

Nonequilibrium Formation of Pyridine (C_5H_5N) in Interstellar Ice Analogs: Implications for Biorelevant Nitrogen Heterocycles in Ryugu and Bennu

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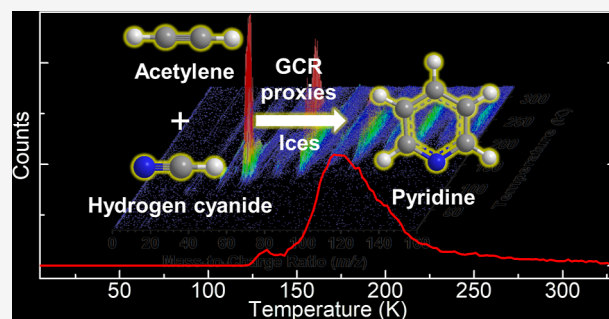
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ABSTRACT: Biorelevant nitrogen heterocycles, including the five canonical nucleobases found in RNA and DNA, have recently been identified in samples returned from the carbonaceous asteroids Ryugu and Bennu, supporting their potential exogenous delivery to the early Earth. Although pyridine (C_5H_5N), the simplest aromatic nitrogen heterocycle, has long been proposed as a key precursor to more complex nitrogen heterocycles, including nucleobases, its formation under astrophysical conditions remains poorly understood. Here, we report the first synthesis of pyridine in low-temperature acetylene–hydrogen cyanide (C_2H_2 –HCN) interstellar ice analogs exposed to energetic electrons as proxies for galactic cosmic rays. Pyridine was identified isomer-selectively in the gas phase by vacuum ultraviolet photoionization reflectron time-of-flight mass spectrometry (ReToF-MS) and resonance-enhanced multiphoton ionization spectroscopy (REMPI). These results fundamentally change our understanding of how aromatic nitrogen heterocycles can emerge from simple interstellar ice constituents under galactic cosmic ray irradiation. As a plausible precursor to more complex prebiotic nitrogen heterocycles, pyridine provides a direct chemical link between interstellar ice chemistry and the molecular inventory detected in Ryugu and Bennu, offering new insight into the chemical evolution of prebiotic organic matter in interstellar environments and its inheritance by primitive Solar System bodies.



INTRODUCTION

Since its first detection in the interstellar medium (ISM) in 1971,¹ hydrogen cyanide (HCN) has attracted sustained interest across astrochemistry,^{2–4} astrobiology,⁵ physical organic chemistry,⁶ and theoretical chemistry.^{7–9} This interest stems largely from its central role in the prebiotic synthesis of nitrogen heterocycles including purine and pyrimidine nucleobases,^{10,11} which are core components of RNA and DNA and are therefore directly relevant to the origins of life.^{12–14} Biorelevant nitrogen heterocycles including quinoline (C_9H_7N , **1**), nicotinamide (a derivative of vitamin B₃; $C_6H_6N_2O$, **2**), the five canonical nucleobases, i.e. uracil ($C_4H_4N_2O_2$, **3**), thymine ($C_5H_6N_2O_2$, **4**), cytosine ($C_4H_5N_3O$, **5**), adenine ($C_5H_5N_5$, **6**), and guanine ($C_5H_5N_5O$, **7**), as well as proteinogenic amino acids such as tryptophan ($C_{11}H_{12}N_2O_2$, **8**) have been identified in carbonaceous chondrites including the Murchison meteorite.^{15–18} Recent analyses of samples returned from the asteroids Ryugu and Bennu have further revealed abundant amino acids and a diverse inventory of nitrogen heterocycles including nucleobases **3–7**^{19–21} and nicotinic acid ($C_6H_5NO_2$, **9**).^{15,22} Pyridine (C_5H_5N , **10**) and indole (C_8H_7N , **11**) have also been identified in Bennu samples, in which the enrichment of pyrimidines relative to purines indicates their origin in

interstellar ices within cold molecular clouds^{15,19} and subsequent exogenous delivery to the early Earth by comets and meteorites.²³ Despite the prebiotic significance of these biorelevant nitrogen heterocycles, their interstellar formation mechanisms remain poorly understood, particularly for **10**, the fundamental 6π Hückel aromatic nitrogen heterocycle.^{24–26}

Upon energetic processing by vacuum ultraviolet (VUV) photons and galactic cosmic rays (GCRs),²⁷ **10** may undergo nonequilibrium reactions with simple molecules in interstellar ices including water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), and ammonia (NH_3),²⁸ thereby forming biorelevant nitrogen heterocycles (Figure 1). Reaction of **10** with water or ammonia may yield 2-pyridinol (C_5H_5NO , **12**) and its tautomer 2-pyridone (C_5H_5NO , **13**) or pyrimidine ($C_4H_4N_2$, **14**), respectively, providing plausible entry points toward nucleobases **3–5**.²⁶ Amination of **10** may also form 2-aminopyridine ($C_5H_6N_2$, **15**), whose hydrogen-bonded com-

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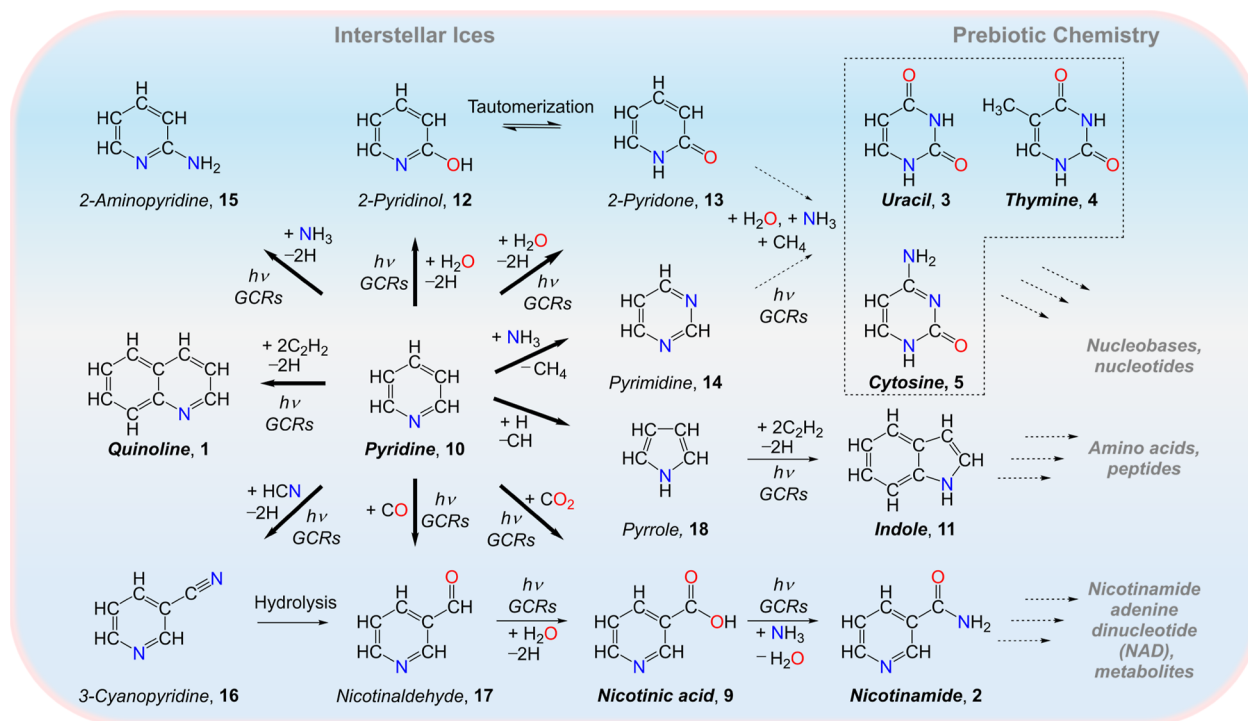


Figure 1. Potential formation pathways of biorelevant nitrogen heterocycle in pyridine-containing interstellar ices and their role as precursors to nucleobases, amino acids and metabolites. In prebiotic chemistry, pyridine (**10**) may serve as a key precursor in the synthesis of the nucleobases through nonequilibrium chemistry. Notably, **1–5** and **9** have been detected in carbonaceous chondrites, whereas **3–5** and **9–11** have been identified in samples returned from asteroids Ryugu and/or Bennu.

plex with **13** reproduces the Watson–Crick arrangement of the uracil (**3**)–adenine (**6**) and thymine (**4**)–adenine (**6**) base pairs.²⁹ Through molecular mass growth involving the successive addition of two acetylene (C_2H_2) molecules,³⁰ **10** may yield **1**, a precursor to nucleobases.³¹ Reactions of **10** with hydrogen cyanide and carbon monoxide may produce 3-cyanopyridine ($C_6H_4N_2$, **16**) and nicotinaldehyde (C_6H_5NO , **17**), respectively. Subsequent hydrolysis of **16** or oxidation of **17** yields nicotinic acid (**9**),^{32,33} whose amidation could form **2**, a precursor to the redox coenzyme nicotinamide adenine dinucleotide (NAD) and its phosphorylated analogue (NADP), which are essential cofactors in cellular metabolism.³⁴ Alternatively, hydrogen-atom addition to **10** may form pyrrole (C_4H_5N , **18**),³⁵ which undergoes acetylene addition and cyclization to **11**,³¹ providing a possible pathway to amino acids such as **8**. Therefore, elucidating the interstellar formation of **10** and its chemical evolution is essential for constraining the origins of nucleobases and amino acids under astrophysical and early planetary conditions.

Here, we report the first synthesis of pyridine (**10**) in low-temperature interstellar ice analogs composed of acetylene (C_2H_2) and hydrogen cyanide (HCN). The ices were exposed to energetic electrons as proxies for galactic cosmic rays (GCRs) at 5 K, with irradiation doses corresponding to $(9 \pm 2) \times 10^6$ years of GCR exposure, equivalent to an evolved stage of a cold molecular cloud.³⁶ **10** was identified isomer-selectively in the gas phase during temperature-programmed desorption (TPD) of the irradiated ices by vacuum ultraviolet (VUV) photoionization reflectron time-of-flight mass spectrometry (PI-ReToF-MS) and resonance-enhanced multiphoton ionization (REMPI), supported by isotopic labeling experiment and desorption profiles. Acetylene can be produced efficiently through the photolytic and radiolytic processing of

interstellar methane ices³⁷ while hydrogen cyanide is ubiquitous in interstellar environments with abundances up to 10^{-6} relative to molecular hydrogen,³⁸ and is considered an abundant component of cometary ices;³⁹ therefore, acetylene–hydrogen cyanide ices represent a model ice to study the abiotic synthesis of **10**. Our results provide direct evidence for the GCR-driven, nonequilibrium synthesis of **10** in acetylene and hydrogen cyanide-rich extraterrestrial ices, and connect interstellar ice chemistry to the inventory of nucleobases, amino acids, and cofactor precursors detected in Ryugu, Bennu, and carbonaceous chondrites (Figure 1). Upon collapse of molecular clouds into star-forming regions, these biorelevant nitrogen heterocycles may be incorporated into planetesimals, comets, and asteroids, including Ryugu- and Bennu-like bodies, and subsequently delivered to early Earth,⁴⁰ thereby contributing exogenous precursors of biomolecules essential to the emergence of life.⁴¹

RESULTS AND DISCUSSION

PI-ReToF-MS was utilized to identify **10** in the gas phase during TPD of the irradiated ices. The resulting PI-ReToF-MS data are compiled in Figure 2a–c. At 10.49 eV, the TPD profile of mass-to-charge ratio (m/z) of 79 exhibits a broad sublimation event commencing at 123 K, peaking at 174 K, and extending to 320 K (Figure 2d). The $m/z = 79$ signal can correspond to closed-shell species with the molecular formulas C_3HN_3 and/or C_5H_5N . Replacing the C_2H_2 –HCN ice with $^{13}C_2H_2$ –HCN ice results in a shift of 4 atomic mass units (amu) from $m/z = 79$ to $m/z = 83$ (Figure 2d), demonstrating the incorporation of four carbon atoms from two acetylene molecules and thereby assigning the sublimation event at $m/z = 79$ to species with the formula C_5H_5N . A blank experiment with C_2H_2 –HCN ice was performed at 10.49 eV under

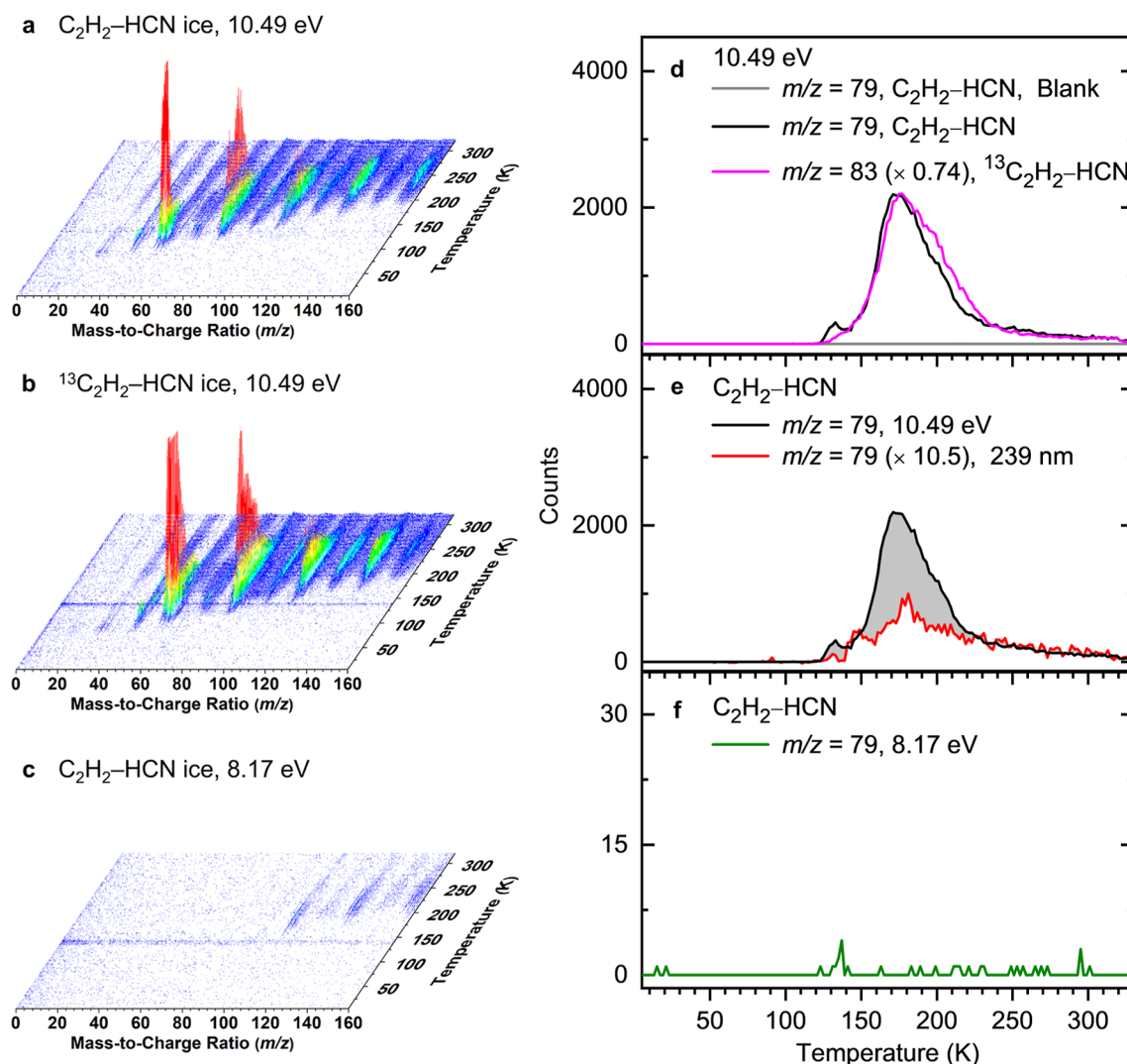


Figure 2. PI-ReToF-MS data recorded during the TPD of acetylene–hydrogen cyanide ices. Data were recorded for C_2H_2 -HCN ice at 10.49 eV (a) and 8.17 eV (c), and for $^{13}\text{C}_2\text{H}_2$ -HCN ice at 10.49 eV (b). TPD profiles of $m/z = 79$ obtained from C_2H_2 -HCN ice at 10.49 eV (d), 5.19 eV (239 nm) (e), and 8.17 eV (f) are shown together with the profile of $m/z = 83$ from $^{13}\text{C}_2\text{H}_2$ -HCN at 10.49 eV (d). The overlay of single-photon ionization (10.49 eV) and [1 + 1] REMPI (239 nm) ion signals for pyridine is shown as a function of temperature (e).

otherwise identical conditions but without electron irradiation; the absence of a sublimation event at $m/z = 79$ confirms that the signal results from electron-induced processing of the ices. Since the photon energy of 10.49 eV exceeds the adiabatic ionization energy (IE) of **10** (9.26 ± 0.01 eV),⁴² **10** can be photoionized; therefore, the sublimation peak at 174 K is consistent with its formation. When the photon energy was reduced to 8.17 eV, below the IE of **10**, no sublimation event was detected at $m/z = 79$ (Figure 2f), providing further evidence for the assignment of this peak to **10**.

However, $\text{C}_5\text{H}_5\text{N}$ may correspond to multiple structural isomers;⁴³ therefore REMPI was utilized to identify the carrier(s) of the $m/z = 79$ signal. In the scheme, resonant absorption of the first photon accesses an electronically excited state of a specific isomer, followed by absorption of a second photon to ionize the molecule.^{31,44,45} A separate REMPI experiment was performed with irradiated C_2H_2 -HCN ice by scanning 220–245 nm to enable ionization of **10** via higher vibrational levels of the S_1 electronic state.⁴⁴ The REMPI spectrum recorded for $m/z = 79$ during TPD from 173 to 223 K agrees well with the previous results of **10** recorded using an

effusive molecular beam at 300 K (Figure 3),⁴⁴ identifying **10** as a carrier of the $m/z = 79$ signal. A complementary experiment was conducted at 239 nm; comparison of the TPD profiles of $m/z = 79$ recorded at 10.49 eV and at 239 nm reveals that **10** accounts for (53 ± 6)% of the total signal (Figure 2e). In the 10.49 eV photoionization experiment, the yield of **10** was determined to be $(1.98 \pm 0.59) \times 10^{-3}$ molecules eV^{-1} using its measured photoionization cross section of $2.8 \times 10^{-17} \text{ cm}^2$ at 10.49 eV⁴⁶ and the calibration factor of our PI-ReToF-MS.⁴⁵ Notably, this yield is approximately one-half of the benzene yield of $(3.72 \pm 1.30) \times 10^{-3}$ molecules eV^{-1} previously reported for electron-irradiated acetylene ice.⁴⁵ The remaining signal is attributed to additional $\text{C}_5\text{H}_5\text{N}$ isomers and a contribution at a level of 6% from singly ^{13}C -substituted benzene (Supporting Information, Figure S3). Future studies should investigate the formation of **10** using different ratios of reactants and upon incorporation of major interstellar constituents such as water (H_2O), carbon monoxide (CO), and carbon dioxide (CO_2) into the ice mixtures. Additional detected mass channels and their proposed molecular formulas are summarized in Table S4.

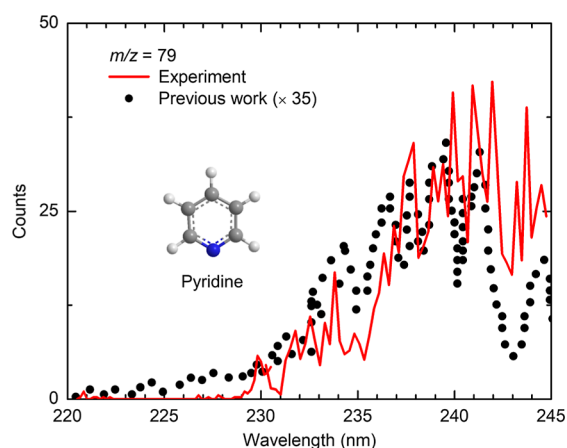
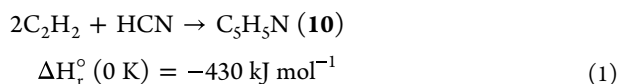


Figure 3. REMPI spectrum recorded during the sublimation of irradiated C_2H_2 –HCN ice. The REMPI signal at $m/z = 79$ (red), measured from 173 to 223 K, is plotted as a function of wavelength after correction for photon flux and the corresponding TPD profile. The reported reference spectrum of pyridine (black dots), recorded with an effusive molecular beam at 300 K, was scaled by a factor of 35 for comparison with the experimental results.

Having provided compelling evidence for the formation of pyridine (**10**) in acetylene–hydrogen cyanide ices (C_2H_2 –HCN) under astrophysical conditions, we now consider possible formation pathways. Previous studies demonstrated that energetic processing of acetylene ices by electron irradiation⁴⁵ and ultraviolet photolysis⁴⁷ can effectively produce benzene (C_6H_6), an isoelectronic analogue of **10**. In analogy with benzene formation, electronically excited acetylene may enable nonequilibrium molecular growth through C_4H_4 intermediates such as vinylacetylene (CH_2CHCCH), followed by C–C and C–N bond formation and cyclization to form **10**. The identification of vinylacetylene by FTIR spectroscopy and PI-ReToF-MS supports its formation in the irradiated ice (Supporting Information, Figure S4). The overall reaction involves two acetylene and one hydrogen cyanide molecule (reaction 1) and is exoergic by 430 kJ mol^{-1} .⁴⁸



Alternatively, energetic electrons can initiate C–H bond cleavage in hydrogen cyanide, yielding suprathermal atomic hydrogen (H) plus cyano (CN) radical. Vinylacetylene may undergo hydrogen atom addition to form 1,3-butadiene ($\text{CH}_2\text{CHCHCH}_2$), which then reacts with cyano radical, yielding **10** followed by cyclization and hydrogen atom loss,^{49,50} an exoergic process releasing 185 kJ mol^{-1} .⁵⁰ In addition, reaction of HCN with C_2H_2 may yield acrylonitrile (H_2CCHCN), which can react barrierlessly with vinyl (C_2H_3) radical formed by H atom addition to C_2H_2 ; subsequent cyclization and H atom elimination lead to **10**,^{51,52} with an exoergic of 122 kJ mol^{-1} .⁵³ Note that previous gas-phase studies indicate that the reaction of the cyano radical and 1,3-butadiene predominantly forms 1-cyano-1,3-butadiene ($\text{CH}_2\text{CHCHCHCN}$), whereas pyridine represents a minor product channel.⁵⁰ In addition, hydrogen cyanide may add to acetylene to yield acrylonitrile (CH_2CHCN); however, its IE of $10.91 \pm 0.01 \text{ eV}$ ⁴² exceeds the 10.49 eV photoionization energy, precluding its detection in the experiments. Therefore,

reaction (1) appears to be the most plausible pathway to **10** due to the higher concentrations of the reactants and the experimental evidence for analogous molecular-growth chemistry in irradiated acetylene ices.

CONCLUSION

In conclusion, we report the first synthesis of pyridine (**10**) in acetylene–hydrogen cyanide ices (C_2H_2 –HCN) under simulated interstellar conditions. The ice mixtures were irradiated at 5 K with GCR proxies in the form of energetic electrons, with doses of $2.3 \pm 0.4 \text{ eV molecule}^{-1}$ for C_2H_2 and $2.1 \pm 0.3 \text{ eV molecule}^{-1}$ for HCN. These doses are equivalent to GCR exposure of interstellar ices for $(9 \pm 2) \times 10^6$ years, corresponding to an evolved stage of a cold molecular cloud.³⁶ Upon irradiation by GCRs, **10** may form during earlier stages of cloud evolution in interstellar ices containing acetylene and hydrogen cyanide and subsequently accumulate with continued energetic processing. By combining VUV PI-ReToF-MS with REMPI spectroscopy, **10** was identified in the gas phase during TPD. The formation of **10** is initiated by GCR proxies and proceeds through C–C and C–N bond formation and cyclization to yield the aromatic pyridine ring, demonstrating the feasibility of forming nitrogen-containing aromatic heterocycles through the direct incorporation of nitrogen into aromatic ring systems under astrophysical conditions. However, no evidence for the formation of (iso)quinoline probed via REMPI⁴⁴ from the irradiated ices could be provided under the current experimental conditions. These results reveal the pivotal role of GCR-driven non-equilibrium chemistry in forming **10** in cold extraterrestrial ices, indicating that the synthesis of nitrogen heterocycles can occur prior to planet formation. Once formed, **10** could serve as a precursor to biorelevant nitrogen heterocycles including **1–5** and **9–18** (Figure 1), some of which have been detected in Ryugu and Bennu, thereby providing a key pathway toward increasing molecular complexity and highlighting the potential role of interstellar ice chemistry in producing complex organics relevant to prebiotic chemistry. In addition, pyridine may remain trapped within interstellar ices during cloud collapse and subsequently be incorporated into planetesimals and asteroidal parent bodies, where relatively limited thermal processing may facilitate its preservation.^{54,55} As icy grains evolve from cold molecular clouds into star-forming regions, **10** can sublime into the gas phase, where subsequent photolysis generates pyridinyl ($\text{C}_5\text{H}_4\text{N}$) radicals that react further with, e.g., vinylacetylene to form biorelevant (iso)-quinoline.^{25,56,57} Among these compounds, indole and (iso)-quinoline represent simple prototypes of polycyclic aromatic nitrogen heterocycles (PANHs), which have been proposed as potential contributors to the unidentified infrared emission bands,^{58,59} suggesting that the formation of **10** may provide an entry point toward the PANH chemistry under astrophysical conditions. These findings demonstrate that nonequilibrium chemistry can generate aromatic nitrogen heterocycles from simple carbon- and nitrogen-bearing precursors in cold extraterrestrial ices, advancing our fundamental understanding of the emergence of prebiotic nitrogen heterocycles in interstellar environments and its potential inheritance by primitive Solar System bodies.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacs.6c14563>.

The Supporting Information includes experimental methods, infrared spectra results (Figures S1–S2; Tables S1–S2), possible candidates for the C₅H₅N isomers, TPD profiles of benzene and vinylacetylene (Figures S3–S4), VUV generation parameters (Table S3), proposed molecular formula for other observed mass channels (Table S4) (PDF)

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Notes

The authors declare no competing financial interest.

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