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The role of atomic collisions in kinetic electron emission from Al surfaces by slow ions

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Abstract

We measured energy distributions of electrons emitted in the interaction of slow Kr^+ and Na^+ with Al surfaces. The data allow to correlate emission intensities with spectral signatures of electron excitation processes. Our results indicate that electron promotion processes leading to the excitation of Al target atoms plays the dominating role in kinetic electron emission from Al surfaces by slow ions. In the case of Kr^+ ions, electron promotion occurs in close atomic collisions between recoiling target atoms. For Na^+ projectiles, a significant contribution to Al excitation comes also from a vacancy transfer process in asymmetric collisions involving ions that have survived neutralization in the interaction with the surface.

1. Introduction

Electron emission in the interaction of slow atomic particles with metal surfaces is a complex phenomenon, that can be determined by several primary excitation processes [1–8]. Charge transfer and secondary effects, such as bulk plasmon excitation and electronic and atomic collision cascade, add further complexity to the phenomenon. This makes often difficult to establish the role of different basic excitation mechanisms, when they concur in determining the intensity of emission and the shape of the energy distribution of emitted electrons. Despite of decades of investigations, this is still the case of electron promotion [9], that is currently the matter of an interesting debate, regarding its competition with other processes, that have been recently investigated to understand non-vanishing electron emission observed at impact energies below the threshold for electron promotion [3–7,10,11].

Electron promotion occurs at the expense of the kinetic energy of incoming projectiles (kinetic electron emission – KEE) when close collisions temporarily create quasimolecules in which some electronic levels are promoted to higher orbital energies, giving rise to direct electron emission or delayed emission after Auger de-excitation [12] or after autoionization of excited states formed by electron capture [13,14].

The main goal of our current investigations is to search for correlations between the intensity of electron emission from Al surfaces and electronic excitations resulting from binary atomic collisions. Indeed, since the measurements of Alonso et al. [15], this question has not yet been fully elucidated, and efforts in this direction have been undertaken only recently [10,11,16]. In a recent paper, we addressed this issue by studying electron emission in the interaction of slow Kr^+ ions with Al surfaces [10]. We found that the dominant primary mechanism for kinetic electron excitation was the Auger decay of Al-2p excitations produced by electron promotion in symmetric collisions between recoiling target atoms. Here we extend and compare those results to the case of electron emission from Al surfaces under the impact of 250–1000 eV Na^+ ions which, due to their low ionization potential, do not release enough potential energy to give rise to the so called

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potential electron emission [2], and have been recently used for studies of KEE [5,17,18]. For the Na^+–Al system [17,18], electron promotion occurs either in binary collisions between the projectile and a target atom (asymmetric collisions) and between a fast recoil and another target atom (symmetric collisions). Asymmetric collisions involve either projectiles that have been neutralized in the interaction with the surface [2] and survived ions. We find that collisions involving survived projectile ions play a significant role in KEE from Al surfaces by slow Na^+ ions.

2. Experiments

Details of the experimental setup have been described previously [10]. Experiments were performed in a UHV chamber with a base pressure of 3×10^{-10} Torr. Noble gas ions were produced in a differentially pumped Atomika ion source operated at low discharge voltage to avoid significant amounts of doubly charged ions from reaching the surface with twice the energy. Na^+ ions were produced with a Kimball Physics ion gun. The ion beam currents were of the order of 10^{-9} A and had Gaussian spatial distribution in both horizontal and vertical directions, as measured with a movable Faraday cup situated in the target position.

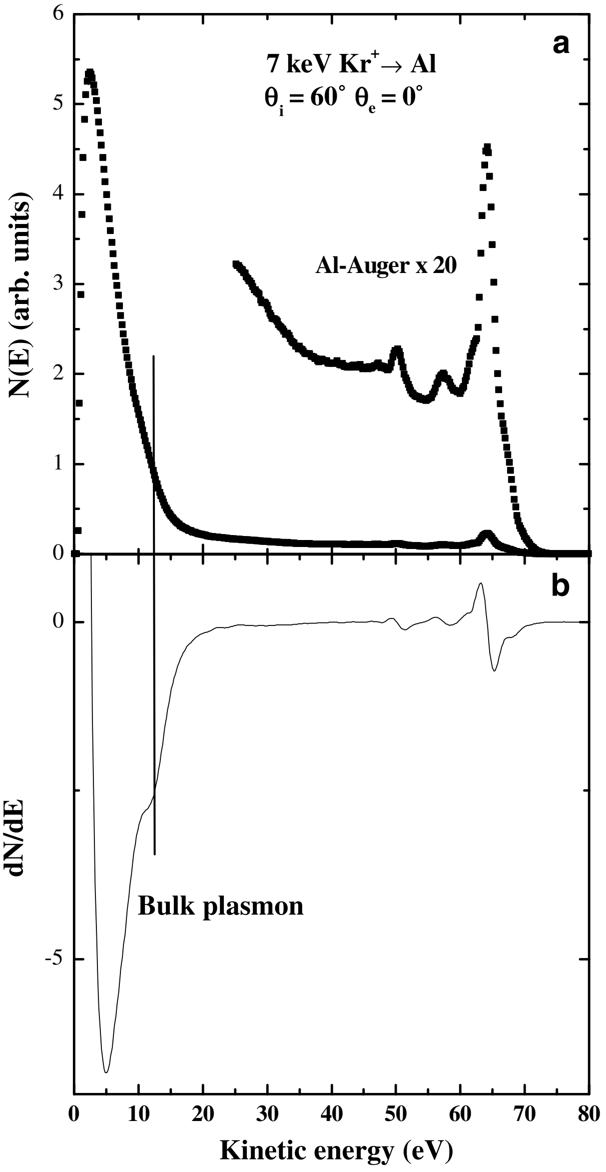

Fig. 1. Top: Energy spectrum of electrons emitted from an Al surfaces by 7 keV Krypton ions for the fixed experimental geometry $\theta_i = 60°$, $\theta_e = 0°$. Bottom: derivative $dN(E)/dE$ that enhances the visualization of structures due to plasmon decay.

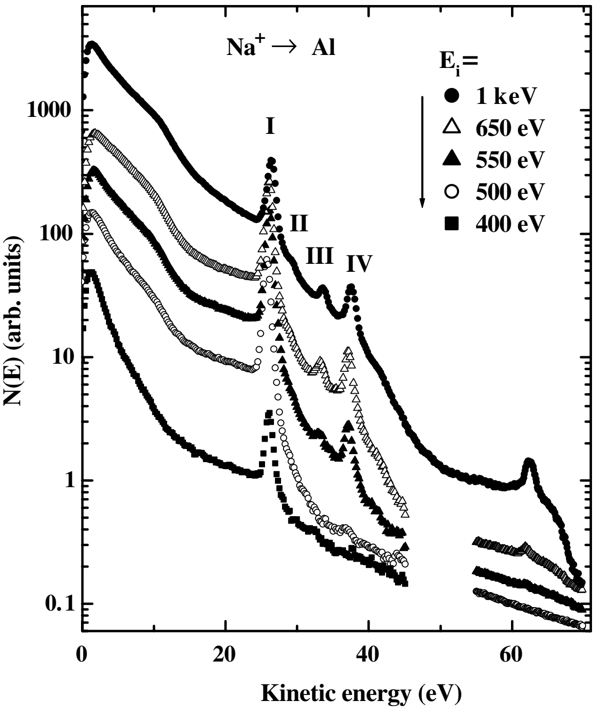

Fig. 2. Energy spectra of electrons emitted from the Al surfaces under the impact of Na^+ ions at varying incident ion energy. The spectra are shown as acquired and arbitrarily displaced on the vertical scale for clarity.

The polycrystalline Al samples (purity 99.999%) was sputter cleaned by 6 keV Ar^+ bombardment. Sample cleanness was assured by the absence of oxygen, carbon and sodium signals in electron induced Auger spectroscopy performed right before and after the acquisition of each spectrum and by the constancy of the energy position of sodium Auger lines during each spectral scan. The energy distributions of emitted electrons was measured by either a hemispherical analyzer mounted on a rotatable goniometer (Fig. 1) or by another fixed hemispherical energy analyzer situated at 60° from the beam direction (spectra in Fig. 2). These analyzers, lying in the incidence plane, had semi-acceptance angles of 1.5° and 25° and were operated at a constant pass-energy ($\Delta E = 50$ and 40 eV, respectively).

3. Results and discussion

Fig. 1 shows N(E), the energy distribution of electrons emitted from Al surface by 7 keV Kr^+ ions at an incident angle of $\theta_i = 60°$ and an observation angle $\theta_e = 0°$, both measured with respect to the surface normal. The as acquired energy spectrum is normalized to the beam current and width. The spectrum in Fig. 1 agrees with those found in the literature [19] and shows typical features of kinetic electron emission. For the Kr–Al system, KEE due to electron promotion has been extensively studied in the past [12]. In this case, Al-2p electrons are promoted in binary collisions between recoiling Al target atoms. This inner-shell excitation is evidenced in the spectra of emitted electrons in the Al-2p Auger signature observed in the 50–70 eV electron energy range and in a feature due to the decay of bulk plasmons excited by those Auger electrons traveling inside the solid (sub-threshold kinetic plasmon excitation [19]). The plasmon feature is usually evidenced by the taking the derivative of the spectrum (Fig. 1(b)), that shows a dip at an energy $E_m = E_{pl} - \Phi$, where $E_{pl} = 15.3$ eV is the bulk plasmon energy and $\Phi = 4.3$ eV is the Aluminum work function. These spectroscopic features are superimposed on a continuum background spectrum due to the cascade of electron–electron collisions, which is a characteristic of KEE.

Recently, we reported measurements of energy distributions of electrons emitted from Al surfaces under the impact of 1–8 keV Kr^+ ions. We observed that total electron emission yields, γ_{tot}, follows the same behavior of the intensity of Auger and plasmon decay electrons, extracted from the measured electron energy distributions by a very simple data analysis [10]. These results indicated that plasmon excitation as well as the continuum background spectrum are produced by the electronic collision cascade initiated by energetic electrons excited in Auger transitions, establishing that electron promotion in binary encounter between recoiling target atoms is the dominant primary mechanism for kinetic electron excitation in Al by slow Kr^+ ions.

Fig. 2 reports energy distributions of electrons emitted from Al surface bombarded by Na^+ ions at varying energy, for an incident angle $\theta_i = 60°$. For sodium impact on Aluminum, the electron promotion model [9] predicts excitations in the 2p level of the projectile. These are evidenced in the narrow peaks labelled I–IV in the 20–45 eV energy range, due to the Auger decay in vacuum of reflected sodium projectiles that have 2p shell vacancies created by electron promotion in a binary collision with Al target atoms. Attribution of the main atomic features appearing in the spectra has already been discussed in [17]. and is consistent with calculations [20]. Here, we notice that peaks II–IV are clearly observed at impact energies above a threshold value of about 500 eV. This observation further confirms the assignment of this peaks, given in [17] in analogy with the case Ne^+ impact, to the decay of doubly excited sodium projectiles due to simultaneous promotion of two 2p electrons in binary collisions between target atoms and incoming ions which have survived neutralization processes in the interaction with the surface. Infact, the ground state configuration of a Na^+ ion is the same of Ne atom and, therefore, collisions involving incoming ions produce both the $2p^5$ and the $2p^4$ excited states [14] with the same threshold energy. On the other hand, at impact energies lower than 500 eV, the structures due to the decay of the singly excited $2p^5$ states are the only atomic features appearing in the spectra. This implies that the observed structures are due to the decay of sodium projectiles that have been resonantly neutralized in the incoming trajectory, before the hard collision with a target atom. Infact, the absence of structures due to decay of doubly 2p excited states excludes contribution to the Auger spectrum of sodium of collisions involving survived ions, that require a smaller closest approach distance for 2p level promotion and, therefore, a higher threshold energy, consistently with our observations.

Very interestingly, Fig. 2 shows that the threshold energy for the observation of the Al-LMM and of the plasmon signals is very similar to the threshold for the observation of Na II–IV peaks and lower than the threshold energy for excitation in target Al–Al symmetric collisions [12]. This suggests that the L-shell vacancy in the target Al atoms can be created also in asymmetric collisions with the lighter Na projectiles. A plausible mechanism is that one of the L-shell vacancies present in the Na $2p^4$ can be transferred to the Al collision partner via a two electron *autoexcitation* mechanism, similar to that observed in the case of Ne^+–Al and other systems [21,22]. In this process, an external electron of Na fills a 2p-Na vacancy, while a 2p-Al electron is promoted in the 2p-Na vacancy, going from the Na^+ $2p^4 3s^2$ (or Na^+ $2p^4 3s3p$) + Al $2p^6 3s^2 3p$ configuration to the Na $2p^6 3s$ + Al^+ $2p^5 3s^2 3p$ configuration.

The observations reported in Fig. 2 reflect in the behaviour of the total electron yield as a function of incoming projectiles energy reported in Fig. 3. We observe that the electron yield shows a dramatic increase at impact energies

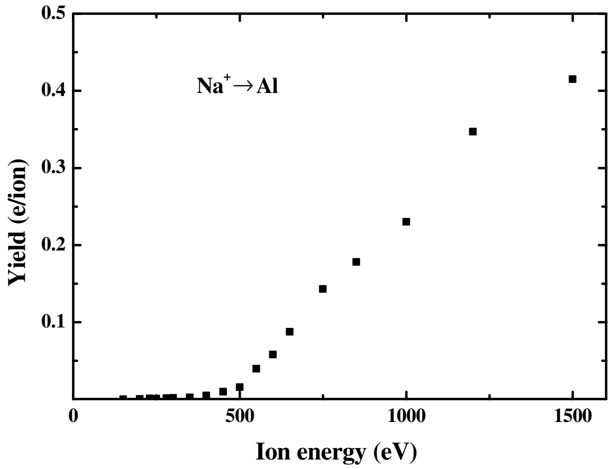

Fig. 3. The total electron emission yields γ_{Na} for $\Theta_i = 60°$ and versus incoming ion energy. The yield was evaluated, with about a 20% uncertainty, by measuring the current on the sample under positive and negative bias. The areas of the as acquired spectra reported in Fig. 2 follow the same behaviour.

closely corresponding to the threshold impact energy for the observation of the Al-Auger and Na II–IV peaks as well as the plasmon decay features.

At impact energies below the threshold for Al-2p signal, electron emission receive contributions from electron promotion in binary atomic collision, similar to those that are clearly signalled by the observed peak I, and also by KEE mechanisms that occur below the threshold for promotion, currently under investigation [6]. The available data are not sufficient to clarify the competition between the two processes and further studies are in progress to address this issue [23].

4. Conclusions

We have reported experimental studies of kinetic electron emission in the interaction of Krypton and Sodium singly charged ions with Al surfaces. Our results indicate that electron promotion processes leading to the excitation of Al target atoms plays the dominating role in kinetic electron emission from Al surfaces by slow ions. In the case of Kr^+ ions, electron promotion occurs in close atomic collisions between recoiling target atoms. For Na^+ projectiles, a significant contribution to Al excitation comes also from asymmetric collisions involving survived ions. In this case, we observe that the intensity of electron emission increases sharply above a threshold impact energy of about 450 eV, being correlated to a vacancy transfer process, that produce L-shell excitation in Al atoms in asymmetric collisions involving projectile ions, below the threshold for L-shell excitation in target Al–Al symmetric collision. This result is surprising because of high neutralization rates for slow ions at metal surfaces; it implies that surface neutralization and charge transfer processes may have a significant role in KEE from metal surface and that KEE induced by ions can be substantially different from that induced by neutral projectiles. Studies of KEE have been recently reported in the case of Neon impact on Al surfaces [7,11], using neutral projectiles to exclude contribution from potential electron emission [2], arising in the case of ion impact. The results of our work can be easily extended to the case of neon impact. Infact, in this case, formation of projectile triply excited states correlated to Al-2p excitation, have been reported for ion impact, but not for neutrals [11,13,22].

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