reaction was monitored by ^1H NMR spectroscopy. After 3 h, signals of the substrates disappeared. The spectrum did not change after the mixture was allowed to stand overnight. Although no peak attributable to byproducts could be observed, a small amount of diphenyl disulfide was detected by VPC. The isomeric ratio of the products (**2am**/**3am**) was determined by peak integrals of ^1H NMR spectrum (4-CH= proton signal at δ 5.60 for (*E*)-**2am** and δ 6.34 for (*Z*)-**2am**, and 4-CH_2 proton signal at δ 3.30 for (*E*)-**3am** and δ 3.25 for (*Z*)-**3am**) and also by VPC. The crude product was purified by medium-pressure column chromatography (silica gel, 0.5–1% ethyl acetate/hexane), giving 5-(phenylthio)-4-hepten-3-one (**2am**) (194 mg, 74.8%, *E*/*Z* = 8:2). The *E* isomer could be isolated pure, but the *Z* isomer was obtained only as a mixture with the *E* isomer: ^1H NMR (*E*) δ 0.96 (t, *J* = 8 Hz, 3 H), 1.23 (t, *J* = 8 Hz, 3 H), 2.23 (q, *J* = 8 Hz, 2 H), 2.85 (q, *J* = 8 Hz, 2 H), 5.60 (s, 1 H), 7.48 (s, 5 H), (*Z*) δ 0.97 (t, *J* = 8 Hz, 3 H), 1.15 (t, *J* = 8 Hz, 3 H), 2.17 (q, *J* = 8 Hz, 2 H), 2.56 (q, *J* = 8 Hz, 2 H), 6.34 (s, 1 H), 7.17–7.78 (m, 5 H); IR (neat) 1680 cm^{-1}. Anal. Calcd for $C_{13}H_{16}OS$: C, 70.87; H, 7.31; S, 14.55. Found: C, 70.59; H, 7.45; S, 14.32.

Acknowledgment. We express appreciation to Prof. K. Okamoto for his stimulating discussions and to Mr. M. Sunami for carrying out exploratory experiments in this series. We are also indebted to Prof. H. M. Walborsky for his helpful suggestions. The present work was partially supported by a Grant-in-Aid for Scientific Research (No. 61550637) from the Ministry of Education, Science and Culture.

Registry No. **1a**, 108425-53-2; **1b**, 58442-43-6; **1c**, 74143-89-8; **1d**, 36144-55-5; **1e**, 22377-44-2; **1f**, 17039-96-2; **1g**, 2861-04-3; (*E*)-**2am**, 109244-74-8; (*Z*)-**2am**, 109244-75-9; (*E*)-**2an**, 109244-77-1; (*Z*)-**2an**, 109244-78-2; (*Z*)-**2ar**, 109244-80-6; (*E*)-**2bm**, 109244-82-8; (*Z*)-**2bm**, 109244-83-9; (*E*)-**2bn**, 109244-85-1; (*E*)-**2bo**, 109244-87-3; (*E*)-**2bp**, 109244-88-4; (*Z*)-**2br**, 109244-91-9; (*E*)-**2bs**, 109244-92-0; (*E*)-**2cm**, 109244-93-1; (*Z*)-**2cr**, 109244-95-3; (*Z*)-**2dr**, 109244-97-5; (*Z*)-**2em**, 109244-99-7; (*E*)-**2em**, 109244-98-6; (*Z*)-**2er**, 109245-01-4; (*E*)-**2fm**, 109245-02-5; (*Z*)-**2fm**, 109245-09-2; **2gm**, 109245-04-7; **2gr**, 109245-05-8; (*E*)-**3am**, 109244-76-0; (*Z*)-**3am**, 109245-06-9; (*E*)-**3an**, 109244-79-3; (*Z*)-**3an**, 109245-07-0; **3at**, 109244-81-7; **3bm**, 109244-84-0; **3bn**, 109244-86-2; **3bp**, 109244-89-5; **3bq**, 109244-90-8; **3cm**, 109244-94-2; **3dm**, 109244-96-4; (*E*)-**3em**, 109245-00-3; (*Z*)-**3em**, 109245-08-1; **3fm**, 109245-03-6; **3gm**, 85895-39-2; PhSH, 108-98-5; *p*-$NO_2C_6H_4SH$, 1849-36-1; *p*-$NH_2C_6H_4SH$, 1193-02-8; *o*-$NH_2C_6H_4SH$, 137-07-5; 2-PySH, 73018-10-7; $PhNH_2$, 62-53-3; $EtCOCH_2C(Cl)$=CHMe, 80060-10-2; *i*-$PrCOCH_2C(Cl)$=CMe_2, 80060-11-3; Ph_3P=CHCOMe, 1439-36-7; $PhCH_2COCl$, 103-80-0; $Ph_2CHCOCl$, 1871-76-7; pyrrolidine, 123-75-1; imidazole, 288-32-4.

Supplementary Material Available: Spectral and analytical data for the addition products (*E*)- and (*Z*)-**2am**, (*E*)-**2bm**, (*E*)-**2cm**, **2an**,**ar**,**bn**,**bo**,**br**,**bs**,**cr**,**dr**,**em**,**er**, and **3am**,**an**,**at**,**bm**,**bn**,**bp**,**bq**,**cm**,**dm**,**em**,**fm**,**gm** (8 pages). Ordering information is given on any current masthead page.

Binding Properties of 1-Pyrenesulfonic Acid in Water

F. M. Menger* and L. G. Whitesell

Department of Chemistry, Emory University, Atlanta, Georgia 30322

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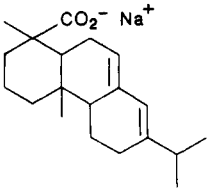
Experiments are described with 1-pyrenesulfonic acid (1-PSA), an unconventional surfactant of the type Ar_n–X where Ar_n is a polycyclic aromatic and X is a water-solubilizing entity. Little is known about the properties of such compounds when dissolved in water at relatively high concentrations (up to 0.1 M). Tensiometry, fluorescence spectroscopy, UV spectrophotometry, NMR spectroscopy, and kinetics were all used to characterize the aqueous 1-PSA systems. 1-PSA dimerizes but resists forming stacks or other multimolecular aggregates ("micelles"); possible reasons for this are discussed. Although possessing a "tail" which is less hydrophobic than those of common aliphatic surfactants, 1-PSA is capable of binding guests tightly (e.g., K_{assoc} with phenol blue = 3×10^4 M^{-1}). It does so as a monomer which has a large aromatic surface exposed to water. Thus, binding processes can be exploited without the complication of micellization; design of an enzyme mimic was attempted on this basis. Ar_n–X compounds have other attractive features: their "tails" are electronically active, and a wide variety of distinctive shapes are readily available.

Conventional surfactants possess a polar head-group attached to a long hydrocarbon chain. Basic research into the chemistry of surfactants has centered around the head-group, the main role of the hydrocarbon tail being to assemble the head-groups and to induce what is known as "micellar chemistry". Generally, a chain of 10 or more carbons suffices for the purpose. But as a result of this philosophy, we know surprisingly little about micellar properties as a function of the hydrophobic portion of the surfactant. For example, we do not know (and cannot even predict) how the catalytic properties of a hexadecyltrimethylammonium bromide micelle[1] would be affected by a phenolic unit at the chain terminus or an amino group at position-5 or an *n*-hexyl attached near the center of the tail. The reason for scarcity of structure–activity data of this type is clear: the necessary compounds are not readily available. A wealth of useful information lies in wait for those willing to overcome the synthetic difficulties.

Although basic research has relied largely on straight-chain surfactants, industrial chemistry has produced an imaginative array of nonlinear materials. For example, tall oil contains 30–50% rosin acids (e.g., abietic acid) whose salts display surfactant-like behavior with good wetting properties.[2]



Naphthalenesulfonic acid–formaldehyde condensates are used as setting agents for powdered pesticides, paints, and other formulations.[3] Surfactants can also be obtained by

(1) Romsted, L. R.; Cordes, E. H. *J. Am. Chem. Soc.* **1968**, *90*, 4404.

(2) Zachary, L. G. *Tall Oil and Its Uses*; F. W. Dodge: New York, 1963.

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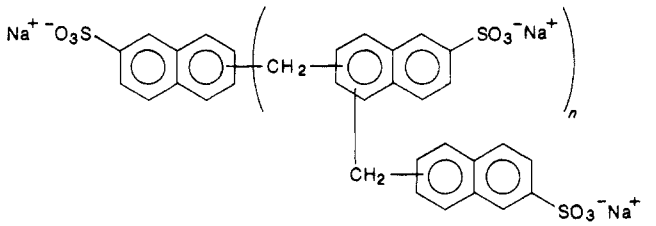
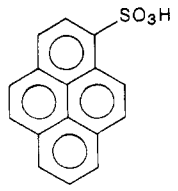
sulfonating lignin, a complex polymeric network of oxygenated aromatic rings.[4]



We have recently begun experimenting with "unconventional" surfactants of the type Ar_n–X where Ar_n is a polycyclic aromatic hydrocarbon and X is a water-solubilizing entity (e.g., SO_3^- or NR_3^+). To our knowledge, virtually nothing has been published on the properties of such compounds when dissolved in water at relatively high concentrations. An attractive variety of polycyclic aromatics, each with its distinctive shape, was available for this study. In the work described below, however, we confine ourselves to 1-pyrenesulfonic acid (1-PSA) and its sodium salt.



1-PSA

Polycyclic aromatics are electronically active: they exhibit fluorescence, phosphorescence, electrochemiluminescence, photoconductivity, and charge-transfer complexation.[5] Hence, there exists a key difference between the common linear surfactants and Ar_n–X molecules. The former have inert chains whereas Ar_n–X surfactants possess chemically interesting hydrophobic moieties. The two types of surfactants differ in another way. Straight-chain surfactants bind and solubilize guest molecules only when aggregated (i.e., above their critical micelle concentrations). Aggregation is not necessarily required for Ar_n–X systems. Thus, Ar_n–X compounds in water expose such large surfaces to the solvent that adsorption processes are conceivable even in the monomeric state. Both hydrophobic and charge-transfer forces could promote such adsorption.

Experimental Section

Preparation of 1-Pyrenesulfonic Acid (1-PSA). Concentrated sulfuric acid (4 mL) was added slowly to a solution of pyrene (5 g, 25 mmol) in nitrobenzene (20 mL), causing a greenish yellow precipitate to form. The solid was collected by filtration, washed with benzene, and dried under reduced pressure. The resulting material was then dissolved in water and precipitated via addition of concentrated HCl. Finally, two "recrystallizations" were carried out by using hot aqueous acid to yield 3.4 g (43%) off-white amorphous solid with spectral properties as described in the next section. 1-PSA analyzed for a dihydrate and melted at 128 °C (compared to a reported 118–119 °C for the monohydrate and 182–184 °C for anhydrous 1-PSA).[6]

Anal. Calcd for $C_{16}H_9O_3S \cdot 2H_2O$: C, 60.4; H, 4.4; S, 10.1. Found: C, 59.3; H, 4.4; S, 10.1.

The sodium salt of 1-PSA was prepared by neutralizing an aqueous solution with sodium bicarbonate; 1-PSANa precipitated when the water was saturated with sodium chloride. Preparative work with 1-PSA and its salt was confined to an efficient hood.

***p*-Nitrophenyl 3,5-Dinitrobenzoate (*p*-NPDNB).** 3,5-Dinitrobenzoyl chloride (0.85 g, 3.7 mmol) in anhydrous ether was added dropwise with stirring at room temperature to an ether solution of *p*-nitrophenol (0.50 g, 3.6 mmol) and pyridine (0.28 g, 3.5 mmol) under a blanket of nitrogen. Stirring was continued for 0.5 h. The ether solution was then washed with aqueous acid, dried over $MgSO_4$, and stripped with the aid of a rotary evaporator to give a solid product, which, after crystallization from acetone, melted at 188–189 °C (lit.[7] mp 190 °C). No attempt was made to optimize yields.

***N,N,N′,N′*-Tetramethyl-*N*-(1-methylpyrenyl)-3-aminopropanaminium Bromide.** Pyrene-1-carboxaldehyde was converted into 1-(hydroxymethyl)pyrene and thereupon into 1-(bromomethyl)pyrene by using known procedures.[8,9] The latter (1.78 g, 6.0 mmol) in 95% ethanol/ether (50/50, 200 mL) was added dropwise to *N,N,N′,N′*-tetramethyl-1,3-propanediamine (1.52 g, 11.7 mmol) in 25 mL of 95% ethanol. The resulting reaction mixture was stirred at room temperature for 42 h, after which the solvent was removed to generate the crude solid product. Recrystallization from MeOH/ether gave a solid, mp 196–200 °C, with the correct NMR spectra and analysis.

Anal. Calcd for $C_{24}H_{29}N_2Br$: C, 67.76; H, 6.87; N, 6.59. Found: C, 67.86; H, 6.93; N, 6.42.

Tensiometry. Surface tension measurements were carried out with a Fisher Tensiomat using a platinum–iridium ring 6 cm in circumference. Data were obtained at room temperature and are uncorrected.

NMR Spectrometry. Spectra were recorded on a Bruker WP-200-SY 200-MHz instrument for ^{13}C and a Nicolet 360-NB 360-MHz instrument for ^1H. Sodium 3-(trimethylsilyl)-1-propanesulfonate was used as the NMR reference in the aqueous solutions.

UV Spectrophotometry. UV–vis spectra were recorded on a Cary 14 spectrophotometer. A thermostated Beckman Acta II was used for kinetic experiments.

Fluorescence Spectroscopy. Experiments were performed with a Perkin-Elmer MPF-4 instrument.

Kinetics. The following procedure is typical of that used throughout. A solution of 1-PSA-Na (1.0 mM in 3.00 mL of pH 10.00 aqueous buffer) was added to a 1-cm cuvette and thermostated in the sample chamber of a spectrophotometer at 25.0 ± 0.1 °C for at least 15 min. A *p*-nitrophenyl ester (25 μL of a 2 mM solution in acetonitrile) was then added with stirring to the cuvette, after which the cuvette was stoppered and the recording begun. The increase in absorbance at 400 nm, resulting from ester hydrolysis, was traced for at least eight half-lives. Pseudo-first-order rate constants were obtained from the absorbance–time data in the usual manner.

Experimental Conditions. Since sulfonic acids are strong acids comparable in strength to sulfuric acid, 1-PSA exists in water as the anion. All experiments (except the kinetics) were carried out by using 1-PSA with no added buffer or salt. One reason for proceeding in this manner, other than simplicity, relates to the greater solubility of 1-PSA in water when metallic counterions are absent (an important factor especially in the NMR experiments where high concentrations were required). Obviously, aggregation properties might be altered in the presence of salts, but we did not investigate this point specifically.

Results and Discussion

Tensiometry. The aggregation behavior of surfactants depends in part upon the size of the head-group relative to the hydrophobic tail. For example, surfactants bearing a single hydrocarbon chain usually form micelles, whereas surfactants with two long tails assemble into bilayers.

(3) Rosen, M. J. *Surfactants and Interfacial Phenomena*; Wiley-Interscience: New York, 1978; p 10.
(4) Bernfeld, P., Ed., *Biogenesis of Natural Compounds*; Macmillan: New York, 1963.
(5) Clar, E. J. *Polycyclic Hydrocarbons*; Academic: New York, 1964; Vol 2.
(6) Abe, Y.; Pei-Chin, H. *Uki Gosei Kagaku* Kyokai Shi **1975**, *33*, 277; *Chem. Abstr.* **1975**, *83*, 58514a. The 1-position (called the 3-position in older articles) is the preferred substitution site (see ref 5, pp 119–121).
(7) Akahori, Y. *Chem. Pharm. Bull.* **1965**, *13*, 368.
(8) Yoshimoto, S.; Okamoto, K.; Hirata, H.; Kusabayashi, S. *Bull. Chem. Soc. Jpn.* **1973**, *46*, 358.
(9) Akiyama, S.; Nakasuji, K.; Nakagawa, M. *Bull. Chem. Soc. Jpn.* **1971**, *44*, 2231.

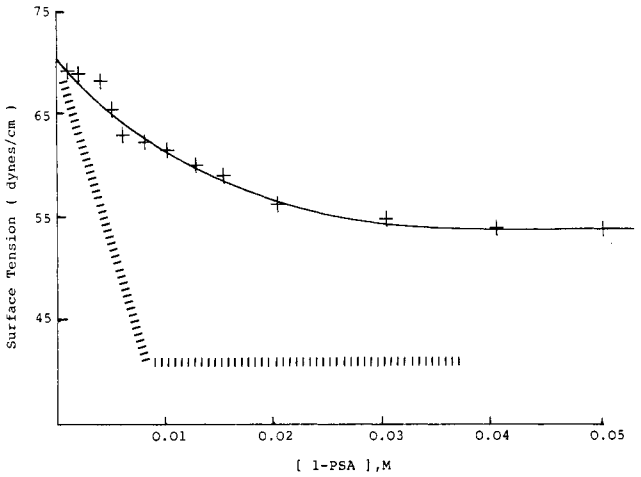


Figure 1. Surface tension vs. concentration of 1-PSA in water. Dotted line represents curve for typical aliphatic surfactant with a critical micelle concentration.

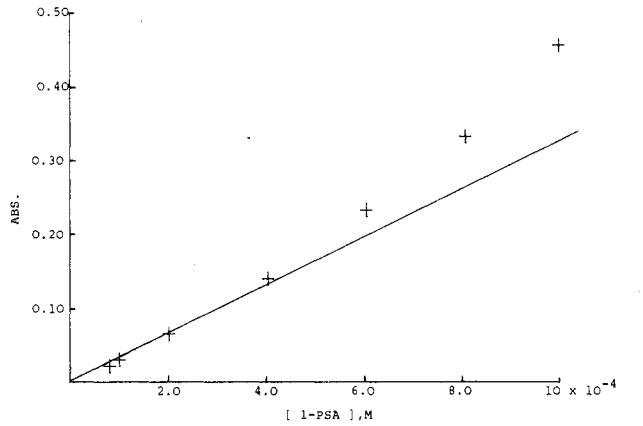


Figure 2. Absorbance of aqueous 1-PSA at 380 nm as a function of concentration showing deviation from Beer's Law.

Aggregates of 1-PSA, if such exist, would most likely consist of molecular "stacks" where aromatic rings lie flat on one another. Dyes with large delocalized electronic systems are known to associate in this manner.[10] Surfactant aggregation can be detected by means of tensiometry. Thus, as the surfactant concentration in water is increased, more and more molecules adsorb at the air–water interface, and the surface tension is continually lowered. Ultimately, however, the critical micelle concentration (cmc) is reached. At this point, surfactant molecules prefer to micellize rather than enter the interface, and hence surface tension vs. concentration plots abruptly level off. A plot of surface tension vs. [1-PSA] is shown in Figure 1. Two features are notable. First, 1-PSA is not highly surface active, the surface tension being lowered to a minimum of 54 dynes/cm (compared to 35 dynes/cm for a typical straight-chain surfactant). Second, no sudden bend in the plot, corresponding to a cmc, is apparent. If aggregation is occurring, it is certainly not a precipitous event, so that in this regard 1-PSA differs from conventional straight-chain surfactants.

UV Spectrophotometry. 1-PSA in water displays high-wavelength absorption maxima at 328 and 343 nm. A plot of absorbance at 380 nm vs. concentration (Figure 2) deviates from linearity above 4×10^{-4} M 1-PSA. This departure from ideality points to dimer or aggregate formation. Since no new long-wavelength bands were observed in the nonlinear concentration region, charge-transfer complexation seems unlikely.

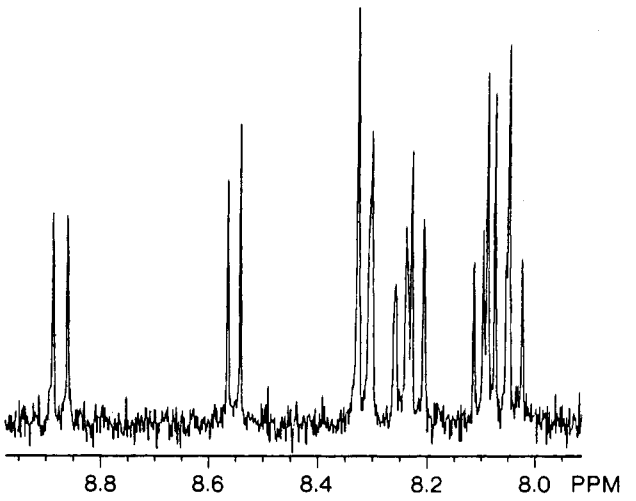


Figure 3. ^{1}H NMR spectrum of 2.0×10^{-3} M 1-PSA in D_2O.

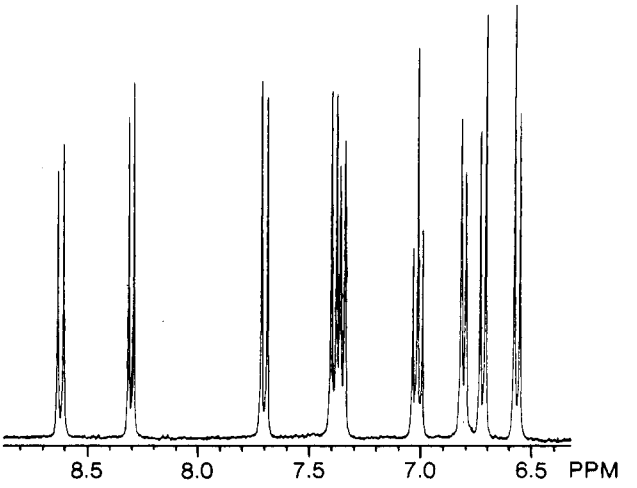


Figure 4. ^{1}H NMR spectrum of 0.10 M 1-PSA in D_2O. Compare chemical shift range with that in Figure 3.

Fluorescence Spectroscopy. The fluorescence spectrum[11] of 1.0×10^{-4} M 1-PSA in water (excitation = 357 nm) shows emission bands at 376 and 394 nm. When the 1-PSA concentration is increased 50-fold to 5.0×10^{-3} M, excimer emission appears at 490 nm. Excimer is formed by excitation of a ground-state dimer (as opposed to a collision between a monomeric ground state with a monomeric excited state). The following results confirm this assertion. Excitation spectra (in which excimer emission was monitored at 490 nm) give a single structureless peak at 385 nm; excitation spectra (in which monomer emission was monitored at 396 nm) give multiple absorbances similar to the UV spectrum of monomeric 1-PSA including one near 357 nm. If the excitation wavelength is set at 385 nm, the ratio of monomer to excimer fluorescence (I_{396}/I_{490}) equals 0.45. But if the excitation wavelength is set at 357 nm, the ratio increases to 2.8, thereby supporting the contention that there exist two ground-state species, each of which generates an excited state. Although excimer fluorescence cannot be observed at 4×10^{-4} M, excitation spectra were found to depend upon concentration near 4×10^{-4} M. This indicates the presence of ground-state complexation at low concentrations in agreement with the UV data.

(10) Haugen, G. R.; Hardwick, E. R. *J. Phys. Chem.* **1963**, *67*, 725.

(11) Klein, U. K. A.; Miller, D. J.; Hauser, M. *Spectrochim. Acta, Part A* **1976**, *32A*, 379.

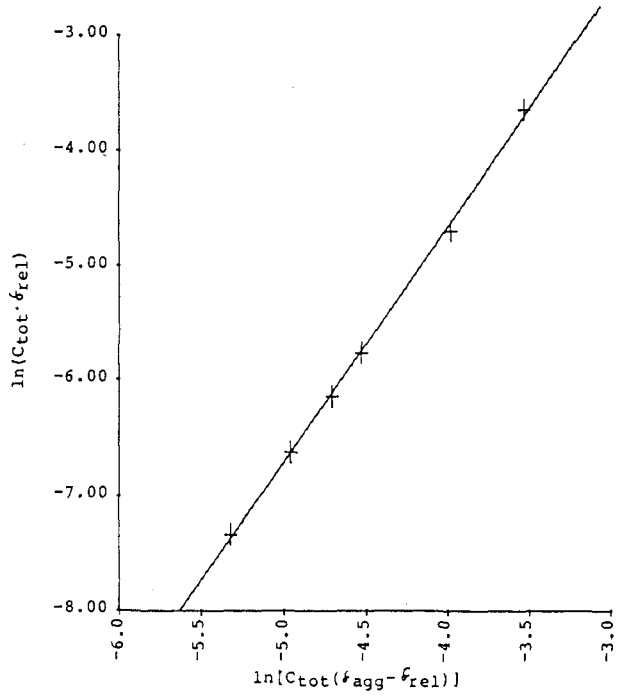


Figure 5. Determination of the 1-PSA aggregation number in D_2O by ^1H NMR. See text for explanation.

NMR Spectrometry. Chemical shifts of 1-PSA protons are concentration dependent (Figures 3 and 4). Thus, an increase in concentration from 2.0 to 100 mM extends the aromatic proton range from 8–9 to 6.5–9 ppm, providing additional evidence for a ground-state dimer or aggregate. Ring current effects therein move the signals upfield. The NMR data are important in that they permit us to assess the number of molecules per aggregate (n) and the equilibrium constant (K) in eq 1. Since aggregation is fast on

$$n(\text{1-PSA}) \overset{K}{\rightleftharpoons} \text{aggregate} \qquad (1)$$

the NMR time scale, an observed shift δ_{obsd} can be expressed as a weighted average of the corresponding monomer and aggregate shifts, δ_{mon} and δ_{agg}, accorrding to eq 2. The C terms in this equation represent monomer,

$$\delta_{obsd} = \frac{C_{mon}}{C_{tot}}\delta_{mon} + \frac{nC_{agg}}{C_{tot}}\delta_{agg} \qquad (2)$$

aggregate, and total concentrations. Combining eq 2 with $K = C_{agg}/C_{mon}^n$ and performing simple algebraic operations yields eq 3, where $\delta_{rel} = \delta_{obsd} - \delta_{mon}$.[12] In order to extract

$$\ln (C_{tot}\delta_{rel}) = n \ln [C_{tot}(\delta_{agg} - \delta_{rel})] + \ln K + \ln (n) - (n-1) \ln \delta_{agg} \qquad (3)$$

n and K from eq 3, we focused on one particular peak (~8.3 ppm at high dilution). A plot of δ_{obsd} vs. [1-PSA] for 10 concentrations (not shown) extrapolated to [1-PSA] = 0 provided a $\delta_{mon} = 8.40$. Similarly, a plot of δ_{obsd} vs. $[\text{1-PSA}]^{-1}$ extrapolated to "infinite" [1-PSA] gave a $\delta_{agg} = 1.36$ relative to δ_{mon}. With δ_{mon} and δ_{agg} in hand, we plotted $\ln (C_{tot}\delta_{rel})$ vs. $\ln [C_{tot}(\delta_{agg} - \delta_{rel})]$ to secure a straight line (Figure 5). Its slope n equals 2.0, signifying that over the 4–40 mM concentration range 1-PSA forms a dimer. Association constant K, obtained from the intercept of Figure 5, equals 22 M^{-1}. A K of this value means that at 1 mM, where deviations from linearity were observed in the UV

(12) Persson, B.; Drakenberg, T.; Lindman, B. *J. Phys. Chem.* **1976**, *80*, 2124.

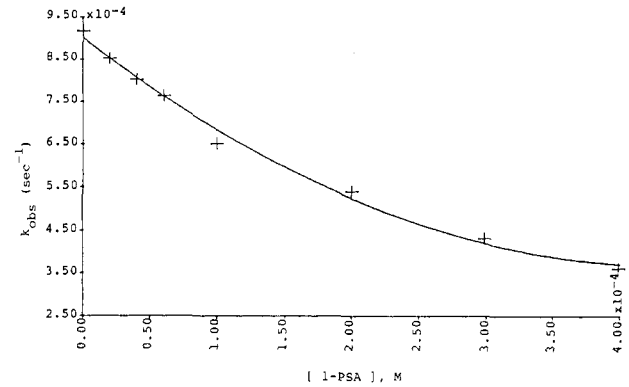
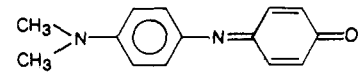


Figure 6. Observed rate constants for the hydrolysis of *p*-nitrophenyl 3,5-dinitrobenzoate in the presence of varying amounts of 1-PSA (25.0 °C, 0.05 M phosphate buffer, pH 8.00).

(Figure), there exists only 2% dimer. This low dimer level can be detected by UV because we monitored the absorbance at 380 nm, which is not a maximum for the monomer but which is, according to fluorescence excitation spectra, near that of the dimer.

In summary, all spectroscopic experiments point toward the presence of aggregation. NMR data prove specifically that the aggregates, under the *salt-free* conditions, are dimeric in nature. Multimolecular aggregates, characteristic of straight-chain surfactants, are not observed below 0.1 M with the Ar_n–X system.

Binding Properties of 1-PSA. Addition of 1.0 mM 1-PSA to an aqueous solution of phenol blue (an indoaniline dye) causes the λ_{max} of the dye to shift from 668 to 575 nm.



Since the same shift is observed in 1.0 mM HCl, protonation of the dye must be taking place. By measuring dye absorbance in the presence of varying amounts of 1-PSA, and by making use of the Benesi–Hildebrand equation,[13] one can determine the association constant K for 1-PSA with the conjugate acid of phenol blue. This is a fairly routine procedure and details will not be provided here[14] except to indicate that the [1-PSA] ranged from 2×10^{-5} to 1×10^{-4} M while the [phenol blue] was maintained at 4×10^{-6} M. Association constant K was found to be extremely large: 3.0×10^4 M^{-1}. Both electrostatic and π–π interactions could be contributing to the binding efficiency. Since under the conditions of the experiment the dimer concentration is insignificant, binding of the dye must involve only monomeric 1-PSA. Thus, 1-PSA has a substantial advantage over conventional surfactants; it need not be aggregated in order to bind guest molecules effectively.

Kinetics. Micelles of conventional surfactants are known to perturb the rates of many organic processes. As a general rule, anionic surfactants catalyze reactions of organic substrates with cations but inhibit reactions with anions. For example, sodium dodecyl sulfate micelles retard the saponification of *p*-nitrophenyl hexanoate by 15-fold.[15] In contrast, 1-PSA (3 mM) has virtually no

(13) Ketelaar, J. A. A.; van de Stolpe, C.; Goudsmit, A.; Dzcubas, W. *Recl. Trav. Chim. Pays-Bas* **1952**, *71*, 1104.

(14) Full details are available in the Ph.D. thesis of L. G. Whitesell (Emory University, 1984) entitled "Part I. Synthesis and Study of a New Functionalized Micellar Catalyst with True Turnover Capabilities. Part II. Intramolecular Reactions and the Limitations of the Page–Jencks Factor. Part III. Solution Properties of the Non-Conventional Surfactant 1-Pyrenesulfonic Acid."

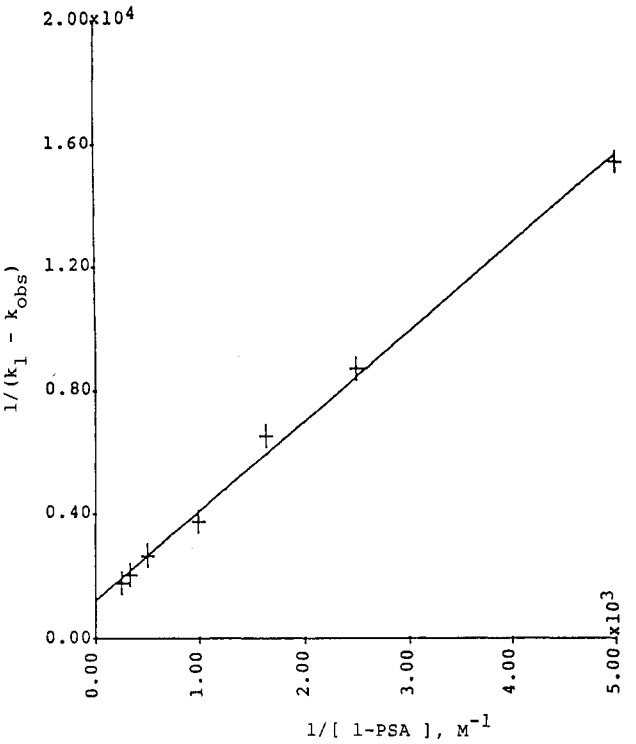


Figure 7. Plot used for determining k_2 and K in eq 4. See text and eq 5 for explanation.

effect on the hydrolysis of *p*-nitrophenyl butyrate or *p*-nitrophenyl octanoate (pH = 10.00, 25.0 °C). Kinetic data cannot disclose whether the esters simply do not bind to 1-PSA or whether binding of ester fails to lower the hydrolysis rate.

Observed rate constants for the hydrolysis of a totally aromatic ester, *p*-nitrophenyl 3,5-dinitrobenzoate, in the presence of excess 1-PSA (pH = 8.0, 25.0 °C) are shown in Figure 6. The rates are seen to decrease with increasing [1-PSA] until the ester is "saturated". Equation 4, where P, E, A, and PE denote 1-PSA, ester, product, and complex, respectively, describes the system assuming a concentration range where monomeric 1-PSA predominates.

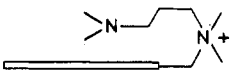
$$\begin{array}{ccccc} P & + & E & \overset{K}{\rightleftharpoons} & PE \\ & & \downarrow k_1 & & \downarrow k_2 \\ & & A & & A \end{array} \qquad (4)$$

Rate constant k_2 for the complex and association constant K can be obtained from eq 5 by plotting $1/(k_1 - k_{obsd})$ vs. $1/[1\text{-PSA}]$ as in Figure 7.[16] We find that $k_2 = 9.6 \times 10^{-3}$

$$\frac{1}{(k_1 - K_{obsd})} = \frac{1}{(k_1 - k_2)} + \frac{1}{(k_1 - k_2)K[1\text{-PSA}]} \qquad (5)$$

s^{-1} compared to $k_1 = 5.5 \times 10^{-2}$ s^{-1} for hydrolysis in the same pH 8.0 buffer but without 1-PSA. The 6-fold inhibition within the complex may stem either from a diminished local hydroxide concentration (as in an anionic micelle) or from $\pi \rightarrow \pi$ electron donation to the substrate. Binding constant K equals 460 M^{-1}, which is smaller than that for phenol blue but sizeable nonetheless.

In a vain attempt to create an enzyme mimic, we synthesized a pyrene derivative bearing a water-solubilizing side chain terminated by a tertiary amine.



No catalytic activity was evident toward *p*-nitrophenyl 3,5-dinitrobenzoate despite effective complexation. Shortening the side chain by one methylene did not improve the situation. Although our initial attempts here were unsuccessful, application of water-soluble polycyclic aromatics to biomimetic chemistry remains a worthy pursuit.

General Remarks. Pyrene is far more soluble in hexane (7×10^{-2} M) than in water (6×10^{-7} M);[17] polycyclic aromatics must obviously be considered "hydrophobic". Yet aromatic hydrocarbons are appreciably more soluble in water and less hydrophobic than cyclic hydrocarbons with the same number of carbons. Unlike aliphatics, aromatics have π electrons that enhance van der Waals attraction to the water.[18] It is hardly surprising, therefore, that surfactants of the type Ar_n–X behave completely differently from the common aliphatic surfactants. Simple dimerization of 1-PSA, rather than precipitous aggregation, was the only process observable by NMR. Dimerization of 1-PSA is only 50% complete at 5×10^{-2} M, a concentration 100-fold greater than the cmc of another 16-carbon surfactant, sodium hexadecyl sulfate. No doubt, geometric factors (e.g., the size and asymmetry of the hydrophobic moiety) also impact adversely on the ability of 1-PSA to aggregate into any structure even remotely resembling a spherical micelle.

One might wonder why 1-PSA prefers to dimerize over forming multimolecular stacks. After all, two "exposed" surfaces remain even after 1-PSA dimerizes back-to-back. Electrostatic repulsion among the sulfonate groups seems an unlikely explanation because (a) a stack of 1-PSA molecules could have their sulfonates staggered and thus positioned far from each other and (b) electrostatics does not impair the assembling of conventional surfactants (even planar ones such as bile salts). In order to rationalize dimerization, it is necessary to review briefly the information available on aqueous hydration of benzene.

Benzene dimerizes in water[19] with an association constant of 0.85 M^{-1} (compared to 22 M^{-1} observed by NMR for 1-PSA). Monte Carlo studies of benzene in water disclose that water molecules "close to the benzene molecule show only small deviations from what is found in pure water".[20] In other words, water structure is only slightly perturbed by the presence of a benzene molecule. Related calculations indicate that the first hydration shell of benzene consists of 23 water molecules.[21] Twenty-one of these comprise a hydrophobic "in-plane" hydration. The other two water molecules solvate the benzene on either side of the ring at the center. Weak hydrogen bonding between the water protons and the π cloud provide much of the interaction energy. Computer simulations were also carried out on a benzene dimer embedded in 510 water molecules.[22] Two distinct minima were detected. One of them corresponds to a contact interaction in which two benzenes reside back-to-back only 4.3 Å apart. The other represents a solvent-separated dimer with a 5.1 Å sepa-

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ration. Six water molecules are situated on the edges of the complex, but none lie directly between the two benzene rings.

The behavior of 1-PSA is at least qualitatively consistent with the above calculations. Since aromatics do not "freeze" water molecules as effectively as do aliphatic chains, solvent release upon aggregation (with its attendant entropic benefits)[23] is not so important. Indeed, structured water collects primarily at the periphery of the aromatics rather than above or below the rings where the actual hydrocarbon-hydrocarbon contact takes place. Multimolecular stacking is not observed presumably because favorable van der Waals interactions are not sufficiently great to overcome an "edge" effect. Thus, a trimer could have difficulty accommodating at the circumference of its inner ring all the water molecules necessary to stabilize "double" association. Whatever its origins, however, the presence of only monomeric and dimeric Ar_n-X is fortunate because it permits the exploitation of hydrophobic and electronically active surfaces in water without the complication of aggregation.

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Registry No. 1-PSA, 26651-23-0; *p*-NPDNB, 1523-21-3; *N*,*N*,*N*′,*N*′-tetramethyl-*N*-(1-methylpyrenyl)-3-aminopropanaminium bromide, 109244-71-5; 1-(bromomethyl)pyrene, 2595-90-6; *N*,*N*,*N*′,*N*′-tetramethyl-1,3-propanediamine, 110-95-2; phenol blue, 2150-58-5.

Substituent Control of Sigmatropic Periselectivity: Application to the Synthesis of (±)-Muscone

Richard W. Thies* and Khushroo P. Daruwala

Department of Chemistry, Oregon State University, Corvallis, Oregon 97331

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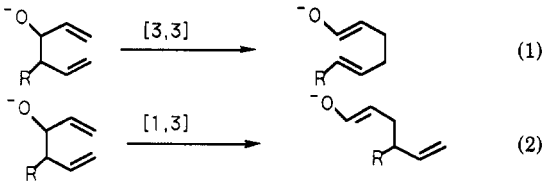
The thermal and anionic rearrangements of *trans*-1-vinylcyclotridec-3-en-1-ol compounds substituted in the α and β vinyl positions have been examined to determine whether the substituents can be used to control the periselectivity. For the anionic rearrangements, trimethylsilyl groups were found to be unsuitable, and terminal vinyl methyl or isopropyl groups did not provide a useful selectivity. Under thermal conditions, either a terminal trimethylsilyl or methyl gave high periselective control favoring the 1,3-shift siloxy Cope ring expansion relative to the 3,3-shift. This was used in a new synthsis of muscone.

A substantial number of recent papers describe applications of anionic oxy Cope reactions[1-3] (eq 1 and 2) to the synthesis of natural products with various ring sizes. For



(1)

(2)

example, the 3,3-shift has been elegantly used to prepare natural products containing 10-membered rings (eucannabinolide,[4] eupasimlicin A,[5] periplanone B[6]), 8-membered rings (poitediol,[7] ophiobolins[8]), and 6-membered rings (juvabione,[9] dihydronepetalactone[10]). The 3,3-shift has also been used to make key intermediates for syntheses aimed toward pseudoguianolides,[11] germacranes,[12] steroids[13], retigeranic acid,[14] and taxol.[15] A 5,5-shift variation[16] suggests a possible route to 14-membered ring compounds like albocycline and erythromycin A. Our studies have developed the 1,3-shift oxy Cope rearrangement as a ring-expansion method applicable to medium and large ring systems[17] including large-ring analogues of steroids.[18] The same principle has recently been used[19] to prepare 5-membered rings, which are common to many natural products such as damsinic acid, pentalene, and the hirsutenes. The 1,3-shift has also been used to produce 6-membered rings.[20,21] The thermal 3,3 oxy Cope has also been applied to natural produce synthesis, e.g., *Lycopodium* alkaloids[22] and *cis*-hydroisoquinolines.[23]

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