

Ketene and Ammonia Forming Acetamide in the Interstellar Medium

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ABSTRACT

Background: Peptide bonds are among the fundamental building blocks of life, polymerizing amino acids to form proteins that make up the structural components of living cells and regulate biochemical processes. The detection of glycine by NASA in comet Wild 2 in 2009 suggests the possibility of the formation of biomolecules in extra-terrestrial environments through the interstellar medium. Detected in the dense molecular cloud Sagittarius B2, acetamide is the largest molecule containing a peptide bond and is hypothesized to be the precursor to all amino acids; as such, viability of its formation is of important biological relevance.

Methods: Under a proposed mechanism of ammonia and ketene reactants, which have also been detected in dense molecular clouds in the ISM, the reaction pathway for the formation of acetamide was modelled using quantum chemical calculations in Gaussian16, using Austin-Frisch-Petersson functional with dispersion density functional theory at a 6-31G(d) basis set level of theory to optimize geometries and determine the thermodynamic properties for the reaction. Stability of the reactants, transition states, and products were examined to establish a reasonable mechanism.

Conclusion: Product formation of acetamide was found to be highly exergonic and exothermic with a low energy barrier, suggesting a mechanism that is viable in the extreme density and temperature conditions found in ISM.

Keywords: Peptide bond, origins of life, interstellar medium, computational chemistry

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INTRODUCTION

Of all the molecules discovered in the interstellar medium (ISM), acetamide (CH_3CONH_2) is of utmost importance because of its unique bond structure that has significant biological implications. Discovered in a dense molecular cloud of Sagittarius B2 in 2006, it is the largest molecule discovered to date with a peptide bond ($-\text{CO}-\text{NH}-$)¹. The ISM is often cited when discussing prebiotic chemistry, as this large territory between star systems contains many unique environments where many organic molecules have been discovered^{2,3}. These molecules containing C, H, O, and N are essential to all living systems, that consist of proteins. The basic subunit of proteins are amino acids, which are linked by peptide bonds. Currently, all amino acids, except for glycine, are too large to be detected in the ISM. However, the core components of peptide bonds have been discovered through isocyanic acid (HNCO), formamide (HCONH_2), and acetamide⁴. The discovery of acetamide in the ISM has important biological relevance because it is considered to be the precursor to all amino acids. Although discovered, the possible formation mechanism is still unknown and understanding potential reaction pathways that can be undertaken provides a better understanding of the formation of other molecules as well. Determining individual reactions can help establish patterns in other reactions including transition state structures, plausibility, energy barriers, mechanisms, and kinetics in the ISM.

Although molecules larger than 8 atoms, especially ones possessing all four key elements, are rare among the ISM, acetamide has a high relative abundance almost equal to less complex, but related molecules such as ketene ($\text{C}_2\text{H}_2\text{O}$), acetaldehyde (CH_3CHO), and formamide (HCONH_2), a smaller molecule with a peptide bond⁴. An isomer of acetamide, N-methyl formamide, was found to be 5-22 times less abundant, potentially indicating acetamide being the most favourable product to be formed of these structures⁴. Most organic molecules including formamide are predicted to form on grain surfaces or ice mantles through hydrogenation, yet experimental abundance levels of formamide in this specific environment does not correspond with acetamide, despite being structurally similar⁵. Synthesis of acetamide was possible in the presence of CO, NH_3 , and methane at 77 K in irradiated ices, but this environment is not found in the interstellar medium⁶. Most of the ISM is relatively low particle density and low temperatures found in cold cores with dense molecular clouds, not hot cores that would be ideal for synthesis⁷. The activation energy barrier associated with forming these molecules in low density and temperature can be overcome through UV radiation, proton flux, or shocks associated with star formation, potentially using comets to spread¹. The relative amount of energy required illustrates that it is

more difficult to find acetamide, a 9-atom molecule, versus formamide, a 6-atom molecule^{8,9}. The similarity in abundance of acetamide, ketene, and formamide despite their difference in complexity suggests that acetamide is a heavily favoured product in ISM.

The proposed mechanism for the formation of acetamide is based on ketene and ammonia reactants, where ketene has been proven to exist at 15 K through isotopic shift testing using B3LYP level of theory, easily forming in ice¹⁰. Ketene can also be formed from the decomposition of acetamide, acetaldehyde, acetone, and acetic acid while dissociating to make CH_2 . These are all constituents used in potential acetamide pathways¹⁰. Ammonia, along with acetamide, has been discovered in Sagittarius B2, the eminent source for the interstellar study of large complex molecules¹¹. Ammonia was also the first polyatomic molecule to be discovered in the ISM and can be used to form formamide, giving high probability of acetamide synthesis as well due to their similarity¹². Due to its prevalence and use in other reactions, acetamide is probably synthesized frequently. Because of these proven formations, molecules with peptide bonds have good probability and relative abundance, with acetamide forming through a promising pathway shown in Figure 1. Experimental simulation of radiation indicated, through infrared spectroscopy, that acetamide, urea, and acetone are all present in the ISM, with urea hydrolysis forming ammonia and acetone pyrolysis forming ketene, two probable reactants for acetamide synthesis⁶.

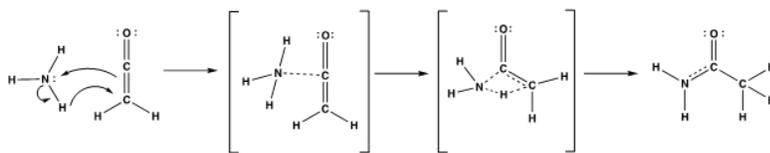


Figure 1 Proposed Acetamide Synthesis Mechanism Through Ammonia and Ketene Reaction

In the proposed reaction via ketene and ammonia, a nucleophilic attack results in the formation of an ionic intermediary step, leading to the reformation of the bonds that form acetamide. After thorough analysis of the reactants to form a viable mechanism, it is hypothesized that acetamide will form in a highly exothermic spontaneous reaction that can provide a precursor to more complex molecules, such as amino acids. This would support the origin of life theories proposing that essential biomolecules were initially formed in space and later arrived on Earth, due to the strongly reductive environment hypothesized by Miller's "RNA World" experiment which demonstrated that formaldehyde and hydrogen cyanide were abundant and important intermediates in glycine synthesis³.

METHODS

Reaction mechanisms and pathways were calculated at standard ISM conditions of 0 atm pressure and 15K temperature. The geometry optimization and frequencies of the calculated structures were computed using density functional theory (DFT) at Austin-Frisch-Petersson functional with dispersion (APFD)/6-31G(d) level of theory to produce quantum chemical calculations using the Gaussian16 software package^{13,14,15}. This method was chosen as DFT can give highly accurate results using a moderate basis set size in comparison to ab initio methods, such as MP2, which require a much larger basis set to get the same result, costly computationally and also in time. The APFD functional is a newer and faster method that is more accurate than more commonly used B3LYP, which also lacks the dispersion correction to make the functional more accurate. Predicted reaction mechanisms and potential transition states were also calculated using the same level of theory and the thermodynamic properties were derived to determine enthalpy, entropy, and Gibbs free energy values. In order to demonstrate a noticeable change in energy, figures and calculations were based relative to the reactant, after converting values in Hartree units to kJ/mol. Molecules were constructed and visualized using the GaussView 5 software¹⁶.

RESULTS

The results of the computations are summarized in Tables S6, S7, and S8, with the reaction pathway shown in Figure 2.

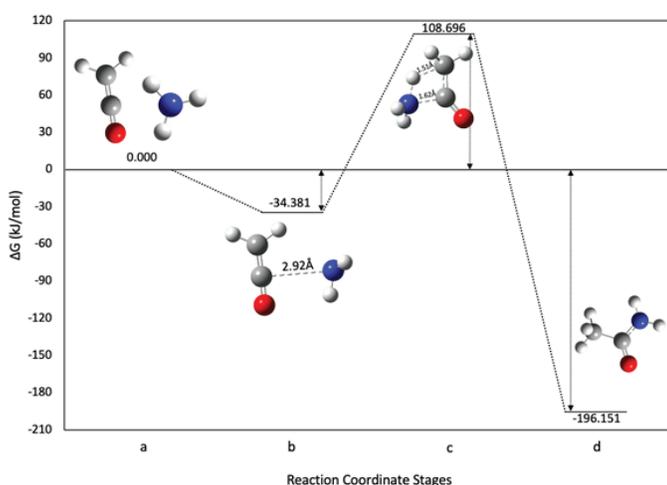


Figure 2 Ammonia and Ketene Reacting in ISM to Synthesize Acetamide Through Changes in Gibbs Free Energy (kJ/mol). a, ketene and ammonia near in ISM. b, first proposed transition state. c, second proposed transition state. d, stable acetamide product.

To narrow down possible reaction mechanisms, viable constitutional isomers were examined and the most stable and probable were selected as reactants for possible acetamide formation mechanisms¹⁷. These rearrangement reactions as well as other synthesis reactants were eliminated because of unviability due to the lack of formation of pi bonds, lack of breakdown of sigma bonds, or excessive free energy values^{17,18}. Based on the sources of energy available in ISM, any larger molecules would not break down into acetamide as molecules greater than 9 atoms of this complexity are less frequently found in ISM^{19,20}. These molecules, containing oxygen, carbon, hydrogen, and nitrogen, usually exist only as polymers^{19,20}. The most likely synthesis came from ketene and ammonia, and structures were located and visually confirmed by intramolecular motions created by frequencies made in GaussView software²¹.

DISCUSSION

In the proposed mechanism, ammonia and ketene on their own (Fig. 2a) are much less stable than the first transition state (Fig. 2b), possibly due to the closeness of the bonds (2.92Å) and electronegativity of nitrogen in the TS. However, the second transition state (Fig. 2c) is the least stable, as bonds start to break and reform, overcoming the high activation barrier (108.696 kJ/mol) to form the product (Fig. 2d). Relative to the reactants, the formation of acetamide is highly favourable and spontaneous with a Gibbs free energy value of -196.151 kJ/mol. As the ΔH and ΔG are highly negative under ISM conditions of 0 atm pressure and 15 K temperature, this highly exothermic and exergonic mechanism is viable in the ISM, forming acetamide. These calculated thermodynamic values give evidence of a highly kinetic and favourable reaction, despite limited sources of energy that are available mostly through UV radiation.

A theorized method of synthesis yielding protonated acetamide from ammonium and acetaldehyde followed by dissociative recombination was suggested, but experimentally determined rate constants determined by Quan and Herbst 2007 produced product slower than in reality⁵. Although the proton transfer transition state was energetically favourable, abundance of protonated acetamide was similarly low¹⁸. Another reaction through the use of protonated methane could potentially work, but it is likely to produce a variety of products, therefore creating the same problem of low relative abundance. Furthermore, protonated methane has also not yet been found in the ISM. The conditions of the ISM also restrict possible mechanisms, as a methylene radical or benzene radical reactant would not form a viable reaction due to the need for a spin flip at high temperatures not found in the ISM^{7,20}.

CONCLUSION

Through the computational chemistry calculations done at a realistic ISM simulation of conditions, a viable mechanism for the synthesis of acetamide was substantiated through thermodynamic values using ketene and ammonia as reactants. Further studies should be conducted to discover other possible mechanisms that demonstrate a higher likelihood of acetamide formation. Although other reactants are proposed and amino acid precursors are abundant in the ISM, more research to corroborate this study is needed to expand the biological significance of these results. If acetamide synthesis is truly viable, it is the antecedent to glycine and more complex amino acid syntheses not yet found, contributing to the beliefs that the biological precursors of life on Earth formed in space.

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COMPETING INTERESTS

No competing interests declared.

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