Polymerized Surfactant Vesicles: Novel Membrane Mimetic Systems

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Summary. Vesicles formed from dialkyl surfactants containing vinyl, methacrylate, diacetylene, isocyano, and styrene groups have been stabilized by polymerization across their bilayers of head groups. Polymerized vesicles have shelf lives of many months and controllable permeabilities and sizes. The kinetics of surfactant vesicle photopolymerization have been determined, and the mechanism of photopolymerization has been discussed as a two-dimensional surface process. Polymerized surfactant vesicles concentrate reagents in their aqueous interiors, in bilayers, and in their inner or outer surfaces. This, in turn, leads to altered reaction rates and sites. Polymerized surfactant vesicles also provide a good media for the generation, in situ, of small, uniform, and efficient colloidal catalysts.

Development of biological membrane–inspired chemistry has become an important discipline (*1, 2*). Molecular organization and compartmentalization in self-assembling surfactants (*3*) and synthetic hosts (*4–7*) are the key concepts in membrane mimetic chemistry. The organization of the substrate can lead to altered solvation, ionization, and reduction potentials, and hence to altered reaction rates, paths, and stereochemistries. These properties are advantageously exploited, in turn, for reactivity control (*8*), catalysis (*9*), transport (*1, 10*), recognition (*1, 11*), drug delivery (*12–14*), and artificial photosynthesis (*15–18*). Faithful modeling of the biomembrane is not an objective of membrane mimetic chemistry (*19*). Rather, essential components of natural systems are recreated by chemists, mostly from man-made molecules, for predetermined utilitarian purposes. Likewise, "obtaining a better understanding" is not a consideration, the insight gained into the functioning of real membranes being only an added bonus.

Attention in this article is focused on the latest and most sophisticated membrane mimetic system, polymerized surfactant vesicles (*20*). Their properties, along with those of their nonpolymerized counterparts are briefly surveyed. Comparisons are made to liposomes (*21*) and polymer membranes. Emphasis is placed on current uses in reactivity control and catalyst stabilization.

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Synthetic Surfactant Vesicles: A Chemical Approach

Vesicles have been formed from synthetic surfactants containing one, two, or three alkyl chains (hydrocarbons or fluorocarbons) and quaternary ammonium, carboxylate, sulfate, sulfonate, hydroxide, or phosphate zwitterionic or functionalized head groups (*1, 22–26*). Unilamellar vesicles are readily formed at temperatures above the gel-to-liquid transition (the phase transition) temperatures during the ultrasonic dispersal of surfactants in water (*1, 22*). Alternatively, vesicles can be formed by the controlled injection of an alcoholic surfactant solution through a small-bore syringe into thermostated water, by detergent dialysis, or by a removal of the organic solvent under reduced pressure from water-in-oil surfactant microemulsions (*1, 27*). Surfactant vesicles, like liposomes, can entrap and retain large molecules in their interiors, are osmotically active (they shrink in hyperosmolar solutions and swell in hypo-osmolar solutions), and undergo fusion and temperature-induced phase transitions (*1*). Surfactant vesicles have been characterized by standard techniques (*1, 22, 23*). Their weight-averaged molecular weights and hydrodynamic diameters (D_H) have been determined by static and dynamic light scattering, respectively. These determinations have been verified by electron microscopy (*26, 28*), by gel filtration and by ultrafiltration. Internal volumes of surfactant vesicles have been determined by entrapments of ^{14}C-labeled glucose (*29*). Absorption, fluorescence, and magnetic resonance spectroscopy have been used extensively for obtaining information on the structural and dynamic behavior of vesicles (*1*). Unilamellar vesicles prepared from charged surfactants are larger (diameters typically 1000 to 1500 angstroms) than liposomes (*22*), obtained from zwitterionic phospholipids (diameters typically 200 to 400 angstroms).

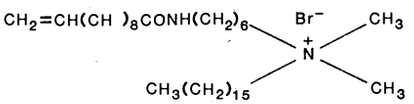
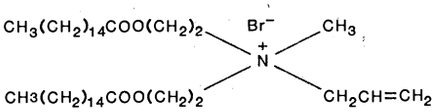
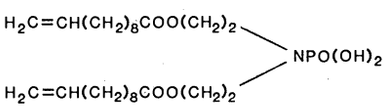
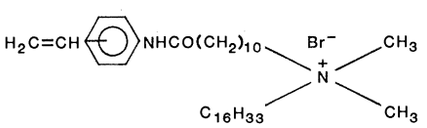
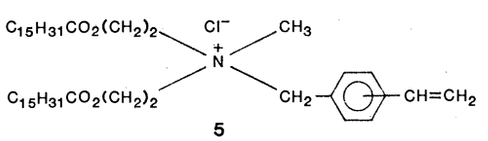
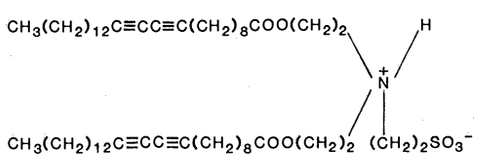
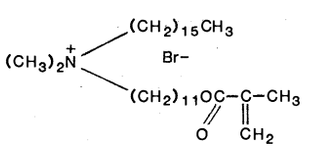
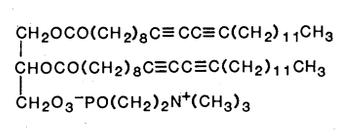
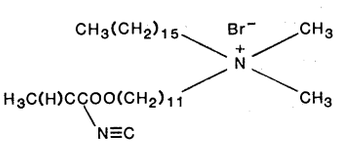
Liposomes have been developed (*30*) and investigated by physiologists, cell biologists, and biochemists. In contrast, surfactant vesicles have been characterized and utilized by chemists (*22, 23*) prompted by the synthetic, structural, and intellectual challenge. What are the minimum and optimal requirements for vesicle formation? Can theory predict these parameters? What is the best theory for predicting surfactant self-association into vesicles? How did membranes evolve? Why are phospholipids the major components of biomembranes? Could membranes have evolved from synthetic surfactants such as dialkylammonium halides? The versatility of surfactant vesicles has provided convenient means for designing experiments to answer these questions. From the chemist's point of view, vesicles prepared from pure synthetic surfactants are more amenable to modification than are liposomes prepared from lipids of biological origin. Development of polymerized vesicles (*31–33*) illustrates a productive interplay of organic, polymer, and colloid chemistries.

Polymerized Surfactant Vesicles

The need for increased stabilities and for controllable permeabilities and sizes led to the syntheses of polymerized surfactant vesicles (*31–33*). Vesicle-forming surfactants functionalized with vinyl, methacrylate, diacetylene, isocyano, and styrene groups (*34–52*) have been synthetized (Table 1). Polymerizable double bonds in these surfactants are located at the end of the hydrocarbon tail of the surfactant or at their head groups. Subsequent to vesicle formation, irradiation by ultraviolet (UV) light, gamma rays, or exposure to an initiator [azobisisobutyronitrile (AIBN) potassium persulfate, for example] resulted in the loss of the polymerizable double bonds (*22, 23*). Depending on the position of the double bonds, vesicles could be polymerized across either their bilayers or their head groups (Fig. 1). It is not known how surfactants link up in vesicle bilayers. Polymerization may be limited to separate halves of the bilayers or it

may result in cross-linking them. More intriguing is the possibility of "zipping-up" separately the inner or outer surfaces of surfactant vesicles having their polymerizable double bonds in their head groups (Fig. 1). This possibility has been realized for vesicles prepared from surfactant **2** (Table 1) (*34*). Irradiation by light resulted in the complete loss of vinyl protons [monitored by Fourier-transform proton magnetic resonance (^{1}H NMR) spectroscopy]. In contrast, external addition of an initiator to sonicated **2** vesicles caused only 60 percent loss of the vinyl protons (Fig. 2). This

Table I. Typical polymerized surfactant vesicles.

Surfactant	Polymerization method	Characterization	Results, conclusions	Reference
 **1**	UV irradiation or exposure to AIBN (60°C) of sonicated dispersions.	^{1}H, ^{13}C NMR, absorption and fluorescence spectroscopy, dynamic light scattering, gel filtration.	Increasing sonication times results in the formation of smaller and less polydisperse vesicles; size of vesicles is retained upon polymerization; vesicles containing double bonds in their head groups can be selectively polymerized.	(*34, 51*)
 **2**				
 **3**				
 **4**				
 **5**				
 **6**	Irradiation of sonicated dispersions.	Absorption spectroscopy, differential scanning calorimetry, electron microscopy.	ATP synthetase incorporated into monomeric and polymeric vesicles by incubation; enzyme is reactivated in vesicles; polymerization enhances enzymatic activity; there are "monomeric domains" in enzyme-containing polymeric vesicles.	(*52*)
 **7**	Sonicated surfactant heated with AIBN (6 hours, 80°C).	Electron microscopy, ^{1}H NMR, [^{14}C]glucose entrapment, stability to ethanol.	Closed polymerized vesicles retained entrapped glucose and remained stable in 25 percent ethanol.	(*38*)
 **8**	Sonicated and ether-injected surfactants irradiated by UV light.	Calorimetry, absorption spectrophotometry.	Large unilamellar and multilamellar vesicles polymerized below phase transition temperature but not above; small unilamellar vesicles did not polymerize at any temperature.	(*43*)
 **9**	Surfactant mixed (Vortex) with nickel capronate and kept at 30°C for 12 hours.	^{1}H NMR, IR, UV spectroscopy, electron microscopy.	Two halves of the bilayer cross-links on polymerization. Polymerized vesicles show increased stabilities.	(*50*)

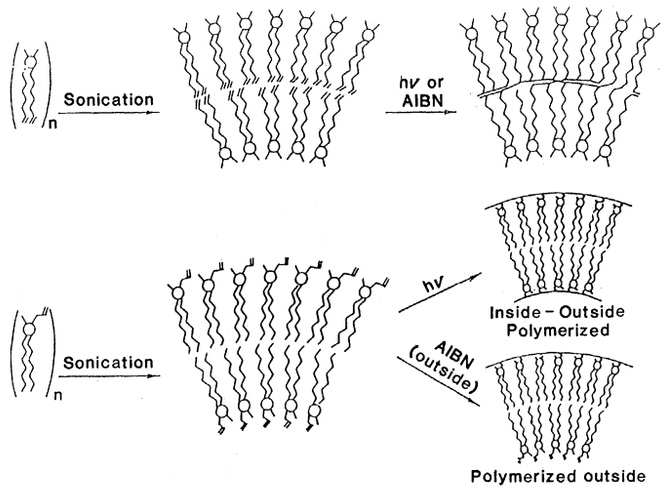
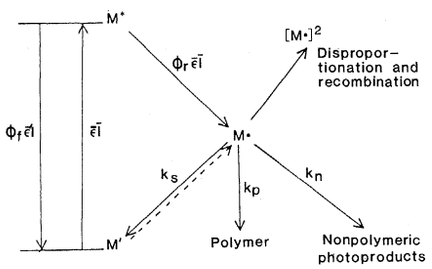


Fig. 1. Schematic representation of vesicle polymerization in the bilayer or at the outer and or inner surfaces.

corresponded to cross-linking only the external surfaces of **2** vesicles (*34*).

Kinetics of photopolymerization of vesicles prepared from a styrene-containing surfactant (**5**) has been investigated in detail (*51*). The molecular weight and hydrodynamic radius of these vesicles are 1.0×10^8 (Fig. 3) and 750 Å, respectively (*51, 53*). Photolysis of argon-bubbled vesicular solutions of **5** by 15-nanosecond bursts of 266 nanometer laser pulses led to the first-order disappearance of styrene absorbances (Fig. 4). Polymerization rates for vesicular **5** were independent of the vesicle concentration but were linearly dependent on the applied laser energy (Fig. 4). In contrast, rates in ethanol depended on the concentration of monomeric **5**. This observation and the fact that sizes of vesicles remained unaltered on polymerization supported the proposed intravesicular surface polymerization. Photopolymerization has been treated as shown in Eq. 1 (*51*) where the styrene free



radical, $M\cdot$, is assumed to form via the excited state (M^*) of the monomer M; Φ_f and Φ_r are quantum efficiencies for nonproductive excited state depletion and $M\cdot$ formation, respectively; $\bar{\epsilon}$ is the average molecular extinction coefficient, and $\bar{I}$ is the average intensity of exciting photons. Several possible fates await the free radical. Most interestingly, it can link successively to other monomers and thus propagate a polymer chain (a process governed by rate constant k_p). $M\cdot$ may also be deactivated and return to the ground state ("suicide," by k_s) or react with oxygen, impurity, and the wall of the vessel (by k_n), or undergo radical disproportionations and recombinations to restore a styrene double bond and partially maintain chain propagation by conserving a free radical. This negligible term is represented by $[M\cdot]^2$. Considering photopolymerization on a per vesicle basis rather than on a concentration or unit volume basis leads to differential equations 2 and 3

$$\frac{dM}{dt} = (\Phi_f - 1)\bar{\epsilon}\bar{I}M + k_s M\cdot - k_p w(t) M\cdot + f[M\cdot]^2 \quad (2)$$

$$\frac{dM\cdot}{dt} = \bar{\epsilon}\bar{I}\Phi_r M - (k_n + k_s)M\cdot - (1 - f)[M\cdot]^2 \quad (3)$$

where $M(t)$ and $M\cdot(t)$ are the number of double bond–containing monomers remaining and free radicals present at time t; f is the fraction of free radicals involved in combinations and disproportionations that restore double-bonded monomers; and $w(t)$ indicates the average number of nearest monomeric neighbors of M at time t. Propagation, $k_p w(t) M\cdot$, present only in Eq. 2, does not affect the $M\cdot$ population, represented in Eq. 3, because the free radical is conserved with each successful polymerization link. The term k_n does not appear in the equation for M (see Eq. 2), as the photoproduct formation does not restore any M.

Experimental data showed the completion of laser photopolymerization of **5** vesicles within the time domain of 1 millisecond to 2 seconds (*51*). Vesicle solutions are restored, therefore, to a new equilibrium of monomers, polymers, and photoproducts before the arrival of the next laser pulse at a repetition rate of 2 hertz. Since the energy is applied in successive, essentially equal, increments, the most useful way of expressing the data is in the form of a graph of monomer concentration plotted against total energy deposited [that is, number of equal energy laser pulses, $M(n)$]. Simplifying and solving Eqs. 2 and 3 led (*51*) to

$$M(n) = M_0(1 - \eta)^n \quad (4)$$

and

$$\frac{dM(n)}{dn} = \ln(1 - \eta)M(n) \quad (5)$$

where M_0 is number of nonpolymerized surfactant molecules in **5** vesicles [$M_0 = 1.4 \times 10^5$ (*51*)] and η is defined as the fraction of the double-bonded monomers consumed after the photochemical events induced by a single laser pulse have subsided.

$$\eta = \frac{\Phi_r \bar{\epsilon} E k_p}{k_n + k_s} \quad (6)$$

where E is the average energy per centimeter squared of the laser pulse. The good linearity of the plots of absorbance versus laser intensity (Fig. 4) justifies the assumptions involved in deriving Eq. 5. The average chain length, $k_p/(k_n + k_s)$ is related to η by

$$\frac{k_p}{k_n + k_s} = \frac{\eta}{\Phi_r \bar{\epsilon} E} \quad (7)$$

Substituting appropriate experimental values into Eq. 7 resulted in a value of 23 for the average chain length obtained in the laser photopolymerization of **5** vesicles. Formation of polymers of relatively low molecular weight is in accord with the observed fluidities of polymerized vesicles (*33*). Attempts are under way in several laboratories to control the extent of vesicle polymerizations and hence permeabilities. Extending the kinetic investigations to vesicles prepared from mixtures of polymerizable and nonpolymerizable surfactants will provide information on lateral surfactant mobilities and domain formation. These are highly relevant to membrane biophysics. Intravesicular polymerization bridges the gap between bulk and surface (solid-state) polymerizations.

Polymerized surfactant vesicles are appreciably more stable than their nonpolymerized counterparts. They have shelf lives of several months, remain stable in up to 20 percent alcohol, and have controllable sizes and permeabilities (*32, 33*). Increasing the sonication time results in smaller and more uniform vesicles. Vesicle sizes are retained after polymerization. Thus, it is possible to prepare stable polymerized vesicles with mean hydrodynamic radii ranging from 250 to 2500 Å (*37*). Furthermore, small polymerized vesicles, 300 Å in diameter,

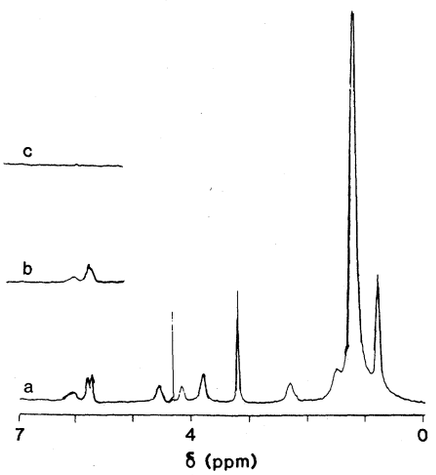


Fig. 2. ^{1}H NMR spectra of vesicles prepared from surfactant **2** (0.01 mg of **2** per 1.00 milliliter of D_2O) sonicated for 7 minutes at 70°C and 70 W (a). The insets show the vinyl signals following polymerization by addition of AIBN to the already formed vesicles (b) and by exposure to UV radiation from a 450-W xenon lamp for 10 hours (c); 50,000 scans on the 200-megahertz instrument of the totally polymerized specimen (by UV irradiation).

prepared from mixtures of dipalmitoylphosphatidylcholine and **4** (DPPC:**4**) retain their sizes for months, while their nonpolymerized counterparts undergo spontaneous growth to vesicles 700 Å in diameter (*53*, *54*). A likely mechanism for preventing the growth of polymerized vesicles is the preclusion of reversed micelle formation. Vesicle fusion is envisaged to proceed via the formation of intermediate reversed micelles (*55*, *56*), thus disrupting the bilayer structure of the collided vesicles (Fig. 5). The role of reversed micelles is to create regions of instability that subsequently provide aqueous channels between the merging vesicles. Changes in vesicle curvature are compensated by the flip-flop of surfactants from the outer to the inner layer of the vesicles. Polymerization prevents the surfactant reorganization necessary for reversed micelle formation and flip-flop. Alteration of the phase transition behavior of DPPC:**4** vesicles upon polymerization cannot be excluded. In any event, one important consequence of these experiments is that mechanisms of fusion can be probed by the use of polymerized vesicles (*54*).

Reactivity Control in Vesicles and Polymerized Vesicles

A distinct feature of surfactant vesicles is their ability to incorporate a large number of reactive molecules per aggregate. The simplest way of treating bimolecular reactions in vesicles is based on the partitioning model (*1*, *9*, *57–60*). Reaction between A and B are considered to occur in bulk water and in the environments of vesicles

$$(A + B)_w \xrightarrow{k_w} \text{products} \quad (8)$$

$$(A + B)_m \xrightarrow{k_m} \text{products} \quad (9)$$

where the subscripts w and m refer to bulk water and to the pseudophase associated with the vesicles (the membrane mimetic agents). The overall rate of reaction is given by

$$R_{total} = k_m[A]_m[B]_m[S]\bar{V} + k_w[A]_w[B]_w(1 - [S]\bar{V}) \quad (10)$$

where $[S]$ and $\bar{V}$ are the concentration and molar volumes of the surfactants in the vesicles. Concentrations of the reagents are given by:

$$[A]_{total} = [A]_m[S]\bar{V} + [A]_w(1 - [S]\bar{V}) \quad (11)$$

$$[B]_{total} = [B]_m[S]\bar{V} + [B]_w(1 - [S]\bar{V}) \quad (12)$$

If reactions 8 and 9 do not alter the partition equilibria

$$[A]_w \rightleftharpoons [A]_m \quad (13)$$

$$[B]_w \rightleftharpoons [B]_m \quad (14)$$

and if both A and B appreciably bind to the vesicles then the observed second-order rate constant (k_2) for the hydrolysis of *p*-nitrophenyl laurate (PNPL) in the presence of vesicles is expressed by (*9*, *61–63*)

$$k_2 = \frac{(k_m/\bar{V})K_AK_B[S] + k_w}{(1 + K_A[S]\bar{V})(1 + k_B[S])} \quad (15)$$

where K_A and K_B are association constants for the interaction of A and B with the vesicles. Rearrangement of Eq. 15 to Eq. 16 allows the graphical treatment of the dependence of k_2 on vesicle concentrations.

$$\frac{[S]}{k_2 - k_w} = x + y[S]\frac{k_2}{k_2 - k_w} + z[S]^2\frac{k_2}{k_2 - k_w} \quad (16)$$

where

$$x = \frac{\bar{V}}{k_mK_AK_B} \quad (17)$$

$$y = K_A + K_B \quad (18)$$

$$z = xK_AK_B \quad (19)$$

Values obtained from the intercepts (x) on plotting the left side of Eq. 16 against $[S]^2k_2/(k_2 - k_w)$ are used for further analysis of the data by Eq. 20

$$\left(\frac{1}{k_2} - \frac{x}{[S]}\right)\left(1 - \frac{k_w}{k_2}\right) = y + z[S] \quad (20)$$

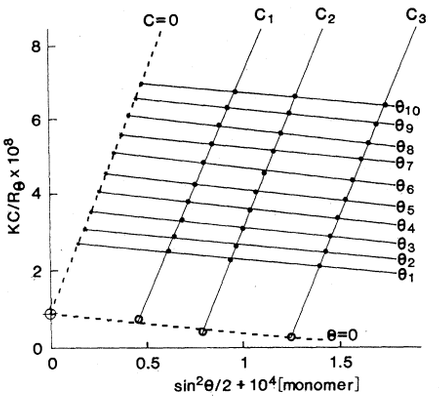


Fig. 3. Zimm plot for the determination of the weight-averaged molecular weight of vesicles prepared from **2** (D_H = 1500 Å from dynamic light scattering). $C_1 = 4.76 \times 10^{-5}$ gram per milliliter or $6.33 \times 10^{-5}M$; $C_2 = 7.893 \times 10^{-5}$ g/ml or $1.05 \times 10^{-4}M$; and $C_3 = 1.25 \times 10^{-4}$ g/ml or $1.67 \times 10^{-4}M$; $\theta_1 = 45°$; $\theta_2 = 50°$; $\theta_3 = 55°$; $\theta_4 = 60°$; $\theta_5 = 65°$; $\theta_6 = 70°$; $\theta_7 = 75°$; $\theta_8 = 80°$; $\theta_9 = 85°$; and $\theta_{10} = 90°$. Molecular weight, $1.1561 \times 10^8 \pm 6$ percent.

which, in turn, allows the assessment of K_A, K_B, and k_m. Equations 16 to 20 have been successfully used for treating the reactions of sodium ascorbate with a stable free radical (*61*), the hydrolyses of 5,5′-dithiobis(2-nitrobenzoic) acid (*62*), and PNPL (*63*). The behavior of the reaction with PNPL was quite different in nonpolymerized vesicles from that in polymerized vesicles prepared from **5** (Fig. 6). The substrate, PNPL, associates appreciably more with nonpolymerized than with polymerized vesicles (*63*). Binding constants obtained from the kinetic treatment of the hydrolyses, agreed well with those determined independently from solubility and *p*H measurements (Table 2). Values obtained for k_m do not differ substantially from k_w values. Most of the enhancements or retardations of the vesicular rate result, therefore, from concentrating the reagents in the pseudophase of vesicles (*9*).

The partitioning model (governed by Eqs. 8 to 20) is a gross oversimplification. It does not provide for more than one substrate interaction site. Reactants, depending on their sizes, hydrophobicities, and charges, can be organized in a number of different compartments offered by the vesicles. Hydrophobic compounds are generally distributed in the bilayers. Polar molecules, particularly those repelled electrostatically from the vesicle surface, move relatively freely in the inner aqueous pools. Ionic reactants whose charges are opposite to those of the vesicle-constituting surfactants are attracted to the inner or outer surfaces of the aggregates. Similarly charged polar molecules can be

Table 2. Association constants (K_{PNPL} and K_{OH^-}) for the interactions of *p*-nitrophenyl laurate and hydroxide ion, respectively, with nonpolymerized and polymerized **5** vesicles [taken from (*63*)]. Kinetic treatment values were obtained from Eqs. 16 to 20.

Interactions	Association constant (M^{-1})	
	From kinetic treatment	From solubility and *p*H measurements
K_{PNPL}		
Nonpolymerized vesicles	1.3×10^4	1.1×10^4
Polymerized vesicles	5.4×10^3	4.8×10^3
K_{OH^-}		
Nonpolymerized vesicles	1.8×10^3	2.7×10^3
Polymerized vesicles	3.6×10^3	2.4×10^3

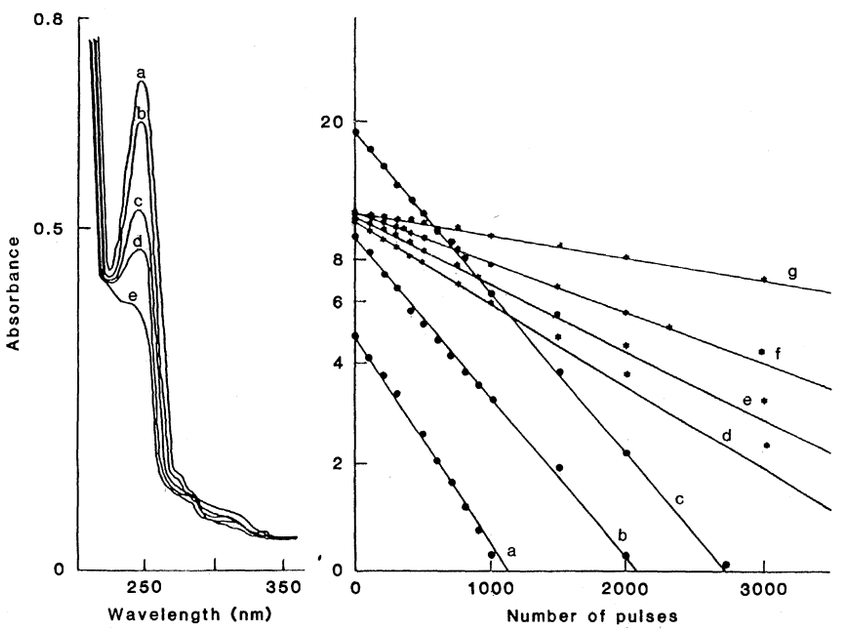


Fig. 4. (Left) Absorption spectra of vesicles [$1.4 \times 10^{-4}M$ surfactant **2** (D_H = 1400 Å from dynamic light scattering)] prepared before (a) and after irradiation by 140 (b), 600 (c), 1000 (d), and 3000 (e) millijoules of laser power. (Right) Log absorbances at 250 nanometers for vesicles prepared from **2** plotted against the number of laser pulses at 1 millijoule per pulse, unless stated otherwise. (a) $7.0 \times 10^{-6}M$; (b) $1.4 \times 10^{-5}M$; (c) $1.4 \times 10^{-4}M$; (d) $1.4 \times 10^{-4}M$ at 0.60 mJ per pulse; (e) $1.4 \times 10^{-4}M$ at 0.50 mJ per pulse; and (f) $1.4 \times 10^{-4}M$ at 0.15 mJ per pulse.

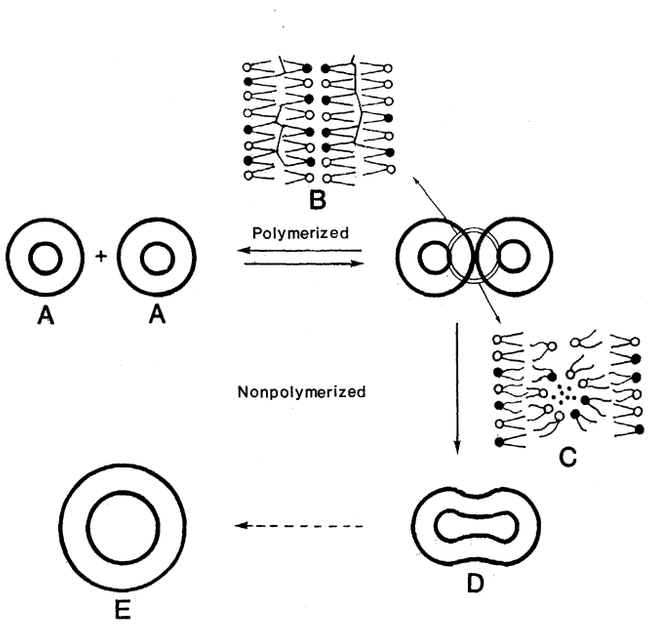


Fig. 5. Schematics of the proposed interactions of nonpolymerized and polymerized DPPC:**4** vesicles. Both nonpolymerized and polymerized vesicles (A) undergo numerous collisions. Formation of intermediary reversed micelles (C) disrupts the bilayer of nonpolymerized vesicles, which leads to their fusion (D). After many such collisions, vesicles increase their sizes to about 700 Å (E). In contrast, polymerization of **4** in DPPC:**4** vesicles precludes reversed micelle formation (B), and hence the collision is nonproductive.

anchored onto the vesicle surfaces by long hydrocarbon tails. In addition, reactants may move from one location to another at times comparable to those required for the reaction to occur, or slower. Furthermore, the position in the vesicles of the reactants, the transition state, and the product formed in the reaction may all be different. Such spatial relocation of molecules as they progress along their reaction coordinates can be exploited in catalyses and product separations. A type of catalyst-containing functional polymerized vesicle can be visualized in which the reactant would enter the vesicle and undergo reaction within the vesicle, and the product would be expelled into the bulk solution. Advantage has been taken of the different dynamic reaction sites for fine-tuning the reactivities for different systems (*63–70*).

Moss and his co-workers (*66–70*) have been concerned with reactions occurring in the interior (endovesicular), the exterior (exovesicular), and across the bilayer (transvesicular) of vesicles. Reaction rates, under appropriate conditions, can be controlled by the transit of one of the reagents across the bilayer. An example is the oxidation of vesicle-entrapped 2-nitro-5-thiolatobenzoate (Ellman's anion) by exovesicular *o*-iodosobenzoate ion (*68*).

Vesicle polymerization provides additional avenues by altering reactivity sites. Aminolysis of PNPL, added to already formed **5** and polymerized **5** vesicles by ethylene diamine (EDA) resulted in biphasic kinetics that were resolved into a fast (k_f) and a slow (k_s) component (*63*). Increasing EDA concentrations increased both k_f and k_s. This rate increment was two orders of magnitude more effective for nonpolymerized than for polymerized vesicles. In nonpolymerized vesicles, 90 percent of the PNPL reacted with EDA. Although only 50 percent of PNPL could be converted to products in polymerized **5** vesicles, the kinetics were still governed by two consecutive (k_f and k_s) first-order steps. These results could be accommodated only by assuming the existence of reaction sites additional to endo- and exovesicular locations and by assuming that PNPL distributes itself differently in nonpolymerized and polymerized vesicles (*63*). A similar situation has been encountered in the dithionite ion cleavage of 5,5′-dithiobis(2-nitrobenzoic acid), Ellman's reagent, in dihexadecyl dimethylammonium bromide vesicles (*69*). The relative contributions of the fast and slow components of the reaction varied as a function of elapsed time (46

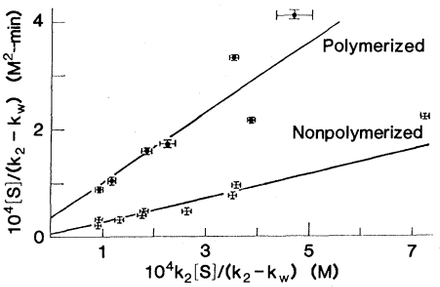


Fig. 6. Kinetic treatment hydrolysis of PNPL in nonpolymerized and polymerized vesicles as given in Eq. 16.

milliseconds to 1 to 5 seconds) between the addition of Ellman's reagent and the dithionite ion. These results were explained in terms of the time required for distribution of the substrate between the vesicle surface (k_f) and subsurface (k_s) (*69*). Distinct exovesicular reactions have provided a means (*35, 71, 72*), additional to direct synthesis (*73*) for preparing chemically dissymmetrical surfactant vesicles.

Catalyst Stabilization and Utilization in Polymerized Vesicles

Compartmentalization provides an unequaled method for forming small, uniform, and efficient colloidal catalysts. The size of the catalyst is quite simply restricted by the size of the compartment and by the amount of the precursor placed in it. Initial work has been carried out in water-in-oil microemulsions (*74–78*). Particularly noteworthy had been the formation of monodisperse platinum, palladium, rhodium, and iridium particles, 30 to 50 Å in diameter, which could be transferred to solid support without agglomeration (*75*). Liquid-phase hydrogenation of 1-hexane and 2-hexane has been reported to be effectively catalyzed by 30-Å colloidal platinum particles confined in pentaethylene glycol dodecyl ether (PEGDE)–entrapped water pools, in hexadecane (*74*). Colloidal gold, silver, platinum, cadmium sulfide, and platinized cadmium sulfide have been generated in Aerosol-OT-reversed micelles by the photolysis in situ of the appropriate ions (*78–80*). In all cases, smaller and more uniform colloidal particles have been formed in reversed micelles than in water. The mechanism of colloidal gold formation in PEGDE microemulsion has been investigated by pulse radiolysis and laser flash photolysis (*78*). Under the experimental conditions, each microemulsion contained approximately eight Au^{3+} ions, which led to the formation of $(Au^0)_n$ particles through the exchange of the contents of neighboring microemulsions. Growth is ultimately limited by statistical considerations (*78*).

Since the contents of surfactant vesicles do not exchange in the absence of fusion (*1*), sizes of colloidal particles generated in situ are functions of only the concentration of their parent ions and the efficiency of their formation. Stable, uniformly small, colloidal platinum colloids have been prepared in situ in the interiors of vesicles prepared from DPPC:**4** (*81*). Platinum ions were entrapped by cosonicating K_2PtCl_4 with the surfactants. Vesicle-entrapped ions were separated from those in the bulk or attached to the outer surface (or both) by passages through ion-exchange resins and gels. Irradiation of K_2PtCl_4-containing vesicles resulted in colloidal platinum and concomitant polymerization of **4** in the matrix of DPPC:**4** vesicles. Polymerized vesicle–entrapped colloidal platinum remained stable for several months (*81*). In contrast, photogenerated colloidal platinum in the absence of added stabilizers precipitated in 2 to 3 days (*82*).

The catalytic efficiency of polymerized vesicle–entrapped colloidal platinum shown by the reduction, by hydrogen bubbling, of methylene blue (MB) and 10-methyl-5-deazaisoalloxazine-3-propane-sulfonic acid (dF), localized in the vesicle bylayers (*80*). No reduction of MB or dF occurred in the absence of colloidal platinum either in vesicles or in water. Reduced DPPC:**4**-entrapped MB or dF could be reoxidized by the addition of $FeCl_3$. Additional hydrogen caused the reduction of the reoxidized species, which could be reverted to their reduced state by adding more $FeCl_3$. The process could be repeated several times (*81*). Apparently, polymerized vesicle–entrapped colloidal platinum can catalyze the hydrogen gas–mediated reduction of extravesicular compounds via vesicle-embedded electron or hydrogen carriers, or both (Fig. 7). Polymerized vesicle–entrapped colloidal platinum also catalyzes alkene hydrogenations (*83*).

Crystalline Ag_2O (*84*), AgCl (*85*), CoS (*86*), and Fe_3O_4 (*87*) particles have also been prepared in compartments provided by microemulsions and liposomes. These studies are related to nucleations and open the door to controlled crystal formation.

Other Applications and Prospects

Within a short time, characterization and utilization of polymerized surfactant vesicles have become significant areas of research. In addition to the applications discussed in this article, polymerized vesicles are used for photochemical solar energy conversion (*80, 88*), for drug delivery (*31, 33, 38–40*), and for obtaining information on lipid-lipid and lipid-protein interactions in biological membranes (*89–91*). Extension of the polymerization concept to other organized surfactant aggregates (*32*) has led to polymerized monolayers (*92–96*), multilayers (*97–99*), and bilayer lipid (black) membranes (*100, 101*). These in turn, find applications in the development of polymeric multilayers for submicron electron beam microlithography used in very large scale integrated microcircuits (*102–105*). Polymerized multilayers can be used to prepare thinner (30 to 1000 Å), stronger and more uniform films that provide high resolution and contrast. Similar principles can be utilized for the preparation of very thin uniform polymer membranes with controllable permeabilities to be used in ultrafiltration, reversed osmosis, and membrane reactors (*106, 107*). Additional applications will surely be developed.

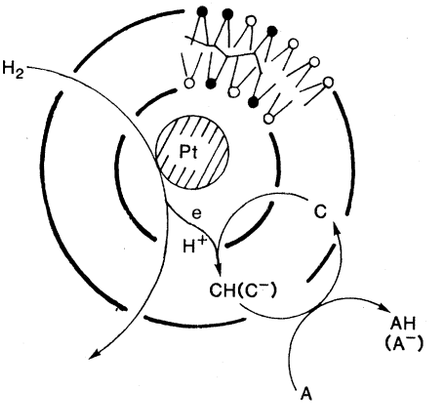


Fig. 7. Use of polymerized vesicle–entrapped colloidal platinum in catalysis. Electron (*e*) or hydrogen carriers, or both, distributed in vehicle bilayers mediate the colloidal platinum–catalyzed reduction of extravesicular molecules by hydrogen bubbling. *C* and *CH* (or C^-) are the oxidized and reduced forms of the electron or hydrogen carrier (or both); *A* and *AH* or (A^-) are the oxidized and reduced forms of the electron hydrogen acceptor (or both); and *Pt* is the polymerized vesicle–entrapped colloidal platinum catalyst.

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3. Aqueous and reversed micelles, microemulsions, monolayers, organized multilayers, bilayer or black lipid membranes (BLM's), and bilayer vesicles are considered to constitute organized associated surfactants (*1, 2*).
4. Synthetic molecular hosts or cavitands include crown ethers or chorands, cryptands, and spherands (*5, 6*). In addition, cyclodextrins (*7*) can be considered to be naturally occurring synthetic hosts.
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19. A subtle but important difference is made between modeling and mimicking. Modeling (diminutive of Latin *modus*, form) implies a more or less faithful duplication of the original in a scaled-down version, whereas mimicking suggests only the imitation of the essential features (Greek *mimetikos*, imitative, from *mimeisthai*, to imitate).
20. The term "polymerized" surfactant vesicle is preferred to "polymeric" surfactant vesicle since the former is believed to convey that polymerization is subsequent to aggregate formation.
21. The term "vesicles" is used to describe spherical or ellipsoidal, single or multicompartmented, closed, bilayer structures, regardless of their chemical compositions. Vesicles composed of naturally occurring or synthetic phospholipids are referred to as liposomes. In contrast, those formed from completely synthetic surfactants are designated as surfactant vesicles.
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108. I thank my co-workers, whose names appear in the references listed, for their enthusiastic, dedicated, and skillful work. The National Science Foundation, Department of Energy, Army Research Office, and Petroleum Research Foundation provided financial support for different aspects of our researches.