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Quantum chemical analysis of the theoretical formation mechanism of glycine in dense molecular clouds

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Abstract

More than ten years ago, the simplest amino acid, glycine (NH_2CH_2COOH), was found in cometary samples by the Stardust project of NASA. Glycine is one of the 20 proteinogenic amino acids that serve as building blocks for proteins. It has been theorized that some biomolecules, including amino acids, originated in space and were brought to Earth by meteorites, therefore playing an important role in the origin of life. The detection of glycine by Stardust may support this theory.

This study proposes a new reaction pathway for the formation of glycine in gas phase under dense cloud conditions of temperature 15 K and pressure 0 atm. The reaction starts with small and abundantly found molecules in interstellar medium (ISM), namely hydrogen cyanide, carbon monoxide, hydrogen gas, and water. Since the temperature and pressure in dense clouds are extremely low, exothermic reactions with low energy barriers are considered feasible.

B3LYP/6-31G(d) level of theory was used to optimize geometries and calculate thermodynamical properties through vibrational frequency calculations under dense cloud conditions. Single point calculations were also performed using MP2/6-31G(d) level of theory to confirm the obtained thermodynamic data. The respective stabilities were examined using the thermodynamic data calculated for the proposed reactants, transition states, and product. Since the proposed reaction is calculated to be exothermic with low energy barriers under dense cloud conditions, theoretically, the criteria for the reaction to occur in ISM have been fulfilled.

Keywords: *Astrobiology, astrochemistry, dense clouds, reaction mechanism, quantum chemical calculations*

Introduction

The origin of life has always been a great subject of research, with many theorizing that the "molecules of life"—nucleic acids, proteins, carbohydrates, and lipids—were introduced to pre-biotic Earth by a comet or meteorite that struck its surface [1]. Early or pre-biotic Earth defines a period about 4.5 billion years ago, before life existed due to the extreme environment on the planet [2]. Proteins are made up of amino acids, which are organic compounds generally characterized by a carboxylic acid group (COOH), an amine group (NH_2), and a specific "R" group, as shown in Figure 1A. While many exist, only 20 of them serve as the building blocks of proteins in organisms. Synthesis of amino acids requires the presence of certain molecules, such as H_2O, NH_3, CH_4, and HCN, which have been found in interstellar medium (ISM) [3].

Interstellar medium is the matter and radiation that exists in galaxies between star systems. ISM is organized into molecular clouds, which are areas dense in chemical species (especially hydrogen and helium), where star formation reactions could occur [4]. Molecular clouds are further divided into various types, depending on conditions such as temperature and density. One such type, dense clouds, are characterized by a temperature of 15–20 K and a molecular density of 10^3-10^6 cm^{-3} [5]. While the temperatures are low, energy sources such as cosmic rays and soft X-rays have been detected [6].

Considering amino acids are of great biological importance, there has been great interest in verifying their existence, as there is a possibility that they have extraterrestrial origins [8,9]. Indeed, studies have shown that some amino acids can be generated in conditions matching those of interstellar dense clouds [7]. Since glycine is the simplest of all amino acids (shown in Figure 1B), much research has been done to verify its presence in ISM.

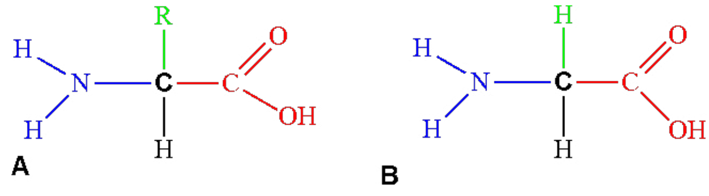

Figure 1*: The structure of amino acids.* A) The generalized structure of an amino acid, highlighting the functional groups. B) Glycine, the simplest of the 20 proteinogenic amino acids (R=H).

There have been many attempts to verify glycine's presence in interstellar clouds in recent years, the most famous being glycine's "detection" in 2003, based on the observation of 27 spectral lines associated with glycine from three different molecular clouds [8-13]. However, the results of this study were disputed after analysis of the data showed that the spectral data could have belonged to a number of different molecules that were structurally similar to glycine, such as formic acid and acetic acid [9]. Furthermore, all of the spectral lines from the three clouds only had three lines in common, which further weakened the evidence for glycine's detection presented in the study [9]. Therefore, glycine's presence in ISM has yet to be confirmed. However, it must be acknowledged that there are difficulties associated with glycine's detection, specifically regarding its weak lines in rotational spectrums [8].

Over a decade ago, NASA probe Stardust obtained cometary samples showing promising data [14]. Analysis of these samples showed organic matter rich in oxygen and nitrogen, while presence of deuterium and N-15 suggested that at least some of the matter had interstellar origins, most likely of dense clouds and/or protostellar nebulae. Additionally, a statistically significant amount of glycine, relatively higher than those in controls, was found in the comet sample returned by Stardust [14]. Further analysis of glycine present in the comet confirmed its detection and interstellar origin based on the stable carbon isotopic ratio. The study also ruled out the possibility of contamination of glycine since it was found on the aerogel (comet-exposed) side of the sample [15]. Overall, the presence of glycine in the comet not only confirms glycine's existence in ISM, but also illustrates the possibility of safe delivery of glycine to Earth, additionally strengthening the theory of interstellar origin of life.

Although glycine and various other molecules have been detected in comets, the mechanism for the formation of gas-phase glycine in dense clouds is unclear, although attempts have been made in numerous studies [16-22]. There is a considerable amount of research in the mechanism for glycine's formation and in precursors that could be of interest for its synthesis. A five-membered heterocyclic compound, hydantoin (glycolylurea), as shown in Figure 2, has been proposed to be a possible precursor. It is known to occur from prebiotic molecules (such as urea and glycolic acid) under ISM conditions and was also detected in carbonaceous chrondites [23]. However, hydantoin has not yet been detected in ISM [19,24].

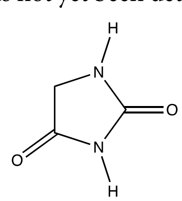

Figure 2: Hydantoin (glycolylurea), a five-membered heterocyclic molecule that is proposed to be a precursor for the formation of glycine in ISM.

Although numerous studies have been conducted to find and verify interstellar glycine, its possible precursors and formation mechanism in various ISM media remain unknown. This study proposes a new reaction for the formation of interstellar glycine in gas phase under dense cloud conditions, based on the reaction mechanism shown in Figure 3. The proposed reaction uses small molecules (HCN, CO, H_2O, and H_2) known to be abundant in ISM [4,25], and is theoretically calculated to be exothermic in ISM, which suggests the possible feasibility of this reaction occurring in dense clouds.

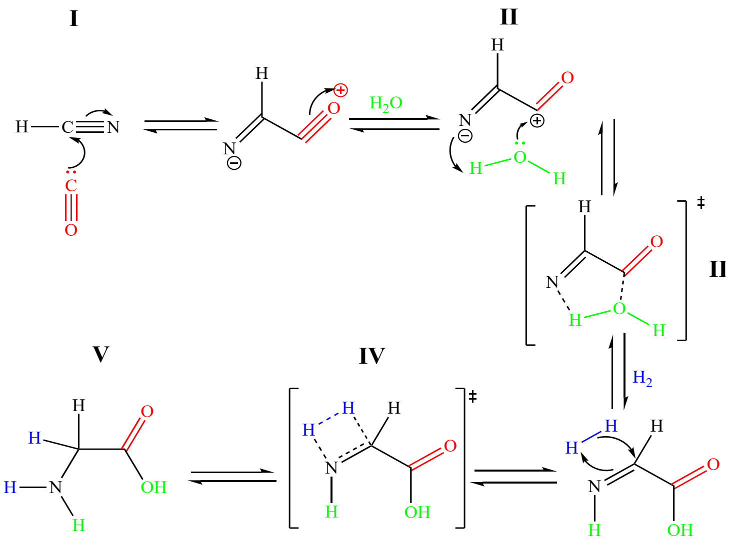

Figure 3: The proposed reaction to form glycine in dense molecular clouds in gas phase starting with small and readily present molecules HCN, H_2O, H_2, and CO.

Methods

The molecules involved in the reaction mechanism were optimized and their thermodynamic calculations were obtained. To optimize the studied species, the B3LYP/6-31G(d) method was used as it is implemented in the Gaussian 09 program package [26]. Geometry optimization and frequencies were calculated with the temperature set as 15 K and the pressure set as 0 atm. Single point calculations were performed using MP2/6-31G(d) level of theory to confirm obtained thermodynamic properties.

Results and discussion

The results of the computational data calculated in conditions that mimic Earth and dense molecular clouds are summarized in Table 1.

For the purposes of this study, changes in Gibbs free energy and entropy are the primary focus for analyzing the stability of the molecules involved in the reaction. As seen in Figures 4 and 5 and Table 1, the overall changes in Gibbs free energy ($\Delta G_{reaction}$) for gly-

	Earth				Dense Molecular Clouds			
	ΔE (kJ/mol)	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (cal/mol-K)	ΔE (kJ/mol)	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (cal/mol-K)
Reactants	220.97	107.77	228.41	171.61	210.12	207.71	210.50	84.99
1st TS	710.46	635.43	715.42	139.03	702.72	701.23	702.97	68.28
Intermediate	105.64	87.41	105.64	89.52	99.42	99.30	99.42	42.53
2nd TS	1066.71	1073.95	1066.71	69.10	1069.83	1069.84	1069.83	40.43
Product	0	0	0	74.91	0	0	0	40.57

Table 1: The relative thermodynamic data of Glycine synthesis under conditions mimicking Earth and dense molecular clouds.

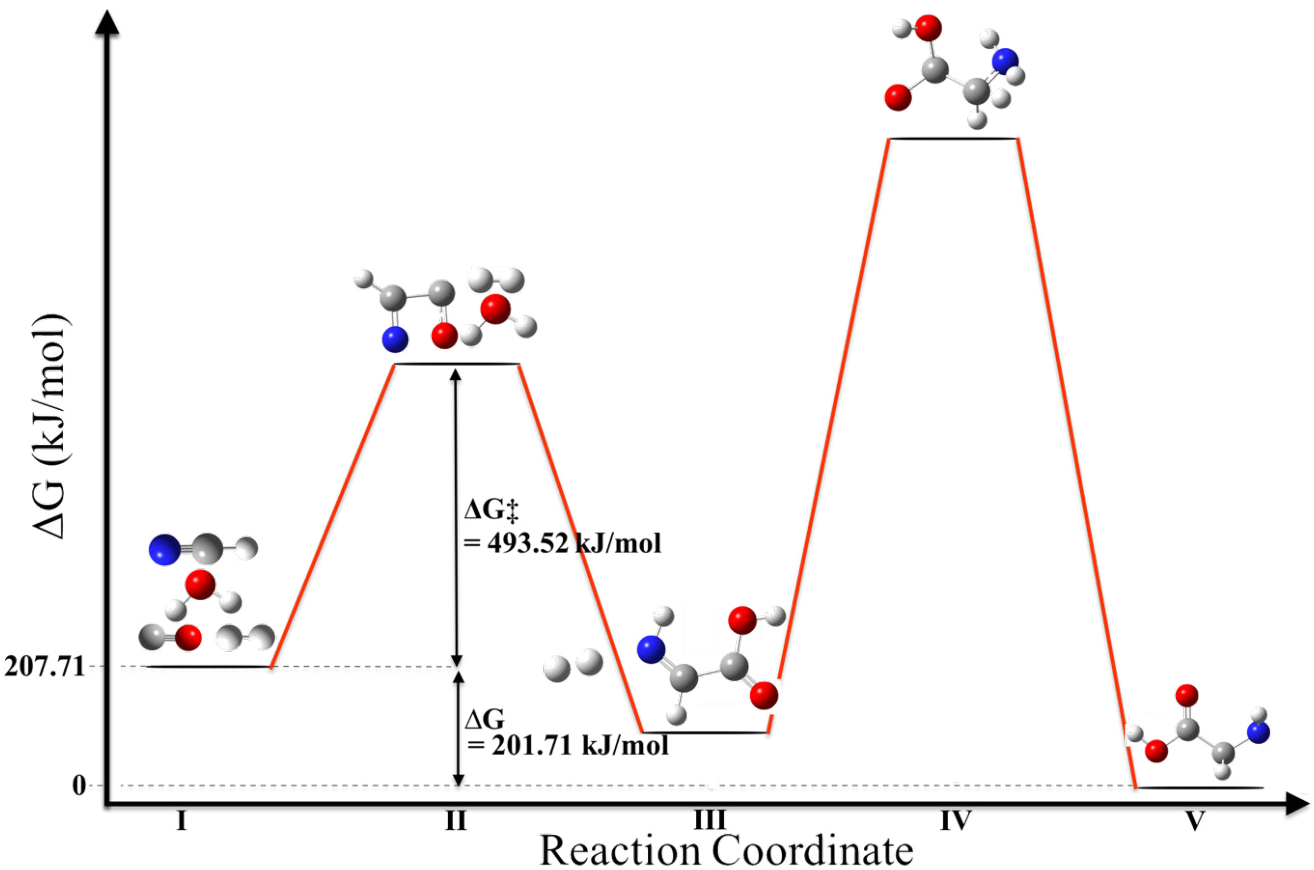

Figure 4: The relative change in Gibbs free energy as a function of reaction coordinate during the formation of glycine. The reaction is exergonic as indicated by ΔG and occurs between H_2, HCN, H_2O, and CO under dense cloud conditions (15 K, 0 atm).

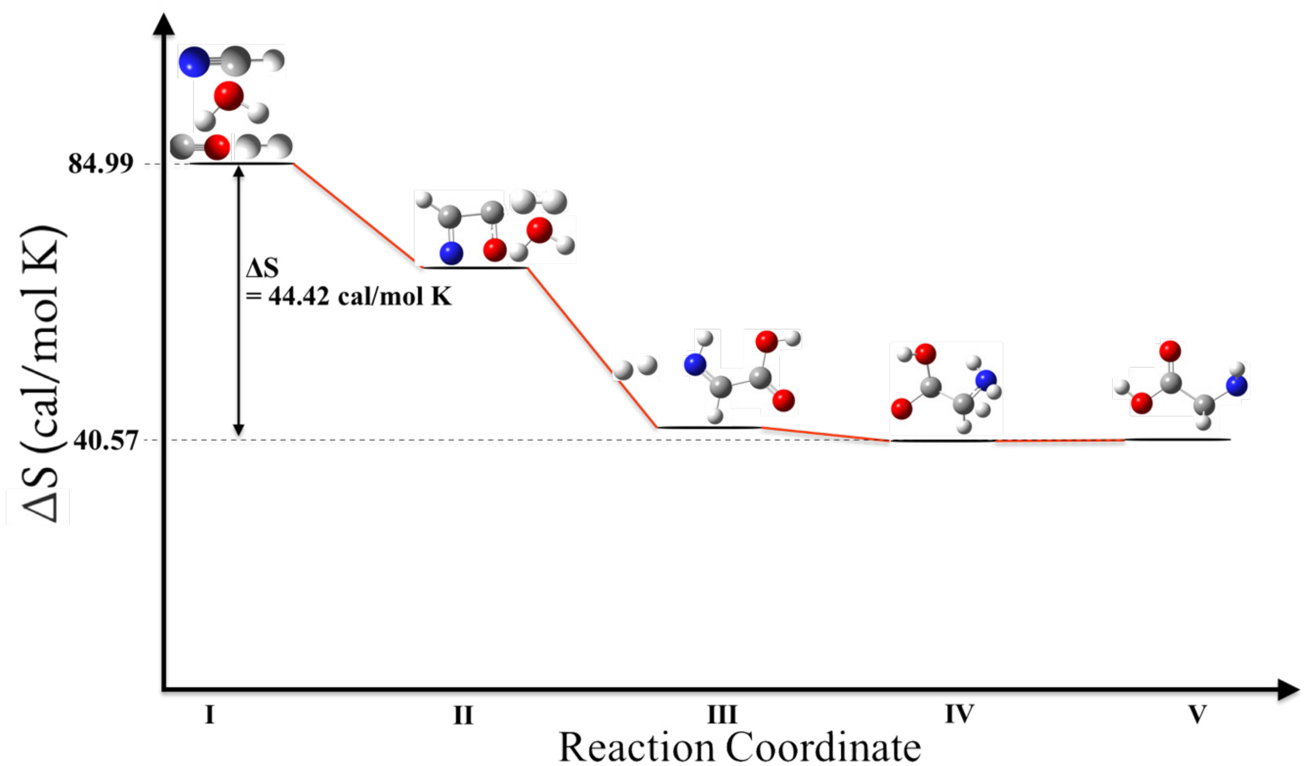

Figure 5: The relative change in entropy as a function of reaction coordinate during the formation of glycine. ΔS indicates a loss in entropy, implying that the final product is much more structured and stable. The reaction occurs between H_2, HCN, H_2O, and CO under dense cloud conditions (15 K, 0 atm).

cine formation were calculated to be -107.77 kJ/mol under Earth conditions and -207.71 kJ/mol under dense cloud conditions, respectively. The activation energies ($\Delta G^{\ddagger}$) were calculated to be 527.66 kJ/mol and 493.52 kJ/mol, and the changes in entropy (ΔS) were calculated to be -96.70 cal/mol-K and -44.42 cal/mol-K under Earth conditions and dense cloud conditions, respectively.

Since $\Delta G_{reaction}$ is negative for the proposed reaction under both Earth and dense cloud conditions, the reaction is exergonic, which indicates a release of energy that is considered favourable, especially in ISM. The activation energies ($\Delta G^{\ddagger}$), however, were found to be quite high (493-527 kJ/mol). In order to overcome this energy barrier, an energy source is required. This energy could be provided by cosmic rays and soft X-rays present in dense clouds that, when striking molecules, can provide enough energy to start the reaction. The mechanism could possibly involve tunneling as well [28].

In terms of entropy, since ΔS of glycine (the product) is lower than that of the reactants under both Earth and ISM conditions, this indicates that glycine is more structured and stable. However, due to the extremely low temperatures in ISM, the gain in entropy would not have a significant impact on the spontaneity of the reaction, based on the equation: $\Delta G = \Delta H - T\Delta S$. The low temperature would also imply that the T component could easily be overcome by the component, indicating that the driving force behind this reaction is the release of heat from differences in chemical potential and not due to changes in entropy.

Overall, ΔS under ISM conditions is less than half of ΔS under Earth conditions, which is consistent with the low temperatures of dense clouds (15 K).

Conclusion

The thermodynamic analysis, done *in silico*, have theoretically demonstrated the thermodynamic feasibility of the proposed reaction in ISM. This reaction is very important to astrobiology given the significance of glycine, the smallest proteinogenic amino acid, as it could underline the possibility of extraterrestrial origins of life. With more research into this field, findings in this paper could indicate prebiotic material, including glycine, to originate from space, confirming the exogenous nature of prebiotic material that could not be produced on Earth.

Furthermore, using insights into the thermodynamic properties analyzed, many more complex amino acids could also be investigated. Additionally, further *in silico* studies using higher levels of theory could be applied to investigate the mechanism. Since the activation energy ($\Delta G^{\ddagger}$) was quite high, and while cosmic rays and soft X-rays are possible sources of energy that are present in dense clouds, further investigation could be pursued to find a mechanism for the reaction to proceed.

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