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VESICLES PROTECT ACTIVATED ACETIC ACID

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ABSTRACT

Methyl thioacetate, or activated acetic acid, has been proposed to be central to the origin of life, and also as an important energy currency molecule in early cellular evolution. We have investigated the hydrolysis of methyl thioacetate under various conditions. Its uncatalyzed rate of hydrolysis is about three orders of magnitude faster ($K = 0.00663\ s^{-1}$; 100°C, pH 7.5, concentration = 0.33mM) than published rates for its catalyzed production making it unlikely to accumulate under prebiotic conditions. However, our experiments showed that methyl thioacetate was protected from hydrolysis when inside its own hydrophobic droplets. Further, we found that methyl thioacetate protection from hydrolysis was also possible in droplets of hexane and in the membranes of nonanoic acid vesicles. Thus, the hydrophobic regions of prebiotic vesicles and early cell membranes could have offered a refuge for this energetic molecule, increasing its lifetime in close proximity to the reactions for which it would be needed. This model of early energy storage evokes an additional critical function for the earliest cell membranes.

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Chapter 1

Introduction

Activated acetic acid, or methyl thioacetate, is an analog to acetyl-CoA postulated to have been important in the origin and early evolution of life on Earth (Wächtershäuser, 2000). The production of methyl thioacetate has been confirmed through experiments from CO and CH_3SH and has been thought to be important for further reactions significant in the origin of life, including the formation of lipids (Wächtershäuser, 1997). Under a variety of origin of life scenarios, thioesters might form and provide an important early energy source during the origin of life (Russell and Martin, 2004) or for early microbial cells (Ferry and House, 2006). Thioesters serve an essential role in early biochemistry and appear in many modern pathways (Russell and Martin, 2004). The roles of thioesters in protometabolism could have included catalysis, free energy, reduction-oxidation reactions, and encapsulation (Brack, 1998). Thioesters are involved in the synthesis of peptides, fatty acids, sterols, terpenes, and porphyrins (De Duve, 1995). Thioesters are formed as key intermediates in some ancient processes that were used to assemble ATP, suggesting that the thioester predated ATP. Thioesters, including acetyl-CoA, can store energy, which can be released when the thioester is broken down into a free thiol and an organic acid (Russell and Martin, 2004), and it is possible that thioesters acted as the energy currency of life in a "thioester world" originally devoid of ATP. ATP could then have come about later by playing a role in allowing the bond formation between phosphate groups (De Duve, 1995). Finally, the enzymatic hydrolysis of acetate thioesters could have supplied an energy conversion pathway early in the evolution of cellular life influencing the evolution of anaerobic pathways (Ferry and House, 2006).

Thioesters are likely to have been important in protometabolism and perhaps the origin of life, and the necessary components to form thioesters were likely present on the early Earth. Organic acids are products of abiotic chemistry that would likely have occurred on the early Earth (Brack, 1998) while

thiols could form if the environment had hydrogen sulfide present in sufficient quantities (Kaschke *et al.*, 1994). There are additional mechanisms for synthesizing thioesters and specifically methyl thioacetate under prebiotic conditions (Orgel, 2004). Methyl thioacetate can be synthesized from methyl mercaptan (CH_3SH) and carbon monoxide with the use of NiS and FeS as catalysts at 100^o C and atmospheric pressure (Huber and Wächtershäuser, 1997). Methyl mercaptan can be synthesized from CO and H_2S over an Fe catalyst (Heinen and Lauwers, 1995). Recently, the production of mercaptan in modern active hydrothermal systems was shown to be from the thermal destruction of preexisting organic matter (Reeves et al., 2014), making its prebiotic availability less certain, but also new possible syntheses relevant to the early Earth are being proposed (Russell et al., 2014).

Under similar conditions that mimic those of a hydrothermal vent, peptides can be formed from amino acids (Huber and Wächtershäuser, 1998 and Huber *et al.*, 2003). Pyruvate, another important compound in metabolism, can also be synthesized under similar conditions but at higher pressures (Cody *et al.*, 2000). Although the potential for hydrothermal vents being suitable sites for origin of life reactions has been controversial (Miller and Bada, 1988), hydrothermal solutions that could carry organic matter could be collected in iron sulfide structures that provide a hydrophobic environment capable of allowing important condensation reactions to occur (Russell and Hall, 1988).

Although thioesters, particularly methyl thioacetate, have been synthesized experimentally under plausible pre-biotic conditions, they are often quite unstable to hydrolysis (Huber and Wächtershäuser, 1997), which produces a free thiol and an organic acid. Previous studies of the hydrolysis of methyl thioacetate found two potential theoretical mechanisms of hydrolysis: a gas phase SN2 concerted mechanism and an aqueous nucelophilic attack by hydroxide on the carbonyl carbon in a stepwise manner (Fu and Lin, 2011). The experimental energy profiles for the degradation were found to be compatible with their theoretical results. In the degradation of methyl thioacetate, acetic acid is produced as a result of the hydrolysis. Generally, the rapid hydrolysis of methyl thioacetate limits its utility in origin of life scenarios. An additional problem encountered with the use of methyl thioacetate in prebiotic chemistry is

that it would likely disperse into the surrounding medium and be diluted to a low concentration, rendering it unable to function as an energy-carrying molecule. In order to be useful in any origin of life scheme where dilution is a possibility, such as a "heterotrophic origin of life" scenario (Lazcano and Miller, 1999), or as an energy molecule for protometabolism, thioesters would need to be synthesized and/or concentrated so that the appropriate concentrations are available. The dilution coupled with rapid hydrolysis of thioesters might seriously limit their importance to the origin of life. There are, however, potential solutions to both problems, which we have explored experimentally.

Here, we report the measured rate of hydrolysis of methyl thioacetate under a range of conditions. We have found that while aqueous methyl thioacetate is relatively unstable, the high-energy compound can be concentrated and protected in hydrophobic droplets or amphiphilic vesicles. This is potentially significant for the origin and early evolution of life on Earth because early prebiotic environments could have contained the long chain carboxylic acids or alcohols necessary to form vesicles (Segre *et al.*, 2001). Molecules that could form vesicles on the early Earth include fatty acids, glycerol esters of fatty acids, sterols, and phospholipids. Generally, the hydrocarbon portions of these molecules need to be of a certain length to produce stable lipid structures (Deamer, 1985). Another potential environment for the protection of hydrophobic compounds is within hydrophobic or amphiphilic peptides, which have been shown to self-assemble (Yu *et al.*, 1996) Organic material that could form membranous structures, such as vesicles or bilayers, could have been delivered to the early Earth by meteorites. Studies of the Murchison meteorite extracts have revealed such nonpolar molecules (Deamer, 1985). Other studies of the compounds in comets show that vesicular structures can be formed (Dworkin *et al.*, 2000). While not universally accepted (see Shapiro, 2011), this suggests that membranous boundary structures were available to participate in the origin and evolution of life reactions on the early Earth (Deamer, 1985).

Chapter 2

Materials and Methods

7.5 mL of 0.1M sodium phosphate was made and the pH was accordingly adjusted (with either hydrochloric acid or sodium hydroxide) for each given experiment in the pH 6-8 range. Experiments in the pH range of 4-5 were buffered with 0.1M sodium acetate, those with pH 9-12 were buffered with 0.1M sodium borate, and those in the 1-3 pH range were unbuffered. Then methyl thioacetate was added to the solution to reach the appropriate initial concentration for each specific experiment. The solution was capped, shaken, and then divided into six Teflon vials, each containing 1.25 mL. These vials were incubated for 0, 10, 30, 60, 120, and 180 minutes. The manner of heating depended on the conditions of the experiment, with "agitated" conditions carried out in a beaker of boiling water with vials allowed to move about as the water boiled. The "un-agitated" conditions were carried out in a rigid and stationary heat block. The UV-Vis Spectrophotometer was blanked with a sample of 0.1M sodium phosphate. Once a given sample was finished incubating, the vial was removed from the heat source and quenched in cold water. After cooling down, a subsample was placed in a quartz cuvette and read by the UV-Vis Spectrophotometer (either at wavelength 259 nm or 285 nm for 0.005M and 0.1M initial concentration, respectively). After all the samples were read by the spectrophotometer, the data were analyzed using pseudo-first-order kinetics. This generates a rate constant for each experiment, which could then be plotted and analyzed. All of the experiments were carried out two or three times to obtain duplicate or triplicate data. The rate constants reported are the averages for a given set of experimental conditions and the errors represent the standard deviations of the individual trials.

For experiments carried out with another protecting molecule, such as hexane or nonanoic acid, a similar procedure was followed. Before adding methyl thioacetate to the solution of sodium phosphate, the appropriate amount of the hexane or nonanoic acid was added to the vial. After, the appropriate amount of methyl thioacetate was added and the solution was shaken. Everything else was carried out in the same manner as experiments described above. Experiments with hexane added had a maximum initial concentration of methyl thioacetate of around 0.15M. The experiments with hexane included were not done at as high initial concentrations as those without hexane. This was due to the observation that the thioester was able to self-protect at these higher concentrations (starting around 0.1M). In other words, with the concentration of hexane at 0.1M, increasing the concentration of the thioester beyond this concentration would cause the thioester to be more likely to self-associate than to associate with the less-abundant hexane.

The concentration of nonanoic acid used in experiments was based on both literature and experimental observations. Nonanoic acid is known to form stable vesicles at concentrations greater than 0.085M (Deamer *et al.*, 2002). When a 0.1M solution of nonanoic acid was prepared, it was extremely turbid due to the micelle formation. To reduce this turbidity and allow for analysis by the spectrophotometer, a 0.05M concentration was used. It was observed by microscopy that vesicles still formed at this concentration (Figure 3A).

The series of experiments designed to examine the temperature dependence of the hydrolysis of methyl thioacetate in each of the four experimental conditions were carried out with a few experimental changes. A concentration of 0.001M methyl thioacetate and a pH of 7.5 were chosen. The level of agitation was kept fairly consistent throughout the experiments with changing temperatures. For un-agitated experiments, the temperature of the heating block was adjusted to the specified temperature and the experiments were carried out in the same manner. For agitated experiments, the samples were heated in a hot water bath of the appropriate temperature and manually disturbed.

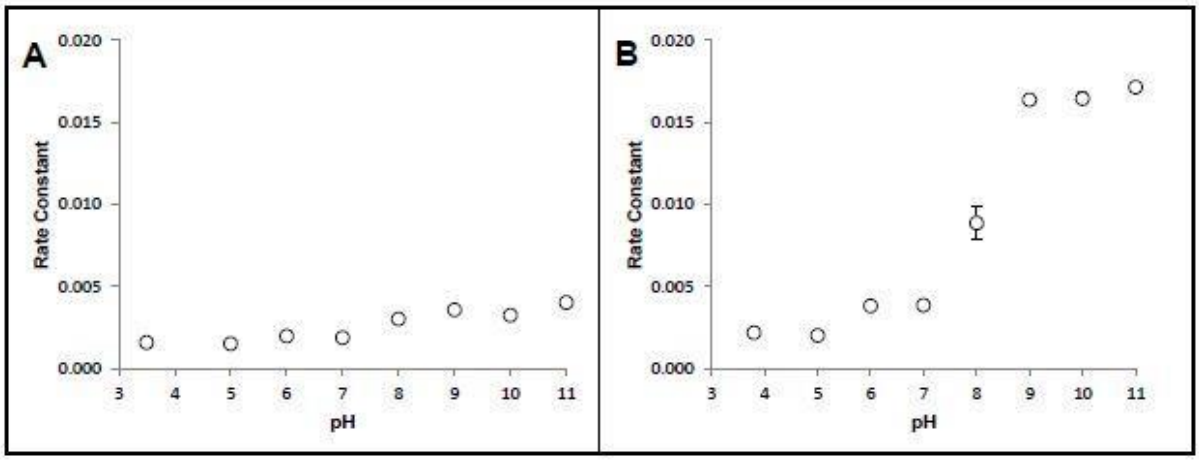
The activation energies for the four experimental conditions were found from the Arrhenius plots (ln(k) vs. 1/T), with the slope of the trend line equal to –Ea/R, where Ea is the activation energy and R is the universal gas constant. Thus, the slope of each trend line was multiplied by -8.314 J/mol/K and the results gave the activation energies, which are listed in the results and discussion section above.

Chapter 3

Results

We first investigated the dependence of the rate of hydrolysis of methyl thioacetate on pH. This was done at two different initial concentrations of the thioester: 0.1M and 0.005M. Figure 1 shows the average rate constant as a function of pH (±1σ). In experiments conducted with 0.1M methyl thioacetate, we found the rate of hydrolysis to be essentially independent of pH. Alternatively, the experiments using 0.005M methyl thioacetate showed an increase in the rate of hydrolysis at basic pHs. While the rate constants at pH <7 were similar to those for the 0.1M experiments, the rate constant at pH 9, 10, and 11 appeared higher by a factor of ~7. The base catalyzed leg seen at an initial concentration of 0.005M was not observed at the higher initial concentration of 0.1M.

Figure 1: Hydrolysis rate of Methyl Thioacetate.

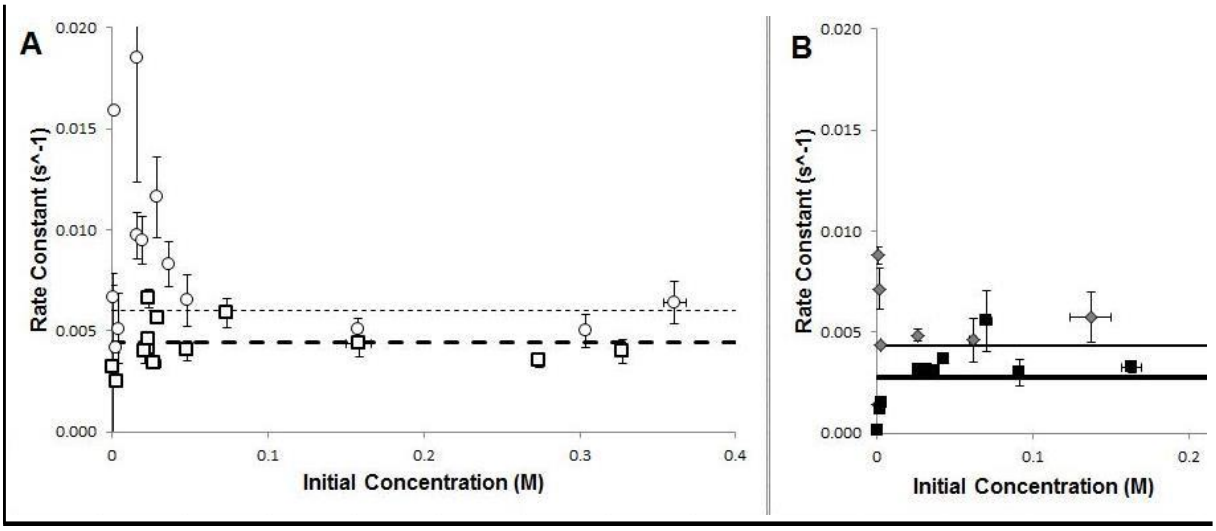


(A) Observed rate of hydrolysis of methyl thioacetate vs. pH for experiments with an initial concentration of 0.1M. (B) Observed rate of hydrolysis of methyl thioacetate vs. pH for an initial concentration of 0.005M. Experiments with the lower starting concentration of methyl thioacetate showed a base catalyzed leg not observed at the higher initial concentration of methyl thioacetate. Higher initial concentrations of methyl thioacetate are forming hydrophobic self-protecting droplets limiting the observed rate of hydrolysis.

Another set of experiments tested the effects of both the agitation of the solutions and the presence of a hydrophobic molecule on the rate of hydrolysis of methyl thioacetate. These parameters

were chosen for study in order to see if there was a way for the methyl thioacetate to be protected, either by another molecule or by itself. Figure 2 shows the results for agitated and un-agitated experiments both with and without hexane. Figure 2A shows the agitated (circles) and un-agitated (squares) experiments without hexane. The agitated experiments have higher observed rate constants than the un-agitated experiments, particularly at lower initial concentrations of methyl thioacetate. Beyond a certain initial concentration around 0.07M, the rate constants for the experiments level out to a fairly consistent value. Figure 2B shows the agitated experiments with hexane (circles) and the un-agitated experiments with hexane (squares). When hexane was added, the rate of hydrolysis was significantly reduced in both the agitated and un-agitated states when compared to experiments without hexane present. The un-agitated experiments have much lower rates that approach zero as the initial concentration is decreased. At higher initial concentrations of methyl thioacetate, the observed rate constants appear to level out. The consistent rate reached at these higher concentrations was lower for experiments containing hexane than for those without hexane.

Figure 2: Hydrolysis rate of Methyl Thioacetate in varied conditions.

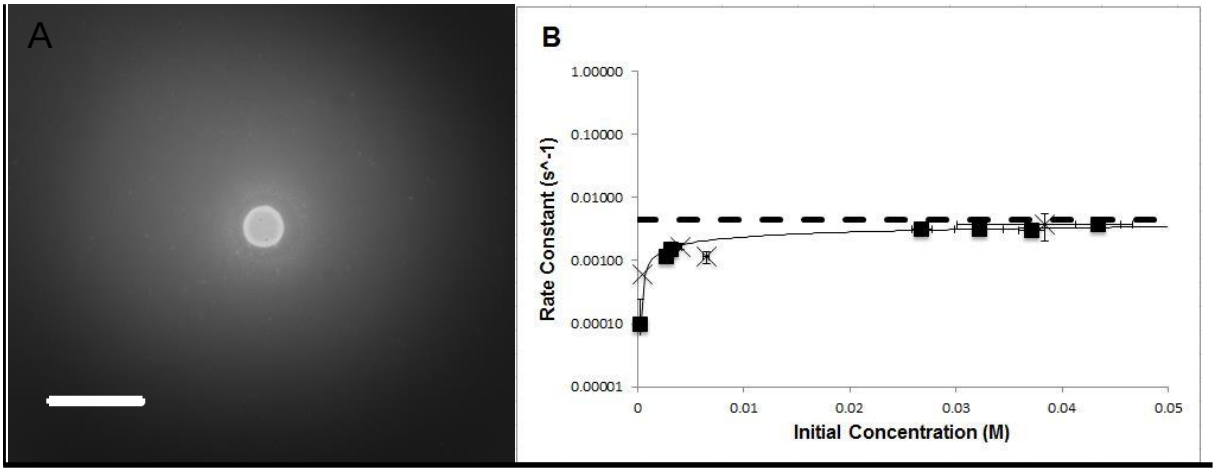


(A) Experiments without the addition of hexane; (B) Experiments with the addition of hexane. In Fig 2(A), the open circles indicate agitated experiments without hexane. The open squares show un-agitated experiments without hexane. In Fig 2(B), closed circles indicate agitated experiments with hexane and closed squares are un-agitated experiments with hexane. Weighted averages have been placed on the figures for each set of conditions. The highest rate of hydrolysis observed was for agitated experiments without addition of hexane. These observed rates of hydrolysis reached a fairly consistent value at higher concentrations of methyl thioacetate. With hexane, the observed rate of hydrolysis is dramatically reduced especially at low

concentrations. The results are all consistent with methyl thioacetate forming self-protecting droplets or being protected in another nonpolar compound and limiting the observed rate of hydrolysis.

Next, similar experiments were carried out with an amphiphilic molecule, nonanoic acid (16) because nonanoic acid is known to form stable vesicles (Figure 3A). Figure 3B shows the protection of the thioester at lower concentrations by another compound, which in these experiments is either hexane (squares) or nonanoic acid (crosses). Here, the rate of hydrolysis is decreased dramatically at lower initial concentrations of methyl thioacetate, where the thioester can be more easily protected in the added compound. The experiments with hexane and nonanoic acid are consistent with each other.

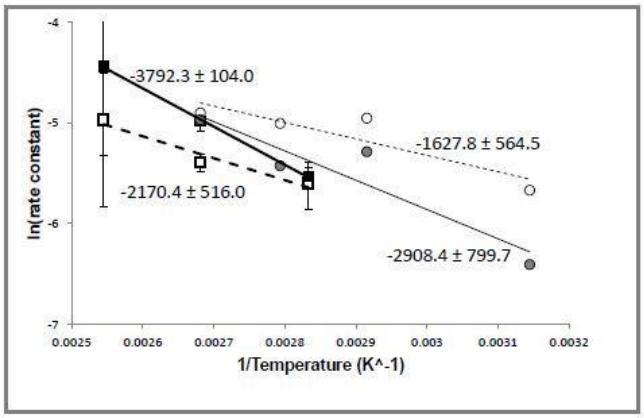
Figure 3: Methyl Thioacetate and Nonanoic Acid



(A) A pH 7.5 solution of 0.05M nonanoic acid stained with rhodamine G6 observed at 1000x magnification, showing a vesicle. The scale bar is 10 μm. (B) The observed rate of hydrolysis of methyl thioacetate dramatically decreases as the concentration of methyl thioacetate decreases due to the ability of the hexane (squares) or nonanoic acid (crosses) to protect the methyl thioacetate in hydrophobic droplets and/or vesicles. The dashed line shows the average rate for all un-agitated experiments without either hexane or nonanoic acid. At higher concentrations of methyl thioacetate, a consistent observed rate is reached that is likely due to methyl thioacetate self-protection at these higher concentrations. Note that the y-axis is on a logarithmic scale.

In addition to the above experiments, procedures were carried out to determine the temperature dependence of the observed rate of hydrolysis of methyl thioacetate for all four experimental conditions (Figure 4). The observed activation energies for the conditions of agitated experiments without hexane, agitated experiments with hexane, un-agitated experiments without hexane, and un-agitated experiments with hexane are respectively 13.5±4.7 kJ/mol, 24.1±6.6 kJ/mol, 18.3±4.2 kJ/mol, and 31.6±0.83 kJ/mol.

Figure 4: Arrhenius plots for various conditions.



This figure shows the Arrhenius plots for all four experimental conditions: agitated without hexane (open circles), agitated with hexane (closed circles), un-agitated without hexane (open squares), and un-agitated with hexane (closed squares). Trend lines are added to the data and the slopes and uncertainties in slope are shown for each set of conditions. The slopes correlate directly to the observed activation energy for each set of conditions. The observed activation energy (slope of the trend lines) increases for un-agitated experiments or experiments with hexane added.

Chapter 4

Discussion

The first set of experiments tested the effect of pH on the observed rate of hydrolysis at two initial concentrations of methyl thioacetate: 0.1M and 0.005M. The presence of a base-catalyzed leg at the lower initial concentration of methyl thioacetate led to the hypothesis that the thioester could be aggregating and forming droplets when present in higher concentrations. When the thioester was associated in these droplets, it would have been more protected and would thus have a lower observed rate of hydrolysis. At the higher concentration of 0.1M, droplets would protect the thioester better than at a concentration of 0.005M, so that the rate of hydrolysis was roughly constant at different pH values. At the dilute concentration of 0.005M, the droplets would not form as well or be as stable due to the small concentration of thioester, so the molecule would be more susceptible to hydrolysis. This hypothesis was supported by the observation that solutions of increased concentrations of methyl thioacetate resulted in visible immiscible droplets of methyl thioacetate.

The hypothesis of droplet formation and subsequent protection from hydrolysis was tested in the second set of experiments (Figure 2). In these experiments, the agitation state was varied and the effects of an added hydrophobic compound were studied. The presence of a hydrophobic or amphiphilic molecule was hypothesized to allow for the formation of droplets or vesicles in the aqueous solution, which would protect the thioester from hydrolysis. These droplets and vesicles would be easier to form and more stable in un-agitated conditions than in agitated conditions. It was hypothesized that adding hexane would allow the thioester to be excluded from water and hydroxide molecules, which would decrease the observed rate of hydrolysis. The results from these experiments generally support the hypothesis of methyl thioacetate being protected, either by agitation state or the presence of a protecting

molecule. When agitated, the methyl thioacetate is not able to easily self-protect, especially at lower concentrations, which is seen by a higher rate of hydrolysis. In the un-agitated experiments, the methyl thioacetate can self-protect more efficiently and thus has a lowered rate of hydrolysis. Furthermore, both agitated and un-agitated states show a leveling off of the rate constant at higher initial concentrations of methyl thioacetate, due to more effective protection in its own hydrophobic droplets. Thus, past a certain threshold initial concentration, any higher concentration should have a fairly consistent hydrolysis rate due to the self-protection of the thioester. Figure 2A also shows the weighted averages for the agitated and un-agitated experiments. As is expected for a case where the methyl thioacetate is forming hydrophobic droplets and self-protecting, the un-agitated average rate is significantly lower than the agitated average rate. When hexane was added (Figure 2B), similar results were observed. The addition of hexane should decrease the observed rate of hydrolysis when compared to experiments without hexane added, which was seen in the results. Furthermore, the state of agitation also played a role. When agitated, the methyl thioacetate and hexane droplets would presumably be interrupted and dispersed on occasion, leaving the methyl thioacetate more susceptible to hydrolysis. The higher observed rate of hydrolysis in the agitated experiments supports this hypothesis. Alternatively, when hexane was present and the conditions were un-agitated, the methyl thioacetate was less susceptible to hydrolysis due to less interrupted associations with hexane. This agrees with the experimental findings that the observed rates of hydrolysis were lower for the un-agitated experiments. Also, when the initial concentration of methyl thioacetate was decreased to very low amounts, the observed rate of hydrolysis nearly went to zero. This is presumably due to almost all of the methyl thioacetate incorporating into the hexane droplets and being almost completely protected from hydrolysis. When the concentration of methyl thioacetate was increased, the observed rate of hydrolysis leveled out to a fairly consistent value, again likely due to self-protection. In these cases, the hexane did not play as great of a role in decreasing the rate of hydrolysis; however, when comparing the average rates of hydrolysis for un-agitated conditions with and without hexane, the average with hexane was lower. This shows that the hexane does help to protect the methyl

thioacetate when the agitation states are kept the same. Overall, when considering the weighted averages of the four different experimental conditions, the order from lowest to highest observed rate of hydrolysis was as follows: un-agitated with hexane, agitated with hexane, un-agitated without hexane, and agitated without hexane. The protection of methyl thioacetate is favored by un-agitated conditions and the presence of a hydrophobic droplet-forming molecule, such as hexane.

When similar experiments using nonanoic acid instead of hexane were performed (Figure 3), the results were consistent with the use of hexane. In nonanoic acid, the observed rate of hydrolysis as a function of the methyl thioacetate concentration appears to flatten out at higher concentrations, probably due to the methyl thioacetate forming droplets and protecting itself. At the lowest concentrations sampled, the rate constant approaches zero, indicating that methyl thioacetate could be preserved in a vesicle or hydrophobic droplet for long periods of time. Overall, these results support the hypothesis that methyl thioacetate could be incorporated into vesicles of amphiphilic compounds, such as long chain carboxylic acids that could have been present on the early Earth and potential precursors to cell membranes.

The last set of experiments (Figure 4) was performed to determine the activation energy for the degradation of methyl thioacetate in the four various conditions. The observed activation energy for the degradation of methyl thioacetate is larger for the un-agitated conditions when compared to the agitated conditions, and the observed activation energy is also larger with hexane added when compared to experiments without the addition of hexane. The highest observed activation energy is for the un-agitated experiments with hexane and is lowest for the agitated experiments without hexane. This trend supports the concept that droplet formation protects methyl thioacetate in the hydrophobic conditions (un-agitated and with hexane) making it more difficult for water to reach the methyl thioacetate.

Previous studies (Huber and Wächtershäuser, 1997) experimentally found rates of the production of acetic acid from CO and CH_3SH. This is a two-step reaction, with methyl thioacetate being the

intermediate. The production of methyl thioacetate is the rate-limiting step, so the overall rate from their experimental data is that of the production of methyl thioacetate. This experimental rate of production of methyl thioacetate can be extrapolated and compared to our observed rates of destruction of methyl thioacetate to compare how favorable it is to have this compound present for significant amounts of time. The rate of production of methyl thioacetate at pH 7.5 is approximately 3.7×10^{-9} M/s (Huber and Wächtershäuser, 1997). From our results, the observed rate of hydrolysis of the lowest concentration sampled in agitated conditions is 2.2×10^{-6} M/s. The observed rate of hydrolysis is about three orders of magnitude greater than the experimental rate of production, which indicates that as methyl thioacetate is produced, it is also quickly destroyed. To compare how much the lifetime might be increased if conditions allowed for protection, the observed rate of destruction for un-agitated conditions with both hexane and nonanoic acid were compared for the lowest concentration sampled. For the lowest initial concentration of methyl thioacetate sampled in un-agitated experiments with hexane, the observed rate of hydrolysis was 3.2×10^{-8} M/s. Similarly, in un-agitated experiments with nonanoic acid added, the observed rate of hydrolysis for the lowest initial concentration of methyl thioacetate used was 3.1×10^{-7} M/s. Comparing these observed rates of destruction can give an idea as to how the different conditions affect the lifetime of the methyl thioacetate. Taking the ratio of the observed rate from the agitated experiment without hexane to the observed rate from the un-agitated experiment with hexane gives a value of 70. Similarly, taking the ratio of the observed rate of hydrolysis from the agitated experiment without hexane to the observed rate of hydrolysis from the un-agitated experiment with nonanoic acid gives a value of 7. If nonanoic acid or another micelle-forming compound were present, the lifetime of methyl thioacetate would conservatively be about seven times longer than if no protecting molecule was present. If hexane, or a similar nonpolar molecule were present, the methyl thioacetate would have a lifetime conservatively around 70 times longer than if no protecting molecule was present. These increases in the lifetime of methyl thioacetate could provide a means to preserve this significant molecule for use in origin of life theories.

Chapter 5

Conclusions

From this work, we suggest that methyl thioacetate and other similar thioesters could potentially be protected in nonpolar droplets or hydrophobic aggregates formed by amphiphilic compounds (e.g., vesicles or micelles). This is intriguing in the context of early life on Earth. Our experiments have suggested that it is possible that methyl thioacetate, or another thioester, could be concentrated, contained, and protected in early cell membranes. This molecule could then be hydrolyzed by the proto-organism to provide energy. Our results provide a straightforward and effective process for increasing the amount of time the thioester is present and available to be used during the origin and early evolution of life. By comparing rates of destruction, it was found that methyl thioacetate could last at least 7 to 70 times longer in an un-agitated environment with another hydrophobic or amphiphilic molecule present. An early cell membrane or vesicle could provide the amphiphilic material that could take-up, protect, and store the thioester in close proximity to the place where the relevant biochemical reactions occur. This model of early energy storage also illustrates an additional critical function for the earliest cell membranes.

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ACADEMIC VITA

Zoe Todd
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Education

Pennsylvania State University
Schreyer Honors College
Expected Date of Graduation: Spring 2015
B.S. Astronomy & Astrophysics; Graduate Studies Option
B.S. Biochemistry and Molecular Biology; Biochemistry Option
B.S. Physics; General Option
Minor in Mathematics
Minor in Astrobiology
International Experience: Travel to Germany in May 2011 as part of a study abroad trip to visit automobile manufacturing plants and cultural landmarks.
Relevant Courses:

- Astronomical Methods and the Solar System
- Astronomy of the Distant Universe
- Observational Astronomy Laboratory
- Stars and Galaxies
- Planets and Planetary System Formation
- Introduction to Astrophysics
- Nebulae, Galaxies and Cosmology
- Astrobiology
- Organic Chemistry I & II
- Organic Chemistry Laboratory
- Physical Chemistry - Thermodynamics
- Honors Intro to Modern Physics
- Intermediate Electricity and Magnetism
- Theoretical Mechanics
- Intro to Quantum Mechanics I
- Thermal Physics
- Special and General Relativity
- Honors Ordinary and Partial Differential Equations
- Calculus and Vector Analysis
- Advanced Calculus for Engineers and Scientists I & II
- General Biochemistry I
- Honors General Biochemistry II

Experience

Penn State Astrobiology Research Center
Researcher University Park, PA Summer 2011-Present

- Study the origin of life by experimenting with methyl thioacetate, a potentially important chemical.
- Explore potential fossilization on Triton, a moon of Neptune.
- Manipulate computer models to study potential theories about the formation of the solar system.

Space Telescope Science Institute
Summer Intern Baltimore, MD June 2014-August 2014

- Study white dwarfs in the local universe to look for signs of metal absorption through spectroscopy.
- Study photometry of local sample of white dwarfs to look for infrared excesses indicative of dust disks.

Organic Chemistry Stockroom
Worker University Park, PA 2012-Present

- Assist in organic chemistry laboratory classes by providing equipment to students, refilling solvents and materials, preparing for lab and cleaning up after lab.
- Aid manager in variety of projects to improve the organic laboratory experience for students.

General Chemistry II (Chem 112) Learning Assistant
Learning Assistant University Park, PA 2012

- Facilitated group work among students in lectures.
- Helped students understand chemistry concepts and learn problem-solving skills.
- Provided input on problem sets to the professor.
- Graded student work.

Skills

Computer Skills:

- UNIX/Linux experience
- IDL
- C++/C
- FORTRAN
- Mathematica
- LaTeX
- Microsoft Word
- Microsoft Excel
- Microsoft PowerPoint
- Microsoft Publisher

General Skills:

- Team projects
- Group problem-solving

Publications/Presentations

- Todd, Zoe R and House, Christopher H. Astrobiology. October 2014, 14(10): 859-865. Doi:10.1089/ast.2014.1185
- Todd, Z.R. and House, C.H. Vesicles Protect Activated Acetic Acid. American Astronomical Society 223rd Meeting Poster Presentation.
- Todd, Z.R. and House, C.H. Vesicles Protect Activated Acetic Acid. Conference for Undergraduate Women in Physics 2014. Poster Presentation.
- Todd, Z.R. and Debes, J. The Search for Dusty White Dwarfs. Natonal Capital Area Disks Meeting. Poster Presentation.
- Todd, Z.R. and Sigurdsson, S. A Moderate Migration Scenario for Jupiter to form the Terrestrial Planets. American Astronomical Society 225th Meeting Poster Presentation.

Honors

Schreyer Honors College Scholar (2011-2015)
Bert Elsbach Honors Scholarship in Physics (2014)
Dean's List (Fall 2014, Spring 2014, Fall 2013, Spring 2013, Fall 2012, Spring 2012, Fall 2011, Spring 2011)
Kadtke Family Endowed Scholarship in Astronomy (2012)
Women in Science and Engineering Research Scholarship (2011, 2012)
NASA Science Mission Directorate/Space Grant Internship Program (2011)
Academic Excellence Scholarship (2011, 2012, 2013, 2014)

Activities

Astronomy Department Outreach Volunteer	2012-Present
AstroFest Feature Presenter and Volunteer	July 2012, 2013
Astrobiology Primer 2.0 Accessibility Reviewer	June 2012
Astronomy Club	2011-2014
Physics and Astronomy for Women	2011-2014
Swing Dance Club	2012-2013
Competitive Horseback Riding	2002-Present