Emission of Electrons from a Clean Gold Surface Induced by Slow, Very Highly Charged Ions at the Image Charge Acceleration Limit

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(Received 10 May 1993)

Total low-energy electron yields for the normal incidence interaction of slow very highly charged ions ($^{136}Xe^{q+}$, $21 \leq q \leq 51$; $^{232}Th^{q+}$, $51 \leq q \leq 80$) with a clean gold surface have been determined from the related measured electron emission statistics. The projectile impact energies could be reduced down to the image charge acceleration limit. The electron emission yield was found to increase proportionally with the increasing projectile charge state in all cases studied, suggesting no saturation in the ability of the Au target to provide necessary electrons within the above surface interaction time (e.g., about 280 electrons/projectile for Th^{79+} in less than 10^{-13} s). Because of the relatively narrow energy distribution and very high charge states of the incident ions, the first clear measurements of image charge acceleration from electron emission yields could be performed. Results of a quantitative study of this acceleration are in good agreement with those of a theoretical model recently developed by J. Burgdörfer *et al.*

PACS numbers: 79.20.Nc, 31.50.+w, 79.90.+b

The approach of highly charged ions [HCI (Z^{q+})] toward a metal surface causes the emission of a large number of electrons. Recent measurements of the related total electron emission yields [1-4], electron emission statistics [3-6], and fast Auger-electron energy distributions [2,7-17], together with the analysis of scattered projectiles [18-20] and soft x-ray emission [12,21-25] have led to the following scenario of the physical processes related to HCI surface collisions [4-6,12,26,27].

An approaching HCI starts to capture electrons from the metal conduction band [resonant neutralization (RN) [26]] into highly excited states at a distance above the surface where electronic transitions over the potential barrier become classically allowed [classical overbarrier model (COB) [26]]. With further approach toward the surface, the continuing RN gives rise to the formation of multiply excited "hollow atoms" and the already occupied projectile energy levels are shifted upwards due to the image interaction [(IS) image shift] and the screening by previously captured electrons [(SS) screening shift] [12]. These multiply excited projectiles continuously decay by autoionization (AI; giving rise to electron emission into vacuum), resonant ionization [(RI) inverse process to RN], and/or Auger loss (AL) to empty states in the conduction band [26,27]. At the same time the projectiles are rapidly reneutralized by RN. In addition to the AL processes, promotion of projectile electrons into the vacuum due to IS and SS, as well as peeling off (PO) of electrons still bound in highly excited projectile states at the very moment of surface impact contribute to the above-surface electron emission [4-6].

As a result of the intrinsic limitation of the interaction time available to the projectile until its impact on the target surface, relaxation of the hollow atoms to their ground states is rather improbable before close contact with the surface, taking place either inside the solid (thus giving rise to the majority of the observable inner shell Auger electron [2,15-17] and x-ray photon emission [12,21-25]) or—if the projectiles are backscattered—on the outgoing projectile trajectory. Because the HCI are attracted to the surface by their own image charge (or more accurately speaking, because of the dielectric response of a conducting surface to the presence of a charged particle [27]), the actual HCI impact velocity cannot be made arbitrarily small. The kinetic energy gain due to this image charge attraction (image interaction energy $\Delta E_{q,\mathrm{im}}$) is directly related to the distance of projectile neutralization, and is therefore a key quantity for testing theoretical models for the formation of hollow atoms. For a HCI with initial charge q impinging on a gold surface, the staircase approximation within the classical overbarrier model [27] predicts a total kinetic energy gain $\Delta E_{q,\mathrm{im}}$ prior to surface impact of

$$\Delta E_{q,\mathrm{im}} \approx 1.2 q^{3/2} (\mathrm{eV}) . \qquad (1)$$

First direct measurements of $\Delta E_{q,\mathrm{im}}$ involved only moderately charged projectiles (Ar^{q+}, $q \leq 6$ [19]; Xe^{q+}, $q \leq 12$ [20]), but have recently been extended to projectiles of higher charge states (Xe^{q+}, $q \leq 33$ [28]). Further evidence for the scenario of hollow atom formation and decay via electron emission is based on experiments using HCI in somewhat higher charge states (e.g., Ar^{q+}, $q \leq 16$; I^{q+}, $q \leq 25$ [1-17]) as well as from an exploratory investigation on electron yields and energy distributions for up to Th^{75+} impinging on gas-covered surfaces [2].

To extend our systematic studies [3-6] of HCI-induced potential electron emission, we have now applied highly charged projectiles up to Th^{80+}, using the electron beam ion trap (EBIT) facility at Lawrence Livermore National Laboratory [2,29,30]. For these ions the potential energy greatly exceeds their kinetic energy. We have determined

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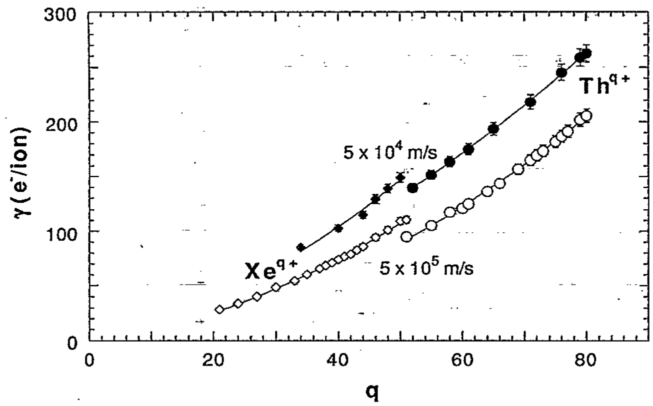

FIG. 1. Measured total electron yields vs charge state q for $^{136}Xe^{q+}$ ($21 \leq q \leq 51$, diamonds) and $^{232}Th^{q+}$ ($51 \leq q \leq 80$, circles) impact on a clean gold surface at 5×10^4 m/s (filled symbols) and 5×10^5 m/s (open symbols) impact velocity, respectively.

total electron yields from the related electron emission statistics [3–6]. The experiments involved projectile ions $^{136}Xe^{q+}$ ($q \leq 51$) and $^{232}Th^{q+}$ ($q \leq 80$) impinging under normal incidence on an atomically clean, polycrystalline gold target surface and the same electron detection methods are reported earlier [3–6,31]. In these measurements, the nominal (i.e., without taking $\Delta E_{q,\mathrm{im}}$ into account) HCI impact velocity has been varied from 5×10^5 m/s to well below 2×10^4 m/s (corresponding to a kinetic energy of ≤ 2 eV/amu). In comparison, the potential energies carried by the projectiles (about 100 keV for Xe^{50+} and about 250 keV for Th^{80+}) are much higher. Special measures have been taken to determine the nominal HCI impact energy precisely to within $\pm 1q$ eV, as well as to minimize the kinetic energy width of the projectile ions [32].

In our recent investigations with Ar^{q+} ($q \leq 16$) projectiles, for a given impact velocity, a nearly linear increase of the electron emission yields with the ion charge state has been found [4–6]. It was thus of primary interest whether this behavior continues toward higher projectile charge states. If the number of emitted electrons would level off, this might indicate that the target metal is no longer capable of providing the increasingly larger number of electrons required to form and sustain the hollow atoms. Measured total electron yields versus charge state q for impact of $^{136}Xe^{q+}$ ($q \leq 51$) and $^{232}Th^{q+}$ ($q \leq 80$) on clean gold at velocities of 5×10^4 m/s, as well as 5×10^5 m/s, are shown in Fig. 1. For both projectile species and impact velocities, the measured yields increase steadily (even slightly more than linearly) with charge state q, clearly showing no saturation. As expected from our earlier measurements [3–6], decreasing the impact velocity from 5×10^5 m/s by a factor of 10 leads to a substantial increase in the electron emission yield by about 30%–40%. In addition, our present measurements show that the particular electronic configuration of the

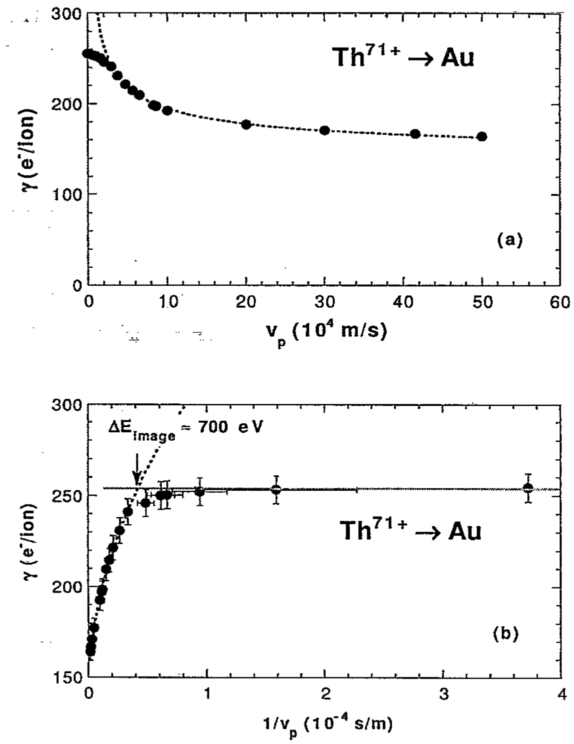

FIG. 2. (a) Measured total electron yield γ vs nominal (cf. text) projectile velocity v_p for impact of $^{232}Th^{71+}$ on clean polycrystalline gold. (b) Same as (a) but plotted vs the inverse nominal projectile velocity, in order to quantify the image charge effect (cf. text). Dashed curve gives electron yields extrapolated according to Eq. (2).

projectile plays some role even at these rather high charge states. For a given charge state q, more electrons are emitted by projectiles which carry a comparably larger potential energy, as may, e.g., be seen by comparing the electron yields induced by Li-like Xe^{51+} and Cu-like Th^{51+}, respectively (cf. Fig. 1).

A typical example of the impact velocity dependence of the total electron yields versus the "nominal" values of v_p is plotted in Fig. 2(a) for the impact of Th^{71+}. As a general trend, the measured yields decrease with increasing impact velocity but level off toward higher impact velocity into an apparently constant value (γ_∞). As already found for lower charge states [3–6], the data obtained for impact velocities $v_p \gtrsim 5\times10^4$ m/s can be nicely fitted by the relation

$$\gamma(v_p) \approx \mathrm{const}/\sqrt{v_p} + \gamma_\infty . \quad (2)$$

Consequently, the interpretation of the electron emission processes involved for moderately charged HCI [4–6] seems to hold also for extremely high charge states insofar as the "peeling off" mechanism and the "IS/SS promotion" are responsible for a substantial fraction of the velocity-independent part γ_∞ of the slow electron yield, whereas the velocity-dependent part can be attributed to AI.

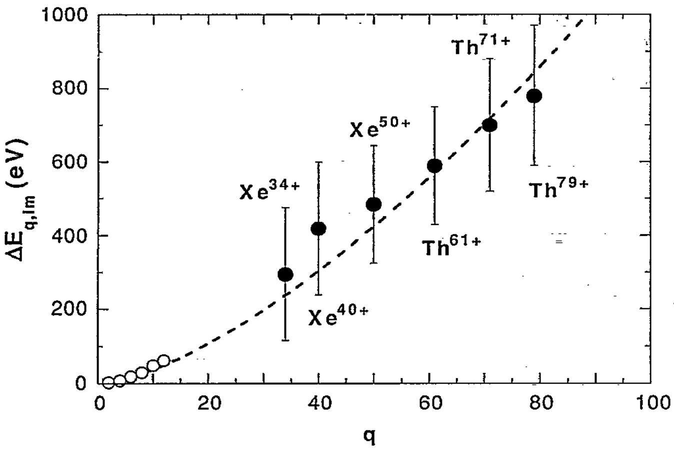

FIG. 3. Evaluated energy gains $\Delta E_{q,\mathrm{im}}$ due to image charge attraction for Xe^{q+} and Th^{q+} projectiles vs charge state q (full symbols). Comparison is made with data for Xe^{q+} ($q \leq 12$) impact on Fe ([20], open symbols) as well as the prediction of the COB model (staircase approximation [27], dotted line).

Apart from presenting the, so far, highest observed potential electron emission yields for slow HCI molecules (e.g., more than 280 electrons/projectile for Th^{79+} ions), our results, as exemplified in Figs. 2(a) and 2(b), not only clearly demonstrate the effect of image charge acceleration, but also serve to quantify the latter. Lowering the (nominal) impact velocity should increase the time available for the relaxation cascade and therefore increase the slow electron yields contributed by the AI processes. The saturation of yields as observable from Figs. 2(a) and 2(b) at $v_p < 5 \times 10^4$ m/s is a direct consequence of the "image charge limit" placed on the lowest-accessible HCI impact velocity caused by the dielectric response of a conducting surface to an approaching charged particle.

Plotting the measured electron yields as a function of the inverse nominal projectile velocity v_p^{-1} permits a direct evaluation of the impact-velocity gain due to the image charge attraction. According to Fig. 2(b) the image charge limited impact velocity of the Th^{71+} ions can be found from the intersection of the saturated yield value and an extrapolation of the yield dependence according to Eq. (2) [dashed curve in Fig. 2(b)] with the parameters being determined for large impact velocities [32]. In the particular case of Th^{71+} projectiles, the resulting kinetic energy gain due to image charge attraction, and therefore the principally lowest accessible impact energy is estimated to be $\Delta E_{q,\mathrm{im}} \approx 700 \pm 160$ eV. The given error depends primarily on the uncertainties of both the absolute value and the width of the nominal ion impact energy (cf. above). A more detailed discussion of this important aspect will be presented elsewhere [32]).

In Fig. 3 the evaluated $\Delta E_{q,\mathrm{im}}$ data for Xe^{34+}, Xe^{40+}, Xe^{50+}, Th^{61+}, Th^{71+}, and Th^{79+} projectiles have been plotted vs initial projectile charge state, together with corresponding data for Xe^{q+} ($q \leq 12$) impact on a clean Fe surface ([20]; the work functions of Fe and Au are comparable) as well as the predictions from the COB model (staircase approximation [27]). Within the comparably large experimental error bars, our results agree rather well with the COB predictions. This indicates on the one hand that the image charge concept for metals remains valid up to the very high charge states ($q \lesssim 80$) involved in this study and, on the other hand, that the HCI neutralization seems to follow the COB predictions, in particular regarding the distance of first electron extraction.

In conclusion, we have presented a quantitative evaluation of the ion image charge acceleration for extremely high initial projectile charge states. This constitutes not only a crucial test of the contemporary scenario of hollow atom formation and decay, but also poses a practical absolute limit to the lowest accessible impact energy of a HCI touching a metal surface. Moreover, up to a projectile charge of $q = 80$ the gold surface seems to be capable of providing enough electrons to form and sustain the hollow atoms, as can be concluded from the ongoing (nearly linear) increase of the electron emission yield with increasing charge state for projectile ions of a given impact velocity.

Work has been performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48 and has also been supported by Austrian Fonds zur Förderung der wissenschaftl. Forschung (Projekt Nr. P8315TEC), and by Kommission zur Koordination der Kernfusionsforschung at the Austrian Academy of Sciences.

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