

terized by X-ray diffraction. Since RNH<sub>2</sub> and PR<sub>3</sub> ligands do not seem to materially alter dimensions of Be-centered clusters (Table I), the ~0.04 Å greater radius of the Zr<sub>6</sub>Cl<sub>12</sub>(PMe<sub>2</sub>Ph)<sub>6</sub> cluster relative to Zr<sub>6</sub>Cl<sub>12</sub>(H)(NH<sub>2</sub>Et)<sub>6</sub> suggests that the former may be an empty 12-electron unit rather than a similar hydride. However, this distinction is lessened by the fact that the earlier structural study was done at room temperature, whereas ours was carried out at -60 °C.

**Acknowledgment.** This research was supported by the National Science Foundation, Solid State Chemistry, via Grants DMR-8318616 and -8902954, and was carried out in facilities of the Ames Laboratory, DOE.

**Supplementary Material Available:** Some synthetic details and tables of refinement data and structural parameters for and distances in (Zr<sub>6</sub>Cl<sub>12</sub>Be)(EtNH<sub>2</sub>)<sub>6</sub>·8CH<sub>3</sub>CN (6 pages). Ordering information is given on any current masthead page.

(13) Cotton, F. A.; Kibala, P. A.; Roth, W. J. *J. Am. Chem. Soc.* **1988**, *110*, 298.

### Self-Replicating Reverse Micelles and Chemical Autopoiesis

Pascale Angelica Bachmann,<sup>†</sup> Peter Walde,<sup>†</sup>  
Pier Luigi Luisi,<sup>\*,†</sup> and Jacques Lang<sup>‡</sup>

*Institut für Polymere, ETH-Zentrum  
CH-8092 Zürich, Switzerland  
Institut Charles Sadron (CRM-EAHP), CNRS  
6, rue Boussingault, F-67000 Strasbourg, France  
Received June 18, 1990*

Whether or not and to what extent synthetic chemical structures are able to self-replicate is a fascinating and important question, as it binds chemistry with one of the most basic cell processes. A few ingenious chemical structures endowed with the property of self-replication have been proposed over the years,<sup>1-3</sup> some of them including nucleotides as basic units.

The analogy with cell replication would be stronger if the self-replicating structure would be closed, i.e., provided with a geometrically defined boundary. It has been proposed recently, in a theoretical paper,<sup>4</sup> that reverse micelles can be good models for such a closed, self-replicating structure.

A reverse micelle is basically a water droplet stabilized in organic solvent by a layer of surfactant. If the reverse micelle hosts guest molecules that by reacting with themselves yield the very surfactant that builds the micelle, we have indeed a situation in which a closed chemical structure is able to replicate itself. Actually, as pointed out in the cited theoretical paper,<sup>4</sup> these are all conditions that correspond to an autopoietic system, according to the definition proposed by Maturana and Varela<sup>5,6</sup> and reviewed by Fleischaker.<sup>7</sup> Autopoiesis is actually an attempt to define the identity of the living, based on a structure defined by a boundary and by a series of interdependent reactions that build the same boundary and components, which then assemble in the structure itself. It is thus a concept that is more general than self-replication (which actually may be seen as a byproduct of autopoiesis). To the best of our knowledge, none of the self-replicating organic structures presented in the literature can be considered as auto-

**Table I.** Changes of the Parameters of the Octanoic Acid Sodium Salt Reverse Micellar System in 9:1 (v/v) Isooctane/1-Octanol during the LiOH-Catalyzed Hydrolysis of Octanoic Acid Octyl Ester

	starting conditns ( <i>t</i> = 0 h)	at half time ( <i>t</i> = 35 h)	at equilibrium ( <i>t</i> = 300 h)
[octanoic acid sodium salt], mM	50	59	68
[octanoic acid octyl ester], <sup>a</sup> mM	25	16	7
<i>w</i> <sub>0</sub>	9.2	7.8	6.8
[M], <sup>b</sup> mM	1.91	2.60	3.03
<i>N</i> <sub>M</sub> <sup>c</sup>	26.1	22.7	22.4
<i>R</i> <sub>w</sub> , <sup>d</sup> Å	12.0	10.7	10.3
<i>R</i> <sub>H</sub> , <sup>e</sup> Å	22.7	<i>f</i>	20.5

<sup>a</sup> As determined by FTIR. Uncertainty ±2%. <sup>b</sup> As determined by fluorescence quenching. Uncertainty ±8%. <sup>c</sup> Number of octanoate molecules per micelle, as calculated from [M]. <sup>d</sup> Calculated from [M]. <sup>e</sup> As determined by quasielastic light scattering. Uncertainty ±2.5%. <sup>f</sup> Not determined.

poietic systems.<sup>4,8</sup> It is the aim of this paper to provide the first experimental evidence of a closed, self-replicating chemical structure, which can be seen as a simple chemical autopoietic system.

The system we used consists of 50 mM octanoic acid sodium salt as surfactant and aqueous LiOH (preferred to NaOH because of its higher water solubility), in 9:1 (v/v) isooctane/1-octanol. The alcohol (which is essential for constituting stable reverse micelles) is actually a cosurfactant, which partitions between the micelle layer and the bulk solvent. Following the method described by Bowcott and Schulman,<sup>9</sup> we could show that 14% of the total 1-octanol, i.e., 90 mM, is localized at the micellar interface. In this reverse micellar system we could solubilize 0.8% (v/v) of aqueous LiOH (2.86 M), which corresponds to a *w*<sub>0</sub> = 9.2 (*w*<sub>0</sub> = [H<sub>2</sub>O]/[octanoic acid salt]) and to 23 mM LiOH (overall concentration).

We have characterized this micellar system at this *w*<sub>0</sub> by quasielastic light scattering,<sup>10</sup> establishing the presence of relatively monodisperse, spherical aggregates having an average radius of 22.7 ± 0.3 Å. This corresponds to a water pool radius *R*<sub>w</sub> of circa 12 Å, taking 10.4 Å for the extended length of one octanoic acid molecule.<sup>11</sup>

The reaction we have utilized is the hydrolysis of octanoic acid octyl ester (typically 25 mM) catalyzed by LiOH. Octanoic acid octyl ester, because of the partly polar character of the ester bond, will also be present at the micellar interface (see Figure 1), although it will be preferentially localized in the bulk solvent.<sup>12</sup> Hydrolysis yields both the surfactant (the octanoic acid salt) and the cosurfactant (1-octanol). Since LiOH is not soluble in the organic phase, it will be localized in the water pool; and therefore the hydrolysis reaction will take place at the micellar interface, i.e., still within the domain of the micelle.<sup>13</sup> Since reverse micelles are highly dynamic entities, which by collision exchange very rapidly the water pool content,<sup>14,15</sup> at any given time, we will have

(8) An inorganic autopoietic system, so-called osmotic growth, has recently been discussed in the literature: Zeleny M.; Klir, G. J.; Hufford, K. D. *Artif. Life* **1988**, 125–139.

(9) Bowcott, J. E.; Schulman, J. H. *Z. Elektrochem.* **1955**, *59*, 283–290.

(10) Quasielastic light scattering experiments were made with a Malvern 4700 PS/MW spectrometer and an argon ion laser (coherent, Innova Model 200-10, λ<sub>0</sub> = 488 nm).

(11) Small, D. M. *Handbook of Lipid Research*; Plenum Press: New York, 1986; Vol. 4, p 67.

(12) Note that the infrared spectrum of the ester in the carbonyl stretching region between 1800 and 1500 cm<sup>-1</sup> is not affected by the reverse micelles, indicating that the ester is localized preferentially in the bulk solvent phase.

(13) This was not so, for example, in the reaction between trimethylamine and cetyl bromide, which leads to the surfactant CTAB (cetyltrimethylammonium bromide) and which was also attempted in CTAB reverse micelles; in this case, due to the unfavorable partition of the reagents, the synthetic reaction takes place mostly in the bulk solvent (Mascolo, G.; Giustini M.; Luisi, P. L.; Lang, J. *J. Colloid Interface Sci.*, in press).

(14) Flechter, P. D. I.; Robinson, B. H. *Ber. Bunsen-Ges. Phys. Chem.* **1981**, *85*, 863–867.

(15) Luisi, P. L.; Giomini, M. P.; Pileni, M. P.; Robinson, B. H. *Biochim. Biophys. Acta* **1988**, *947*, 209–246.

\* To whom correspondence should be addressed.

<sup>†</sup> Institut für Polymere, ETH-Zentrum.

<sup>‡</sup> Institut Charles Sadron (CRM-EAHP), CNRS.

(1) Von Kiedrowski, G. *Angew. Chem.* **1986**, *98*, 932–934.

(2) Zielinski, W. S.; Orgel, L. E. *Nature* **1987**, *327*, 346–347.

(3) Tjivikua, T.; Ballester, P.; Rebek, J., Jr. *J. Am. Chem. Soc.* **1990**, *112*, 1249–1250.

(4) Luisi, P. L.; Varela, F. *Origins Life Evol. Biosphere* **1989**, *19*, 633–643.

(5) Maturana, H.; Varela, F. *Autopoiesis and Cognition: The Realization of the Living*; D. Reidel: Boston, 1980.

(6) Varela, F.; Maturana, H.; Uribe, R. *BioSystems* **1974**, *5*, 187–196.

(7) Fleischaker, G. R. *BioSystems* **1988**, *22*, 37–49.

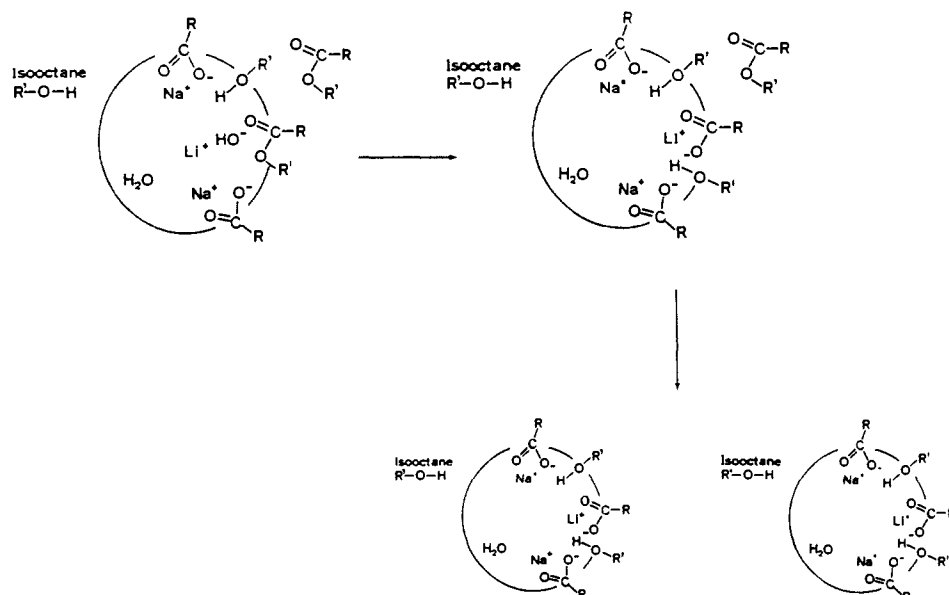


Figure 1. Schematic representation of the reverse micellar reaction system used;  $R = (\text{CH}_2)_6\text{CH}_3$  and  $R' = (\text{CH}_2)_7\text{CH}_3$ .

a homogeneous distribution of all materials among all micelles.

There is no reaction in a control experiment carried out by suspending the same amount of LiOH in the organic mixture without octanoic acid sodium salt, i.e., there is no reaction in the absence of micelles. The situation in the micellar system can therefore be pictured as shown in Figure 1.

The reaction has been monitored by FTIR, by following the decrease of the ester band at  $1744\text{ cm}^{-1}$  and the parallel increase of the band of the octanoic acid sodium salt at  $1570\text{ cm}^{-1}$ .<sup>16</sup>

After ca. 100 h (close to equilibrium), 18 mM "fresh" octanoic acid salt has been produced, with a corresponding increase in the concentration of reverse micelles. Representative kinetic data are reported in Table I.

Since the "newly born" micelles can only be built at the expense of the preexisting ones, the average  $w_0$  value will decrease during time. If for example the surfactant concentration would increase by a factor of 2, the final  $w_0$  would decrease by a factor of 2, leading to a decrease in the water pool radius, the volume of the micelles, and the aggregation number.<sup>4</sup>

We have used the technique of time-resolved fluorescence quenching to directly determine the concentration change of micelles.<sup>17,18</sup> The fluorescent probe 1-pyrenesulfonic acid sodium salt and the quencher sodium iodide are ions localized in the water pool. Since the magnitude of the intramicellar quenching of the probe is proportional to the quencher concentration and inversely proportional to the micelle concentration,<sup>17,18</sup> the method allows the determination of the concentration of the reverse micelles.<sup>19</sup>

Results are given in Table I. It can be seen that the concentration of the micelles  $[M]$  increases by ca. 60%, whereas  $R_w$  decreases by 14%.

The value for the final micellar radius has been determined by quasielastic light scattering, which is also reported in Table I, and found to be in good agreement with that determined by fluorescence.

In conclusion, this work confidently demonstrates that the reverse micellar system presented here is endowed with the property of self-replication. Since the reaction is localized within the boundary of the structure itself, and since the reaction leads to the production of the components of the boundary which in

terms define the identity of the structure, this work also provides the first chemical example of autopoietic organization. The fidelity of self-replication is not perfect, as the dimensions of the micelles become smaller from generation to generation; however, this "single-phase autopoietic cycle" can in principle be amended by a continuous supply of water.<sup>4,20</sup> More generally, micellar systems appear as suitable model systems for autopoiesis; and we are presently pursuing this work with a CTAB-based micellar aqueous system and with a lecithin-based liposomal system.

**Acknowledgment.** We thank Peter Schurtenberger for carrying out the quasielastic light scattering measurements, Francisco Varela, Ulrich Müller-Herold, and Peter Schmidli for helpful discussions, and Claudio Nastruzzi for technical advice.

(20) Note that in ref 4, where the "single-phase" and the "two-phase autopoietic cycle" are theoretically presented, the text of figures 2 and 3 has been mistakenly exchanged.

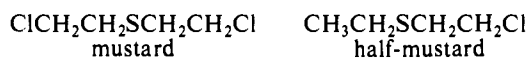
## Rapid Deactivation of Mustard via Microemulsion Technology

F. M. Menger\* and A. R. Elrington

Department of Chemistry, Emory University  
Atlanta, Georgia 30322

Received July 11, 1990

Notable progress in the destruction of nerve agents has been reported by Moss<sup>1</sup> and ourselves.<sup>2</sup> Recently, our attention has turned to another family of loathsome compounds, the mustards. Mustards are environmentally persistent cytotoxic alkylating agents that are manufactured with low technology and are used in chemical warfare.<sup>3</sup> Their detoxification is hampered by an extreme insolubility in the solvent where they are potentially most reactive, water. We have oxidized mustard simulants (e.g., "half-mustard") to nontoxic sulfoxides<sup>3</sup> on a reasonable scale with



(16) Further details about the general principle of the method have been described earlier: Walde, P.; Luisi, P. L. *Biochemistry* **1989**, *28*, 3353-3360.

(17) Lang, J.; Jada, A.; Malliaris, A. *J. Phys. Chem.* **1988**, *92*, 1946-1953.

(18) Verbeeck, A.; De Schryver, F. C. *Langmuir* **1987**, *3*, 494-500.

(19) With this method, the ratio of the concentration of quencher molecules to the concentration of reverse micelles,  $[Q]/[M]$ , is determined. Since  $[Q]$  is known,  $[M]$  can be calculated, and by knowing  $[M]$ , the radius of the micelle water pool,  $R_w$ , can be calculated from simple geometrical considerations by assuming sphericity of the reverse micelles.<sup>19</sup>

(1) Moss, R. A.; Kim, K. Y.; Swarup, S. *J. Am. Chem. Soc.* **1986**, *108*, 788.

(2) Menger, F. M.; Gan, L. H.; Johnson, E.; Durst, H. D. *J. Am. Chem. Soc.* **1987**, *109*, 2800. Menger, F. M.; Tsuno, T. *J. Am. Chem. Soc.* **1989**, *111*, 4903.

(3) Jackson, K. E. *Chem. Rev.* **1934**, *15*, 425.