Hyperthermal and low-energy Ne\textsuperscript{+} scattering from Au and Pt surfaces

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Abstract

Energy spectra of Ne\textsuperscript{+} ions scattered off Au and Pt polycrystalline targets at low (200–1400 eV) and hyperthermal (down to 40 eV) energies were studied by mass-resolved ion-scattering spectrometry. Two scattering peaks with presumably different nature were revealed and their characteristics, namely, the relative energy position, the full-width at half-maximum (FWHM) and the normalized intensity, as a function of the primary energy were investigated. One of these peaks, named as the binary collision approximation (BCA)-peak, was interpreted using the BCA model. Another one, the so-called high-energy (HE)-peak, was situated at an energy position near to the primary energy, and we explain its origins in terms of non-binary (collective) interactions. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Binary or pairwise collision approximation (BCA) is defined as a collision between two particles alone or “free” (unbounded). In the case of a particle–solid interaction, the definition is more complicated, namely, “a collision, which is well

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\[ E = E_0 \left( \frac{\cos \theta \pm \sqrt{z^2 - \sin^2 \theta}}{1 + z} \right)^2 = E_0 k, \]  

(1)

where \( z = M_1/M_0 \) is the relative mass (the target-to-projectile mass ratio) and \( k = k(z, \theta) \) is the kinematic factor. The dual sign applies to the case of the projectile heavier than the surface atom \( (z \leq 1) \), and only the positive sign is valid for lighter ones \( (z > 1) \). Moreover, for heavier projectiles the scattering angle should be less than \( \theta_{\text{max}} = \arcsin z \). Eq. (1) is valid for elastic collisions, in which the projectile and target atom interact only through a central force that vanishes at large separation.

Sometimes, the experimental energy position \( E_{\text{exp}} \) of the scattering peak is found to be less than the theoretical value \( E \) calculated from Eq. (1) [8,9]. Most authors explain this displacement in terms of an inelastic energy loss \( Q \) associated with the mutual interaction of electrons of projectiles and solids (for a recent review, see [10–12]). On the other hand, the double (or multiple) scattering events are responsible for the high-energy shoulder of the binary elastic peak. In contrast to ion–gas collisions, multiple scattering is a rather typical process for projectile–solid interaction. Under certain conditions it can cause pronounced peaks interpreted within the framework of the BCA model as a result of sequential pairwise collisions between the projectile and surface atoms (for a review, see e.g. [13] and references cited therein).

On the whole, the validity of Eq. (1) for projectiles with a primary energy \( E_0 > 0.5–1 \) keV, a relative mass \( z > 1.2–1.5 \) scattered from the surface atoms under \( \theta > 60–90^\circ \) and not at grazing incidence \((>10–15^\circ \) on to the sample surface) was justified by numerous studies and is not a contentious issue in the literature now.

The situation at hyperthermal energy is not so clear. The terminology “hyperthermal” usually implies the fuzzy energy band placed in the range from a few eV to a few hundred eV. Scattering is among the fundamental processes that are important, both to understanding hyperthermal collision dynamics [14], plasma–wall interaction [15,16], and for technological applications such as ion-beam deposition of the thin films, ultra shallow junction formation, reactive etching, etc. [17,18].

In recent years a great deal of work has been carried out in the field of hyperthermal scattering. Their main aims and findings are summarized in our paper.

Several research groups explored gas-surface scattering using supersonic atomic beams [19–22]. Hyperthermal alkali-ion scattering from metal surface was intensively studied by Hulpke and Mann [23–25], Cooper’s group [26–29], Kleyn and colleagues [30–33], Vekslers, Eustifeev and co-workers [34–37]. The noble-gas electronic structure of singly ionized alkalis simplifies the construction of interaction potentials used in simulations, and the relatively well understood charge transfer behavior facilitates the interpretation of energy spectra.

Results obtained for atomic and molecular reactive ions, such as \( \text{O}^+ \) and \( \text{O}_2^+ \), \( \text{N}_2^+ \), \( \text{C}^+ \), \( \text{CO}^+ \) and \( \text{CO}_2^+ \), and grazing incidence \( \text{Si}^+ \), scattered from different metal surfaces are presented in [14,38–44]. Along with scattering events, many other complicated processes such as trapping, coupling, striking, skipping motion, adsorption, dissociation of molecular ions, etc. are rather typical for these types of projectiles in the hyperthermal energy range.

After the pioneering work of Tongson and Cooper [45], more than 25 years ago, subsequent experimental studies of noble-gas ion-scattering in the range of the primary energy \( E_0 < 0.3 \) keV have been very rare [38,39,46–52], mainly because of high cost instrumental requirements for primary beam generation and low signal intensity of scattered ions, making detection difficult. Nowadays, it is of interest to utilize a combination of low (hyperthermal)-energy secondary ion mass spectrometry (SIMS) and mass-resolved ion-scattering spectrometry (MARISS) [53,54] for ultra-shallow depth profiling and to summarize the advantages of these techniques in one instrument (see, e.g., our work [55], where such a SIMS–MARISS combination was realized).

The correctness of the BCA in describing the scattering events at hyperthermal energy is currently being debated [56]. Some authors [19–22,26–29,34–37,50–52] have interpreted the displacement
of a scattering peak towards higher energy, than that predicted by Eq. (1), as a demonstration of the non-binary (many-body or collective) nature of a projectile–surface interaction. According to this concept, atoms on a surface are considered as bounded (not isolated) during the impact, and a so-called “effective mass” can be calculated from Eq. (1). The effective mass is defined as a mass of hypothetical surface formation, namely \( M_{\text{eff}} = nM_1 \), where \( n \) is the total of surface atoms involved in collision process. This approach was originally proposed by Veksler [34], who explored the energy distributions of heavy alkaline ions (Cs\(^+\), Rb\(^+\) and K\(^+\)) impinging on refractory metal (W, Mo) surfaces with energies in the range of 100–300 eV, and later on was used by others (for a historical review, see [56]).

From the theoretical point of view, the deviation from the BCA should be evident when the time of the projectile–surface atom interaction becomes comparable with the period of the atom vibrations, and the energy of the colliding particles is similar to the binding energy of the surface atoms (several eV) [1,2,13]. These conditions are easily realized for heavy projectiles (\( z \ll 1 \)) scattered under an angle larger than \( \theta_{\text{max}} \). A detailed review of such studies both for noble gas and alkaline ions can be found in [50–52].

We emphasize that the present study focuses only on investigations of the scattering of noble gas ions, whose mass is lighter than a surface atom, since it is an optimal selection for analytical applications. Tongson and Cooper [45] found that for \( E_0 \geq 40 \text{ eV (He}^+\text{-to-Cu)} \) and \( E_0 \geq 20 \text{ eV (Ne}^+\text{-to-Cu)} \) the position of the single scattered peak was in a good agreement with BCA model. Mass-energy analysis or, rather, the mass analysis with a preceding energy calibration, was used for the separation of scattered and sputtered (desorbed) secondary ions.

The following results were published in limited access periodicals and practically were not cited anywhere. Volkov and colleagues [47,48] probed He\(^+\) and Ne\(^+\) hyperthermal scattering from different targets (Au, Bi, Pb, Si, InAs, etc.). Only energy analysis of scattered ions was carried out by use of a cylindrical mirror analyser. The authors revealed that the binary elastic collision approximation is true down to \( E_0 = 1.5–2 \text{ eV} \). Additionally, a strange peak at an energy approximately equal to the primary energy was measured for most of the targets investigated. The appearance of this peak had been associated with a local surface crystalline phase. An initially proposed mechanism of the energy transfer from soliton-wave to the scattered ions was not corroborated afterwards by computer simulations of the same authors [49].

Kang and coauthors reported the scattering of Ne\(^+\) from Ni (1 1 1) [38] and He\(^+\) and Ne\(^+\) from Si (1 0 0) [50] for colliding energies of 20–300 eV and 90° scattering angle. The time-of-flight (TOF) technique was used to analyse both neutral and ion fractions of scattered particles [38]; scattered ions were mass-analysed by a quadrupole mass spectrometer and, at the same time, their kinetic energy was measured in a TOF mode [50]. The authors found that the scattering events could be approximated to a sequence of quasi-binary collisions with unbounded surface atoms for \( E_0 > 100 \) eV, and that it were a many-body (collective) nature for lower collision energy. These conclusions have been confirmed by classical trajectory simulations performed using a Ziegler–Biersack–Littmark (ZBL or Universal) potential [57].

Computer simulation of hyperthermal energy noble gas scattering from solid surfaces was the subject of a whole series of publications [38,49,51,58]. In general, the calculation employed a molecular dynamic (MD) approach (for a review see, e.g., [1]) and aimed to elucidate, or to foresee theoretically, what kind of phenomenon appears under the interaction. But, a crucial input to all scattering codes is, of course, the interaction potential. Significant doubts about applicability of purely repulsive short-range potentials, such as the widely used ZBL potential, for colliding energies lower than 100 eV, exist. Hulpke [23] interpreted the scattering of Li\(^+\) from W (1 1 0) and Si (1 1 1) at \( E_0 = 2–20 \) eV within the framework of the BCA model by appending an attractive part to the repulsive potential, which is associated with image interaction between the ion and the conduction electrons in metal (for a recent review see, e.g., [59] and references cited therein). The importance of this additional attractive term has been also noted in other studies for hyperthermal alkali [26–33]
and reactive [38–42] ion-scattering. This image interaction produces an attractive force that depends on the distance from the surface and therefore violates one of the basic requirements necessary for the validity of Eq. (1), namely, that the potential depends only on the projectile–target atom relative coordinates. The attractive well depth $D$ is about 1–3 eV for alkali ions [28]; for neutral noble gas it can be estimated as 0.1 eV or less, but we have not found any information regarding the $D$-value in the literature for noble gas ions. Some authors modeled the repulsive part of the interaction potential as a total of Hartree–Fock pair potentials, summed over the six or more surface atoms nearest the scattering ion at each point in its trajectory [28]. In this case, the long-range tails of the repulsive potential cause simultaneous small momentum transfer collisions of the projectile with the nearest-neighbor surface atoms, that is, in fact, very close to the “effective mass” concept.

In this paper, we present a detailed study of energy distributions of Ne$^+$ ions scattered off Au and Pt surfaces at low (200–1400 eV) and hyperthermal (down to 40 eV) energies using mass-resolved ion-scattering spectrometry. Recently, this advanced technique has been successfully employed in our laboratory for the evaluation of inelastic losses [12] and for investigating the neutralization [54] of low-energy Ne$^+$ scattered from metal surfaces.

2. Experimental

Tongson and Cooper [45] have clearly demonstrated the significance and necessity of mass-separation at hyperthermal energy in order to avoid the interference between scattered and sputtered (or desorbed) secondary ion species. This is one of the prime advantages of our experimental MARISS investigations performed using a custom-built instrumental set-up based on the Hiden EQS 1000 Mass Energy Analyser. Our versatile apparatus, which operates, along with the MARISS, in secondary ion mass spectrometry, residual gas analysis and secondary neutral mass spectrometry modes, has been described elsewhere [12,54]; only features which are important for the present investigation are given here.

The inert gas ion gun “3M” manufactured by Kratos, consisting of an electron-impact ionization source with non-line-of-sight filament and two-lens electrostatic focusing system, produced a neon ion-beam in the energy range of 0.04–5 keV. The primary-ion current was 10–1000 nA. At the minimum primary energy ($E_0 \leq 50$ eV) the beam diameter (FWHM) was about 3 mm with a 0.5–1° half-angular divergence. Since a precise measurement of the primary energy was an important aspect of our study, the following calibration procedures were used. The acceleration potential was controlled directly on the ion gun electrode with an accuracy of ±(0.1–0.5) V. But, the actual ion energy $E_0$ may contain a small plasma potential component and other energy variations. Due to the very high primary-ion beam intensity it was not possible to use the mass-energy analyser for the measurement of $\Delta E_0$, as had been done in [26–29], without damaging the channeltron detector. Instead, a retarding field analyser with a relative energy resolution less than 0.5% was used. The total primary-ion beam energy discrepancy $\Delta E_0$ was ca. 2–4 eV for optimum ion gun conditions (i.e., the electron emission current is 10–15 mA, the grid voltage is 60–80 V, 99.999% pure Ne gas with the source pressure of $10^{-3}$ Pa). The additional mass analysis of scattered ions compensated for the lack of primary beam mass-separation.

The Ne$^+$ projectiles were directed at a fixed incident angle $\psi = 60°$ on to the sample surface. The laboratory scattering angle $\theta = 120° \pm 1°$ was also fixed and specular reflection conditions were realized. All measurements were carried out at “in-plane” geometry, that is, with axes of the incident beam and the analyser laying in same plane as the sample normal.

Scattered ions were mass-energy analysed using the EQS 1000, which combines a 45° sector field electrostatic energy analyser with a mean radius of 75 mm and a triple quadrupole mass-filter (9 mm pole diameter). In our opinion, energy analysis of the hyperthermal scattered ions, using a classical electrostatic analyser–deflector, has some advantage over the TOF technique, since it does not require a prior energy calibration, which is a ne-
cessity in TOF measurements (see, for example, [50]). The effective angular acceptance of the analyser $\Delta \theta$ was less than $\pm 1^\circ$, which corresponds to a solid angle of $\Omega = 10^{-4}$ sr. At the passing energy of 80 eV the energy resolution $\Delta E_a$ was 3.5 eV full-width at half-maximum (FWHM). The transmission and energy resolution were constant over the energy range up to 1000 eV. The mass resolution was 5–10 $M$ (FWHM), where $M$ is the mass of the analysed ions, in the mass range 1–1000 m/z. Unlike similar instruments (see, for example, [53]), the EQS 1000 operated in the MARISS mode with the sample at a fixed (ground) potential, without any extracting electric fields between sample and analyser, which can distort angular and energy distributions of the ions under investigation.

The samples probed were polished polycrystalline pure (99.9\%) gold and platinum targets. Surface topography was measured by Tencor Stylus Profiler P-10 before and after experiments. Surface cleanliness was ascertained by the SIMS mode.

The pressure in the analytical chamber was typically $5 \times 10^{-8}$ Pa. Partial gas pressure was controlled by the residual gas analysis mode. During experiments the Ne-pressure was maintained at $5 \times 10^{-6}$ Pa; the pressure of gas-contaminant species was at least two orders of magnitude smaller.

Mass-resolved energy spectra of the scattered ions were measured using a digital scan mode with 0.05–0.2 eV energy step and 0.5 s dwell time. The accuracy of the energy measurements is limited by the uncertainty in the contact potential between the sample and the detector. We estimated this uncertainty to be less than $\pm 0.5$ eV.

3. Results

Mass-resolved energy spectra of $^{20}$Ne$^+$ scattered off the gold sample within the primary energy range 40–1000 eV are shown in Fig. 1; data for $^{20}$Ne$^+$-to-Pt are presented in Fig. 2. Energy distributions consisted of three main features (peaks): (1) so-called SP (sputtered) peak; (2) BCA peak; and (3) high-energy (HE)-peak, that is, a peak with the energy approximately equal to the primary energy.

Fig. 1. Mass-resolved energy distributions of $^{20}$Ne$^+$ ions scattered off the Au-sample at different primary energies $E_0$ ($\theta = 120^\circ$, $\psi = 60^\circ$); SP: sputtered (re-emitted projectiles) peak; BCA: binary collision approximation peak; HE: high-energy peak.

The position of the first, narrow peak (SP) was near zero energy, this peak resulted from primary ions implanted and subsequently re-emitted, pre-
20Ne⁺-to-Pt (Fig. 2) the sputtered peak merged with another, wider background peak (Fig. 2).

The main peak, which we named BCA-peak, is found to result from binary elastic collisions, and the peak energy compared well with that predicted by Eq. (1). Step-by-step modification of the BCA-peak versus the primary ion-energy is shown for 20Ne⁺-to-Au in Fig. 3(a) and for 20Ne⁺-to-Pt in Fig. 3(b). The evident shoulder on the low-energy side can be attributed to subsurface scattering. This shoulder increased with decreasing primary energy starting with E₀ < 400 eV. Multiple scattering events were accountable for the high-energy tail of the BCA-peak. This tail was more intensive for the Pt-sample than for the gold.

The third peak (HE), shown in Figs. 1 and 2, was very puzzling, since it is caused by the projectiles, which changed their initial direction to the angle of 120° with only a small loss of kinetic energy ΔE = (0.01–0.04)E₀. Recently, a similar peak has been revealed in work [47] for different projectile-to-surface atom combinations at the energy E₀ ≈ 50–70 eV. In our study, the HE-peak showed up at the primary energy ca. 100 eV for 20Ne⁺-to-Au (Fig. 1); for the Pt-sample it was outlined only at E₀ = 40 eV (Fig. 2). The intensity of this peak was 50–80 cps (with a root-mean-square of the noise at a level of 3–5 cps) for gold and only 8–10 cps for the platinum. These results were difficult to compare with those published in [47] due to the limited information regarding their experimental conditions.

The following figures depict, in detail, energy dependencies of the relative energy position E/E₀ (Fig. 4), the FWHM ΔE (Fig. 5) and the normalized intensity I/I₀ (Fig. 6) for each BCA- and HE-peak. The peak height I was estimated as a mean value of the 5-point intensity measurements on the top of the peak (mini-integration procedure). Comparison of these data with the correct integration done at the level of FWHM of the peak gave a very little difference of about 2–5%, which could not influence the results presented in Fig. 6. The relative scattering energy of the BCA-peak was in a good agreement with the evaluated value of the kinematic factor k down to 60 eV for Au (Fig. 4(a)), and 100 eV for Pt (Fig. 4(b)). On the other hand, the relative energy of the HE-peak was

![Figure 2](image-url)

*Fig. 2. Mass-resolved energy distributions of 20Ne⁺ ions scattered off the Pt-sample at different primary energies E₀ (θ = 120°, ψ = 60°); SP: sputtered (re- emitted projectiles) peak; BCA: binary collision approximation peak; HE: high-energy peak.*
near unity for both samples. Peak width dependence versus primary energy for $^{20}\text{Ne}^+\text{-to-Au}$ is shown in Fig. 5; it was practically the same for $^{20}\text{Ne}^+\text{-to-Pt}$ (not shown here). We believe that the peak width is determined for $E_0 < 100$ eV by the value of absolute energy resolution of the energy analyser, and, at the moment, we are not able to improve $\Delta E_a$ because of the reduction in sensitivity of our EQS 1000 Analyser.

Relative peak heights $I/I_0$, i.e., ion-scattering yields, increased with decreasing primary energy for both samples and peaks. The intensity of the BCA-peak for $^{20}\text{Ne}^+\text{-to-Au}$ tends to saturate at $E_0 < 100$ eV (Fig. 6(a)); for $^{20}\text{Ne}^+\text{-to-Pt}$ (Fig. 6(b)) one can see some drop in the ion yield below $E_0 = 60$ eV. The intensity of the HE-peak strongly increased with decreasing $E_0$.

It is interesting, that the HE-peak could not be measured from the very outset of the experiments at small primary ion-dose $F$, i.e., for ‘‘fresh’’ samples, whereas the SP- and BCA-peaks already have been confidently registered. Before starting the main hyperthermal probing, the samples must be thoroughly cleaned or conditioned (implanted) by the Ne$^+$-beam (typically, 1 keV/1 μA, 1 h, $F = 10^{16}$ ions/cm$^2$). Initially, our samples were polished polycrystalline targets, but after ion-beam treatment the surface root-mean-square (RMS) roughness measured by Tencor Stylus Profiler P-10 greatly increased, namely, from $380 \pm 190$ to
2100 ± 1300 Å for the Au-sample and from 310 ± 90 to 920 ± 90 Å for Pt-sample, respectively. Nevertheless, this roughness did not hinder and, maybe, even assisted the appearance of the HE-peak in our study.

The HE-peak has been probed for the other rare gas ions, namely for He⁺ and Ar⁺. Only for He⁺-to-Au was a very small HE-peak revealed. Searching for the HE-peak in other samples, including polycrystalline noble (Cu and Ag) and refractory (Ta) metals, and semiconductor crystals (Si and InP) has not yet revealed any positive results for Ne⁺ and other primaries.

Fig. 4. Dependencies of the relative scattering energy $E/E_0$ of the BCA- and HE-peaks on the primary energy $E_0$ ($\theta = 120^\circ$, $\psi = 60^\circ$, $k$ is the kinematic factor): (a) $^{20}$Ne⁺-to-Au; (b) $^{20}$Ne⁺-to-Pt.

Fig. 5. Dependencies of the FWHM $\Delta E$ of the BCA- and HE-peaks on the primary energy $E_0$ ($\theta = 120^\circ$, $\psi = 60^\circ$, $\Delta E_\text{a}$ is the absolute energy resolution of the energy analyser).

4. Discussion

One of the most interesting results presented in this paper is that there is not only the existence of the HE-peak with energy close to $E_0$, but also simultaneous presence in energy spectra of both BCA- and HE-peaks. In the following, we try to clarify, as far as possible, the origins of these phenomena.

4.1. Instrumental artifacts

Direct transmission of the primary beam into the analyser, i.e., without impinging against the sample, was absolutely excluded under the angular configuration involved in our experiments. Also, there were no electric fields, extracting or otherwise, in the space between the sample and the analyser, which could cause deflection of primary ions ($E_0 \geq 40$ eV) onto the angle of 120°. We used pure, high-conductivity samples and we monitored the surface conditions by secondary ion mass spectra during all experiments. The main impurities for both samples were alkaline (Li, Na and K) and alkaline-earth (Ca) metals with very low concentration (less than 100 ppm). This guaranteed us the absence of the strong surface charging effects, which could influence primary and scattered ions, namely, BCA and HE peaks. The sit-
recognized easily, because of its energy at the twice the energy of the BCA-peak, namely 1.47E₀ for ²⁰Ne⁺-to-Au. No peaks resulting from this source (on the level of the apparatus sensitivity) appeared in our energy spectra.

4.2. Upshift of the energy distribution due to preferential neutralization of low-energy scattered ions

Recently, Kang and coauthors [52] have proposed that the peaks of hyperthermal Ar⁺ and Xe⁺ ions scattered off Si (1 0 0) are located at the high-energy end of total energy distribution of scattered particles (ions plus neutrals) due to preferential neutralization of low energy scattered ions. Such explanation is debatable and seems not appropriated for our experimental data.

4.3. Multiple scattering events

Theoretically, it is possible to get wide-angle scattering with minimal energy loss by combining many small-angle (or large impact parameter) events. The maximum possible energy of the ions scattered into the angle θ as a result of m-sequential binary elastic collisions with surface atoms is given by [13]

$$E_{m}^{\max} = E_0 \left( \cos \left( \frac{\theta}{m} \right) + \sqrt{\frac{z^2 - \sin^2 \left( \frac{\theta}{m} \right)}{1 + z}} \right)^{2m}$$

The dependence of the maximum relative peak energy $E_{m}^{\max}/E_0$, i.e., the kinematic factor of multiple scattering, on the number $m$ of collisions is shown in Fig. 7. An assessment of the events, which is needed for explanation of the HE-peaks (Figs. 4(a) and (b)), gives an unrealistic value of $m > 15–20$. Moreover, we cannot soundly elucidate the absence of other lower-number collision peaks, whose occurrence probabilities, of course, should grow with decreasing $m$-value.

Thus, it is difficult to understand the genesis of the high-energy peak within the framework of binary collision model using well-known central force repulsive potentials. To proceed further with

Fig. 6. Dependencies of the relative intensity $I/I_0$ of the BCA- and HE-peaks on the primary energy $E_0$ ($\theta = 120^\circ$, $\psi = 60^\circ$, $I_0$ is the primary-ion current): (a) ²⁰Ne⁺-to-Au; (b) ²⁰Ne⁺-to-Pt.

When the experimental dependence of the intensity of the peak on the scattering angle of the target was corrected for the ion gun voltage, we found that the SP-peak intensity was not so evident, because its energy was really near zero. We cannot rule out both negligible stray electric fields, which can exist in any vacuum chamber, and other ones, caused by the difference in work functions of the different facets of polycrystalline samples (the so-called “field of the spots”).

The ionization (grid) voltage of the ion gun was set at 60 V in order to minimize contamination of the primary ion-beam by doubly charged ions. Also, we point out that the MARISS technique readily separated Ne⁺⁺ scattered ions. A singly charged Ne⁺ scattered peak due to the doubly charged primaries is often observed in low-energy scattering experiments (see e.g. [60]) and can be
our discussion, we need to consider other possibilities.

4.4. Attractive interaction potential

The role, which the attractive term plays in the energy transfer between projectile and surface, is discussed in [28]. These authors revealed that the image force accelerates the ion towards the surface; as a result, an actual incident energy is $E_0 + D$, where $D \leq 3$ eV being the depth of the attractive well, and trajectory bending causes a larger total scattering angle $\theta + \Delta \theta$ during the collision. In the outgoing (exit) part of the trajectory the scattered ion decelerates and changes again its direction. A slightly modified BCA model [28], assuming that the attractive and repulsive forces act sequentially, allows the estimation of a relative scattered energy:

$$E/E_0 = k(x, \theta + \Delta \theta) - (D/E_0)[1 - k(x, \theta + \Delta \theta)],$$

(3)

where $k(x, \theta + \Delta \theta) < k(x, \theta)$ is the modified kinematic factor. Due to the small value of $D$, even for alkali ions, an influence of the attractive force on the scattered energy is marked only for $E_0 < 10$–15 eV. Moreover, computer simulation [28] has clearly demonstrated that attractive interaction causes a lower relative peak energy in comparison with that calculated by Eq. (1) and increases this difference with reducing $E_0$. By this way we are able to explain the dependency $E/E_0$ versus the primary energy for the BCA-peaks obtained in our study (see Figs. 4(a) and (b)), but cannot elucidate the nature of the HE-peak.

4.5. Wave nature of projectiles

The de Broglie wavelength, evaluated for a 40 eV Ne ion of 0.01 Å, being a quite small in comparison with surface atomic distance (lattice constant) of solids. So, even at the lowest energies in this study, a classical description of trajectories is appropriate and wave effects can be neglected.

4.6. Acquiring of energy from the target

We may assume a small possibility of energy loss due to interaction of hyperthermal primary ions with phonons, but the reverse process seems a very improbable event. Energy transfer between scattered ions and (quasi) soliton-waves on a surface have not been validated by computer simulation [49], because of slow-rate movement of these waves in comparison with collision times down to $E_0 = 10$ eV.

4.7. Effective mass

Let us suppose that the scattered ions, which were responsible for the HE-peak in our experiments, have impinged upon unknown surface structure with effective mass $M_e$. If this structure plays the role of the “target particle”, one finds from Eq. (1) that

$$M_e = M_0 \frac{1 + E/E_0 - 2 \sqrt{E/E_0} \cos \theta}{1 - E/E_0}.$$  

(4)

The value of $M_e$ evaluated for the HE-peak was in the range of the total mass of $n = 10$–15 atoms for both samples studied. At the moment, we do not contend that the real gold super-structure like cluster formation exists on the surface. Also, we agree with the authors of [56] that the approach based on the introduction of effective mass is merely a simplified description, which cannot explain the origins of a phenomenon, but points out
the problem of the BCA model at hyperthermal energy range for the projectiles both heavier and lighter than the surface atoms. It is very likely that two independent channels of energy transfer between projectile and surface atom(s) open and coexist together at these energies. One of them, which can be interpreted within the framework of true binary elastic collision model, tends to attenuate with decreasing collision energies. Another, that is, non-binary (or collective, or many-body, etc.) interaction intensifies as the energy nears the thermal range of a few eV. It is probable that there is no sharp limit (or cut-off) between the phenomena responsible for the peaks discussed. Until recently, probably, only instrumental issues have hindered their simultaneous experimental investigation. Also, there is a good reason to believe that more strong neutralization of scattered ions suppressed the HE-peaks for the other materials investigated in this study, but the scattering kinematics remained the same for all samples. The study of neutralization of hyperthermal Ne$^+$ ions scattered from metal surface using an updated dual-isotope method [54] is in progress now.

We are aware that the interpretation stated here is only speculation, but it is based on reliable experimental data. Of course, computer MD simulation is required, but we currently do not have ideas about interaction potentials suitable for the treatment of both observed peaks simultaneously. Adjustment or creation of new potentials for fitting of the experimental data do not, in the end, lead to true understanding of the phenomena. Our opinion is that an approach based on the consistent physical interpretation of non-binary interactions is required.

5. Summary

The basic result of the presented study is that the two peaks with presumably different origins have been simultaneously measured for hyperthermal neon ions scattered off gold and platinum polycrystalline surfaces. One of these peaks, namely the BCA-peak, was readily interpreted using BCA down to the lowest energies in this study. Another one, the so-called HE-peak, was situated at energy position near to the primary energy, and we explain its nature in terms of non-binary (collective) interactions, but, on the whole, genesis of this peak is still not entirely clear and is open to further investigation.

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References

[34] V.I. Vekslar, JETP 49 (1965) 90 (in Russian).