X-ray emission in slow highly charged ion-surface collisions

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Abstract. X-rays emitted in the collisions of highly charged ions with a surface have been measured to investigate dissipation schemes of their potential energies. While 8.1\% of the potential energy was dissipated in the collisions of He-like I ions with a W surface, 29.1\% has been dissipated in the case of He-like Bi ions. The x-ray emissions play significant roles in the dissipation of the potential energies in the interaction of highly charged heavy ions with the surface.

1. Introduction

When a slow highly charged ion approaches a surface, a lot of electrons are captured into highly excited states of the ion, leading to the formation of a hollow atom. Such high Rydberg electrons are peeled off at the time the ion reaches the surface. Below the surface the ion captures electrons into lower excited states and becomes a more compact hollow atom. In the interaction of highly charged ions, the potential energies of the ions dissipate through several processes such as secondary particle and photon emissions and, in part, excitations of the solid.

Recently the potential energy dissipation has been measured quantitatively. Schenkel \textit{et al.} \cite{1} measured the energy dissipation into the solid, in which they irradiated a Si solid state detector with Ne-like Au and He-like Xe ions and measured pulse height signals from the detector. They showed that approximately 35\% and 40\% of the potential energy of Ne-like Au and He-like Xe ions, respectively, were traced in excitations to produce electron-hole pairs more than 50 nm deep inside of the detector. Kentsch \textit{et al.} \cite{2} also reported that from 30\% to 40\% of the potential energy was converted into heat in a Cu target for highly charged Ar ions with charge states up to 9. Recently we measured the energy dissipation through x-ray emissions \cite{3}. Highly charged I ions with the charge state \(q\) from 34 to 53 were used, which were incident on a hydrogen terminated Si surface. It was shown that the energy dissipation was almost negligible for the ions which had only \(M\) shell vacancies (\(q \leq 43\)), while it increased with the number of \(L\) shell vacancies and reached 10\% for the He-like ion (\(q = 51\)). Moreover in the cases of H-like and bare ions approximately 30\% and 40\% of the potential energy, respectively, dissipated through x-ray emissions.
The energy dissipation is closely related to the fluorescence yields in connection with radiative and Auger transition rates of the highly charged ions. Therefore it can be considered that the dissipation mode should depend strongly not only on $q$ with the different electron configuration but also on the atomic number $Z$. From the previous experiments 40% of the potential energy dissipated in the solid-state excitations for He-like Xe ions ($Z = 54$) [1], and 10% through x-ray emissions for He-like I ions ($Z = 53$) [3]. We have measured x-ray emission yields and the potential energy dissipation through x-ray emissions for the ions with higher $Z$ to investigate the importance of x-ray emissions to the potential energy dissipation of high $Z$ highly charged ions colliding with a surface.

2. Experiment
The experimental set up was the same as the previous experiment [3]. An electron beam ion trap (EBIT) at the University of Electro-Communications [4] was used to produce highly charged ions. He-like I ($Z = 53$) and He-like Bi ($Z = 83$) ions were used as projectiles, which were incident on a W surface with the kinetic energy of $q \times 3.5$ keV. The emitted x-rays were detected with a Si(Li) solid state detector. The energy scale of the detector was calibrated with the lines from radioisotopes of $^{241}$Am and $^{55}$Fe. The detection efficiency was considered to be 100% between 2 keV and 20 keV. Above 20 keV, the efficiency was calibrated by comparing the intensity of Bremsstrahlung spectra produced by a 63 keV electron beam in the EBIT with that by a Ge detector whose detection efficiency was 100% in this energy range. Between 1 keV and 2 keV, the efficiency was estimated from the transmission coefficient of the Be window (8 μm thickness) of the detector. Below 1 keV the obtained signals were truncated, because of the transmission of the Be window. A burst signal due to the secondary electrons emitted at a single highly charged ion collision was counted with an annular-type micro-channel plate located in front of the target, which made the detection of the collision events with 100% efficiency possible [5]. The number of counted signals was used for the normalization of the x-ray signals and an individual signal was also used to gate the x-ray signals to eliminate noise from the detector system.

3. Results and discussion
Figures 1 and 2 are the x-ray spectra in collisions of He-like I and Bi ions with the W surface, respectively. The x-ray counts were corrected by the detector efficiency and the observation solid angle, and normalized to the number of the ion incidences. The counts were also normalized to the x-ray energy width corresponding to one channel of the multi-channel analyzer used in the measurement.

In the spectrum of He-like I ions in Fig. 1, the two peaks between 3.6 keV to 9 keV are $L$ x-rays. The peak at the lower energy corresponds to $L$-ray transitions from $n = 3$ to $n = 2$ and that at the higher energy to be a mixture of transitions from $n \geq 4$ to $n = 2$. The x-rays below 3.6 keV are $M$ x-rays, which are the transitions to $n = 3$ from $n \geq 4$. On the other hand the spectrum of He-like Bi ions in Fig. 2 is quite different from that of He-like I ions and shows a similar structure to that of He-like U ions incident on an Au surface [6]. The x-rays above 11 keV are $L$-rays, where in the rough structure three peaks are seen. The peak around 12 keV is $L_\alpha$ and that around 14 keV $L_\beta$. The x-rays above 16 keV are the transitions from $n \geq 5$ to $n = 2$. The x-rays between 2.3 keV and 11 keV are mainly due to $M$ x-ray transitions. In this region two peaks are observed at 8.4 keV and 9.7 keV, which correspond to $L_\alpha$ and $L_\beta$ of the target W atoms. These are the so-called fluorescence x-rays emitted from W atoms which absorb $L$ x-rays of Bi ions.

From the spectra, the numbers of the $L$ and $M$ x-ray photons per ion incidence, which were namely x-ray emission yields, were obtained. In the case of the He-like I ions, the $L$ x-ray emission yield is $1.58 \pm 0.16$ and the $M$ x-ray yield $0.38 \pm 0.04$. These results can be compared with the result of the previous experiment in which hydrogen terminated Si was used as a target [3]. In
Figure 1. X-ray spectrum obtained in collisions of He-like I ions with the W target, where the intensity is photon counts emitted into a full solid angle by an incident ion per unit x-ray energy width (keV).

Figure 2. X-ray spectrum obtained in collisions of He-like Bi ions with the W target, where the intensity is photon counts emitted into a full solid angle by an incident ion per unit x-ray energy width (keV).

the previous experiment, the x-ray emission yield of $M$ x-ray was $0.34 \pm 0.03$ and that of $L$ x-ray was $1.90 \pm 0.13$. In comparison, for the present results obtained with a metal target, the x-ray emission yield of $M$ x-ray is larger and that of $L$ x-ray is smaller than the previous results with
a semiconductor target. For the Bi ions on the W target the x-ray emission yield of $L$ x-ray was $5.54 \pm 0.57$ and that of $M$ x-ray $3.62 \pm 0.37$. These are much larger than the results for the I ions. Since the numbers of $L$ shell and $M$ shell vacancies of He-like ions are 8 and 18, respectively, 69% of $L$ and 20% of $M$ shell vacancies were filled through x-ray transitions in the case of Bi projectiles, while 20% of $L$ shell and 2.1% of $M$ shell were filled in the case of I projectiles. The present measurements show that the radiative decay rate of the hollow atoms would increase significantly with $Z$.

The potential energy of a highly charged ion is the sum of binding energies of the electrons which have been removed during ionization. The potential energy of He-like I ions is calculated to be 112 keV, while that of He-like Bi ions is 363 keV [7]. From the spectra in Figs. 1 and 2, the potential energies dissipated through x-ray emissions were obtained. In the case of the I ions, the dissipation was $9.1 \pm 0.6$ keV, which was 8.1% of the potential energy. This value is slightly smaller than that for the hydrogen terminated Si target (11.0 ± 0.7 keV) [3]. On the other hand, in the case of the Bi ions the dissipation amounted to 105.5 ± 9.1 keV, which reached 29.1% of the potential energy. As described before, we have observed that 30% and 40% of the potential energy were dissipated through x-ray emissions for bare and H-like I ions, and only 10% for He-like I ions [3]. In the present experiment, even for He-like ions, about 30% of the potential energy was dissipated through x-ray emissions. Therefore it can be concluded that for heavy $Z$ projectiles the radiative decay is a significant process in the hollow atoms produced in highly charged ion-surface collisions.

4. Conclusion
X-ray spectra have been measured in collisions of He-like I and Bi ions on a W surface. 8.1% and 29.1% of the potential energy were dissipated through x-ray emissions for He-like I and Bi ions, respectively. In particular, about 70% of the $L$ shell vacancies were filled through x-ray emissions in the case of He-like Bi ions. The x-ray emissions play significant roles in the decay of hollow atoms produced in ion-surface collisions.

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