

INVESTIGATING THE ENTHALPIC PROPERTIES OF DICATIONIC
ALKYLAMMONIUM BROMIDE GEMINI SURFACTANTS

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DEDICATION

For my wife, Desirae Sutorius, and my father Gary and mother Val, and along with my friends, committee, and department faculty and staff, thank you for your love, support, and patience. I could not have done this without all of you.

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ABSTRACT

THOMAS JOSEPH SUTORIUS

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MAY 2019

Surfactants reduce the surface tension of water. They appear in many places throughout our lives: in detergents, soaps, gels, creams and cosmetics we apply; in food; and in many prescriptions. Surfactants have substantial industrial applications as well. Thus, it is important to understand the chemical and physical properties of these molecules by utilizing various instrumental methods. In this study we investigate a series of Dicationic Alkylammonium Bromide Gemini Surfactants, on the order of 12- m -12 (where $m = 2, 3,$ or 4). These Gemini surfactants contain two quaternary ammonium head groups and a dodecyl chain bonded to each head group. The linkage denoted as 'm' has been varied by 2, 3, or 4 methylene units. Using Isothermal Calorimetry, the thermodynamics of micelle formation and the critical micelle concentration were determined. By conducting these experiments at various temperatures, we have been able to determine the change in heat capacity for micelle formation.

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CHAPTER I

INTRODUCTION

Surfactants have been around since 1929, when they were discovered by Kurt von Neergaard during experiments performed relevant to a newborn's first breathe (Halliday, 2008). They are used every day in: 1) household items such as soaps and detergents; 2) industrial processes such as enhanced oil recovery; 3) medical and pharmaceutical applications. There are many different uses for surfactants, and many are extremely specific in their purpose. One specific type of surfactant is the Dicationic Alkylammonium Bromide Gemini Surfactant. This surfactant has the potential for being an effective skin permeation enhancer among other possible uses. However, a critical factor for all surfactants is knowing the stability of the micelle's structure.

Stability can be related to the change in energy of the system during formation or demicellization of the micelles and can be measured by investigating, in this particular case, the change in enthalpy (heat content) or ΔH . Traditionally, to measure the enthalpy change for reactions, a device called a calorimeter is used. Calorimetry is used to effectively study and collect enthalpy data. One of the best methods for determining heats of reactions is isothermal titration calorimetry (ITC). Here we report on investigations into the enthalpic properties of the three related Gemini surfactants using ITC.

CHAPTER II

BACKGROUND

Surfactants are compounds that lower the surface tension between two states of matter, such as liquid and another liquid, a gas and a liquid, or a solid and a liquid. Surfactants are compounds of an organic nature usually and have the general composition of a hydrophilic end, called the head, and a hydrophobic end referred to as the tail. The hydrophilic head can be composed of any combination of single elements or more complex compounds such hydrocarbon rings. The tail of the molecule is typically a hydrocarbon chain that varies in length and shape. These tail shapes can range from branched, linear, or aromatic. This structure allows the molecule to interact with both polar and non-polar compounds; this property is referred to as amphiphilic (Textor et al. 2015). Amphiphilic molecules can form larger structures made from these smaller molecules, but only under certain conditions. One example of this structural change is the aggregation of these molecules into spherical shapes. This is done by introducing the molecules into a compound that can be either polar or non-polar. If the compound is polar, then the hydrophobic tails will be repelled from the polar solution and will turn in toward each other (Román et al. 2010).

Conversely, the polar heads are left exposed on the surface, all facing outward toward the polar compound. The resulting structure formed is a classic sphere, otherwise known as a micelle (Paula et al. 1995). In a nonpolar compound, the micelle forms the inverse of the example previously described. The polar heads will congregate inward,

while the nonpolar tails are facing outward. The surfactant does not exist solely as a two-state transition from individual molecules to micelles (Sarac et al. 2017). The transition is more gradual from a state of suspended individual surfactant molecules beginning to come together, as the concentration changes, to a mixture of micelles and surfactant molecules, and finally the solution contains just fully formed micelles. This process, called micellarization, occurs as the concentration of surfactant is increased from none, or very low, to fully saturated.

Conversely, the opposite is true as well. A fully saturated surfactant solution can be diluted to the point where micelles no longer form. This process is referred to as demicellularization (Textor et al. 2015). Furthermore, there is an equilibrium point, where both molecules and micelles exist in equal ratios, known as the critical micelle concentration, or the CMC (Wang et al. 2014). A classic example of this type of micelle formation is introducing dish soap into water. The evidence in this example is the bubbles formed by the soap. This ability of the surfactant to form micelles has many unique and diverse applications.

The application of a surfactant can vary extensively from a single specific purpose to a wide range utility type surfactant. Some surfactants have a simple purpose, such as decreasing the friction between soluble and non-soluble compounds (i.e., dish soap breaking down grease for water removal). Other surfactants are more complex in design, such as the micelle formed in the human body for lipoprotein transportation and intercellular interaction (Halliday, 2005). Micelles can also be used as delivery devices to

administer drugs or other substances. When used as a delivery tool the surfactant surrounds and isolates a drug so that it allows the micelle to absorb in the skin and then is released into the body. This method of delivery is ideal for substances, or drugs, that may not be absorbed effectively or at all (Sastry et al. 2018). An example of this particularly useful micelle is the Dicationic Alkylammonium Bromide Gemini Surfactant (DABGS); its structure, formula, and properties are like other surfactants.

DABGS, has the typical features of a surfactant and some similar properties to other surfactants, such as amphiphilic body, hydrocarbon chain tail, polar head, and the ability to form micelles in either polar or non-polar solutions (Almeida et al. 2011). Each tail is a hydrophobic chain made up of 12 carbons in a straight chain with hydrogen molecules attached to either side of each carbon. Each tail starts at the polar head group and ends with a methyl group as the twelfth and final carbon (Bai et al. 2001). The polar head for this DABGS is two central nitrogen molecules. Attached around the nitrogen are two hydrogens, a hydrocarbon tail, and a hydrocarbon bridge to another central nitrogen molecule. There are a few significant structural differences that distinguish the DABGS from other surfactants. These include the dual, or Gemini, polar head, a single hydrophobic tail attached to each of the two heads, and the major difference, a connecting carbon chain varying in length attached between each nitrogen head (Sikiric et al. 2002). Each side of the nitrogen head is attached to either a hydrogen or a carbon. The hydrogens are bonded on the top side, opposite the tail, and on the outermost side, opposite the short, connecting carbon chain between the two nitrogen polar heads. The

connecting carbon chain is another hydrocarbon $(\text{CH}_2)_n$ bridge. This hydrocarbon connecting chain can vary in length, with two, three, or four carbons for this set of DABGS. This change in carbon-carbon chain length varies not only the distance between the nitrogen heads, but it also affects the micelle structure formed and stability as well (Wang et al. 2014).

The stability of the micelle to hold shape is dependent on many variables (Zheng et al. 2016). As aforementioned, concentration is key for the CMC, or formation of the micelle. As the micelle forms or dissociates, depending on the solution, the disorder of the surfactant changes, as well as the heat content of the system (Paula et al. 1995). These are entropy and enthalpy respectively. The formation on the micelle requires free energy and will have a unique entropic and enthalpic value (Bijma et al. 1998). These values can be measured and quantified by measuring the energy of the transition of the system as the micelle forms from amphiphilic molecules into the micelle, or vice versa (Tadros, 2013). This means the energy released to form the micelle is equal in magnitude, but opposite in sign (i.e. positive versus negative), to the energy required for demicellization (Khan Academy, n.d). Enthalpy and entropy can be quantified based on the free energy of the system, referred to as Gibbs free energy (Bodner Research Web, n.d.). The standard Gibbs free energy (ΔG°) equation takes in account the standard entropy, (ΔS°), standard enthalpy (ΔH°), and the temperature (T):

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ \quad (1)$$

Using this equation, the enthalpy can be isolated by keeping the temperature constant and accounting for the change in disorder, therefore leaving enthalpy as the sole factor affecting the energy of the system.

A direct method for measuring enthalpy in a model free fashion is calorimetry. The original design of the experiment was made to monitor changes in temperature as a physical or chemical process progresses. Calorimetry is useful for measuring the exothermic and endothermic values in these experiments. This ability to directly measure and quantify the heat of reactions and phase changes or phase transitions as a function of temperature allows for heat capacities to be determined (Freire et al. 1990).

The heat capacity at constant pressure (C_P) is the amount of energy needed to raise 1 gram of a substance by 1 degree Celsius, or an equivalent ratio of units (Hanrahan, 2012). Since the unit for energy in calorimetry is usually either Joules or calories, heat capacities have units of $J/g^{\circ}C$ or $cal/molK$, for example. Many substances, and compounds have measured and known heat capacities such as that of water, at $4.184 J^{\circ}/g^{\circ}C$. The known heat capacity of water is what makes a typical calorimeter work efficiently. Historically, the heat capacity of a substance was determined by heating a known mass of the substance to a specific temperature. Once this substance reaches this temperature, it is then placed into a measured mass or volume of water in the calorimeter at a fixed temperature. The thermometer reflects the temperature change of the water based on the heat released or absorbed by substance while in the water. Once equilibrium has been reached, the temperature will stop changing. Using the relationship:

$$q = mC_p\Delta T \quad (2)$$

where q is heat, m is mass, and $\Delta T = T_f - T_i$ (final T minus initial T) and the notion that the heat lost by the substance is equal to the heat gained by the water:

$$-q_{\text{substance}} = q_{\text{water}} \quad (3)$$

the heat capacity of the substance can readily be determined. This is traditionally how heat capacities were derived.

Another type of calorimetry is called bomb calorimetry. Bomb calorimetry (BC) works by monitoring the temperature of the reaction or state change at a constant volume (Polik, n.d.). This experiment takes place inside of a small vessel that is pressurized with gas and a sample of substance being tested. Once sealed and pressurized, the vessel is connected to two lead wires and submerged into the calorimeter full of water. A lid with a thermometer and a stirring mechanism are placed on top to seal the chamber of the water bath. These tools ensure the change in water temperature is better distributed, and the thermometer reflects the change in heat, absorbed or released, by the reaction within the submerged vessel (Libretexts, 2018). This method attempts to ensure that all the heat or energy is captured directly by the oxygen within the BC, and therefore isolating the reaction.

One example where measuring the heat change of a reaction would be useful for titration reactions. A simple titration of a base, such as sodium hydroxide with an acid, like hydrochloric acid, yields a mixture of water and dissolved salt (sodium chloride), and

is an exothermic reaction. This method is referred to as titration calorimetry. Measuring the enthalpy of the titration can be carried out at a constant temperature, or otherwise called, isothermal titration calorimetry.

Isothermal titration calorimetry, or ITC, is for measuring enthalpy, binding affinity, stoichiometry, and binding constants (Ghai et al. 2012). ITC can be classified into two main categories, micro and nano scale. The difference between the two is volume of the experiment conducted. The ITC instrument is set up with two electronically temperature-controlled cells. One cell is a reference, or the “control” cell, and the other is the sample or experiment cell. The control cell is filled with usually water, or a like substance to that being tested. The sample cell is where the reaction or experiment takes place. The ITC heats or cools both cells using solid state thermoelectric heating and cooling systems to precisely control temperature (Malvern Panalytical, n.d.). The cells are surrounded by an adiabatic jacket, ensuring that external factors do not affect the titration experiment (Morsbach et al. 2012). TA Instruments has specifically designed an ITC (the Nano ITC) with an approach to solve another factor of having the mechanical stirrer separate or be inefficient. TA has combined both the injector needle and the stirrer into one part. With the sample chamber so small, this modification design is highly efficient in ensuring even distribution of heat from a titration in the ITC. The Nano ITC injector needle has 50 micro liters (μL) markings for ease of access measuring volume for loading titrants. To monitor the change in temperature in the sample cell, a cell feedback heater is attached. The effective temperature range that the TA Nano ITC

can monitor is from 2 °C to 80 °C. However, in addition to this wide range of temperatures, the ITC is accurate enough to record temperature fluctuations as small as 0.05 μJ (TA Instruments, n.d.). This ability to measure record miniscule heat change values makes the Nano ITC ideal for experimenting with small phase changes, and therefore ideal in observing heat changes (Duff et al. 2011). This means the ITC is ideal because the change in enthalpy for the phase change from single surfactant molecule to micelle is extremely small.

This process of micellization at surfactant concentration greater than the CMC is enthalpically favorable through: 1) the formation of ion-dipole interaction between the polar head groups of the surfactant with water and, 2) the formation of dispersion type interactions between the hydrophobic tails. Entropically, however, there are two competing contributions: 1) an unfavorable conformational entropy due to the ordering of the surfactant in the micelle and 2) a highly favorable entropy due to the release of water from the surfactant during the aggregation process. It is this release of water that is the driving force for micelle formation.

The ITC allows for this process to monitor the micellization or demicellization depending on the experiment set up (Textor et al. 2015). Demicellization has the same magnitude in enthalpy change as micellization, the only difference is the signs are reversed. The enthalpy of demicellization was investigated for three different Gemini surfactants by ITC. The surfactants differed by the number of carbons in the linker between the two quaternized nitrogens. These studies allowed for the determination of

the CMC. Further, by conducting the titration at different temperatures, we were able to determine ΔC_p , the difference in heat capacities between the individual surfactant molecule and the micelle.

CHAPTER III

MATERIALS and METHODOLOGY

MATERIALS:

The surfactants were synthesized in Dr. Steve Bachofer's research lab at St. Mary's College of California and delivered to Texas Woman's University. Deionized water was used and collected in house by Sartorius Arium 611VF water collecting station. Surfactant solutions and correct concentrations were made by dissolving the surfactant into deionized water and stored in 250 mL volumetric flasks. Usable samples were stored in 1.5 mL Eppendorf tubes, and those were placed in an Eppendorf tube holder rack. The TA Instruments Nano ITC standard volume model was used to conduct all titration experiments. All solutions were stored at room temperature.

All surfactants of different connecting chain length, 12-4-12, 12-3-12, and 12-2-12, have similar physical properties, shape and size while dry and stored at room temperature. All three compounds are a white, glossy, crystal-like powder in appearance. The 12-4-12 micelle chain was the focus in these experiments. The empirical formula for this compound as the dibromide salt is $C_{28}H_{62}N_2Br_2$. Using this empirical formula, a mass of 1.60095 grams was measured out to prepare a 15mM solution in 250 mL total volume.

METHODOLOGY:

The ITC experiment was set up through the user interface program application on a Windows desktop PC. The parameters of each experimental runs were as follows: the active/reaction cell was filled with 300 μL of deionized and degassed water, using the loading syringe of 500 μL . This process was done very slowly, and by hand, as not to agitate the water too much to reduce the risk of integrating air into the active cell. 300 μL of the same water was placed in the reference cell for all experiments. For each titration, 50 μL of the 12-4-12 surfactant at 15 mM was loaded into the injection syringe, after a small amount was used to “rinse” and coat the inside of the syringe. Once filled, the injection syringe was threaded into the housing for the injection syringe. The syringe housing was then reattached to the ITC base. The volume for each injection was set at 2 μL every 3 minutes. The stir rate for each titration reaction was set at 300 rpm. The temperature for each titration was changed by increments of 5 $^{\circ}\text{C}$, starting at 15 $^{\circ}\text{C}$ for the first titration and ending at 35 $^{\circ}\text{C}$ for the final experiment for a total of 5 ITC experiments. Each experiment was auto-equilibrated before titration began through the pre-set algorithm programmed by the TA software. The stir rate and injection time were calibrated to produce the least amount of machine and experimental noise. The calibration of these variables was done using water into water titrations, at varying temperatures from 15 $^{\circ}\text{C}$ to 55 $^{\circ}\text{C}$, stir rates from 200 to 400 rpm, injections intervals ranging from 1 minute to 5 minutes between injections, and varying injection volumes from 1 to 3 μL . This entire process was repeated for both the 15 mM 12-3-12 surfactant and the 15mM 12-2-12 surfactant.

The design of each titration was to start with low concentration of micelles in whole form and inject them into water, thereby dissociating the micelle into individual surfactant molecules. Time was set between each injection to allow the solution to reach reaction equilibrium. Injections continued until the equivalence point of both states was reached in the active cell. Finally, injections continued past equilibrium to a formation of full micelles, but at a lower concentration within the active cell. The purpose was to see the dissociation of the micelle into surfactant molecules. The enthalpy energy for the dissociation of the micelle is the same heat of formation, just opposite sign direction, and therefore can be used to effectively and accurately measure the heat of formation of the micelle.

CHAPTER IV

RESULTS and DISCUSSIONS

Figure 1 shows the general formula for the Gemini surfactants studied here. Each is characterized by having two quaternized amines separated by a linker of 2 to 4 carbons. Each nitrogen also has two methyl groups and one dodecyl chain. This amphiphilic molecule forms micelles in water at concentrations below 1 mM (ref). The goal of this work was to study the thermodynamics of micelle formation for these surfactants using ITC. Experimentally, we found it easier to titrate the surfactant at high concentrations into water than to titrate water into micelles. Thus, aqueous solutions of each surfactant were titrated into pure water to determine the enthalpy of demicellization at different temperatures.

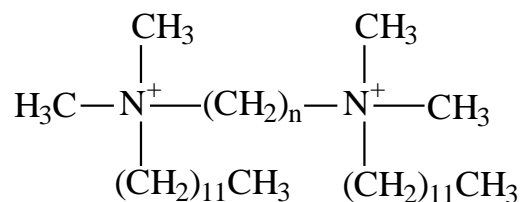


Figure 1. The Gemini surfactants (as the bromide salts) used in this study. They will be designated as 12-2-12 (for $n = 2$), 12-3-12 (for $n = 3$) and 12-4-12 (for $n = 4$).

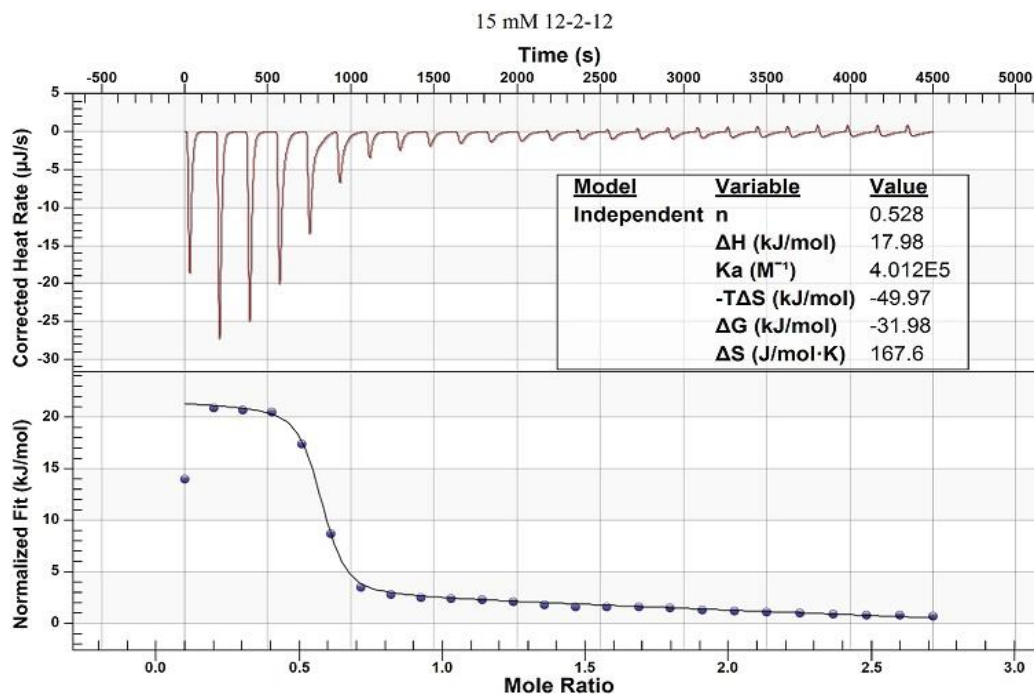


Figure 2. Typical raw data (top) for the titration of 15 mM 12-2-12 into water at 25 °C and the resultant thermogram (bottom). The difference between the upper and lower baselines reveals the total enthalpy (ΔH) for the dissociation of the micelles into individual monomers. The midpoint to the transition is the critical micelle concentration (cmc).

The upper panel of Figure 2 shows the raw data for the titration of the 12-2-12 surfactant into water at 25 °C. As expected, the demicellization is endothermic. The lower panel shows the resultant isotherm. Similar data were obtained for the titrations of the 12-3-12 and 12-4-12 surfactant into water at 25 °C. In these experiments, 2 μ l of surfactant at 15 mM was titrated into 300 μ l of water. Hence, early in the titration, the concentration of surfactant in the cell will be much less than the *cmc* and hence complete demicellization will occur with each injection. However, as the titration continues, the concentration of surfactant in the cell approaches the *cmc* and demicellization will diminish until, later in the titration, only dilution of micelles is occurring with subsequent

injections. Thus, the isotherm shown in the lower panel is sigmoidal indicative of a two-state transition. Further, the midpoint of the transition is the critical micelle concentration (*cmc*).

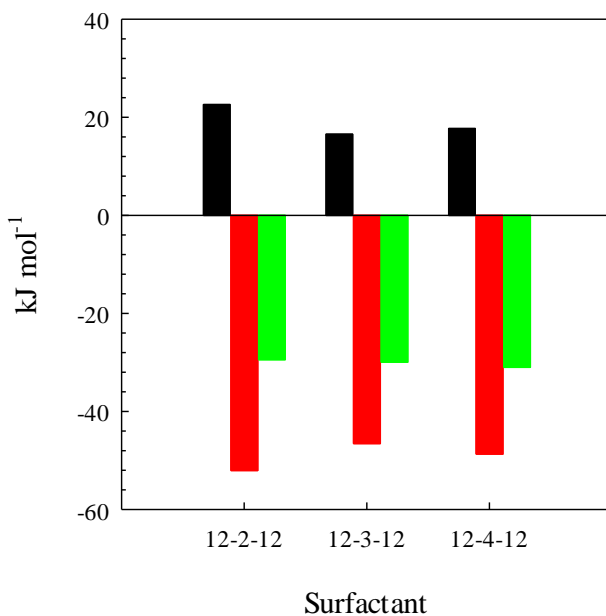


Figure 3. A comparison of the thermodynamic parameters (ΔH , black; $-T\Delta S$, red; and ΔG , green) of micelle dissociation at 25 °C. As can be seen, dissociation is energetically favorable and entropically driven.

The resultant thermodynamic parameters for the titrations at 25 °C are graphically represented in Figure 3. As can be seen, the demicellizations for all three surfactants are energetically favored and entropically driven. While ΔH values range from 16.6 kJ/mol to 22.6 kJ/mol (i.e., $\Delta\Delta H = 6.0$ kJ/mol) and $T\Delta S$ values range from -46.5 kJ/mol to -52.0 kJ/mol (i.e., $\Delta T\Delta S = 5.5$ kJ/mol) at 25 °C, free energy values, ΔG , have a much smaller range of values from -30.9 kJ/mol to -29.4 kJ/mol (i.e., $\Delta\Delta G = 1.5$ kJ/mol). Hence

differences in enthalpies are compensated by differences in entropies leading to small differences in free energies.

Titration experiments were repeated at temperatures ranging from 15 °C to 35 °C. The effect of temperature on the measured thermodynamic values can be seen in Figures 4 to 6. The line parameters are listed in Table 1 and all measured thermodynamic properties as a function of temperature are listed in Table 2. Whereas, enthalpy increases with temperature, both entropy and free energy decrease with increasing temperature. Hence, demicellization is: 1) enthalpically unfavorable and becomes even more unfavorable with increasing temperature; and 2) entropically favorable and becomes even more favorable with increasing temperature (see Figure 8).

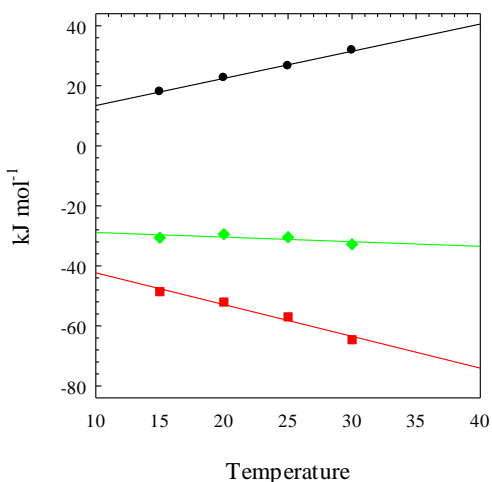


Figure 4. Plots of the enthalpy (ΔH , black), entropy (as $-T\Delta S$, red), and free energy (ΔG , green) of demicellization as a function of temperature for the 12-2-12 surfactant.

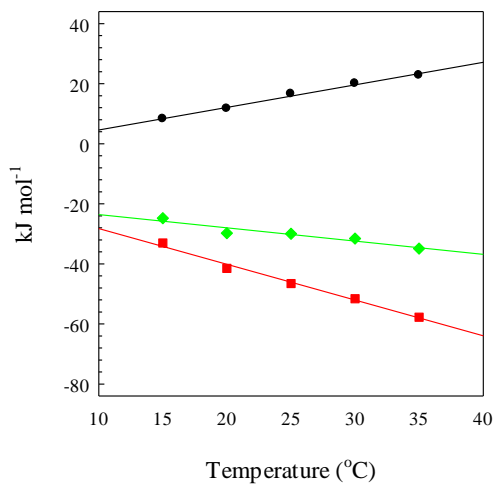


Figure 5. Plots of the enthalpy (ΔH , black), entropy (as $-T\Delta S$, red), and free energy (ΔG , green) of demicellization as a function of temperature for the 12-3-12 surfactant.

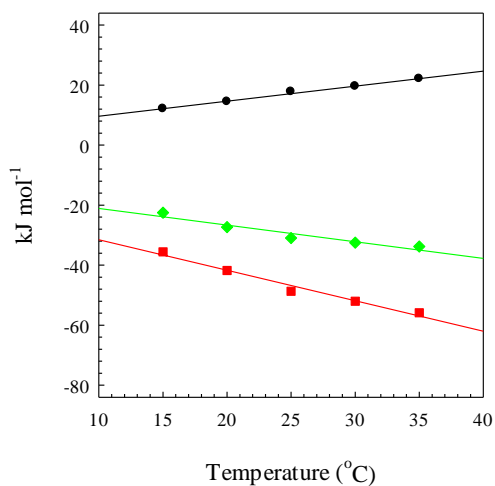


Figure 6. Plots of the enthalpy (ΔH , black), entropy (as $-T\Delta S$, red), and free energy (ΔG , green) of demicellization as a function of temperature for the 12-4-12 surfactant.

Table 1

Line parameters for plots of ΔH , ΔS , and ΔG vs T

Thermodynamic Parameter	Slope (kJ/°C)	Y-Intercept	r^2
<i>12-2-12 Surfactant</i>			
ΔH vs T	0.916	4.36	0.997
ΔS vs T	-1.06	-31.7	0.970
ΔG vs T	-0.153	-27.5	0.478
<i>12-3-12 Surfactant</i>			
ΔH vs T	0.749	-2.86	0.991
ΔS vs T	-1.19	-16.3	0.990
ΔG vs T	-0.441	-19.2	0.904
<i>12-4-12 Surfactant</i>			
ΔH vs T	0.501	4.62	0.993
ΔS vs T	-1.02	-21.4	0.977
ΔG vs T	-0.555	-15.7	0.927

Table 2

Thermodynamic parameters for the dissociation of micelles formed from the various Gemini surfactants as a function of temperature

12-4-12						
T	$K_d \times 10^6$	n	ΔH	$-T\Delta S$	ΔG (kJ/mol)	cmc
(°C)	(M)		(kJ/mol)	(kJ/mol)		(mM)
15	0.082	6.22	12.04	-35.58	-22.54	
20	0.134	5.70	14.43	-41.77	-27.34	
25	3.76	5.84	17.72	-48.69	-30.97	0.58
30	2.48	5.02	19.52	-52.04	-32.52	
35	1.85	6.99	22.02	-55.84	-33.82	

12-3-12						
	K_d x 10⁶ (M)	<i>n</i>	ΔH (kJ/mol)	-TΔS (kJ/mol)	ΔG (kJ/mol)	cmc (mM)
15	0.323	7.53	8.26	-33.03	-24.77	
20	4.93	6.64	11.67	-41.46	-29.79	
25	5.70	6.14	16.59	-46.52	-29.93	0.58
30	3.67	6.43	20.02	-51.57	-31.55	
35	1.21	6.78	22.81	-57.72	-34.91	
12-2-12						
	K_d x 10⁶ (M)	<i>n</i>	ΔH (kJ/mol)	-TΔS (kJ/mol)	ΔG (kJ/mol)	cmc (mM)
15	3.56	5.04	18.00	-48.58	-30.58	
20	7.04	5.24	22.61	-52.02	-29.41	0.58
25	5.76	3.25	26.56	-56.97	-30.41	
30	2.76	5.31	31.78	-64.58	-32.80	

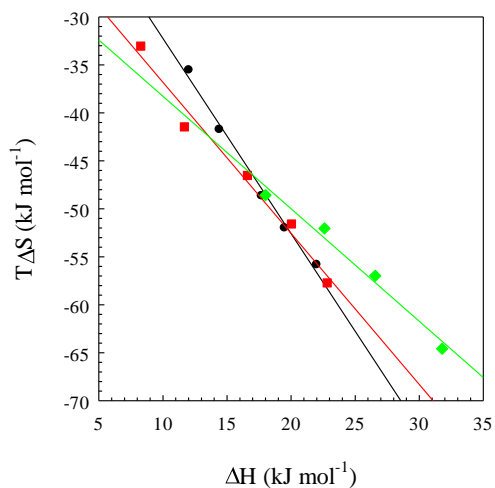


Figure 7. Enthalpy entropy compensation for demicellization for the 12-2-12 (black), 12-3-12 (red), and 12-4-12 (green).

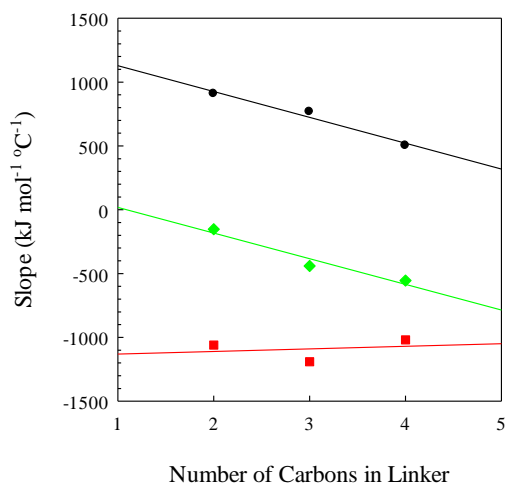


Figure 8. The dependence of the slopes of the linear regression fits in Figure 4-6 (ΔH vs T , black; $-T\Delta S$ vs T , red; and ΔG vs T , green) as a function of number of carbons in the linker.

The slopes of the least squares linear fits for the plot in Figure 4-6, and shown in Table 1, reveal the temperature dependence of each thermodynamic parameter. As a result of the enthalpy-entropy compensation shown in Figure 7, the favorable free energy of demicellization becomes more favorable with increasing temperature. In the case of enthalpy, the slopes of the lines reveal the difference in heat capacity (ΔC_p) between the micelle and single molecule:

$$\Delta C_p = C_{p,micelle} - C_{p,single\ molecule}$$

The ΔC_p values, summarized in Table 3, depend upon the number of carbons in the linker.

Table 3

Change in Heat Capacities

Surfactant	ΔC_p (kJ C⁻¹ mol⁻¹)
12-4-12	0.50
12-3-12	0.77
12-2-12	0.91

As can be seen in Figure 8, ΔC_p decreases in a linear fashion with increasing number of carbons in the linker. Although $-T\Delta S$ values are essentially temperature independent, the measured ΔG values decrease linearly with increasing number of linking carbons. Thus, demicellization becomes more favorable enthalpically and energetically as the number of carbons in the linker increase.

CHAPTER V

CONCLUSION

The research was successful in exploring and collecting data on the deformation, and conversely the formation stability of Dicationic Alkylammonium Bromide Gemini Surfactants from individual amphiphilic molecules to micelles. A key discovery was demicellization becomes more favorable enthalpically and energetically as the number of carbons in the linker increase. The benefit gained from this understanding of micellular stability can be used for future endeavors of surfactant application. Knowing the properties, limits, and behaviors of surfactants allows for better control, manipulation, and application of surfactants. Some applications include pharmaceutical cancer cell targeting drug delivery, isolation of compounds or proteins for transport within the body and provide protection to increase shelf life of a compound. By better understanding the stability and formation of micelles, improvements can be made to the applications that before were unachievable due to the lack of insight to this surfactant.

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