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Secondary Electron Emission from Cu Surface by Bombardment of Cu Cluster Ions

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Statistics of secondary electron emission from the Cu metal surface bombarded with 30 keV Cu_n^+ cluster ions(n=1, 2, 5, 6, 8, 9, 10, 12, 15, 16, 20, 30 and 40) have been studied by measuring the total energy spectra of emitted electrons with use of a solid-state electron detector. The spectra have been least-square-fitted to a multi-Gaussian function incorporated with corrections for backward scattering of electrons from the detector surface. The resulting emission statistics are quite well described by a Pólya distribution. Assuming the sum rule for cluster ion impacts, the average emission yield per atom should be proportional to the velocity of cluster ion v with the threshold velocity v_{TH}. In the present study, it seems to be valid only for the cluster ions Cu_n^+ with $n \geq 9$. The Pólya parameter b decreases monotonically with an increase of the average emission yield for small-sized cluster impacts while such correlation seems to disappear for large-sized cluster impacts. A strong correlation has been found between b and the average emission yield per atom. With an increase of average emission yield per atom, b decreases rapidly down to its minimum, i.e., 0, and then begins to increase slowly. The minimum of b is achieved for the cluster size 9, i.e., one of the magic numbers for single-charged metal cluster cation. b may be thought to be closely related to the stability of cluster. Anyway, the reason of the change observed in both the average emission yield per atom and the Pólya parameter b for below and above the cluster size 9 is open for further study.

Key words: Secondary Electron, Emission Statistics, Cluster Impact

1. INTRODUCTION

Secondary electron emission from the metal surface bombarded with an atomic ion has been studied for long time [1,2]. Today, it is still a complicated phenomenon to be challenged both in experimental side and in theoretical side. On one hand, the energy dissipation process associated with many kinds of interactions between the projectile ion and the surface atoms and electrons has been attracting a great interest from a fundamental point of view. On the other hand, the detection of secondary emitted electrons has been one of the fundamental issues in experimental physics closely related with a detection method for heavy particles.

Two mechanisms have proposed for the secondary electron emission associated with the particle bombardment of metal surface. One is a potential emission, the other is a kinetic emission. In early days, only the electron emission due to release of potential energy, i.e., the potential emission, was discussed. Later, it was also realized that the electron emission due to release of kinetic energy, i.e., the kinetic emission, becomes important with increase of the projectile velocity.

The potential emission has been understood theoretically in great depth as an Auger de-excitation process, while the kinetic emission has not been understood well until now. The basic physical mechanism of the energy transfer from the projectile ion to the target electrons is still in debate. In other words, the theoretical understanding of the kinetic electron emission is not established in some details.

Measurements of the secondary electron emission from the surfaces impacted by atomic clusters have been carried out since the late 1970's [10-12]. These measurements have opened a new dimension 'cluster size', i.e., a number of atoms involved in the projectile ion, in the study of secondary electron emission. In addition, the study of secondary electron emission by impacts of the other kinds of poly-atomic ions such as biomolecule ions and multiple-charged proteins has become available since the mid 1980's.

The electron emission yield γ consists of a sum of two contributions γ_{PE}, i.e., the potential emission term, and γ_{KE}, i.e., the kinetic emission term, as follows:

$$\gamma = \frac{Y}{Q} = \gamma_{PE} + \gamma_{KE}, \tag{1}$$

where Y is the total number of emitted electrons and Q is the total number of projectile ions. Since the conversion of the potential energy of projectile ion into electron emission via the process of an Auger neutralization or an Auger recombination is a main mechanism for the potential emission, γ_{PE} should not depend on the velocity of projectile ion.

According to Kishinevskii [3], γ_{PE} can be calculated as follows:

$$\gamma_{PE} = \frac{0.2}{E_f}(0.8E_i - 2\phi), \qquad (2)$$

where E_f is the Fermi energy of target material, E_i the ionization energy of projectile ion and ϕ the work function of target material.

The conversion of the kinetic energy of projectile ion is a main mechanism for the kinetic emission. Several authors have reported that γ_{KE} is proportional to the velocity of incident particle in the region of velocity higher than $10^6 - 10^7$ [cm/sec] [4,5].

The emission yield γ_{PE} is considerably small compared with the emission yield γ_{KE} in usual, but the former dominates the latter as the velocity of projectile ion becomes small near the threshold velocity.

When a cluster ion is a projectile, it has been reported that there is a sum rule for the electron emission yield in the case when the kinetic emission dominates the potential emission [6]. The sum rule says that the electron emission yield γ_{KE} from the surface impacted by Nb_n (n=1-7) cluster ions is n times larger than the one from the surface impacted by Nb ions. Such sum rule has been also observed for the impact of $(\mathrm{H_2O})_n$ (n=10-10000) cluster ions [12].

Most of the previous measurements of γ have been made with use of a current integration method. which gives only the averaged value of γ. Actually, γ has some statistical fluctuation in its nature, which should give a new clue to understand further about the underlying mechanism of secondary electron emission. The emission statistics method developed by Dietz and Sheffield [13] is expected to open a substantially new possibility to evaluate the number distribution of emitted electrons due to such a statistical fluctuation.

In the present study, we have evaluated the number distributions of emitted electrons by measuring the total energy spectra of emitted electrons from the surface of Cu target impacted by Cu_n^+(n=1, 2, 5, 6, 8, 9, 10, 12, 15, 16, 20, 30 and 40) cluster ions.

2. EXPERIMENTAL METHOD

The experimental setup has a configuration similar to the so-called a Daly-type particle detector [7] in principle. The Cu metal target is set on the dynode. We have simulated the ion trajectories by using the ion traffic simulator SIMION [8] in order to determine the optimum setup configuration possible to catch up all the electrons emitted from the Cu target. The clusters with an energy of 2 keV are size-selected under a mass resolution of about 500 and accelerated by a dynode bias voltage of -30kV. They impact the Cu target at an angle of 45 degrees. The electrons emitted from the surface of Cu target are accelerated by the same bias voltage and led onto the solid state detector(SSD).

When n electrons, each of which has an energy of E_0, are led onto the SSD simultaneously, the resulting signal obtained from the SSD should be proportional to their total energy $E = nE_0$ within a finite range of energy resolution. If it is so, we can count up directly the number of emitted electrons with use of the total energy signal from SSD. Therefore, the total energy spectrum from SSD is a direct reflection of the number distribution of emitted electrons. Unfortunately, it is not the case. In order to obtain the number distribution, we must consider some further complication, i.e., the energy response function of SSD for the incidence of n electrons.

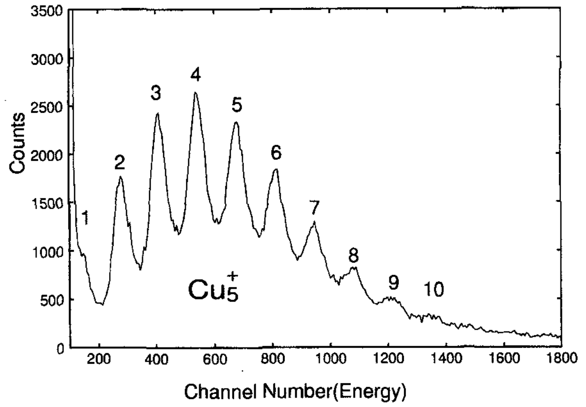

FIG. 1. Energy spectrum of SSD for secondary electrons from Cu target bombarded with Cu_5^+ cluster ions; the number assigned for each enhanced peak structure means the number of emitted electrons.

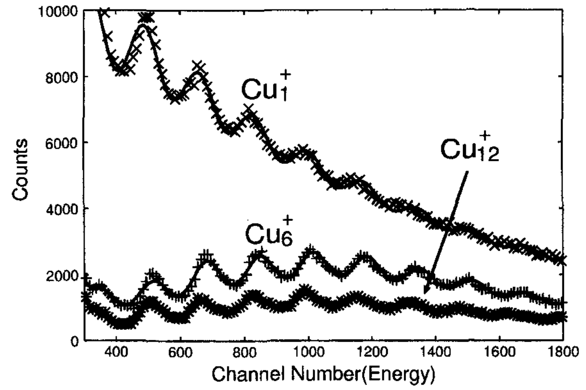

FIG. 2. Results of multi-Gaussian fitting; for the cases of Cu^+ ion impacts, Cu_6^+ cluster ion impacts and Cu_{12}^+ cluster ion impacts.

The energy response function of SSD is expressed by a sum of n+1 Gaussian functions, each of which corresponds to the number of backscattered electrons from 0 to n, as follows:

$$F_n(E) = \sum_{i=0}^{n} G(E; \mu_i, \sigma_i), \qquad (3)$$

where i is the number of backscattered electrons, $G(E; \mu_i, \sigma_i)$ a Gaussian function with the average value μ_i and the variance σ_i. μ_i is taken as $(n - 0.6i)E_0$ and

σ_i as $\sigma_0 + \sigma_{BS} * i$. σ_0 is a detector resolution while σ_{BS} is a width broadening per backscattered electron [4].

We adjusted the intensity of Cu cluster ion beam to a value of 1k to 8k [counts/sec] so as to guarantee that only one Cu cluster ion impacts the Cu target at a time. Figure 1 shows an energy spectrum of SSD when the Cu target is bombarded with Cu_5^+ clusters. We can realize the successive peak structures enhanced over the broad background structure. The enhanced peak structures are due to the total energy peak without any backscattering electron from the surface of SSD. The broad background structure is a superposition of the broadened peak structures associated with the backscattered electrons. The number assigned for each enhanced peak structure means the number of emitted electrons.

We have tried a multi-Gaussian fitting to the obtained spectrum with use of the profile function $S(E)$ given by

$$S(E) = \sum_{n=1}^{N} Y_n F_n(E), \tag{4}$$

where Y_n is the intensity of n'th peak and $F_n(E)$ the response function of SSD given by Equation 3. A set of Y_n (n=1, 2, 3,.., N) forms the number distribution of emitted electrons. Figure 2 shows the typical results of multi-Gaussian fitting. As expected, the number distribution of emitted electrons seems to follow an exponential decay function for small-sized clusters while it seems to follow a Gaussian function for large-sized clusters.

A Poisson distribution has been proposed to describe the number distribution $\{Y_n; n = 1, 2, .., N\}$, i.e., statistics of the number of emitted electrons. It has the form given by

$$P(n, \gamma) = \frac{\gamma^n}{n!} e^{-\gamma}, \tag{5}$$

where γ is the average emitted electron yield and n the number of emitted electrons. However, most of the results obtained by the present experiment were apparently deviated from the Poisson distribution.

Instead, we have tried a Pólya distribution:

$$P(n, \mu, b) = \frac{\mu^n}{n!}(1 + b\mu)^{-n-1/b} \prod_{i=1}^{n} (1 + (i-1)b), \tag{6}$$

where μ is equal to the average emitted electron yield γ, n the number of emitted electrons and b the variance parameter with $0 \leq b \leq 1$. When $b = 0$, the Pólya distribution becomes the Poisson distribution. As shown in Figure 3, it is found that the Pólya distribution works very well to fit the number distributions obtained by the present experiment.

3. RESULTS AND DISCUSSIONS

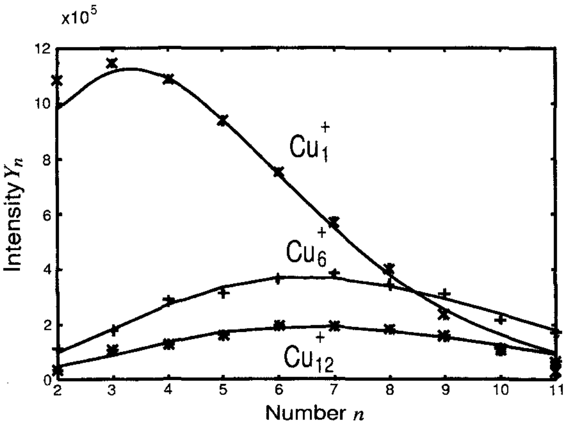

FIG. 3. Number distributions of emitted electrons resulted from multi-Gaussian fitting and Pólya distributions used to describe them.

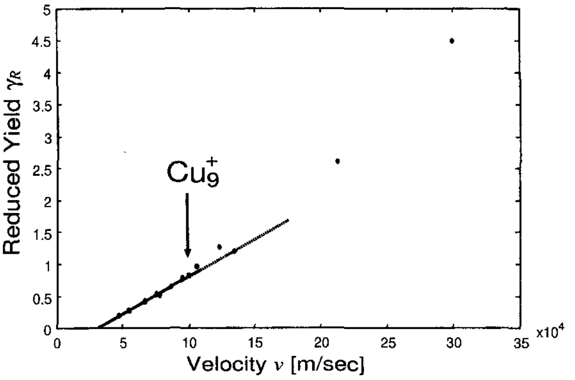

FIG. 4. Correlation between the reduced emitted electrons yield γ_R, i.e., γ per atom, and the velocity of cluster ion; the solid line is a result of least-square fitting.

Figure 4 shows a correlation between the velocity of cluster and the reduced electron emission yield γ_R, i.e., γ per atom. The electron emission yield γ is evaluated by a least-square fitting of the number distribution $\{Y_n; n = 1, 2, .., N\}$ to the Pólya distribution. It seems that the sum rule for the emitted electrons is not valid in the present case, i.e., the case of $\mathrm{Cu}_n^+ (n = 1, 2, .., 40)$ cluster ions. However, it seems to be valid for the cluster ions Cu_n^+ with $n \geq 9$. The solid line is obtained as a result of a least-square fitting to the linear function $g(v) = \alpha(v - v_{th})$, where v is the velocity of cluster and v_{th} the threshold velocity, carried out under such restriction. The threshold velocity v_{th} is determined as 3.4×10^6 [cm/sec].

Figure 5 shows a correlation between the electron emission yield γ and the Pólya parameter b, which is also evaluated by the least-square fitting of number distribution. The recent experimental data by Itoh et al. [14] suggests the existence of strong correlation between γ and b, which is given by the equation $b \sim \gamma^{-1.1}$. Any kind of such correlation does not observed in the results of present experiment.

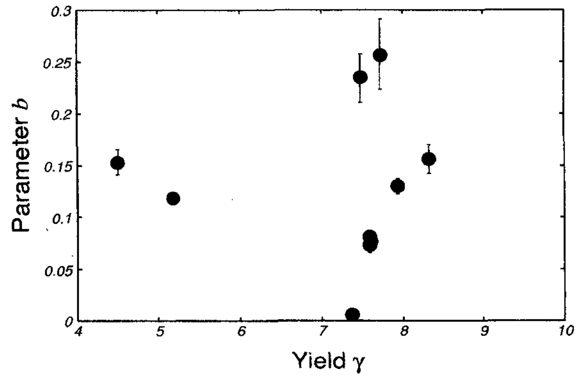

FIG. 5. Correlation between the emitted electrons yield γ and the Pólya parameter b.

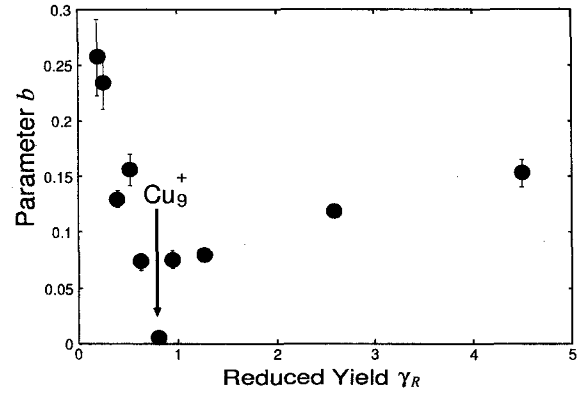

FIG. 6. Correlation between the reduced emitted electrons yield γ_R, i.e., γ per atom, and the Pólya parameter b.

Figure 6 shows a correlation between the reduced electron emission yield γ_R and the Pólya parameter b. Apparently, there are two tendencies for the parameter b as a function of γ_R. One is a monotonic decrease with an increase of γ_R. The other is a monotonic increase with an increase of γ_R. The former is observed for the cluster ions Cu_n^+ with $n \leq 9$ while the latter for the cluster ions Cu_n^+ with $n > 9$. The tendency switches at the cluster size 9, i.e., a magic number for single-charged metal cluster cation. At this point, the parameter b becomes zero and the number distribution is equal to a Poisson distribution.

4. SUMMARY

Statistics of secondary electron emission from the Cu metal surface bombarded with 30 keV Cu_n^+ cluster ions(n=1, 2, 5, 6, 8, 9, 10, 12, 15, 16, 20, 30 and 40) have been studied by measuring the total energy spectra of emitted electrons with use of a solid-state electron detector. The spectra have been least-square-fitted to a multi-Gaussian function incorporated with corrections for backward scattering of electrons from the detector surface. The resulting emission statistics, i.e., the number distribution of emitted electrons, are not described by a Poisson distribution at all. They are quite well described by a Pólya distribution. We have determined the Polya parameters μ, i.e., an equivalent to the average emission yield γ, and b, i.e., a variance parameter, via the least square fitting of the emission statistics to the Pólya distribution. If the sum rule is valid for the secondary electron emission associated with a cluster ion impact, the reduced average emission yield γ_R, i.e., γ or μ divided by the cluster size n, should be proportional to the velocity of cluster ion v with the threshold velocity v_{TH}. However, the sum rule seems to be valid only for the cluster ions Cu_n^+ with $n \geq 9$, resulting the threshold velocity v_{th} as 3.4×10^6 [cm/sec]. We have examined the correlation between b and γ, which was suggested in the recent study for polyatomic molecular impacts [14]. In the present study, b decreases monotonically with an increase of γ for small-sized cluster impacts as expected while it has no correlation with γ for large-sized clusters. However, a strong correlation has been found between b and γ_R. At first, b decreases rapidly down to its minimum, i.e., 0, with an increase of γ_R. Then, it begins to increase slowly. The minimum is achieved for the cluster size 9, i.e., one of the magic numbers for single-charged metal cluster cation. It may be thought that the Pólya parameter b is closely related with the structural stability of bombarding cluster. Whether the geometrical structure or the electrical structure is responsible for the observed tendency is open for further study.

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