# Image Acceleration of Highly Charged Xenon Ions in Front of a Metal Surface

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(Received 4 May 1993)

$Xe^{q+}$ ions with charge up to $q=33$ and energies $3.7q$ keV are scattered under a grazing angle of incidence from a clean and flat Al(111) surface. Because of the image charge interaction the ions are accelerated on the incident path towards the surface plane which results in increased effective angles of incidence for the scattered projectiles. From the angular distributions for reflected neutralized projectiles we deduce the image charge interaction energies gained by the incident ions in front of the surface. Our data are in fair agreement with a $q^{3/2}$ dependence for the image energies as predicted from a simple classical overbarrier model.

PACS numbers: 79.20.Nc, 34.70.+e, 79.90.+b

In recent years the study of the interactions of slow multiply charged ions with surfaces has developed into a very active field of research in particle solid interactions. Investigations of x rays and in particular electron emission have provided important data for elucidating the relevant interaction mechanisms. There is convincing evidence that the multielectron capture and loss processes in front of a metal surface result in the population of multiply and highly excited levels in the projectile and that most of the sparsely populated inner shells of those "hollow atoms" survive the approach to the surface [1-5]. As a consequence most of the high initial potential energy of the projectile is available close to the surface plane and is liberated there or in the bulk in close encounters with target atoms and conduction electrons.

In all these studies the kinetic energy of the projectiles with respect to the approach to the surface is an important parameter, since this energy is related directly to the interaction times with the surface. Already at an early stage in the study of the scattering of multicharged ions from surfaces it was pointed out that the acceleration of ions due to their image charge interaction sets a lower bound with respect to the interaction energies and interaction times with the surface [6]. Experimental studies on electron emission phenomena at low effective projectile energies (eV domain) have revealed clear indications for such effects [7-9]. Recently we have demonstrated a method to measure directly those image interaction energies [10].

Aside from the relevance of image interaction energies for a reliable knowledge of the effective interaction energies/times in scattering experiments, their magnitude also provides important information on the interaction mechanisms. Since the image charge interaction is strongly dependent on the charge state of the particle, image interaction energies reflect the dynamics of neutralization of the multicharged ions *in front* of the surface plane [6-12]. Based on the demonstration of the feasibility of our method with ions in low charge states [10], we present here first consequent studies of image charge interaction energies for incident ions ranging from low to relatively high charges.

In our experiments we scatter $Xe^{q+}$ ions under a grazing angle of incidence $\Phi_{in} \approx 1.5°$ from a clean and flat Al(111) surface and observe the polar angular distributions of the scattered (neutralized) projectiles with a channeltron detector. A schematic of the essential experimental components and the geometry of scattering is given in Fig. 1. The experiments are run under UHV conditions with base pressures ranging from $10^{-11}$ mbar to low $10^{-10}$ mbar, and the preparation of the Al(111) target is performed by cycles of grazing sputtering with 25 keV $Ar^+$ or $Xe^+$ ions and annealing by heating the sample to about 500 °C. Ions of low charge ($q \leq 11$, energy $E=25$ keV) are obtained from a Penning ion source, ions of higher charge ($20 \leq q \leq 33$, $E=3.7q$ keV) are extracted from the EBIS at the Manne Siegbahn Institute [13] to pulsed ion beams with $\Delta t \approx 100$ μsec at repetition rates of typically Hz.

In grazing collisions with surfaces the trajectories of projectiles are due to a sequence of small angle scattering events with the surface atoms, i.e., conditions of (planar) channeling [14]. The trajectories can be deduced from a collective planar potential $U(y)$ which depends only on the distance $y$ from the topmost layer of the surface and can be obtained from averaged screened Coulomb in-

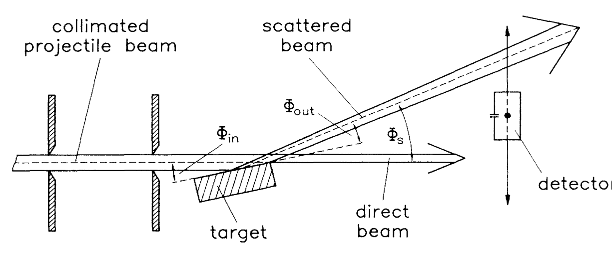


FIG. 1. Schematics of the collision geometry and the experimental setup.

0031-9007/93/71(12)/1939(4)$06.00

teraction potentials [14,15]. As a consequence the energy for the interaction with the surface (motion along $y$) $E_y = \frac{1}{2} M v_y^2 + U(y)$ is conserved, where $M$ and $v_y$ are the mass and the normal velocity component of the projectile. $E_y = E \sin^2\Phi_{in}$ is determined by the macroscopic settings of the projectile beam relative to the surface plane, where $\Phi_{in}$ denotes the grazing angle of incidence. At the conditions of our experiments we have $E_y \approx 7\times 10^{-4}E$, so that $E_y$ amounts to typically 10 to 100 eV depending on the charge $q$ of the projectile.

Our experiments are based on the concepts illustrated in Fig. 2. The solid line represents the trajectory of a neutral projectile with $\Phi_{in} = \arcsin(E_y/E)^{1/2}$. Under the assumption of conservation of $E_y$ and small energy losses of the total projectile energy $E$ we find

$$\Phi_{out} = \arcsin(E_y^{out}/E_{out})^{1/2} \approx \Phi_{in} ,$$

i.e., specular reflection conditions. Measurements of the reflection of a He-Ne laser beam collinear with an incident beam of neutral atoms confirm these assumptions. For ionized projectiles we have to take into account effects due to the dielectric response of the metal at already relatively large distances from the surface, which can be approximated by the concept of image charges. This description satisfies the boundary condition of a constant potential plane for the metal surface and results in an additional force along $y$ on ions in the charge state $q$ described in the classical limit by $F_y = -q^2/2R$, where $R = y - y_{im}$ denotes the distance from the electronic image plane ($y_{im} \approx 4$ a.u. for aluminum [16]).

The attractive image force accelerates the ions on their incident trajectory towards the surface until the image interaction is "switched off" by the neutralization of the projectiles. Assuming that the neutralization sequence of the projectiles is completed at a distance $R_0$, the ions gain image interaction energies $V_{im} = \int_{\infty}^{R_0} dR\, q(R)^2/2R$, where $q(R)$ describes the projectile charge state during the approach to the metal surface. Based on this feature we can deduce from image interaction energies $V_{im}$ information on the neutralization dynamics *in front* of the surface plane.

The image interaction increases the energy for the normal motion so that the effective angles of incidence for ions are larger than for neutral atoms: $\Phi_{in}^q = \arcsin[(E_y + V_{im})/E]^{1/2} > \Phi_{in}$ (see Fig. 2). In our experiments we checked with a pair of electric field plates between target and detector that the projectiles leave the surface predominantly neutralized. Thus an image charge interaction will be negligible on the outgoing trajectory. Since the neutralization of the ions is expected to be completed, before they have reached the image plane and the apex of the trajectory (see below), we find for specular reflection conditions $\Phi_{out}^{q,0} = \Phi_{in}^q > \Phi_{out}$ as shown in Fig. 2. In the experiments the image interaction energies $V_{im}$ are obtained from precise measurements of the angular distributions of scattered projectiles. For neutral projectiles we have angles of scattering $\Phi_s = \Phi_{in} + \Phi_{out} = 2\Phi_{in}$ and for incident ions $\Phi_S^{q,0} = \Phi_{out}^{q,0} + \Phi_{in}$, so that

$$V_{im} = E(\sin^2\Phi_{in}^q - \sin^2\Phi_{in}) = E(\sin^2(\Phi_s^{q,0} - \Phi_s/2) - \sin^2(\Phi_s/2)) . \quad (1)$$

As an example we show in Fig. 3 angular distributions for 25 keV $Xe^+$ ions and 107 keV $Xe^{29+}$ projectiles, respectively, obtained under otherwise identical experimental conditions. The data for $Xe^{29+}$ ions show a clear shift towards larger angles of scattering, which we attribute to an enhanced image charge interaction in comparison to

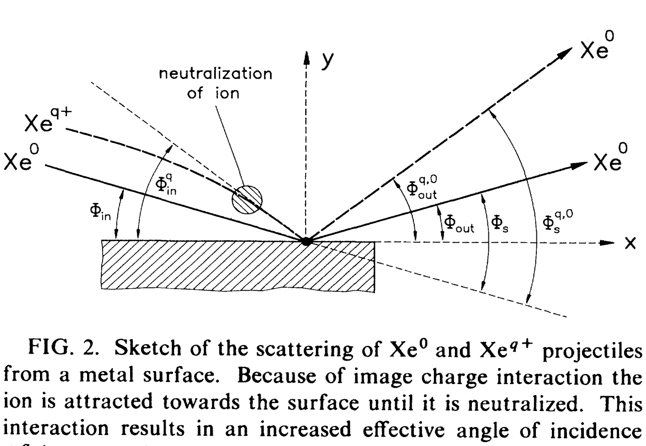


FIG. 2. Sketch of the scattering of $Xe^0$ and $Xe^{q+}$ projectiles from a metal surface. Because of image charge interaction the ion is attracted towards the surface until it is neutralized. This interaction results in an increased effective angle of incidence $\Phi_{in}^q$ in comparison to the angle of incidence for a neutral atom $\Phi_{in}$. Under the assumption that the ions leave the surface as neutral atoms (no image interaction) specular reflection conditions yield $\Phi_{out}^{q,0} = \Phi_{in}^q + \Phi_{in}$.

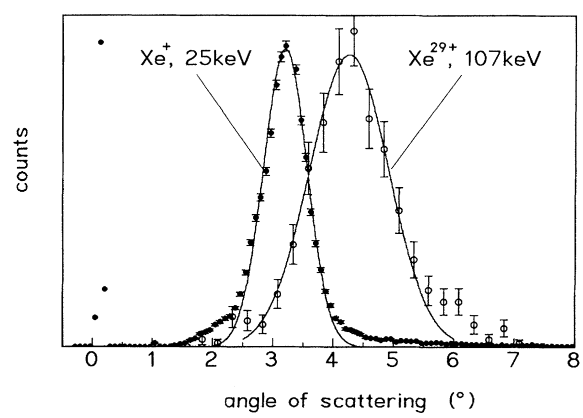


FIG. 3. Polar angular distributions of 25 keV $Xe^+$ (dots) and 107 keV $Xe^{29+}$ (open circles) projectiles scattered from an Al(111) surface. The sharp peak on the left side is due to $Xe^+$ projectiles that have passed the target without interaction (see Fig. 1); the intensity of this peak is suppressed by a factor 7 in comparison to the rest of the $Xe^+$ data. The intensities of the two distributions are normalized to achieve about the same maximum. The solid lines represent best fits to a Gaussian line shape.

$Xe^+$. The narrow peak on the left side is due to a fraction of projectiles that have passed above the surface plane without interaction (see Fig. 1) This peak serves as a reference for the angle of scattering with respect to the incident beam. The solid lines represent best fits to the data by a Gaussian line shape to obtain the peak positions of the angular distributions and the most probable angles of scattering. Whereas the $Xe^+$ ions are almost specularly reflected with respect to $\Phi_{in}$ by $\Phi_s \approx \Phi_s^{+,0} = 3.22°$ ($V_{im} < 1$ eV), we find for $Xe^{29+} \Phi_s^{29+,0} = 4.26°$. So $Xe^{29+}$ ions interact finally with the surface under an angle of incidence $\Phi_{in}^{29+} = 2.65°$ ($E_y^{29+} = 230$ eV) instead of $\Phi_{in} = 1.61°$ ($E_y = 85$ eV) as given by the macroscopic settings of the direction of the incident ion beam and the target. The difference of the normal energies is $V_{im} = 145$ eV. The same result can be obtained from the angles and Eq. (1).

The magnitude of the image interaction energy has two important aspects concerning the interaction of slow multiply charged ions with metal surfaces. First, as we have pointed out above, the energy of 145 eV is the lower limit for the interaction of $Xe^{29+}$ ions with an Al(111) surface Second, this energy gives evidence for the neutralization of the ions at relatively large distances from the surface, i.e., a population of multiply excited Rydberg levels in front of the surface. If the neutralization proceeded predominantly via electron transfer mechanisms into inner shells, one could expect such a process to occur at distances on the order of $R \approx$ a.u. with image energies in the keV domain. This is in clear disagreement with the experimental result.

In Fig. 4 we display $V_{im}$ versus the projectile charge state, where the availability of a charge state is related to conditions of the ion sources used here. The somewhat better experimental conditions in the measurements with the Penning ion source ($q \leq 11$) allows a more precise determination of the image interaction energies. For the highly charged projectile ions, the lower count rates, the higher projectile energies, and the somewhat poorer quality of the target surface yield clearly larger uncertainties. The data show a monotonic increase of $V_{im}$ with the charge state. For the highest charged projectiles we seem to observe indications for a saturation; however, the current data do not allow definite conclusions in this respect. Because of the nature of ion extraction through a fixed potential difference, the projectile energies differ with the ion charge. In a detailed study with $Xe^{7+}$ ions with energies ranging from 20 to 160 keV we find only a slight variation of $V_{im}$.

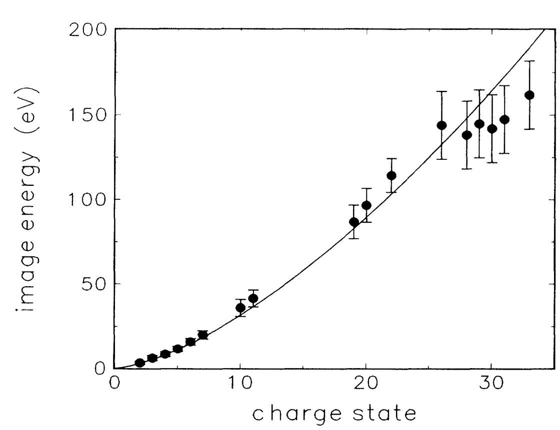


FIG. 4. Image charge interaction energies $V_{im}$ of $Xe^{q+}$ projectiles at an Al(111) surface. The solid line represents $V_{im} = q^{3/2}$ as predicted from an overbarrier model of stepwise neutralization.

The solid line in Fig. 4 represents the image energies calculated from a simple model of staircase neutralization of the incident ions in front of the surface, where the distance $R_c(q)$ for the onset of resonant electron transfers to the ion in charge state $q$ is obtained from a classical overbarrier model: $R_c(q) = (2q)^{1/2}/W$ [11], where $W$ is the work function of the metal. The image interaction energies can be approximated by $V_{im} = [W/3(2)^{1/2}]q^{3/2}$. For an Al(111) surface with $W = 4.26$ eV (measured via photoemission) one obtains the relation $V_{im} \approx q^{3/2}$ eV. In view of the oversimplified description of the complex multielectron transition problem the agreement with the data is surprisingly good. We note that ignoring the image interaction contributions to the potential barrier yields $R_c(q) = q/W$ [17] and $V_{im} \approx (W/2)q$. These image energies are about a factor of 2 smaller than our data, which may serve as an indication for the pronounced sensitivity of the data on the description of the interaction potentials.

In conclusion, we report on the first consequential measurements of image charge interaction energies of highly charged ions in front of a metal surface. Interaction energies up to about 150 eV are observed. The data establish a $q^{3/2}$ dependence predicted from an overbarrier approach. Indications for a saturation of $V_{im}$ at high charge states are present in the current data. However, further work with better accuracy and with higher charge states should be performed before one speculates on the presence of possible effects concerning charge transfer or in particular saturation phenomena of the image charge interaction for such high charges and resulting fields.

The assistance of H. W. Ortjohann in the preparation of the experiments is gratefully acknowledged. This work is supported by the Sonderforschungsbereich 216 (Bielefeld/Münster).

*Note added.*—After completion of this work we learned of related work by Aumayr *et al.* [18], where information on the image charge acceleration of highly charged Xe and Th ions is obtained from total electron yields. A discussion of this work can be found in the following paper.

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