

Nonequilibrium Formation of C₄ Carbonyls in Interstellar Ices Linked to Amino Acids

Zesen Wang, Jia Wang, Anastasia S. Shishova, Sergey O. Turchin, Mason McAnally, Andrew M. Turner, Niki Jabari, and Ralf I. Kaiser*



Cite This: *ACS Cent. Sci.* 2026, 12, 1458–1467



Read Online

ACCESS |



Metrics & More

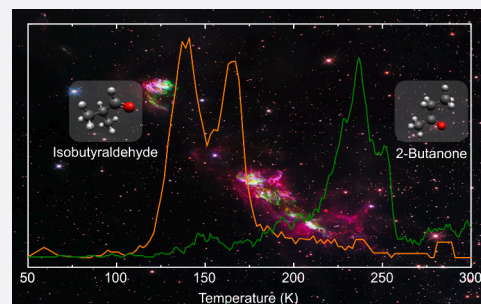


Article Recommendations



Supporting Information

ABSTRACT: Complex organic molecules in interstellar ices and carbonaceous asteroids record key steps in the chemical evolution toward life, yet the origin of branched carbonyl compounds—a fundamental class of biorelevant molecules—remains unresolved. Here, we demonstrate the efficient formation of C₄ carbonyls, isobutyraldehyde ((CH₃)₂CHCHO) and 2-butanone (CH₃CH₂COCH₃) via barrierless radical–radical recombination in carbon monoxide–propane (CO–C₃H₈; 1:1.1 ± 0.2) and ethane–acetaldehyde (C₂H₆–CH₃CHO; 1.5 ± 0.3:1) ice mixtures at 5 K irradiated with 5 keV electrons as proxies for secondary electrons generated by galactic cosmic rays. Isobutyraldehyde arises from recombination of formyl (HCO) and isopropyl (CH₃CHCH₃) radicals, whereas 2-butanone forms through acetyl (CH₃CO) and ethyl (CH₃CH₂) radical coupling. Using isomer-selective photoionization mass spectrometry with isotopic labeling, we provided strong evidence for these products together with the enol 2-methylprop-1-en-1-ol ((CH₃)₂CCHOH) in the gas phase. These results establish a plausible low-temperature mechanism for molecular mass growth that generates branched carbon skeletons without activation barriers, bridging a critical gap between simple interstellar species and structurally complex, biorelevant organics. The demonstrated pathways operate under cosmic-ray-driven, nonequilibrium chemistry in icy grains, providing a plausible route to C₄ backbone motifs found in prebiotic molecules, including amino acids and fatty acids. Our findings show that chemical complexity—including carbon skeleton branching—can emerge in deep space prior to planetary accretion, implying a plausible extraterrestrial origin for key molecular precursors delivered to early Earth and exo planetary systems.



INTRODUCTION

Since the first detection of formaldehyde (H₂CO, **1**)¹ and acetone (CH₃COCH₃, **2**)² in the interstellar medium (ISM), aldehydes (RCHO) and ketones (RCOR') have attracted extensive attention from the astronomy,^{3–5} astrochemistry,^{6–8} astrobiology,^{9–11} and laboratory astrophysics^{12–16} communities due to their roles as key intermediates in molecular mass growth toward biorelevant molecules linked to the origins of life.^{9,10,16–18} To date, 12 aldehydes and three ketones, including **1**, **2**, acetaldehyde (CH₃CHO, **3**),^{19–21} propanal (CH₃CH₂CHO, **4**),²² and hydroxyacetone (CH₃COCH₂OH, **5**)²³ have been detected in the interstellar medium (Figure S1). In addition, carbonaceous chondrites harbor not only **1–4** but also more complex aldehydes and ketones including butyraldehyde (CH₃CH₂CH₂CHO, **6**),^{24–27} isobutyraldehyde ((CH₃)₂CHCHO, **7**),²⁴ and 2-butanone (CH₃CH₂COCH₃, **8**).^{24,25,27}

These findings indicate that these organics form in extraterrestrial environments, survive incorporation into comets, asteroids, and planetesimals, and may ultimately be delivered to planets such as early Earth, providing an exogenous source of prebiotic matter.^{28,29} However, despite their importance as precursors to astrobiologically relevant

molecules such as amino acids and fatty acids, the fundamental formation mechanisms of complex carbonyl compounds in interstellar environments remain largely unresolved in particular for the biorelevant species **7** and **8**, which provide direct entry into amino acid precursor chemistry via the Strecker synthesis.^{30–34}

In prebiotic chemistry, **7** and **8** may react with ammonia (NH₃) to form the corresponding imines, isobutylimine ((CH₃)₂CHCHNH, **9**) and 2-butanimine (CH₃CH₂C(NH)CH₃, **10**) (Figure 1). **9** and **10** could then undergo hydrogen cyanide (HCN) addition to valinonitrile ((CH₃)₂CHCH(NH₂)CN, **11**) and isovalinonitrile (CH₃CH₂C(CH₃)(NH₂)CN, **12**). Hydrolysis of **11** and **12** could yield the proteinogenic amino acid valine ((CH₃)₂CHCH(NH₂)COOH, **13**) and the nonproteinogenic amino acid isovaline (CH₃CH₂C(CH₃)(NH₂)COOH, **14**). Valine (**13**) is essential

Received: May 30, 2026

Revised: August 10, 2026

Accepted: August 11, 2026

Published: September 2, 2026



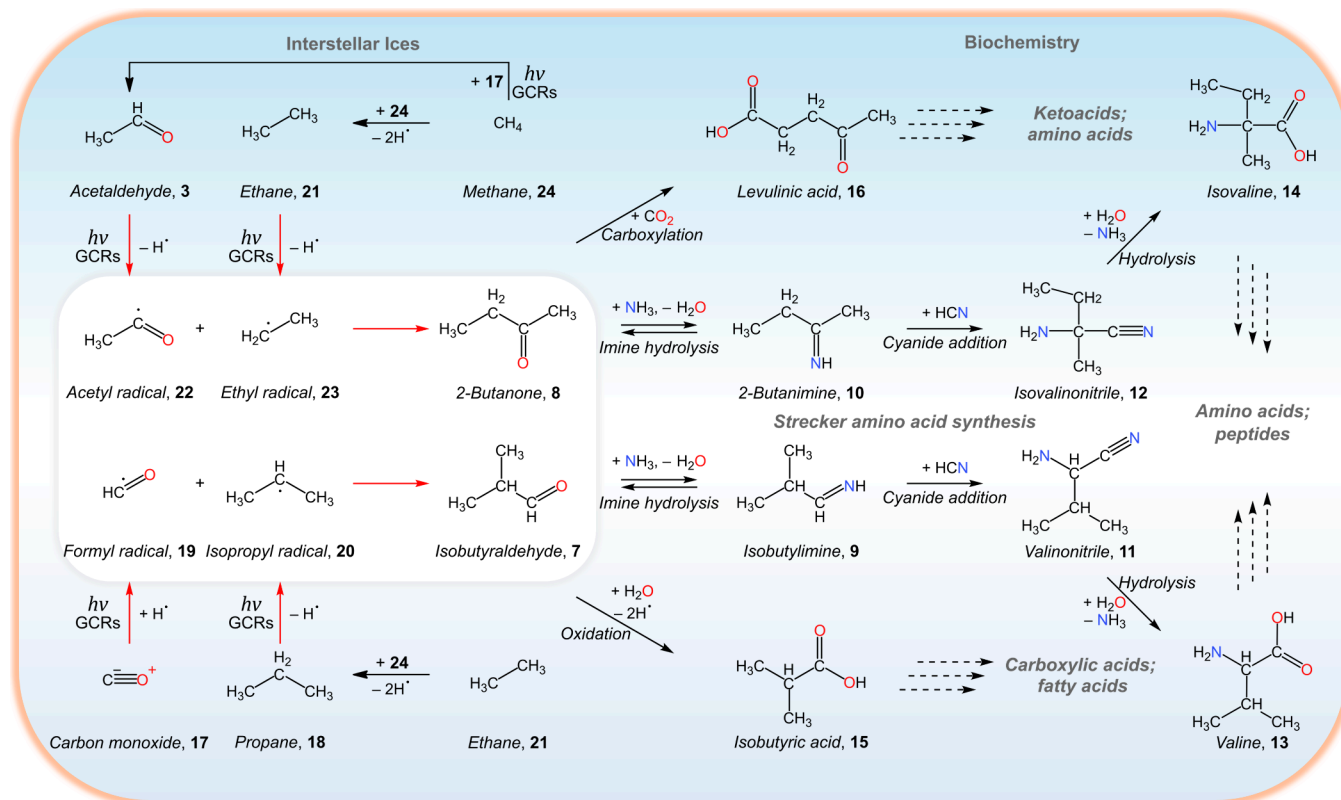


Figure 1. Schematic formation pathways of isobutyraldehyde ($(\text{CH}_3)_2\text{CHCHO}$, 7) and 2-butanone ($\text{CH}_3\text{CH}_2\text{COCH}_3$, 8) in interstellar ices and their potential role as precursors to prebiotic molecules. The boxed region highlights the reaction network investigated in this work. Exposure of interstellar ice analogues carrying carbon monoxide (17) and propane (18) as well as acetaldehyde (3) and ethane (21) to proxies of galactic cosmic rays initiates a complex set of radical–radical reactions of formyl (HCO , 19) with isopropyl ($(\text{CH}_3)_2\text{CH}$, 20) and acetyl (CH_3CO , 22) with ethyl (CH_3CH_2 , 23) yielding isobutyraldehyde (7) and 2-butanone (8), respectively. 7 and 8 serve as fundamental precursors to isobutyric acid (15) and levulinic acid (16), respectively, contributing to the formation of amino acids such as valine (13) and isovaline (14) as well as carboxylic and keto acids.

for protein structure and metabolic regulation,^{35,36} while isovaline (14) represents a precursor to branched-chain amino acid and a marker of prebiotic chemistry.^{37–39} Beyond amino-acid-related chemistry, oxidation of 7 could result in the formation of isobutyric acid ($(\text{CH}_3)_2\text{CHCOOH}$, 15), a precursor to branched-chain fatty acids.⁴⁰ Carboxylation of 8 may lead to levulinic acid ($\text{CH}_3\text{COCH}_2\text{CH}_2\text{COOH}$, 16), linking this ketone to a broader inventory of prebiotically relevant keto acids.⁴¹ Notably, 13–16 have been identified in carbonaceous meteorites such as Murchison.^{39,42–44} Consequently, 7 and 8 may serve as key precursors to keto acids, fatty acids, and amino acids (Figure 1), and may contribute to inventories of prebiotic precursors. Elucidating their interstellar formation is therefore critical for unraveling fundamental abiotic synthesis routes of a key class of complex organic molecules (COMs) in deep space: aldehydes and ketones.

Here, we report the first preparation of isobutyraldehyde ($(\text{CH}_3)_2\text{CHCHO}$, 7) and 2-butanone ($\text{CH}_3\text{CH}_2\text{COCH}_3$, 8) in interstellar ice analogues exposed to proxies of galactic cosmic rays (GCRs). The formation of 7 is accomplished in low temperature (5 K) carbon monoxide (CO , 17)–propane (C_3H_8 , 18) interstellar analogue ices through barrierless recombination of formyl (HCO , 19) with isopropyl (CH_3CHCH_3 , 20) radicals (Figures 1 and 2), whereas 8 is produced in low temperature acetaldehyde (CH_3CHO , 3)–ethane (C_2H_6 , 21) ice via barrierless carbon–carbon bond coupling through recombination of acetyl (CH_3CO , 22) and

ethyl (CH_3CH_2 , 23) radicals (Figures 1 and 3). Carbon monoxide (17) is among the most abundant constituents of interstellar ices with an abundance of up to 55% relative to water.^{14,45,46} Propane (18) and ethane (21) form in methane (CH_4 , 24)-rich interstellar ices through irradiation-driven radical chemistry.^{47,48} Acetaldehyde (3) has been detected in diverse extraterrestrial environments, including cold molecular clouds,⁴⁹ star-forming regions,^{20,50} meteorites⁵¹ and comets,⁵² and has also been reported in interstellar ices with upper limits of 10% relative to water.⁵³ Utilizing tunable vacuum ultraviolet (VUV) photoionization reflectron time-of-flight mass spectrometry (PI-ReToF-MS) together with isotopic substitution studies, 7 and its enol 2-methylprop-1-en-1-ol ($(\text{CH}_3)_2\text{CCHOH}$, 25), as well as 8, were identified isomer-selectively during the temperature-programmed desorption (TPD) of processed ices. These findings unravel non-equilibrium reaction pathways leading to 7 and 8 in interstellar ices thus advancing our fundamental understanding of molecular mass growth to complex aldehydes and ketones under astrophysical conditions. This work provides a mechanistic framework between ice chemistry and the molecular foundations of life, highlighting a plausible extraterrestrial pathway for the formation of biologically relevant organics that could be available to early Earth and exoplanetary bodies.

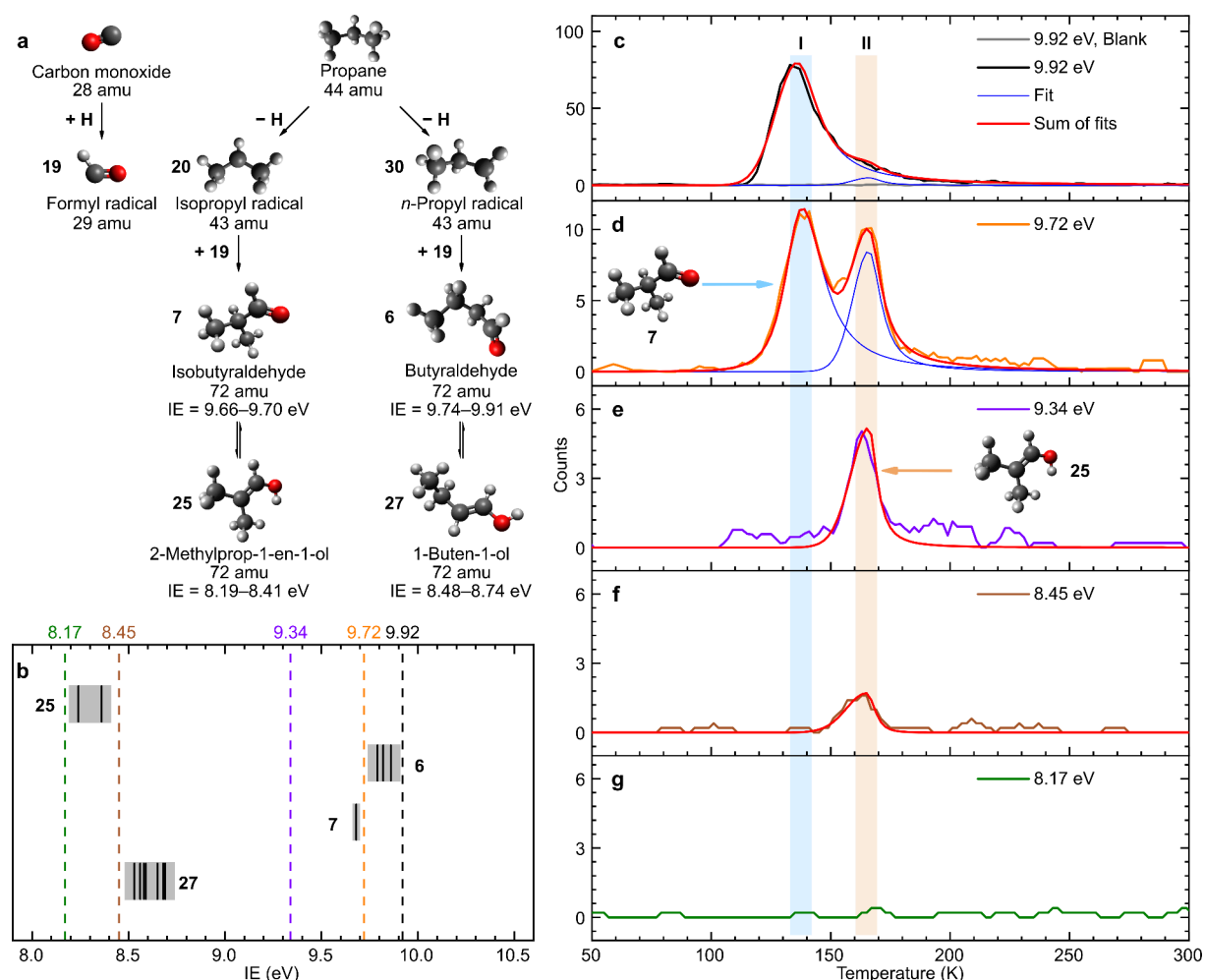


Figure 2. (a) Proposed formation pathways of four C_4H_8O ($m/z = 72$) isomers in irradiated CO– C_3H_8 ices. Barrierless radical–radical reactions produce 6 and 7, followed by tautomerization to enols 27 and 25. The computed adiabatic ionization energies (IEs; black solid line) and ranges of their conformers (gray area) are compiled (b). Dashed lines indicate the VUV photon energies used for photoionization. TPD profiles of $m/z = 72$ in CO– C_3H_8 ices recorded at 9.92 eV (c), 9.72 eV (d), 9.34 eV (e), 8.45 eV (f) and 8.17 eV (g). The TPD profiles are fitted with two peaks (I and II), highlighted by the shaded regions. Peaks I and II are assigned to isomers 7 and 25, respectively. The red lines represent the overall fits.

RESULTS

Fourier Transform Infrared Spectroscopy

Fourier transform infrared (FTIR) spectroscopy was employed to monitor the chemical evolution of the carbon monoxide (CO)–propane (C_3H_8), ethane (C_2H_6)–acetaldehyde (CH_3CHO) ices along with isotopically labeled ethane (C_2H_6)–acetaldehyde- d_3 (CD_3CHO) systems before, during, and after exposure to ionizing irradiation (Figures S2–S5). Detailed assignments of the absorptions are provided in Tables S1–S4. In the pristine CO– C_3H_8 ice, the infrared absorptions are dominated by the overtone and fundamental modes of carbon monoxide such as $2\nu(CO)$ at 4246 cm^{-1} and $\nu(CO)$ at 2135 cm^{-1} ,⁵⁴ together with the fundamentals and combination bands of propane (Figure S2).^{55–57} In the unprocessed C_2H_6 – CH_3CHO and isotopically labeled C_2H_6 – CD_3CHO ices, the spectra can be assigned to the vibrational fundamentals and combination modes of ethane (C_2H_6) and acetaldehyde (CH_3CHO/CD_3CHO), such as CH_3 stretching modes of C_2H_6 at 2973 cm^{-1} (ν_{10}), 2956 cm^{-1} (ν_1), and 2880 cm^{-1} (ν_3)^{58–60} and the C=O stretching mode of CH_3CHO/CD_3CHO at 1723 cm^{-1} (ν_4)^{61,62} (Figures S3–S5).

Following the low dose irradiation simulating $(8 \pm 2) \times 10^5$ years of GCR exposure in cold molecular clouds, several new absorption features emerged; these were deconvoluted into multiple Gaussian peaks.^{63,64} In the irradiated CO– C_3H_8 ices, a new absorption at 1796 cm^{-1} is assigned to the formyl radical ($H\dot{C}O$, 19, ν_3)⁶⁵ (Figure S2 and Table S1), whereas the exposed C_2H_6 – CH_3CHO ices reveal new absorptions at 2130 cm^{-1} , 1839 cm^{-1} , and 1570 cm^{-1} ; the former two are linked to carbon monoxide ($\nu(CO)$) and the acetyl radical ($CH_3\dot{C}O$, 22, ν_3),^{54,66,67} while 1570 cm^{-1} is tentatively assigned to the vinoxy radical ($\dot{C}H_2CHO$, 26, ν_4)^{67,68} (Figure S3 and Table S2). In the irradiated isotopically labeled C_2H_6 – CD_3CHO ices, absorptions at 2137 and 1849 cm^{-1} are attributed to carbon monoxide ($\nu(CO)$) and 22- d_3 ($\nu_3(CD_3\dot{C}O)$), while the new absorption at 2096 cm^{-1} is assigned to the ketene- d_2 ($\nu_2(CD_2CO)$)^{54,65,66,69} (Figure S5 and Table S4).

At a higher irradiation dose, which mimics $(6 \pm 2) \times 10^7$ years in cold molecular clouds, the spectra of the C_2H_6 – CH_3CHO system are more complex, revealing a broader product inventory (Figure S4 and Table S3). New absorptions at 4496 and 1301 cm^{-1} can be attributed to combination ($\nu_2 + \nu_3$) and fundamental (ν_4) modes of methane,⁶⁰ while absorptions at 3092 and 954 cm^{-1} , 2338 cm^{-1} , and 2133

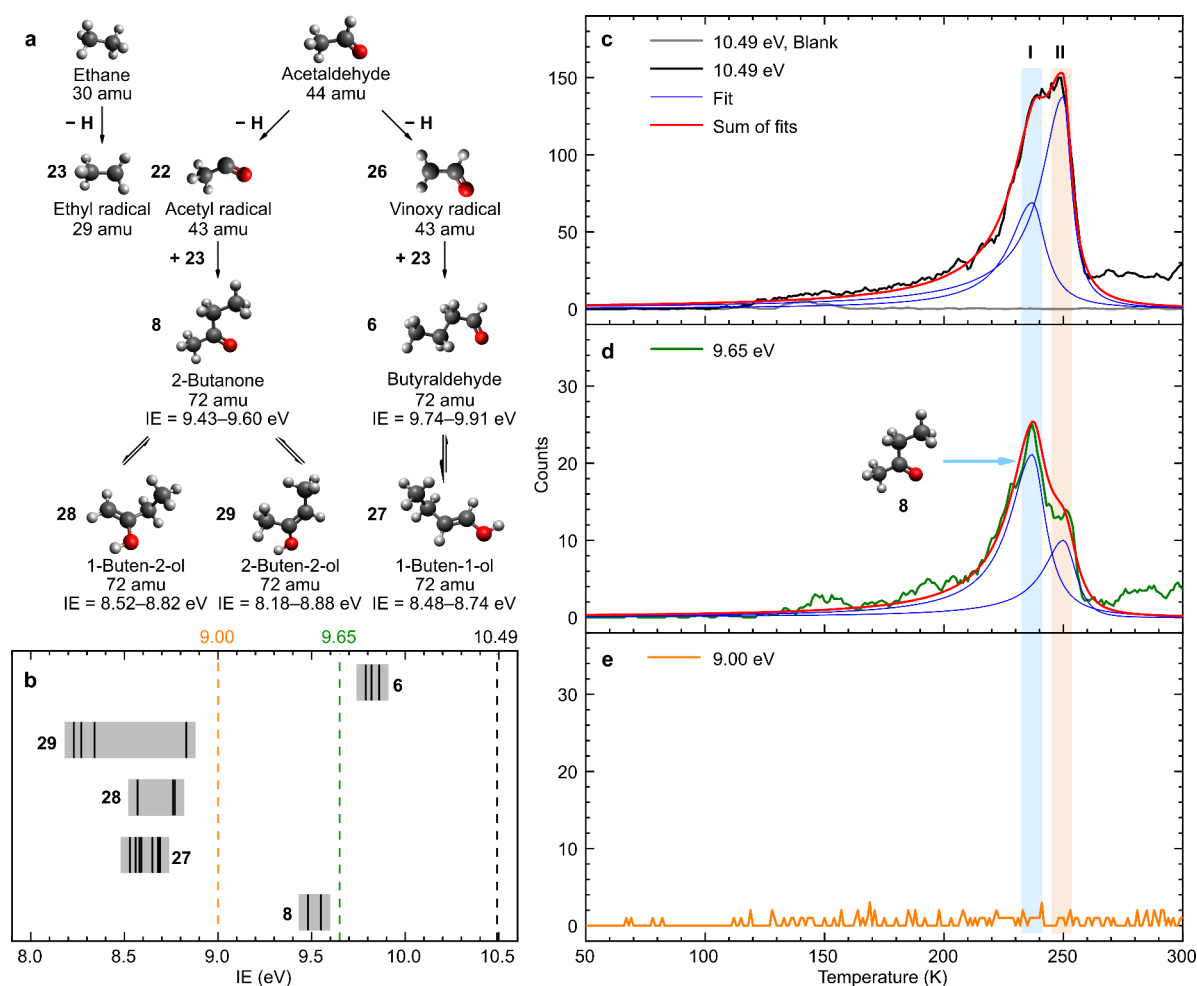


Figure 3. (a) Proposed formation pathways of five C_4H_8O ($m/z = 72$) isomers in irradiated $C_2H_6-CH_3CHO$ ices. Barrierless radical–radical reactions produce **6** and **8**, followed by tautomerization to enols **27**, **28**, and **29**. The computed adiabatic ionization energies (IEs; black solid line) and ranges of their conformers (gray area) are compiled (b). Dashed lines indicate the VUV photon energies used for photoionization. TPD profiles of $m/z = 72$ in $C_2H_6-CH_3CHO$ ices recorded at 10.49 eV (c), 9.65 eV (d), and 9.00 eV (e) are shown. The TPD profiles are fitted with two peaks (I and II), highlighted by the shaded regions. Peak I is assigned to isomer **8**. The red lines represent the overall fits.

cm^{-1} , correspond to ethylene (C_2H_4), carbon dioxide (CO_2), and carbon monoxide (CO), respectively.^{60,70} Additionally, absorptions at 3314 cm^{-1} and 3213 cm^{-1} are linked to acetylene (C_2H_2).⁶⁰ These additional products indicate that high dose irradiation promotes secondary decomposition and sequential reaction chemistry beyond the first-generation radical formation observed under low dose conditions. While FTIR spectroscopy reveals the formation of radical intermediates and small products in the irradiated ices, the C_4 carbonyls such as **7** and **8** cannot be uniquely identified via the infrared data alone: their absorptions are expected to overlap with those of reactants and a complex suite of products carrying the same carbonyl functional group.^{71,72} Therefore, an alternative, isomer-selective technique is clearly required to identify individual reaction products formed in these ices.

Photoionization Reflectron Time-of-Flight Mass Spectrometry

The photoionization reflectron time-of-flight mass spectrometry (PI-ReToF-MS) technique was utilized to identify individual C_4H_8O isomers formed in electron-irradiated ices during TPD based on their desorption profiles, isotope shifts, and adiabatic ionization energies (IEs).^{72,73} PI-ReToF data of the irradiated carbon monoxide (**17**)–propane (**18**) ices

during TPD are compiled in Figure 2 and Figure S6. Recall that the ices were studied at a low dose equivalent of cold molecular cloud galactic cosmic ray exposure of only $(8 \pm 2) \times 10^5$ yr to minimize sequential reactions,⁷⁴ thereby limiting the formation pathways to first-generation products.

In the $CO-C_3H_8$ system, five photon energies of 9.92, 9.72, 9.34, 8.45, and 8.17 eV were selected to distinguish the C_4H_8O isomers **6** and **7** accessed via radical–radical recombination and enolization, i.e. 1-buten-1-ol ($CH_3CH_2CHCHOH$, **27**) and 2-methylprop-1-en-1-ol ($((CH_3)_2CCHOH$, **25**) (Figure 2). At 9.92 eV, which can ionize all isomers if present, the TPD profile of $m/z = 72$ reveals sublimation events (Figure 2c), which can be deconvoluted into Peaks I and II using split Pearson VII distributions.^{62,75,76} A blank experiment carried out under otherwise identical conditions, but without electron irradiation, shows no sublimation event at $m/z = 72$ (Figure 2c and Figure S6a), confirming that Peaks I and II are caused by radiation-induced processing of the ices. Since all isomers **6** (IE = 9.74–9.91 eV), **7** (IE = 9.66–9.70 eV),⁷⁷ and their corresponding enols **27** (IE = 8.48–8.74 eV) and **25** (IE = 8.19–8.41 eV), can be photoionized at 9.92 eV (Figure 2 and Tables S5–S10), Peaks I and II could potentially originate from any of these isomers. Thereafter, the photon energy was

lowered to 9.72 eV, at which isomer **6** (IE = 9.74–9.91 eV) is not expected to be efficiently ionized; both Peaks I and II persisted (Figure 2d), indicating that no evidence for the formation of isomer **6** can be provided. Upon reducing the photon energy to 9.34 eV, at which only the enols **25** and **27** can be ionized, Peak I disappears while Peak II remains (Figure 2e); this finding suggests that Peak I can be associated with **7**. At an even lower photon energy of 8.45 eV, where only **25** can be ionized, a weak signal of Peak II remains (Figure 2f), indicating that Peak II can be assigned to **25**. Further lowering the photon energy to 8.17 eV, no signal is detected (Figure 2g), providing further support for the formation of **25**. Additionally, the ratio of the integrated areas of Peak I at 9.92 and 9.72 eV is 7.69 ± 0.76 ; this finding agrees well with the ratio of 7.51 ± 1.06 derived from the reference photoionization data of **7**,⁷⁸ providing further evidence for the formation of **7**.

The data for the $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ system are compiled in Figures 3 and 4 and Figure S8. VUV photons with energies of

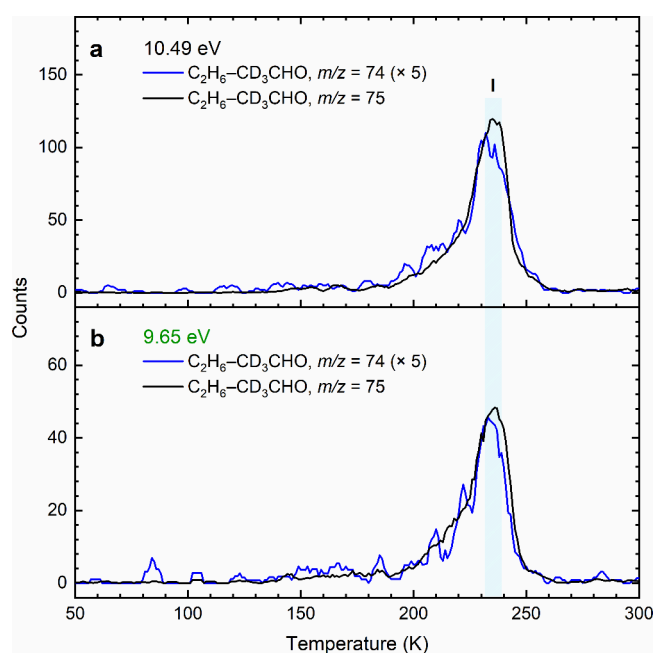


Figure 4. TPD profiles for $m/z = 74$ and 75 in irradiated $\text{C}_2\text{H}_6\text{--CD}_3\text{CHO}$ ice recorded at 10.49 eV (a) and 9.65 eV (b). The $m/z = 74$ traces are multiplied by a factor of 5 for clarity. The same scaling factor is applied at both photon energies, illustrating that the relative Peak I intensities at $m/z = 74$ and 75 remain essentially unchanged between 10.49 and 9.65 eV.

10.49, 9.65, and 9.00 eV were employed to photoionize and distinguish the first-generation $\text{C}_4\text{H}_8\text{O}$ products **6** and **8**, as well as their enols **27**, 1-buten-2-ol ($\text{CH}_2\text{C}(\text{OH})\text{CH}_2\text{CH}_3$, **28**), and 2-buten-2-ol ($\text{CH}_3\text{C}(\text{OH})\text{CHCH}_3$, **29**) (Figure 3). At 10.49 eV, all isomers can be ionized (Figure 3b). The TPD profile of ion signal at $m/z = 72$ obtained for the $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ice was deconvoluted to two split Pearson VII distributions peaking at 237 K (Peak I) and 250 K (Peak II), respectively (Figure 3c). A blank experiment of $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ice was performed without electron irradiation under otherwise identical conditions; no sublimation event was observed at $m/z = 72$ (Figure 3c and Figure S8a), confirming that the ion signal at $m/z = 72$ arises from the irradiation of ices. When the photon energy was lowered to 9.65 eV, at which isomer **6** (IE = 9.74–9.91 eV) is not expected to be

ionized, both Peaks I and II remain (Figure 3d). Therefore, no evidence for the formation of isomer **6** can be provided. Thereafter, the photon energy was further reduced to 9.00 eV; at this energy, enols **27** (IE = 8.48–8.74 eV), **28** (IE = 8.52–8.82 eV), and **29** (IE = 8.18–8.88 eV) can still be ionized, but not isomer **8** (IE = 9.43–9.60 eV). However, no sublimation events were observed at 9.00 eV (Figure 3e), indicating that the ion signals of Peaks I and II at 9.65 eV may be attributed to **8**, with no evidence for the formation of enols **27–29** in the low dose irradiation experiments. Additional support for the formation of **8** is provided by the isotopic substitution experiments in ethane–acetaldehyde- d_3 ($\text{C}_2\text{H}_6\text{--CD}_3\text{CHO}$) ices (Figure 4). According to the proposed reaction pathways in the $\text{C}_2\text{H}_6\text{--CD}_3\text{CHO}$ ice (Figure S9), isomer **6** shifts to $m/z = 74$ ($6\text{-}d_2$), whereas isomer **8** shifts to $m/z = 75$ ($8\text{-}d_3$). At 10.49 eV, the TPD profiles at $m/z = 74$ and 75 exhibit Peak I (Figure 4a). Since both $8\text{-}d_3$ and $6\text{-}d_2$ can be photoionized at 10.49 eV (Figure 3b), Peak I can be associated with both isomers. However, when the photon energy was reduced to 9.65 eV, at which only $8\text{-}d_3$ can be ionized, Peak I remains in TPD profiles of both $m/z = 74$ and 75 . Moreover, the relative intensity ratio of Peak I at $m/z = 74$ and 75 remains essentially the same at 10.49 and 9.65 eV, indicating that the ion signals at $m/z = 75$ and 74 originate from the same isomer and therefore supporting the assignment of Peak I to $8\text{-}d_3$.

To examine whether the ion signal at $m/z = 74$ may arise from the dissociative photoionization of $8\text{-}d_3$, gas phase experiments were conducted with isomer **8** at 10.49 eV (Figure S10); no ion signal at $m/z = 71$, which would correspond to a hydrogen atom loss from **8**, was detected. Therefore, ion signal at $m/z = 74$ observed in the $\text{C}_2\text{H}_6\text{--CD}_3\text{CHO}$ system does not arise from the fragmentation of $8\text{-}d_3$. Instead, this signal is rationalized by secondary H/D scrambling involving the CD_2CHO radical, formed via deuterium atom loss from CD_3CHO , followed by rapid hydrogen atom addition to generate CD_2HCHO prior to subsequent reactions. Consequently, no conclusive evidence for the formation of $6\text{-}d_2$ can be provided; Peak II in the $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ experiment is associated with fragment ions produced from higher-molecular-weight products, paraldehyde ($\text{C}_6\text{H}_{12}\text{O}_3$).¹⁵ Additionally, a high dose irradiation experiment of $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ice was performed. The TPD profile at $m/z = 72$ reveals a broad sublimation event at 9.00 eV (Figure S11), showing that enolization occurs under high dose processing; due to overlapping ionization energies, no attempt was made to discriminate these enol isomers.

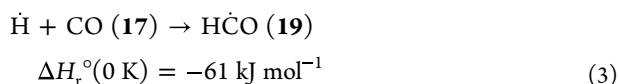
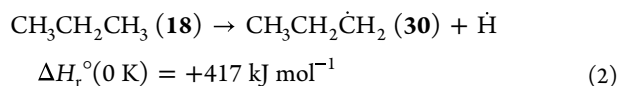
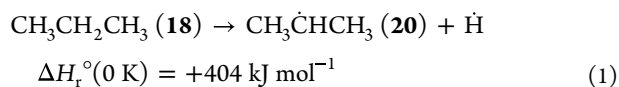
The formation yields of isomers **7** and **8** were quantified by combining calibration experiments using pure ices of **7** and **8** with the total energy deposited during electron irradiation in $\text{CO--C}_3\text{H}_8$ and $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ices. The numbers of molecules in the calibration ices were determined from their thicknesses and densities. The TPD profiles of the pure reference ices used for calibration are shown in Figure S7. Comparison of the integrated PI-ReToF-MS peak area of the isomer **7** calibration ice with that of Peak I at 9.92 eV (Figure 2c) yielded $(5.93 \pm 1.33) \times 10^{15}$ molecules of **7** in the irradiated $\text{CO--C}_3\text{H}_8$ ice. Similarly, comparison of the integrated peak area of the isomer **8** calibration ice with that of Peak I at 10.49 eV (Figure 3c) yielded $(8.78 \pm 1.76) \times 10^{14}$ molecules of **8** in the irradiated $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ice. The total energies deposited into the $\text{CO--C}_3\text{H}_8$ and $\text{C}_2\text{H}_6\text{--CH}_3\text{CHO}$ ices were calculated from the irradiation parameters and electron backscattering and transmission data obtained from

CASINO simulations, yielding $(1.43 \pm 0.21) \times 10^{17}$ and $(1.53 \pm 0.21) \times 10^{17}$ eV, respectively. Normalization of the product numbers to the corresponding deposited energies provided formation yields of $(4.14 \pm 1.11) \times 10^{-2}$ molecules eV^{-1} for 7 in the irradiated $\text{CO}-\text{C}_3\text{H}_8$ ice and $(5.75 \pm 1.40) \times 10^{-3}$ molecules eV^{-1} for 8 in the irradiated $\text{C}_2\text{H}_6-\text{CH}_3\text{CHO}$ ice (Table S11). Further details of the yield calculations are provided in the Supporting Information.

DISCUSSION

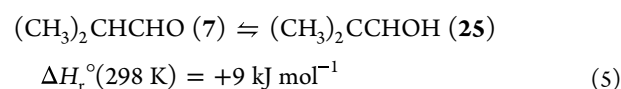
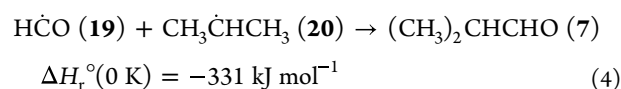
Having provided compelling evidence for the formation of isobutyraldehyde (7) and its enol 2-methylprop-1-en-1-ol (25) in irradiated interstellar ice analogues composed of carbon monoxide–propane ($\text{CO}-\text{C}_3\text{H}_8$), as well as 2-butanone (8) in irradiated ethane–acetaldehyde ($\text{C}_2\text{H}_6-\text{CH}_3\text{CHO}$) ices, we now turn our attention to potential formation mechanisms. In present experiments, the low dose irradiation was designed to minimize sequential reactions¹⁶ and thus to constrain the possible formation pathways of $\text{C}_4\text{H}_8\text{O}$ isomers. The electrons employed here act as proxies for secondary electrons generated by GCRs as they penetrate interstellar ices in cold molecular clouds.⁷⁹

In the exposed ices, propane ($\text{CH}_3\text{CH}_2\text{CH}_3$, 18) undergoes unimolecular decomposition through carbon–hydrogen bond cleavage to produce atomic hydrogen ($\dot{\text{H}}$) together with either the isopropyl radical ($\text{CH}_3\dot{\text{C}}\text{HCH}_3$, 20) via reaction 1, or the *n*-propyl radical ($\text{CH}_3\text{CH}_2\dot{\text{C}}\text{H}_2$, 30) via reaction 2. Reactions 1 and 2 are endoergic by 404 and 417 kJ mol^{-1} ,⁸⁰ and the required energy can be supplied by the impinging GCR proxies. The suprathermal hydrogen atom can add to carbon monoxide (CO , 17) to form the formyl radical ($\text{H}\dot{\text{C}}\text{O}$, 19) through reaction 3 with a reaction exoergicity of 61 kJ mol^{-1} .¹⁶ Previous work by Bennett et al. suggested an entrance barrier for reaction 3 to be 11 kJ mol^{-1} , which can be overcome by the excess kinetic energy of the suprathermal hydrogen atom.⁸¹ Recall that the formation of the formyl radical (19) in the irradiated $\text{CO}-\text{C}_3\text{H}_8$ ice is confirmed via the infrared absorption at 1796 cm^{-1} (ν_3).^{65,70}

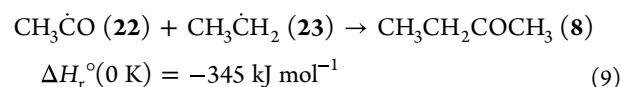
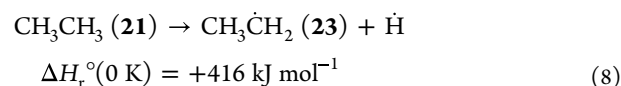
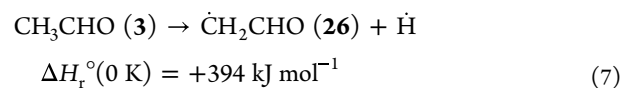
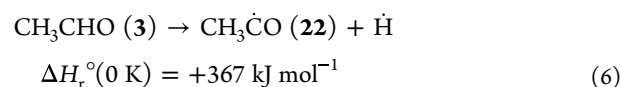


Once formed, 19 and 20 can recombine barrierlessly through carbon–carbon bond formation to yield isomer 7 via reaction 4, which is exoergic by 331 kJ mol^{-1} .^{80,82} It is worth noting that the radical–radical recombination can proceed either during irradiation at 5 K or during TPD at higher temperatures. However, the FTIR spectra indicate formation of carbonyl-bearing products, consistent with but not uniquely diagnostic of C_4 carbonyl formation at 5 K. Additionally, 7 can tautomerize to enol 25 with a reaction endoergicity of 9 kJ mol^{-1} via reaction 5.^{83,84} Although thermal tautomerization is unlikely at 5 K, energy deposited by energetic electrons as GCR proxies may promote the keto–enol tautomerization through nonequilibrium processing.⁸⁵ Previous irradiation experiments on acetaldehyde (3) ices demonstrated that

GCR proxies can induce keto–enol tautomerization through an intramolecular [1,3]-hydrogen shift under cold molecular cloud conditions.⁶² A similar irradiation-induced hydrogen-transfer mechanism may enable the conversion of 7 to 25 in the present ice system. Although butyraldehyde ($\text{CH}_3\text{CH}_2\text{CH}_2\text{CHO}$, 6) represents a plausible $\text{C}_4\text{H}_8\text{O}$ isomer in the $\text{CO}-\text{C}_3\text{H}_8$ system through recombination of radical 19 and radical 30, no evidence of 6 was observed, indicating that 30 is either not formed or is present at insufficient concentrations to produce detectable levels of 6 under our experimental conditions.



In the $\text{C}_2\text{H}_6-\text{CH}_3\text{CHO}$ system, upon interaction with energetic electrons as GCR proxies, acetaldehyde (CH_3CHO , 3) can undergo carbon–hydrogen bond cleavage to form the hydrogen atom plus the acetyl radical ($\text{CH}_3\dot{\text{C}}\text{O}$, 22) or the vinoxy radical ($\dot{\text{C}}\text{H}_2\text{CHO}$, 26) through reactions 6 and 7, which are endoergic by 367 and 394 kJ mol^{-1} , respectively.⁸⁰ Under the low dose conditions, acetaldehyde (3) is expected to produce 22 more efficiently than 26.^{73,86,87} Recall that acetyl radical (22) was identified by FTIR absorptions at 1839 cm^{-1} for 22 ($\text{CH}_3\dot{\text{C}}\text{O}$, ν_3) in irradiated $\text{C}_2\text{H}_6-\text{CH}_3\text{CHO}$, and at 1849 cm^{-1} for 22-*d*₃ ($\text{CD}_3\dot{\text{C}}\text{O}$, ν_3) in the irradiated $\text{C}_2\text{H}_6-\text{CD}_3\text{CHO}$ ice. Ethane (CH_3CH_3 , 21) undergoes carbon–hydrogen bond cleavage, yielding the ethyl radical ($\text{CH}_3\dot{\text{C}}\text{H}_2$, 23) via reaction 8, which is endoergic by 416 kJ mol^{-1} .⁸⁰ If radicals 22 and 23 are in a favorable, neighboring geometry within the ice matrix, barrierless carbon–carbon coupling can form isomer 8 through reaction 9, which is exoergic by 345 kJ mol^{-1} .⁸⁰



Carbon monoxide (17) and acetaldehyde (3) have been detected in interstellar ices at up to 55%^{14,45,46} and 10%⁵³ relative to water. Although the abundances of ethane (21) and propane (18) remain poorly constrained observationally, they can readily form in methane-bearing interstellar analogue ices under ionizing radiation such as GCRs.^{47,48} Therefore, the precursor combinations investigated here are chemically plausible constituents in interstellar icy grains. However, these binary ice mixtures were designed as simplified mechanistic systems to isolate the relevant reaction pathways and do not represent typical interstellar ice compositions, in

which water is a major component.⁸⁸ In water-rich interstellar ices, the ice composition may affect radical formation and subsequent reactions. Further experiments with water-containing ices may reveal the formation of other compounds and additional formation pathways. During the evolution of a cold molecular cloud toward a star-forming region, warming of icy grain mantles can release newly formed organics into the gas phase.¹⁶ The detection of **7** and **8** during TPD thus simulates the thermal desorption of these carbonyls during the warm-up stage. Since aldehydes and ketones constitute a key class of interstellar and meteoritic complex organic molecules,^{24–27} the present work provides laboratory evidence that C₄ carbonyls can be formed from simple ice constituents through irradiation-driven radical chemistry. Beyond astrochemical molecular growth, the formation of **7** and **8** provides possible connections to broader prebiotic reaction networks. As potential downstream chemistry, **7** and **8** may participate in Strecker-type chemistry to yield valine (**13**) and isovaline (**14**), respectively. In addition, oxidation of **7** could yield isobutyric acid (**15**), a precursor to branched-chain fatty acid chemistry, while carboxylation of **8** could provide access to levulinic acid (**16**). These downstream reactions were not investigated in the present study but are presented as plausible chemical connections. Therefore, **7** and **8** play crucial roles in linking low-temperature carbonyl formation to amino acids and fatty acids. The detection of **7**, **8**, and **13–16** in carbonaceous meteorites and asteroid-return samples^{27,34,39,42–44,89} is consistent with a broader scenario in which complex organic molecules formed in extraterrestrial environments,⁹ while the specific formation pathways in their parent bodies remain to be established. Altogether, the present study establishes a mechanistic foundation for the abiotic synthesis of C₄ carbonyls in interstellar ices, advancing our understanding of how biologically relevant molecules can be synthesized via nonequilibrium chemistry in deep space.

CONCLUSIONS

To conclude, we present the first formation pathways of isobutyraldehyde (**7**) and its enol 2-methylprop-1-en-1-ol (**25**), as well as 2-butanone (**8**), in low-temperature interstellar ice analogues composed of carbon monoxide–propane (CO–C₃H₈) and ethane–acetaldehyde (C₂H₆–CH₃CHO). The ice mixtures were exposed to energetic electrons, which simulate secondary electrons produced by GCRs as they penetrate icy grains in cold molecular clouds, corresponding to $(8 \pm 2) \times 10^5$ yr of GCR exposure.⁷⁴ Isomers **7**, **8**, and **25** were identified in the gas phase during TPD utilizing photoionization reflectron time-of-flight mass spectrometry (PI-ReToF-MS) along with isotopic substitution experiments. Isomers **7** and **8** were formed via radical–radical recombination of the formyl (HCO, **19**) radical with the isopropyl (CH₃CHCH₃, **20**) radical, and the acetyl (CH₃CO, **22**) radical with the ethyl (CH₃CH₂, **23**) radical, respectively; the enol **25** was produced through keto–enol tautomerization of **7**. The detection of these C₄ carbonyls highlights the critical roles of non-equilibrium chemistry in providing viable routes to complex aldehydes, ketones, and their enols under astrophysical conditions. It is important to note that CO–C₃H₈ and C₂H₆–CH₃CHO ices employed in this study serve as simplified model systems to probe the formation mechanisms of C₄H₈O isomers upon exposure to GCR proxies. Further studies using realistic multicomponent interstellar ice compositions may reveal additional reaction pathways and products.

MATERIALS AND METHODS

The experiments involved the preparation of low-temperature carbon monoxide–propane (CO–C₃H₈), ethane–acetaldehyde (C₂H₆–CH₃CHO), and isotopically labeled ethane–acetaldehyde-*d*₃ (C₂H₆–CD₃CHO) ice mixtures on silver substrate at 5 K in an ultrahigh vacuum chamber maintained at pressure of 5×10^{-11} Torr. The carbon monoxide–propane and ethane–acetaldehyde ices had compositions of $1:(1.1 \pm 0.2)$ and $(1.5 \pm 0.3):1$, respectively, as determined from infrared band integrations. The ices were irradiated with 5 keV electrons over an area of 1.6 cm² to initiate nonequilibrium chemistry. Low dose experiments were conducted at 20 nA for 5 min, corresponding to an electron flux of 7.8×10^{10} electrons cm⁻² s⁻¹ and a fluence of 2.3×10^{13} electrons cm⁻². The high dose C₂H₆–CH₃CHO experiment was performed at 106 nA for 60 min, corresponding to an electron flux of 4.1×10^{11} electrons cm⁻² s⁻¹ and a fluence of 1.5×10^{15} electrons cm⁻². CASINO 2.42 simulations showed that 99% of the deposited electron energy in low dose irradiation was confined within depths of 659 ± 22 nm for the CO–C₃H₈ ice and 532 ± 17 nm for the C₂H₆–CH₃CHO ice. Infrared spectra were recorded in situ before, during, and after irradiation. During TPD, the CO–C₃H₈ ices were heated from 5 to 320 at 1 K min⁻¹, whereas the C₂H₆–CH₃CHO and C₂H₆–CD₃CHO ices were heated at 0.5 K min⁻¹. The resulting ions during TPD were mass analyzed by tunable vacuum ultraviolet photoionization reflectron time-of-flight mass spectrometry (PI-ReToF-MS). Adiabatic ionization energies and relative energetics were calculated using the CBS-QB3 composite method. Additional experimental and computational details are provided in the Supporting Information.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acscentsci.6c00923>.

Methods (Experimental and Computational); Yield calculation; Aldehydes and ketones identified in interstellar medium (Figure S1); FTIR spectra data of irradiated carbon monoxide–propane and ethane–acetaldehyde ices (Figures S2–S5, Tables S1–S4); PI-ReToF-MS data during TPD of carbon monoxide–propane and ethane–acetaldehyde ices (Figures S6 and S8); TPD profiles of $m/z = 72$ for pure 2-butanone, butyraldehyde and isobutyraldehyde ices (Figure S7); Proposed formation pathways of isomers **6** and **8** in irradiated C₂H₆–CD₃CHO ices (Figure S9); Gas phase mass spectra of 2-butanone and butyraldehyde samples recorded at 10.49 eV (Figure S10); TPD profiles of $m/z = 72$ recorded at 9.00 eV in irradiated C₂H₆–CH₃CHO ices (Figure S11); Error analysis of adiabatic ionization energies and relative energies (Tables S5–S10); Parameters used to calculate the yields of isobutyraldehyde and 2-butanone (Table S11); Experimental conditions (Tables S12 and S13); VUV generation parameters (Table S14); Cartesian coordinates (Å), and harmonic frequencies (cm⁻¹) of isomer **6**, **8**, **25**, **27**, **28**, **29** (Table S15–S20) (PDF)

AUTHOR INFORMATION

Corresponding Author

Ralf I. Kaiser – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States; orcid.org/0000-0002-7233-7206; Email: ralfk@hawaii.edu

Authors

Zesen Wang – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States

Jia Wang – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States

Anastasia S. Shishova – Samara National Research University, Samara 443086, Russia

Sergey O. Tuchin – Samara National Research University, Samara 443086, Russia

Mason McAnally – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States;
orcid.org/0009-0000-7799-9914

Andrew M. Turner – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States

Niki Jabari – W. M. Keck Research Laboratory in Astrochemistry and Department of Chemistry, University of Hawaii at Manoa, Honolulu, Hawaii 96822, United States

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acscentsci.6c00923>

Author Contributions

R.I.K. designed research; Z.W., J.W., M.M., A.M.T., and N.J. performed research; Z.W. and J.W. analyzed data; A.S.S. and S.O.T. performed calculations; Z.W. and R.I.K. wrote the paper.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The experiments were conducted at the University of Hawaii at Manoa and supported by the U.S. National Science Foundation (NSF), Division of Astronomical Sciences (AST-2403867). We also thank the University of Hawaii at Manoa and the W. M. Keck Foundation for funding the construction of the experimental setup.

REFERENCES

- (1) Snyder, L. E.; Buhl, D.; Zuckerman, B.; Palmer, P. Microwave Detection of Interstellar Formaldehyde. *Phys. Rev. Lett.* **1969**, *22* (13), 679–681.
- (2) Combes, F.; Gerin, M.; Wootten, A.; Wlodarczak, G.; Clauset, F.; Encrenaz, P. J. Acetone in Interstellar Space. *Astron. Astrophys.* **1987**, *180*, L13–L16.
- (3) McGuire, B. A. 2021 Census of Interstellar, Circumstellar, Extragalactic, Protoplanetary Disk, and Exoplanetary Molecules. *Astrophys. J. Suppl. Ser.* **2022**, *259* (2), 30.
- (4) Sanz-Novato, M.; Belloche, A.; Rivilla, V. M.; Garrod, R. T.; Alonso, J. L.; Redondo, P.; Barrientos, C.; Kolesniková, L.; Valle, J. C.; Rodríguez-Almeida, L.; Jiménez-Serra, I.; Martín-Pintado, J.; Müller, H. S. P.; Menten, K. M. Toward the Limits of Complexity of Interstellar Chemistry: Rotational Spectroscopy and Astronomical Search for *n*- and *i*-Butanal. *Astron. Astrophys.* **2022**, *666*, A114.
- (5) Li, C.; Qin, S.-L.; Liu, T.; Liu, X.; Li, X.; Chen, L.; Liu, H.-L.; Xu, F.; Liu, M.; Tang, M.; Shi, H.; Zhang, T.; Wu, Y. ALMA Observations of CH₃COCH₃ and the Related Species CH₃CHO, CH₃OH, and C₂H₅CN in Line-Rich Molecular Cores. *Astron. Astrophys.* **2025**, *696*, A7.
- (6) Herbst, E.; Van Dishoeck, E. F. Complex Organic Interstellar Molecules. *Annu. Rev. Astron. Astrophys.* **2009**, *47* (1), 427–480.
- (7) Abplanalp, M. J.; Gozem, S.; Krylov, A. I.; Shingledecker, C. N.; Herbst, E.; Kaiser, R. I. A Study of Interstellar Aldehydes and Enols as Tracers of a Cosmic Ray-Driven Nonequilibrium Synthesis of Complex Organic Molecules. *Proc. Natl. Acad. Sci. U. S. A.* **2016**, *113* (28), 7727–7732.
- (8) Ramal-Olmedo, J. C.; Menor-Salván, C. A.; Fortenberry, R. C. Mechanisms for Gas-Phase Molecular Formation of Neutral Formaldehyde (H₂CO) in Cold Astrophysical Regions. *Astron. Astrophys.* **2021**, *656*, A148.
- (9) Ehrenfreund, P.; Charnley, S. B. Organic Molecules in the Interstellar Medium, Comets, and Meteorites: A Voyage from Dark Clouds to the Early Earth. *Annu. Rev. Astron. Astrophys.* **2000**, *38* (1), 427–483.
- (10) De Marcellus, P.; Meinert, C.; Myrgorodska, I.; Nahon, L.; Buhse, T.; d'Hendecourt, L. L. S.; Meierhenrich, U. J. Aldehydes and Sugars from Evolved Precometary Ice Analogs: Importance of Ices in Astrochemical and Prebiotic Evolution. *Proc. Natl. Acad. Sci. U. S. A.* **2015**, *112* (4), 965–970.
- (11) Sandford, S. A.; Nuevo, M.; Bera, P. P.; Lee, T. J. Prebiotic Astrochemistry and the Formation of Molecules of Astrobiological Interest in Interstellar Clouds and Protostellar Disks. *Chem. Rev.* **2020**, *120* (11), 4616–4659.
- (12) Bennett, C. J.; Osamura, Y.; Lebar, M. D.; Kaiser, R. I. Laboratory Studies on the Formation of Three C₂H₄O Isomers—Acetaldehyde (CH₃CHO), Ethylene Oxide (c-C₂H₄O), and Vinyl Alcohol (CH₂CHOH)—in Interstellar and Cometary Ices. *Astrophys. J.* **2005**, *634* (1), 698–711.
- (13) Singh, S. K.; Fabian Kleimeier, N.; Eckhardt, A. K.; Kaiser, R. I. A Mechanistic Study on the Formation of Acetone (CH₃COCH₃), Propanal (CH₃CH₂CHO), Propylene Oxide (c-CH₃CHOCH₂) along with Their Propenol Enols (CH₃CHCHOH/CH₃C(OH)CH₂) in Interstellar Analog Ices. *Astrophys. J.* **2022**, *941* (2), 103.
- (14) Cuppen, H. M.; Linnartz, H.; Ioppolo, S. Laboratory and Computational Studies of Interstellar Ices. *Annu. Rev. Astron. Astrophys.* **2024**, *62* (1), 243–286.
- (15) Wang, J.; Turner, A. M.; Marks, J. H.; Fortenberry, R. C.; Kaiser, R. I. Formation of Paraldehyde (C₆H₁₂O₃) in Interstellar Analog Ices of Acetaldehyde Exposed to Ionizing Radiation. *ChemPhysChem* **2024**, *25* (22), No. e202400837.
- (16) Wang, J.; Zhang, C.; Marks, J. H.; Evseev, M. M.; Kuznetsov, O. V.; Antonov, I. O.; Kaiser, R. I. Interstellar Formation of Lactaldehyde, a Key Intermediate in the Methylglyoxal Pathway. *Nat. Commun.* **2024**, *15* (1), No. 10189.
- (17) Oba, Y.; Takano, Y.; Naraoka, H.; Watanabe, N.; Kouchi, A. Nucleobase Synthesis in Interstellar Ices. *Nat. Commun.* **2019**, *10* (1), 4413.
- (18) Ziurys, L. M. Prebiotic Astrochemistry from Astronomical Observations and Laboratory Spectroscopy. *Annu. Rev. Phys. Chem.* **2024**, *75* (1), 307–327.
- (19) Gottlieb, C. A. Detection of Acetaldehyde in Sagittarius. In *Molecules in the Galactic Environment*; John Wiley and Sons, 1973; p 181.
- (20) Fourikis, N.; Sinclair, M.; Robinson, B.; Godfrey, P.; Brown, R. Microwave Emission of the 2₁₁→2₁₂ Rotational Transition in Interstellar Acetaldehyde. *Aust. J. Phys.* **1974**, *27* (3), 425–430.
- (21) Gilmore, W.; Morris, M.; Palmer, P.; Johnson, D. R.; Lovas, F. J.; Turner, B. E.; Zuckerman, B. Observation of the 6₁₆-5₁₅ Transitions of Acetaldehyde in Sagittarius B2. *Astrophys. J.* **1976**, *204*, 43.
- (22) Hollis, J. M.; Jewell, P. R.; Lovas, F. J.; Remijan, A.; Møllendal, H. Green Bank Telescope Detection of New Interstellar Aldehydes: Propanal and Propanol. *Astrophys. J.* **2004**, *610*, L21–L24.
- (23) Zhou, Y.; Quan, D.-H.; Zhang, X.; Qin, S.-L. Detection of Hydroxyacetone in Protostar IRAS 16293–2422 B. *Res. Astron. Astrophys.* **2020**, *20*, 125.
- (24) Aponte, J. C.; Whitaker, D.; Powner, M. W.; Elsila, J. E.; Dworkin, J. P. Analyses of Aliphatic Aldehydes and Ketones in Carbonaceous Chondrites. *ACS Earth Space Chem.* **2019**, *3* (3), 463–472.

- (25) Simkus, D. N.; Aponte, J. C.; Hilts, R. W.; Elsila, J. E.; Herd, C. D. K. Compound-specific Carbon Isotope Compositions of Aldehydes and Ketones in the Murchison Meteorite. *Meteorit. Planet. Sci.* **2019**, *54* (1), 142–156.
- (26) Aponte, J. C.; Séguin, F.; Siguelnitzky, A. J.; Dworkin, J. P.; Elsila, J. E.; Glavin, D. P.; Connolly, H. C.; Lauretta, D. S. Molecular Distribution and ^{13}C Isotope Composition of Volatile Organic Compounds in the Murchison and Sutter's Mill Carbonaceous Chondrites. *Meteorit. Planet. Sci.* **2024**, *59* (2), 286–300.
- (27) Glavin, D. P.; Eckley, S. A.; Aponte, J. C.; Berger, E. L.; Burton, A. S.; Dworkin, J. P.; Elsila, J. E.; Ferguson, F. T.; Furukawa, Y.; Graham, H. V.; Koga, T.; Liss, M.; McLain, H. L.; Naraoka, H.; Oba, Y.; Parker, E. T.; Richter, K.; Schmitt-Kopplin, P.; Simkus, D. N.; Takano, Y.; Connolly, H. C.; Lauretta, D. S. Investigating the Impact of X-ray Computed Tomography Imaging on Soluble Organic Matter in the Murchison Meteorite: Implications for Benu Sample Analyses. *Meteorit. Planet. Sci.* **2024**, *59* (1), 105–133.
- (28) Chyba, C.; Sagan, C. Endogenous Production, Exogenous Delivery and Impact-Shock Synthesis of Organic Molecules: An Inventory for the Origins of Life. *Nature* **1992**, *355* (6356), 125–132.
- (29) Ehrenfreund, P.; Menten, K. M. From Molecular Clouds to the Origin of Life. In *Astrobiology: The Quest for the Conditions of Life*; Horneck, G.; Baumstark-Khan, C., Eds.; Springer Berlin Heidelberg: Berlin, Heidelberg, 2002; pp 7–23, DOI: 10.1007/978-3-642-59381-9_2.
- (30) Ashe, K.; Fernández-García, C.; Corpinot, M. K.; Coggins, A. J.; Bučar, D.-K.; Powner, M. W. Selective Prebiotic Synthesis of Phosphoroaminonitriles and Aminothioamides in Neutral Water. *Commun. Chem.* **2019**, *2* (1), 23.
- (31) Tran, Q. P.; Adam, Z. R.; Fahrenbach, A. C. Prebiotic Reaction Networks in Water. *Life* **2020**, *10* (12), 352.
- (32) Magrino, T.; Pietrucci, F.; Saitta, A. M. Step by Step Strecker Amino Acid Synthesis from Ab Initio Prebiotic Chemistry. *J. Phys. Chem. Lett.* **2021**, *12* (10), 2630–2637.
- (33) Koga, T.; Naraoka, H. Synthesis of Amino Acids from Aldehydes and Ammonia: Implications for Organic Reactions in Carbonaceous Chondrite Parent Bodies. *ACS Earth Space Chem.* **2022**, *6* (5), 1311–1320.
- (34) Baczynski, A. A.; McIntosh, O. M.; Simkus, D. N.; McLain, H. L.; Dworkin, J. P.; Glavin, D. P.; Elsila, J. E.; Matney, M.; House, C. H.; Freeman, K. H.; Connolly, H. C.; Lauretta, D. S. Multiple Formation Pathways for Amino Acids in the Early Solar System Based on Carbon and Nitrogen Isotopes in Asteroid Benu Samples. *Proc. Natl. Acad. Sci. U. S. A.* **2026**, *123* (8), No. e2517723123.
- (35) De Zotti, M.; Biondi, B.; Crisma, M.; Hjørringgaard, C. U.; Berg, A.; Brückner, H.; Toniolo, C. Isovaline in Naturally Occurring Peptides: A Nondestructive Methodology for Configurational Assignment. *Pept. Sci.* **2012**, *98* (1), 36–49.
- (36) Furukawa, Y.; Otake, T.; Ishiguro, T.; Nakazawa, H.; Kakegawa, T. Abiotic Formation of Valine Peptides Under Conditions of High Temperature and High Pressure. *Orig. Life Evol. Biospheres* **2012**, *42* (6), 519–531.
- (37) Pizzarello, S.; Zolensky, M.; Turk, K. A. Nonracemic Isovaline in the Murchison Meteorite: Chiral Distribution and Mineral Association. *Geochim. Cosmochim. Acta* **2003**, *67* (8), 1589–1595.
- (38) Glavin, D. P.; Dworkin, J. P. Enrichment of the Amino Acid L-Isovaline by Aqueous Alteration on CI and CM Meteorite Parent Bodies. *Proc. Natl. Acad. Sci. U. S. A.* **2009**, *106* (14), 5487–5492.
- (39) Glavin, D. P.; Elsila, J. E.; McLain, H. L.; Aponte, J. C.; Parker, E. T.; Dworkin, J. P.; Hill, D. H.; Connolly, H. C.; Lauretta, D. S. Extraterrestrial Amino Acids and L-enantiomeric Excesses in the CM2 Carbonaceous Chondrites Aguas Zarcas and Murchison. *Meteorit. Planet. Sci.* **2021**, *56* (1), 148–173.
- (40) Whaley, S. G.; Frank, M. W.; Rock, C. O. A Short-Chain Acyl-CoA Synthetase That Supports Branched-Chain Fatty Acid Synthesis in *Staphylococcus Aureus*. *J. Biol. Chem.* **2023**, *299* (4), No. 103036.
- (41) Cooper, G.; Reed, C.; Nguyen, D.; Carter, M.; Wang, Y. Detection and Formation Scenario of Citric Acid, Pyruvic Acid, and Other Possible Metabolism Precursors in Carbonaceous Meteorites. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108* (34), 14015–14020.
- (42) Mimura, K.; Yamada, R.; Maejima, N.; Kawamura, K.; Kunwar, B.; Hashiguchi, M. Analysis of Monocarboxylic Acids in the Murchison Meteorite by Sequential Extraction. *ACS Earth Space Chem.* **2024**, *8* (7), 1313–1323.
- (43) Burton, A. S.; Stern, J. C.; Elsila, J. E.; Glavin, D. P.; Dworkin, J. P. Understanding Prebiotic Chemistry through the Analysis of Extraterrestrial Amino Acids and Nucleobases in Meteorites. *Chem. Soc. Rev.* **2012**, *41* (16), 5459–5472.
- (44) Koga, T.; Naraoka, H. A New Family of Extraterrestrial Amino Acids in the Murchison Meteorite. *Sci. Rep.* **2017**, *7* (1), 636.
- (45) Boogert, A. C. A.; Gerakines, P. A.; Whittet, D. C. B. Observations of the Icy Universe. *Annu. Rev. Astron. Astrophys.* **2015**, *53* (1), 541–581.
- (46) Thi, W.-F.; Van Dishoeck, E. F.; Dartois, E.; Pontoppidan, K. M.; Schutte, W. A.; Ehrenfreund, P.; d'Hendecourt, L.; Fraser, H. J. VLT-ISAAC 3–5 μm Spectroscopy of Embedded Young Low-Mass Stars: III. Intermediate-Mass Sources in Vela. *Astron. Astrophys.* **2006**, *449* (1), 251–265.
- (47) Bennett, C. J.; Jamieson, C. S.; Osamura, Y.; Kaiser, R. I. Laboratory Studies on the Irradiation of Methane in Interstellar, Cometary, and Solar System Ices. *Astrophys. J.* **2006**, *653* (1), 792–811.
- (48) Abplanalp, M. J.; Jones, B. M.; Kaiser, R. I. Untangling the Methane Chemistry in Interstellar and Solar System Ices toward Ionizing Radiation: A Combined Infrared and Reflectron Time-of-Flight Analysis. *Phys. Chem. Chem. Phys.* **2018**, *20* (8), 5435–5468.
- (49) Matthews, H. E.; Friber, P.; Irvine, W. M. The Detection of Acetaldehyde in Cold Dust Clouds. *Astrophys. J.* **1985**, *290*, 609–614.
- (50) Nummelin, A.; Dickens, J. E.; Bergman, P.; Hjalmarsen, A.; Irvine, W. M.; Ikeda, M.; Ohishi, M. Abundances of Ethylene Oxide and Acetaldehyde in Hot Molecular Cloud Cores. *Astron. Astrophys.* **1998**, *337*, 275–286.
- (51) Jungclaus, G. A.; Yuen, G. U.; Moore, C. B.; Lawless, J. G. Evidence for the Presence of Low Molecular Weight Alcohols and Carbonyl Compounds in the Murchison Meteorite. *Meteoritics* **1976**, *11* (3), 231–237.
- (52) Crovisier, J.; Bockelée-Morvan, D.; Colom, P.; Biver, N.; Despois, D.; Lis, D. C. The Composition of Ices in Comet C/1995 O1 (Hale-Bopp) from Radio Spectroscopy: Further Results and Upper Limits on Undetected Species. *Astron. Astrophys.* **2004**, *418* (3), 1141–1157.
- (53) Gibb, E.; Nummelin, A.; Irvine, W. M.; Whittet, D. C. B.; Bergman, P. Chemistry of the Organic-rich Hot Core G327.3–0.6. *Astrophys. J.* **2000**, *545* (1), 309–326.
- (54) Bouilloud, M.; Fray, N.; Bénilan, Y.; Cottin, H.; Gazeau, M.-C.; Jolly, A. Bibliographic Review and New Measurements of the Infrared Band Strengths of Pure Molecules at 25 K: H_2O , CO_2 , CO , CH_4 , NH_3 , CH_3OH , HCOOH and H_2CO . *Mon. Not. R. Astron. Soc.* **2015**, *451* (2), 2145–2160.
- (55) Gough, K. M.; Murphy, W. F.; Raghavachari, K. The Harmonic Force Field of Propane. *J. Chem. Phys.* **1987**, *87* (6), 3332–3340.
- (56) Ghosh, J.; Hariharan, A. K.; Bhui, R. G.; Methikkalam, R. R. J.; Pradeep, T. Propane and Propane–Water Interactions: A Study at Cryogenic Temperatures. *Phys. Chem. Chem. Phys.* **2018**, *20* (3), 1838–1847.
- (57) Hudson, R. L.; Gerakines, P. A.; Yarnall, Y. Y.; Coones, R. T. Infrared Spectra and Optical Constants of Astronomical Ices: III. Propane, Propylene, and Propyne. *Icarus* **2021**, *354*, No. 114033.
- (58) Kaiser, R. I.; Maity, S.; Jones, B. M. Infrared and Reflectron Time-of-Flight Mass Spectroscopic Analysis of Methane (CH_4)–Carbon Monoxide (CO) Ices Exposed to Ionization Radiation – toward the Formation of Carbonyl-Bearing Molecules in Extraterrestrial Ices. *Phys. Chem. Chem. Phys.* **2014**, *16* (8), 3399–3424.
- (59) Bennett, C. J.; Kaiser, R. I. The Formation of Acetic Acid (CH_3COOH) in Interstellar Ice Analogs. *Astrophys. J.* **2007**, *660* (2), 1289–1295.

- (60) Abplanalp, M. J.; Kaiser, R. I. Complex Hydrocarbon Chemistry in Interstellar and Solar System Ices Revealed: A Combined Infrared Spectroscopy and Reflectron Time-of-Flight Mass Spectrometry Analysis of Ethane (C_2H_6) and D6-Ethane (C_2D_6) Ices Exposed to Ionizing Radiation. *Astrophys. J.* **2016**, 827 (2), 132.
- (61) Crighton, J. S.; Bell, S. Structure and Potential Energy Functions for Acetaldehyde: *Ab Initio* Calculations of $\tilde{X}^1A'$, $\tilde{A}^1A''$, and $\tilde{B}^1A'$ States. *J. Mol. Spectrosc.* **1985**, 112 (2), 285–303.
- (62) Kleimeier, N. F.; Kaiser, R. I. Interstellar Enolization-acetaldehyde (CH_3CHO) and Vinyl Alcohol ($H_2CCH(OH)$) as a Case Study. *ChemPhysChem* **2021**, 22 (12), 1229–1236.
- (63) McMurtry, B. M.; Turner, A. M.; Saito, S. E. J.; Kaiser, R. I. On the Formation of Niacin (Vitamin B3) and Pyridine Carboxylic Acids in Interstellar Model Ices. *Chem. Phys.* **2016**, 472, 173–184.
- (64) Abplanalp, M. J.; Borsuk, A.; Jones, B. M.; Kaiser, R. I. On the Formation and Isomer-Specific Detection of Propenal (C_2H_3CHO) and Cyclopropanone ($c-C_3H_4O$) in Interstellar Model Ices—A Combined FTIR and Reflectron Time-of-Flight Mass Spectroscopic Study. *Astrophys. J.* **2015**, 814 (1), 45.
- (65) Eckhardt, A. K.; Bergantini, A.; Singh, S. K.; Schreiner, P. R.; Kaiser, R. I. Formation of Glyoxylic Acid in Interstellar Ices: A Key Entry Point for Prebiotic Chemistry. *Angew. Chem., Int. Ed.* **2019**, 58 (17), 5663–5667.
- (66) Jacox, M. E. The Reaction of F Atoms with Acetaldehyde and Ethylene Oxide. Vibrational Spectra of the CH_3CO and CH_2CHO Free Radicals Trapped in Solid Argon. *Chem. Phys.* **1982**, 69 (3), 407–422.
- (67) Hudson, R. L.; Ferrante, R. F. Quantifying Acetaldehyde in Astronomical Ices and Laboratory Analogues: IR Spectra, Intensities, ^{13}C Shifts, and Radiation Chemistry. *Mon. Not. R. Astron. Soc.* **2020**, 492 (1), 283–293.
- (68) Kleimeier, N. F.; Turner, A. M.; Fortenberry, R. C.; Kaiser, R. I. On the Formation of the Popcorn Flavorant 2,3-butanedione ($CH_3COCOCH_3$) in Acetaldehyde-containing Interstellar Ices. *ChemPhysChem* **2020**, 21 (14), 1531–1540.
- (69) Hudson, R. L.; Loeffler, M. J. Ketene Formation in Interstellar Ices: A Laboratory Study. *Astrophys. J.* **2013**, 773 (2), 109.
- (70) Wang, J.; Marks, J. H.; Batrakova, E. A.; Tuchin, S. O.; Antonov, I. O.; Kaiser, R. I. Formation of Methylglyoxal ($CH_3C(O)CHO$) in Interstellar Analog Ices – a Key Intermediate in Cellular Metabolism. *Phys. Chem. Chem. Phys.* **2024**, 26 (36), 23654–23662.
- (71) Abplanalp, M. J.; Förstel, M.; Kaiser, R. I. Exploiting Single Photon Vacuum Ultraviolet Photoionization to Unravel the Synthesis of Complex Organic Molecules in Interstellar Ices. *Chem. Phys. Lett.* **2016**, 644, 79–98.
- (72) Turner, A. M.; Kaiser, R. I. Exploiting Photoionization Reflectron Time-of-Flight Mass Spectrometry to Explore Molecular Mass Growth Processes to Complex Organic Molecules in Interstellar and Solar System Ice Analogs. *Acc. Chem. Res.* **2020**, 53 (12), 2791–2805.
- (73) Wang, J.; Marks, J. H.; Turner, A. M.; Nikolayev, A. A.; Azyazov, V.; Mebel, A. M.; Kaiser, R. I. Mechanistical Study on the Formation of Hydroxyacetone (CH_3COCH_2OH), Methyl Acetate (CH_3COOCH_3), and 3-Hydroxypropanal ($HCOCH_2CH_2OH$) along with Their Enol Tautomers (Prop-1-Ene-1,2-Diol ($CH_3C(OH)CHOH$), Prop-2-Ene-1,2-Diol ($CH_2C(OH)CH_2OH$), 1-Methoxyethen-1-ol ($CH_3OC(OH)CH_2$) and Prop-1-Ene-1,3-Diol ($HOCH_2CHCHOH$)) in Interstellar Ice Analogs. *Phys. Chem. Chem. Phys.* **2023**, 25 (2), 936–953.
- (74) Yeghikyan, A. G. Irradiation of Dust in Molecular Clouds. II. Doses Produced by Cosmic Rays. *Astrophysics* **2011**, 54 (1), 87–99.
- (75) Wang, J.; Zhang, C.; Marks, J. H.; Kaiser, R. I. Formation of All Three C_2H_4O Isomers—Ethylene Oxide ($c-C_2H_4O$), Acetaldehyde (CH_3CHO), and Vinyl Alcohol (CH_2CHOH)—in Ethanol-Containing Interstellar Analog Ices. *Astrophys. J.* **2025**, 984 (2), 138.
- (76) Wang, J.; Marks, J. H.; Eckhardt, A. K.; Kaiser, R. I. Bottom-Up Formation of Antiaromatic Cyclobutadiene ($c-C_4H_4$) in Interstellar Ice Analogs. *J. Phys. Chem. Lett.* **2024**, 15 (5), 1211–1217.
- (77) Lias, S. G. Ionization Energy Evaluation. In *NIST Chemistry WebBook*; Linstrom, P. J., Mallard, W. G., Eds.; NIST Standard Reference Database Number 69; National Institute of Standards and Technology: Gaithersburg, MD, DOI: 10.18434/T4D303.
- (78) Yang, B.; Wang, J.; Cool, T. A.; Hansen, N.; Skeen, S.; Osborn, D. L. Absolute Photoionization Cross-Sections of Some Combustion Intermediates. *Int. J. Mass Spectrom.* **2012**, 309, 118–128.
- (79) Kaiser, R. I.; Roessler, K. Theoretical and Laboratory Studies on the Interaction of Cosmic-Ray Particles with Interstellar Ices. I. Synthesis of Polycyclic Aromatic Hydrocarbons by a Cosmic-Ray-Induced Multicenter Mechanism. *Astrophys. J.* **1997**, 475 (1), 144–154.
- (80) Ruscic, B.; Bross, D. *Active Thermochemical Tables (ATcT) Values Based on Ver. 1.220 of the Thermochemical Network 2025*, DOI: 10.17038/CSE/2568691.
- (81) Bennett, C. J.; Jamieson, C. S.; Osamura, Y.; Kaiser, R. I. A Combined Experimental and Computational Investigation on the Synthesis of Acetaldehyde [$CH_3CHO(X^1A')$] in Interstellar Ices. *Astrophys. J.* **2005**, 624 (2), 1097–1115.
- (82) Harrison, A. W.; Kable, S. H. Photodissociation Dynamics of Propanal and Isobutanal: The Norrish Type I Pathway. *J. Chem. Phys.* **2018**, 148 (16), No. 164308.
- (83) Turecek, F.; Brabec, L.; Korvola, J. Unstable Enols in the Gas Phase. Preparation Ionization, Energies, and Heats of Formation of (E)- and (Z)-2-Buten-2-ol, 2-Methyl-1-Propen-1-ol, and 3-Methyl-2-Buten-2-ol. *J. Am. Chem. Soc.* **1988**, 110 (24), 7984–7990.
- (84) Wiberg, K. B.; Crocker, L. S.; Morgan, K. M. Thermochemical Studies of Carbonyl Compounds. 5. Enthalpies of Reduction of Carbonyl Groups. *J. Am. Chem. Soc.* **1991**, 113 (9), 3447–3450.
- (85) Wang, J.; Marks, J. H.; Tuli, L. B.; Mebel, A. M.; Azyazov, V. N.; Kaiser, R. I. Formation of Thioformic Acid ($HCOSH$)—The Simplest Thioacid—in Interstellar Ice Analogues. *J. Phys. Chem. A* **2022**, 126 (51), 9699–9708.
- (86) Kleimeier, N. F.; Eckhardt, A. K.; Schreiner, P. R.; Kaiser, R. I. Interstellar Formation of Biorelevant Pyruvic Acid ($CH_3COCOCH_3$). *Chem.* **2020**, 6 (12), 3385–3395.
- (87) Kleimeier, N. F.; Eckhardt, A. K.; Kaiser, R. I. A Mechanistic Study on the Formation of Acetic Acid (CH_3COOH) in Polar Interstellar Analog Ices Exploiting Photoionization Reflectron Time-of-Flight Mass Spectrometry. *Astrophys. J.* **2020**, 901 (1), 84.
- (88) Öberg, K. I. Photochemistry and Astrochemistry: Photochemical Pathways to Interstellar Complex Organic Molecules. *Chem. Rev.* **2016**, 116 (17), 9631–9663.
- (89) Naraoka, H.; Takano, Y.; Dworkin, J. P.; Oba, Y.; Hamase, K.; Furusho, A.; Ogawa, N. O.; Hashiguchi, M.; Fukushima, K.; Aoki, D.; Schmitt-Kopplin, P.; Aponte, J. C.; Parker, E. T.; Glavin, D. P.; McLain, H. L.; Elsila, J. E.; Graham, H. V.; Eiler, J. M.; Orthous-Daunay, F.-R.; Wolters, C.; Isa, J.; Vuitton, V.; Thissen, R.; Sakai, S.; Yoshimura, T.; Koga, T.; Ohkouchi, N.; Chikaraishi, Y.; Sugahara, H.; Mita, H.; Furukawa, Y.; Hertkorn, N.; Ruf, A.; Yurimoto, H.; Nakamura, T.; Noguchi, T.; Okazaki, R.; Yabuta, H.; Sakamoto, K.; Tachibana, S.; Connolly, H. C.; Lauretta, D. S.; Abe, M.; Yada, T.; Nishimura, M.; Yogata, K.; Nakato, A.; Yoshitake, M.; Suzuki, A.; Miyazaki, A.; Furuya, S.; Hatakeda, K.; Soejima, H.; Hitomi, Y.; Kumagai, K.; Usui, T.; Hayashi, T.; Yamamoto, D.; Fukui, R.; Kitazato, K.; Sugita, S.; Namiki, N.; Arakawa, M.; Ikeda, H.; Ishiguro, M.; Hirata, N.; Wada, K.; Ishihara, Y.; Noguchi, R.; Morota, T.; Sakatani, N.; Matsumoto, K.; Senshu, H.; Honda, R.; Tatsumi, E.; Yokota, Y.; Honda, C.; Michikami, T.; Matsuoka, M.; Miura, A.; Noda, H.; Yamada, T.; Yoshihara, K.; Kawahara, K.; Ozaki, M.; Iijima, Y.; Yano, H.; Hayakawa, M.; Iwata, T.; Tsukizaki, R.; Sawada, H.; Hosoda, S.; Ogawa, K.; Okamoto, C.; Hirata, N.; Shirai, K.; Shimaki, Y.; Yamada, M.; Okada, T.; Yamamoto, Y.; Takeuchi, H.; Fujii, A.; Takei, Y.; Yoshikawa, K.; Mimasu, Y.; Ono, G.; Ogawa, N.; Kikuchi, S.; Nakazawa, S.; Terui, F.; Tanaka, S.; Saiki, T.; Yoshikawa, M.; Watanabe, S.; Tsuda, Y. Soluble Organic Molecules in Samples of the Carbonaceous Asteroid (162173) Ryugu. *Science* **2023**, 379 (6634), No. eabn9033.