in the 0.5 to 1 MeV range [4]. Channeling was developed into a useful tool for the analysis of solid state properties [5]. In comparison, surface channeling plays a minor role due to the problems of preparing surfaces with sufficiently large terraces [6]. The steps on terraced surfaces allow the penetration of the fast particles which can then leave the surface again; in such way the surface channeling is in an intriguing way mixed with bulk or subsurface channeling. Furthermore, in surface channeling the conditions of proper or hyperchanneling have to be fulfilled [7,8]. In bulk channeling these terms describe the effect when the ions traveling through a solid stay within one planar or axial channel. Note that the 3D potential in a solid which governs the motion of the ions is not necessarily a closed surface; i.e., a particle can wander between different channels without violating the channeling conditions. At a surface, however, normal channeling means penetration into the bulk. In order to avoid the penetration very small grazing angles are necessary. In 1965 Okorokov proposed that the surface of a single crystal provides a periodic potential which should cause the resonant excitation of atoms which scatter along the surface with the "right" velocity [9]. If the atom velocity $v = \nu_r d$, where $h\nu_r = \Delta E_{ij}$ an atomic excitation energy and d is the atomic distance in, e.g., a chain of atoms, the atom feels a periodic disturbance and a resonant coherent excitation (RCE) can be observed. In the case of highly charged, fast ions the excitation leads to enhanced ionization, which is hence the signature of RCE. The first verification of the RCE was experiments with highly charged, hydrogenlike ions channeling through Au axial channels at energies in the 10 to 30 MeV range [8]. The effects observed are quantitatively understood [10]. More recently planar channeling was also used for the RCE of fast ions [11]. In the case of axial channeling it is the energy of the ions which is varied to find the resonances. In the case of planar channeling the energy is kept constant and the tilting angle to the channels is varied. The results provide detailed insight of the interaction of fast ions with solids. Items to be included in the theoretical treatment are the change of the binding energy of the electronic states in question, the dynamic screening of the fast ions, and the wake potential induced by the fast ions [12]. Recently RCE was reported for surface axial channeling too, using 4.5–6.4 MeV B^{3+} heliumlike ions and a SnTe(001) surface [13]. Here we present the first results of a surface channeling experiment with 21.8 and 23 MeV N^{6+} hydrogenic ions using a Pt(110)-(1×2) single crystal surface. The experimental conditions are equivalent to the corresponding bulk experiments with N ions and Au, since the lattice constants of Pt and Au are comparable. We use a fixed ion energy and vary the azimuthal angle (Fig. 1), such that for the $[1\bar{1}0]$ direction RCE conditions for the 2nd harmonic of the $1s$-$2s2p$ excitation of N^{6+} are met. The resonance can be estimated from Eq. (1):

$$E_r[\mathrm{MeV/amu}] = 3.03 k^{-2} d_{\mathrm{\AA}}^2 \Delta E_{\mathrm{keV}}^2 \,. \qquad (1)$$

Even though the binding energies are shifted by the interaction with the solid, Eq. (1) gives a good estimate because the difference of the binding energies enters into the equation. The difference is much less affected by the interaction with the solid than the absolute values [12].

The experimental setup is an UHV chamber with a target preparation stage using ion sputtering for the target cleaning, low energy ion scattering for the control of the target cleanliness, and LEED for the control of the target surface structure. In a previous study we have established reliable preparation conditions using LEED and scanning tunneling microscopy [14]. The Pt(110) is reconstructed in the missing row (1×2) structure and forms rhombohedric terraces with an average length of 600 Å along the $[1\bar{1}0]$ surface direction. In the lower part of the UHV chamber the scattering experiments are performed in a μ-metal screened environment. Details of the systems are described previously [15]. The system is hooked to the Berlin ISL cyclotron providing the ion beams using

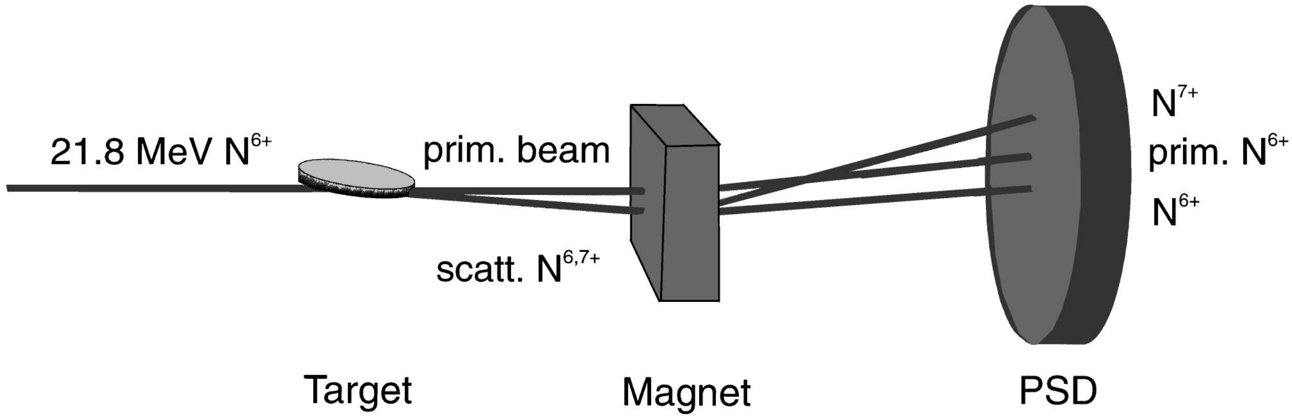

FIG. 1. Sketch of the experimental setup with target, magnet, and position sensitive detector (PSD). The trajectories of the primary beam and the scattered N^{6+} and N^{7+} beams are shown schematically. The distance from the target to magnet is 1.7 m. The distance from target to the PSD is 2.4 m.

filters to obtain the exact ion energy. The ion energy is measured by NMR (nuclear magnetic resonance) which is possible since ^{15}N is used. Beam adjustment is the most time-consuming part of the experiment. The downstream side of the experiment uses a sector field magnet for charge separation, a position sensitive detector (PSD) placed 2.4 m down stream from the target position (Fig. 1), and a surface barrier detector (SBD) placed 4.1 m down stream for particle detection. The PSD is, in connection with the usual set of diaphragms and Faraday cups, a very useful tool for the adjustment of the primary beam. The beam has to be small and parallel. The application of a PSD for surface channeling experiments was used first at low energies (2 keV) [6,16], and more recently with multiply charged ions at moderate energies (20 keV) [17,18]. Here it is for the first time used at 20 MeV. The beam dimensions are 0.2 mm $\times$ 0.2 mm which means that at grazing angles of 0.1° the target of 10 mm diameter will be fully covered by the beam. Figure 2(a) shows surface channeling for a 23 MeV N^{6+} beam. The target is moved into the beam such that the beam intensity is cut to about $\frac{1}{2}$. The scattered ions are seen at the right side of the primary beam, separated by the scattering from the primary beam. In addition there is a separation by the magnetic field according to the energy loss of the ions at the surface. There is no evidence of N^{7+}, i.e., of ionization, in agreement with the expected equilibrium charge of 6.1 at these energies. The actual grazing angle is estimated from the position on the PSD to be 0.03°. The PSD is in fact the only tool to control the impact angle. Tuning the beam to 21.8 MeV the PSD pattern changed, and N^{7+} ions are found on the left side of the primary beam [Fig. 2(b)]. For all azimuthal angles close to the $[1\bar{1}0]$ channels N^{7+} ions are found. The yield ratio of these data shows a maximum at $\phi = 0°$ (Fig. 3). Using the SBD we obtain, when varying the magnetic field, momentum and energy analyzed spectra of the primary beam and the scattered ions (Fig. 4, inset). From left to right, i.e., from low to high magnetic field we see the scattered N^{7+}, N^{6+} and the primary beam, respectively. The separation between the primary beam and the N^{6+} is due to the energy loss of the scattered ions with no charge change. The N^{7+} ions are separated from the other beams owing to their higher charge and also due to the energy loss. In fact, the N^{7+} ions have a lower loss than the N^{6+} ions [19]. The yield data obtained with the SBD for a set of azimuthal angles and as a function of the grazing angle are shown in Fig. 4. For these measurements the magnetic field is kept at a fixed value, i.e., such that the valley of the two scattered beams (Fig. 4, inset) is met. There we have the N^{7+} ions with the lowest energy loss, which are the best channeled ions. We see in the yield data a strong enhancement for the $[1\bar{1}0]$ direction, stronger than in the yield data of the PSD,

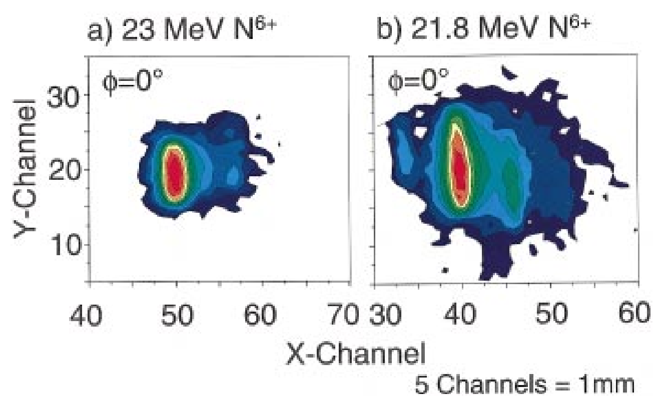

FIG. 2(color). (a) Surface channeling picture of a 23 MeV N^{6+} beam with magnetic field. The strong peak is the primary beam which passes over the target. On the right side is the contribution of the scattered N^{6+} ions. There is no evidence of N^{7+}. (b) Surface channeling picture of 21.8 MeV N^{6+} beam with magnetic field. On the left side are the scattered N^{7+} ions, in the middle the primary beam, and to the right the scattered N^{6+} ions. At $\phi = 0°$ the plane of scattering is parallel to the $[1\bar{1}0]$ surface direction.

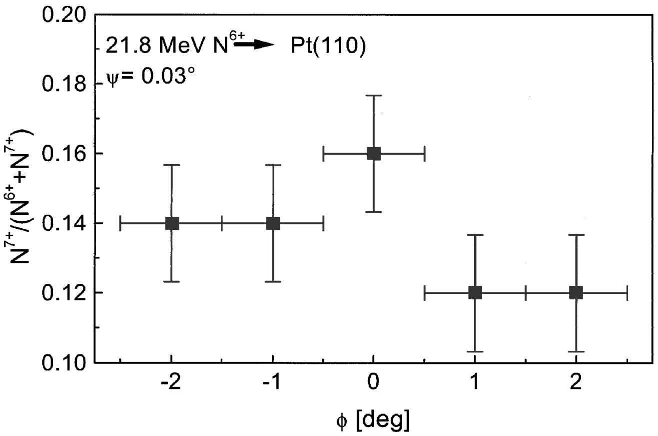

FIG. 3. Fraction of scattered N^{7+} ions versus the azimuthal angle ϕ. There is a maximum of $N^{7+}/(N^{6+} + N^{7+})$ at $\phi = 0°$ (PSD results).

since with the SBD the particles are momentum and energy analyzed; i.e., we can tune into the part of the energy spectra with the lowest energy loss. The critical angle for channeling is estimated from Lindhard's equation

$$\psi_{\mathrm{crit}} = \sqrt{\frac{2Z_1Z_2e^2}{d\,E}}\,, \tag{2}$$

with Z_1, Z_2 being the atomic numbers of projectile and target atoms, respectively, E the initial energy, and d the spacing along an atomic row of the target. This yields a value of 0.92° which is generally accepted as being too large for practical purposes [4,5]. Other estimates are obtained from considering the "perpendicular" energy which is $E = E_0(\sin\psi)^2$. Estimates based on this term are related to the breakthrough angle [6] describing the transition from channeling to penetration. For $\psi =$ 0.03° the perpendicular energy of a 20 MeV N^{6+} ion is 5.97 eV. SBD measurements indicate that channeling may persist up to $\psi = 0.4°$ [19]. The RCE is observed at the lowest grazing angles only (Figs. 3 and 4), but with the SBD over a smaller range of azimuthal angles compared to the PSD results. This can be understood when considering that in the surface semichannels three types of trajectories persist: (i) string scattering from the top atomic rows, (ii) straight trajectories between the top rows, and (iii) zigzag trajectories between the rows forming the channel [6]. In the PSD results we do not discriminate between these trajectories. The zigzag trajectories will be found at the "upper" and "lower" ends of the scattering distribution of Fig. 2. In the SBD data we selected the fastest N^{7+} ions, which are the string scattered (i) or straight (ii) scattered ions mainly. Because of the geometry of the experiment the zigzags may miss the 10 mm diameter SBD. These considerations explain the finding that in the SBD data the resonance appears "sharper" than in the PSD data.

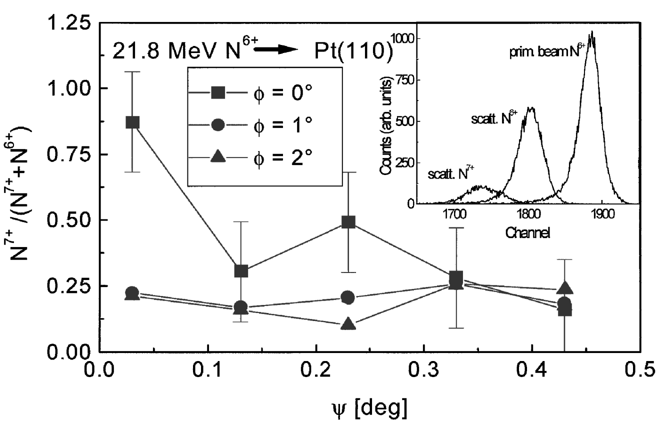

FIG. 4. Fraction of scattered N^{7+} ions versus the angle of incident ψ for three azimuthal angles ϕ. For $\phi = 0°$ the N^{7+} fraction increases to a maximum at $\psi = 0.03°$ with decreasing angle of incident. The lines are drawn to guide the eyes. The inset shows the momentum and energy analyzed spectra of the primary beam and the scattered ions at different magnetic fields (SBD results).

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