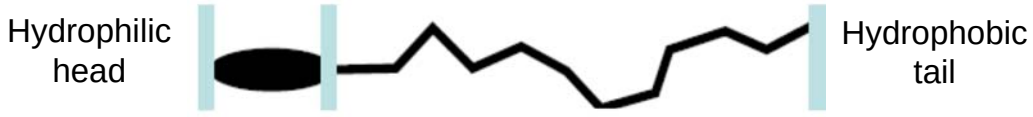
Surfactants and Interfacial Phenomena

ESS5855 Lecture

Fall 2011

Surfactant Structures

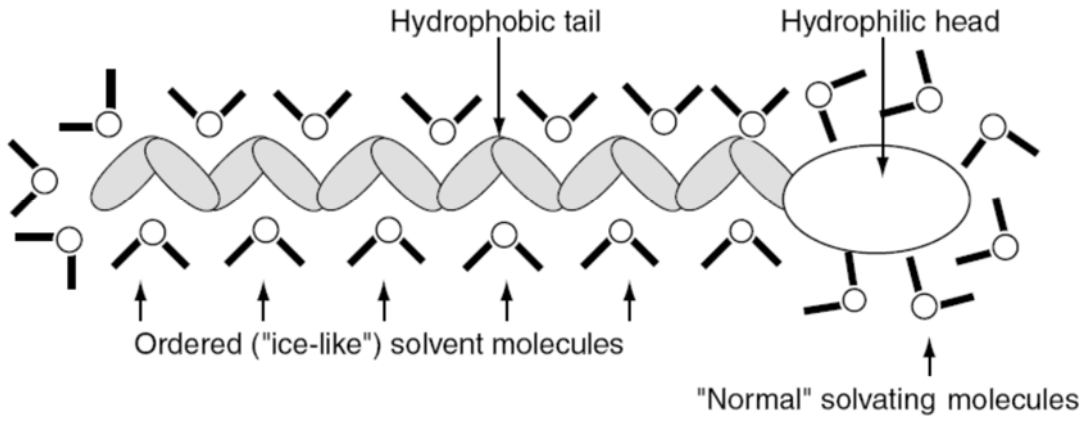
- Surfactants possess a characteristic chemical structure that consists of
  - Molecular components that will have little attraction for one surrounding (i.e., the solvent) phase, normally called the lyophobic group
  - Chemical units that have a strong attraction for that phase – the lyophilic group



The basic molecular structure of a surfactant includes the hydrophobic (or lyophobic) group having little attraction for water (or the solvent) and the hydrophilic (or lyophilic) group having strong interactions with water (or the solvent)

Characteristics

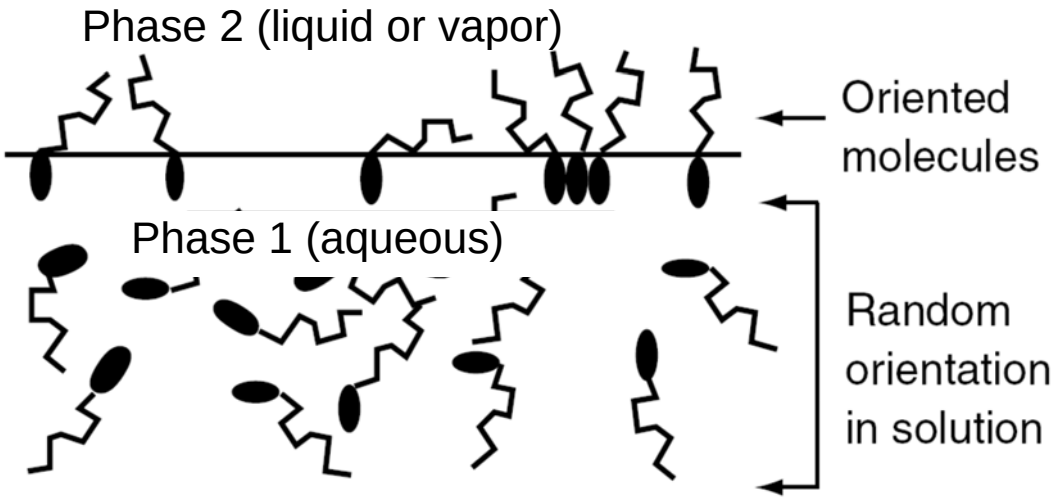
- Surfactants are generally referred to as being amphiphilic (“liking both”), indicating that they have some affinity for both two essentially immiscible phases
- When a surfactant is dissolved in a solvent, the presence of the lyophobic group causes an unfavorable distortion of the liquid structure, increasing the overall free energy of the system
- In an aqueous surfactant solution, for example, such a distortion (in this case ordering) of the water structure by the hydrophobic group decreases the overall entropy of the system
- That entropy is regained when surfactant molecules are transported to an interface and the associated water molecules released



For a surfactant molecule in water, the hydrophobic tail will be “solvated” with an ice-like structure of associated solvent molecules. The hydrophilic head will be solvated in the usual way.

Characteristics

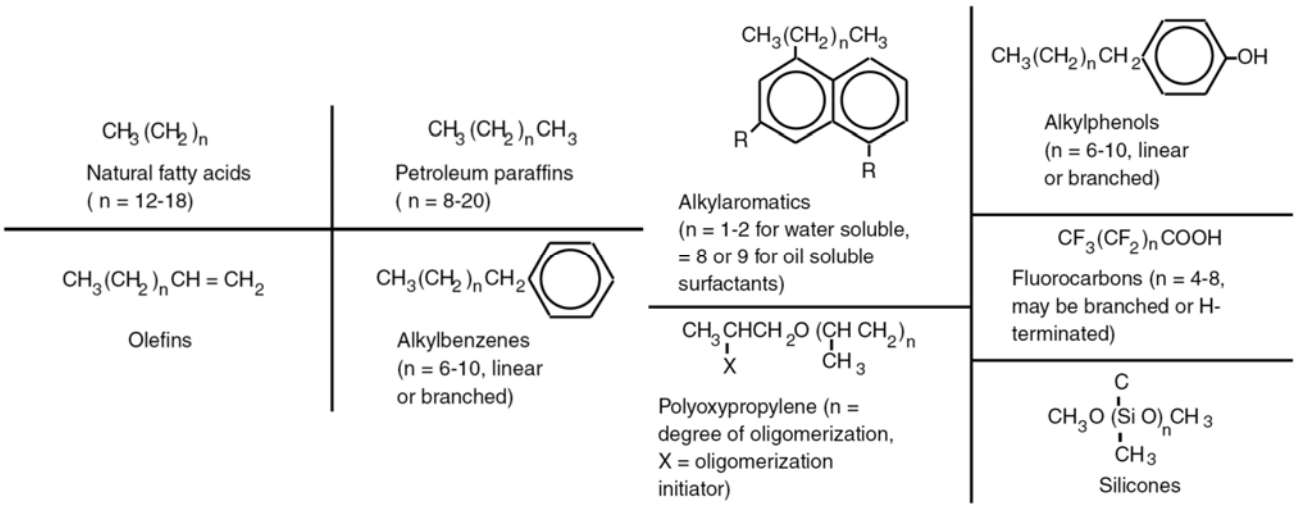
- The surfactant will therefore preferentially adsorb at interfaces, or it may undergo some other process to lower the energy of the system (e.g., micelle formation)
- Since less work is required to bring surfactant molecules to an interface relative to solvent molecules, the presence of the surfactant decreases the work required to increase the interfacial area resulting in a decrease in interfacial tension



When adsorption occurs at the interface, the adsorbed molecules will have a preferred orientation that tends to minimize unfavorable interactions between the aqueous phase and the surfactant molecular sections.

Characteristics

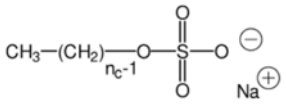
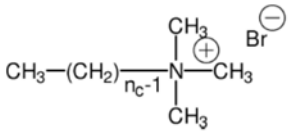
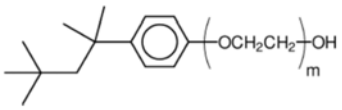
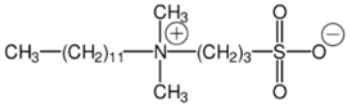
- The chemical structures having suitable solubility properties for surfactants vary with the nature of the solvent system to be employed and the conditions of use
- In water, the hydrophobic tail may be, for example, a hydrocarbon, fluorocarbon, or siloxane chain of sufficient length to produce the desired solubility characteristics when bound to a suitable hydrophilic head
- The hydrophilic head will be ionic or highly polar, so that it can act as a solubilizing functionality
- In a non-polar solvent such as hexane the same groups may function in the opposite sense



The most commonly encountered hydrophobic materials used in the commercial manufacture of surfactants.

Classification

- Anionic, with the hydrophilic group carrying a negative charge such as carboxyl ($RCOO^-M^+$), sulfonate ($RSO_3^-M^+$), or sulfate ($ROSO_3^-M^+$)
- Cationic, with the hydrophile bearing a positive charge, as for example, the quaternary ammonium halides ($R_4N^+X^-$)
- Nonionic, where the hydrophile has no charge but derives its water solubility from highly polar groups such as polyoxyethylene ($-OCH_2CH_2O-$), sugars or similar groups
- Amphoteric (and zwitterionic), in which the molecule has, or can have, a negative and a positive charge on the principal chain (as opposed to a counterion, M^+or X^-) such as the sulfobetaines, $RN^+(CH_3)_2CH_2CH_2SO_3^-$

Surfactant		CMC
Anionic		
Sodium alkylsulfate	$n_C = 8$, sodium octylsulfate	139
	$n_C = 10$, sodium decylsulfate	34
	$n_C = 11$, sodium undecylsulfate	17
	$n_C = 12$, sodium dodecylsulfate (SDS)	8.9
Cationic		
Alkyltrimethylammonium bromide	$n_C = 10$, decyl trimethylammonium bromide	66
	$n_C = 12$, dodecyl trimethylammonium bromide	15
	$n_C = 14$, tetradecyl trimethylammonium bromide (TTAB)	3.5
	$n_C = 16$, hexadecyl trimethylammonium bromide (CTAB)	0.9
Nonionic		
Poly(ethylene oxide) *iso*-octylphenyl ether	$m = 7, 8$, Triton$^{(R)}$ X-114	0.20
	$m = 10$, Triton$^{(R)}$ X-100	0.24
	$m = 40$, Triton$^{(R)}$ X-405	0.81
Zwitterionic		
Alkyldimethylpropanesultaine	N-dodecyl-N,N-dimethyl propanesultaine	
		

Insoluble Monolayer Films

- A dilute solution is prepared from an aliphatic solvent and an organic solute RX in which R is a long-chain alkyl group and X is a polar group
- A small amount of this solution is placed on a large volume of water with a horizontal surface
- The components of this system were chosen because they are assumed to meet the criteria:
  - The solubility in water of both components of the organic phase is negligible at room temperature
  - The likelihood of any complex being formed between the organic solvent and solute is low
  - The volatility of the organic solvent is high and that of the solute is low

Insoluble Monolayer Films

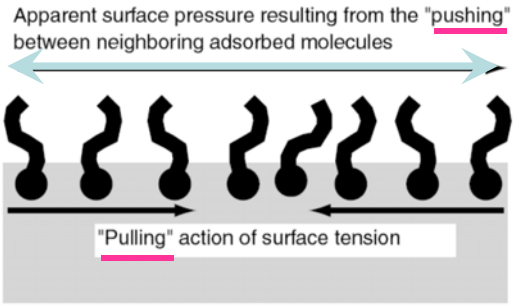
- After spreading, allow sufficient time to elapse for all the solvent to evaporate from the spread layer
- At this point the surface will contain a layer of the organic solute similar to that which would result from the spreading of a sessile drop of pure liquid solute or from the adsorption of vapors of the solute component from the gas phase
- Using a solution with a volatile solvent to form such a layer is a very common technique and has the advantage of permitting very small amounts of solute to be quantitatively deposited on a surface

Properties

equilibrium film pressure. $\pi = \gamma_0 - \gamma$

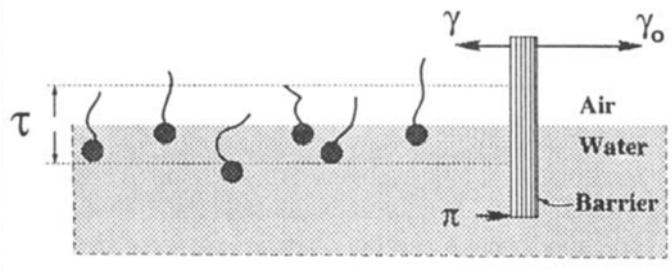
where γ_0 refers to the surface tension of any phase in the absence of an adsorbed layer, and γ refers to the tension of the same surface with an adsorbed layer.

If the barrier represents the limit of the monolayer, then it is clear that the contractile force exerted by the surface is different on opposite sides of the barrier. Since γ is less than γ_0, it is as if the film were exerting a force on the barrier along the perimeter of the film equal to π. Force per unit length—the units of γ—is the two-dimensional equivalent of force per unit area, the units of pressure in the bulk.



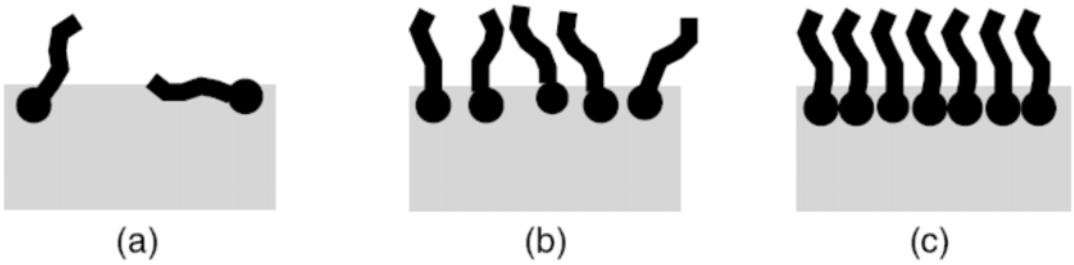
The surface layer does not have zero thickness, of course, even though it is conceptually convenient to think of it as two-dimensional matter. If we assume that the film pressure π extends over the entire thickness of the film, then it is an easy problem to convert the two-dimensional pressure to its three-dimensional equivalent. Taking 10 mN m^{-1} as a typical value for π and 1.0 nm as a typical value for τ enables us to write

$$p = \frac{\pi}{\tau} = \frac{10^{-2}\ \mathrm{N\ m^{-1}}}{10^{-9}\ \mathrm{m}} = 10^{7}\ \mathrm{N\ m^{-2}} \approx 100\ \mathrm{atm}$$

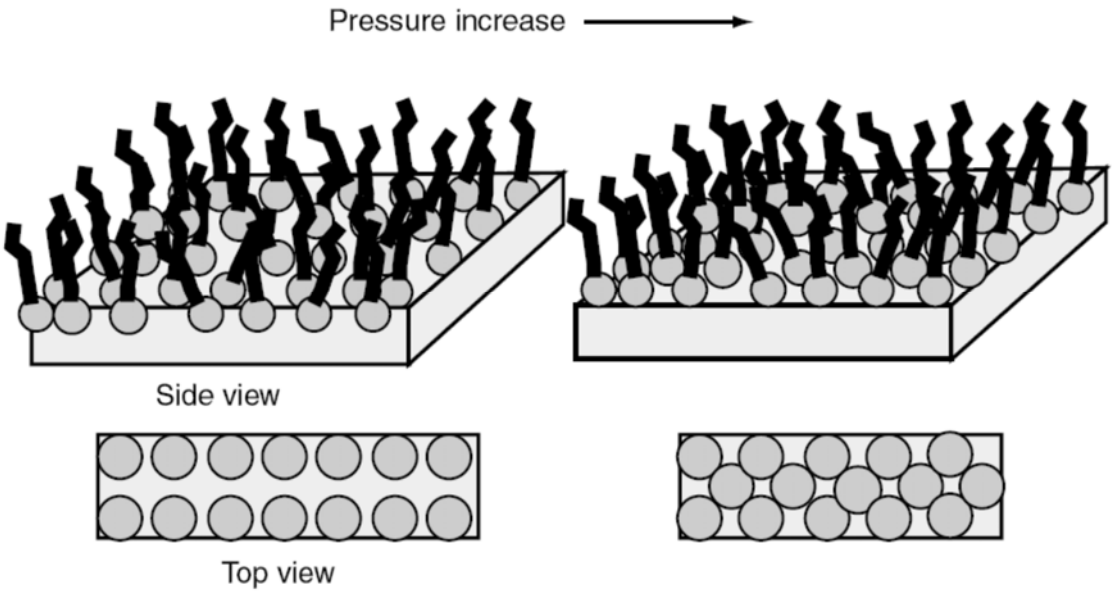


Physical States

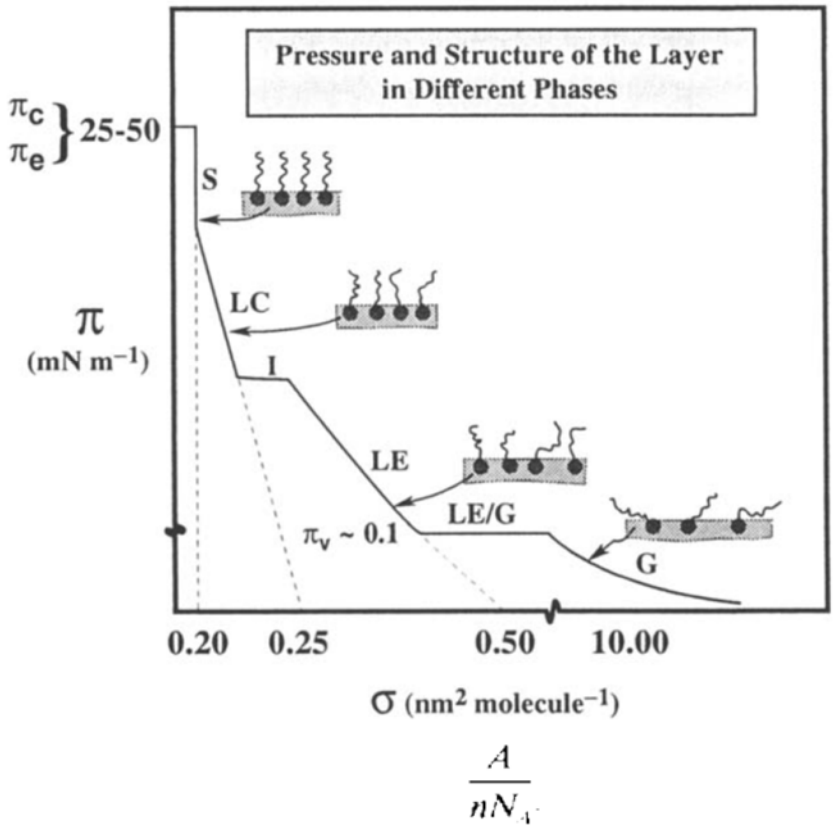
- Condensed films, which are coherent, rigid (essentially incompressible), and densely packed, with high surface viscosity. The molecules have little mobility and are oriented perpendicular (or almost so) to the surface
- Expanded films, roughly equivalent to the liquid state, in which the monolayer is still coherent and relatively densely packed but is much more compressible than condensed films. Molecular orientation is approximately perpendicular to the surface, but the tails are less rigidly packed
- Gaseous films, in which the molecules are relatively far apart and have significant surface mobility. The molecules act essentially independently, much as a bulk phase gas and molecular orientation will be random



Molecules in a monomolecular film are usually considered to exist in one of three principle “states.” (*a*) The gaseous state is that in which the molecules are relatively far apart and have little mutual interaction; the film is compressible. (*b*) The liquid expanded state is that in which the head groups are relatively closely packed, but there is significant degree of tail mobility; the film is compressible to a limited extent. (*c*) The condensed state in which the molecules are closely packed and have very limited mobility; the film is essentially incompressible.

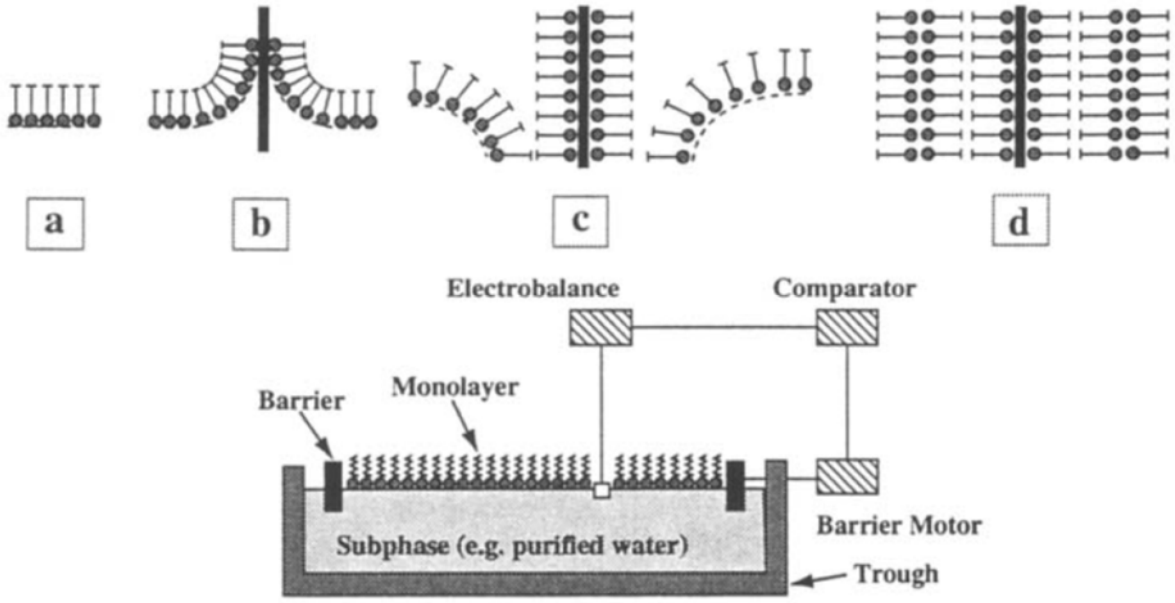


As pressure is applied to a condensed film, the adsorbed molecules can rearrange to a small extent by a change in packing structure (e.g., cubic to hexagonal). Beyond that point added pressure will result in film ‘‘buckling.’’

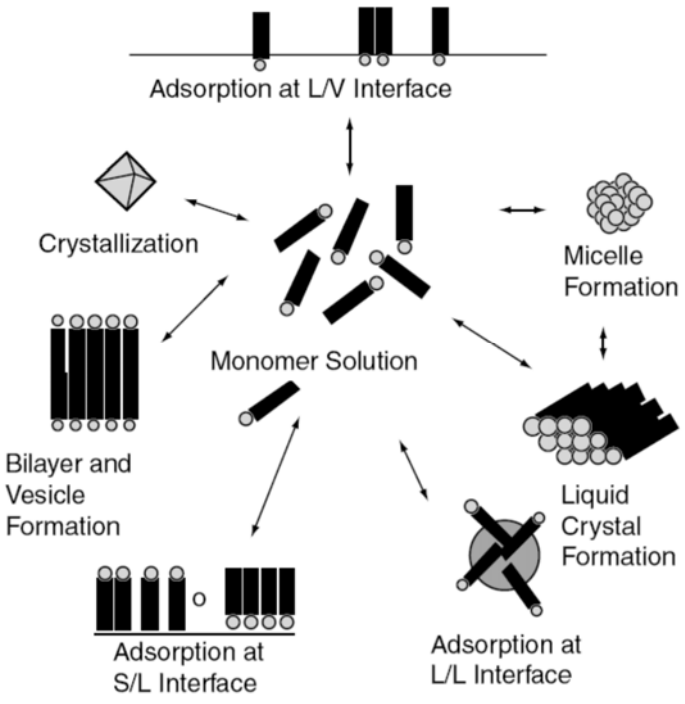


$$\frac{A}{nN_A}$$

Film Deposition



Self-Assembled Colloids

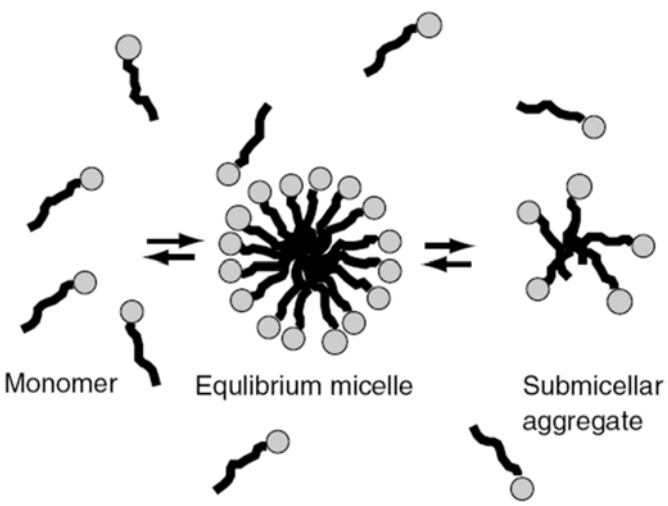


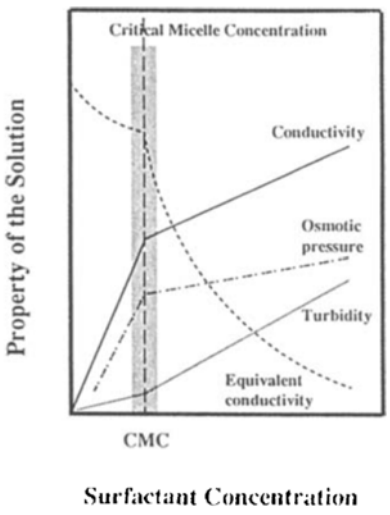
A surfactant in solution has various options in terms of its surface activity.
Depending on the system composition, surfactants can (and usually do) “play the field,” completing various functions at the same time.
Usually, the multi-role playing is advantageous, although there are situations in which such flexibility can be counterproductive.
For that reason, surfactant selection can be an important decision in many applications.

Micelles

- Structurally resembles the solid crystal or a crystalline hydrate
- Thermodynamically, the formation of micelles favors an increase in solubility
- Micelles will be the predominant form of surfactant present above a critical surfactant concentration: the critical micelle concentration (cmc)
- The total solubility of the surfactant will depend not only on the solubility of the monomeric material but also on the solubility of micelles

The threshold concentration at which micellization begins is known as the critical micelle concentration. Below the breaks in the curves in the figure, anionic surfactants behave as expected for strong electrolytes; above the CMC, however, the behavior observed is consistent with the presence of particles in the colloidal size range.





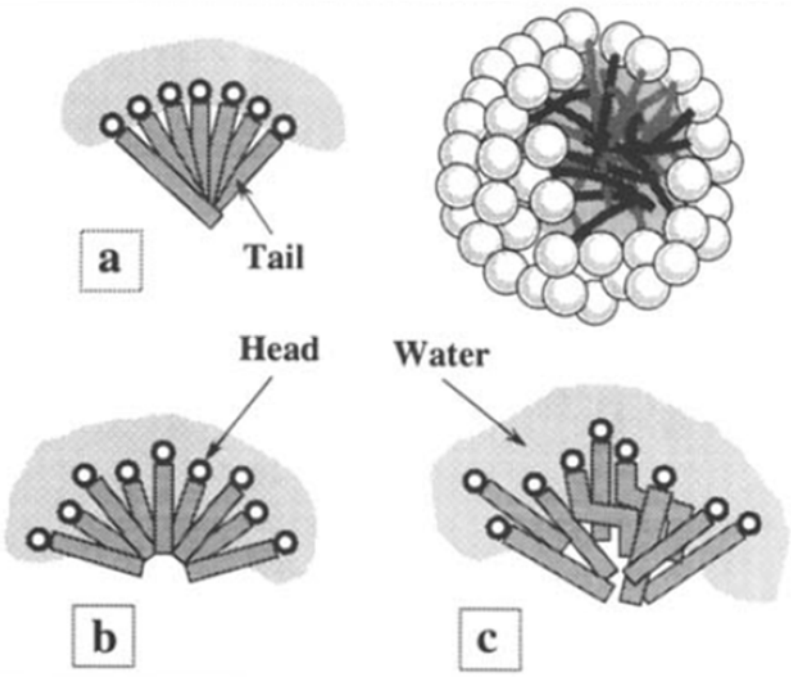
Structures

1. The central core is predominantly hydrocarbon. The expulsion of the hydrophobic tails of the surfactant molecules from the polar medium is an important driving force behind micellization. The amphipathic molecules aggregate with their hydrocarbon tails pointing together toward the center of the sphere and their polar heads in the water at its surface. For the surfactant this mode of organization competes with monolayer adsorption, which it somewhat resembles.

2. In ionic micelles the hydrocarbon core is surrounded by a shell that more nearly resembles a concentrated electrolyte solution. This consists of ionic surfactant heads and bound counterions in a region called the *Stern layer* (see Chapter 11, Section 11.8). Water is also present in this region, both as free molecules and as water of hydration.

3. In typical nonionic micelles the shell surrounding the hydrocarbon core also resembles a concentrated aqueous solution, this time a solution of polyoxyethylene. The ether oxygens in these chains are heavily hydrated, and the chains are jumbled into coils to the extent that their length and hydration allow.

4. Beyond the Stern layer, the remaining z counterions exist in solution. These ions experience two kinds of force: an electrostatic attraction drawing them toward the micelle and thermal jostling, which tends to disperse them. The equilibrium resultant of these opposing forces is a diffuse ion atmosphere, the second half of a double layer of charge at the surface of the colloid. Chapter 11 provides a more detailed look at the diffuse part of the double layer.



A schematic representation of the structure of an aqueous micelle. Three possibilities are illustrated: (a) tails overlap at the center; (b) water penetrates core; and (c) chain protrusion and bending correct deficiencies of (a) and (b).

Example 8.2 *Calculating the Geometric Parameters of the Core of a Micelle.* Calculate the radius, volume, and surface area of the core of a micelle formed by the aggregation of dodecyl groups. The fully extended chain has a zigzag structure with angles of 109.5°, and the carbon-carbon bond length is 0.154 nm. The van der Waals radius of the terminal methyl group equals 0.21 nm, and 0.06 nm may be taken as half the length of the bond to the polar head.

Solution: The radius of the spherical core equals the length of the fully extended hydrocarbon tail (see Example 8.3 below). The 12 carbon atoms are connected by 11 bonds, each of length 0.154 nm. What must be added together, however, are the projections of these bond lengths along the direction of the chain. The distance between every other carbon in the fully extended chain—the base of a triangle opposite the tetrahedral angle—is given by the law of cosines:

$$a = (b^2 + c^2 - 2bc\cos\theta)^{1/2} = [(2)(0.154)^2(1 - \cos 109.5°)]^{1/2} = 0.252\ \text{nm}$$

Half of this is the projection of each bond along the chain length; the sum of these projections is (11)(0.252/2) = 1.39 nm. Adding the contributions of the two ends to this gives the radius of the sphere: 1.39 + 0.21 + 0.06 = 1.66 nm. (Compare this with the length obtained from Equation (4) for a chain with 12 carbon atoms.)

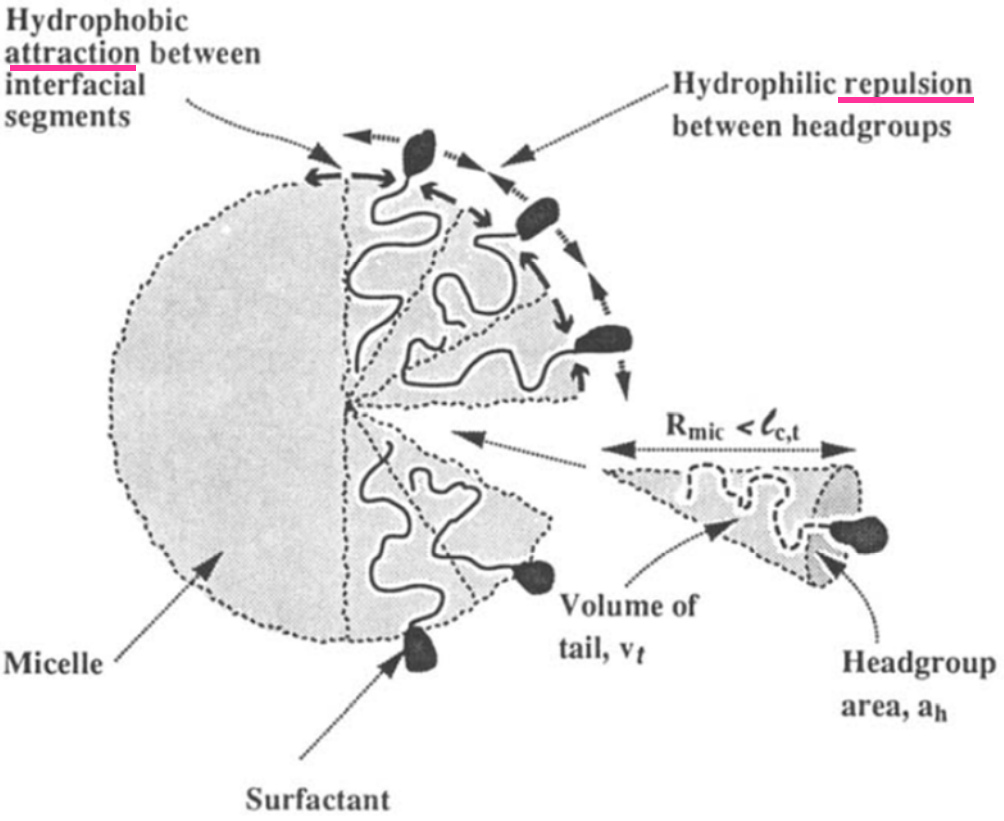
The volume and surface area of the core are now readily calculated:

$$V = (4/3)\pi(1.66)^3 = 19.1\ \text{nm}^3, \quad \text{and}$$
$$A = 4\pi(1.66)^2 = 34.5\ \text{nm}^2$$

■

8.4 MOLECULAR ARCHITECTURE OF SURFACTANTS, PACKING CONSIDERATIONS, AND SHAPES OF MICELLES

Although one expects the *details* of the molecular architecture of a surfactant molecule to play a prominent role in the shapes and structures of association colloids the surfactant forms in solution, a remarkably useful picture of the shapes of the resulting aggregates can be obtained using packing considerations based on some of the crude, general geometric features of the surfactant. This is somewhat analogous to the simple van der Waals picture of gas-liquid phase transition in atomic and molecular fluids in which one uses two parameters (one for the "size" or "excluded-volume" effects of repulsion and another for attraction) to deduce the general features of phase transition. In the case of surfactant solutions, one can predict with a reasonable accuracy the shapes of the association colloids resulting from self-assembly using three effective geometric parameters of the surfactant: (a) the optimal head group area a_h, (b) the volume v_t of the tail, and (c) the critical chain length $l_{c,t}$ of the tail (see Fig. 8.5).



8.4a Optimal Head Group Area

The surface area a taken up by the head group of each surfactant molecule on the surface of a micelle depends on a number of factors, some of which tend to increase the area per head group while others tend to decrease it. This idea of two mutually opposing forces, suggested by Tanford (1980), refers to (a) an attractive force caused by the hydrophobic attraction of the hydrocarbon chain units at the hydrocarbon-water interface, and (b) a repulsive force between adjacent head groups arising from hydrophilic, steric, and ionic (in the case of charged head groups) repulsion. These opposing forces together determine the *optimal* area occupied by the head group, as illustrated in Figure 8.5.

The hydrophobic attraction is due to the preference of the hydrocarbon units near the surface to be close to its counterparts in the adjacent surfactant molecule. This attraction tends to decrease the effective area occupied by the head group. The attractive free energy contribution arising from this force is proportional to a and can be written as γa, where γ is about 20–50 mJ m^{-2}. The repulsive force mentioned in the previous paragraph is more complex and is not well understood presently. We know that this repulsion is caused by the tendency of the hydrophilic head groups to allow as many water molecules as possible in their neighborhood and by simple steric forces. Moreover, additional contributions to this repulsion may also come from electrostatic repulsion if the head groups carry charges. Although exact quantitative details of the repulsion are hard to formulate, the magnitude of the repulsion is expected to vary inversely with area a. The repulsion, of course, tends to increase the effective area occupied by each head group.

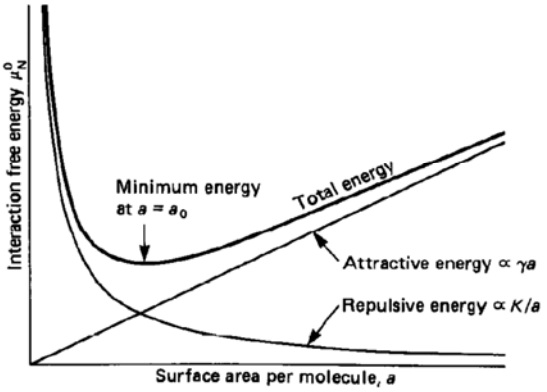
The total contribution to the interfacial free energy G may therefore be written as

$$G = \gamma a + (K/a) \tag{2}$$

where K is a constant that can be eliminated by writing it in terms of the optimal head group area a_h i.e., the area that minimizes G (i.e., $\partial G/\partial a = 0$ at $a = a_h$). The minimization of G in Equation (2) implies that $K = \gamma a_h^2$, and the value of G at the minimum is therefore $2\gamma a_h$. One can now rewrite Equation (2) in terms of a_h as

$$G = 2\gamma a_h + (\gamma/a_h)(a - a_h)^2 + \text{term of the order of } (a - a_h)^3 \tag{3}$$

using Taylor's series expansion (see Appendix A). Equation (3) allows us to express G in terms of two measurable parameters. Although the above equations are approximate, they represent the interactions among the surfactants to a first approximation and illustrate the meaning of *optimal* in the term *optimal head group area*. The above arguments can be refined further to account for specific head group interactions (e.g., ionic interactions), effects of curvature, and so on, but these are not important for our purpose here.



8.4b Volume and Critical Chain Length of the Hydrocarbon Tail

We saw in Section 8.3b.2 that the core of the micelle is essentially a hydrocarbon liquid, and we may assume this to be incompressible. This in essence defines the *volume* v_l of the hydrocarbon tail of the surfactant in the core; that is, v_l is simply the volume of the hydrocarbon liquid per hydrocarbon molecule. The critical chain length $\ell_{c,l}$ of the tail is the effective length of the hydrocarbon chain in the liquid state. This length sets a rough upper limit on the effective length of the chain, i.e., large extensions beyond this limit may prevent the collection of hydrocarbon chains from being considered a liquid. The chain length thus defined is a semiempirical parameter, although it is expected to be of the same order as the length of the fully extended hydrocarbon molecule ℓ_{max}. Following arguments similar to Example 8.2, Tanford (1980) has given the following expressions for $\ell_{c,l}$ (and v_l) for saturated hydrocarbon chains of n carbon atoms:

$$\ell_{c,l} \leq \ell_{max} = (0.154 + 0.1265\, n)\ \text{nm} \tag{4}$$

and

$$v_l = (27.4 + 26.9n) \cdot 10^{-3}\ \text{nm}^3 \tag{5}$$

Since both expressions are linear in n, for large values of n (in fact, even for n larger than 5), the ratio $(v_l/\ell_{c,l})$ approaches 0.21 nm^2, which defines the minimum cross-sectional area a hydrocarbon can have.

Once the estimates for a_h, v_l, and $\ell_{c,l}$ are available, one can determine the preferred shapes of the surfactant aggregates using geometric packing considerations, as discussed in the following subsection and illustrated in Example 8.3.

8.4c Packing Considerations and Shapes of Aggregates

The basic packing considerations that restrict the shape of an aggregate are rather straightforward and simply serve to reconcile the volume-to-surface-area ratio of an aggregate of any shape to the requirements imposed by the optimal head group area and the liquidlike structure of the core. The optimal head group area determines the number of surfactants that can be accommodated in an aggregate of any specified shape and, therefore, the volume of the corresponding hydrocarbon tails. The packing considerations demand that the shape and the size of the core of the aggregate for the volume of the tails thus obtained be such that the aggregate has a *liquidlike* hydrocarbon core. For instance, for a spherical micelle to have a liquidlike core, the ratio $(R_s/\ell_{c,t})$, where R_s is the radius of the micelle, has to be less than or equal to unity. For larger R_s, the chains will extend further or will have more space than needed for a liquidlike core. This implies that the volume-to-surface-area ratio of the micelle specified by the radius R_s must be consistent with the ratio of the volume of the chain of the surfactant in question to its optimal head group area; otherwise, aggregation into a spherical micelle is not possible for the given surfactant (see Example 8.3).

These considerations imply that a dimensionless group, known as the *packing parameter* $\mathcal{P}$ given by

$$\mathcal{P} = v_t/(a_h\ell_{c,t}) \tag{6}$$

can be defined and used as an indicator of the shapes one can expect for the aggregate. We illustrate this using the example below and consider subsequently what this implies for predicting and controlling the aggregate shapes using variables such as pH, electrolyte concentration, and the like.

Example 8.3 *Packing Parameter for Spherical Micelles.* Show that the packing parameter $\mathcal{P}$ of a surfactant has to be less than 1/3 for it to form spherical micelles.

Solution: For a spherical micelle of radius R_s and aggregation number n_a, one has

$$n_a = [(4/3)\pi R_s^3]/v_t = 4\pi R_s^2/a_h$$

This implies that

$$(v_t/a_h) = (R_s/3)$$

that is,

$$\mathcal{P} = v_t/(a_h\ell_{c,t}) = (R_s/\ell_{c,t})(1/3)$$

Since R_s has to be less than or equal to $\ell_{c,t}$ for the core of the micelle to be liquidlike, $\mathcal{P}$ has to be less than or equal to 1/3 for the micelle to be spherical. ■

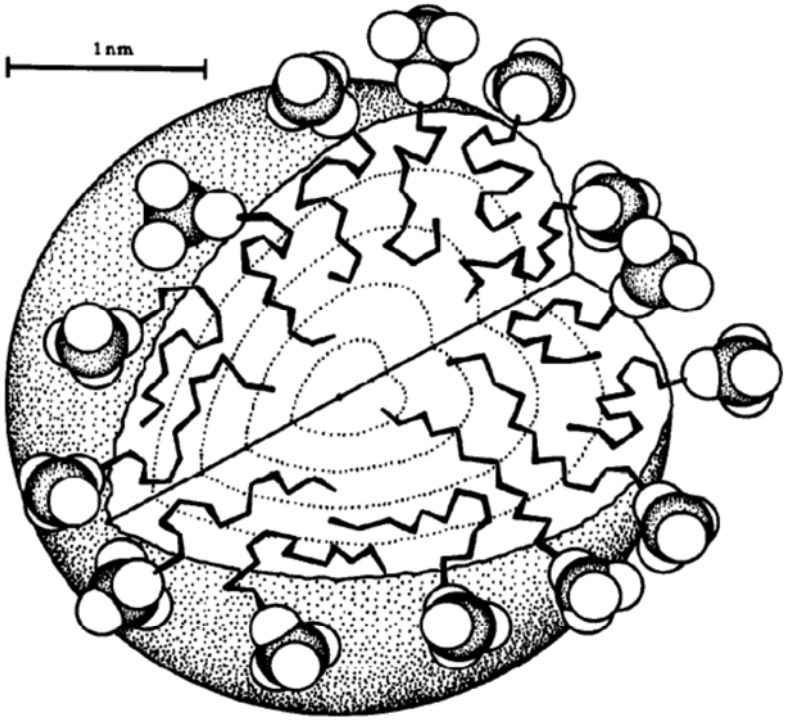
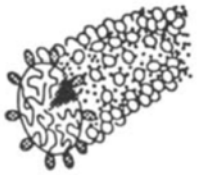
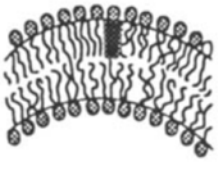


Fig. 17.3. A sodium dodecylsulphate (SDS) micelle drawn to scale. The micelle contains 60 sodium dodecylsulphate molecules. The hydrocarbon chains pack at liquid hydrocarbon density in the core where they are almost as disordered as in the bulk liquid state. Each of the five spherical shells contains approximately the correct number of chain segments to ensure even chain packing density throughout. Note that all segments of the chain spend an appreciable proportion of time near the micelle surface. Thus, even though the core is almost completely devoid of water each segment samples the hydrophilic environment. Drawing based on calculations by Gruen (1981) and Gruen and de Lacey (1984).

TABLE 8.2 Packing Parameter and Its Relation to Shapes of Aggregates

Lipid	Critical packing parameter	Critical packing shape	Structures formed
Single-chained lipids (surfactants) with large head group areas: SDS in low salt	< 1/3	Cone 	Spherical micelles 
Single-chained lipids with small head group areas: SDS and CTAB in high salt, nonionic lipids	1/3–1/2	Truncated cone 	Cylindrical micelles 
Double-chained lipids with large head group areas, fluid chains: phosphatidyl choline (lecithin), phosphatidyl serine, phosphatidyl glycerol, phosphatidyl inositol, phosphatidic acid, sphingomyelin, DGDG,[a] dihexadecyl phosphate, dialkyl dimethyl ammonium salts	1/2–1	Truncated cone 	Flexible bilayers, vesicles 

Double-chained lipids with small head group areas, anionic lipids in high salt, saturated frozen chains: phosphatidyl ethanolamine phosphatidyl serine + Ca^{2+}	~1	Cylinder	Planar bilayers
Double-chained lipids with small head group areas, nonionic lipids, poly (cis) unsaturated chains, high T: unsaturated phosphatidyl ethanolamine, cardiolipin + Ca^{2+} phosphatidic acid + Ca^{2+} cholesterol, MGDG[b]	>1	Inverted truncated cone or wedge	Inverted micelles

Source: Adapted with permission from Israelachvili 1991.
[a]DGDG: digalactosyl diglyceride, diglucosyl diglyceride.
[b]MGDG: monogalactosyl diglyceride, monoglucosyl diglyceride.

8.11 BIOLOGICAL MEMBRANES

We have already noted in connection with Figure 7.7 that a monolayer may collapse into a bilayer that leaves the surfactant in a tail-to-tail configuration. This is exactly the arrangement of molecules in the lipid portion of a cell membrane. Protein molecules are arrayed in or on this lipid bilayer. Vignette 1.2 presented in Chapter 1 discusses this briefly. More details may be found in Bergethon and Simons (1990) and Goodsell (1993).

Figure 8.15 is a sketch of one possible relationship between the lipid bilayer and the membrane proteins. Molecules are free to move laterally in these membranes; hence the structure pictured in Figure 8.15 is called the *fluid mosaic model* of a cell membrane.

Cell membrane lipids are natural surfactants and display most of the properties of synthetic surfactants. The principal difference between these molecules and the surfactants that we discussed above in the chapter is that lipids contain two hydrocarbon tails per molecule. Table 8.5 shows the general structural formula of these cell membrane lipids and the names and formulas for some specific polar head substituents. The alkyl groups in these molecules are usually in the C_{16}–C_{24} size range and may be either saturated or unsaturated.

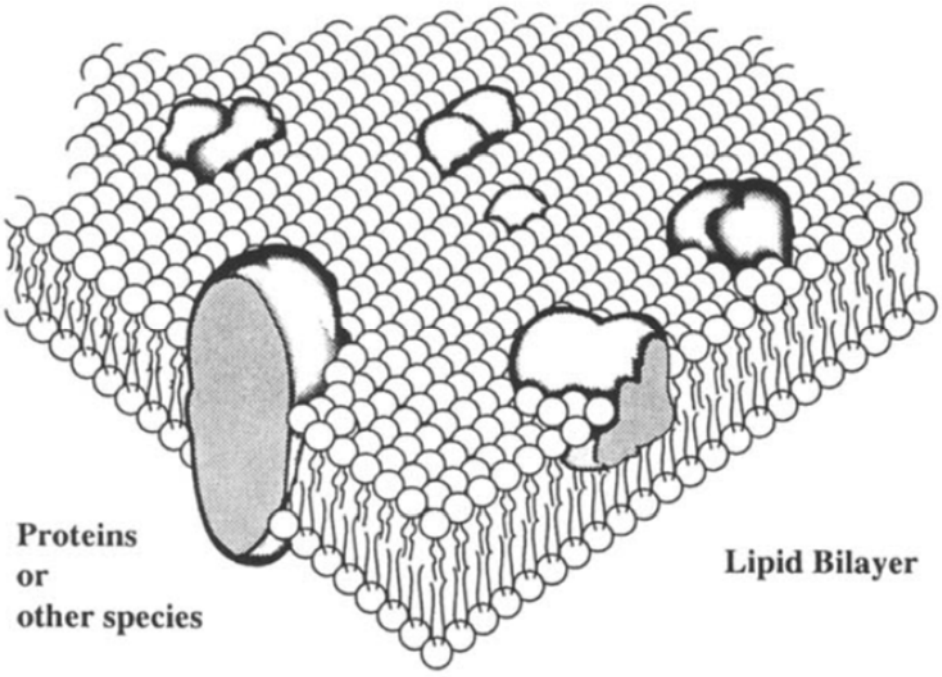
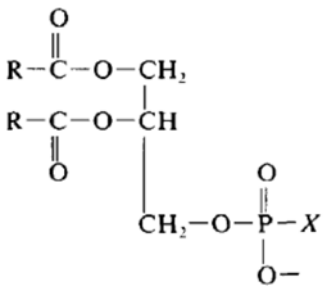


TABLE 8.5 Names and Structures of Some Typical Phospholipid Surfactants



Name	X
Phosphatidic acid	$-OH$
Phosphatidylcholine	$-OCH_2CH_2\overset{+}{N}(CH_3)_3$
Phosphatidylethanolamine	$OCH_2CH_2NH_2$
Phosphatidylserine	$-OCH_2\underset{\displaystyle COOH}{\underset{\vert}{C}}HNH_2$
Phosphatidylthreonine	$-OCH\underset{\displaystyle CH_3COOH}{\underset{\vert}{-}}CH-NH_2$
Phosphatidylglycerol	$-OCH_2\underset{\displaystyle OH}{\underset{\vert}{C}}HCH_2OH$

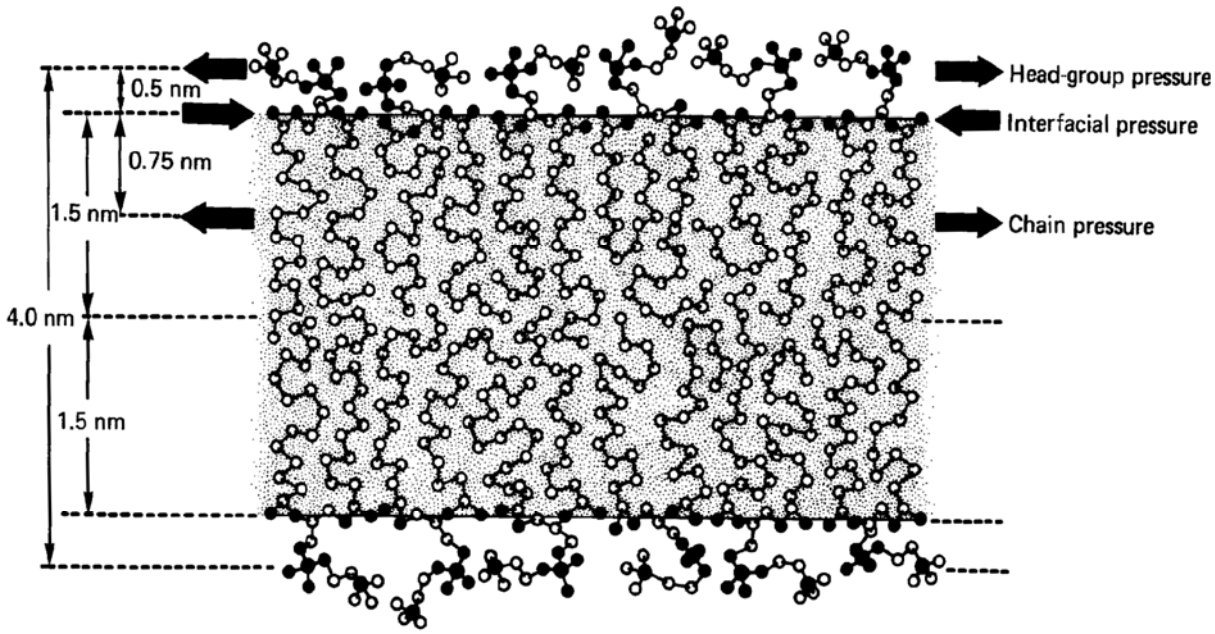


Fig. 17.4. Lecithin bilayer drawn to scale. The lipid bilayer is the basic structure of biological membranes, and most membrane lipids contain two hydrocarbon chains. The lipids diffuse rapidly in the plane of the bilayer, covering a distance of about 1 μm in 1 s. They also cross the bilayer from one side to the other ('flip-flop'), as well as exchange with lipids in the solution, but at much slower rates, of the order of hours (cf. the lifetime of single-chained surfactants in micelles of 10^{-3} to 10^{-1} s). (From Israelachvili *et al.*, 1980a.)

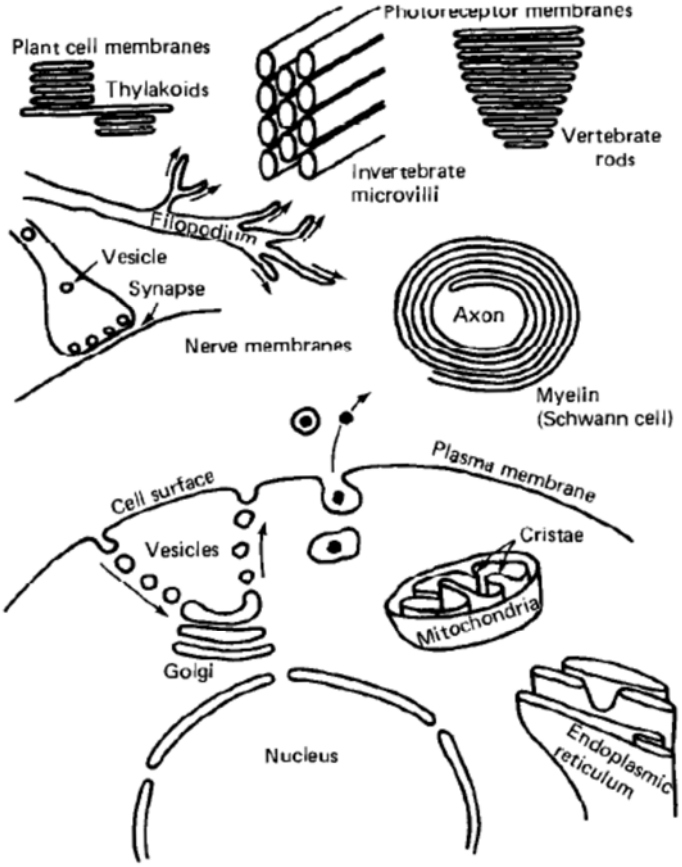


Fig. 17.6. Cellular membranes are thin sheets of lipids and proteins. Most biological membranes offer little resistance to bending.

MEMBRANE LIPIDS

Most biological membrane lipids are *double-chained* phospholipids or glycolipids, with *16 to 18* carbons per chain, one of which is *unsaturated* or *branched* (see Table 16.1). These properties are not accidental but carefully designed by nature to ensure

(i) that biological lipids will self-assemble into thin bilayer membranes that can compartmentalize different regions within a cell as well as protect the inside of the cell from the outside;

(ii) that because of their extremely low CMC the membranes remain intact even when the bathing medium is grossly depleted of lipids; and

(iii) that because of the unsaturation or branching the membranes are in the fluid state at physiological temperatures.

A further important aspect of lipid chain fluidity is that different lipid types can pack together, that is, mutually accommodate each other as well as other molecules, while remaining within a planar or curved bilayer configuration. In addition, the curvature can be regulated by altering the ratio of its constituent lipids.

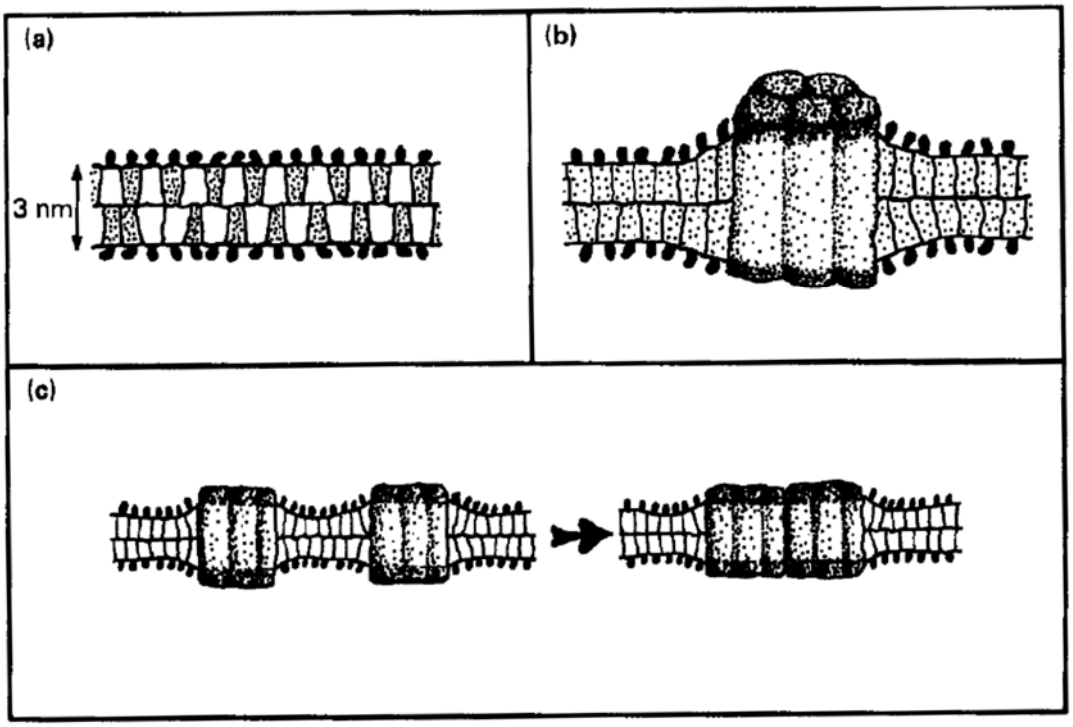


Fig. 17.7. (a) Mixture of two different lipids packing together within a planar membrane. The shaded lipids are cone-shaped ($v/a_0 l_c < 1$); the white lipids are wedge-shaped ($v/a_0 l_c > 1$). (b) Packing constraints induced in the hydrocarbon chain regions of lipids around a protein molecule, which may be relaxed when proteins aggregate, as shown in (c).

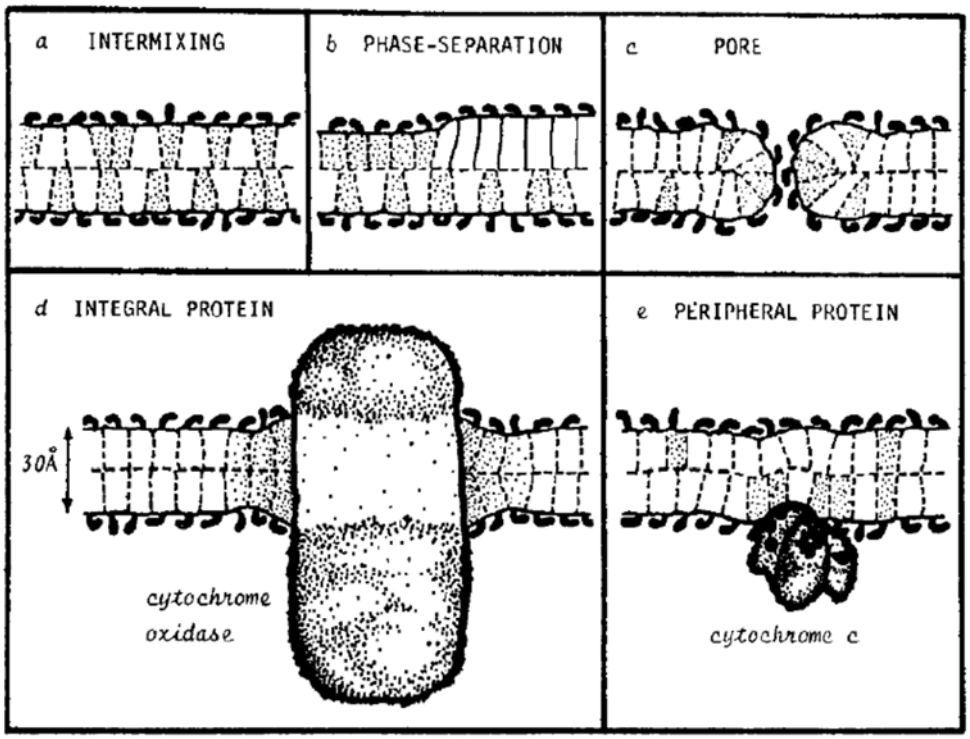


Fig. 17.9. Mean packing conformations of mixed lipid and lipid-protein membranes, showing how local packing stresses may cause clustering of specific lipids and/or non-bilayer shapes (shaded lipid regions). All the figures have been drawn to scale. Note the relatively large size of the cytochrome oxidase protein molecule which protrudes greatly from the bilayer. (From Israelachvili *et al.*, 1980a.)

Even closer to cell membranes than monolayers and bilayers are organized surfactant structures called *black lipid membranes* (BLMs). Their formation is very much like that of an ordinary soap bubble, except that different phases are involved. In a bubble, a thin film of water—stabilized by surfactants—separates two air masses. In BLMs an organic solution of lipid forms a thin film between two portions of aqueous solution. As the film drains and thins, it first shows interference colors but eventually appears black when it reaches bilayer thickness. The actual thickness of the BLM can be monitored optically as a function of experimental conditions. Since these films are relatively unstable, they are generally small in area and may be formed by simply brushing the lipid solution across a pinhole in a partition separating two portions of aqueous solution.

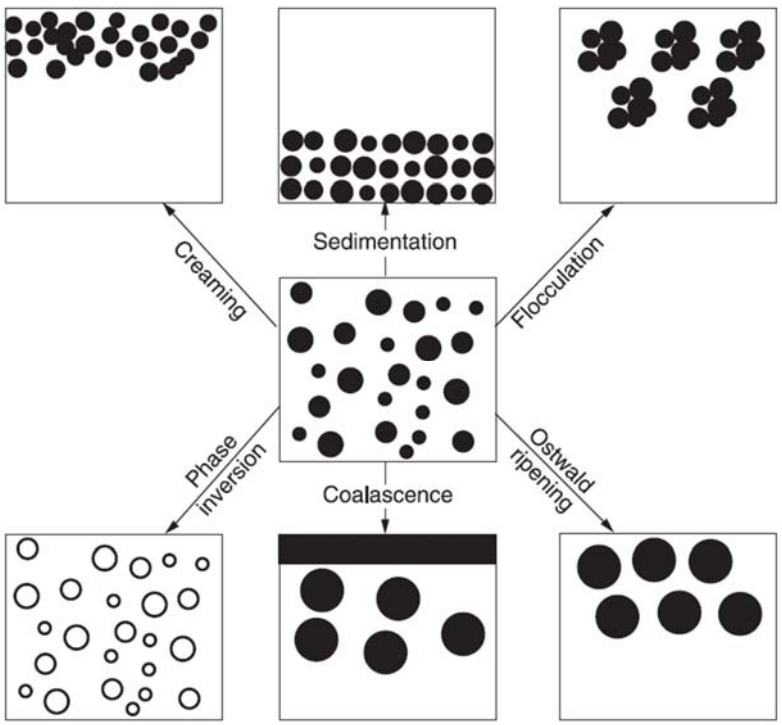
Because they are binary lipid films sandwiched in water, BLMs are excellent models for membranes in terms of electrical and permeability properties. Membrane potential, conductivity, and capacitance measurements have all been made on BLMs, and the effects on these quantities of electrolytes, proteins, and organic additives have all been studied. For example, 2,4-dinitrophenol, a known hydrogen ion carrier, has been observed to decrease the resistance significantly between electrodes on opposite sides of a BLM. Similarly, high applied voltages thin the BLM, with a simultaneous reversible increase in its permeability and conductance. The rate of permeation of water through BLMs is greater than that of nonpolar compounds; however, ions permeate BLMs more slowly than biological membranes.

The final surfactant structures we consider as models for biological membranes are *vesicles*. These are spherical or ellipsoidal particles formed by enclosing a volume of aqueous solution in a surfactant bilayer. When phospholipids are the surfactant, these are also known as *liposomes*, as we have already seen in Vignette I.3 in Chapter 1. Vesicles may be formed from synthetic surfactants as well. Depending on the conditions of preparation, vesicle diameters may range from 20 nm to 10 μm, and they may contain one or more enclosed compartments. A multicompartment vesicle has an onionlike structure with concentric bilayer surfaces enclosing smaller vesicles in larger aqueous compartments.

Phospholipid vesicles form spontaneously when distilled water is swirled with dried phospholipids. This method of preparation results in a highly polydisperse array of multicompartment vesicles of various shapes. Extrusion through polymeric membranes decreases both the size and polydispersity of the vesicles. Ultrasonic agitation is the most widely used method for converting the lipid dispersion into single-compartment vesicles of small size.

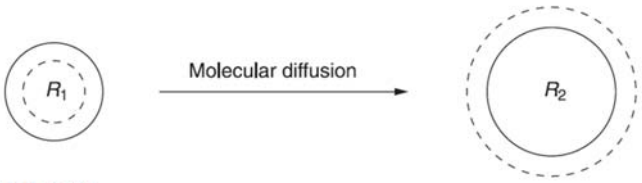
Phase transitions, electrical properties, and permeability have all been investigated for vesicle bilayers. Especially important are the molecular dynamics of transverse motion through the bilayer. Use of isotopic labels shows that lipid molecules can flip-flop from one surface to another in the bilayer. Techniques have been developed for incorporating protein and other molecules into liposomes, and it has been observed that proteins facilitate lipid flip-flop in the bilayer. Liposomes shrink and swell osmotically as the activity of water in the surrounding aqueous phase is changed by additives. Depending on the surface phase state, the addition of cholesterol to the liposome may decrease the water permeability of the bilayer in vesicles. Transport of ions through the vesicle walls is thought to occur either through channels or via carriers. Since these surfaces are orders of magnitude more permeable to H^+ and OH^- compared to other univalent ions, transmission through the vesicle wall by a hydrogen-bonded network of water molecules is proposed just as the high mobility of these ions in water is explained.

Emulsion Stabilization



Ostwald Ripening

The driving force for Ostwald ripening is the difference in solubility between small and large droplets (the smaller droplets have higher Laplace pressure and higher solubility than the larger ones).



Scheme 6.1

The difference in chemical potential between different sized droplets was given by Lord Kelvin [35],

$$S(r) = S(\infty)\exp\left(\frac{2\gamma V_m}{rRT}\right) \tag{6.66}$$

where $S(r)$ is the solubility surrounding a particle of radius r, $S(\infty)$ is the bulk solubility, V_m is the molar volume of the dispersed phase, R is the gas constant and T is the absolute temperature. The quantity $2\gamma V_m/rRT$ is termed the characteristic length. It has an order of ~1 nm or less, indicating that the difference in solubility of a 1 μm droplet is of the order of 0.1% or less. Theoretically, Ostwald ripening should lead to condensation of all droplets into a single drop [27]. This does not occur in practice since the rate of growth decreases with increasing droplet size.

Hydrophile-Lipophile Balance (HLB)

- A quantitative way of correlating the chemical structure of surfactant molecules with their surface activity through some quantitative relationship that would facilitate the choice of material for use in a given formulation
- Employs certain empirical formulas to calculate the HLB number, normally giving answers within a range of 0–20 on some arbitrary scale
- At the high end of the scale lie hydrophilic surfactants, which possess high water solubility and generally act as good solubilizing agents, detergents, and stabilizers for O/W emulsions
- At the low end are surfactants with low water solubility, which act as solubilizers of water in oils and good W/O emulsion stabilizers

HLB

- HLB numbers could be calculated on the basis of group contributions according to the formula

$$\mathrm{HLB} = 7 + \sum(\text{hydrophilic group numbers}) - \sum(\text{hydrophobic group numbers})$$

TABLE 9.2. Typical Group Numbers for Calculation of HLB Numbers

Group	HLB Number	Group	HLB Number
Hydrophilic		Hydrophobic	
$-SO_4Na$	38.7	$-CH-$	−0.475
–COOK	21.1	$-CH_2-$	−0.475
–COONa	19.1	$-CH_3$	−0.475
–N (tertiary amine)	9.4	$=CH-$	−0.475
Ester (sorbitan)	6.8	$-CF_2-$	−0.87
Ester (free)	2.4	$-CF_3$	−0.87
–COOH	2.1	Miscellaneous	
–OH (free)	1.9	$-(CH_2CH_2O)-$	0.33
–O–	1.3	$-(CH_2CH_2CH_2O)-$	−0.15
–OH (sorbitan)	0.5		

TABLE 11.3. HLB Values for Typical Nonionic Surfactant Structures

Surfactant	Typical Commercial Name	HLB
Sorbitan trioleate	Span 85	1.8
Sorbitan tristearate	Span 65	2.1
Propylene glycol monostearate	"Pure"	3.4
Glycerol monostearate	Atmul 67	3.8
Sorbitan monooleate	Span 80	4.3
Sorbitan monostearate	Span 60	4.7
Diethylene glycol monolaurate	Glaurin	6.1
Sorbitan monolaurate	Span 20	8.6
Glycerol monostearate	Aldo 28	11
Polyoxyethylene(2) cetyl ether	Brij 52	5.3
Polyoxyethylene(10) cetyl ether	Brij 56	12.9
Polyoxyethylene(2) cetyl ether	Brij 58	15.7
Polyoxyethylene(6) tridecyl ether	Renex 36	11.4
Polyoxyethylene(12) tridecyl ether	Renex 30	14.5
Polyoxyethylene(15) tridecyl ether	Renex 31	15.4

$$\mathrm{HLB}_{\mathrm{mix}} = f_A \times \mathrm{HLB}_A + (1 - f_A) \times \mathrm{HLB}_B$$

HLB in Emulsion Formulation

HLB Ranges and Their General Areas of Application

HLB Range	General applications
2–6	W/O emulsions
7–9	Wetting and spreading
8–18	O/W emulsions
3–15	Detergency
15–18	Solubilization

HLB Numbers for Typically Encountered Oil Phases

Oil Phase	Nominal HLB
Lauric acid	16
Oleic acid	17
Cetyl alcohol	15
Decyl alcohol	14
Benzene	15
Castor oil	14
Kerosene	14
Soybean oil	13
Lanolin	12
Carnauba wax	12
Paraffin wax	10
Beeswax	9

calculate the HLB number of a surfactant and match that number with the HLB of the oil phase which is to be dispersed

Phase Inversion Temperature

- For a nonionic surfactant of the polyethoxylated type as temperature increases, the surfactant head group becomes less hydrated and hence the surfactant becomes less soluble in water and more soluble in oil
- The surfactant affinity and hence the type of emulsion can be tuned by temperature
- A W/O emulsion is first prepared at high temperature and then is rapidly cooled below the PIT to obtain an O/W emulsion without the need for stirring
- The phase in which the surfactant is preferentially soluble tends to become the continuous phase

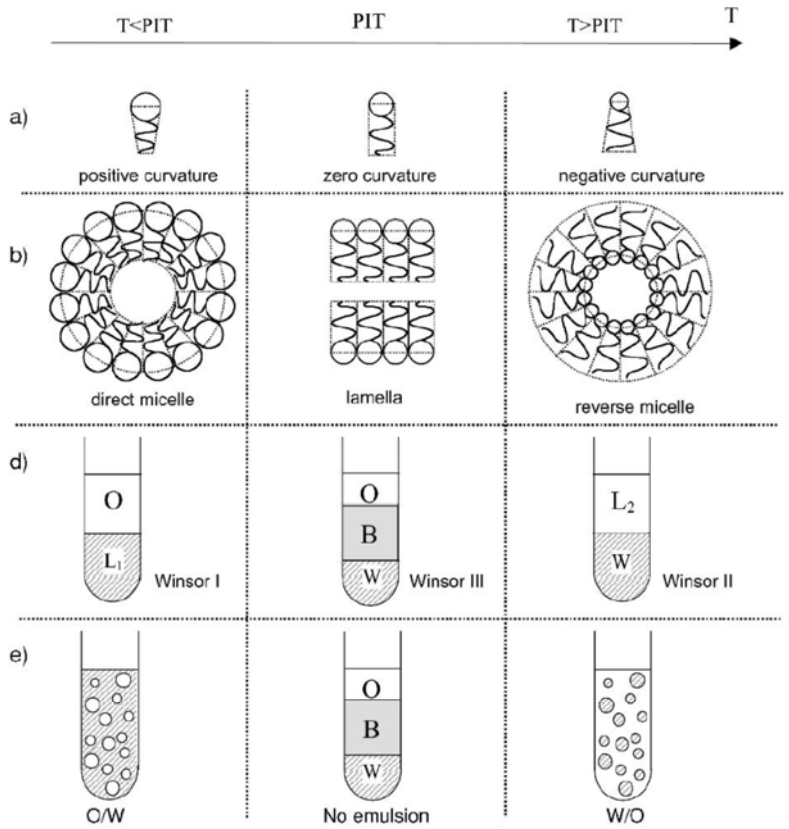


FIGURE 1.4. For a nonionic surfactant, influence of the temperature on **(a)** the surfactant morphology and hence the spontaneous curvature, **(b)** the type of self-assembly, **(c)** the phase diagram, the number of coexisting phases is indicated **(d)** the coexisting phases at equilibrium, and **(e)** the corresponding emulsions.

Nucleation and Growth

- Nucleation is the spontaneous appearance of a new phase from a metastable (supersaturated) solution of the material in question
- The initial stages of nucleation result in the formation of small nuclei where the surface-to-volume ratio is very large and hence the role of specific surface energy is very important
- With the progressive increasing size of the nuclei, the ratio becomes smaller and, eventually, large crystals appear, with a corresponding reduction in the role played by the specific surface energy
- Addition of surfactants can be used to control the process of nucleation and the size of the resulting nucleus

According to Gibbs [4] and Volmer [5], the free energy of formation of a spherical nucleus, ΔG, is given by the sum of two contributions: a positive surface energy term ΔG_s which increases with increase in the radius of the nucleus (r) and a negative contribution ΔG_v due to the appearance of a new phase, which also increases with increasing r,

$$\Delta G = \Delta G_s + \Delta G_v \tag{7.1}$$

ΔG_s is given by the product of area of the nucleus and the specific surface energy (solid/liquid interfacial tension) γ; ΔG_v is related to the relative supersaturation (S/S_0),

$$\Delta G = 4\pi r^2 \gamma - \left(\frac{4\pi r^3 \rho}{3M}\right) RT \ln\left(\frac{S}{S_0}\right) \tag{7.2}$$

where ρ is the density, R is the gas constant and T is the absolute temperature.

In the initial stages of nucleation, ΔG_s increases faster with increasing r than does ΔG_v, and ΔG remains positive, reaching a maximum at a critical radius r^*, after which it decreases and eventually becomes negative. This occurs since the second term in Eq. (7.2) rises faster with r than the first term (r^3 versus r^2). When ΔG becomes negative, growth becomes spontaneous and the clusters grow rapidly. This is illustrated in Figure 7.1, which shows the critical size of the nucleus r^* above which growth becomes spontaneous. The free energy maximum ΔG^* at the critical radius represents the barrier that has to be overcome before growth becomes spontaneous. Both r^* and ΔG^* can be obtained by differentiating Eq. (7.2) with respect to r and equating the result to zero. This gives the following expressions,

$$r^* = \frac{2\gamma M}{\rho RT \ln(S/S_0)} \tag{7.3}$$

$$\Delta G^* = \frac{16}{3} \frac{\pi \gamma^3 M^2}{(\rho RT)^2 [(\ln(S/S_0)]^2} \tag{7.4}$$

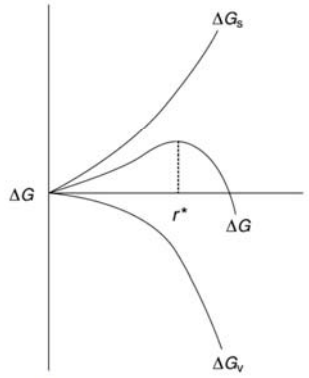


Fig. 7.1. Variation of free energy of formation of a nucleus with radius.

Equations (7.1) to (7.4) clearly show that the free energy of formation of a nucleus and the critical radius r^* above which the cluster formation grows spontaneously depend on two main parameters, γ and (S/S_0) both of which are influenced by surfactants; γ is influenced directly, by adsorption of surfactant on the surface of the nucleus, which lowers γ and this reduces r^* and ΔG^*. In other words, spontaneous formation of clusters occurs at smaller critical radii. In addition, surfactant adsorption stabilises the nuclei against any flocculation. The presence of micelles in solution also affects the process of nucleation and growth, both directly and indirectly. The micelles can act as "nuclei" on which growth may occur. In addition, they may solublise the molecules of the material, thus affecting the relative supersaturation, which can effect both nucleation and growth.