Binary encounter peaks for 0° electrons in collisions of 0.8 MeV/amu Bi^{q+} with H_2 and He

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The binary encounter electrons produced in 0.8 MeV/amu Bi^{q+} on H_2 and He collisions were measured at zero degrees with respect to the beam direction. The incident projectile charge (q_i) dependence of intensity of the binary encounter electrons in the region of $q_i/Z_1 < 0.4$, Z_1 being the projectile atomic number, was measured. In the case of a heavy projectile and in this q_i region, the intensity of the binary encounter electrons increases as q_i increases. The peak energy shift of the binary encounter electrons is explained by the Bohr-Lindhard model.

Introduction

Ejected electrons from energetic ion-atom collisions have been studied to study the collision mechanism and the electronic structure of the ions.[1] In the ejected electron spectra from the energetic ion-atom collisions observed at 0°, three kinds of peaks are observed;[1] (1) the cusp peak, (2) the binary encounter peak, and (3) Auger peaks from projectile ions and target. The cusp peak electrons have the same velocity of the projectile ions. Auger electrons are ejected by the decay process of the doubly excited ions excited by energetic collisions. Binary encounter electrons are target electrons ionized through direct, hard collisions with energetic projectiles. Usually, binary encounter electrons have the highest energy in the ejected electrons from energetic ion-atom collisions. Using elastic two-body collision dynamics for heavy-ion impact on a free electron, the energy of the recoiling electron can be shown to equal $4 \times E_p \times (m/M) \times \cos^2\theta$ and is known as the binary encounter electron peak energy, where E_p is the projectile ion energy and m the electron mass, M the projectile ion mass, and θ the observation angle with respect to the beam direction.

In the collisions of the bare projectile ions on H_2 and He, the cross sections of the binary encounter electrons measured at 0° have been confirmed by Lee *et al.* to be scaled by q_i^2 (q_i is the incident charge). This means that the collisions involve only "quasi-free" electrons which have an initial momentum distribution due to their orbital motion around the target nucleus.[2] The momentum distribution of the active electron gives rise to broadening of the binary encounter electron peak and the quasi-free nature of the electron results in a small shift of the peak to energies lower than $E_b = 4 \times E_p \times (m/M)$. Lee *et al.* showed that these effects influenced the binary encounter electrons peak.[2]

The dependence of the binary encounter peaks of the projectile charge state for partially stripped ions was measured at zero degrees by using light projectile ions (F and Si).[2,3] Their results are (1) the "anomalous" charge-state dependence of the binary encounter electron production cross section (the cross section increases with the decreasing incident charge state),[2,3] and (2) the peak energy shift dependence on the incident projectile charge state.[3] These are explained by the outer screening of the projectile electrons and the effect of the electron bound to the target, respectively.[2,3]

At RIKEN, We study the binary encounter peaks in the collision between a heavy ion and a target, to study the effect of a partially stripped heavy ion on the binary encounter peaks. We used the Bi ions as the heavy projectile ions. Here, we present the charge-state dependence on the binary encounter peaks in collisions of 0.8 MeV/amu Bi^{q+} on H_2 and He measured at zero degrees, in the region of $q_i/Z_1 < 0.4$.

Experiment and Discussion

The beams of 0.8 MeV/amu $Bi^{10+,14+,32+}$ from RILAC were magnetically analyzed, collimated by two sets of four-jaw slits system and focused on a target gas cell. The target gas cell was 5 cm in length. Ejected electrons were measured at zero-

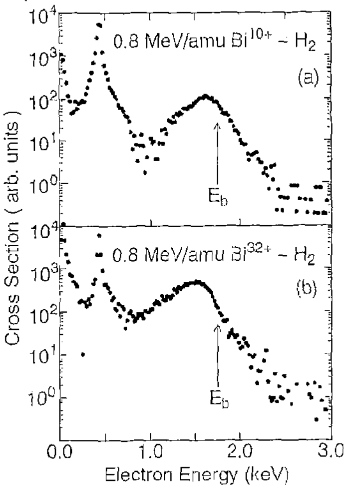

Fig. 1. Measured binary encounter electron spectra. E_b indicates the energy position of the binary peaks for the free electron target. (a) For Bi^{10+}-H_2 system, (b) For Bi^{32+}-H_2 system.

degrees respect to the beam direction. The spectrometer was a tandem type electron spectrometer with two 45° parallel-plate electrostatic analyzers. Zero-degrees electron spectra for 0.8 MeV/amu $Bi^{10+,32+}$ on H_2 are shown in Fig. 1. Two clear peaks in the figures can be found; one is the cusp peak around 440 eV and another the binary encounter peak around 1650 eV. In our collision condition, we cannot observe Auger electrons from Bi ions, because of the very small intensity of Auger peaks. The binary encounter peak intensity increases and the peak energy decreases as the incident charge state increases. The peak energy is changed with changing q_i and targets. The peak energy shift values are tabulated in Table 1.

Table 1. Binary encounter peak shift for 0.8 MeV/amu Bi ions on H_2 and He target.

	peak shift (eV)			
projectile	H_2		He	
	exp	Bohr-Lindhard	exp	Bohr-Lindhard
Bi^{10+}	136±20	172	216±40	239
Bi^{14+}	132±20	203	212±40	283
Bi^{32+}	220±30	308	300±40	427

The incident charge dependence of the binary encounter electron peak intensity for Bi^{q+}-H_2 is shown in Fig. 2. The intensity is normalized by that for Bi^{10+}. The q_i^2 dependence is indicated as the broken line in Fig. 2. In our collision system and the collision energy, the incident charge state dependence of the binary encounter electron intensity is "normal"; the intensity increases as the incident charge state increases. But, the charge state dependence is not scaled by q_i^2. This is completely different from the fully stripped ions. We estimated the double differential cross section of binary peaks of bare projectile ions by extrapolating that of He^{2+} projectile to the heavy projectile ions as shown by the dotted line in Fig. 2. The absolute double differential cross section of binary encounter electrons produced in the collisions of $Bi^{10+,14+,32+}$ ions on H_2 is strongly enhanced, compared with that of the bare projectile ions with the same charge state (10+, 14+, and 32+). The same enhancement effect was observed for the He target case. This phenomenon was also observed in lighter ion-atom collisions, and may be explained by the outer screening in the same way as for the lighter ions case.[4)]

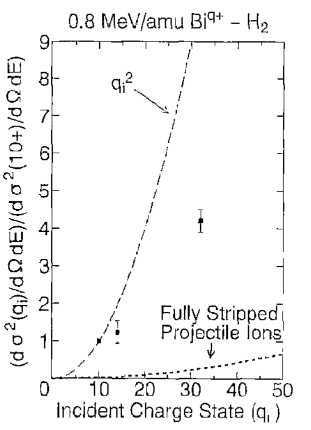

Fig. 2. Projectile incident charge state dependence of the binary encounter electron production cross section relative to Bi^{10+} ions of 0.8 MeV/amu $Bi^{10+,14+,32+}$ with H_2 target. Broken line indicates the q_i^2 dependence. Dotted line indicates the ratio between the double differential cross section of fully stripped projectile ions and Bi^{10+} ions.

The q_i dependence of the energy shift of the binary encounter peaks can be explained by the Bohr-Lindhard model.[5)] Here, we describe it briefly. In this model, there is some characteristic distance R_r (the release distance). When the projectile ions come to this distance, target electrons are released from the target atoms because of the balance between the force from the projectile ions and the binding to the target atoms. After that, released electrons collide with the projectile ions as free electrons. Based on this model, the energy shift ΔE_b from E_b is given by following;

$$\Delta E_b = 54.43 \times (q_i)^{1/2}(I_t/I_0)^{3/4}Z_2^{-1/6} \quad \text{(eV)}. \qquad (1)$$

Here, q_i is the incident charge state, I_t the ionization potential of the target, I_0 the ionization potential of a hydrogen atom, and Z_2 the target atomic number.[5)] Pedersen et al. used this formula to evaluate the energy shift for the fully stripped ions case.[5)] But, if R_r is larger than the radius of a clothed (partially stripped) projectile ion, Eq. (1) is applicable for the clothed projectile ions case.[4)] Calculated shift values ΔE_b for our collision system are also shown in Table 1. In our case, R_r for the H_2 target are $\sqrt{10}$, $\sqrt{14}$, and $\sqrt{32}$ a.u. for Bi^{10+}, Bi^{14+}, and Bi^{32+}, respectively. The radius of outer electron orbit of $Bi^{10+,14+,32+}$ ions is 1–0.5 a.u. Our assumption that R_r is larger than the radius of projectile ions is not so bad in our system.

By using heavy projectile ions, we could observe clearly the incident charge state dependence of the binary encounter peak energy and intensity. The peak shift of the binary encounter electrons comes from, mainly, the total charge of the projectile ions, because the peak shift in our measurements are qualitatively explained by the Bohr-Lindhard model.[4-6)] In case of fully stripped projectile ions, the peak intensity of the binary encounter electrons at 0° is scaled by q_i^2,[2)] and in case of clothed projectile ions that cross section is not scaled by q_i^2 and strongly enhanced, compared with the fully stripped projectile ions as shown in Fig. 2. From these experimental results, the double differential cross section of the binary encounter electrons at 0° and at the peak energy must be due to the shape of the potential produced by not only the projectile nucleus but also the electron cloud of the projectile ions.

References

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