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ABSTRACT

We evaluated the dissociation of isolated gas-phase nucleobase molecules induced by mega electron volt (MeV)-energy ions to gain fundamental insights into the reactions of nucleobases upon fast ion irradiation. We studied five nucleobase molecules—adenine, guanine, cytosine, thymine, and uracil—as gas-phase targets. We compared the fragmentation patterns obtained from carbon ion impacts with those obtained from proton impacts to clarify the effect of heavy ion irradiation. We also compared the results with electron impact and photoionization results. In addition, we identified several delayed fragmentation pathways by analyzing the correlation between fragment pairs generated from singly and doubly charged intermediate ions. To determine the lifetimes of delayed fragmentation from singly charged intermediate ions, we evaluated the detection efficiencies of the microchannel plate detector for the neutral fragment HCN as a function of kinetic energy using a new methodology. As the first demonstration of this method, we estimated the lifetimes of $C_5H_5N_5^+$ generated by 1.2-MeV C^+ and 0.5-MeV H^+ collisions to be 0.87 ± 0.43 and 0.67 ± 0.09 μs , respectively. These lifetimes were approximately one order of magnitude longer than those of the doubly charged intermediate ion $C_5H_5N_5^{2+}$.

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I. INTRODUCTION

Understanding the initial physical and chemical processes induced by radiation is crucial for safe and effective applications of radiation.¹ One of the key processes involved in radiation damage in living cells is DNA degradation.^{2,3} Thus, it is essential to obtain information about the dissociation processes and bond strengths of DNA components. Gas-phase biomolecules are ideal targets for fundamental research because isolated molecules are the most straightforward systems for revealing the individual properties of each molecule and are a good starting point for understanding the properties in complex environments.

Nucleobases have been extensively studied because of their role in DNA damage. They are classified into purine bases (adenine and guanine) and pyrimidine bases (cytosine, thymine, and uracil). Purine bases consist of two ring structures: a six-membered pyrimidine ring and a five-membered imidazole ring, whereas pyrimidine bases have one pyrimidine ring. Rice *et al.*^{4,5} performed one of the earliest studies on the dissociation of nucleobase

molecules: a study of the dissociation pathways of various nucleobases and related molecules with electron impacts. Various experimental methods over the years have been used to study nucleobase dissociation, including electron impacts,^{6–9} photoionization,^{10–13} collision-induced dissociation,^{14,15} ion collisions,^{16–25} and neutral particle collisions.^{19,26} In recent years, several analogous computational chemistry studies have also been performed.^{27,28} However, few experimental studies have focused on fast heavy ions.^{24,25} The effects of high linear energy transfer of heavy ions on isolated biomolecules have not been extensively studied.

Delayed fragmentation is characteristic of the dissociation of polyatomic molecules. Large molecules undergo delayed fragmentation via statistical processes. Therefore, the lifetime of intermediate ions contains information about their internal excitation energies. Analyzing the fragmentation pathways can also help identify the positions of the weak bonds during thermal dissociation and help identify sequential processes. To date, delayed fragmentation of gas-phase molecules has been observed in various studies (including adenine,^{19–21} cyclodipeptide,^{29,30} C_{60} ,³¹ hydrocarbons,³²

and triatomic molecules such as CO_2 and N_2O ³³) using energetic ion collisions, electron impacts, and photoionization. The delayed pathways can be classified into the following two categories: One category is the dissociation of singly charged intermediate ions into one positive ion and one neutral fragment. The other category is the dissociation of the doubly charged intermediate ions into two positive ions. Few studies have been conducted on the former because of the requirement to detect neutral fragments. Martin *et al.* observed delayed fragmentation from singly charged adenine molecules in 36-keV Ar^{8+} collisions by inserting an Einzel lens in a time-of-flight (TOF) mass spectrometer.²¹ Delayed fragmentation of $\text{C}_5\text{H}_5\text{N}_5^+$ and $\text{C}_4\text{H}_4\text{N}_4^+$ into $\text{C}_4\text{H}_4\text{N}_4^+ + \text{HCN}$, $\text{C}_3\text{H}_3\text{N}_3^+ + \text{HCN}$, and $\text{C}_2\text{H}_2\text{N}_2^+ + \text{C}_2\text{H}_2\text{N}_2$ has been reported. However, studies on fast ion-induced delayed fragmentation of gas-phase nucleobase molecules have not been reported. Regarding delayed dissociation, no studies of nucleobase molecules other than adenine have been reported, even with other excitation sources such as photons or electrons.

In this study, we performed experimental studies on the fragmentation of gas-phase nucleobase molecules induced by MeV-energy fast ion collisions. We obtained the fragmentation patterns of the five nucleobase molecules (adenine, guanine, cytosine, thymine, and uracil) with MeV-energy proton and carbon ion collisions. In addition, we identified delayed fragmentation pathways based on the correlation between fragments. We determined the dissociation lifetimes of singly charged intermediate ions after evaluating the detection efficiency of the microchannel plate detector for neutral fragments using a novel methodology.

II. EXPERIMENTAL

The experiments were performed at the accelerator facility of the Quantum Science and Engineering Center of Kyoto University. In these experiments, 0.5-MeV H^+ and 0.7–4.0-MeV C^{q+} ($q = 1\text{--}3$) from a 1.7-MV Cockcroft–Walton-type tandem accelerator were used as projectiles. The beam was collimated to $2.0 \times 2.0 \text{ mm}^2$ or less and chopped using an electrostatic deflector to $\sim 25\text{-ns}$ width at repetition rates of 20 kHz. To increase the statistics, the pulse width was slightly wider than in a typical setting. The beam current was monitored using a Faraday cup located downstream of the collision region. Other details of the setup are described elsewhere.^{34–37}

Gas-phase molecular targets were introduced by heating and sublimating powder samples of adenine $\text{C}_5\text{H}_5\text{N}_5$ ($m = 135$, Nacalai Tesque, purity $\geq 97.0\%$), guanine $\text{C}_5\text{H}_5\text{N}_5\text{O}$ ($m = 151$, Tokyo Chemical Industry, purity $\geq 98.0\%$), cytosine $\text{C}_4\text{H}_5\text{N}_3\text{O}$ ($m = 111$, Tokyo Chemical Industry, purity $\geq 98.0\%$), thymine $\text{C}_5\text{H}_6\text{N}_2\text{O}_2$ ($m = 126$, Tokyo Chemical Industry, purity $\geq 98.0\%$), and uracil $\text{C}_4\text{H}_4\text{N}_2\text{O}_2$ ($m = 112$, Tokyo Chemical Industry, purity $\geq 98.0\%$). The sublimated molecules were formed with a 2.0-mm-diameter aperture before entering the collision region. The oven temperature was set at 433, 553, 453, 413, and 433 K for the sublimation of adenine, guanine, cytosine, thymine, and uracil, respectively. The relative yields of the fragment ions did not change substantially in the following temperature ranges: 413–513 K for adenine, 513–633 K for guanine, 433–533 K for cytosine, 413–493 K for thymine, and 413–433 K for uracil. Hence, the initial temperature of the target molecules had little effect on the measurements. The background pressure in the

collision chamber was $< 3 \times 10^{-6} \text{ Pa}$. In addition, to reduce impurities, preliminary heating of the powder samples was performed at $\geq 353 \text{ K}$ for at least 72 h. The gas-phase nucleobase molecules were captured with a trap wall cooled with liquid nitrogen after passing through the collision region.

The projectile beams crossed the target molecules. The product ions generated by the collisions were extracted using electrostatic fields and detected with a microchannel plate (MCP) detector. The fragment ions were analyzed using a TOF mass spectrometer. The spectrometer was operated basically under the Wiley–McLaren condition,³⁸ whereas the electrodes had no mesh to separate electric field regions. This geometry was originally prepared for velocity map imaging; however, it creates a long potential gradient from the collision area to the inside of the drift tube entrance, which is suitable for observing delayed fragmentation. The fragments generated in the potential gradient can be analyzed for the delayed process as described in Sec. III B. This method is basically the same as that by Martin *et al.*²¹ but does not require an additional Einzel lens to optimize the potential gradient. The TOF data were recorded in event-by-event (list) mode using a fast multichannel scaler. The correlation between the fragments generated in each collision event was analyzed using multi-stop measurements.

III. RESULTS AND DISCUSSION

A. TOF spectra

Figure 1 shows the TOF spectra obtained with 0.7-MeV C^+ (red lines) and 0.5-MeV H^+ (blue lines). We normalized the counts with the peak height of each parent ion to compare the fragmentation patterns. The mass resolution was slightly low because we intentionally widened the beam pulse width to obtain sufficient yields for delayed fragmentation events. Product ions at $m/q = 18$ (H_2O^+), 28 (N_2^+/CO^+), 32 (O_2^+), and 44 (CO_2^+) are mainly because of residual molecules in the sample powders. In the guanine spectra, the contribution of the residual gases was greater than that of other target molecules because of the low target density. Note that the peak at $m/q = 28$ may contain CH_2N^+ from the target nucleobase molecules. H^+ , N^+ , and O^+ can also be attributed to nucleobases and residual gases.

As a common feature for all targets, the fragmentation patterns in the mass region $> m/q \sim 60$ did not change substantially depending on the projectile. In contrast, the production of small fragment ions [including fragments containing no hydrogen atoms; such as $m/q = 12$ (C^+), 24 (C_2^+), 26 (CN^+), 36 (C_3^+), 38 (C_2N^+), and 50 (C_3N^+)] was enhanced in carbon ion collisions. Similar features have been confirmed for other gas-phase molecules, such as hydrocarbons.^{34–36} The larger fragment ions are mainly generated in single ionization events, whereas the smaller fragment ions are emitted through Coulomb explosions after multiple ionization, which is enhanced in heavy ion collisions.

Table I lists the relative yields of the fragment ions to the parent ions and compares them with the results reported with electron impact^{4,8,9} and photoabsorption.^{10,11} Fragment ions with $m/q < 38$ are not included in Table I because there is a possibility of contamination from residual gases. Proton impact (this work) and electron impact^{4,8,9} exhibit similar relative yields in most fragment ions. The relative yields of fragment ions in photoabsorption also exhibit similar trends to those in proton and electron impacts. However, the

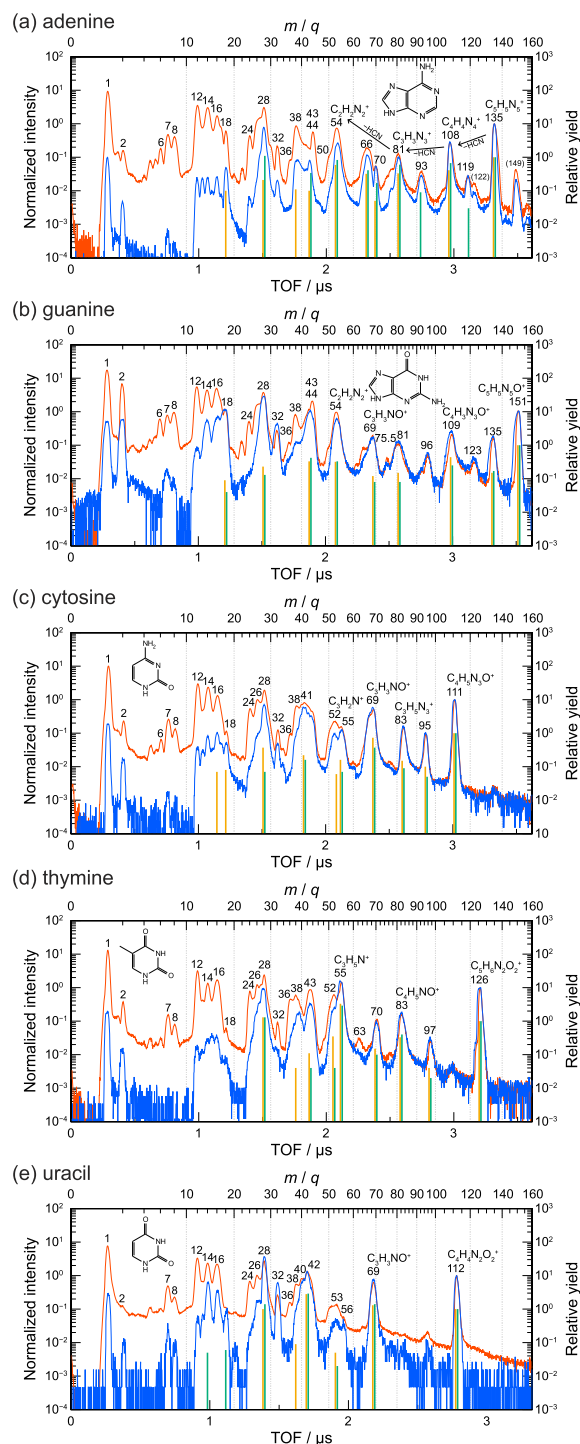


FIG. 1. TOF spectra for (a) adenine, (b) guanine, (c) cytosine, (d) thymine, and (e) uracil molecules induced by 0.7-MeV C^+ (red lines) and 0.5-MeV H^+ (blue lines). The numbers indicate the m/q value for each peak. The peaks at $m/q = 122$ and 149 in the adenine spectra are impurities in the sample. The bars indicate the relative yield of fragment ions for each prominent peak reported with electron impact^{4,8,9} (orange) and photoabsorption^{10,11} (green). Table I also lists relative yields.

relative yields in photoabsorption are slightly higher for adenine¹⁰ and lower for guanine and cytosine. This may indicate different fragmentation processes because of the different excited states of the parent ions.

Adenine exhibits a characteristic dissociation pattern of HCN, 2HCN, and 3HCN loss. The fragment ions at $m/q = 108$ ($C_4H_4N_4^+$), 81 ($C_3H_3N_3^+$), and 54 ($C_2H_2N_2^+$) are thus produced. In addition, we observed other fragment ions such as $m/q = 119$ ($C_5H_3N_4^+$), 93 ($C_4H_3N_3^+$), 70 ($C_2H_4N_3^+$), 66 ($C_3H_2N_2^+$), and 53 ($C_2HN_2^+$). Unlike the adenine molecule, other molecules exhibit losses of CO, HCO, CNO, CHNO, and CH_2NO . The presence of an oxygen atom drastically changes the dissociation pathways. The difference in the structures of thymine and uracil in terms of a methyl group. Thus, a comparison of their spectra provides information about the effects of the methyl group on the dissociation pathway, including the difference in degrees of freedom.^{4,10} For example, a new channel of HCO loss was evident in the dissociation of parent thymine ions, which generate fragment ions at $m/q = 97$ ($C_4H_5N_2O^+$), whereas there was no corresponding pathway in uracil. In addition, the probabilities of CHNO loss ($m/q = 83$ and 69 for thymine and uracil, respectively) were substantially different. The peaks at $m/q = 75.5$ in guanine, $m/q = 63$ in thymine, and $m/q = 56$ in uracil correspond to doubly charged parent ions.

B. TOF correlation maps

The right-hand panels in Fig. 2 show TOF correlation maps between the first and second fragments when we detected two fragments in each collision event. The presence of delayed fragmentation is recognized as diagonal tail structures.^{21,29,30} Delayed fragmentation occurs from singly and doubly charged intermediate ions. First, consider dissociation from doubly charged intermediate ions (e.g., $M^{2+} \rightarrow A^+ + B^+$). Let $t(A^+)$ and $t(B^+)$ be the TOFs of A^+ and B^+ , respectively, when the dissociation occurs without delay. If delayed fragmentation occurs in the acceleration region of the spectrometer, the TOFs of A^+ and B^+ shift from $t(A^+)$ and $t(B^+)$, respectively. When dissociation occurs in the field-free region after entering the drift tube, the TOFs for both A^+ and B^+ become almost equal to the original TOF of M^{2+} , $t(M^{2+})$. Consequently, delayed fragmentation from doubly charged ions forms a long tail between the islands of $t(A^+) - t(B^+)$ and $t(M^{2+}) - t(M^{2+})$. These structures have been well studied for hydrocarbon molecules.³²

In the dissociation of singly charged intermediate ions, positive and neutral fragments are generated (e.g., $M^+ \rightarrow A^+ + B$). In prompt fragmentation, the neutral fragments cannot be detected because they are not extracted by the electric field. However, when dissociation occurs with some delay time, the neutral fragment B becomes detectable because B is formed after the acceleration of M^+ . B continues to travel at the same velocity as M^+ when the dissociation occurs.²¹ In the case of delayed fragmentation in the drift tube, A^+ and B are detected at around $t(M^+)$. For the delayed fragmentation in the acceleration region, the TOF of A^+ is between $t(A^+)$ and $t(M^+)$, and neutral B has a longer TOF than $t(M^+)$. As a result, a long tail diagonally asymptotes from the island of $t(M^+) - t(M^+)$ to infinity along $t(A^+)$.

We observed delayed fragmentation from singly charged intermediate ions for all the nucleobase molecules. A few studies have

TABLE I. Relative yields of main peaks. We evaluated some unresolved peaks together.

Adenine	m/q	Main ions	0.7-MeV C ⁺	0.5-MeV H ⁺	95-eV electron ⁹	20-eV photon ¹⁰
	38	C ₂ N ⁺	1.4	0.20	0.11	
	53–54	C ₂ H ₂ N ₂ ⁺	1.2	0.49	0.59	0.83
	64–66	C ₃ H ₂ N ₂ ⁺	0.40	0.23	0.32	0.41
	70	C ₂ H ₄ N ₃ ⁺	0.060	0.057	0.05	0.17
	80–82	C ₃ H ₃ N ₃ ⁺	0.20	0.17	0.33	0.60
	92–93	C ₄ H ₃ N ₃ ⁺	0.069	0.055		0.09
	107–108	C ₄ H ₄ N ₄ ⁺	0.32	0.35	0.41	0.67
	118–119	C ₅ H ₃ N ₄ ⁺	0.039	0.039		0.03
	135	C ₅ H ₅ N ₅ ⁺	1	1	1	1
Guanine	m/q	Main ions	0.7-MeV C ⁺	0.5-MeV H ⁺	95-eV electron ⁹	21-eV photon ¹¹
	38	C ₂ N ⁺	1.3	0.20		
	53–54	C ₂ H ₂ N ₂ ⁺	1.7	0.82	0.32	0.33
	68–69	C ₂ H ₃ N ₃ ⁺	0.35	0.24	0.12	0.08
	80–82	C ₃ H ₃ N ₃ ⁺	0.27	0.24	0.15	0.08
	95–97	C ₃ H ₄ N ₄ ⁺ , C ₃ H ₃ N ₃ O ⁺	0.076	0.076		
	108–110	C ₄ H ₄ N ₄ ⁺ , C ₄ H ₃ N ₃ O ⁺	0.34	0.37	0.44	0.25
	123–124	C ₄ H ₅ N ₅ ⁺ , C ₄ H ₄ N ₄ O ⁺	0.059	0.062		
	134–135	C ₅ H ₃ N ₄ O ⁺	0.20	0.20	0.15	0.17
	151	C ₅ H ₅ N ₅ O ⁺	1	1	1	1
Cytosine	m/q	Main ions	0.7-MeV C ⁺	0.5-MeV H ⁺	78-eV electron ⁸	21-eV photon ¹¹
	38	C ₂ N ⁺	0.94	0.16		
	52–53	C ₃ H ₂ N ⁺	0.55	0.15	0.06	
	55–56	C ₂ H ₃ N ₂ ⁺	0.28	0.18	0.16	0.07
	67–69	C ₃ H ₄ N ₂ ⁺ , C ₃ H ₃ NO ⁺	1.1	1.0	0.73	0.37
	83–84	C ₃ H ₅ N ₃ ⁺ , C ₃ H ₄ N ₂ O ⁺	0.22	0.22	0.15	0.09
	95	C ₄ H ₃ N ₂ O ⁺	0.12	0.12	0.10	0.05
	111	C ₄ H ₅ N ₃ O ⁺	1	1	1	1
Thymine	m/q	Main ions	0.7-MeV C ⁺	0.5-MeV H ⁺	70-eV electron ⁴	20-eV photon ¹⁰
	38	C ₂ N ⁺	0.85	0.13	0.04	
	42–43	CH ₃ N ₂ ⁺	1.9	0.48	0.11	0.04
	51–52	C ₃ H ₂ N ⁺	1.0	0.27	0.35	0.04
	54–56	C ₃ H ₅ N ⁺	2.2	1.8	3.3	2.9
	70–71	C ₃ H ₅ N ₂ ⁺ , C ₃ H ₄ NO ⁺	0.22	0.12	0.15	0.10
	82–84	C ₄ H ₅ NO ⁺	0.30	0.25	0.33	0.40
	97–98	C ₄ H ₅ N ₂ O ⁺	0.045	0.038	0.04	0.02
	126	C ₅ H ₆ N ₂ O ₂ ⁺	1	1	1	1
Uracil	m/q	Main ions	0.7-MeV C ⁺	0.5-MeV H ⁺	70-eV electron ⁴	20-eV photon ¹⁰
	38	C ₂ N ⁺	0.18	0.06	0.09	
	40–43	C ₂ H ₃ N ⁺ , C ₂ H ₂ O ⁺	4.6	2.8	2.8	2.9
	68–70	C ₃ H ₃ NO ⁺	0.98	1.0	1.3	1.4
	112	C ₄ H ₄ N ₂ O ₂ ⁺	1	1	1	1

focused on the delayed fragmentation of singly charged intermediate ions.^{21,29,30} However, to our knowledge, no studies have reported on delayed fragmentation induced by ion collisions, except for adenine.²¹ We observed delayed fragmentation from doubly charged

intermediate ions only for adenine and guanine. This indicates that the doubly charged intermediate ions of the pyrimidine bases have shorter lifetimes than those of the purine bases, probably because of their smaller molecular sizes. We identified the delayed

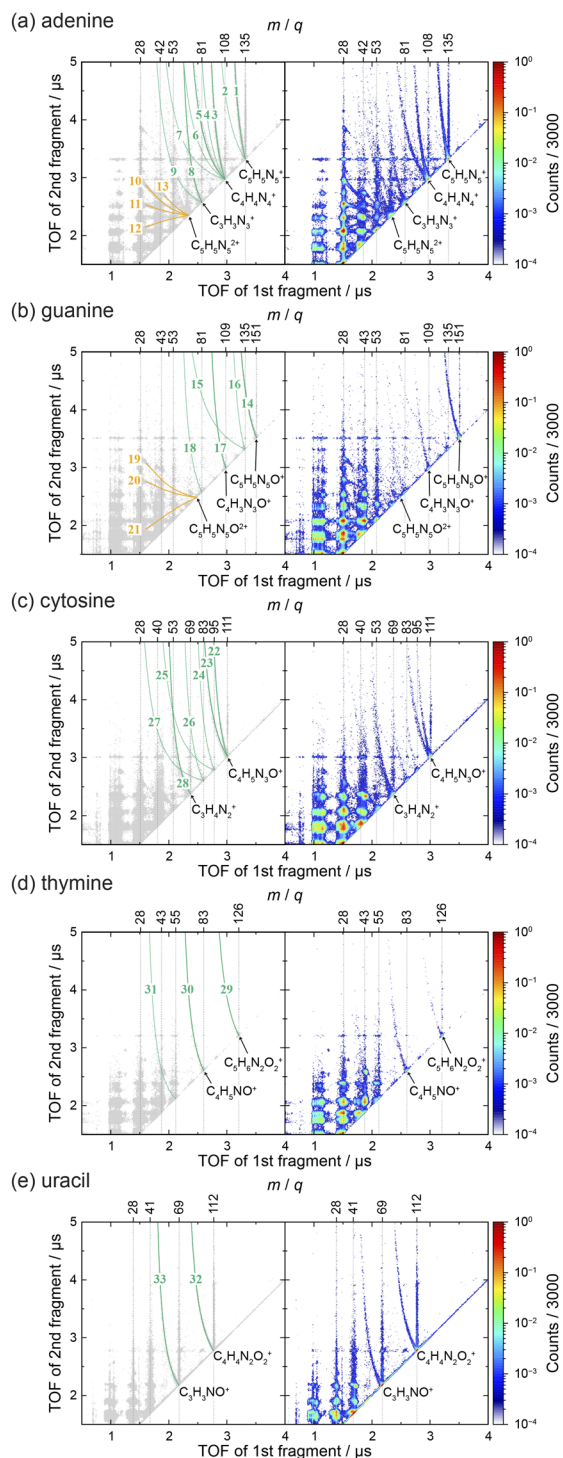


FIG. 2. TOF correlation maps between two fragments for (a) adenine, (b) guanine, (c) cytosine, (d) thymine, and (e) uracil. The projectiles were 0.5-MeV H^+ for adenine; 0.7-MeV C^+ for cytosine, thymine, and uracil; and 0.9-MeV C^+ for guanine. The left-side maps indicate calculated traces for the delayed fragmentation pathways indicated by the numbers in the text. The thickness of the lines (two levels) corresponds to the intensity.

fragmentation pathways by reproducing the tail structures with trajectory simulation of the fragments with SIMION software.³⁹ The left-hand panels in Fig. 2 show simulation results of the TOF correlation of the two fragments generated after some delay time. All the observed tails are well reproduced, as indicated in subsequent paragraphs.

1. Adenine

Figure 3 shows an expanded view of the TOF correlation map of adenine. We identified the delayed fragmentation pathways of singly charged intermediate ions from adenine and labeled the pathways with numbers as follows:

1. $C_5H_5N_5^+ \rightarrow C_4H_4N_4^+ + HCN$.
2. $C_5H_5N_5^+ \rightarrow C_3H_3N_3^+ + C_2H_2N_2$.
3. $C_4H_4N_4^+ \rightarrow C_3H_3N_3^+ + HCN$.
4. $C_4H_4N_4^+ \rightarrow C_3H_2N_2^+ + CH_2N_2$.
5. $C_4H_4N_4^+ \rightarrow C_2H_2N_2^+ + C_2H_2N_2$.
6. $C_4H_4N_4^+ \rightarrow CH_3N_2^+ + C_3HN_2$.
7. $C_4H_4N_4^+ \rightarrow HCN^+ + C_3H_3N_3$.
8. $C_3H_3N_3^+ \rightarrow C_2H_2N_2^+ + HCN$.
9. $C_3H_3N_3^+ \rightarrow HCN^+ + C_2H_2N_2$.

We observed several new pathways in addition to channels 1, 3, and 5, which a previous study reported with slow, highly charged ion collisions.²¹ This might be because of the improved statistics and probably the large energy deposition in fast ion collisions. Channels 1, 3, and 8 correspond to successive losses of HCN. Channel 2 has been suggested in studies using selectively isotope-substituted adenine^{6,7} and quantum chemical calculations.²⁷ In the present study, we confirmed this pathway as delayed fragmentation. Channels 3–9 indicate that sequential processes after $C_4H_4N_4^+$ and $C_3H_3N_3^+$ are promptly generated. Although the tails were obscured, we observed delayed emission of CH_2N_2 , C_3HN_2 , and $C_3H_3N_3$ from $C_4H_4N_4^+$ (channels 4, 6, and 7). Some previous studies^{5,10,26,40} implied prompt dissociation pathways of CH_2N_2 or C_3HN_2 loss from $C_4H_4N_4^+$. Previous studies^{9,26} reported isomerization for $C_4H_4N_4^+$, which might lead to different dissociation pathways.

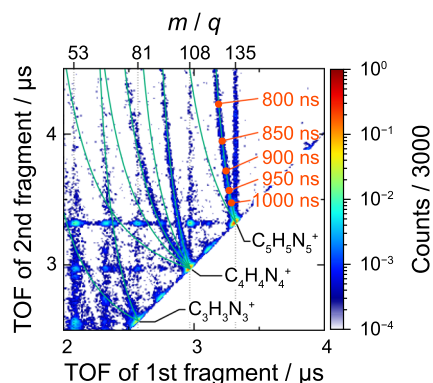


FIG. 3. Expanded view of the TOF correlation map of adenine. Red values at each point on the tail of channel 1 indicate the corresponding delay time calculated by simulations.

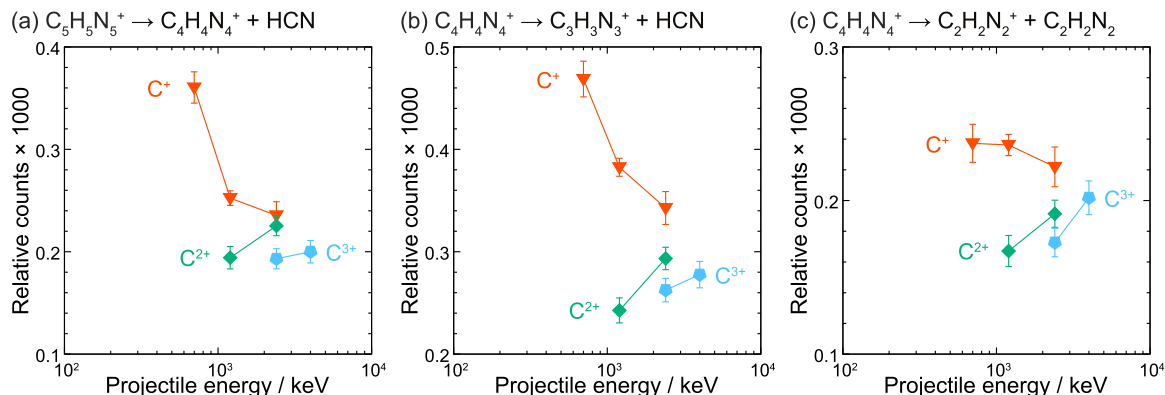


FIG. 4. Relative counts of (a) channel 1: $C_5H_5N_5^+ \rightarrow C_4H_4N_4^+ + HCN$, (b) channel 3: $C_4H_4N_4^+ \rightarrow C_3H_3N_3^+ + HCN$, and (c) channel 5: $C_4H_4N_4^+ \rightarrow C_2H_2N_2^+ + C_2H_2N_2$ of adenine depending on the C^{p+} ($p = 1-3$) projectile energy.

Figure 4 shows the projectile energy dependencies of the delayed fragmentation yields of channels 1, 3, and 5. Here, we simply compared the total counts in the delay time window of 550–950 ns after normalizing by the parent $C_5H_5N_5^+$ counts. In C^+ collisions, the relative counts decrease with increasing projectile energy. In contrast, C^{2+} and C^{3+} collisions exhibit opposite dependencies. The decrease in the relative yields of delayed fragmentation in lower energy for multiple charged ion (C^{2+} and C^{3+}) collisions is probably because of the larger contribution of electron capture in C^{2+} and C^{3+} collisions, which do not deposit sufficiently high internal energy to dissociate. C^{3+} has much larger electron capture cross sections than C^+ ,^{41,42} and the electron capture cross sections increase with decreasing energy in this range.⁴¹ This explains the reason for the lower yields of the delayed fragmentation in C^{2+} and C^{3+} collisions compared to C^+ collisions with lower projectile energy.

We identified the delayed fragmentation pathways from doubly charged intermediate ions as follows:

10. $C_5H_5N_5^{2+} \rightarrow C_4H_3N_4^+ + CH_2N^+$.
11. $C_5H_5N_5^{2+} \rightarrow C_3H_2N_3^+ + CH_2N^+ + HCN$.
12. $C_5H_5N_5^{2+} \rightarrow C_2H_3N_2^+ + CH_2N^+ + C_2N_2$.
13. $C_5H_5N_5^{2+} \rightarrow C_4H_2N_3^+ + CH_3N_2^+$.

For channels 12 and 13, the experimental results were well reproduced when assuming that a neutral fragment and two fragment ions were emitted simultaneously. These dissociation pathways and their lifetimes were reported in previous studies.^{16,17,19–22} We observed the same delayed fragmentation pathways from doubly charged intermediate ions in fast ion collisions.

2. Guanine

We identified the delayed fragmentation channels of singly charged intermediate ions from guanine as follows:

14. $C_5H_5N_5O^+ \rightarrow C_4H_3N_3O^+ + CH_2N_2$.
15. $C_5H_3N_4O^+ \rightarrow CH_2N_2^+ + C_4HN_2O$.
16. $C_5H_2N_4O^+ \rightarrow C_4H_2N_4^+ + CO$.
17. $C_4H_3N_3O^+ \rightarrow C_3H_3N_3^+ + CO$.
18. $C_3H_3N_3^+ \rightarrow C_2H_2N_2^+ + HCN$.

Channels 14 and 16–18 have been reported in various works as prompt dissociation.^{5,9,40} The yields of channels 14 and 17 are relatively large. This suggests that $C_5H_5N_5O^+$ and $C_4H_3N_3O^+$ have long lifetimes. HCN emission occurs after $C_3H_3N_3^+$ intermediates are produced (channel 18), as observed in adenine (channel 8). $C_5H_3N_4O^+$ in channel 15 and $C_5H_2N_4O^+$ in channel 16 are generated by the prompt elimination of NH_2 and NH_3 , respectively. Channels 14, 17, and 18 can form successive dissociation pathways, although processes involving multiple delayed dissociations were not included in the present analysis. $C_5H_3N_4O^+$ and $C_5H_2N_4O^+$ exhibit largely different fragmentation pathways (channels 15 and 16), despite the difference in a single hydrogen atom. Sadr-Arani *et al.* indicated substantially different molecular structures in $C_5H_3N_4O^+$ and $C_5H_2N_4O^+$ by density functional theory calculations.²⁸

The delayed fragmentation pathways of doubly charged intermediate ions of guanine are as follows:

19. $C_5H_5N_5O^{2+} \rightarrow C_4H_3N_4O^+ + CH_2N^+$ or $C_4H_5N_5^+ + CO^+$.
20. $C_5H_5N_5O^{2+} \rightarrow C_3H_2N_3O^+ + CH_2N^+ + HCN$ or $C_3H_4N_4^+ + CO^+ + HCN$.
21. $C_5H_5N_5O^{2+} \rightarrow CHNO^+ + CH_2N^+ + C_3H_2N_3$ or $CH_3N_2^+ + CO^+ + C_3H_2N_3$.

For channels 20 and 21, the simulations indicated that three fragments are generated simultaneously. The fragment ion with $m/q = 28$ cannot be determined (whether it is CO^+ or CH_2N^+), and therefore, we list both possible pathways.

3. Cytosine

For cytosine, we identified the delayed fragmentation pathways of singly charged intermediate ions as follows:

22. $C_4H_5N_3O^+ \rightarrow C_3H_5N_3^+ + CO$.
23. $C_4H_5N_3O^+ \rightarrow C_3H_4N_2^+ + CHNO$.
24. $C_4H_3N_2O^+ \rightarrow C_3H_2NO^+ + HCN$.
25. $C_4H_3N_2O^+ \rightarrow CH_2N^+ + C_3HNO$.
26. $C_3H_5N_3^+ \rightarrow C_2H_4N_2^+ + HCN$.
27. $C_3H_5N_3^+ \rightarrow NH_4^+ + C_3HN_2$.
28. $C_3H_4N_2^+ \rightarrow C_2H_3N^+ + HCN$.

We observed various sequential pathways and competing processes. We observed delayed emission of CO (channel 22) and CHNO (channel 23) from the parent ions as competing processes. Channel 23 involves the retro-Diels–Alder reaction.⁴ Channels 24, 26, and 28 were also discussed in previous studies.^{4,23} We confirmed them as delayed fragmentation pathways by detecting positive fragments and neutral fragments. $C_4H_5N_3O^+$ in channels 24 and 25 is generated by the prompt emission of NH_2 . $C_3H_5N_3^+$ in channels 26 and 27 and $C_3H_4N_2^+$ in channel 28 might be produced through prompt processes in channels 22 and 23, respectively.

4. Thymine

For thymine, we identified the delayed fragmentation channels of singly charged intermediate ions as follows:

29. $C_5H_6N_2O_2^+ \rightarrow C_4H_5NO^+ + CHNO$.
30. $C_4H_5NO^+ \rightarrow C_3H_5N^+ + CO$.
31. $C_3H_5N^+ \rightarrow CH_2N^+ + C_2H_3$.

Although thymine has a higher degree of freedom than cytosine, the number of identified delayed fragmentation pathways was much less than in cytosine. These dissociation pathways have been discussed in several previous studies.^{4,10,23} Channel 29 was implied to involve a retro-Diels–Alder reaction, as in cytosine.⁴ Channels 29–31 form successive dissociation pathways.

5. Uracil

Uracil exhibited only two delayed channels, as follows:

32. $C_4H_4N_2O_2^+ \rightarrow C_3H_3NO^+ + CHNO$.
33. $C_3H_3NO^+ \rightarrow C_2H_3N^+ + CO$.

Although thymine has an additional methyl group in uracil, the observed delayed fragmentation pathways were similar. The existence of the methyl group in thymine appears to have a negligible effect on the delayed fragmentation processes. These dissociation channels have been revealed in previous studies to be prompt dissociation.^{4,10} The difference from thymine is the absence of the third step of C_2H_3 emission (channel 31). $C_2H_3N^+$ was less likely to be in a metastable state, which leads to delayed fragmentation because of the smaller number of degrees of freedom than $C_3H_5N^+$.

C. Lifetimes

Delayed fragmentation is a statistical process, and therefore, the earlier the events, the higher the yields. However, the intensity distributions of the tails in Fig. 2 seem to have an opposite tendency. This is because of a drastic decrease in the MCP detection efficiency for neutral fragments with lower kinetic energies, which are generated with shorter delay times. The impact energy of neutral fragments at the surface of the MCP detector becomes less than several hundred eV. The detection efficiency of the MCP detector $f(E)$ for some neutral atoms has been reported to be a function of the impact energy E in the region <1 keV.^{43,44} However, the detection efficiency of MCP detectors strongly depends on the mass of incident particles. In addition, because the neutral fragments detected in the present experiment are molecules such as HCN, differences in the detection efficiency between molecules and atoms should be considered. Therefore, we needed to determine the detection efficiency of specific neutral fragments to evaluate their lifetime. We assumed that

the detection efficiencies for the positive ions were constant because positive fragment ions were accelerated sufficiently to saturate the detection efficiency.

To determine the detection efficiency for a neutral fragment, we devised and demonstrated a novel method that analyzes the results obtained at two different extraction voltages. We performed the measurements with the original extraction voltages (setup L) and with $1.1\times$ higher voltages of the extraction electrodes and drift tube (setup H). The MCP front potentials were common. A neutral fragment generated at a delay time, t_d , hits the MCP with kinetic energy, $E_H(t_d)$, in setup H. This energy is larger than the energy, $E_L(t_d)$, in setup L because the intermediate ion is increasingly accelerated before dissociation with the increasingly high extraction electric field of setup H. It provides a higher detection efficiency of neutral fragments in setup H, $f[E_H(t_d)]$, than the efficiency in setup L, $f[E_L(t_d)]$, for each t_d . We calculated $E_H(t_d)$ and $E_L(t_d)$ with SIMION software³⁹ as a function of t_d . From the experimental data, we obtained the intensities of the delayed events between t_d and $t_d + \Delta t$. The intensities normalized by the parent-ion counts are denoted as $Y_H(t_d)\Delta t$ and $Y_L(t_d)\Delta t$ for setups H and L, respectively. We obtained the ratio of the detection efficiencies of the two setups—i.e., $f[E_H(t_d)]/f[E_L(t_d)]$ —from $Y_H(t_d)/Y_L(t_d)$ because the detection efficiency for the parent ion is saturated in both setups. Thus, the derivative of $\ln f[E(t_d)]$ can be evaluated by the following equation at an energy E between $E_L(t_d)$ and $E_H(t_d)$:

$$F(E) \equiv \frac{d}{dE} \ln f(E') \Big|_{E'=E} \approx \frac{\ln f[E_H(t_d)] - \ln f[E_L(t_d)]}{E_H(t_d) - E_L(t_d)} = \frac{\ln \{f[E_H(t_d)]/f[E_L(t_d)]\}}{E_H(t_d) - E_L(t_d)} = \frac{\ln \{Y_H(t_d)/Y_L(t_d)\}}{E_H(t_d) - E_L(t_d)}. \quad (1)$$

Sufficient statistics were required, and therefore, we demonstrated this method for the delayed processes of HCN emission from $C_5H_5N_5^+$ and $C_4H_4N_4^+$ (channels 1 and 3). Figure 5 shows the $F(E)$ of HCN evaluated for several t_d . Here, we take $E = (E_H + E_L)/2$. The

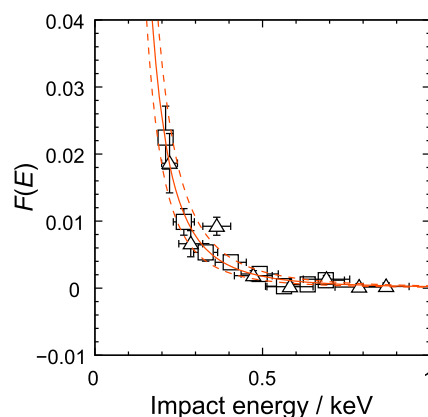


FIG. 5. $F(E)$ of HCN from parent adenine ions $C_5H_5N_5^+$ and its dissociated ions $C_4H_4N_4^+$ (squares and triangles, respectively). We fitted these points with a power function (red curve). The dashed lines indicate the range of errors.

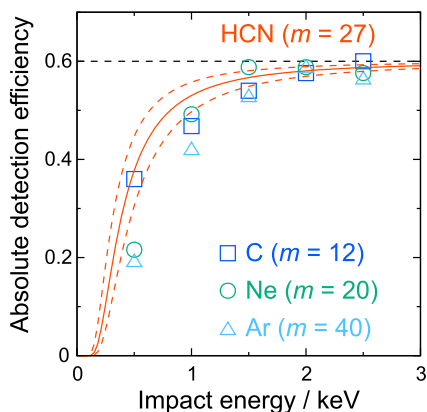


FIG. 6. Absolute detection efficiencies of the MCP detector for HCN evaluated in the present work (red curve) as well as for C, Ne, and Ar (squares, circles, and triangles, respectively) reported in previous studies.^{43,44} The dashed lines indicate the range of errors.

horizontal error bars indicate the range of E_H and E_L , and the vertical error bars are statistical errors. We derived an analytical expression for $F(E)$ by fitting, assuming a power function. Thus, we obtained $f(E) = C \times \exp(-6.5 \times 10^4 \times E^{-1.9})$ with a constant C .

Figure 6 shows a comparison with absolute detection efficiencies previously reported for some neutral atoms^{43,44} with the assumption that the detection efficiency is saturated to the open area ratio of the MCP detector (0.60). The range of arbitrariness of the fit of $F(E)$ in Fig. 5 results in an uncertainty of about 10%, as shown in Fig. 6. The absolute detection efficiencies decrease as the impact energy decreases by <1 keV. The $f(E)$ of HCN obtained in this study exhibits a similar tendency to those of the other atoms. Heavier atoms tend to have lower absolute detection efficiencies. However, the $f(E)$ of HCN exhibits a larger absolute detection efficiency than Ne, despite HCN ($m = 27$) having a larger mass than Ne ($m = 20$). This result might be because of the differences between the molecule and atom or because of the effect of excited states of HCN generated by delayed fragmentation.

Figure 7 shows the decay profile of channels 1 and 3 obtained after correction with $f(E)$. We evaluated the lifetimes of these channels in this time range by assuming a single exponential decay. Table II summarizes the results for 1.2-MeV C^+ and 0.5-MeV H^+ collisions. Although the error is large, it seems that the lifetimes do not strongly depend on the projectile species. This suggests that delayed fragmentation proceeds through a specific internal energy state. In addition, channel 3 has a longer lifetime than channel 1. This may indicate that $C_4H_4N_4^+$ has lower internal energy

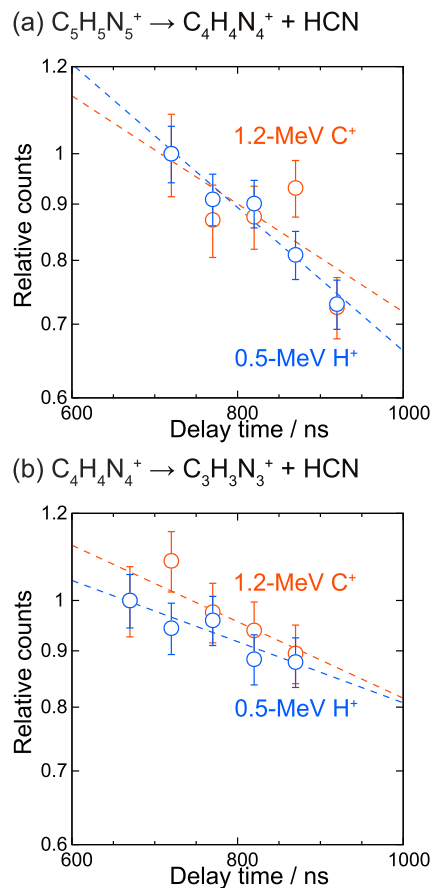


FIG. 7. Relative intensities of the delayed fragmentation of (a) channel 1: $C_5H_5N_5^+ \rightarrow C_4H_4N_4^+ + HCN$ and (b) channel 3: $C_4H_4N_4^+ \rightarrow C_3H_3N_3^+ + HCN$ induced by 1.2-MeV C^+ (red circle) and 0.5-MeV H^+ (blue circle) as a function of the delay time. The counts were normalized at the intensity at the shortest delay time for each dissociation channel. The dashed lines are the fitting lines.

than $C_5H_5N_5^+$ because $C_4H_4N_4^+$ has already lost one HCN from $C_5H_5N_5^+$.

In the case of doubly charged intermediate ions, lifetimes can be obtained in a more straightforward manner without considering the variation of the detection efficiencies because both fragment ions hit MCP with sufficiently high kinetic energies. The dissociation lifetimes for channels 10, 11, and 13 are 120 ± 16 , 195 ± 28 , and 77 ± 28 ns, respectively.²⁰ Although it was difficult to determine their lifetimes in the present measurements because of the many overlapped islands in the correlation maps, we confirmed that the

TABLE II. Dissociation lifetimes of singly charged intermediate ions produced from adenine.

Pathways	1.2-MeV C^+ (μs)	0.5-MeV H^+ (μs)
$C_5H_5N_5^+ \rightarrow C_4H_4N_4^+ + HCN$	0.87 ± 0.43	0.67 ± 0.09
$C_4H_4N_4^+ \rightarrow C_3H_3N_3^+ + HCN$	1.4 ± 0.6	1.6 ± 0.4

timescale of the decay profiles was the same. The lifetimes of the singly charged intermediate ions are approximately one order of magnitude longer than those of the doubly charged ions, $C_5H_5N_5^{2+}$. The high internal energy and the possibly low dissociation energy of doubly charged ions may contribute to prompt dissociation.

IV. SUMMARY

In this work, we obtained TOF mass spectra of product ions generated from gas-phase adenine, guanine, cytosine, thymine, and uracil molecules with MeV-energy carbon ions and protons. The relative yields of the fragment ions are essential for understanding the characteristics of molecular fragmentation induced by fast ions. We quantitatively indicate the production of additional small fragment ions in heavy ion collisions from a comparison with the results of proton impact.

We also studied delayed fragmentation for adenine, guanine, cytosine, thymine, and uracil, including sequential processes. Delayed emission of HCN was dominant in adenine, whereas we mainly observed delayed emission of CHNO or CO in other nucleobases. We observed delayed emission of CHNO from parent ions in all pyrimidine base molecules.

We devised a new method to determine the detection efficiency of the MCP detector for neutral particles to evaluate the dissociation lifetimes of singly charged intermediate ions. Here, we demonstrated this method for delayed emission of HCN for adenine. As a result, we estimated the time scale of the lifetime observed in the present measurement to be $\sim 1 \mu s$, which was one order longer than that of doubly charged intermediate ions. Further systematic studies of the lifetimes will lead to an understanding of the stability of intermediate ions and the internal excitation caused by fast ion collisions or other reactions.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

T. Nakao: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal). **R. Takasu:** Investigation (equal). **H. Tsuchida:** Writing – review & editing (equal). **M. Saito:** Supervision (equal); Writing – review & editing (equal). **T. Majima:** Conceptualization (equal);

Data curation (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Software (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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