Slow highly charged ion O^{4+} induced electron emission from clean solid surfaces*

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Abstract The total electron emission yields following the interaction of slow highly charged ions (SHCI) O^{4+} with different material surfaces (W, Au, Si and SiO_2) have been measured. It is found that the electron emission yield γ increases proportionally with the projectile velocity v ranging from 5.36×10^5m/s to 10.7×10^5m/s. The total emission yield is dependent on the target materials, and it turns out to follow the relationship $\gamma(\mathrm{Au}) > \gamma(\mathrm{Si}) > \gamma(\mathrm{W})$. The result shows that the electron emission yields are mainly determined by the electron stopping power of the target when the projectile potential energy is taken as a constant, which is in good agreement with the former studies.

Key words Slow highly charged ion (SHCI), electron emission, electron stopping power

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1 Introduction

A slow highly charged ion (SHCI) carries a large amount of potential energy when its initial velocity is relatively small, where "slow" means the velocity is less than the Bohr velocity ($v_{\mathrm{Bohr}}=2.19\times10^6$m/s). When a SHCI impacts on a solid surface, tens to hundreds keV of potential energy can be deposited into the solid surface layers within a nanometer depth in 5 to 10 fs, and the energy power density can reach to 10^{14} W/cm^2 which would create the defects in the size of the nanometer order. These new features had attracted a lot of attention of many well-known laboratories in the world. Slow electron, projectile and target particle can be ejected in SHCI-surface interaction, and X-ray and the visible light can also be detected. Since electron emission (EE) always occurs whenever ions interact with matter, the knowledge of electron yields as well as their energy and angular distributions are of major importance in a variety of research fields, such as radiation physics, chemistry, biology, plasma-wall interactions, and surface analysis [1—5].

Ion-induced electron emission can be used to investigate the basic features of charged-particle interactions with condensed matter. Since only a very small amount of momentum is transferred from the target electrons to the projectile, no backscattering of projectiles by the target electrons has to be considered. However, EE has to be taken into account whenever it is necessary to obtain the rate of charged particles by measuring their associated charge current. Thus, precise data of EE yields as well as a shortcut calculation of the EE yields are important for ion-beam experiments in atomic and nuclear physics, especially in material modification and anal-

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ysis.

A few experiments about the electron emission from solid targets by SHCI had been reported before [6—9]. It's found that EE from a solid surface under the bombardment of SHCIs may be caused by two essentially different mechanisms [10, 11], which are Potential emission(PE) and Kinetic emission(KE). PE results from the interaction of empty projectile states with the surface valence-band states, and the PE contributions from Auger neutralization, Auger deexcitation after resonance neutralization, and autoionization after multiple resonance captures for multiply charged ions can be specified. On the other hand, KE is initiated in close encounters between the incident ions and target particles when the kinetic energy of the projectile is dissipated to the target electrons and caused the slow electrons to be emitted from the target. KE can only proceed beyond a certain threshold incident velocity of typically 10^5 m/s.

A common observable in EE is the statistical electron emission yield γ, which is defined as the average number of electrons emitted per projectile. The PE and KE processes are considered to be independent, so the total electron emission yieldsγ for both processes is given by

$$\gamma = \gamma(S_\mathrm{e}) + \gamma(E_P) \ . \tag{1}$$

where $\gamma(S_\mathrm{e})$ is KE yield, $\gamma(E_P)$ is PE yield, S_e is the electron stopping power, and E_P is the potential energy of projectile ions. It should be mentioned that in the most popular theoretical models[12, 13] , the EE yield γ is considered to be proportional to the electronic stopping power $S_\mathrm{e} = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_\mathrm{e}$, where $\mathrm{d}E$ is the energy loss spent in electronic processes per unit path length $\mathrm{d}x$. This leads to a general relationship

$$\gamma = B\frac{S_\mathrm{e}}{\cos\theta} \ . \tag{2}$$

Where, θ is the incident angle of the projectile relative to the surface normal (0° in our case), and B is a factor which depends on the depth distribution, the energy distribution, and the escape probability of electrons from the solid[9].

For proton bombardment, it has been confirmed experimentally that $B = \gamma/S_\mathrm{e}$ was roughly a constant within about 10% accuracy in the wide projectile energy range of 10 keV/u to 24 MeV/u[10, 14] for various targets. As for heavy ions(HI) bombardment, deviations from the simple rule $B = \gamma/S_\mathrm{e}$ have been observed, especially at low incident velocities[15, 16]. It's reported that B increased with decreasing v at $v^2/2 < 25$ keV/u[15].

The most important purpose of this work was to measure the EE yields from different solid surfaces (Si, W, Au and SiO_2) bombarded by the O^{+4} ions at different velocities, and to test whether the theoretically predicted and experimentally confirmed Eq. (2) is also valid for heavy ion bombardment at lower incident velocities. In this case, the yield induced by the projectile potential energy deposition can be taken as a constant[17], thus, the factor B, i.e. the ratio of EE yields to electron stopping power for various target materials can be obtained.

2 Experimental setup

The ion beams were provided by the 14.5 GHz electron cyclotron resonance (ECR) ion source at the national laboratory of Heavy Ion Research Facility in Lanzhou (HIRFL). A plenty of experiments on SHCI-surfaces interactions have been performed on this platform[6, 17, 18]. In the present experiment, the ion beams of O^{4+} with a current of a few tens of nA were focused and collimated to a diameter of about 3 mm, and impacted vertically onto the surfaces of W, Au, Si and SiO_2 respectively. The target surface area was 19×24 mm^2 and the base vacuum in the chamber was kept in the order of 10^{-8} mbar.

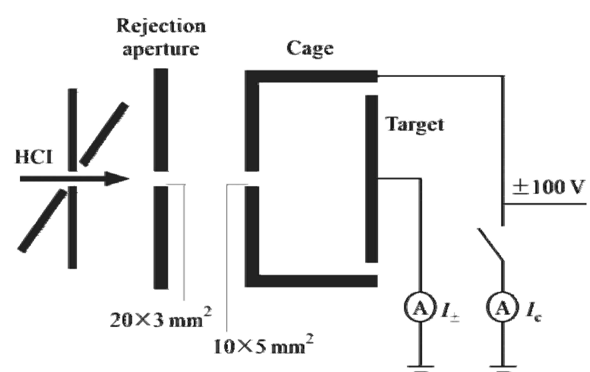

Fig. 1. Schematic diagram of experimental setup used to measure electron yields at HIRFL.

The apparatus adopted to measure the electron yields is shown schematically in Fig. 1. The ion beams were collimate by a rejection aperture (20×3 mm^2), then passed through the left window (10×5 mm^2) of a cage which worked as a Faraday cup, and finally arrived on the target surface where the electron emission took place. The outgoing electrons were collected by the cage. The cage current I_c was almost zero under the condition that the cage was at zero voltage if the incoming ions were well collimated.

Our measurement followed two steps. In the first measurement, the cage was biased to a positive voltage of +100 V so as to accelerate the secondary electrons toward the cage. Under this condition, the target current I_+ is the sum of the projectile beam current I_i and the electron emission current I_e. This leads to[9]

$$I_+ = I_i + I_e = I_i + \gamma(I_i/q) \ , \tag{3}$$

where γ is the EE yield per incident ion and q is the charge state of the projectile ions. In the second measurement, the cage was biased to a negative voltage of −100 V. Since the abundance of emitted electrons with energy higher than 50 eV is negligibly small, almost all of the emitted electrons were suppressed by the negative voltage and returned back to the target surface. The target current I_- is the sum of the projectile beam current and the sputtering ions current. Since the yield of the sputtering ions is at least three orders less than the EE yield and negligible, we can consider I_- as the projectile beam current I_i approximatively. Therefore, the EE yield γ is given by

$$\gamma = \frac{I_+ - I_-}{I_-/q} \ , \tag{4}$$

and the electron yields can thus be obtained.

3 Results and discussion

The total electron emission yields for different target surfaces as a function of impact velocity were shown in Fig. 2. The targets include gold (Au), tungsten (W), silicon (Si) and silicon dioxide (SiO_2). The velocities of the incident O^{4+} ions ranged from 5.36×10^5 m/s to 10.7×10^5 m/s, which correspond to projectile kinetic energies ranging from 6 keV/ion to 24 keV/ion.

Figure 2 shows that the electron yields increase with the increasing projectile velocity v and are roughly proportional to v in the velocity range of our experiments (5.36×10^5 m/s $< v <$ 10.7×10^5 m/s). The EE yields are highest for Au followed by W, Si and SiO_2, that is $\gamma(\mathrm{Au}) > \gamma(\mathrm{W}) \sim \gamma(\mathrm{Si}) > \gamma(\mathrm{SiO_2})$, and the slope of the EE yields verse velocity is also highest for Au followed by W, Si and SiO_2. A slightly larger electron yield for W surface than that for Si surface is observed. For SiO_2, the electron yields are nearly zero (even a bit smaller than zero) in our experiments. However, in Ref. [7], the measured yields was about 10 e^-/ion for the same target SiO_2 and almost the same projectile kinetic energy and charge state. We notice that in the experiments of Ref. [7], the target surfaces were biased to a voltage of −2 kV to favor the detection of emitting electrons, while the target surfaces in our experiments were earthed. Our results demonstrate that the electron emission yield from an insulator surface is about the same as (even slightly less than) the sputtering yield from the insulator surface.

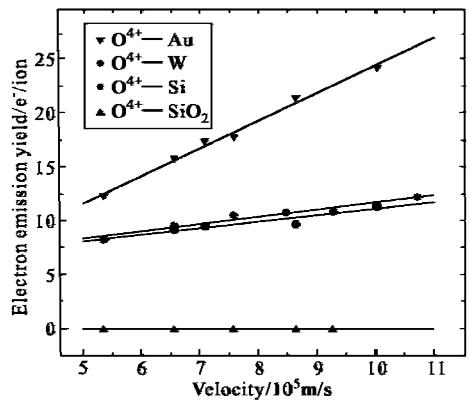

Fig. 2. Total electron emission yields γ for impact of O^{4+} on clean surface of Au, W, Si and SiO_2 vs impact velocity v.

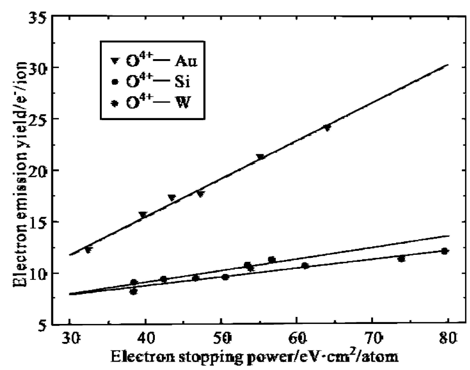

Fig. 3. Total electron emission yields γ for impact of O^{4+}on clean surface of Au, W, and Si surface vs electron stopping power of incident ions, which was calculated from TRIM 2003.

Figure 3 shows the electron emission yields γ for the bombardment of the O^{4+} ions on clean Au, W, and Si surfaces as a function of the electron stopping power S_e which was calculated by TRIM 2003. The results in Fig. 3 indicate that the electron yields are proportional to electron stopping power, as implies that for a given target, the slope B is indeed a constant for heavy ions at lower incident velocities. This is in good agreement with the previous studies in different energy ranges[10, 19]. The values of slope B for the Au, W, and Si targets were deduced and illustrated in Table 1.

Table 1. The value of B for different targets.

	Au	Si	W
$B/\mathrm{e}^-\cdot\mathrm{atom}/(\mathrm{ion}\cdot\mathrm{cm}^2\cdot\mathrm{eV})$	0.37	0.11	0.09
error	3.1%	1.4%	3.9%

Our results indicate that the relation $B=\gamma/S_\mathrm{e}=$ const also holds for heavy ion projectiles at low incident velocities within a uncertainty less than 4%. Unlike the result of the proton bombardment, the value of B for heavy ion bombardment depends on the atomic number of a target Z_T and it follows the relationship $B(\mathrm{Au}) > B(\mathrm{Si}) > B(\mathrm{W})$ for the Au, W, and Si targets.

4 Conclusions

The electron emission yield in the interactions of slow and highly charged ions with solid surface is due to both potential electron emission and kinetic electron emission. In this paper, we compared the electron emission yields from a series of materials by projectile O^{4+} with different kinetic energies. The results showed a linear dependence of the total yield on the projectile velocity. Further investigations showed that, γ are indeed proportional to S_e, and therefore the results confirmed the validity of the Eg. (2). It was also found that the value of B for heavy ion bombardment depends on the type of targets (see Table 1). The values of B for the Au, W, and Si targets turn out to fulfill the relationship $B(\mathrm{Au})>B(\mathrm{Si})>B(\mathrm{W})$.

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References

1 Aumayr F, Winter H P. Surf. Sci. Nanotech., 2003, **1**: 171

2 Takahashi S, Tona M. Nucl. Instrum. Methods B, 2005, **235**: 456

3 Baragiola R A, Dukes C A. Phys. Rev. Lett., 1996, **76**: 2547

4 Schenkel T, Hamza A V, Barnes A V et al. Progr. Surf. Sci., 1999, **61**: 23

5 Minniti M, Commisso M, Sindona A et al. Phys. Rev. B, 2007, **75**: 045424

6 WANG Yu-Yu, ZHAO Yong-Tao, XIAO Guo-Qing et al. Acta Phys. Sin., 2006, **55**: 673 (in Chinese)

7 McDonald J W, Schenkel T, Hamza A V et al. Nucl. Instrum. Methdos B, 2005, **240**: 829

8 Aumayr F, Winter H P. Nucl. Instrum. Methdos B, 2005, **233**: 111

9 Ritzau S M, Baragiola R A. Phys. Rev. B, 1998, **58**: 2529

10 Baragiola R A, Alonso E V, Oliva-Florio A et al. Phys. Rev. B,1979, **19**: 121

11 Stöckl J, Suta T, Ditroi F et al. Phys. Rev. Lett., 2004, **93**: 263201

12 Sternglass E J. Phys. Rev., 1957, **108**: 1

13 Schou J. Phys. Rev. B, 1980, **22**: 2141

14 Clouvas A, Rothard H, Burhard M et al. Phys. Rev. B, 1989, **39**: 6316

15 Rothard H, Kroneberger K, Clouvas A et al. Phys. Rev. A, 1990, **41**: 2521

16 Rothard H, Kroneberger K, Veje E et al. Phys. Rev. B, 1990, **41**: 3959

17 WANG Yu-Yu, ZHAO Yong-Tao, Qayyum A et al. in press, doi:10.1016/j.nimb.2007.09.047

18 XIAO Guo-Qing, ZHAO Yong-Tao, ZHANG Xiao-An et al. 16th International Workshop on Inelastic Ion-Surface Collisions(IISC-16), Austria, 2006. 138

19 Allegrini F, Wimmer-Schweingruber R F, Wurz P et al. Nucl. Instrum. Methods B, 2003, **211**: 487