

# Double- and single-electron transfer in $H^+ + K$ collisions from 0.3 to 4keV: Separation of direct double transfer and two-step successive single-electron transfer

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Double-electron transfer and two-step single-electron transfer in collisions of proton with potassium-metal target are measured in the collision energy from 0.3 to 4 keV by using a charge-inversion mass spectrometry. Two prominent  $H^-$  ion peaks are observed with different values of the energy loss and show different target density dependences. The peak with larger energy loss is identified as double-electron transfer and the other as two-step successive single-electron transfer from the analysis of the target density dependence. The two-step single-electron transfer is considered to occur as the process accompanying spontaneous Ly- $\alpha$  emission, followed by negative  $H^-$  formation. A theoretical analysis is also carried out, and the single-electron transfer cross section obtained is found to be in excellent agreement with the present measurement, while the present measurement for double-electron transfer is found to be much smaller than those evaluated earlier and the present theory.

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## I. INTRODUCTION

Electron transfer is one of the most fundamental and important processes occurring in ion-atom collisions and hence has attracted a vast volume of experimental as well as theoretical investigations over the years, making significant contributions to our basic understanding of atomic physics. Electron transfers in collision of proton with alkali-metal targets are important for various applications and are known to possess large cross sections in a wide energy range because of the near-resonant condition from low ionization energies of the targets [1]. Upon the collision of protons on alkali-metal targets, single- and double-electron transfer processes are possible, but the branching of these two processes and corresponding dynamics are not well studied yet. We have observed earlier that, even for relatively low-density gas targets, direct and two-step double-electron transfers resulting in  $H^-$  ion formation do take place simultaneously in a collision cell and mix [2]. Therefore, it is necessary to separate these two processes to accurately determine double-electron transfer dynamics and its cross section. However, the separation of these processes has not been carefully performed before. Furthermore, double-electron transfer is relevant to negative-ion beams in thermonuclear fusion research [3], and hence, there is of some practical importance in this study. Recently, the usefulness of alkali-metal targets for structure differentiation in a mass spectrometry was reported by one of the authors [4].

In 1987, Ebel and Salzborn [5] studied single and double transfer of protons in collisions with K and Na targets and reported cross sections for double-electron transfer which are much lower than those reported earlier by Gruebler *et al.* [6]

and Anderson *et al.* [7]. As described, accurate evaluation of cross sections for double-electron transfer requires unambiguous separation of the  $H^-$  ions produced from the two-step successive single-electron transfer. All of earlier studies [5–7] have separated these two processes only by discriminating the pressure dependence, which is not sufficiently appropriate as described more in details below.

In the present work, these two processes were separated and identified not only by using the pressure dependence but also by analysis of the energy-loss spectrum. Hence, cross sections of direct double-electron transfer and the successive two-step single-electron transfer were unambiguously identified and evaluated by using this separation technique with high precision.

Total cross sections of electron transfer for alkaline-metal-atom targets including the present system were examined by many groups [8–10]. In addition, based on experimental cross sections compiled in Ref. [9], an analytical fitting formula for these cross sections was proposed by Tabata *et al.* [11], which has been extensively employed for extrapolation and interpolation of measured data.

As far as theory is concerned, while many quantitative theoretical calculations for single-electron transfer cross sections have been reported as seen in Ref. [10], only a few simple calculations have been carried out for charge-inversion double-electron transfer [12–14]. These calculations could not explain, even qualitatively, all measured results above [15].

We report the present measurement for separation of double-electron transfer and successive two-step single-electron transfer in addition to the evaluation of a single-electron transfer process and theoretical analysis based on a molecular close-coupling method.

## II. EXPERIMENTAL SETUP

The experiment was carried out using a single-focusing mass spectrometer, which had been described in more detail previously [16]. Primary positive ions were produced by electron impact in a Nier-type ion source (IS) and enter a target chamber (TCH) in the energy range of keV region without mass analysis. Secondary negative ions were formed from positive ions by two-electron transfer with alkali-metal target existing in the 5-cm-long TCH. The alkali-metal target was supplied as vapor via an insulator from a cell which contained alkali metal by heating the cell. The absolute density of the alkali-metal vapor was estimated from the temperature of the cell and TCH using the vapor pressure curves. The relative density of alkali-metal vapor in TCH was measured using an alkali-metal monitor of a surface ionization type. Both negative ions formed in the TCH and primary positive ions were analyzed by the single-focusing mass spectrometer by changing its polarity. By using this method, the transmission of negative ions was made as in the same procedure as that of positive ions. The magnet has a  $90^\circ$  bending angle and a 200-mm ion orbital radius.

The mass-analyzed positive and negative ions were detected by a channel-type secondary electron multiplier (SEM). To successfully detect both positive and negative ions which have low kinetic energies, the entrance of the multiplier was maintained at +0.7 kV for negative ions and at -1.5 kV for positive ions. Signals passing through a high-voltage proof capacitor entered a multichannel analyzer (MCA) (Tracor Northern, TN-7200). The multiplication voltage between the entrance and exit of the electron multiplier was adjusted in the region from 3.5 to 4.5 kV, so that the pulse height of the signal was high enough in a pulse-height analysis mode of the MCA to ensure the reliability of pulse counting. To detect high-intensity positive ions accurately, signals passing through the high-voltage capacitor were converted into the transistor-transistor logic (TTL) pulse using a preamp and a TTL comparator and were counted by the MCA. By this method, signal intensities of more than  $10^6$  counts/s could be registered without any counting loss. By this counting method, the intensity ratio up to 0.0001 between negative and positive ions can be measured with reasonable accuracy. Consequently, the measurement under the low-target-density condition becomes possible.

## III. THEORETICAL MODEL

Theoretical methods used are rather standard and have been described in detail elsewhere [17]. Hence, only a brief outline of the basic technique is provided here.

### A. Molecular states

The *ab initio* calculations for the determination of molecular electronic states were performed using a pseudopotential method. Molecular energies and wave functions were obtained using a linear combination of Slater determinant. Slater-type orbitals were employed. In this approach,  $K^{2+}$ -ion core ( $1s^2 \cdots 3s^2 3p^5$ ) was represented by the  $l$ -dependent pseudopotential, and hence, active two electrons are consid-

ered explicitly. All details of this method and specific parameters used were reported earlier [18].

Adiabatic potential curves for this system are rather smooth without much structure except a series of strong avoided crossings between a polarization interaction arising from a singly charged ion-neutral interaction and a Coulomb interaction from an ion pair dominate at larger internuclear separations. Because of the weak-coupling feature described above, the dynamical coupling mechanism is a typical Demkov-type coupling [17]. Hence, the relevant and primary radial coupling matrix elements are found to be all weak except for those in excited states.

### B. Semiclassical approach

A semiclassical molecular orbital expansion method with a straight line trajectory was employed to study the present collision dynamics [17]. Transitions are driven by nonadiabatic couplings. The total scattering wave function was expanded in terms of products of a molecular electronic state and atomic-type electron translation factors (ETF's). Substituting the total wave function into the time-dependent Schrödinger equation and retaining the ETF correction up to the first order of relative velocity yields a set of the first-order coupled equations [molecular orbital close-coupling method (MOCC)]. By solving the coupled equations numerically, we obtain the scattering amplitudes for transitions: the square of the amplitude gives the transition probability, and integration of the probability over impact parameter gives the cross section. Molecular states included in the calculations were the initial [ $H^+ + K$ ] state, single-electron transferred [ $H(n, n=1, 2, 3) + K^+$ ] states, and double-electron transferred [ $H^- + K^{2+}$ ] state. The total number of molecular states employed in the present MOCC was seven MO's.

## IV. RESULTS AND DISCUSSION

### A. Energy-loss spectrum

One of the authors has previously reported that the formation of  $H^-$  ion from  $H^+$  impact on alkali-metal targets could be a successive two-step single-electron transfer in collisions and shows quadratic dependence on the target density [19]. By measuring the energy-loss spectra, the  $H^-$ -ion peak from  $H^+$  ions is found to compose two pronounced peaks with different energy loss [2]. The present results for the energy-loss spectra under the condition of different target densities are shown in Figs. 1(a) and 1(b). The experimental conditions for these spectra are as follows: the collision energy is taken as 3.0 keV, the densities (a)  $2 \times 10^{13} \text{ cm}^{-3}$  and (b)  $9.3 \times 10^{12} \text{ cm}^{-3}$ , respectively. Peak I in Fig. 1(a) is 2.1 times as large as that in Fig. 1(b), which shows a linear dependence on the target density. From the linear dependence on the target density, peak I is identified to originate from double-electron transfer in a single collision. Peak II in Fig. 1(a) is 4.4 times as large as that in Fig. 1(b), which shows a quadratic dependence on the target density. From the quadratic dependence, peak II is ascribed to two-step single-electron-transfer processes in successive two collisions.

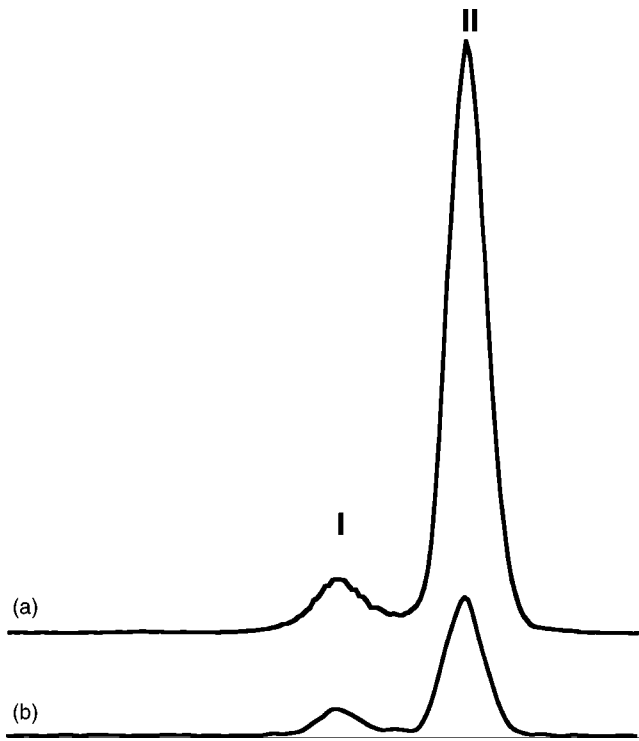


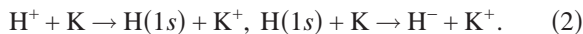
FIG. 1. Energy-loss spectra of the peaks associated with H<sup>-</sup> ions from H<sup>+</sup> ions in collisions with a K target. Reprinted with permission from the authors of Ref. [2].

The absolute energy-loss value from the precursor positive ion could not be evaluated due to change of the polarity of analyzing magnet [2]. The translational energy difference was calibrated by both changing the voltage of ion acceleration and monitoring the magnetic field strength. The energy-loss value in the H<sup>-</sup> ion spectrum evaluated by both calibration methods was found to agree within an experimental error. The energy difference between peaks I and II is found to be constant with a value of  $17.4 \pm 0.5$  eV in the collision energy region considered, in which peak I is observed. The absolute energy loss ( $\Delta E_{DE}$ ) of double-electron transfer in a single collision can be evaluated from Eq. (1):

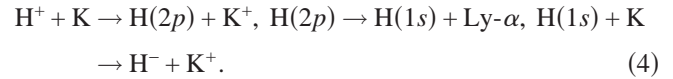
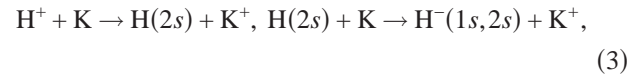
$$\Delta E_{DE} = K_{IE} + K_{IE}^+ - H_{IE} - H_{EA}, \quad (1)$$

where the subscripts IE and EA indicate ionization energy and electron affinity, respectively. Using values of  $K_{IE} = 4.34$  eV,  $K_{IE}^+ = 31.81$  eV,  $H_{IE} = 13.60$  eV, and  $H_{EA} = 0.75$  eV, the energy loss for double-electron transfer—viz.,  $\Delta E_{DE}$ —is evaluated as 21.80 eV, which corresponds to the energy loss of peak I. As the energy difference between the two peaks was 17.4 eV, the energy loss for peak II, due to two-step single-electron transfer processes, was estimated to be 4.4 eV by subtracting 17.4 eV from 21.8 eV.

The energy loss cannot be explained from the reaction (2) below, which gives the energy gain of 5.76 eV:



The possible processes which could explain the present energy-loss value of 4.4 eV may be the two-step reactions



Although both reactions give the same energy-loss value of 4.48 eV, the reaction (3) should be excluded since there exists no stable H<sup>-</sup>(1s, 2s) ion. Hence, peak II should be originated from process (4), which consists of the neutralization forming H(2p) by the first collision following the Ly- $\alpha$  emission, and then, negative-ion formation by the second collision—i.e., two-step processes in successive two collisions.

### B. Two-step single-electron transfer

The product of two-step single-electron transfer cross sections, first forming a neutral-atom formation ( $\sigma_{+0}$ ) and then a negative-ion formation ( $\sigma_{0-}$ ), in two collisions, can be described from the peak intensity and target density shown in Fig. 1 as follows [4]:

$$\sigma_{+0}\sigma_{0-} = \frac{2I^-}{I^+D^2l^2} \quad (5)$$

where  $I^+$  and  $I^-$  are the positive- and negative-ion intensities, respectively,  $D$  is the absolute density of the target, and  $l$  is the effective collision length.

$I^+$  and  $I^-$  were measured under the same target density condition only by changing the polarity of the magnet and detector. Since  $I^+$  decreases mainly by the neutralization reaction,  $I^+$  depends on the position in the TCH. At the collision energy of 3.0 keV and under the target density of  $1 \times 10^{13}$  atoms/cm<sup>3</sup>, the value of  $I^+$  at the exit of the TCH was estimated to be 75% of that at the entrance of the TCH based on the neutralization cross section of  $5.0 \times 10^{-15}$  cm<sup>2</sup> recommended by Morgan *et al.* [10]. The averaged  $I^+$  was estimated to be 1.15 times larger than the detected  $I^+$  intensity. As  $I^-$  decreases by the electron detachment reaction,  $I^-$  at the exit of the TCH is expected to be smaller than that formed in the TCH. At the collision energy of 3.0 keV and under the target density of  $1 \times 10^{13}$  atoms/cm<sup>3</sup>, the value of  $I^-$  at the exit of the TCH was estimated to be 75% of that at the entrance of the TCH based on the electron detachment cross section of  $5.0 \times 10^{-15}$  cm<sup>2</sup> estimated by the formula of Tabata *et al.* [11]. The decrease of  $I^+$  by neutralization takes place simultaneously with that of  $I^-$  by electron detachment reaction depending on the target density. If the neutralization or the electron detachment affects the change of  $I^{+(-)}$  significantly, then the density dependence would change and show a deviation from the quadratic dependence. However, as shown in the Fig. 4 in Ref. [2], the H<sup>-</sup> intensity shows a quadratic dependence on the target density. In order to avoid neutralization and electron detachment reactions, the cross sections were measured under the target density with around  $1 \times 10^{13}$  atoms/cm<sup>3</sup>. In the evaluation of  $I^-/I^+$ , the decrease of  $I^+$  by neutralization compensates that of  $I^-$  by electron detachment reaction. As a result, the uncertainty due to esti-

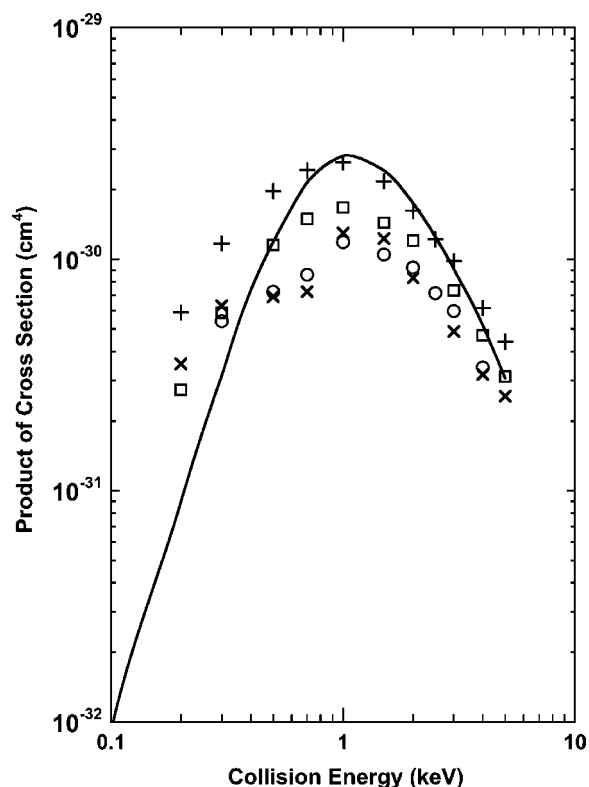


FIG. 2. The collision energy dependence of the product of cross sections—i.e.,  $\sigma_{+0}\sigma_{0-}$ —of neutralization and  $H^-$  formation.  $\circ$ , the present experiment;  $\square$ ,  $\sigma_{+2p}\sigma_{0-}$  by Kimura *et al.* [18]; Solid line, Tabata *et al.* [11]; +, Morgan *et al.* [10];  $\times$ ,  $\sigma_{+2p}\sigma_{0-}$  by Fritsch [22].

mation of  $I^-/I^+$  should be less than 10%. The relative error in the cross sections at each collision energy was estimated to be less than 20%.

The leak of the target gas from the entrance and exit slit affects the effective collision length. The widths of the entrance and exit of the TCH are 0.3 mm and 0.5 mm, respectively [16]. As the slit widths are much narrower than the 5-cm-long TCH,  $l$  is taken as 5 cm. As described in the Ref. [16], the target density was evaluated by both the temperatures of the TCH, and the cell and the monitor current equipped at the TCH. The fluctuation in the evaluation of the square of the target density was considered to be less than 50% as the intensity ratio ( $I^-/I^+$ ). The experimental data reported here were determined by taking an average of measured values of many trials, and about 90% of the reported value lies within  $\pm 50\%$  of all measured results of ( $\sigma_{+0}\sigma_{0-}$ ). The results thus evaluated from Eq. (5) are plotted in Fig. 2. From this result, we have derived separate single-transfer cross sections as discussed below.

In order to make a comparison of the present result, those from other studies for the product of neutralization and negative-ion formations are also included in Fig. 2. An analytical formula proposed by Tabata *et al.* [11] for the product shows a sharp decrease after reaching a maximum at around 900 eV with decreasing collision energy, while the present result and others including recommended values of Morgan *et al.* [10] have somewhat broader maximum than those of

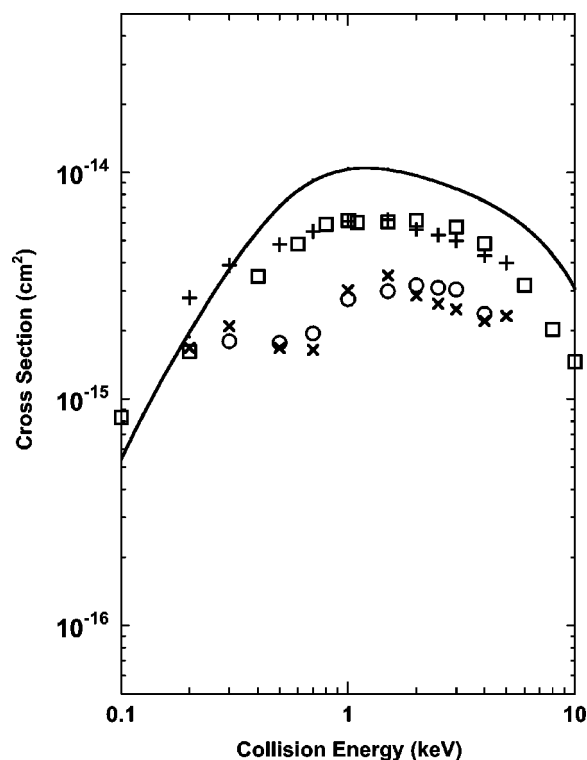


FIG. 3. Single-electron-transfer cross sections ( $\sigma_{+0}$  and  $\sigma_{+2p}$ ) as a function of the collision energy. The present results:  $\circ$ , the present experimental result;  $\square$ ,  $\sigma_{+2p}$  by the present theory. Solid line,  $\sigma_{+0}$  by Tabata *et al.* [11]; +,  $\sigma_{+0}$  by Morgan *et al.* [10];  $\times$ ,  $\sigma_{+2p}$  by Fritsch [22].

Tabata *et al.* and begin to decrease at much lower energies. In this report, we take those by Morgan *et al.* as a reference value for comparison below.

Although the present results are slightly smaller than those of Morgan *et al.* [10], they are in reasonably good accord with those of the product of the state selective cross section of  $\sigma_{+2p}$  and negative-ion formation cross section  $\sigma_{0-}$ , in which this close agreement appears to confirm the energy-loss measurement. The present results are slightly smaller than those by Morgan *et al.*, probably because those  $\sigma_{+0}$  of Morgan *et al.* contain electron transfer cross sections to other channels than  $2p$  state. The present data have an uncertainty of about a factor of 1.5 mainly due to inaccuracy for density determination.

### C. Single-electron transfer: Neutralization

By adopting the recommended cross section for negative-ion formation from neutrals by Morgan *et al.* [10], we have extracted single-electron transfer cross sections and these are illustrated in Fig. 3 along with the present theoretical results. The agreement between the experiment and theory is found to be very good in magnitude and energy dependence. The neutralization cross section  $\sigma_{+0}$  and negative-ion formation cross section  $\sigma_{0-}$  from alkali-metal atoms have been a popular subject for study, and corresponding data have been compiled in previous papers [8–10]. As to some representative experimental and theoretical investigations, for specific state-



selective measurements, those for the H(2*p*) formation  $\sigma_{+2p}$  were carried out by Nagata and Kuribara [20] and those for the H(2*s*) formation  $\sigma_{+2s}$  by Berkowitz and Zorn [21].

Theoretically, Kimura *et al.* [18] have calculated H(2*s*) and H(2*p*) formation cross sections by using a MOCC method, while the similar calculation based on an atomic orbital (AO) CC method was carried out by Fritsch [22]. The state-selective cross section  $\sigma_{+2s}$  forming H(2*s*) by Berkowitz and Zorn [21] showed good agreement with that by Fritsch [22]. The agreement between theories and experiments is found to be generally reasonable. In keV collision energy, the neutralization forming H(2*s*) and H(2*p*) states is the most dominant process because they satisfy electronically the near-resonant condition. And therefore, the sum of the  $\sigma_{+2p}$  and  $\sigma_{+2s}$  is considered to correspond to the total neutralization cross section  $\sigma_{+0}$ . The present experimental results, where  $\sigma_{+2p}$  is evaluated by subtracting  $\sigma_{+2s}$  of Fritsch from  $\sigma_{+0}$  of Morgan *et al.* [10], are in reasonable accord with all experimental and theoretical ones cited, although the present result is somewhat in better agreement with  $\sigma_{+2p}$  by Fritsch [22].

#### D. Direct double-electron transfer

The cross section for direct double-electron transfer in a single collision is given by [4]

$$\sigma_{+-} = \frac{\Gamma}{\Gamma + D_I}, \quad (6)$$

where  $\Gamma$  represents a peak area of peak I in the negative ion spectra. Similarly to the evaluation in successive single-electron transfer cross section discussed above, the relative error of the cross sections at each collision energy was estimated to be less than 20%. The negative-ion intensity of double-electron transfer was evaluated from the peak ratio between peaks I and II. The uncertainty in the absolute values of the double-electron transfer cross section ( $\sigma_{+-}$ ) was estimated to be of  $\pm 30\%$ , because the target-density dependence of successive two-step single-electron transfer is twice of that of the double-electron transfer. The cross sections are shown in Fig. 4 with the present theoretical result. Some of previously reported experimental results are also included. The magnitude of the present theoretical results appears to lie between the present measurements and those of Ebel and Salzborn [5], but the energy dependence is much closer to that of the present experimental trend. Since the H<sup>-</sup> negative-ion channel crosses many high-lying single-transfer channels which the present theory did not consider, the present calculation is likely to overestimate the double-transfer cross section. In the present collision energy domain below keV, the ladder-climbing mechanism, or sequential two-electron transfer, for double transfer should be more probable than direct double transfer. Indeed, the present result indicates the importance of the two-step electron transfer.

The experimental results by Gruebler *et al.* [6] and Anderson *et al.* [7] are found to be much larger than those of the present study. Both of them have been measured by using the fraction method in target density region with a density of  $10^{13}$  atoms/cm<sup>3</sup>. The experimental values by Ebel and

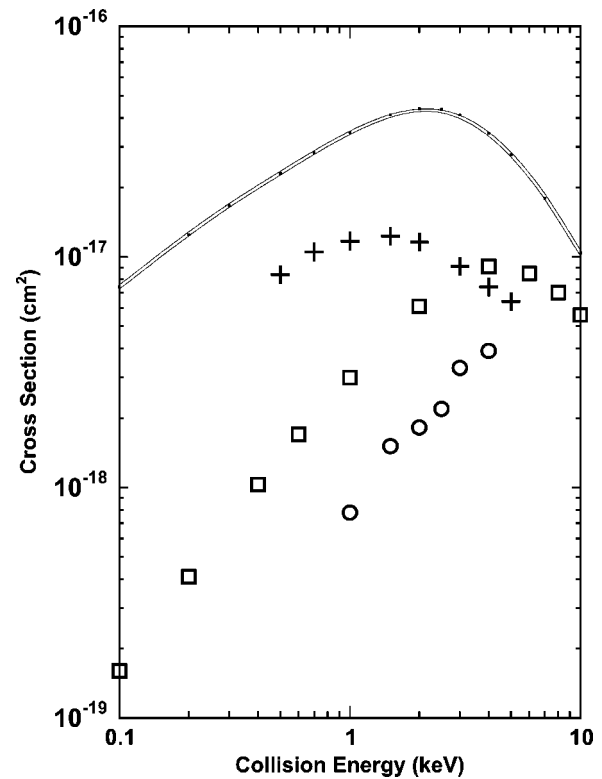


FIG. 4. Double-electron-transfer cross sections as a function of the collision energy. The present results: ○, the present experimental result; □, the present theory. Solid line, Tabata *et al.* [11]; +, Ebel and Salzborn [5], which is recommended by Morgan *et al.* [10].

Salzborn [5] are also larger than the present results in the entire energy region studied. Ebel and Salzborn [5] employed the growth-rate method, in which it is known that this cross section shows a linear dependence with target thickness for thickness less than  $5 \times 10^{12}$  atoms/cm<sup>2</sup>. In their study, the double-electron-transfer cross section ( $\sigma_{+-}$ ) reported was  $8.7 \times 10^{-18}$  cm<sup>2</sup> at 3.0 keV. As shown in Fig. 1(b), even at a density lower than  $1 \times 10^{13}$  atoms/cm<sup>3</sup>, which corresponds to a target thickness of  $5 \times 10^{13}$  atoms/cm<sup>2</sup> and target length 5 cm in the present work, two-step single-electron transfer has been found to be larger than double-electron transfer. At a collision energy of 3.0 keV and under a target thickness of  $5 \times 10^{12}$  atoms/cm<sup>2</sup>, while the intensity ratio ( $I^-/I^+$ ) of direct-double electron transfer evaluated is found to be  $1.65 \times 10^{-5}$ , that of successive single-electron transfer is  $7.5 \times 10^{-6}$ —that is, about half of the direct double transfer. Hence, we suspect that Ebel and Salzborn [5] may not have fully eliminated the influence from successive single-electron transfers on direct double transfer. In our measured results, the double-electron-transfer cross section ( $\sigma_{+-}$ ) was found to be  $3.3 \times 10^{-18}$  cm<sup>2</sup> at 3.0 keV. If the cross section of direct double-electron transfer was evaluated from the sum of total intensity of direct double-electron transfer and successive single-electron transfers, then the apparent cross section for double-electron transfer becomes 1.5 times larger than that of the present direct double-transfer result. The cross section of the direct double-electron transfer by Ebel

and Salzborn [5] is reported to be about 2.6 times larger than that of the present result. This large difference cannot be rationalized only by the contributions from successive single-electron transfer. As indicated by Ebel and Salzborn [5], another possible source of error is an admixture of neutral hydrogen atoms in the primary beam entering the alkali-metal–vapor electron-transfer cell, which would also increase the apparent cross section. Only 2% of hydrogen atoms included in the proton beam increase the intensity ratio ( $I^-/I^+$ ) by the amount of  $1.8 \times 10^{-5}$  which is calculated from the cross section  $\sigma_{0-}$  of  $1.8 \times 10^{-16}$  cm<sup>2</sup> under the target thickness of  $5 \times 10^{12}$  atoms/cm<sup>2</sup>. Since the length between the ion source and the target chamber of 2 cm in the present experiment is much shorter than that in the experiment of Ebel and Salzborn [5], we believe that these causes may also be the origin of the discrepancy seen between the present result and earlier ones. The agreement shown in two-step single-electron transfer with relevant previous data seems to suggest that the detection for both primary positive ions and secondary negative ions by the counting method and the estimation of the target density are sufficiently accurate in the present work.

## V. CONCLUSIONS

In electron-transfer collisions with alkali-metal targets, single-electron transfer is known to give very large cross

sections because of the near-resonant condition from small ionization energy of alkali metals, while double-electron transfer becomes much smaller because of larger energy defects due to double-ionization energies. It may be reasonable that an accurate measurement of the double-electron-transfer cross section cannot be possible without performing a simultaneous energy analysis. Qualitative and quantitative comparisons of the calculated results with experiments for double-electron transfer would become possible using the present reliable cross sections and provide deeper understanding of dynamics. Similar investigations of other members of the alkali-metal and alkali-earth atoms are underway.

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- [1] See, for example, *Atomic and Molecular Processes in Fusion Edge Plasmas*, edited by R. K. Janev (Plenum Press, New York, 1995).
- [2] S. Hayakawa, K. Kadomura, and K. Fujii, *J. Mass Spectrom. Soc. Jpn.* **43**, 239 (1995).
- [3] H. Tawara (unpublished).
- [4] S. Hayakawa, *J. Mass Spectrom.* **39**, 111 (2004).
- [5] F. Ebel and E. Salzborn, *J. Phys. B* **20**, 4531 (1987).
- [6] W. Gruebler, P. A. Schmelzbach, V. Kornig, and P. Marmier, *Helv. Phys. Acta* **43**, 254 (1970).
- [7] C. J. Anderson, A. M. Howald, and L. W. Anderson, *Nucl. Instrum. Methods* **165**, 583 (1979).
- [8] H. Tawara and A. Russek, *Rev. Mod. Phys.* **45**, 178 (1973).
- [9] Y. Nakai, T. Shirai, M. Sakata, and T. Sugiura (unpublished).
- [10] T. J. Morgan, R. E. Olson, A. S. Schlachter, and J. W. Gallagher, *J. Phys. Chem. Ref. Data* **14**, 971 (1985).
- [11] T. Tabata, R. Ito, Y. Nakai, T. Shirai, M. Sakata, and T. Sugiura, *Nucl. Instrum. Methods Phys. Res. B* **31**, 375 (1988).
- [12] D. Mathur, *Int. J. Mass Spectrom. Ion Processes* **83**, 203 (1988).
- [13] D. P. Almeida and M. L. Langford, *Int. J. Mass Spectrom. Ion Processes* **96**, 331 (1990).
- [14] V. Krishnamurthi, *Int. J. Mass Spectrom. Ion Processes* **125**, 155 (1993).
- [15] S. Hayakawa, N. Terazawa, and T. Sugiura, *J. Mass Spectrom. Soc. Jpn.* **41**, 225 (1993).
- [16] S. Hayakawa, A. Matsumoto, M. Yoshioka, and T. Sugiura, *Rev. Sci. Instrum.* **63**, 1958 (1992).
- [17] M. Kimura and N. F. Lane, in *Advances in Atomic, Molecular, and Optical Physics*, edited by D. Bates and B. Bederson (Academic, New York, 1989), Vol. 26, p. 76.
- [18] M. Kimura, R. E. Olson, and J. Pascale, *Phys. Rev. A* **26**, 3113 (1982).
- [19] S. Hayakawa, *Int. J. Mass Spectrom. Ion Processes* **90**, 251 (1989).
- [20] T. Nagata and M. Kuribara, *J. Phys. Soc. Jpn.* **55**, 500 (1986).
- [21] J. K. Berkowitz and J. C. Zorn, *Phys. Rev. A* **29**, 611 (1984).
- [22] W. Fritsch, *Phys. Rev. A* **30**, 1135 (1984).