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Synthesis of amino acids in intense laser-irradiated primary amine solutions†

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Mechanical interatomic bond formation under ultrahigh pressure induced by laser-driven shock waves has been demonstrated for C–C, C–O, and O–O bonds. In this study, molecules generated in primary amine solutions irradiated with high-intensity lasers were identified. When methylamine or ethylamine was dissolved in methanol or ethanol, molecules likely formed through C–C or O–N bonds between the amine and alcohol were detected. Additionally, molecules thought to be formed through the bonding of amines were confirmed. In mixed solutions of amine and formic acid, the formation of amino acids, such as glycine and alanine, which are presumed to result from C–C bond formation, was also confirmed. The generation of these molecules is attributed to mechanical bond formation due to the ultrahigh pressure generated by laser shock waves. This phenomenon is expected to offer a new perspective on the synthesis of complex organic molecules, particularly in relation to the origins of life in space and on Earth.

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Introduction

Amino acids are essential building blocks of proteins that constitute living organisms.[1–5] However, it remains a matter of debate whether amino acids are formed in space[6–8] or on Earth.[9–11]

It has been noted that extremely high pressure is generated during planetary[12] and meteorite[6] collisions, a phenomenon common to space and the Earth. It has been demonstrated that the ultrahigh pressure generated by laser shock waves can form new interatomic bonds between molecules, resulting in the polymerization of acetylene in liquid,[13] and the production of amino acids in gaseous mixtures[14] and complex structures in shock tubes.[15] It was previously reported that the formation of C–C bonds between alkanes takes place, leading to the dominant formation of their dimers.[16,17] We have also demonstrated that in methanol and ethanol, C–O, O–O, and C–C bonds are formed, and hemiacetals such as methoxymethanol, which have not been studied much, are significantly produced.[18,19] In this reaction, the formation of oligomers is dominant because all the atoms comprising the original molecules are retained in the newly formed molecules, except for hydrogen and water, because of dehydrogenation or dehydration, respectively. Additionally, unlike chemical reactions induced by excitation, ionization, and radicalization of molecules by cosmic rays or high-energy electromagnetic waves,[20–23] the molecules produced have structures that are simply determined by the combination of atoms from the starting molecules, making the products easy to predict. Interestingly, it has been reported that the radiolysis of alkanes primarily produces dimers, which are identical to those observed in laser-induced shock waves.[24–26] Moreover, alkane isomers with a small number of carbon atoms exhibit similar behavior. However, their product distributions differ from those observed in laser-induced shock waves, likely due to the differing reaction time scales between the radiolysis and laser shock wave process.

In this study, we analyzed primary amine solutions irradiated with high-intensity laser pulses to identify the molecules that were produced. In alcohol solutions containing amines, we detected molecules composed of amine and alcohol as well as molecules composed of only amines. Additionally, in a mixed solution of amine and formic acid, the production of amino acids (glycine, α-alanine, and β-alanine) was confirmed, which is consistent with predictions based on simple carbon atom combinations. This molecular synthesis method, which uses ultrahigh pressure induced by intense laser irradiation, shows promise as a candidate for amino acid synthesis, both in space, where ultrahigh pressure is generated during planetary collisions, and on Earth, through meteorite impacts.

Results and discussion

Methylamine and ethylamine dissolved in alcohol or water serve as primary amines. The alcohol solutions---methylamine (40%) in methanol, ethylamine (30–40%) in methanol, methylamine (9%) in ethanol, and ethylamine (30–40%) in ethanol—were

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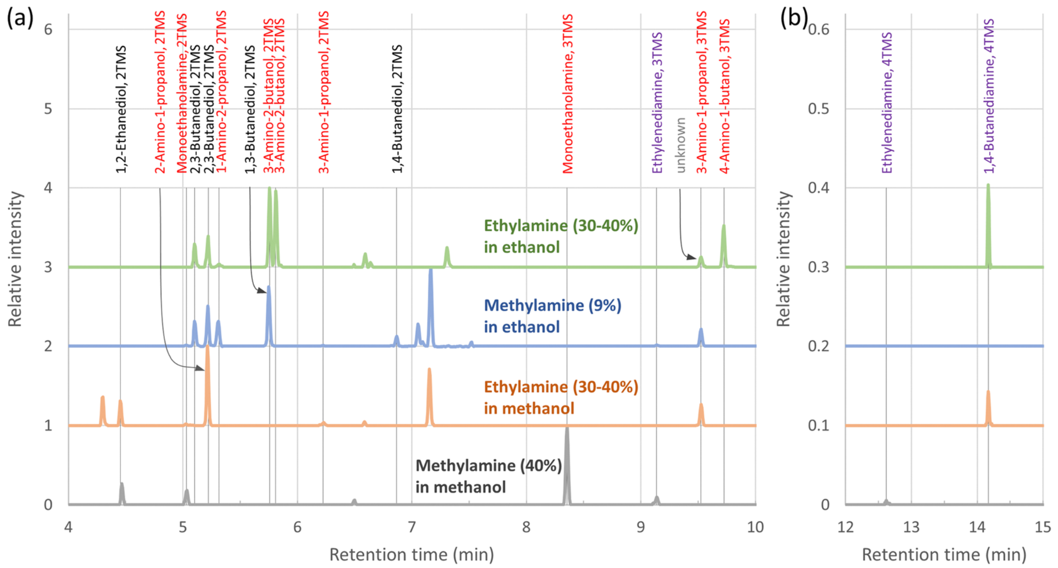

Fig. 1 Chromatograms of intense-laser-irradiated mixtures of amines (methylamine and ethylamine) and alcohols (methanol and ethanol) in retention times ranging from (a) 3 to 10 min and (b) 12 to 15 min. The samples were derivatized with trimethylsilyl (TMS). The name of each identified molecule is shown at the top of each peak. If two peaks overlap, a separate peak is indicated by an arrow. Diols, molecules with both amino and hydroxyl groups, and diamines are represented in black, red, and purple, respectively. Unidentified molecules are not listed.

obtained from Tokyo Chemical Industry and used without further purification. The predicted molecules resulting from the simple combination of amines and alcohols in these four solutions are summarized in Table S1 (ESI†). In this context, molecules with four interatomic bonds, namely C–C bonds, C–O bonds, C–N bonds, and O–N bonds, could form. As in the previous experiment, a Ti:sapphire laser pulse with a wavelength of 800 nm, pulse width of 100 fs, pulse energy of 5 mJ, and repetition rate of 200 Hz was focused using a lens with a focal length of 8 mm into 2 mL of amine solution in a glass cell. The laser-irradiated samples were exposed for 60 min and analyzed using gas chromatography–mass spectrometry (GC–MS; Agilent 8860 and 5977B). An HP-5 ms Ultra Inert column was used. To detect nonvolatile molecules, the samples were derivatized with trimethylsilyl using a solid-phase cartridge (Aisti Science Presh-SPE CXs). Fig. 1 depicts the gas chromatograms of the four samples. Peaks observed in the nonirradiated sample were removed in advance. The names of unidentified molecules were not listed. The retention times and assignments are listed in Table S2 (ESI†).

In the chromatogram shown in Fig. 1, the peaks corresponding to diols (1,2-ethanediol[18] and 2,3-butanediol[19]), which resulted from C–C bond formation through dehydrogenation between methanol and ethanol, respectively, were clearly detected. Conversely, methoxymethanol and 1-ethoxyethanol, which were presumed to be produced by C–C bond formation upon dehydration, were not observed. This is because these molecules were converted to imines, as will be described later. Additionally, the peaks of molecules containing both amino and hydroxyl groups (listed in the top row of Table S1, ESI†), which were predicted to be produced by C–C bond formation accompanied by dehydrogenation between amine and alcohol, were also prominent. However, in the ethanol solution of methylamine, the peak intensity of the corresponding molecule (1-amino-2-propanol) was relatively low because the concentration of methylamine was only 9%, much lower than that of the other solutions. Furthermore, 3-amino-1-propanol, anticipated to form in both the methanol solution of ethylamine and the ethanol solution of methylamine, was detected at the same retention time.

Among the molecules identified in this study, we focused on three molecules with branched carbon chains: 2-amino-1-propanol, 1-amino-2-propanol, and 3-amino-2-butanol. It has been reported that a so-called dropout process, in which part of the starting molecule is removed, is characteristic of bond formation by laser-driven shock waves.[16,18,19] If this phenomenon occurred in a similar way in this experiment, it was predicted that monoethanolamine would be produced during the formation of 2-amino-1-propanol and 1-amino-2-propanol due to the dropout of a methyl group, as shown in Fig. S1 (ESI†). Similarly, 1-amino-2-propanol and 2-amino-1-propanol are produced during the formation of 3-amino-2-butanol. Although the signal intensities for the molecules were not strong enough to be recognized in Fig. 1, it was possible to identify the corresponding peaks by closely examining the chromatograms in detail. First, the mass spectra of monoethanolamine were obtained in a methanol solution of ethylamine and an ethanol solution of methylamine, as illustrated in Fig. 2. The mass spectra were almost identical to those produced in the process without dropout in the methanol solution of methylamine, indicating the formation of monoethanolamine *via* the dropout process. Next, the mass spectrum of 1-amino-2-propanol in the ethanol solution of ethylamine is depicted in Fig. 3(a). Because the signal was very weak, the mass spectrum was highly noisy. However, the mass distribution was quite similar to that measured in the ethanol solution of

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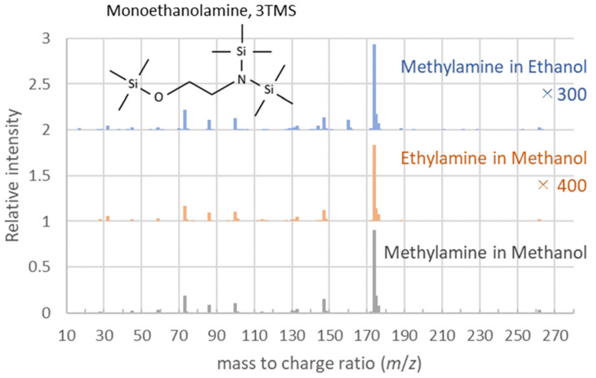

Fig. 2 Mass spectra of monoethanolamine, 3TMS, in the laser-irradiated samples derivatized with TMS. The spectra obtained from an ethanol solution of methylamine (light blue) and a methanol solution of ethylamine (light red) were multiplied by 300 and 400, respectively. In both cases, monoethanolamine was presumed to be formed *via* the dropout process.

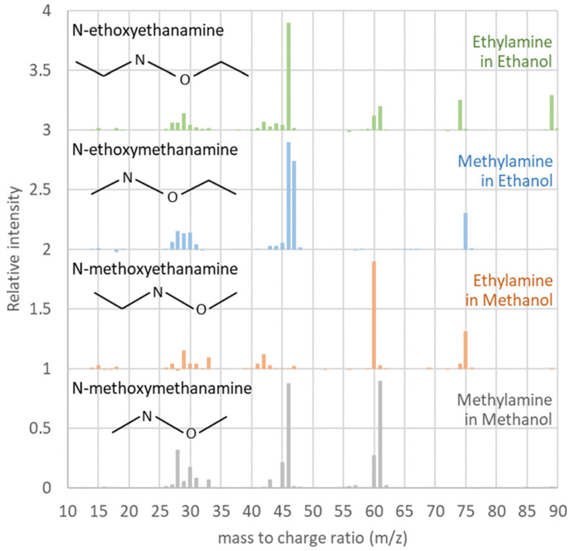

Fig. 4 Mass spectra of the molecules produced through N–O bond formation in laser-irradiated alcohol solutions of amine. From top to bottom, the laser-irradiated samples were ethanol solution of ethylamine, ethanol solution of methylamine, methanol solution of ethylamine, and methanol solution of methylamine.

methylamine, shown in the bottom of Fig. 3(a), indicating the production of 1-amino-2-propanol. In contrast, the peak for 2-amino-1-propanol occurred at the same retention time as that for 2,3-butanediol (Fig. 1). Therefore, the mass spectrum after subtracting 2-butanediol is illustrated in Fig. 3(b). The mass spectrum was also almost identical to that observed in the methanol solution of ethylamine. Consequently, the molecules predicted to be produced by the dropout process were detected, strongly supporting the formation of molecules during the ultrahigh-pressure process induced by the laser shock waves. It should be noted that the molecules predicted by the possible elimination of an amino group, instead of a methyl or hydroxyl group, during the dropout process were not detected.

In contrast to the molecules generated through the aforementioned C–C bond formation, no molecules predicted through C–O or C–N bond formation were detected. However, undetected molecules cannot be excluded from the list of produced molecules because their mass spectra are largely unknown, making identification challenging. In contrast, four molecules with alkoxy groups, which were predicted to form O–N bonds, were found in the chromatograms without derivatization, as depicted in Fig. 4. The reaction schemes are shown in Fig. S2 (ESI†). All molecules except *N*-methoxymethanamine were absent from the mass spectrum database. For *N*-methoxyethanamine, the dominant mass-to-charge ratios (*m*/*z*) of 75 and 60 corresponded to the molecular weight and loss of the methyl group, respectively. This mass pattern aligned with the empirical rule indicating that cleavage between atoms, including nitrogen, is unfavorable. The mass spectrum presumed for *N*-ethoxymethanamine also followed this rule, as the molecular weight of 75 corresponded to *m*/*z* = 75, and the fragment resulting from O–C bond cleavage corresponded to *m*/*z* = 46 and 47. Additionally, for *N*-ethoxyethanamine, the molecular weight of 89 coincided with *m*/*z* = 89, whereas *m*/*z* = 74 corresponded to the elimination of a methyl group and *m*/*z* = 60 and 61 corresponded to the cleavage of the O–C bond.

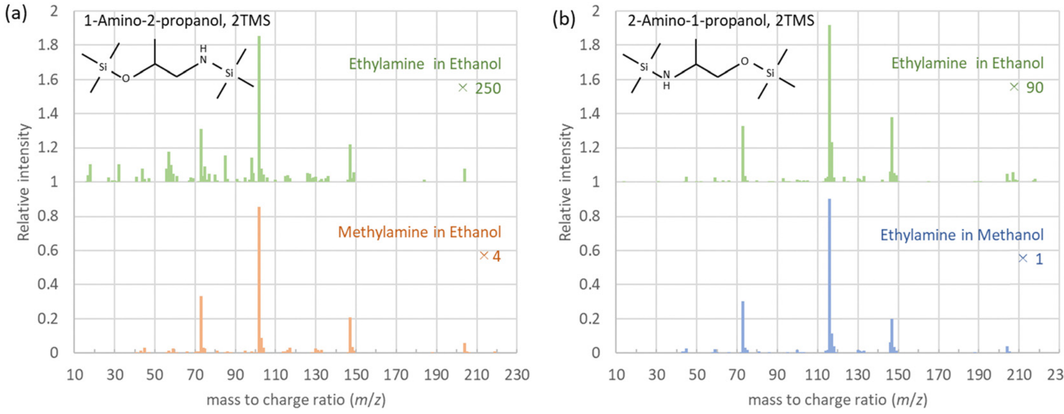

Fig. 3 Mass spectra of (a) 1-amino-2-propanol, 2TMS, and (b) 2-amino-1-propanol, 2TMS, presumed to be produced through the dropout process during the production of 3-amino-2-butanol in a laser-irradiated ethanol solution of ethylamine.

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Table S3 (ESI†) presents the molecules predicted to be generated *via* bond formation between amines. In the experiment, the formation of ethylenediamine (Fig. 1(b)) *via* C–C bond formation and 1,2-dimethylhydrazine *via* N–N bond formation was confirmed for methylamine (Fig. S3, ESI†). For ethylamine, only 1,4-butanediamine was confirmed for C–C bond formation. In the ethanol experiment, the production of molecules through binding with carbon at locant 1 is dominant.[19] If this tendency is also applicable to ethylamine, 2,3-butanediamine would most likely be produced. Although its mass spectrum may display a double peak in the gas chromatogram due to the structure containing two asymmetric carbons, like 2,3-butanediol and 3-amino-2-butanol, the corresponding molecule was not identified. However, 1,2-diethylhydrazine formed *via* N–N bond formation was confirmed (Fig. S3, ESI†). Identification of the molecules predicted to be produced by C–N bond formation was challenging, primarily due to the severe lack of available mass spectrum data.

Hemiacetals, such as methoxymethanol and 1-ethoxyethanol, which are primarily formed through C–C bond formation between alcohol molecules,[18,19] were not detected in Fig. 1, as mentioned above. Acetalization is unlikely to occur under the basic conditions of an amine solution.[27] Therefore, even if hemiacetals are formed, they would exist in equilibrium with their decomposition into aldehyde (formaldehyde or acetaldehyde) and alcohol. Consequently, primary amines (methylamine and ethylamine) could react with aldehydes to produce imine, as shown in Fig. S4 and Table S4 (ESI†). Fig. 5 displays the mass spectra of molecules identified as imines in four types of laser-irradiated mixtures of amines (methylamine and ethylamine) and alcohols (methanol and ethanol). Although these imines were not explored in detail, we identified each molecule as follows: first, the maximum *m*/*z* value in each mass spectrum was equal to the molecular weight. Given the unfavorable cleavage between nitrogen and its adjacent atom, as previously noted in relation to Fig. 4, *N*-methylmethanimine might fragment minimally, resulting in dominant mass peaks at approximately m/z = 43. In *N*-methyleneethanamine and *N*-methylethanimine, both having a molecular weight of 57, the prominent peak at m/z = 42 corresponded to the fragment caused by the elimination of a methyl group. The fragment at m/z = 56, due to the elimination of a methyl group, was also observed for *N*-ethylideneethanamine with a molecular weight of 71. Furthermore, the retention times of the peaks in the chromatograms depicted in Fig. 5 exhibited a positive correlation with molecular size, further supporting its validity.

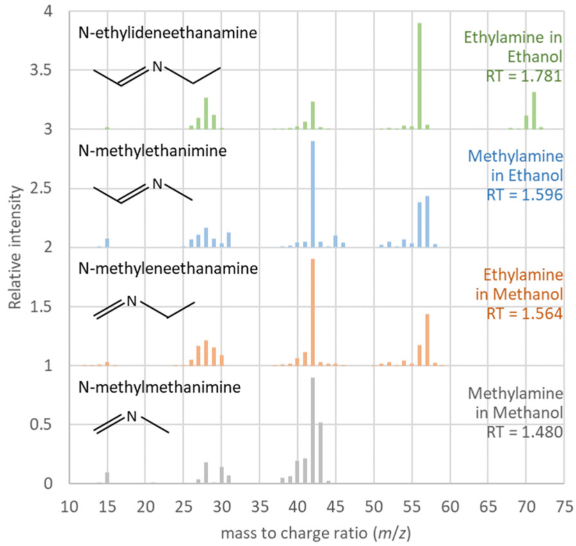

Fig. 5 Mass spectra of imines identified in laser-irradiated mixtures of alcohol (methanol and ethanol) solutions of amine (methylamine and ethylamine). The RT indicated below the name of each sample represents the retention time in minutes for each peak in the chromatogram.

The molecules identified above were in agreement with those predicted to be generated by high-intensity laser irradiation of alcohol solutions of amines, particularly through C–C bond formation. In the following sections, we discuss amino acid production through C–C bond formation between amines and formic acid. Because liquid formic acid is primarily composed of hydrogen-bonded dimers in a mixture with methanol,[28] aqueous solutions of amines [methylamine (40%) in water and ethylamine (70%) in water: Tokyo Chemical Industry] were used in the experiment. To achieve equal molar concentrations of formic acid and amines, 0.57 mL of formic acid (Fujifilm Wako Pure Chemicals) was added to an aqueous solution of methylamine, and 0.83 mL of formic acid was added to an aqueous solution of ethylamine to create a 2 mL mixture. Due to the high viscosity of the mixture of aqueous amine and formic acid, small bubbles generated by laser irradiation remained near the focal point. These bubbles disrupt the laser beam due to the refractive index mismatch in the optical path, leading to a lower light intensity at the focus than anticipated, thereby weakening the shock wave's strength. Consequently, the repetition frequency was lowered to 10 Hz, and the irradiation time was extended to 48 h. The molecules predicted to be generated by bond formation between amines and formic acids, as well as between formic acids, are summarized in Tables S5 and S6 (ESI†), respectively.

Fig. 6 shows the gas chromatogram of the laser-irradiated mixture of ethylamine and formic acid. The retention times and assignments are listed in Table S7 (ESI†). Amino acids anticipated to form through C–C bond formation between ethylamine and formic acid (α-alanine and β-alanine) were detected. Another amino acid, glycine, was also detected, likely formed through the dropout process involving the methyl group of ethylamine during the formation of α-alanine. This strongly supports the role of mechanical interatomic bond formation driven by laser shock waves. Furthermore, carboxylic acids containing two carbon atoms were identified, including oxalic acid, which had the strongest peak and was thought to have formed through C–C bond formation between formic acids upon dehydrogenation, and glycolic acid, thought to have been formed by deoxygenation (Table S6, ESI†). This deoxygenation process was observed for the first time in a series of experiments on molecular formation by laser shock waves.[16,18,19] Additionally, two hydroxy acids with three carbon atoms—tartronic acid and glyceric acid—were found. Assuming that these

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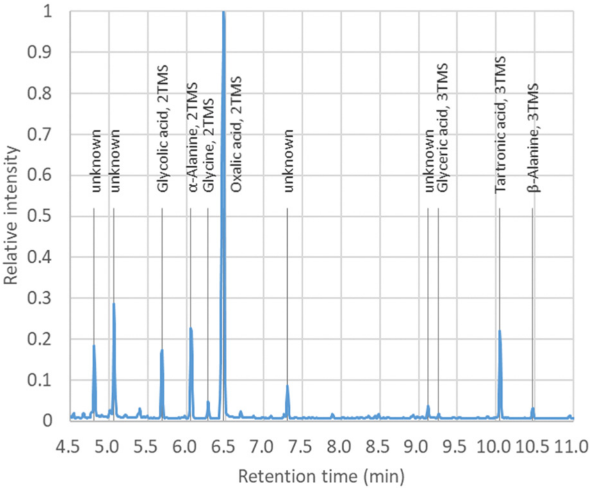

Fig. 6 Gas chromatogram of a laser-irradiated mixture of an aqueous solution of ethylamine and formic acid. The sample was derivatized with trimethylsilyl (TMS).

compounds arise from the further binding of formic acid to oxalic or glycolic acid, as depicted in Table S6 (ESI†), their production can also be explained by two processes: dehydrogenation and deoxygenation. In other words, although dehydration and dehydrogenation processes have been documented in molecular production *via* laser shock waves,[16,18,19] it can be noted that the deoxygenation process is also possible in the case of formic acid.

In contrast, molecules predicted to be produced by C–O and O–O bond formation were not detected. However, as the mass spectra of these molecules were not found in the database, identifying them was difficult even if they were produced; some of them may correspond to the unknown peaks in Fig. 6. Additionally, in the mixture of an aqueous solution of methylamine and formic acid, α-alanine and β-alanine were not detected, but a stronger peak for glycine was obtained (Fig. S5, ESI†), indicating that the mechanical interatomic bond formation driven by laser-induced shock waves may contribute to the production of amino acids in the amine–formic acid mixture.

Conclusions

In summary, the analysis of molecules formed in amine solutions irradiated with high-intensity laser light using GC–MS revealed that all identified molecules matched those predicted to form through mechanical interatomic bond formation under the ultrahigh pressure of laser shock waves. Notably, the production of molecules anticipated for C–C bond formation was substantial. Molecules formed *via* the dropout process, in which a methyl group was eliminated during bond formation, were also detected, providing strong evidence for the molecular formation mechanism under ultrahigh pressure, while further investigation is needed to fully elucidate the role of the shock waves in this process. Importantly, the expected amino acids were identified in the mixture of amine and formic acid. Methylamine,[29] ethylamine,[30] and formic acid[31] have been recognized as interstellar matter, indicating that ultrahigh pressure may play a role in the formation of new molecules, including life-related molecules, through collisions that occur in space and on the surface of the Earth.

Author contributions

S. S. conceived the idea, acquired the funding, administered the project, designed the experiments, analysed the data and wrote the manuscript. S. S. and W. I. carried out the experimental work and data analysis.

Data availability

All the data have been presented in the manuscript and ESI.†

Conflicts of interest

The authors declare no conflicts of interest.

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References

1 K. Ruiz-Mirazo, C. Briones and A. de la Escosura, *Chem. Rev.*, 2014, **114**, 285–366.
2 M. Neinast, D. Murashige and Z. Arany, *Annu. Rev. Physiol.*, 2019, **81**, 139–164.
3 G. Wu, *Amino Acids*, 2009, **37**, 1–17.
4 M. P. Kroonblawd, R. K. Lindsey and N. Goldman, *Chem. Sci.*, 2019, **10**, 6091–6098.
5 N. Goldman, E. J. Reed, L. E. Fried, I. F. William Kuo and A. Maiti, *Nat. Chem.*, 2010, **2**, 949–954.
6 M. H. Engel and S. A. Macko, *Nature*, 1997, **389**, 265–268.
7 Z. Martins, M. C. Price, N. Goldman, M. A. Sephton and M. J. Burchell, *Nat. Geosci.*, 2013, **6**, 1045–1049.
8 M. Nuevo, U. J. Meierhenrich, G. M. Muñoz Caro, E. Dartois, L. d'Hendecourt, D. Deboffle, G. Auger, D. Blanot, J.-H. Bredehöft and L. Nahon, *Astron. Astrophys.*, 2006, **457**, 741–751.
9 K. Plankensteiner, H. Reiner, B. Schranz and B. M. Rode, *Angew. Chem., Int. Ed.*, 2004, **43**, 1886–1888.
10 C. Huber and G. Wächtershäuser, *Science*, 2006, **314**, 630–632.
11 Y. Takeuchi, Y. Furukawa, T. Kobayashi, T. Sekine, N. Terada and T. Kakegawa, *Sci. Rep.*, 2020, **10**, 9220.
12 M. Miyahara, N. Tomioka and L. Bindi, *Prog. Earth Planet. Sci.*, 2021, **8**, 59.
13 K. Aoki, S. Usuba, M. Yoshida, Y. Kakudate, K. Tanaka and S. Fujiwara, *J. Chem. Phys.*, 1988, **89**, 529–534.
14 A. Bar-Nun, *Orig. Life*, 1975, **6**, 109–115.

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15 S. V. Singh, J. Vishakantaiah, J. K. Meka, V. Sivaprahasam, V. Chandrasekaran, R. Thombre, V. Thiruvenkatam, A. Mallya, B. N. Rajasekhar, M. Muruganantham, A. Datey, H. Hill, A. Bhardwaj, G. Jagadeesh, K. P. J. Reddy, N. J. Mason and B. Sivaraman, *Molecules*, 2020, **25**, 5634.

16 W. Ishikawa and S. Sato, *ChemPhysChem*, 2020, **21**, 2104–2111.

17 S. Harris, E. Kaplan, M. Aftel and K. M. Tibbetts, *J. Phys. Chem. B*, 2024, **128**, 10481–10491.

18 W. Ishikawa and S. Sato, *AIP Adv.*, 2024, **14**, 025322.

19 W. Ishikawa and S. Sato, *ChemPhysChem*, 2024, **25**, e202400164.

20 M. Castillejo, S. Couris, E. Koudoumas and M. Martín, *Chem. Phys. Lett.*, 1999, **308**, 373–380.

21 M. F. Kling, Ch Siedschlag, A. J. Verhoef, J. I. Khan, M. Schultze, T. Uphues, Y. Ni, M. Uiberacker, M. Drescher, F. Krausz and M. J. J. Vrakking, *Science*, 2006, **312** 246–248.

22 Y. Sato, T. Kodama, H. Shiromaru, J. H. Sanderson, T. Fujino, Y. Wada, T. Wakabayashi and Y. Achiba, *Carbon*, 2010, **48**, 1673–1676.

23 A. A. Zaidi, A. Hu, D. E. Henneke and W. W. Duley, *Chem. Phys. Lett.*, 2019, **723**, 151–154.

24 H. Widmer and T. Gäumann, *Helv. Chim. Acta*, 1963, **46**, 2766–2780.

25 E. Pancini, V. Santoro and G. Spadaccine, *Int. J. Radiat. Phys. Chem.*, 1970, **2**, 147–157.

26 K. Shinsaka and S. Shida, *Bull. Chem. Soc. Jpn.*, 1970, **43**, 3728–3740.

27 M. Jones, Jr. and S. A. Fleming, *Organic Chemistry*, W. W. Norton & Company, 2014.

28 Y. Han, Z. Wang, R. Qiao, J. Cheng, C. Jiang and H. Wang, *Phys. Chem. Chem. Phys.*, 2023, **25**, 18048–18055.

29 N. Kaifu, M. Morimoto, K. Nagane, K. Akabane, T. Iguchi and K. Takagi, *Astrophys. J.*, 1974, **191**, L135–L137.

30 S. Zeng, I. Jiménez-Serra, V. M. Rivilla, J. Martín-Pintado, L. F. Rodríguez-Almeida, B. Tercero, P. de Vicente, F. Rico-Villas, L. Colzi, S. Martín and M. A. Requena-Torres, *Astrophys. J., Lett.*, 2021, **920**, L27.

31 B. Zuckerman, J. A. Ball and C. A. Gottlieb, *Astrophys. J.*, 1971, **163**, L41.