

Fragmentation of Small biomolecules induced by highly charged ion impact

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The fragmentation is a characteristic behaviour of complex systems such as large molecules and clusters upon excitation. A large number of experimental investigations have been performed on C_{60} and small molecules of DNA bases during the last years using photon excitation (laser and synchrotron source) and electron or ion beam impact excitation. Collision induced fragmentation using highly charged ions from ECR source has been demonstrated to be a powerful method providing complementary information comparing to other experimental methods. The specificity of experiments with an ECR source is related to the large choice of the charge and the atom of beams, the easy scan and high selectivity of the kinetic energy and the possibility to perform multi-coincidence measurements in event by event mode.

In this poster, we present experimental results on the fragmentation of DNA bases induced by impact of highly charged ions, Kr^{17+} (13 kV) and Xe^{23+} (10 kV). Multicharged ion beams delivered by the ARIBE facility allowed us to prepare charged molecules at low internal energy via electron capture process at large impact distances. By coincidence detection of the scattered projectile, the charged fragments and the ejected electron number, we were able to study the fragmentation dynamics and delayed dissociation processes. These results will be compared with the fragmentation patterns of DNA bases induced by singly charged ion beams using a novel experimental method, the so-called CIDEDEC (collision induced dissociation under energy control) [1-3].

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EVIDENCE OF GIANT DIPOLE PLASMON RESONANCE IN ELECTRON SPECTRUM OF C₆₀ AND BEAM INDUCED POLARIZATION

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Mechanisms of electron emission in collisions with clusters involving C₆₀-fullerene are governed by more complicated processes than in ion-atom collisions. The fullerenes are “small” particles with diameter $\sim 10\text{\AA}$ over which a large electron density similar to that of a solid is sampled. Fullerenes are known to exhibit collective excitation: *giant dipole plasmon resonance* (GDPR). Effect of GDPR on x-ray emission from fullerene and multiple ionization under heavy ion impact has been reported earlier [1-5]. However, a direct evidence of this process in fast ion-collisions was awaited. The plasmon excitation de-excites through emission of electrons of particular energy, which is characteristic of the plasmon frequency. This presents a unique possibility of observing the GDPR peak in the low energy electron spectrum of C₆₀. The electron energy due to the decay of GDPR-excited state is expected at ~ 10 eV (i.e. $20 \text{ eV} - I_p$, I_p =ionization potential). We measured the low energy (1-300 eV) e^- - DDCS spectrum from C₆₀ in collisions with 4 MeV/u bare F ions at various angles. We observe a broad hump like structure near the expected GDPR peak position in all the electron spectra. The C₆₀ DDCS spectra are different from the DDCS spectra of other atomic gaseous targets like Ne [Fig.1]. The low energy spectrum was collected with lot of precaution and spectrometer performance was verified by measuring expected spectral shapes from atomic targets.

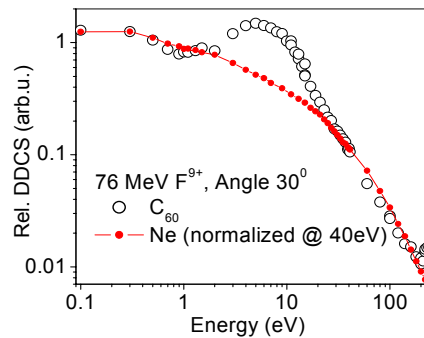


Fig.1 : Typical electron DDCS spectrum from C₆₀ (o) and Ne.

We have also measured the angular distributions of the electrons. The electron emission (at ~ 10 eV i.e. at GDPR peak) is maximum in forward and backward direction w.r.t. to the projectile beam and a dip is observed at 90° . This distribution is just opposite to the expected behaviour for atomic targets. The angular distribution suggests that the dipole oscillations are induced preferably along the projectile beam direction. This is for the first time that such an angular distribution of e-emission in plasmon decay in C₆₀ or any type of clusters has been measured.

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ANGULAR ANISOTROPY IN K-LL AUGER ELECTRON EMISSION FROM C_{60} AND CH_4 IN COLLISION WITH 4 MeV/u F^{9+}

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The energy and angular distributions of low energy electrons in ion-atom collisions are useful tool to identify various collisions mechanisms. We have shown that the low energy electron spectrum from C_{60} under the HCI impact reveals the evidence of the plasmon resonance peak (This HCI abstract book). It would be therefore interesting to check the angular distributions of the higher energy electrons produced in much low impact parameter collisions. Auger electron spectroscopy is widely used in atomic and molecular collision studies. High resolution Auger spectroscopy serve to identify the electronic configuration of the atomic species involved in the collisions. Also, the angular distribution of Auger electrons reveals the orientation and symmetry of the parent molecule as well as the polarization effects of the molecule during the collision. We have measured the K-LL Auger electron angular distribution from C_{60} , CH_4 and Ne in collisions with 4 MeV/u F^{9+} ions. The projectile beam is obtained from 14MV BARC-TIFR Pelletron accelerator and the secondary electrons were energy analyzed using an electrostatic hemispherical analyzer. We observe a K-LL Auger peak at 240 eV for C_{60} and CH_4 corresponding to Carbon K-LL, whereas the Ne K-LL Auger peak is detected at 740 eV. We observe that Auger electron angular distribution from C_{60} is highly anisotropic and peaks at forward and backward angles. Anisotropic behaviour was also observed for the case of CH_4 although its magnitude is much less compared to C_{60} . Contrary to this, Ne K-LL Auger angular distribution is isotropic within experimental errors, which is, however, expected. One possible reason for this anisotropy in case of C_{60} could be the polarization of the valence electron cloud in the molecule by the highly charged projectile ions. The C_{60} molecule is known to be highly polarizable, which can lead to preferred axis of electron emission w.r.t. to the projectile beam direction. In order to check this we have also measured the angular distributions of the KLL Auger electrons induced by 6 keV electrons on Ne, N_2 , and CH_4 and the distributions were found to be isotropic.

In addition, to the K-LL Auger electron peak due to single K-vacancy we have also identified the K-hypersatellite (2K-LL !) Auger line at an energy of ~ 280 eV arising due to double K-vacancy in the C-atoms. The intensity of this line is found to be approximately 10% of the K-LL line. The details will be provided.

LOW ENERGY CARBON ION IRRADIATION OF WATER ICES

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Ion processing plays an important role in the chemical and physical modification of ice surfaces in astrophysical environments. Magnetospheric ions surrounding the Gas Giants in the outer Solar System impinge upon and modify the icy satellite surfaces creating new chemical species, incorporating elements not originally present in the local ice composition.

$^{13}\text{C}^+$ and $^{13}\text{C}^{2+}$ ions were produced by an Electron Cyclotron Resonance ion source, accelerated by a low energy accelerator and were incident upon pure water ice samples. Modifications to the ice were measured using an FTIR spectrometer. The most significant modifications observed within the IR spectra were the growth of features corresponding to $^{13}\text{CO}_2$ and H_2O_2 and the decrease of features corresponding to H_2O . Additionally, a feature corresponding to 'dangling OH' bonds was seen to decrease, indicating a change in the porosity of the ice being irradiated. It was also interesting to note that no signature for ^{13}CO was observed at any stage during the experiments.

Figure 1 shows the formation of $^{13}\text{CO}_2$ as a function of ion fluence at kinetic energies of 2 (left) and 4 keV (right). It is clear that, at both energies, significantly different yields of $^{13}\text{CO}_2$ were observed with the two different ion charge states. This difference is believed to be a result of the additional potential energy deposited by the doubly charged ion during an electron capture event.

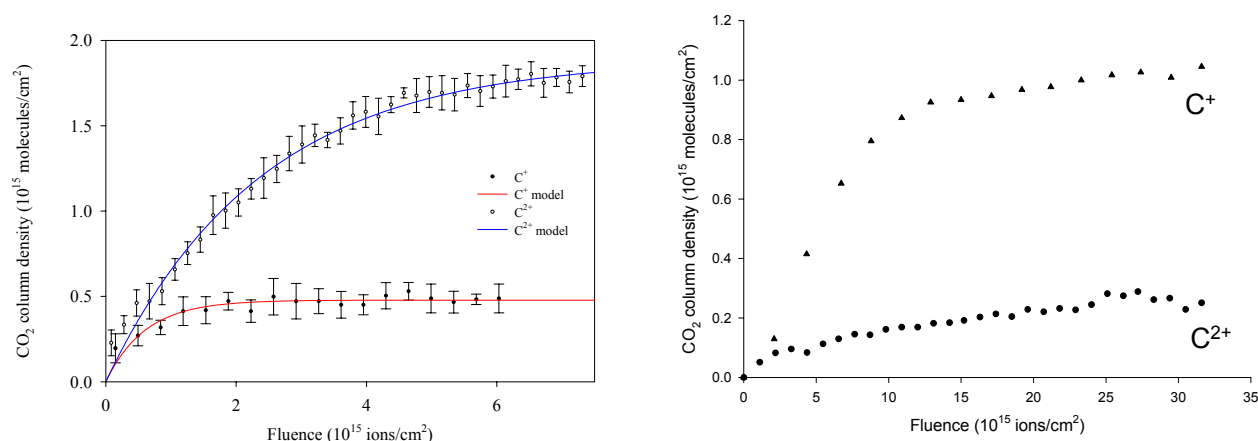


Figure 1: CO_2 growth at 2 (left) and 4 (right) keV. In both cases, the yield of CO_2 is significantly different for the two charge states.

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OPTICAL EMISSION SPECTROSCOPY OF EXCITED ATOMS SPUTTERED ON A Ti SURFACE UNDER IRRADIATION WITH MULTICHARGE Ar IONS

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Optical emission spectroscopy of excited atoms was carried out in order to investigate the sputtering processes on solid surfaces under irradiation of slow multicharged ions. Many atomic lines of Ti I (neutral) and Ti II (single-charged ions) were observed in wavelengths from 250 to 750 (nm) with irradiation by Ar³⁺ (30 keV) on a Ti surface which was placed in a low pressure O₂ atmosphere as seen in Fig. 1.

Emission intensity of Ti I (520 nm) decreased monotonically with an increase of O₂ partial pressure, whereas that of Ti II (670 nm, a 2nd order wavelength of 335 nm) slightly increased as seen in Fig. 2. The difference in O₂-pressure between Ti I and II is considered to be due to the change of survival probabilities of sputtered Ti* and Ti⁺* atoms interacting with the oxygen-covered Ti surface. [1]

From a semi-logarithmic plot of emission intensity for the 670 nm spectrum as a function of distance from the surface, the mean velocity of the sputtered Ti* (3d²4s4p x³G) in a normal direction parallel to the surface, e.g. $\langle v_{\perp} \rangle$, was determined. [2] As a result, $\langle v_{\perp} \rangle$ of Ti* is rather large compared with $\langle v_{\parallel} \rangle$ of Al* emitted from Al and Al₂O₃ surfaces interacting with Ar^{q+} (q = 3 – 8). [3]

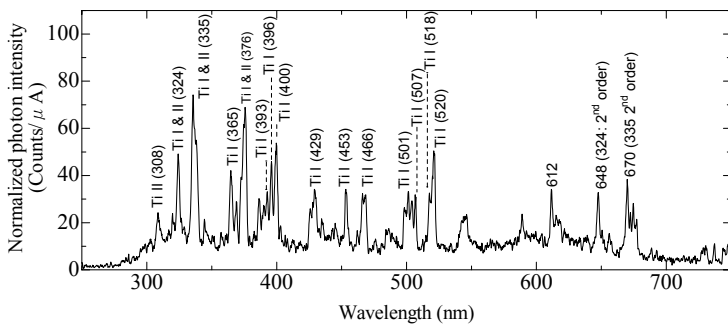


Fig. 1 Optical emission spectrum of excited atoms sputtered on a Ti surface interacting with Ar³⁺ (30 keV) ions.

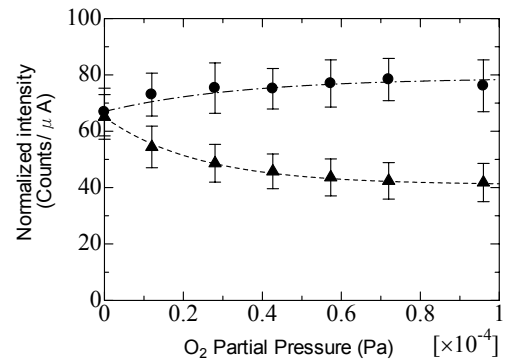


Fig. 2 Normalized emission intensity of ▲; Ti I (520 nm) and ●; Ti II (670nm, a 2nd order wavelength of 335 nm) spectra as a function of O₂ partial pressure.

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POTENTIAL ENERGY THRESHOLD FOR NANO-HILLOCK FORMATION ON CaF_2 BY IMPACT OF VERY SLOW, HIGHLY CHARGED IONS

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Upon impact on a solid surface the potential energy stored in slow highly charged ions is primarily deposited into the electronic system of the target. We present experiments with very slow (down to impact velocities as low as 0.03 a.u. or 30 eV/amu) highly charged xenon ions creating hillock-like topographic nanostructures on the surface of $\text{CaF}_2(111)$ single crystals which are stable in air and non erasable by AFM scanning [1]. Surprisingly, these nanostructures closely resemble those created by swift heavy ions at a CaF_2 surface, while leaving deeper layers of the target undamaged. We find first unambiguous experimental evidence that potential energy alone is sufficient to cause these nano-sized hillocks. The observed dependence of the feature size on the kinetic energy of the projectile ions is very weak. A sharp and well-defined threshold of potential energy is required for the onset of nano-hillock formation [1,2].

Simulations of the dissipation of potential energy into the target material on the basis of an extended classical over-the-barrier model have been performed to facilitate the interpretation of the experimental findings [3]. The experimentally observed threshold of potential energy for hillock formation is linked to a solid-liquid phase transition.

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ELECTRON EMISSION FROM INSULATORS BOMBARDED WITH VERY SLOW HIGHLY CHARGED IONS

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Electron emission induced by impact of slow highly charged ions (HCI) on metallic surfaces has been studied extensively over the past 15 years [1]. The “classical-over-the-barrier” (COB) model [2] was very successful in modelling the formation of so-called “hollow atoms” in front of the surface and the subsequent emission of electrons due to Auger and other processes. Because of the finite hole mobility and differences in image charge potentials the response of insulator surfaces to slow HCI impact, however, is less well understood. We have recently used an electron statistics (ES) detector [3] to measure yields and number statistics of electrons emitted from (insulating) LiF(001) and CaF₂(111) surfaces bombarded by moderately slow ($v < 1$ a.u.) Ar^{q+} ($q \leq 18+$), Xe^{q+} ($q \leq 50+$), and Hg^{q+} ($q \leq 68+$) projectile ions under various impact angles [4]. The results show a clear deviation in the behaviour of potential electron emission as compared to metallic surfaces in this velocity regime. This deviation is explained by a strong sub-surface electron emission contribution from the insulating targets.

In this work we present electron yields from very slow Xe^{q+} impact on clean, single crystalline KBr(001), LiF(001) and CaF₂(111) surfaces, all of which have recently found to be susceptible to nanostructuring by single slow HCI impact [5] [6]. Charge states were varied between $q = 10$ and 44. Moderate heating of the targets was applied to counter any macroscopic charge-up during ion irradiation. We have constructed a new ES setup that was implemented into the deceleration station of the EBIT at the Forschungszentrum Dresden. Applying multiple electrical potentials, we first bend the ion beam (up to 70°) to hit a tilted target under normal incidence and then - with the same electrical field - collect close to 100% of the electrons emitted during the impact event. We have determined the true ion beam energy and its energy spread by applying a retarding field on the electron repeller aperture at the entrance of the chamber while monitoring the number of ions hitting the target. With this setup, we were able to measure electron yields for impact energies of less than 2 eV/amu up to 1.5 keV/amu, where a good agreement with previous data [4] for higher impact velocities was found. For the first time, electron yields from insulators have been obtained in the velocity regime close to the image-charge acceleration limit.

This work has been supported by Austrian Science Foundation FWF (P17449-N02) and by the European Project RII3\#026015. Transnational access to the Rossendorf ion beam facilities was provided through AIM (EU contract no. 025646).

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SECONDARY-ION EMISSION FROM GaN(0001) AND DODECANETHIOL/Au(111) SURFACES IRRADIATED WITH Ar^{q+} ($q = 3-6$) AT GLANCING ANGLE

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Secondary-ion mass spectroscopic (SIMS) studies have been performed to investigate desorption or sputtering processes of various solid surfaces interacting with highly charged ions (HCIs). [1-2] To eliminate kinetic sputtering processes, we focused on glancing collisions between HCIs and surfaces. We recently developed an HCI-SIMS apparatus capable of detecting secondary ions, secondary electrons, and scattered atoms/ions simultaneously. This apparatus allows us to analyze solid surfaces in four different operating modes: 1) low-energy ion scattering spectroscopy (LEIS), 2) SIMS in coincidence with LEIS, 3) SIMS triggered by scattered neutral atoms, and 4) SIMS triggered by secondary electrons.

Figure 1 shows the experimental setup of the HCI-SIMS apparatus. Multichannel plates labeled D_1 , D_2 , and D_3 can detect secondary ions, scattered atoms/ions, and secondary electrons, respectively. The time of flight (TOF) of secondary ions is measured with the start signals of secondary electrons or scattered atoms/ions. The position y shown in Fig. 2 reflects the energy and charge-state dispersion of the scattered ions. The horizontal axis in Fig. 2 represents the TOF of secondary ions, measured from the difference between the arrival time of a secondary ion (T_1) and that of a scattered ion (T_2). Three arrows indicate the velocity (or energy) components of Ar^+ ions, which were scattered at three different lattice sites of GaN. This result suggests that protons were mainly emitted from three different lattice sites. [3] The preliminary results for a Dodecanethiol self-assembled monolayer (SAM) surface will also be presented.

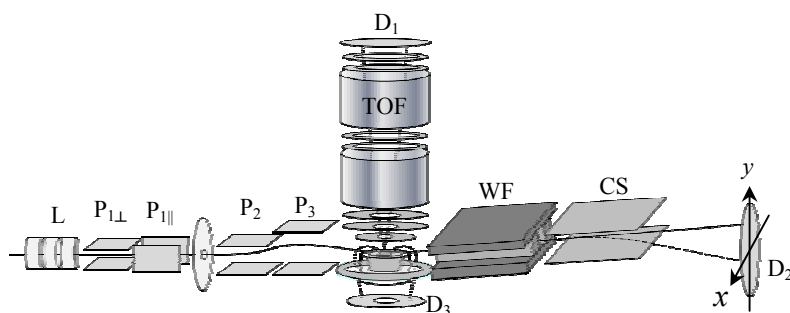


Fig. 1 Schematic illustration of a novel HCI-SIMS apparatus. L, electrostatic lens; P, parallel plates; TOF, time of flight analyzer of secondary ions; WF, Wien filter (velocity separator) of scattered ions; CS, charge-state separator of scattered ions; D_1 , 2D position sensitive ion detector; D_2 , 2D position sensitive ion/atom detector; D_3 , electron detector

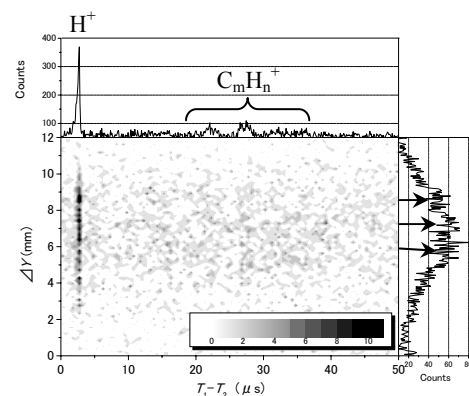


Fig. 2 Correlation map between TOF ($T_1 - T_2$) of secondary ions and displacement (Δy) of scattered Ar^+ in Ar^{6+} (15 keV)-GaN(0001) glancing collision.

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SIMULATION OF ION GUIDING THROUGH NANOCAPILLARIES: ENERGY DEPENDENCE

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The transmission of highly charged ions (HCI) through insulating nanocapillaries at angles larger than the geometric opening angle has attracted much research interest in recent years. As HCIs are largely transmitted in their initial charge state, rather than being neutralized in a close collision with the capillary walls, the term “guiding” has been frequently used. The key to this process is the electrostatic deflection of HCI from the inner wall after a self-consistent charge-up. Numerous groups have studied this phenomenon employing capillaries of different geometry, material, and ion charge state. Comprehensive measurements of parameter dependences exist so far only for Polyethylene-terephthalate (PET) capillaries [1]. Recently, we have presented an theoretical treatment of HCI guiding through insulating nanocapillaries based on a calculation of classical trajectories in the electric field of a self-consistently charged capillary. A crucial aspect in our model is the charge transport on and into the inner walls. This invokes no free parameters but involves known material properties only. Within our approach, qualitative (and in part also quantitative) agreement with experiments employing PET capillaries could be found [2]. We will present simulations for PET capillaries with a diameter of 200 nm and analyze the dependence on the energy of incidence of HCI in the range of 2-9 keV. Comparison to recent experiments [1] serves as a further test of our model.

We will also analyze the recently observed transmission of electrons with an energy of several hundred eV through insulating PET nanocapillaries [3]. Contrary to the case of HCI, a significant inelastic component of the transmitted projectiles was observed. Consequently, transmission is not only established by deflection in (conservative) electrostatic fields alone. We have developed a model to simulate transmission of electrons through nanocapillaries which reproduces basic features of the experiment. Similarities and differences of electron and HCI guiding will be discussed.

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Potential energy threshold of surface nanostructures formation by the interaction of slow Xeon ions on a HOPG surface

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The interactions between highly charged ions (HCIs) and surfaces are of importance not only for fundamental researches but also for potential applications. The possibility of exploiting the huge amount of potential energy stored in HCIs for nanostructure formation with a Scanning probe microscope (SPM) has attracted great attention. The slow HCIs could as a unique tool for the surface etching, the ultra-thin film growth and the nanostructure fabrication. Previous experiments have shown that the size of nano-dots depend strongly on the charge state but are independence of the velocity of the ions [1, 2]. However, the mechanism of the surface nanostructures formation is not well known in details and further systematic experiments are needed.

At the new experimental terminal for surface physics, the 320kV ECR Platform at IMP, Lanzhou, experiments on nanostructure formation irradiated by slow highly charged Xe^{q+} ($q=15-29$) ions on High Orientated Pyrolytic Graphite (HOPG) surface have been carried out. During the experiment, the pressure of vacuum chamber keeps below 10^{-9} mbar. The ions' velocity fix on 7.5×10^5 m/s and the fluxes of ions keep on 10^{10} ions/cm² in order to exclude other possible influences. In the tapping mode Atomic Force Microscope (AFM) image, the generation of the nano-sized hillocks protruding from the surfaces is probed. As shown in Fig. 1, the hillock-like nanostructure protruding from the HOPG surfaces can be observed only for Xeon ions with the charge state $q \geq 27$ which is lower than the charge state threshold for nano-hillock formation by Xeon ions ($q \geq 30$) on a CaF_2 (111) surface, and the height and the diameter of the nanostructure formation increase with the projectile ion charge state. The present results reveal a similarity between the nanostructure formation produced by slow HCIs and the track formation induced by the swift heavy ions [2, 3].

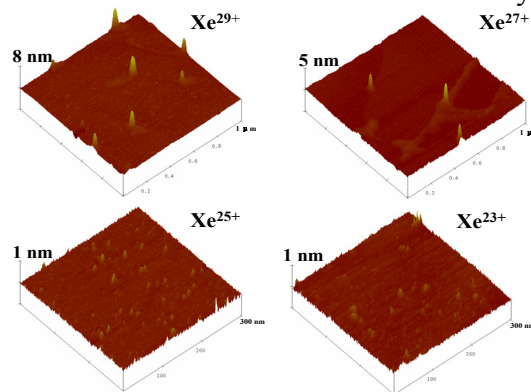


Fig. 1 AFM images of nanostructures formed by irradiation of slow Xe^{q+} ($q=23, 25, 27, 29$, $v=7.5 \times 10^5$ m/s) ions on HOPG surfaces. Note the different lateral and vertical scales.

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ABSOLUTE SPUTTERING YIELDS FROM SOLID RARE GASES BY SINGLY- AND MULTIPLY-CHARGED ION IMPACT

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Interaction of slow multiply charged ions (MCIs) with a solid surface has been studied in past 20 years [1]. Most of the experimental studies, however, are limited to the metal and semiconductor surfaces, and very few are reported for the insulator surfaces. Rare gas solids have several characteristics very different from the other materials; small cohesive energy (e.g., 0.02 eV/atom for Ne), large band gap energy (e.g., 21.6 eV for Ne), long diffusion length of excitons (e.g., ~ 200 nm for Ne), etc. We have studied the sputtering of atoms from the surface of rare gas solids by singly- and multiply-charged ion impact. The purpose of this study is to reveal qualitatively by observing the sputtered (desorbed) particles how such a large internal energy of MCI is consumed at the surface and/or in the bulk of very fragile rare gas solids.

Figure 1 shows total sputtering yields of solid Ne by Ar^{q+} ($q = 1, 4, 6$) impact as a function of the incident ion energy. Thickness of the solid Ne film is about 500 atomic layers. The results show surprisingly large sputtering yield even at relatively low incident energy, and that the yield is almost proportional to the incident ion energy.

The fact that no dependence on the charge state, i.e. potential energy, is observed in this energy region can be explained as follows; An exciton or an ion created in solid Ne induces the desorption of 1 - 5 atoms [2]. If we assume that all of the potential energy of the incident ion can be used to create excitons ($E_{\text{exciton}} = 17.2$ eV) or ions ($E_g = 21.6$ eV), the potential sputtering yield will be at most 100 even by Ar^{6+} (potential energy: 310 eV) impact, which is too small to be observed within the present experimental uncertainty.

Detail will be given at the conference.

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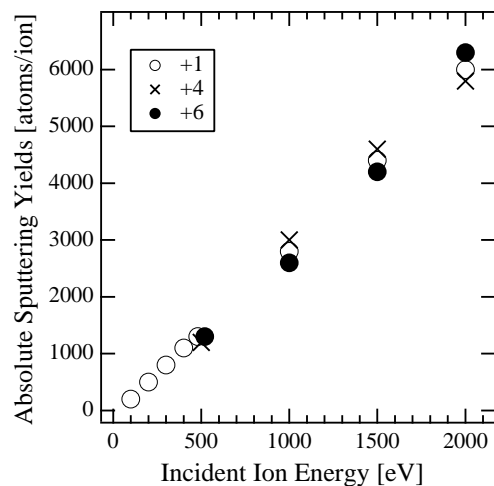


Figure 1: Absolute sputtering yield of solid Ne by Ar^{q+} ($q = 1, 4, 6$) impact as a function of the incident ion energy. Thickness of the sample film is about 500 atomic layers.

POTENTIAL SPUTTERING OF IONIC SPECIES FROM RARE GAS SOLIDS BY MULTIPLY CHARGED ION IMPACT

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Interaction of rare gas solids (RGS) with low energy photons and electrons were well studied in these two decades [1]. In these studies, creation of excitons and ions is found to play an important role in the desorption processes. Sputtering of ions from RGS by singly charged ion impact has been investigated by some groups [2, 3], however little report can be found by multiply charged ion impact. Here we report the results for the potential sputtering yields of ions from RGS by multiply charged ion impact.

Figure 1 shows mass spectra of ions sputtered by the impact of 1 keV Ar^+ and Ar^{7+} from solid Ne. Very large cluster ions up to cluster size $n \sim 100$ are observed (not shown in the figure). One can find that the intensity and size distribution for small clusters ($n \leq 3$) strongly depend on the charge state q of the incident ion, while almost no dependence on q has been observed for the large clusters ($n \geq 7$), suggesting that the kinetic sputtering is dominant for the desorption of large cluster ions.

Considering that the potential energy of Ar^+ (15.76 eV) is less than the creation energy of an exciton (17.1 eV) and an ion (21.6 eV) in solid Ne, we assume that only the kinetic sputtering occurs by Ar^+ impact, and estimate the potential sputtering yield Y_{PS} . The results (Fig. 2) show that Y_{PS} is proportional to the potential energy of the projectile ion, which suggests that all of the potential energy is consumed to create excitons and ions in the solid. Detailed discussion will be given at the conference.

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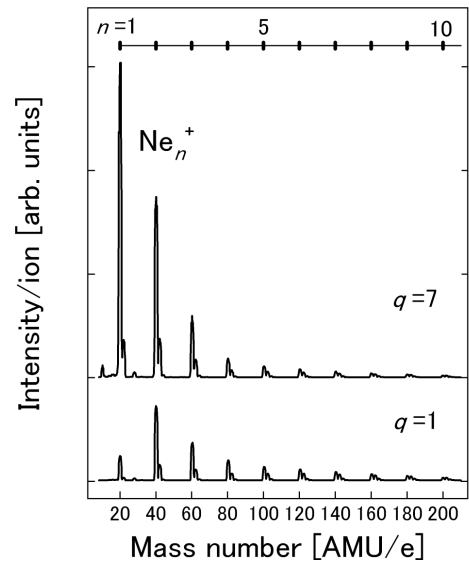


Fig. 1. Mass spectra of sputtered ions from the surface of the solid Ne by 1keV Ar^{q+} ($q = 1, 7$) impact. Thickness of the solid Ne is about 600ML.

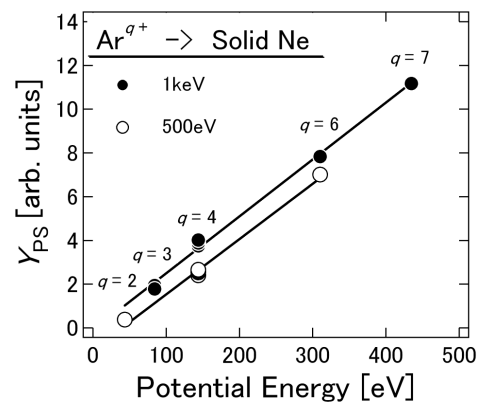


Fig. 2. Potential sputtering yields of ions sputtered by Ar^{q+} ($q = 2, 3, 4, 6, 7$) from the surface of solid Ne. Full and open circles correspond to 1 keV and 500 eV impact energy of incident ions, respectively.

SECONDARY ION EMISSION FROM A KCl(001) SURFACE BY GRAZING-ANGLE INCIDENCE OF SWIFT IONS

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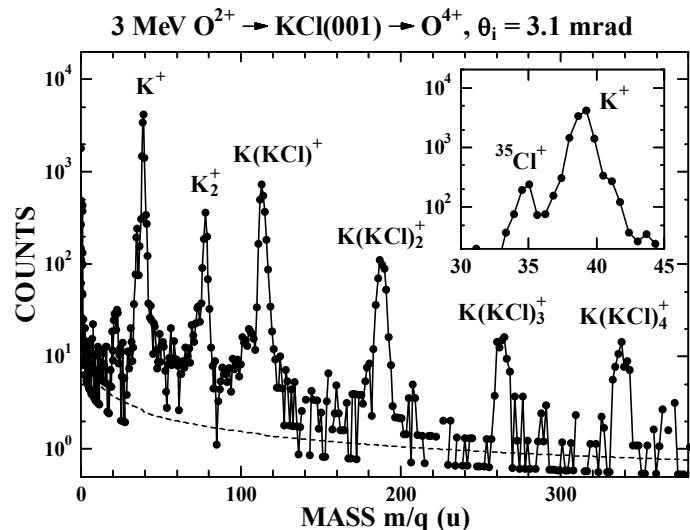
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When energetic ions are incident on an atomically flat surface at a grazing angle, most of them are scattered around the angle of specular reflection. This phenomenon referred to as specular reflection of ions is favorable for studies on the ion-surface interaction because the ions are reflected in front of the surface atomic layer without the close collisions with the target atoms or the penetration inside. In addition, one can easily examine the dependence of the interaction on the distance from the surface by means of changing the angle of incidence [1,2].

In this paper, the yield and the mass distribution of positive-charged secondary ions emitted from a KCl(001) surface were measured along with the energy loss of the reflected ions, when MeV ions are incident on the surface at grazing angle θ_i ranging from 1 to 5 mrad. Single-charged secondary ions such as K^+ , Cl^+ , KCl^+ , K_2^+ and small clusters, $K(KCl)_n^+$ ($n = 1-4$) were detected under the incidence of various MeV ions, 0.8 MeV He^+ , 1.34 MeV Li^+ , 2.1 MeV B^{2+} , 3 MeV O^{2+} , 1.5 MeV Si^{2+} and 6 MeV Si^{3+} . The total yield of the secondary ions increased with the angle θ_i regardless of kind of projectiles, while the energy loss of the reflected ions was almost independent of θ_i . The position-dependent production rate $P(x)$ of the secondary ions, i.e. the average number of secondary ions emitted per unit path length of a projectile traveling at a distance x from the outermost atomic plane, was derived from θ_i -dependence of the total yield. The production rate $P(x)$ is compared with the position-dependent stopping power $S(x)$ for the projectile at x . $P(x)$ shows an overlinear increase with $S(x)$ as $P(x) \sim S(x)^n$, but the index n varies from 1.4 to 2.6 depending on $S(x)$.

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Example of mass spectrum of secondary ions from a KCl(001) surface under grazing-angle incidence of 3 MeV O^{2+} ions.

GUIDING OF VERY HIGHLY CHARGED IONS WITH A GLASS CAPILLARY

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Highly charged ions produced in an electron-beam ion trap, I^{q+} , $q = 10 \sim 50$, were transmitted through a tapered glass capillary, having diameter of $50 \mu\text{m}$ at the end. We found, for a particular beam current, there exists an optimum tilting angle of the capillary, in which a steady output of ions was observed, while for other smaller angles, the ion-counts exhibit first rise and gradual decay on the minutes time scale. In case of steady transmission, the charge state distribution was found to be slightly shifted towards the lower side.

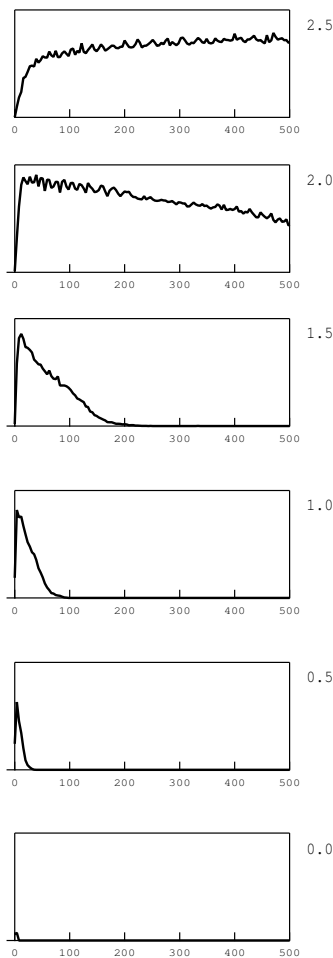


Figure 1: Time behavior of the transmitted highly charged ions. The numbers below the horizontal axes are time in seconds and the numbers at the right are tilt angles in degree.

STM OBSERVATIONS OF HIGHLY CHARGED ION IRRADIATED ALKANETHIOL MONOLAYERS

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Alkanethiols are long chain carbon molecules with a thiol group (-SH) at one end and a functional group at the other end. When these molecules are allowed to interact with a metal or semiconductor surface they form a stable monolayer with the thiol group covalently bonded to the substrate and the functional group forming a new surface. These structures are called self assembled monolayers (SAM) and have been the subject of intensive research recently due to their potential applications in functionally tailoring and nano-structuring surfaces [1]. We have used highly charged ions to irradiate alkanethiol SAM fabricated on flat gold surfaces. After irradiation scanning tunneling microscopy (STM) was used to observe the defects created in the SAM by highly charged ion impact.

Monolayers of the alkanethiol molecules 11-Mercaptoundecanoic acid, $\text{HS}(\text{CH}_2)_{10}\text{COOH}$, and Dodecanethiol, $\text{HS}(\text{CH}_2)_{11}\text{CH}_3$, were prepared on atomically flat Au(111) which was deposited as a thin film (200 nm) on freshly cleaved mica. The quality of the gold surface was confirmed by STM observations and the SAM formed by placing the clean gold samples into a 1 millimolar solution of the thiol in pure ethanol. Ar^{q+} ($q = 7,8$) ions generated by the high-Tc superconducting electron beam ion source (EBIS) located at RIKEN were used to irradiate the SAM surfaces under UHV with a typical ion dose of 10^9 ions/cm².

SAM surfaces were observed by STM before and after irradiation. Small craters in the SAM surface due to ion irradiation were observed. The density of these defects was approximately equal to the density of incident ions suggesting that individual ion impacts cause each defect. In most cases the defects were stable although under certain scanning conditions they could be made to disappear after several scans. For irradiation with Ar^{7+} ions at a kinetic energy of 14 keV the size distribution of the craters was found to be 2 – 4 nm, with an average depth of 0.2 nm. The nature of these defects is discussed in the light of complementary sputtering experiments from the same surfaces [2].

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THEORY OF CRYSTAL-ASSISTED FREE-BOUND PAIR PRODUCTION BY RELATIVISTIC IONS

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When a relativistic ion enters a crystal, it feels the periodic field by crystal atoms. In ion's rest frame the periodic field is equivalent to a bunch of monochromatic photons. If the ion is sufficiently relativistic, these equivalent photons may cause pair production in which an electron is produced in a bound state of the relativistic ion while a positron is in a free-like state (Fig. 1). A theory for the same kind of process was reported by Kunashenko and Pivovarov [1]. Using the virtual photon method and the relativistic photoelectric cross section, we calculate the bound-free pair production rate as a function of the impact parameter. We compare our results with the theory using strong laser fields by Müller et al . [2].

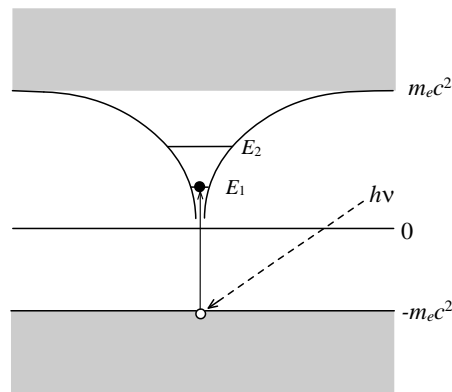


Fig. 1: Free-bound pair production

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Electron transfer process in ion neutralisation on nanoscale metal systems

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Nanoscale metal systems - supported clusters- play an important role in a number of applications including in particular heterogeneous catalysis, pigments etc. The properties of such systems and their interaction with atoms & molecules is thus of considerable interest. It is a well established fact that the size, shape and nature of support affect the properties of the nanoparticles and can play a crucial role in determining their use in a particular application. A considerable effort is being made to understand the various aspects that govern the properties of these systems, although a full understanding has not been achieved. The size effects have been discussed in terms of morphology and electronic structure and questions of the interaction with the substrate are addressed. It is thus interesting to investigate the evolution of electron transfer rates between ions and nanoparticles and follow their size dependence. Similarly recent theory (1,2) has also addressed the case of electron transfer on ultrathin films and the effect of quantization because of the finite thickness of the film.

Recently we have conducted experiments on Li neutralisation on Ag and Au clusters (3) supported on TiO₂, which have revealed a strong size dependence of the neutralization of Li⁺ ions, which turns out to be several times more efficient on nanoparticles of circa 3nm size. We are now extending these measurements to the case of Al₂O₃ support. In an attempt to understand these results we performed a study of Li⁺ neutralization on (100) and (111) surfaces of bulk Cu, Ag and Au (4) for which in certain cases of very high workfunctions an anomalously high neutralisation was observed. In relation to these questions, recent theory indicates that resonant neutralization processes besides the workfunction, depend on such properties as positions of the surface states and bandgap (5). In order to attempt to highlight these we performed experiments for thin films for which the above characteristics evolve as a function of film size and thickness. Thus we studied Li⁺ neutralisation on Ag submonolayer to multilayer films on Cu(111) and Au(111). Interestingly significant changes in neutralisation were however not observed.

These results will be presented and discussed.

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Density matrix description of resonant coherent excitation of swift highly charged ions in oriented crystals

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Experimental and theoretical studies on resonant coherent excitation (RCE) of channeled ions in crystals started about 40 years ago from pioneering works of V.Okorokov [1]. Unambiguous observation of *the Okorokov effect* by S.Datz group at Oak-Ridge and wide variety of RCE measurements performed recently by Tokyo collaboration have made main contribution to the present-day image of the RCE process [2].

Density matrix description [3,4] considers RCE ion as an open quantum system involved into coherent and incoherent interactions with the crystal medium. Systematic numerical calculations based on the generalized Master equation for density matrix show it as a good instrument for unified approach to charge state distribution of the RCE ions and the yield and angular distribution of their characteristic X-ray radiation. Other RCE observables including metastable ion production in a usual RCE process [5] and Auger electron production in a doubly resonant process (dRCE) [6] were considered in the same theoretical approach and suggested for experimental observation. Following our long-time interest in the problem of alignment of excited ions in the RCE process we extend previous density matrix calculations [3,7,8] on this point by theoretical predictions for Stokes parameters of linear and circular polarization of the X-ray radiation from relativistic resonant coherently excited channeled ions.

Our current theoretical studies in the field [9] being closely correlated with main trends in the latest RCE experiments by the Tokyo group [10-13] concern also such novel aspects of the RCE process as its trajectory resolved characteristics and resonant coherent excitation of highly charged ions in non-channeling conditions. Corresponding calculation results and our seeing of general perspectives of further development of the density matrix approach in the RCE studies will be presented at the conference.

The work is supported by the Russian Foundation for Basic Research (grant 06-02-16367).

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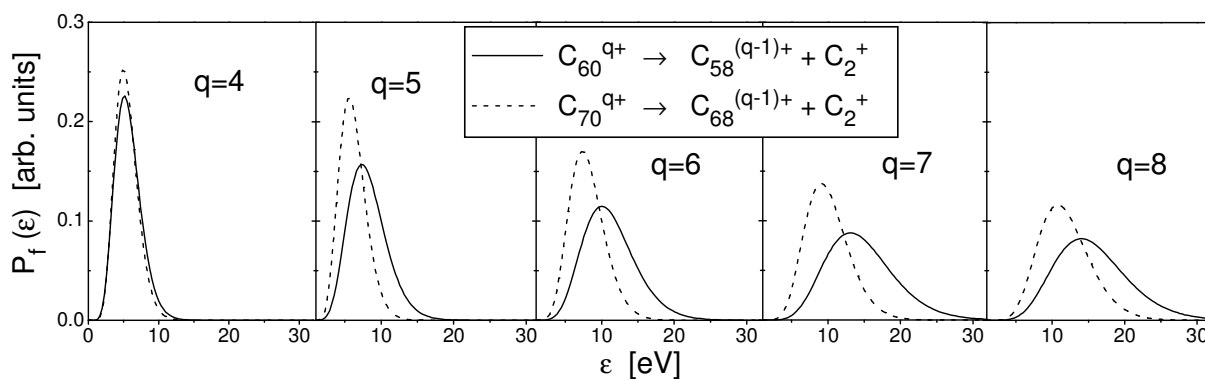
UNEXPECTED DIFFERENCES BETWEEN KINETIC ENERGY RELEASE DISTRIBUTIONS FOR C_2^+ -EMISSION FROM MULTIPLY CHARGED C_{60} AND C_{70} FULLERENES

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We have measured kinetic energy release distributions for asymmetric fission, $C_{60}^{q+} \rightarrow C_{58}^{(q-1)+} + C_2^+$ and $C_{70}^{q+} \rightarrow C_{68}^{(q-1)+} + C_2^+$, of multiply charged C_{60} and C_{70} fullerenes ($q=4-8$). The experimental technique involves a linear time-of-flight spectrometer with a position sensitive detector at the end. The kinetic energy distributions for the heavy fragments, $C_{58}^{(q-1)+}$ and $C_{68}^{(q-1)+}$, give corresponding two-dimensional position distributions on the detector which are reproduced by simulations including the initial thermal distributions in the target fullerene jets, the finite overlap volume of the jet and the ionizing pulsed beam of 57 keV Xe^{19+} -ions, the time delay between ionization and extraction, and kinetic energy release distributions of the form $P(\epsilon) = a\epsilon^k \exp(-k \epsilon / \epsilon_{\max})$. Here, $k = 8.5$ for C_{60} and 10.0 for C_{70} , and $\epsilon = \epsilon_{\max}$ is the kinetic energy release where $P(\epsilon)$ has its maximum. The resulting $P(\epsilon)$ -distributions, using ϵ_{\max} as a fit parameter, are very similar for C_{60} and C_{70} in the case of $q=4$ as can be seen in the figure below. For higher q , however, the C_{60} -distributions are significantly wider and peak at significantly higher ϵ -values than for C_{70} [1].



Further, we use a statistical model to describe the competitions between the asymmetric fission processes and evaporation processes in which a neutral C_2 unit is emitted. Relying on recent theoretical results for the dissociation energies for these two channels [2,3], and our experimental ratios which deviate significantly from zero and unity for $q=4-6$, we deduce semi-empirical fission barriers which compare favourably with recent theoretical results.

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Hydrogen atoms sputtered by highly charged ions from a Si(111)-H surface

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During approach of highly charged ions on a surface, electrons in the small area of the surface, typically several nm², are sucked up, which causes the repulsive force by the charges of the ions and results in the explosion of surface atoms. This explosion is called Coulomb explosion and the sputtering by the Coulomb explosion is called potential sputtering.

Tona *et al.* [1] have measured sputtered atomic and molecular ions from a hydrogen terminated Si(111) surface by the bombardment of slow highly charged iodine ions. Sharp increases of the ionic species with the increase of the charge state q of the projectile were observed. In the case of proton, which dominated over the other ions, the emission yields increased as $q^{3.4}$ and reached 4.6 per incident ion at $q = 50$. On the other hand according to the morphological observations of the impact sites of highly charged iodine ions with $q = 50$, about 20 of the surface hydrogen could be sputtered by the single ion bombardment [2]. Therefore the large amount of sputtered particles was lost, which means loss of the information of sputtering processes.

We measured Ly α and H α photons from the hydrogen atoms sputtered from a Si(111)-H surface by the impact of slow highly charged iodine ions quantitatively. Based on these measurements we will discuss the sputtering of atoms by slow highly charged ions from a surface.

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IMAGING DYNAMICS OF CHARGE-SELF-ORGANISATION IN GLASS CAPILLARIES: LATEST RESULTS AND PROSPECTIVES

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Multiply charged ion beam transmission through insulating capillaries is today a very active field of research [1]. Thanks to the work of several groups during the last five years, several features of this unexpected process have been evidenced. The open challenge is to understand and control the self-organized charging-up of the capillary walls which leads finally to the ion transmission. Up to now, the specific charge distribution on the inner surface, as well as the dynamics of the build-up, are still to be understood.

While capillaries usually studied are microscopic pore networks etched in different materials [2, 3], our concern is in macroscopic single capillaries made of glass. With a length of several centimeters and a diameter of a few micrometers at the exit, these capillaries have nevertheless the same aspect ratio as the etched pores (length/diameter ≈ 100). One of the leading goals of this research on single capillaries is to produce multi-charged ion beams with diameters smaller than a micrometer (nano-beams). Collimation by diaphragms is generally used to achieve this scale, but at the price of a drastic ion flow reduction. These glass capillaries offer the opportunity to use them as an ion funnel due to their amazing properties of guiding and focusing highly charged ion beams without altering neither their initial charge state nor the beam emittance ($< 10^{-3}$ mm.mrad) [4,5]. However, the understanding of the underlying process is not complete and relies on models assuming charge patches distributed along the capillary [6] and which still need to be tested. Our latest observations concerning the dynamics of the charging-up process show that the 230keV Xe^{23+} transmitted beam is deflected back and forth several times as the outgoing current increases (Fig.1). This is in agreement with the picture of charge patches created sequentially along the capillary and thus deflecting the beam. These latest results together with near future projects concerning charge patch imaging will be presented at the conference.

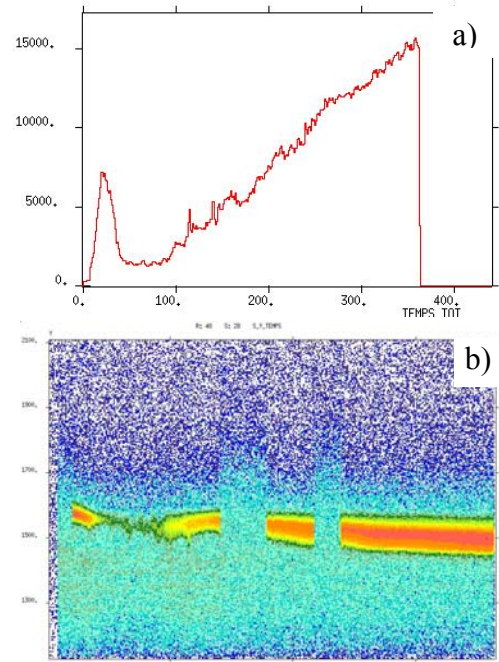


Fig.1 : a) 230 keV Xe^{23+} transmitted beam intensity as a function of time (1 channel = 20s) ; b) Horizontal position of the beam as a function of time (100 channels = 226 μ m).

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