Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Number distribution of emitted electrons by MeV H^+ impact on carbon

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ARTICLE INFO

Article history:
Received 16 July 2016
Received in revised form 28 January 2017
Accepted 15 February 2017
Available online xxxx

Keywords:
Secondary electron
Emission statistics
Energy loss

ABSTRACT

The statistical distributions of the number of the forward- and backward-emitted secondary electrons (SE's) from a thin carbon foil have been measured in coincidence with foil-transmitted H^+ ions of 0.5–3.0 MeV in every 0.5 MeV step. The measured SE energy spectra were fitted by assuming a Pólya distribution for the simultaneous *n*-SE emission probabilities. For our previous data with a couple of the carbon foils with different thicknesses, a similar analysis has been carried out. As a result, it was found that the measured spectra could be reproduced as well as by an analysis without placing any restriction on the emission probabilities both for the forward and backward SE emission. The obtained *b*-parameter of the Pólya distribution, which is a measure of the deviation from a Poisson distribution due to the cascade multiplication by high energy internal SE's, increases monotonically with the incident energy of proton beams. On the other hand, a clear foil-thickness dependence is not observed for the *b*-parameter. A theoretical model which could reproduced the magnitude of the b-parameter for the SE energy spectra obtained with thick Au, Cu and Al targets is found to overestimates our values for thin carbon foils significantly. Another model calculation is found to reproduce our b-values very well.

1. Introduction

Kinetic emission of secondary electrons (SE's) from solid surfaces under fast ion bombardments has been studied intensively for a long time [1,2]. It is well known that the kinetic SE emission can be described by the following three-step model; (1) the creation of excited electrons via collisions of projectiles with target atoms in the solid, (2) the transport of liberated electrons through the bulk to the surface including higher order ionizations by high energy internal SE's, (3) there is the transmission through the exit-surface potential barrier [3]. As far as the proton-incidence on carbon foils of several to 10 $\mu g/cm^2$ in thickness is concerned, it is experimentally certified that the SE yields (i.e. the average number of the emitted electrons per projectile) is proportional to the electronic stopping power S_e over a wide energy range from 0.02 to 10 MeV [4].

Besides the conventional current measurement, the measurement of the emission statistics is an alternative method to measure the SE yields. This method can also determine the probability of *n* SE emission and was firstly employed by Krebs [5]. Then, it has been applied to the basic research on ion-surface interactions [6–8]. Up to now, the emission statistics has been discussed from a view point of the deviation from a Poisson distribution or of a description of a Pólya distribution [6,9–12]. Benka et al. have measured the distribution of the number of emitted SE for MeV H^+- and He^{2+}-ion impact on Au, Cu and Al targets [13]. Based on a simplified theoretical picture, they could explain that the *b*-parameter of the Pólya distribution is responsible for the cascade process of the high energy SE's in the target. Using a thick Au target, Itoh et al. have carried out a similar experiment with several kinds of atomic and molecular ions in the energy range 0.3–2.0 MeV and analyzed their data assuming a Pólya distribution [14]. They have found that the *b*-parameter is roughly proportional to the SE yields, that is the average number of emitted SE's per projectile. This trend is also compatible with the theoretical consideration by Benka et al. [13]. Thus, several authors have analyzed their data of the SE emission statistics assuming a Pólya distribution for the probabilities of simultaneous *n*-SE emission. To our knowledge, however, this kind of analysis has been carried out only for the backward SE emission obtained with thick targets where incident ions completely stopped. As for the emission statistics data with thin target foils where projectiles penetrate, the comparison with a Pólya distribution has not been reported yet.

In the present work, the SE emission in the forward and the backward directions has been measured with a thin carbon foil

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http://dx.doi.org/10.1016/j.nimb.2017.02.023
0168-583X/

Please cite this article in press as: H. Ogawa et al., Number distribution of emitted electrons by MeV H^+ impact on carbon, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.02.023

in coincidence with foil transmitted protons of 0.5–3.0 MeV. Together with the previously measured ones with a couple of thin carbon foils with different thickness [15,16], the data were analyzed assuming a Pólya distribution for the simultaneous n-SE emission probabilities. Since the number of the projectiles were measured directly in our experiment, the probability of no SE emission, and hence the SE yields could determined unambiguously. This means that an adjustable one in a Pólya distribution is only the b-parameter. The observed behavior of the b-parameter is discussed.

2. Experiment

The experiment was performed using 0.5–3.0 MeV H^+ ions obtained with a 1.7-MV tandem Van de Graaff accelerator at Nara Women's University. The beam was transported to a target carbon foil using the method described in our previous papers [17,18]. The incident beam was collimated with a couple of diaphragms of 0.5 mm in diameter and 224 cm apart. A baffle of 1.5 mm in diameter was placed about 5 cm behind the second diaphragm to prevent edge-scattered particles from hitting the target. In the measurement of the statistical distribution, the target foil was placed 7 cm behind the baffle and tilted by 45° relative to the normal angle of incidence. The foil was floated at a potential of −30 kV. The emitted electrons were accelerated to a grounded electrode that was parallel to the foil and 40 mm away. At the grounded electrode a solid-state Si detector (SSD) of 100 mm^2 sensitive area faced the target foil. The thickness of the carbon target foil was determined by measuring the transmitted fraction of 2.5 MeV H^0, while accounting for the electron loss and capture cross sections involved [17]. The thickness of the present carbon was found to be 4.2 ± 0.1 μg/cm^2. This value is that tilted by 45° from the normal to the surface and is $\sqrt{2}$ times of that for the normal incidence. The foil-transmitted projectiles were detected by a Si photo diode(PD) of 800 mm^2 sensitive area. The signals of the forward- and backward-emitted electrons were stored simultaneously together with the projectiles with a digitizer. The counting rate of projectiles at the PD was kept to be 200 ∼ 300 cps. The data acquisition of emitted SE's was continued until the total number of the foil-transmitted projectiles amounted to $\sim 2 \times 10^6$ counts for each incident energy.

3. Data analysis

Fig. 1 denotes a typical energy spectra of SE's detected by the SSD. The position of each peak corresponds to the energy of 30n keV, where n represents the number of SE's simultaneously emitted from the foil per projectile. This spectrum can be expressed by the following equation,

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

where Y_n and $F_n(E)$ denote the total events and the normalized energy distribution of simultaneously detected n SE's, respectively. $F_n(E)$ is expressed by the superposition of $n+1$ Gaussian functions corresponding to the number of SE's reflected at the detector surface [6]. At the first step, the measured energy spectra were fitted with Eq. (1) without placing any restriction on Y_n's. In this process, all of the parameters such as the energy resolution of the SSD, the position of the first peak, the interval of adjacent peaks and so forth were adjusted carefully and the values of Y_n's were determined. In the present analysis, the maximum number of simultaneously emitted SE's observed in the spectra, $n_{\max}$, ranged from 15 to 19. As a results, the SE yields, μ, could be given as,

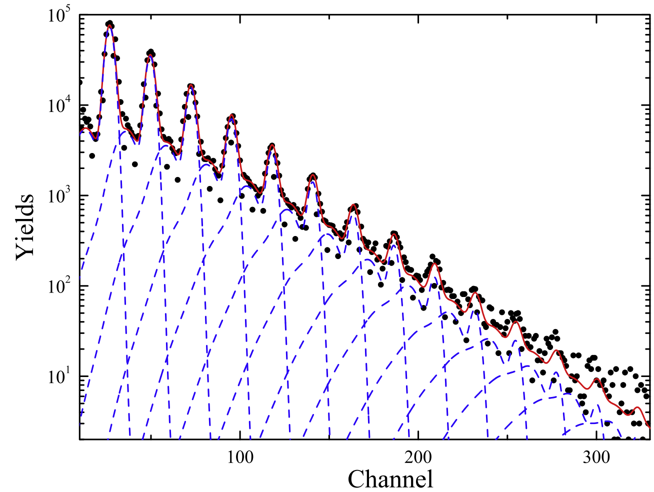

Fig. 1. A typical energy spectrum of the electron detected by the SSD. The circles represent the experimental data and a solid curves gives the fitted result with Eq. (1), where Y_n's are assumed to be proportional to a Pólya distribution given by Eq. (3). Dashed Curves represent the contribution from each$Y_n F_n(E)$ shown in Eq. (1).

$$\mu = \sum_{n=1}^{n_{\max}} n P_n \text{ with } P_n = Y_n/N, \tag{2}$$

where N and P_n denote the total number of incident particles and the probability of simultaneous emission of n SE's. This analysis is referred to as 'Free Analysis', hereafter.

At the next step, each value of Y_n was assumed to be proportional to a Pólya distribution given by

$$P_n(\mu, b) = \frac{\mu^n}{n!}(1 + b\mu)^{-n-1/b} \prod_{i=1}^{n} [1 + (i-1)b], \tag{3}$$

where μ is the mean value of emitted electrons, that is the SE yields, and b is a measure for the deviation from a Poisson distribution due to the cascade multiplication of high energy internal SE's in the target. In this connection, for the case of $b = 0$, the Pólya distribution becomes a Poisson distribution. Since the SE yields μ and all of the parameters in $F_n(E)$ were determined at the first step, the only adjustable parameter, b, was determined by the least squares fitting of $S(E)$ to the measured energy spectrum of SE. In Fig. 1, the circles represent the experimental data and a solid curve is the fitted ones assuming a Pólya distribution for Y_n's. Dashed curves represent the contribution from each $Y_n F_n(E)$. This analysis is referred to as 'Pólya Analysis', hereafter. In addition to the present data, we have carried out the Pólya Analysis for the SE energy spectra obtained from our previous measurements, where proton beams of 0.5–3.5 MeV and a couple of thin carbon foils were employed. Their thicknesses 45°-tilted from the normal to the foil surface were 2.7 ± 0.1 and 3.5 ± 0.1 μg/cm^2 [15,16].

Fig. 2 represents the ratio of χ^2 of the least squares fitting with Eq. (1) for the Pólya Analysis to that for the Free Analysis. Circles, triangles and squares represent the values for the target foils of 4.2, 3.5 and 2.7 μg/cm^2, respectively. Solid and open marks are for the forward and backward spectra, respectively. As is clear from this figure, the Pólya Analysis can reproduce the measured energy spectra both in the forward and backward direction with a same degree as the Free Analysis.

4. Results and discussion

Figs. 3(a) and (b) represents the simultaneous n-SE emission probabilities, P_n's, determined by the Free and the Pólya Analysis for the spectra measured with the carbon foils of 4.2 μg/cm^2 in

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