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Gemini Surfactants: A New Class of Self-Assembling Molecules

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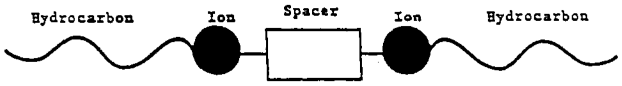
Abstract: "Gemini surfactant" is a name assigned to a family of synthetic amphiphiles possessing, in sequence, a long hydrocarbon chain, an ionic group, a spacer, a second ionic group, and another hydrocarbon tail. Intramolecular chain/chain association was inhibited through the use of rigid spacers, thereby averting self-assembly into conventional micellar structures. Aggregation of the geminis was investigated by (a) surface tension, (b) film-balance methods, (c) dynamic light scattering, (d) ^{1}H and ^{23}Na NMR, and (e) spectral changes in an adsorbed dye. Among the more striking properties of geminis, one should cite the following: (a) a ***higher*** critical micelle concentration (according to surface tension and NMR) for geminis with two long chains of 16–20 carbons than that for shorter-chain analogs; (b) the lift-off areas in monomolecular films that are several times those of phospholipids, indicating that the geminis lie absolutely horizontally at the air/water interface; and (c) the formation of only small micelles, despite the potential to grow, polymer-like, into extended strands. It is argued that geminis, especially the longer-chain members, engage in self-coiling or submicellar aggregation when first exposed to water. Self-assembly into micelles and adsorption at the air/water interface then take place over hours or days at 23 °C but much more rapidly at 50 °C. Spectral data provide strong evidence for submicellar structures.

A decade of intense experimental work followed the 1979 suggestion that the classical Hartley micelle model (*i.e.*, the "oil droplet in an ionic coat") might be incorrect.[1] This experimental work has, by and large, substantiated many aspects of a proposed revision:[1] (a) bent and looped chains arranged in a disorganized "brush heap"; (b) rough surfaces replete with water-filled cavities; and (c) a high degree of hydrocarbon–water contact.[2] Recent computer simulations, allowing for complete size distribution, also showed the extreme disorder expected from the amended model.[3]

Experimental work on micellar structure has now plateaued. Simply put, it is becoming more and more difficult to extract fundamentally new structural information on conventional micellar systems. Two strategies are available to counter this problem: (a) One can develop (or wait for) new instrumentation to spur further research in the area and (b) one can synthesize new surfactants, especially ones with unusual structural elements, and then investigate how these modifications affect the self-assembling process. Being too impatient to wait, and being rather fond of synthetic organic chemistry, we chose the latter approach—a preference that has given rise to the current paper on "gemini surfactants".

Before defining "geminis", we should mention that other reports have recently appeared that describe surfactants ("amphiphiles") with unusual features. A few examples, and this is not meant to be a complete list, are now cited. Kahne *et al.*[4] prepared "facial amphiphiles" comprised of glycosylated bile acids. These materials have hydrophobic and hydrophilic faces as opposed to a linear hydrophobic tail attached to a hydrophilic headgroup. Stein and Gelman[5] synthesized amphiphiles with a unique headgroup topology (*i.e.*, two carboxylates rigidly held on a dibenzobarrelane skeleton). Nusselder and Engberts[6] examined the relationship between amphiphile structure and aggregate morphology in 1,4-dialkylpyridinium salts. And we ourselves experimented with "unnatural" amphiphiles in which the hydrophobic moiety was a polynuclear aromatic ring system[7] or a hyperextended linear chain.[8]

In 1991, the name gemini surfactants was assigned to a group of amphiphiles possessing, in sequence, a long hydrocarbon chain, an ionic group, a rigid spacer, a second ionic group, and another hydrocarbon tail.[9] The rigid spacer (*e.g.*, a stilbene unit) is critical in that it inhibits chain/chain association within a single molecule. If the spacer were short and flexible (*e.g.*, an ethylene group), then a "hair-pin" turn could align the two chains of a molecule and lead to conventional micelle formation.[10] Geminis with rigid spacers, however, might conceivably grow linearly (not unlike a "living polymer" except that the monomeric units are joined by hydrophobic forces rather than by covalent bonds). Chart I depicts additional possible morphologies, all of which involve an unusually high level of hydrocarbon–water contact even for a micelle. Indeed, at the beginning, we feared that the compounds would not dissolve in water. When initial tests proved otherwise, we prepared a series of cationic and anionic geminis (Chart II) and now report on their properties. In the ensuing text, geminis will be designated according to their class (**A**, **B**, or **C** in Chart II) and to the number of carbons in each chain (*e.g.*, **B**-20 or **C**-12).



As the present article was being written, a publication appeared entitled "Geminis: A New Generation of Surfactants".[11] The review confines itself to geminis with flexible spacers.[12] These surfactants are about 3 orders of magnitude more efficient at reducing surface tension and more than 2 orders of magnitude

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⊕ Abstract published in *Advance ACS Abstracts*, October 1, 1993.

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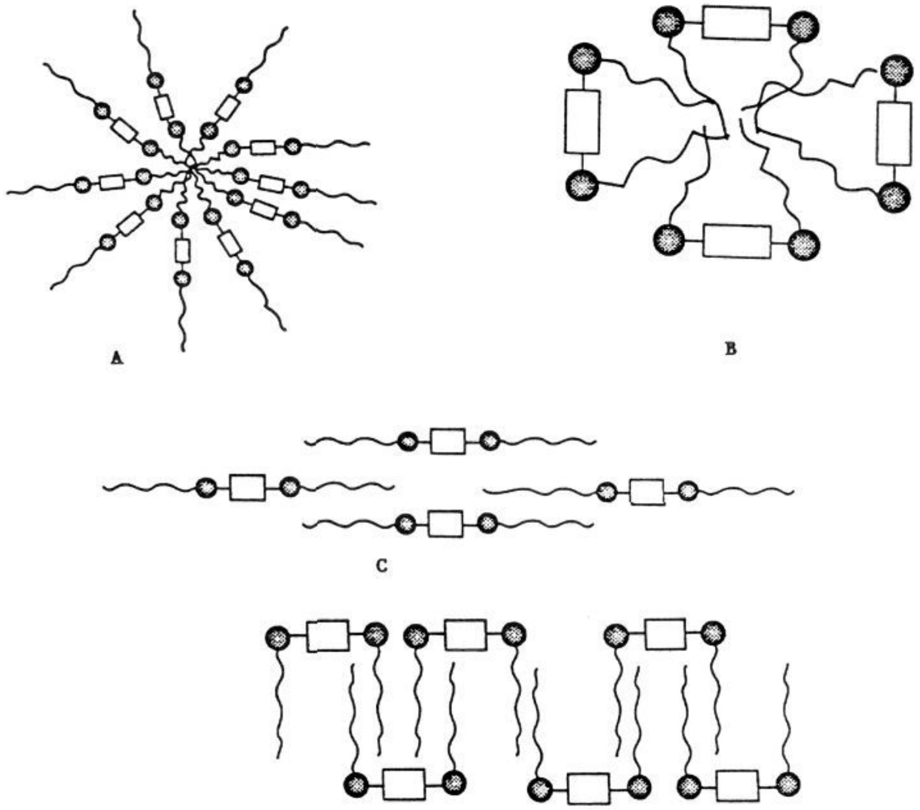
Chart I



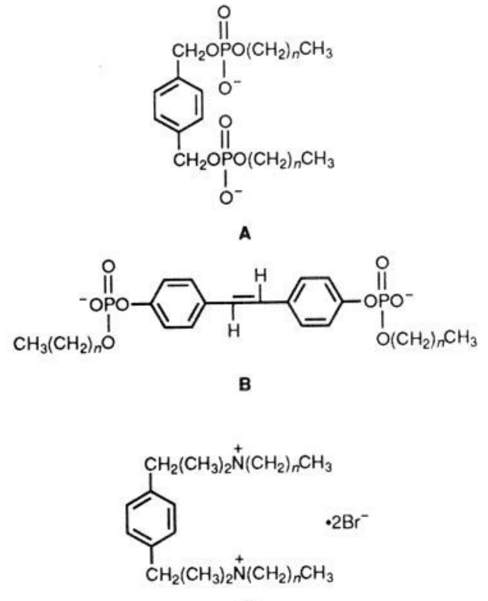
A

B

C

D

Chart II



A

B

C

more efficient at forming micelles than are conventional ionic surfactants. The remarkable properties were attributed, somewhat vaguely, to distortion of the water structure by the two hydrophobic chains in the molecules.[11,13] If this is true, then the geminis in Chart II, each bearing two chains (one per headgroup), should likewise display unusual properties. Of course, our particular geminis have rigid spacers that could affect adsorption and micellization if the relative geometric disposition of the chains is important to surfactant behavior.

Results and Discussion

Since we will be dealing with a variety of methodologies applied to a large number of compounds, it is best to meld the Results and Discussion sections. In this manner, the conclusions need not be too far segregated from the data on which they are based.

Synthesis. Xylylene diphosphates, series **A**, were prepared by first phosphorylating a long-chain alcohol *via* the procedure of Nelson and Toy (Scheme I).[14] The resulting alkyl phosphate, in its dianionic form, could then be used to prepare mixed dialkyl phosphates by the Bauman method.[15] This latter method relies on the fact that a monoalkyl phosphate is a better nucleophile (toward α,α'-dibromo-p-xylene in our case) than a dialkyl phosphate. All phosphate-based geminis were converted into their disodium salts prior to examination.

Series **B** compounds, containing the stilbene spacer, were synthesized according to a sequence developed by Eibl (Scheme II).[16] Cationic geminis with stilbene spacers were too water-insoluble to study. Series **C** compounds was obtained in one step by treating α,α'-dibromo-p-xylene with the requisite long-chain tertiary amine.

Representative synthetic procedures are given in the Experimental Section. Series **A** and **B** (in the conjugate acid form) and series **C** were all characterized by ^{1}H NMR, ^{13}C NMR, MS (low-resolution FAB, TEA matrix), and elemental analyses.

Surface Tension. "Surfactant" is a contraction of "surface active agent", indicating the ability to adsorb at the air/water

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(12) When we first coined the word gemini,[9] it was applied only to double-surfactants with rigid spacers. Rosen[11] extended the meaning of the word to all such double-surfactants regardless of the spacer.

(13) Rosen, M. J.; Zhu, Z. H.; Hua, X. Y. *J. Am. Oil Chem. Soc.* **1992**, *69*, 30.

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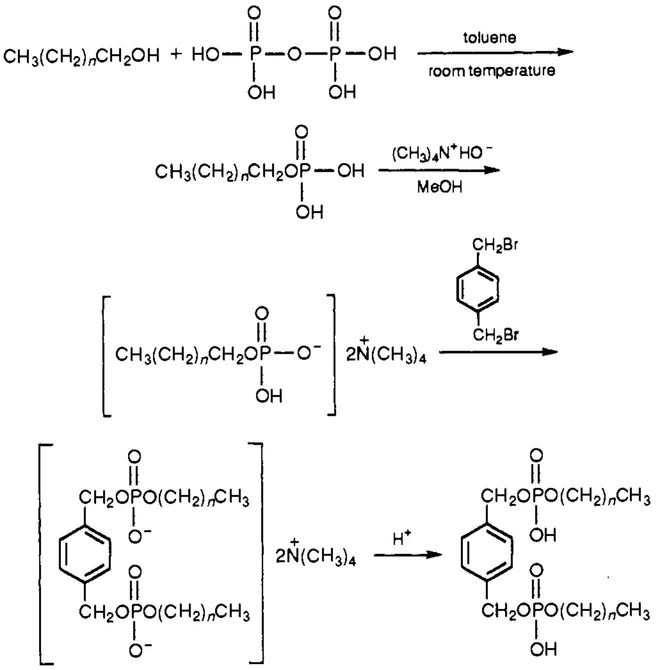
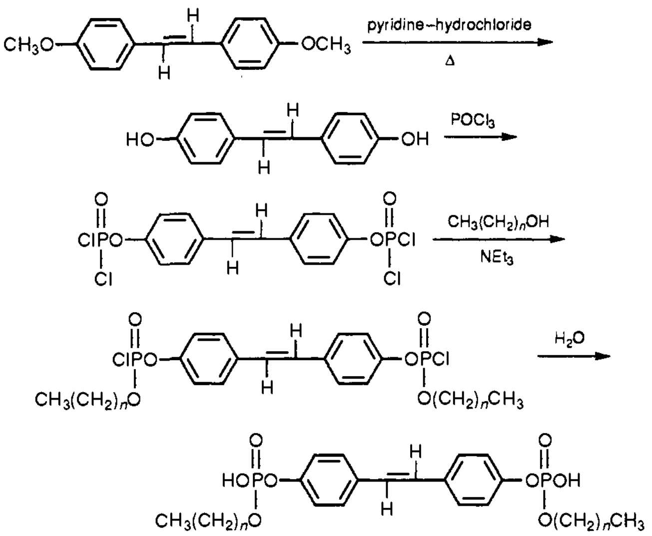
Scheme I



Scheme II



interface and thereby lower the surface tension. Thus, a plot of surface tension *vs* log[surfactant] is often linear up to a concentration, called the critical micelle concentration (cmc), at which the surfactant begins to aggregate into a micelle. At this point, the micelle competes with the interface for surfactant molecules, and the slope of the plot abruptly diminishes. The break in the plot, often represented by the intersection of two straight lines, defines the cmc.

The Du Nuoy method,[17] based on the force in dynes/cm required to "pop" a platinum ring off a water surface, was used to determine surface tension. In this manner, we could evaluate (a) the cmc and (b) the surfactant efficiency (*i.e.*, the amount of surfactant required to reduce the surface tension by a given amount).

At the outset, we had little notion of what to expect with regard to the surface-active properties of the geminis. A "normal" surfactant, having but one tail and headgroup, aligns itself at the air/water interface with its headgroup immersed in water and its tail extended into the air at an angle depending upon the surface pressure (Figure 1, **A**). A gemini, on the other hand, might assume a linear conformation that would place only one of its hydrophobic tails into the air; the other tail would be forced to dip entirely into the water (Figure 1, **B**). Alternatively, a "horseshoe" conformation would place both chains into the air (Figure 1, **C**), but they would be separated from one another by a distance equal to the length of the spacer. Finally, a gemini might prefer to lie flat on the water surface (Figure 1, **D**), an orientation that would occupy an extraordinarily large surface area per molecule.

Figure 2 shows a surface tension *vs* log[gemini] plot for **C-18** (measured at 50 °C because the diammonium bromide geminis are water-insoluble at room temperature). The cmc values of four **C** compounds are listed in entries 1–4 of Table I, and already an anomaly is evident: **C-18** has a cmc (3.7×10^{-4} M) significantly higher than that of **C-16** (6.7×10^{-5} M). Generally, in the protected duchies of academia, it is taught that a longer hydrocarbon tail always lowers the cmc.[18] In order to determine whether our unusual violation of accepted wisdom was a general phenomenon, we next performed a series of experiments on anionic geminis that are completely water-soluble at room temperature (*i.e.*, series **A** in Scheme I). For comparison purposes, the surface-tension studies were also carried out at 50 °C.

Surface-tension data with the xylylene diphosphates are as aberrant as with series **C** compounds. Thus, according to entries 6–11 in Table I the following are true. (a) The normal cmc trend at 50 °C again reverses itself between **A-12** and **A-16**. Remarkably, **A-16** has a cmc 24 times larger than that of **A-12** (a gemini with eight fewer carbons). (b) **A-16** displays only minor surface activity at 23 °C (compare Figures 3A and 4, at 23 and 50 °C, respectively). Lack of surface activity does not necessarily preclude aggregation, but it does indicate an impaired adsorption at the air/water interface. Note that two control compounds benzyl dodecyl phosphate and benzyl hexadecyl phosphate (entries 12 and 13 in Table I) are normal in their dependence on chain length. Anomalous behavior is, therefore, tied directly to the gemini surfactants' unique structure.

Actually, the behavior of **A-16** is even more complicated than indicated above. It turns out that the surface tension *vs* log[**A-16**] plots are time-dependent. As seen in the three plots of Figure 3, surface tension at 23 °C varies with the age of the sample. Plot A was obtained immediately after dissolving **A-16** in water. Plot C was taken after leaving the covered samples undisturbed for 24 h and then making only a single surface-tension reading at each concentration. If several repeat readings were made on a single concentration, the values continually drifted upward since, apparently, the organized array of molecules at the interface was perturbed as the Du Nuoy ring popped off the water. Thus, plot B represents aged samples averaged over 10 quickly repeated measurements per sample. The upward drift relative to that in plot C is obvious.

It seems clear that geminis, particularly those with tails of 16 or 18 carbons, experience severe problems adsorbing to the air/water interface. In contrast to conventional surfactants, long-tailed geminis cannot instantaneously align at the interface. Elevating the temperature from 23 to 50 °C speeds the adsorption process and produces surface-tension plots with normal "breaks". The break in Figure 4 for **A-16** corresponds, however, to a cmc of 2.7×10^{-3} M, which is high for a compound with a 16-carbon chain per headgroup. **A-16** has difficulty organizing itself both at the air/water interface and within its molecular assemblages.

Since the two long tails within an **A-16** molecule might be able to reach each other (at least at their termini), we investigated geminis with stilbene spacers that would prevent intramolecular chain–chain association altogether. The data for these geminis (series **B** with chains varying from 12 to 20 carbons) are compiled in entries 14–25 of Table I.

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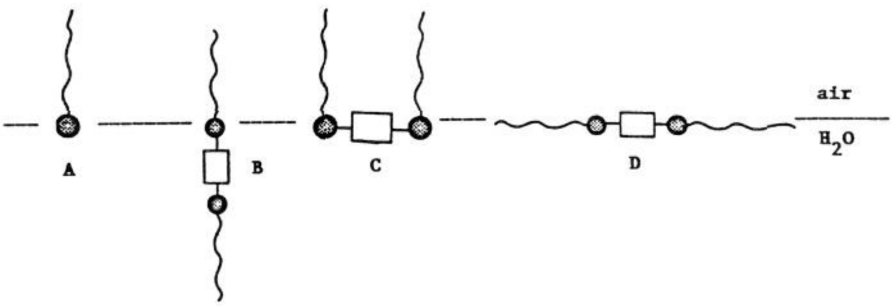


Figure 1. Possible orientations of a conventional surfactant (**A**) and gemini surfactants (**B**–**D**) at an air/water interface.

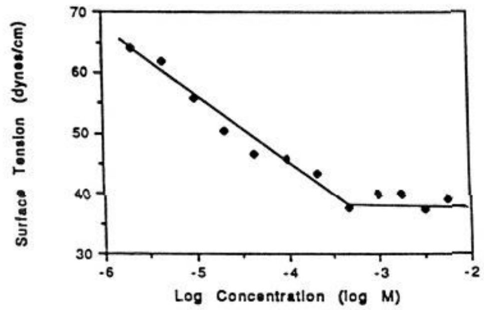


Figure 2. Surface tension *vs* log[**C**-18] at 50 °C.

Table I. Surface-Tension Data on Gemini Surfactants **A**, **B**, and **C** in Chart II

run	compd	temp (°C)[a]	cmc (M)[b]	ST at cmc (dynes/cm)	comments[c]
1	**C**-8	50	1.0×10^{-2}	38	
2	**C**-12	50	1.0×10^{-3}	39	
3	**C**-16	50	6.7×10^{-5}	41	
4	**C**-18	50	3.7×10^{-4}	38	
5	DTAB[d]	50	2.1×10^{-2}	38	
6	**A**-8	23	5.5×10^{-3}	42	
7	**A**-8	50	4.1×10^{-3}	42	
8	**A**-12	23	1.7×10^{-4}	43	
9	**A**-12	50	1.1×10^{-4}	41	
10	**A**-16	23	none		
11	**A**-16	50	2.6×10^{-3}	38	
12	DBP[d]	23	1.1×10^{-3}	37	
13	HBP[d]	23	5.5×10^{-5}	38	
14	**B**-12	23	6.3×10^{-4}	41	
15	**B**-12	23	2.7×10^{-4}	46	aged
16	**B**-12	50	1.1×10^{-4}	38	
17	**B**-12	50	1.2×10^{-4}	45	aged
18	**B**-16	23	none		
19	**B**-16	23	1.6×10^{-3}	54	aged
20	**B**-16	50	4.0×10^{-3}	38	
21	**B**-16	50	7.1×10^{-4}	37	aged
22	**B**-20	23	none		
23	**B**-20	23	1.8×10^{-3}	60	aged
24	**B**-20	50	2.4×10^{-3}	42	
25	**B**-20	50	9.2×10^{-4}	40	aged

[a] Temperatures were controlled to ±0.5 °C. [b] Values represent apparent cmc values that, as discussed in the text, are affected by an inordinately slow equilibration. [c] Samples were aged for 24 h at 23 °C and 30 min at 50 °C where indicated. [d] Control compounds DTAB, DBP, and HBP represent dodecyltrimethylammonium bromide, dodecyl benzyl phosphate, and hexadecyl benzyl phosphate, respectively.

The main observations on the stilbene-based geminis are now summarized. (a) Aging effects are evident even for **B**-12. Thus, the cmc at 23 °C diminishes 2-fold after a 24-h wait (entries 14 and 15). At 50 °C, equilibration of **B**-12 occurs quickly and aging is inconsequential (entries 16 and 17). (b) A surface-tension plot of **B**-16 at 23 °C (10^{-5}–10^{-2} M) again shows a structureless decrease from about 72 to 55 dynes/cm; there is no break consistent with a cmc. At 50 °C, fresh and 30-min-aged samples of **B**-16 gave cmc values of 4.0×10^{-3} and 7.1×10^{-4} M, respectively. Additional aging had little further effect. (c) **B**-20 showed much the same behavior as **B**-16: no cmc at 23 °C with fresh samples and a sharp cmc at 50 °C of 2.4×10^{-3} M (entry 24) that diminished 2-fold upon sitting undisturbed for a day. Data from nonaged systems are presented in Figure 5.

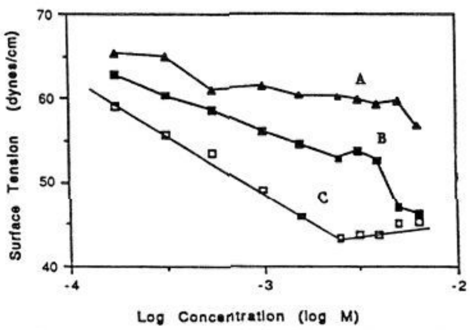


Figure 3. Surface tension *vs* log[**A**-16] at 23 °C. Curves: (A) nonaged solutions; (B) aged 24 h, each point being the average of 10 successive measurements; and (C) aged 24 h, each point representing a single measurement.

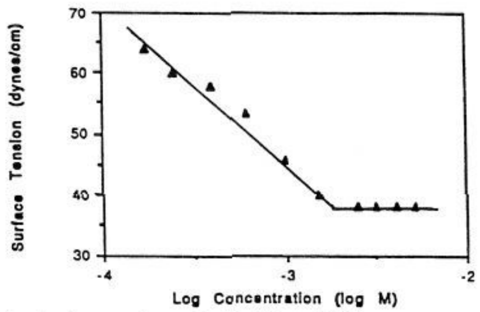


Figure 4. Surface tension *vs* log[**A**-16] at 50 °C.

Table I constitutes a remarkable set of numbers. Perhaps the most surprising result is that, consistently, the longer chains are associated with the higher cmc values. Consider entries 17, 21, and 25 in Table I involving samples aged for 24 h at 50 °C. Since heating to 50 °C accelerated equilibration and since additional heating induced no further changes, we can reasonably assume that the three samples had attained equilibrium. Yet the cmc of **B**-20 is eight times higher than that of **B**-12! The trend is also seen in entries 15, 19, and 23, where samples were aged at 23 °C for 24 h. Although we are less certain that equilibrium had been reached here, the increase in cmc with chain length is likewise evident. Moreover, the surfactant effectiveness (*i.e.*, the surface-tension reduction at the cmc) is clearly impaired in entries 19 and 23. Adsorption of **B**-16 and **B**-20 at the air/water interface is both inordinately slow and ineffective despite their seemingly favorable amphiphilic components.

How might the "nonclassical" behavior of the geminis be rationalized at the molecular level? In attempting to answer this key question, it is natural to focus on the one feature that distinguishes our geminis from all other surfactants: The two chains within a single gemini molecule are unable to efficiently

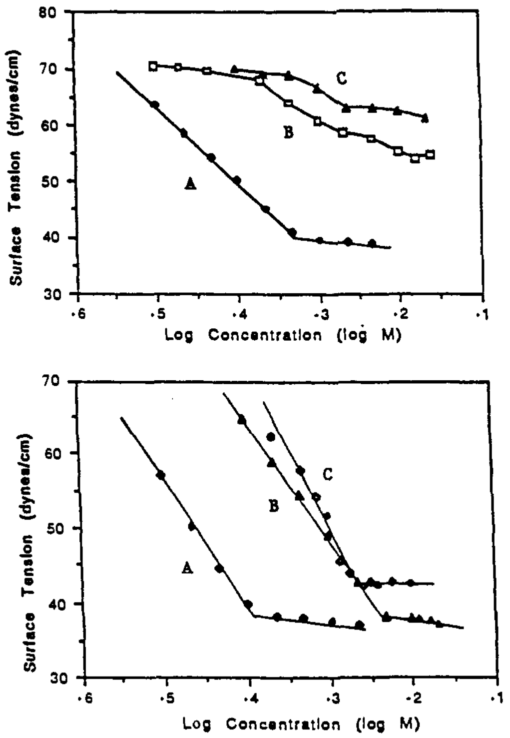


Figure 5. Surface tension *vs* log of concentration plots. Top: (A) B-12, (B) B-16, and (C) B-20 at 23 °C (nonaged). Bottom: (A) B-12, (B) B-16, and (C) B-20 at 50 °C (nonaged).

interact with one another. Self-assembly into traditional micellar or lamellar structures is, therefore, impeded. Two avenues are open to geminis, especially those with 16 or more carbons per headgroup, to reduce hydrocarbon/water contact when first exposed to water. (a) A gemini molecule might self-coil in a manner discussed in detail by Jiang, Fan, and Hui.[19] (b) Geminis might form submicellar aggregates[20,21] such as dimers or tetramers. Over time, and with the application of higher temperatures, geminis could uncoil or reorganize, thereby permitting the slow reorientation into higher order aggregates. In other words, an uncoiling or reorganization process is superimposed upon the aggregation/adsorption phenomena. Long chains, in particular, would be adversely affected by the energy requirements for uncoiling and reorganization prior to micellar assembly (Eqs 1 and 2). Reversals in the cmc with chain length

$$\text{gemini} \rightarrow \text{self-coiling} \rightarrow \text{uncoiling} \rightarrow \text{assembly} \qquad (1)$$

$$\text{gemini} \rightarrow \text{submicelle} \rightarrow \text{assembly} \qquad (2)$$

might originate from one or both of these mechanisms that manifest themselves indirectly, *via* the surface-tension behavior.

Support for this working hypothesis will accrue in the remainder of the paper.

Monolayer Studies. C-18, a diammonium gemini, is sufficiently water-insoluble at room temperature to permit standard film-balance studies.[22] A film balance measures the pressure exerted by a film, one-molecule thick, resting upon a water surface. By adjusting a moveable barrier, the area available to the film can be diminished. Molecules lying flat on the water surface are thereby forced into more vertical positions where they require less space. The ease of compressing the film and the area per molecule at a given pressure reveal how readily a molecule tolerates the presence of neighbors. A film balance is a simple and ingenious device for elaborating the packing properties of molecules at the air/water interface.

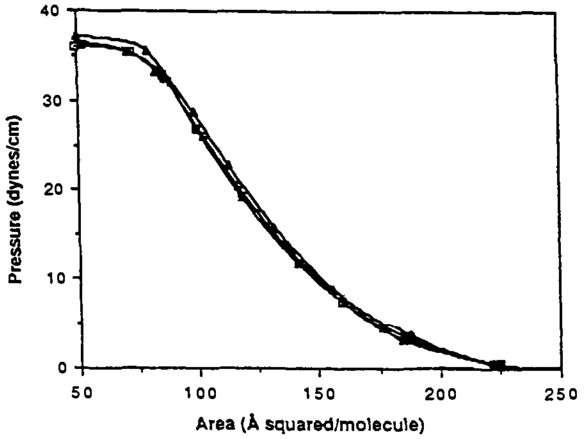
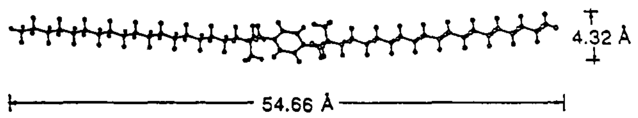


Figure 6. Pressure–are isotherms at 18.0, 23.5, and 26.5 °C for C-18 obtained at a compression rate of 18.4 Å^2/molecule/min.

Figure 6 shows the pressure–area isotherms for C-18 at temperatures ranging from 18.0 to 26.5 °C. The plots are superimposable within experimental error, indicating that temperature-dependent solubilization of C-18 into the aqueous subphase is not a problem. Perhaps the most remarkable feature of the isotherms is their extremely high "lift-off area" of about 240 Å^2/molecule. A lift-off area (*i.e.*, the area at which the film pressure first rises above the base line) provides useful information about the molecular orientation at the onset of intermolecular contact.[23,24] The 240 Å^2/molecule area for C-18 corresponds closely to the 236 Å^2/molecule area calculated from the dimensions of its all-anti conformation. Evidently, C-18 lies absolutely flat upon the water surface (see Figure 1, **D**) with little empty space between the molecules.



In sharp contrast, distearoylphosphatidylcholine (a phospholipid with two chains also 18-carbons long) has a lift-off area of only 60 Å^2/molecule. To achieve such a small area, both phospholipid chains must stand side-by-side above the water surface in a packing mode reminiscent of a bilayer leaflet. Clearly, the rigid spacer separating the two chains in C-18 has a dramatic effect on the molecule's inclination to organize at the air/water interface.

What happens to C-18 when the film pressure is increased to make less area available within the monolayer? Figure 6 shows that the film compresses without an apparent phase transition until it ultimately collapses at about 76 Å^2/molecule. This collapse area is somewhat greater than the 52 Å^2/molecule area calculated for the area of the spacer plus the two ammonium groups which, presumably, remain on the water surface. We conclude that with sufficient film pressure (*ca.* 34 dynes/cm), it is possible to reorient both horizontal chains into a vertical arrangement (Figures 1, **C** and 7). Certainly the collapse area of 76 Å^2/molecule is much too large to verify an interfacial orientation in which one chain extends into the air while the other dips into the water (Figure 1, **B**).

Dynamic Light Scattering (DLS). Having defined the packing properties at the air/water interface, we next turned our attention to the structure of the gemini aggregates that exist in the bulk

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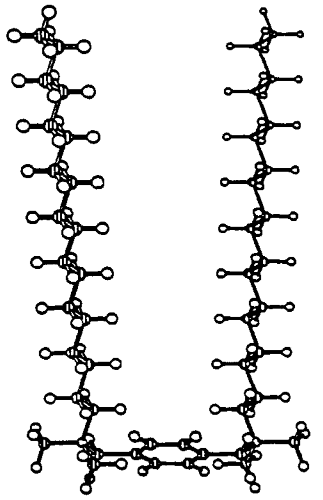


Figure 7. Schematic of C-18 at the air/water interface in the condensed state.

aqueous phase. One point is immediately obvious from an observed absence of solution viscosity: Geminis do not form long polymer-like strands such as depicted in Chart I, structure C. Moreover, according to dynamic light scattering carried out on 0.01 M samples (25 °C), gemini aggregates have diameters of less than 10 nm. Although our particular DLS laser allowed only an upper limit to the size determination,[25] there is no doubt that the gemini aggregates fall into the micellar range. Vesicular structures (≥30 nm) are not present. Only **B**-20, with a particle diameter of 5–18 nm, displayed a size somewhat larger than the typical micelle. In principle, geminis could grow indefinitely (one chain adsorbing to the aggregate and the other providing a site for continued growth), but this was not observed. Gemini micelles, like all micelles, are elusive, and chain organization within them remains obscure.

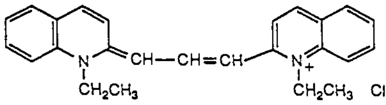
^{1}H and ^{23}Na NMR. Small spherical micelles show fairly narrow ^{1}H NMR signals. Significant resonance broadening can occur, however, in the course of sphere-to-rod transitions. For example, Ulmius and Wennerstromn[26] found that when the concentration of cetyltrimethylammonium bromide was increased from 0.16 to 0.53 M (encompassing the sphere-to-rod transition), the line width increased from 8 to 96 Hz. Decreased molecular motion, leading to increased correlation times and broadened peaks, provides a convenient way to monitor micellar growth. In the interest of brevity, NMR data will not be tabulated here; suffice it to mention that we observed little or no broadening even at concentrations considerably above the cmc values. For example, **B**-16 had a vinyl singlet with a $w_{1/2}$ of 10.0 and 11.2 Hz at 1 mM and 0.1 M, respectively. The line-width data are, therefore, consistent with the observations based on viscosity and DLS, namely that geminis prefer to assemble into small, rapidly tumbling aggregates.

Gustavsson and Lindman[27] were among the first to exploit ^{23}Na NMR in the determination of cmc values. Changes in the ^{23}Na NMR chemical shift upon aggregation are generally small (*ca.* one-tenth that observed in shifting from water to ethanol), yet ^{23}Na NMR is well-behaved and, equally important, utilizeable at concentrations as low as 1×10^{-5} M with a 24-h collection time. This means that for most systems, ^{23}Na NMR spectra can be directly compared below and above the cmc. Experimentally, one merely measures the abrupt increase in chemical shift as the cmc is exceeded. Under conditions of fast exchange, eq 3 applies where δ_{obsd}, δ_f, and δ_m are the observed chemical shift and the chemical shift of totally free and totally bound sodium, respectively; β is the counterion-to-surfactant ratio in a micelle (*i.e.*, the degree of counterion binding); and C_t is the total surfactant concentration.[28] A plot of δ_{obsd} *vs* $1/C_t$ yields two straight lines that intersect at the cmc as is illustrated for **B**-16 in Figure 8. All phosphate geminis were analyzed in this manner, and the resulting cmc values are listed in Table II.

$$\delta_{obsd} = \delta_1 + \beta(\delta_m - \delta_1) - (\beta \times \mathrm{cmc}/C_t)(\delta_m - \delta_1) \qquad (3)$$

Agreement between the NMR and surface-tension-based cmc values ranges from fair (**A**-18, **A**-12, and **B**-12 in Table II) to poor (**B**-16 and **B**-20 in Table II). It may be no coincidence that the two geminis whose cmc values are more "method-dependent" are those that gave no cmc at all by surface tension unless the samples had been aged for 24 h. As explained earlier, kinetics plays a key role in the adsorption of geminis, and even with prolonged aging and heating, we could not be absolutely certain that equilibrium at the air/water interface had been reached. The NMR-based cmc values are, perhaps, the more trustworthy because they are unrelated to adsorption processes, because they are time-independent, and because the NMR plots such as Figure 8 show sharp breaks. Nonetheless, the data in Table II are counterintuitive. **A**-16 has a higher cmc than **A**-12. **B**-12, **B**-16, and **B**-20 (with vastly differing hydrophobicities) have rather similar cmc values. We persist with our earlier explanation: Geminis engage in tight premicellar coiling or association. These poorly understood equilibria reveal themselves because they are incorporated into the "global" cmc values (eqs 1 and 2).

Spectral Changes of an Adsorbed Dye. In 1946, Corrin *et al.* established the use of a dye, pinacyanol chloride, to investigate micellization of anionic surfactants.[29] The method was based on the fact that the dye's absorbance at 610 nm increases dramatically as a micelle forms and binds the dye. A typical absorbance *vs* [surfactant] plot for a conventional surfactant, benzyl dodecyl phosphate, is given in Figure 9. Actually, a spectrophotometer is hardly necessary to detect the micelle formation; solutions change from a light shade of pink below the cmc to a bright blue above it.



In the interest of maintaining a reasonable length to this article,[30] we will cite only the single most important observation of the dye studies: Among the anionic geminis, three of them (**A**-16, **B**-16, and **B**-20) showed anomalous behavior. These three gave micelle-type spectra (a "bright blue color" in visual terms) at all concentrations. For example, as seen in Figure 10, absorbance at 610 nm occurs even at 1.0×10^{-5} M **B**-20 (102-fold less than the surface-tension-based cmc). One possible explanation is that the 1.0×10^{-6} M dye used in the experiments induced micelle formation, although one is hard pressed to understand why this would not occur for all the geminis. More likely, submicellar species (of the type discussed above) managed to bind the dye and promote the pink-to-blue spectral change. Clearly, a consistent pattern has emerged from our multimethod approach: Geminis with long tails engage in associative equilibria far more complex than the monomer ⇌ micelle relationship that satisfactorily describes most conventional surfactants. Submicellar aggregation has become here a dominant factor. It is hoped that the peculiar gemini behavior can eventually be exploited for

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[25] Menger, F. M.; Lee, J-J.; Aikens, P.; Davis, S. *J. Colloid Interface Sci.* **1989**, *129*, 185.

[26] Ulmius, J.; Wennerström, H. *J. Magn. Reson.* **1977**, *28*, 309.

[27] Gustavsson, H.; Lindman, B. *J. Chem. Soc., Chem. Commun.* **1973**, 93.

[28] Durairaj, B.; Blum, F. D. *J. Colloid Interface Sci.* **1985**, *106*, 561.

[29] Corrin, M. L.; Klevens, H. B.; Harkins, W. D. *J. Chem. Phys.* **1946**, *14*, 480.

[30] For a full account, including all the raw data and structure proofs for all the compounds, see: Littau, C. A. Geminic Surfactants: The Synthesis and Study of a Novel Class of Surfactants. Ph.D. Thesis, Emory University, 1991.

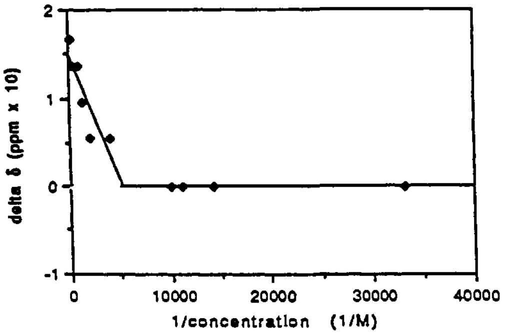

Figure 8. Change in the ^{23}Na NMR chemical shift (×10) of B-16 *vs* the reciprocal of its concentration.

Table II. ^{23}Na NMR-Based cmc Values for Geminis at 23 °C

gemini	cmc (M)	NMR/ST[a]
A-8	1.6×10^{-2}	2.9
A-12	2.5×10^{-4}	1.5
A-16	3.3×10^{-4}	
B-12	4.8×10^{-4}	1.8
B-16	1.9×10^{-4}	0.12
B-20	2.5×10^{-4}	0.14

[a] Ratio of cmc values from NMR and surface tension methods.

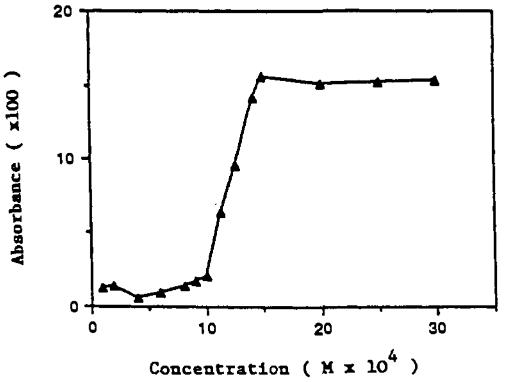

Figure 9. Absorbance of 1×10^{-6} M pinacyanol chloride at 610 nm as a function of A-12 concentration.

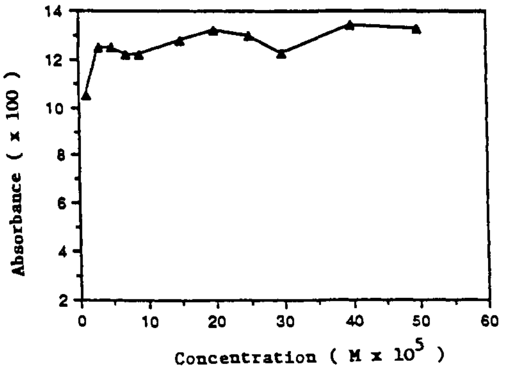

Figure 10. Absorbance of 1×10^{-6} M pinacyanol chloride at 610 nm as a function of B-20 concentration.

the public good, but the prospects for geminis taking their place among the useful surfactants are not yet known.

Conclusion

We have accomplished the following: (a) synthesized a new set of surfactants called geminis and (b) characterized some of their properties and found them to behave in an unconventional manner, indicative of substantial premicellar aggregation. We do not yet know the structural details of the aggregates, but this should not be surprising. Even hundreds of publications on much simpler surfactants have not fully defined the structure of their aggregates. Such is often the nature of "systems research":[2] an ongoing quest for understanding, not necessarily a collection of final, definitive statements.

Experimental Section

Gemini Surfactants. Syntheses of C-18, A-12, and B-16 will be provided to typify the preparation, purification, and characterization of all gemini surfactants. "Recipe format" is used with the syntheses to maintain brevity and to avoid excessive use of the passive voice. See Schemes I and II for the synthetic pathways.

(*p*-Phenylenedimethylene)bis(octadecyldimethylammonium) Dibromide (C-18). Dissolve with stirring 2.0 g (7.6 mmol) of α,α′-dibromo-*p*-xylene in 50 mL of warm acetone in an oven-dried 100-mL round-bottom flask. Add 5.1 g (16 mmol) of 95% *N*,*N*-dimethyloctadecylamine (Pfaltz and Bauer) diluted with 3 mL of acetone. A white precipitate forms almost immediately. Add 25 mL of additional acetone, and stir for 4 h. Remove the solid by filtration, wash the solid with 10 mL of acetone, and recrystallize the product twice from chloroform/acetone to obtain 5.7 g (87%) of C-18 as a white powder, mp 215–215.5 °C.

^{1}H NMR (300 MHz, $CDCl_3$): δ 7.77 (s, 4H), 5.34 (s, 4H), 3.51 (m, 4H), 3.20 (s, 12 H), 1.82 (m, 4H), 1.34–1.23 (m, 60 H), 0.85 (t, 6H, *J* = 6.7 Hz). ^{13}C NMR (75 MHz, $CDCl_3$): δ 133.9, 129.9, 66.2, 64.8, 49.3, 31.8, 29.6, 29.5, 29.4, 29.3, 29.2, 26.3, 22.5, 14.0. MS (low-resolution FAB, TEA matrix): *m*/*z* 779 $(M - {}^{81}Br)^+$, 777 $(M - {}^{79}Br)^+$. Anal. Calcd for $C_{48}H_{94}N_2Br_2$: C, 67.11; H, 11.03; N, 3.26. Found: C, 67.14; H, 11.07; N, 3.23.

(*p*-Phenylendimethylene)bis(dodecyl hydrogen phosphate) (A-12). Combine 10.0 g (54 mmol) of *n*-dodecanol and 20 mL of toluene in a 200-mL flask. Add pyrophosphoric acid (12.3 g, 67 mmol) to the solution. After 4 days of stirring, add 200 mL of ether to the reaction mixture and wash it with water (two portions of 100 mL each). Gently swirl the ether layer with 200 mL of water containing 6 g of NaOH, being careful to avoid emulsion formation as much as possible. Collect the aqueous phase, and add more water to the ether portion to reclaim additional product. (It was found easier to accept low yields than to devote time to isolate all the product from the emulsion.) Acidify the combined water layers with concentrated HCl to form a white precipitate. Take up this precipitate in ether, and extract the water layer further with three 75-mL portions of ether. Combine the ether extracts, and remove the ether to produce a waxy white solid which can be purified by crystallization from hexane to produce shiny white crystals, mp 55–57 °C of mono-*n*-dodecyl phosphate in 27% yield.

Dissolve 1.00 g (3.75 mmol) of the dodecyl phosphate in 2.7 g of 25% tetramethylammonium hydroxide in methanol plus another 15 mL of dry, freshly distilled methanol. Concentrate the solution under reduced pressure to produce a semisolid material to be dissolved in 50 mL of acetonitrile contasining 0.50 g (3.75 mmol equiv) of α,α′-dibromo-*p*-xylene. Boil the mixture, now containing a white precipitate, under reflux for 1.5 h. Remove the solvent under vacuum, and dissolve the resulting white residue in 50 mL of water. Acidify with 4 mL of concetrated HCl to form a white solid. Wash this solid (plus that obtained from an ether wash of the acidified water) with water and dry *in vacuo* overnight to obtain 1.0 g (84%) of crude A-12. Recrystallize the product to yield a pure fluffy white solid, mp 117–119 °C.

^{1}H NMR (300 MHz, warm $CDCl_3$): δ 7.23 (s, 4H), 4.86 (d, 4H, *J* = 8.1 Hz), 4.04 (q, 4H, *J* = 4.7 Hz), 1.69 (m, 4H), 1.24 (m, 36H), 0.86 (t, 6H, *J* = 6.3 Hz). MS (low-resolution FAB, TEA matrix): *m*/*z* 633 (M – H). Anal. Calcd for $C_{32}H_{60}O_8P_2$: C, 60.55; H, 9.53. Found: C, 60.59; H, 9.56.

((*E*)-Vinylenedi-*p*-phenylene)bis(hexadecyl hydrogen phosphate) (B-16). Convert 4,4′-dimethoxystilbene into 4,4′-dihydroxystilbene according to the directions of Laarhoven *et al.*[31] Use this compound to prepare B-16 in the following manner. Transfer 1.0 g (11 mmol) of $POCl_3$ to a dry 250-mL 3-neck round-bottom flask fitted with a condenser, an addition funnel, and a nitrogen inlet. Immerse the flask in an ice bath, and add 1.7 mL of triethylamine (12 mmol) in 10 mL of THF. When evolution of a white vapor ceases, add dropwise 1.5 g (7 mmol) of 4,4′-dihydroxystilbene in 30 mL of THF *via* the addition funnel over a period of 45 min. Magnetically stir for 30 min, and then add 3.4 mL (25 mmol) of triethylamine in 15 mL of THF. Next, add dropwise 2.3 g (9.5 mmol) of hexadecanol in 25 mL of THF over 30 min. Remove the flask from the ice bath, and allow it to warm to room temperature. Stir overnight

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(31) Laarhoven, W. H.; Nivard, R. J. F.; Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1961**, *80*, 775.

under a N_2 stream. Filter to remove salts, add 60 mL of water, stir overnight, and filter again to obtain a white solid. Triturate the solid first with ether and then with water. Dry the product overnight *in vacuo* to obtain 3.2 g (73%) of B-16, mp 133–139 °C.

^{1}H NMR ($CDCl_3$/DMSO-d_6): δ 7.63 (s, <2H), 7.19 (m, 8H), 6.87 (s, 2H), 3.91 (q, 4H, J = 7.3 Hz), 1.51 (m, 4H), 1.10 (m, 52H), 0.73 (t, 6H, J = 6.7 Hz). MS (low-resolution FAB, 3-NAB matrix): m/z 841, 819, 515, 321, 210, 79. Anal. Calcd for $C_{46}H_{78}O_8P_2 \cdot H_2O$: C, 65.85; H, 9.61. Found: C, 65.80; H, 9.50.

Surface Tension. Surface-tension measurements were performed with a Model 21 Fisher Tensiomat utilizing the Du Nuoy ring method. The 6-cm platinum ring was raised and lowered manually. After a set of readings at a particular concentration, the ring was rinsed successively with deionized water, 10% HCl, and deionized water prior to drying in a flame. A thermostated beaker was strapped to the tensiometer platform for measurements at 50 °C. Surface tensions from aged samples were obtained by allowing solutions to stand in covered beakers for 1 or 2 days at 23 °C and for 30 min at 50 °C. Care was taken not to agitate the samples as they were uncovered and placed in the tensiometer.

^{23}Na NMR. Spectra were obtained with a Bruker WP-200 SY FT NMR spectrometer equipped with a tunable broad-band probe. Samples of 2.5 mL at ambient temperature were placed in 10-mm NMR tubes, and their chemical shifts were determined relative to 0.01 M NaBr (δ = 0.0 ppm). The acquisition parameters used are as follows: AQ = 0.6840320, SW = 2994.012, TE = 297, LB = 1.0, SI = TD = 4 K, $^{Hz}/_{PT}$ = 1.462, RD = 0.3, SF = 52.9389505, FW = 3800, PW = 8.0, and RG = variable with sample, usually 400. The number of scans (NS) and acquisition time (AT) necessary to obtain a satisfactory S/N depended upon the sample. Typical values are 10 mM A-12 (NS = 225 and AT = 3.7 min), 0.1 mM A-12 (NS = 45 200, and AT = 12.2 h), 10 mM A-16 (NS = 600 and AT = 9.8 min), and 0.0.25 mM A-16 (NS = 95 500 and AT = 26.1 h).

Spectral Change. Pinacyanol chloride was purchased from Aldrich Chemical Co. The dye (5 μL of 6×10^{-4} M in methanol) was added to 3.00 mL of each gemini solution in a cuvette, and the solutions were allowed to equilibrate for 20 min before absorbance measurements at 610 nm were taken on a Varian DMS-20 spectrophotometer.

Dynamic Light Scattering. DLS measurements were performed with a Nicomp 370 Submicron particle sizer on samples filtered through a 0.6- or 1.0-μm membrane filter.

Film Balance. The methods described previously in detail[22] were followed exactly. We should emphasize again the need for purity and cleanliness in film-balance work.

Acknowledgment. This work was supported by the National Institutes of Health and the National Science Foundation. We thank Dr. Susan Richardson for obtaining the film-balance data.