Kinetic energy distributions of product ions from singly and multiply ionized C₂H₂ molecules induced by 0.8 MeV C⁺ collisions

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We measure kinetic energy distributions (KEDs) of product ions from singly and multiply ionized acetylene, $C_2H_2^{r+*}$ (r = 1-4), generated as intermediate states prior to fragmentation in collisions between C_2H_2 and 0.8 MeV C⁺ ions, in single-electron capture conditions. The KEDs are systematically obtained as functions of the charge state r by performing coincidence measurements between momentum imaging of the product ions and counting of the number of emitted electrons. The KEDs of the fragment ions exhibit a variety of dependences on r, reflecting the variation of fragmentation dynamics and dominant fragmentation pathways. In particular, the KEDs of C_2^+ present a characteristic dependence on r because of the different symmetries of charge distributions in three-body fragmentation.

Keywords: molecular fragmentation; multiple ionization; fast ion collisions

1. Introduction

Understanding the fragmentation mechanisms of multiply ionized molecules is of fundamental interest in physics and chemistry, ranging from interstellar space to biological tissues [1]. Two- or three-body fragmentation processes of small molecules have been studied in detail using reaction microscopes with position-sensitive time-of-flight (TOF) mass spectrometers [2, 3]. For larger polyatomic molecules, such as fullerene (C_{60}) and biological molecules, a direct measurement of the number of emitted electrons is useful, as the pioneering work of Martin *et al.* has shown in collisions of slow highly charged ions [4, 5]. It is difficult to analyze the charge states of multiply ionized molecules only from measurements of product ions unless all the constituent atoms are detected as ionic fragments since detection efficiency of product ions is not high enough. On the other hand, the number of emitted electrons directly provides the charge state of intermediate ions. In previous studies, we applied this technique to study fast-ion-induced multiple ionization and subsequent fragmentation of C_{60} [6, 7] and ethane (C_2H_6) molecules [8]. Distributions of fragment ions were obtained as functions of the charge states of the intermediate states.

Multiply ionized polyatomic molecules can fragment in various ways. As a simple example of linear polyatomic molecules, extensive research has been conducted on the fragmentation processes of acetylene (C_2H_2) by photoionization [9–14], electron impacts [15–20] and ion collisions [21–26], supplemented by theoretical studies [27–31]. Proton migration during isomerization of acetylene into vinylidene was observed using Auger electron-ion-ion coincidence [32] and pump-probe laser experiments [33, 34]. Moreover, in fast ion collisions, bending from the linear structure were reported [22, 25]. To understand those mechanisms in detail, the kinetic energy distributions (KEDs) of the fragment ions are necessary as they provide information on the fragmentation pathways and dynamics. However, the discussion was limited to certain fragmentation pathways that can be tracked by ion-ion coincidence

measurements, such as the two-body fragmentation of $CH^+ + CH^+$, $H^+ + C_2H^+$, and $C^+ + CH_2^+$ [26, 35–42]. Although the charge state of the intermediate ion can be determined in Auger electron-ion-ion coincidence experiments [32], it has been limited to the doubly charged state.

In this study, we measure KEDs of ions produced from singly and multiply ionized $C_2H_2^{r+*}$ ions for r = 1-4 by C⁺ impact at the energy of 0.8 MeV, in single-electron (1*e*) capture collision conditions. In our previous setup based on a TOF spectrometer with parallel electric fields [6–8, 26], it was difficult to obtain a precise momentum measurement for each fragment ion unless all fragments were detected in coincidence so as to deduce their initial production position from their center of mass. Here, we employ a time-resolved momentum imaging technique based on velocity map imaging [43], which provides the momentum of each product ion without information of the other fragment ions for determining the initial production position because broadening of the initial position is corrected by the lens electronic field. By performing the coincidence measurements with the number of electrons, the KEDs of product ions are systematically obtained as functions of the charge state *r* of the intermediate $C_2H_2^{r+*}$ ions. These results allow us to study the fragmentation processes of multiply ionized C_2H_2 as functions of the charge state *r* and charge distribution symmetries among fragment ions.

2. Experimental method

The experiment was carried out at the 1.7 MV tandem accelerator facility of the Quantum Science and Engineering Center of Kyoto University. A schematic diagram of the experimental setup, without the herein employed time-resolved momentum imaging technique, is outlined in a previous paper [8]. A well-collimated beam of 0.8 MeV C⁺ was transported into the beam line. A magnetic charge selector purified the charge states just before entry into the collision chamber. The beam current was a few picoamperes at the collision region. The base pressure of the chamber was below 2×10^{-6} Pa and the pressure of the C₂H₂ gaseous

target was typically about 4×10^{-4} Pa during the measurements.

Product ions were extracted to a linear TOF mass spectrometer with mesh-less electrodes, thus forming a lens, where the velocity map imaging technique was employed [43]. A multichannel plate (MCP, PHOTONIS) detector in conjunction with a position-sensitive delay-line detector (DLD, RoentDek) was used to measure the momentum of each detected ion. The combination of electric fields to be applied to the electrodes so as to maximize focus was first investigated using the trajectory simulation software SIMION 8.1 [44]. The simulation-derived values were further adjusted during the actual measurements to obtain optimally focused images. Slight deviations of the TOF depending on the detection positions due to the lens effect [45, 46] were corrected using the values calculated in the trajectory simulations. Ion signals from the DLD were recorded event by event using a digital storage oscilloscope (LeCroy, WavePro7000).

The electrons emitted in the collisions were extracted in the direction opposite to the product ions and were detected by a semiconductor detector (SSD_e, CANBERRA, PD150-13-300AM) at a potential of ± 25 kV. The SSD_e provides signals with pulse heights corresponding to $25n_e$ keV depending on the number of electrons n_e emitted in each collision event. A multichannel analyzer recorded the pulse heights of the signals from the SSD_e within an appropriate time window. Note that, when no electrons are emitted in a collision event, a height of baseline fluctuations caused by thermal noise of the SSD_e detector is recorded. The collection efficiency for electrons was estimated to be 0.93 [8]. This is consistent with the transmission rate of 0.94 of the mesh electrode used for electron extraction. The number distributions of emitted electrons n_e were derived by appropriate fitting of the pulse-height distributions of the SSD_e signals. In the fitting procedure, in addition to the collection efficiency, the effects of backscattered electrons on the detector surface [6–8, 47] as well as the contribution of false stray electrons were considered. The latter effect is outlined in Sec. 3.1.

The outgoing projectiles at different charge states were separated by an electrostatic deflector and selectively detected by a movable semiconductor detector (SSD_p, CANBERRA, PD25-12-100AM). The detection of charge-selected outgoing projectiles provides trigger timing for the TOF measurements. In this work, 1*e* capture conditions were employed. The count rates were ~100 cps for projectiles and a few thousand cps for ions and electrons. The coincidence rate was less than 10 cps.

3. Results and discussion

3.1. The number of emitted electrons and product ion species

Figure 1 shows a two-dimensional (2D) correlation map between the TOF of ions produced from multiply ionized C₂H₂ by C⁺ impact at the energy of 0.8 MeV in 1*e* capture collision conditions and the number of emitted electrons n_e . The charge state *r* is given in terms of n_e through the relationship $r = n_e + 1$ because one electron is transferred to the projectile ion. The dominant ion species produced from the intermediate ions C₂H₂^{*r*+*} shift to smaller fragment ions as *r* increases. By projecting the 2D data onto the vertical axis, the total n_e distribution can be deduced. The peak at " $n_e = 0$ " (see Fig. 1) corresponds to the collision events where no electrons are detected. The total distribution has maximum intensity at $n_e = 0$. This indicates that the predominant process is pure electron capture, i.e., one electron in a C₂H₂ molecule transfers to a projectile ion without additional electron emission into the vacuum. The fractions of C₂H₂^{*r*+*} for r = 1–4, corresponding to $n_e = 0$ –3, were estimated to be 58, 26, 9, and 4%, respectively, by the fitting analysis of the total n_e distribution. Note that an island of C₂H₂⁺ appeared around $n_e = 1$ (r = 2). This was assumed to be due to additional detection of a false stray electron. This additional component was eliminated when the n_e distributions were evaluated by fitting analysis of the coincidence data.

It is observed that the total TOF spectrum, projected onto the horizontal axis, has six peaks corresponding to $C_2H_n^+$ (n = 0, 1, 2), CH^+ (or $C_2H_2^{2+}$), C^+ , and H^+ ions. Doubly charged

 $C_2H_2^{2^+}$ ions are recognized as the additional sharp peak on the broad CH⁺ peak in the TOF spectra, since the $C_2H_2^{2^+}$ ions have only thermal translational energies. Coincidence measurements with the number of emitted electrons support this association as shown in the 2D map, where the sharp component appears in the island at r = 2. A small peak at a mass-tocharge ratio of 14 is observed with an intensity of 5.8 % relative to CH⁺. This is sufficiently larger than that of the ¹³CH⁺ expected from the isotope ratio of 1.1% of ¹³C. Thus, this peak shows a production of CH₂⁺ via bond rearrangement before the C–C bond breaks. In our previous study on C_2H_2 fragmentation induced by 2 MeV Si²⁺ collisions, a weak peak of H₂⁺ was observed as another evidence of proton migration [26]. The H₂⁺ peak, however, does not appear in the present measurements. In soft X-ray irradiation research, H₂⁺ ions are exclusively produced after C1s⁻¹ $\rightarrow \pi^*$ core excitation through cis-bending [48]. The relative probability of core excitation might be smaller in the present experiment with 0.8 MeV C⁺ (v= 1.63 a.u.) collisions compared to 2 MeV Si²⁺ (v = 1.69 a.u.) collisions.

3.2. Kinetic energy distributions of $C_2H_n^+$ (n = 0, 1, 2)

Figure 2 shows the KEDs of the product ions of $C_2H_n^+$ (n = 0, 1, 2), where the C–C bond is retained. The total KED for each $C_2H_n^+$ has a peak at less than 0.1 eV, which becomes broader with decreasing number of constituent H atoms (n). Contributions from the different intermediate charge states r to the total KED (referred to, hereafter, as "partial KED") are also plotted in the same figure. Notably, the partial KEDs become available owing to coincidence measurements with the number of emitted electrons.

The production pathway of C_2H^+ ions from singly charged intermediate ions (r = 1) is uniquely associated with the binary fragmentation of $C_2H_2^{+*} \rightarrow C_2H^+ + H$. Although this partial KED has a distribution almost similar to that of $C_2H_2^+$, a slight enhancement is observed at KEs higher than 0.1 eV. The KE of H is deduced by multiplying the KE value of C_2H^+ by 25, based on the momentum conservation law. Thus, the kinetic energy release (KER) of this process is deduced by multiplying the KE value of C_2H^+ by 26 since the KER is the sum of the KE values of C_2H^+ and H. It provides a KER distribution with a peak at around 1 eV. The KED of C_2H^+ emitted from singly charged states (r = 1) was previously studied by applying a retarding potential in the photoion-photoelectron coincidence measurements at 21.22 eV photon energy [49]. In that experiment, the C_2H^+ ions were solely emitted from singly charged states because the photon energy was lower than the double ionization threshold of 32.2 ± 0.2 eV [50]. That study showed that the KED has a shape mostly similar to that of $C_2H_2^+$ with a slight enhancement in the tail of the distribution. This is essentially consistent with the present distributions.

The partial KED of C_2H^+ emitted from doubly charged states (r = 2), i.e., through the fragmentation pathway of $C_2H_2^{2+*} \rightarrow C_2H^+ + H^+$, exhibits much higher KE values compared to those for r = 1, as we can expect from the Coulomb repulsion between C_2H^+ and H^+ . A peak is observed at ~0.2 eV and the distribution extends up to ~0.6 eV. A large number of measurements for the KE of C_2H^+ at r = 2 with various projectiles have been reported [23, 26, 35–39] since this process can explicitly be analyzed only from the coincidence detection of the C_2H^+ and H^+ ions. The peak position of the KED at 0.2 eV is in good agreement with those obtained in previous studies using photoionization and electron impact ionization [35–39]. However, in the present measurements, the tail of the distribution extends up to a higher KE, roughly of 0.5 eV, compared to approximately 0.3 eV in previous studies. This is probably due to a higher excitation of $C_2H_2^{2+*}$ induced by fast ion collisions.

To confirm the reliability of the present procedure to derive the partial KEDs using the number of emitted electrons, the partial KED of C_2H^+ for r = 2 is compared with the distribution conventionally reproduced, i.e., under the condition that the C_2H^+ ions were actually detected in coincidence with the counter H^+ . Both the conditions select the same fragmentation pathway of $C_2H_2^{2+*} \rightarrow C_2H^+ + H^+$. As shown in Fig. 2(d) in an expanded scale, the two distributions are in good agreement with each other, except for their intensities. The

difference in intensity is due to the finite efficiency of detecting the H^+ ion. The multiplying factor of 1.5 means that the detection efficiency of a H^+ ion is 0.67, which is consistent with the detection efficiency of the MCP detector itself.

Partial KEDs of C_2^+ have little dependence on the intermediate charge state r, in contrast to the results for C_2H^+ ions. The partial KEDs of C_2^+ for r = 2 and 3 are included in Fig. 2(d) to compare them with each other and with the distribution of C_2H^+ for r = 2. C_2^+ clearly has lower mean KEs than those of C_2H^+ when r = 2. Furthermore, the KEs of C_2^+ decrease from r= 2 to 3.

The mean partial KEDs of C_2H^+ and C_2^+ are plotted in Fig. 3 as a function of the intermediate charge state r. At r = 1, the mean KE of C₂⁺ (which is produced via C₂H₂^{+*} \rightarrow H $+ C_2^+ + H$ or $C_2^+ + H_2$) is higher than that of C_2H^+ (via $C_2H_2^{+*} \rightarrow C_2H^+ + H$). Based on the mechanism of symmetric fragmentation from linear geometrical configuration, C_2^+ is expected to have a lower KE. The higher KE of C_2^+ implies asymmetric fragmentation of $C_2H_2^{+*}$ ions via structural deformation before fragmentation, as the first excited state of $C_2H_2^{+*}$ (A² Σ_g^{+}) may trigger proton migration [33, 42]. At r = 2, the mean KE of C_2^{+} (produced via $C_2H_2^{2+*} \rightarrow H + C_2^+ + H^+$) is lower than that of C_2H^+ at r = 2 (via $C_2H_2^{2+*} \rightarrow C_2H^+ + H^+$). The KED of the neutral fragment H emitted in the fragmentation pathway of $C_2H_2^{2+*} \rightarrow H +$ $C_2^+ + H^+$ can be derived from the momentum vectors of the other fragments of C_2^+ and H^+ based on momentum conservation. The mean KE of the neutral H emitted via this process is estimated to be 7.2 eV. The KER distribution is deduced from the sum of the KEs of H^+ , C_2^+ and H in each event. The mean KER of this pathway is evaluated to be 15 eV. Although the KER is much higher than the mean value of 6.7 eV obtained for the fragmentation pathway of $C_2H_2^{2^{+*}} \rightarrow C_2H^+ + H^+$, a large portion of the KER is shared by H and H⁺ in the pathway of $C_2H_2^{2^{+*}} \rightarrow H + C_2^+ + H^+$. The C_2^+ ion is even decelerated by ejection of the H atom. At r = 3, the mean KE of C_2^+ (produced via $C_2H_2^{3+*} \rightarrow H^+ + C_2^+ + H^+$) becomes even lower than that at $r = 2 (C_2 H_2^{2^{+*}} \rightarrow H + C_2^{+} + H^{+})$. The mean KER in the pathway of $C_2 H_2^{3^{+*}} \rightarrow H^{+} + C_2^{+} + H^{+}$

is evaluated to be 20 eV, which is 5 eV higher than that in $C_2H_2^{2+*} \rightarrow H + C_2^+ + H^+$. The smaller KE of C_2^+ at r = 3 represents a characteristic feature of symmetric fragmentation of linear molecules. The Coulomb repulsion forces are effectively canceled by symmetric charge distributions in the intermediate $C_2H_2^{3+*}$.

Figure 4 shows ion-ion TOF coincidence maps between the first detected fragment ion (t_1) and the second one (t_2) , produced in the same event. The islands of H⁺-C₂H_n⁺ (n = 0, 1) are plotted for r = 2 and 3. We emphasize that, in the present experiment, the ion-ion coincidence maps can be plotted separately for the different r values. It is well known that the slope of each island indicates the relationship between the momenta of the two fragment ions [51]. Negative slopes of H⁺-C₂H_n⁺ (n = 0, 1) pairs mean that two fragment ions are emitted in the opposite direction. In particular, the island of $H^+-C_2H^+$ has a slope of -1 since the two fragment ions are emitted in the opposite direction with the same momentum magnitude as the result of the two-body breakup. The slope of the island for the H⁺-C₂⁺ pair at r = 2becomes less steep and undefined, i.e., between -1 and 0. In a photoionization experiment, it is reported that the slope for $H^+-C_2^+$ pair changes from -1 to -0.57 as the incident photon energy increases from 40.8 eV to 65 eV [14]. This variation in the slope depending on the photon energy is explained by the different KEs of the H atom caused by the different KERs. In the present case of the island of the $H^+-C_2^+$ pair for r = 2, the slope is undefined because the intermediate C₂H₂^{2+*} ions with various internal energies can be generated in fast heavy ion collisions. The slope for the H⁺-C₂⁺ pair at r = 3 is nearly 0 owing to the symmetric fragmentation. A similarly flat shaped island for the H⁺-C₂⁺ pair was observed in collisions with 1.2-MeV Ar⁸⁺ ions (v = 1.1 a.u.) [23]. Although the intermediate charge state r was not selected in that experiment, our present work suggests that the H⁺-C₂⁺ ion pairs were mainly produced from triply charged states (r = 3) in 1.2-MeV Ar⁸⁺ collisions.

3.3 Kinetic energy distributions of CH⁺, C⁺, and H⁺

Figures 5(a) and (b) show KEDs of CH^+ and C^+ , respectively; the KED values are of the order of eV. We do not show the results for CH₂⁺ because of lack of enough data for reliable statistics. The total KED of CH^+ exhibits two peaks around 0 and 2 eV. The partial KED for r = 1 has a peak at around 0.4 eV and accounts for most of the lower-energy regime in the total distribution. The distribution at r = 2 consists of two peaks: one is a sharp peak at 0 eV and the other is a broader peak at around 2-4 eV. The former is reasonably explained by the contribution of $C_2H_2^{2+}$ with a thermal energy distribution. Thus, we can suggest that the latter peak represents the KED of CH^+ produced from the doubly charged state (r = 2). It shows a large shift from r = 1. The partial KED of CH⁺ for r = 3 is found to have a similar distribution to that for r = 2, contrary to expectations from the larger Coulomb repulsive force. To explain the small increase in the KE of CH^+ from r = 2 to 3, we suggest a mechanism of sequential fragmentation of $C_2H_2^{3+*} \rightarrow C_2H^{2+*} + H^+ \rightarrow CH^+ + C^+ + H^+$. The C_2H^{2+*} ions produced in the first step will gain a small amount of KE because of the large mass difference from the counter fragment of H⁺. Thus, in this mechanism, the CH⁺ ions mainly gain KE in the fragmentation of doubly charged ions of C_2H^{2+*} in the second step. As a result, the KE value at r = 3 is not expected to significantly increase from the KE of the CH⁺ at r = 2.

The total KEDs of CH⁺ have been measured in electron impact experiments with electron energies less than 200 eV [15, 52], in which the KEDs might consist of components corresponding to various charge states r. At any electron energy, the KED has a dominant broad peak with one maximum at less than 1 eV, except for the peak corresponding to C₂H₂²⁺. The tail of the broad peak spreads to higher energies with increasing electron energy. It reaches up to 8.0 eV above the electron energy of 40 eV [52]. The present results indicate that the dominant peak observed in the electron impact experiments was mainly due to single ionization (r = 1) and the contribution of the double and triple ionization (r = 2, 3) increases with increasing electron energy.

Although the structure of the total KED of C^+ is rather monotonous compared with that of

CH⁺, the partial KEDs exhibit a variety of features depending on *r*. The intensity of the partial KED for r = 1 smoothly decreases from 0 eV to approximately 3 eV. This is consistent with the result of KEs for C⁺ produced in electron collisions with electron energies lower than the double ionization threshold of 32.2±0.2 eV [53]. The distribution for r = 2 has two peaks around 0.5 and 2.0 eV with a tail extending to about 7 eV. These values are also consistent with the KEs measured in electron impact experiments with impact energy above 60 eV [53] where double ionization can be involved. From an analysis of ion species detected in coincidence with C⁺, it is found that the peaks around 0.5 and 2.0 eV are associated with the production of C⁺ + H⁺ and C⁺ + CH_m⁺ (m = 0, 1), respectively. This tendency is qualitatively reasonable because a lighter ion tends to take away a larger KE to fulfill momentum conservation. In the partial KED of C⁺ for r = 3, the peak around 0.5 eV observed for r = 2 disappears probably because the repulsion from the other C⁺ or CH⁺ becomes dominant.

Figure 5(c) shows the KEDs of H⁺. The total KED seems to have a single peak at around 5 eV with a tail extending up to around 25 eV. The partial KEDs exhibit a large dependence on the intermediate charge state r. Since the H atoms are located at the ends of the molecule, no atoms interfere the emission of H⁺. In addition, H⁺ can hardly be affected by differences in the subsequent fragmentation dynamics, since H⁺ moves away very rapidly from the residual fragments. As a result, the increase of the Coulomb repulsive potential is directly reflected in the KE of H⁺. The mean KEs of H⁺ and C⁺ when the H⁺ and C⁺ ions are detected in the same event are listed in Table 1 as a function of the intermediate charge state r. We can see that the mean KEs of H⁺ and C⁺ increase monotonously with increasing r. In the same table, results obtained by 4 keV electron impacts [18] and 1.2 MeV Ar⁸⁺ collisions [23] are compared. In the electron impact study, the two ions were detected with Auger electrons in coincidence. This means that the ion pairs were emitted from doubly charged states (r = 2) generated through the Auger decay following inner shell ionization. The mean KEs at r = 2 obtained in our measurements are higher than those obtained in the electron impact study. This suggests

contributions of a higher internal energy induced by fast heavy ion collisions. The mean KEs reported in 1.2 MeV Ar^{8+} collisions are close to the present results at r = 3 or 4. This is reasonable since the dominant charge state r in 1.2 MeV Ar^{8+} collisions is likely to be as high as r = 3 or 4.

4. Summary

We have performed coincidence measurements between momentum imaging of product ions and the number of electrons emitted from C_2H_2 induced by 0.8 MeV C⁺ collisions under the single-electron capture condition. The kinetic energy distributions of product ions were systematically obtained as functions of the charge state *r* of the intermediate ions $C_2H_2^{r+*}$ prior to fragmentation. The partial KEDs for *r* = 1 and 2 explain well the KEDs previously observed in photoionization and electron impact ionization experiments. We observed that the partial KEDs of the fragment ions, except for H⁺, exhibit involved dependences on *r* due to the variation in fragmentation dynamics and dominant fragmentation pathways that have different counter ions produced together. The partial KEDs of H⁺ seem to reflect rather directly an increase of the Coulomb potential energy. This is reasonable if we assume prompt ejection of H⁺ as it will be less affected by the other fragments and subsequent dynamics. The partial KEDs of C₂⁺ exhibit a characteristic dependence on *r*, reflecting different symmetries of charge distributions in the three-body fragmentation.

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Table

Table I. Mean KEs of H⁺ and C⁺ for r = 2-4 derived from the coincidence events of a H⁺-C⁺ pair. They are compared to results reported by experiments at 4 keV electron impacts [18] and 1.2 MeV Ar⁸⁺ collisions [23].

| | mean KE (eV) | |
|--------------------------|------------------|---------------------|
| | H^{+} | C^+ |
| r = 2 | 10.7 ± 0.4 | 1.9±0.1 |
| r = 3 | 14.9±1.0 | 3.6±0.1 |
| r = 4 | 18.3±1.8 | 4.8±0.3 |
| 4 keV e⁻ | 8.5±3.4 | $0.96{\pm}0.41^{a}$ |
| 1.2 MeV Ar ⁸⁺ | 18 | 3.8 ^b |
| an - f | | |

^aReference [18]. ^bReference [23].

List of figure captions

Fig. 1. A coincidence map between the number of emitted electrons (n_e) and the TOF of product ions in 0.8 MeV C⁺ collisions with C₂H₂, under the 1*e* capture condition.

Fig. 2. Total and partial KEDs of (a) $C_2H_2^+$, (b) C_2H^+ , and (c) C_2^+ produced by 0.8 MeV C^+ collisions in 1*e* capture condition. (d) Comparison of the partial KEDs of C_2H^+ and C_2^+ for r = 2 and 3 on an expanded scale. Distribution of C_2H^+ deduced from the coincidence events with H^+ counter also plotted.

Fig. 3. Mean KEs of C_2H^+ and C_2^+ as a function of the charge states (*r*) of $C_2H_2^{r+*}$ produced by 1*e* capture collisions with 0.8 MeV C⁺.

Fig. 4. Ion-ion coincidence maps for $H^+-C_2H_n^+$ (n = 0, 1) pairs at (a) r = 2 and (b) r = 3. The two axes represent the first detected fragment ion (t_1) and the second one (t_2) in the same event.

Fig. 5. Total and partial KEDs of (a) CH^+ , (b) C^+ , and (c) H^+ ions produced by 1*e* capture collisions with 0.8 MeV C^+ .



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5