ION SCATTERING COEFFICIENT AS A FUNCTION OF COLLIDING-PARTICLE MASS RATIO

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Submitted to JETP editor April 10, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 845-850 (October, 1957)

The double-modulation method has been used to study secondary ion emission in the case in which the mass of the bombarding ion is greater than the mass of the target atom. It is shown that when Ni is bombarded by Cs ions or when Mo is bombarded by Ba ions no ions are observed at the "reverse" angle. When $V_i > \varphi$ secondary ion emission is not observed at any target temperature; when $V_i < \varphi$ the secondary ion emission which is observed at high target temperatures consists of ions which diffuse from the interior of the target and are evaporated at the surface.

IT has been shown by us[1-3] that there is a group of secondary ions when the mass of the bombarding ions m_2 is smaller than the mass of the target atoms m_1, which are characterized by high energies, the limiting value of which is determined by elastic scattering relations. It has also been shown that the dependence of the limiting energy on angle of incidence of the primary ion and emission angle of the secondary ion is in good agreement with the assumption of an elastic interaction between bombarding ion and target atom. These experiments furnish a reasonable basis for assuming that at least the limiting-energy ions are the result of a single elastic scattering of the primary ions on individual target atoms.

However, these experiments also indicate that there are secondary ions which have energies lying between thermal energy and the limiting higher energy. The interpretation of these ions in terms of multiple elastic collisions with target atoms is in need of additional verification. Hence it is of interest to study secondary ion emission in the case in which the mass of the bombarding ion is larger than that of the target atom. In this case, as is well known, for normal incidence of the primary ions on the plane of the target a single scattering of the primary ions at the reverse angle cannot occur. In practice there should also be no secondary ions resulting from multiple collisions since there is only a small probability of the required number of successive collisions in which the angle of deflection of the primary ion is close to the limiting value required for reversing the sign of the velocity; moreover, the velocity of these secondary ions is. small. Consequently, when the mass of the bombarding ion is larger than the mass of the target atom, the primary ion should, for the most part, penetrate the target to a substantial distance. Under these conditions there should be no secondary ion emission if the target is cold.

At high temperatures the targets are penetrated and the primary ions which are absorbed in the target enter into the thermal motion of the target atoms, thereby diffusing to the surface and subsequently being evaporated in the form of ions or neutral atoms. The ratio of the number of evaporated neutral particles to the number of positively charged particles is found to be in agreement with the well-known Saha-Langmuir relation:

$$n_+ / n_0 = A \exp\left(-\frac{V_i - \varphi}{kT}\varepsilon\right).$$

Thus, when $m_1 < m_2$, especially when $V_i < \varphi$ (V_i is the ionization potential of the ion, φ is the work function of the target), one expects that the secondary ions will comprise two ion groups — ions which are evaporated directly after adsorption and ions which, having penetrated the target to some depth, are evaporated after diffusion to the surface. Both of these ion groups will appear only at high target temperatures and will obey the usual relation for surface ionization.

Having these possibilities in view, we have considered two cases known to be different with respect to target-surface work function and ionization potential of the bombarding ion. We have studied scattering of positive Cs ions on Ni ($V_i < \varphi$) and Ba ions on Mo ($V_i > \varphi$).

The work was carried out using the experimental arrangement described in Ref. 2, under the same

vacuum conditions. The measurements were performed by the double-modulation method used by us in studying the secondary processes at the surfaces of pure metals in the case $m_1 > m_2$.[2,4]

CESIUM ON NICKEL

In Fig. 1 is shown an oscilloscope photograph of the retardation curve (volt-ampere characteristic) for a pure nickel target bombarded by cesium ions with energies of 400 ev. On the same figure are shown retardation curves for an incandescent target (1350° K, Curve 1) and a cold target (Curve 2). To obtain quantitative measurements four pulses of the total ion current I_Σ (Curve 3) were taken on the same photograph.

It is apparent from Curve 1 that ion secondary-emission coefficient for the incandescent target is better than 90 percent. The energies of these ions are small: the secondary ions are completely inhibited by a rather small retarding field. Examination of Curve 2 of the same figure indicates that in the cold-target case the ions secondary-emission coefficient is extremely small, being about 6 — 7 percent (these ions apparently originate in surface impurities). Consequently, the overwhelming majority of secondary ions (when $m_1 < m_2$ and $V_i < \varphi$) appear as a result of evaporation of ions of the primary beam which have been adsorbed at the surface of the target.

Further verification of this description can be found in Fig. 2, which shows two retardation curves taken with a lower modulation frequency of the primary beam and a target temperature of 1300° K (Curve 1) and a temperature of 1100° K (Curve 2). At 1300° K the "lifetime" of the ions adsorbed at the target surface is so small that the desorption process is completed almost immediately after the primary ions are cut off. Hence the variation of the secondary current follows the pulses of the primary ion beam. A different pattern is observed at the lower target temperature: in this case the "lifetime" of the adsorbed ions is considerable and the desorption process requires a certain period of time after ions from the primary beam no longer enter the target. Hence, Curve 2 of this photograph does not reproduce exactly the π-shaped pattern of the applied pulses, but rises and falls in a way which suggests an exponential relation.

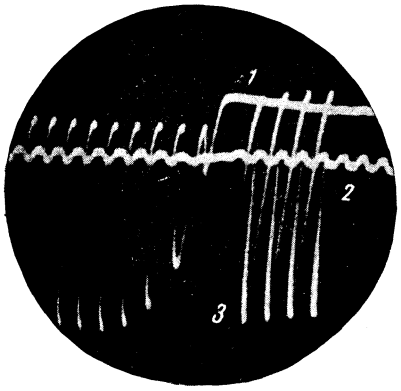

FIG. 1

FIG. 2

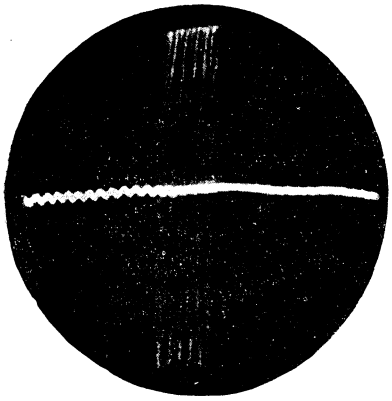

FIG. 3

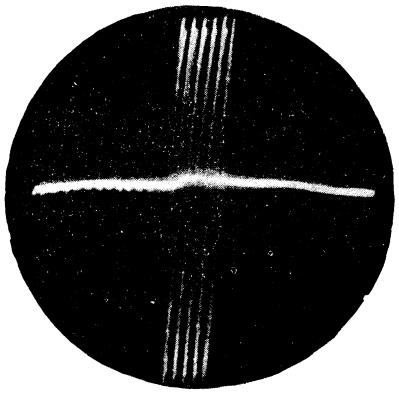

FIG. 4

The oscilloscope photographs in Fig. 1 and Fig. 2 also indicate the presence of secondary ions characterized by considerable delay, indicating fairly deep penetration of the primary ions into the target. The ions which penetrate the target to greater depths participate in the thermal motion, diffuse to the surface, and are then evaporated. Because of this effect a certain component of ion current from the target does not follow the modulation of the primary ion current. This phenomenon is clearly shown in the displacement of the base line of the oscillogram.

The experimental data which have been presented and calculations which have been performed indicate that the secondary ion emission from a pure nickel target at 1350° K bombarded by positive cesium ions consists mainly of evaporation (86 percent) and diffusion (14 percent) secondary ion currents. It should be emphasized that when a nickel target at high temperature is bombarded by cesium ions there is virtually no scattering or evaporation of cesium atoms.

Thus, it follows from the photographs shown in Fig. 1 and Fig. 2 that the secondary ion emission in the case $m_1 < m_2$ and $V_i < \varphi$, for example with Cs on Ni, does not take place at the expense of the energy of the primary ion beam. There is no change in the sign of the primary-ion velocity after interaction; consequently no ions are observed at the reverse angles. The secondary ions which are observed are ions which have penetrated into the target and then been evaporated from the surface because of the thermal motion due to the high temperature.

BARIUM ON MOLYBDENUM

It is also of interest to investigate the interaction between ions and target atoms in the case in which $m_1 < m_2$ but $V_i > \varphi$, i.e., when the surface ionization currents are vanishingly small.

In this work barium ions were used as bombarding particles. This element was chosen because its high ionization potential inhibits ion evaporation at elevated temperatures. Molybdenum was used as a target because it has a low work function as compared with nickel. In this case the difference between the work function and the ionization potential is known beforehand to be negative and the evaporation should consist mainly of neutral atoms.

In Fig. 3 is shown a photograph of the volt-ampere characteristic for a pure molybdenum surface at a temperature of 300° K bombarded by positive Ba ions with energies of 560 ev. It is apparent from the oscilloscope photograph that with a pure cold surface the secondary ion emission is negligibly small. A comparison of the secondary ion emission with the pulses of total primary ion current I_Σ (shown in the same photograph) gives a secondary ion emission coefficient $k < 1\%$.

A similar situation obtains at high target temperatures. In Fig. 4 is shown an oscilloscope photograph of the volt-ampere characteristic for the secondary currents when a molybdenum target at a temperature of 1300° K is bombarded by Ba ions with energies of 560 ev. In contrast to the case of Cs on Ni, in this case, as is apparent from the figure, there are no evaporated Ba ions at high target temperatures. Thus when a molybdenum surface is bombarded by Ba ions ($V_i > \varphi$, $m_1 < m_2$) the secondary ion emission is relatively small at any temperature of the bombarded target.

MECHANISM FOR SECONDARY ION EMISSION

On the basis of the foregoing sections and Refs. 1—4 we propose that when ions collide with a target the incident particles do not interact with the target as a whole, but rather with individual atoms of the crystal lattice. Under these conditions there is a strong analogy to the scattering of heavy particles in gases.

Thus a metal target can be considered as a system of gas atoms compressed into a very small volume. When $m_1 > m_2$, a large number of the observed scattered particles result from single collisions on surface atoms of the target. These particles have maximum energies, determined by the elastic-scattering relation

$$E = E_0 \frac{(m_1 - m_2)^2}{m_2^2 [\cos\beta + \sqrt{(m_1/m_2)^2 - \sin^2\beta}]^2}, \tag{1}$$

where E is the maximum energy of the secondary ions, E_0 is the energy of the primary ions, β is the angle between the incident direction and scattering direction of the ion, and m_1 and m_2 are the masses of the target atoms and the ions.

We have investigated the validity of this relation for a number of angles, in each case defining E as the limiting energy of the scattered particles at a given angle.[3] When the target-atom mass is smaller than the mass of the bombarding ion, the angle defining the maximum possible deflection of the bombarding particle is given by the expression:

$$\beta = \sin^{-1}(m_1/m_2). \tag{2}$$

For example, in the experiments in which the nickel target was bombarded by cesium atoms, after the first collision, having been driven into the target, the cesium ion cannot be deflected from its original direction by an angle greater than 26°. In the present experiments an extremely important conclusion can be derived from these relations: when $m_1 < m_2$ there will be no scattered primary ions. The experimental verification of this conclusion is a strong argument for the individual-interaction hypothesis proposed above.

On the other hand, when light ions bombard heavy targets, scattering at any angle can occur. This fact is also understandable from the point of view of single collisions. It follows from Eq. (2) that when $m_1 > m_2$ there is no limiting angle and ion scattering in any direction is possible. Complete experimental verification has also been obtained for this case.

A further indication that the primary ions penetrate into the target is given by the absence of "scattered" ions in the case in which nickel is bombarded by cesium. Both for the case $m_1 < m_2$ as well as $m_1 > m_2$ (Ref. 4) there is always penetration of the bombarding particle deep into the target. However, there is a difference in these two cases. When $m_1 < m_2$ all the bombarding particles penetrate to a certain depth and apparently have a definite range. In the second case there is strong scattering and only a small fraction of the primary particles reach the inside of the target. Whence it follows directly that the target atoms which are bombarded by ions with energies of several hundreds of volts are capable of being highly deformed, as a consequence of which there occur mainly individual collisions. These considerations are in agreement with existing interpretations. For example, using simple calculations Seitz[5] has shown that two protons with a relative energy of approximately 600 ev should approach to a distance of 2.4×10^{-11} cm, i.e., a distance equal to 1/100 of an atomic radius. Strong atomic deformation also occurs at lower energies: at an energy of approximately 20 ev, two atoms can collide so that the nucleus of one is found at the outermost radius of the other. At energies of the order of a hundred electron volts the atoms can approach to a distance of the order of 1/10 of a radius. Hence, in oblique collisions the incoming ion may penetrate into the metal just as a fast atom or ion penetrates a gas.

From this point of view the relatively slow secondary ions which reproduce the shape of the primary currents without "inertia" effects in the present experiments may be explained as follows. These slow inertialess ions are multiply-scattered primary particles which have experienced several collisions with deep-lying atoms of the target. The presence of slow ions with energies of approximately $0 - 10$ ev can be explained only by collisions with atoms at a reasonable depth since the reduction of the particle energy by a factor of 10 or 100 requires at least $5 - 10$ collisions. If these collisions were to take place at the surface, the particle, having an energy many times greater than the heat of evaporation, would have an extremely high probability for escaping from the target. Since the scattered ions with energies corresponding to a single elastic collision never total more than several percent, it may be assumed that the main fraction of the bombarding ions which experience oblique collisions penetrate into the target. These ions continue to move about in the target until they are no longer hindered by oblique collisions with target atoms or until they experience a head-on collision resulting in a loss of velocity which prevents escape.

In addition to those secondary ions which emerge without "inertia" effects, there are ions with very small (thermal) energies, the behavior of which is marked by extreme inertia effects. These ions are characterized by a definite delay with respect to the original ions and are observed only at rather high target temperatures. These ions are usually referred to as secondary ions. However, the presence of these ions is not directly related to the bombardment of the target by ions. This group of particles can be seen clearly only when $V_i < \varphi$ and appears as a result of thermal diffusion of the absorbed atoms and the subsequent surface ionization of these particles, which are converted into "adatoms."

The existence of an adsorbed layer of "adatoms," produced by virtue of the peculiar absorption of primary ions described above and diffusion, explains the time effects which have been observed both with galvanometers and oscilloscopes.

It should be noted that the appearance of a large number of "adatoms" associated with bombarding ions means that the target is covered by atoms with masses equal to the mass of the bombarding ions. In this case the parameters of the colliding particles are changed and instead of the condition $m_1 > m_2$ we have $m_1 = m_2$. As a result high-velocity ions are removed from the secondary-emission distribution. The ion velocity is completely lost in a head-on collision while in an oblique collision the ion enters into the target and may reappear only after several collisions, having lost a considerable part of its initial energy in the process.

CONCLUSIONS

On the basis of the experimental investigations reported here we propose the following:

1. From the example of positive Cs ions with Ni atoms for the case $V_i < \varphi$, $m_1 < m_2$ it has been shown that (a) there is virtually no secondary ion-electron emission from a pure cold (300° K) nickel surface or a heated (1350° K) nickel surface; (b) within the accuracy of these experiments the secondary ion emission contains no scattered Cs ions. At high temperatures the secondary ion emission from a pure nickel target consists only of evaporated ions which appear at the surface after diffusion.

2. From the example of positive Ba ions with Mo atoms for the case $V_i > \varphi$ and $m_1 < m_2$ it has been shown that (a) within an accuracy of about 1 percent there is no secondary ion-electron emission from a pure cold (300° K) molybdenum surface or a heated (1300° K) molybdenum surface; (b) within the accuracy of the experiments there is no secondary ion emission of any kind.

3. A qualitative examination of the results leads to the conclusion that secondary ion emission results from multiple individual scattering of ions which penetrate deep into the target and interact with target atoms.

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[1] U. A. Arifov and A. Kh. Aiukhanov, Dokl. Akad. Nauk Uz. SSR 4, 12 (1951).

[2] Arifov, Aiukhanov, and Starodubtsev, Dokl. Akad. Nauk Uz. SSR 1, 12 (1953); J. Exptl. Theoret. Phys. (U.S.S.R.) 26, 714 (1954).

[3] U. A. Arifov and A. Kh. Aiukhanov, J. Exptl. Theoret. Phys. (U.S.S.R.) 27, 87 (1954).

[4] U. A. Arifov and A. Kh. Aiukhanov, Izv. Akad. Nauk SSSR Ser. Fiz 20, 1165 (1956).

[5] F. Seitz, Discussions of the Faraday Society 5, 271 (1949).

Translated by H. Lashinsky
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FORMATION OF NEGATIVE H^- IONS IN COLLISIONS OF ELECTRONS WITH HYDROGEN MOLECULES

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Submitted to JETP editor April 23, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 851-855 (November, 1957)

The formation of H^- ions has been observed when electrons collide with H_2 molecules. In the curve of H^- ion yield as a function of electron energy there is a sharp maximum at 14.5 ev, attributed to the resonance capture of electrons by the H_2 molecules. The formation of H^- ions at higher electron energies apparently results from the dissociation of H_2 molecules into positive and negative ions.

WHILE studying the ionization of hydrogen molecules by electron bombardment, Lozier[1] found negative ions present in his apparatus; these were formed in a narrow range of electron energy, with maxima occurring at 6.6 and 8.8 ev. Mass-spectrometric analyses carried out by Bleakney showed that they were atomic ions, H^-.

The number of ions so formed was extremely small, and Lozier suspected that they came, not from H_2 molecules, but from molecules of H_2O which might have entered the apparatus as an impurity in the