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# 2 Spontaneous Emulsification: Recent Developments with Emphasis on Self-Emulsification

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## Abstract

The phenomenon of spontaneous emulsification is reviewed with emphasis on results obtained in recent years. Several recent studies have provided insight into the mechanism of self-emulsification of oils brought into contact with water with gentle stirring to form oil-in-water emulsions consisting of small droplets. In particular, diffusion and/or chemical reactions can cause changes in composition or environment and hence in spontaneous curvature of surfactant films between oil and water, which in turn cause inversion from an oil-continuous to a water-continuous microemulsion. Since the latter is not able to solubilize all of the oil present, local supersaturation and subsequent nucleation of oil droplets occurs. Under suitable conditions in some systems the lamellar liquid crystalline phase forms during the inversion process and coats the small droplets, thereby hindering coalescence and reducing the initial surfactant concentration required to obtain small droplets.

Self-emulsification can also occur without large changes in spontaneous curvature when the surfactant films are initially near the balanced state of zero spontaneous curvature. Formation of the lamellar phase during emulsification appears to be essential for obtaining small droplets in this case. Sometimes most, if not all, of the oil is converted to the lamellar phase before oil droplets nucleate. In other situations vesicles of an oil-rich lamellar phase have been observed to

disintegrate during swelling by a process resembling an explosion, which is thought to disperse oil drops into the aqueous phase.

“Nanoemulsions” with drop sizes of order 100 nm or less have been produced by self-emulsification processes involving spontaneous emulsification accompanied by gentle stirring. When polymer is dissolved in the droplets, removal of the solvent yields small polymer nanoparticles, which are of interest in applications such as drug delivery.

The results of these studies show that knowledge of equilibrium phase behavior is important in choosing suitable systems and conditions for self-emulsification.

## 2.1 INTRODUCTION

When oil and water phases are mixed, high shear rates are typically required to generate emulsions consisting entirely of small drops with diameters of order 1  $\mu\text{m}$  or less. If it is necessary or desirable to obtain such emulsions without using high shear rates, spontaneous emulsification is an option. Compositions of the initial oil and water phases are chosen in such a way that small droplets form spontaneously when the phases are brought into contact, i.e., no external energy of agitation is required.

Because it is an intriguing phenomenon, an extensive literature exists on spontaneous emulsification whether or not the drops formed are small. Various mechanisms have been suggested, some based on breakup of an interface between oil and water to produce drops, others based on formation of drops during phase transformation, e.g., by nucleation or spinodal composition in regions of local supersaturation produced by diffusion and/or chemical reaction. Davies and Rideal (1) reviewed the older literature on mechanisms of both types. Lopez-Montilla et al. (2) presented a recent comprehensive review of spontaneous emulsification. Here a brief discussion of mechanical mechanisms with emphasis on recent work is followed by a more extensive account of mechanisms involving phase transformation and local supersaturation. Particular attention is given to so-called self-emulsification of oil–surfactant mixtures leading to small droplets, indeed in some cases to nanoscale droplets or particles. This formation of nanoscale droplets and particles has attracted considerable attention in recent years owing to potential applications in delivery of poorly water soluble active ingredients in pharmaceutical, personal care, plant protection and other products (3).

## 2.2 MECHANICAL MECHANISMS

Prominent among proposed mechanical mechanisms of spontaneous emulsification is breakup produced by transient local negative values of interfacial tension. Davies and Rideal’s review includes their own ideas on this mechanism (1). Gopal (4) presented an analysis of interfacial instability produced by negative tensions. More recently, Granek et al. (5) developed an improved instability model, and Theissen and Gompper (6) presented an analysis utilizing the lattice Boltzmann method. It is difficult to say whether transient negative tensions between oil and water are actually achieved in experiments because in oil–water–surfactant systems where ultralow tensions have been observed, intermediate microemulsion and/or liquid crystalline phases typically form at the interface when tensions reach very low positive values, i.e., before they become negative. Also since some mass transfer, e.g., of surfactant, invariably accompanies the reduction in tension, drop formation by nucleation in regions of local saturation produced by diffusion could be responsible for the emulsification.

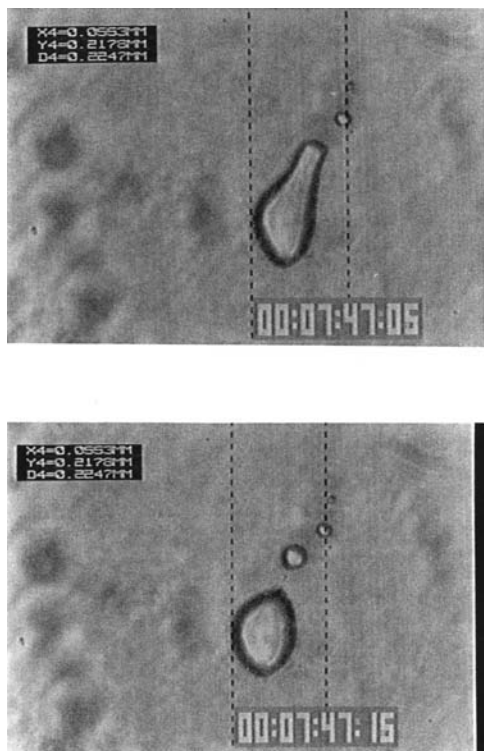
Vigorous Marangoni flow leading to breakoff of drops from an interface has also been proposed as a mechanism of spontaneous emulsification. Such flow is produced by interfacial tension

gradients arising from an instability that frequently develops when diffusion occurs near an interface (7). Here too, however, it is difficult to rule out emulsification produced by local supersaturation. When this latter mechanism is active, the simultaneous occurrence of Marangoni flow greatly increases the rate of emulsification by increasing rates of mass transport near the interface, which produces the supersaturation (1,8). Pfennig (9) employed molecular simulation techniques to investigate Marangoni flow. Some emulsification was predicted to develop near the interface for the particular system investigated. The relevant phase diagram suggests – at least to the present author – that the source of the drops was, in fact, local supersaturation. It is noteworthy that in surfactant systems mass transport leading to both Marangoni flow and local supersaturation may involve transport not only of individual molecules but also of micelles or other aggregates or within liquid crystalline or microemulsion phases.

Yeung et al. (10) observed instability leading to formation of water droplets when a larger drop of water some 20  $\mu\text{m}$  in diameter held at the end of a micropipette and immersed for a few minutes in a toluene/heptane mixture containing 10% bitumen was suddenly deflated. The rather flexible interface nevertheless had some structure and developed multiple undulations projecting into the oil phase as its area decreased, eventually causing many water droplets having diameters of order 1  $\mu\text{m}$  to detach and become dispersed in the oil phase. The authors suggested that these observations were related to “budding,” which has been seen in giant unilamellar vesicles having phospholipid bilayer membranes (11). Such budding, which typically exhibits only one smaller vesicle forming and detaching at a time from the initial vesicle, has been explained theoretically as resulting from curvature elasticity effects which arise when a temperature change or some other change in environment imposes a high spontaneous curvature on the membrane (12). Perhaps also related to the emission of water droplets during the bitumen experiment is another theoretical analysis (13), which predicts that an interface having low interfacial tension and actual curvature much less than its spontaneous curvature will buckle under compression, generating long fingers which can break up into droplets. If spontaneous curvature in such a situation favored a water-in-oil arrangement, as seems likely in the bitumen system, the fingers would be of water projecting into the oil phase and would be expected to break up into water droplets.

Sequential budding events, each involving release of a single droplet or vesicle, were observed by Tungsubutra (14) using videomicroscopy when a drop of oleic acid or an oleic acid/triolein mixture some 50  $\mu\text{m}$  in diameter was contacted with a 2 wt% solution of the pure nonionic surfactant  $\text{C}_{14}\text{E}_6$  in a thin rectangular glass cell maintained at 35 °C (Figure 2.1). A thin layer of lamellar phase formed at the surface of the drop following contact of the phases. Diffusion of surfactant to the drop surface with subsequent adsorption could have generated the spontaneous curvature in the lamellar layer required by the budding mechanism developed for giant vesicles.

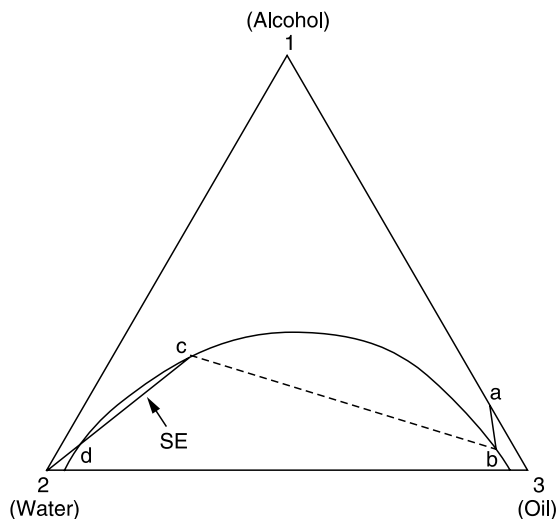
Finally, as is well known, the Rayleigh–Taylor instability can cause spontaneous emulsification due to instability of an oil–water interface which is nearly planar and horizontal when the denser phase is located above the lighter phase and the lateral extent of the interface is much greater than the capillary length  $[\gamma/\Delta\rho g]^{1/2}$ . For instance, a shallow oil pool on a horizontal solid surface can exhibit emulsification when contacted with an aqueous solution containing a surfactant which reduces interfacial tension to low values, thereby greatly reducing the capillary length. A striking example of such behavior was described recently by Hirasaki and Zhang (15). A solution containing sodium carbonate, sodium chloride, and a small amount of anionic surfactant was placed carefully on top of a thin layer of crude oil resting on a solid surface strongly wetted by the oil. The alkali converted the naphthenic acids in the oil to soap, which acted together with the added surfactant to reduce interfacial tension to very low values. At a suitable NaCl concentration all the oil was emulsified.



**FIGURE 2.1** Budding for a drop initially containing 25% triolein and 75% oleic acid in a 2 wt% solution of  $C_{14}E_6$  at 35 °C. Times after drop injection are indicated at bottom of frames (h:min:sec:frame), the lower frame being taken approximately 1/3 sec after the upper. Distance between dashed lines is approximately 50  $\mu\text{m}$ .

### 2.3 LOCAL SUPERSATURATION: GENERAL CONSIDERATIONS

As indicated previously, the alternate to spontaneous emulsification caused by mechanical instabilities is formation of droplets in regions of local supersaturation produced by diffusion. That diffusion is responsible for emulsification in some systems has long been recognized, as discussed by Davies and Rideal (1), who described it as “diffusion and stranding.” Ruschak and Miller (16) presented an analysis which clarified how and when regions of local supersaturation could develop. They started with the diffusion equations in a ternary system for semi-infinite immiscible phases brought into contact without mixing. When plausible assumptions are made, a similarity solution exists, and it is readily shown that the set of compositions in the system is independent of time and thus can be plotted directly on the ternary phase diagram, the so-called “diffusion path.” For example, abcd2 in Figure 2.2 represents the diffusion path in an oil/water/alcohol system when an oil/alcohol mixture a is contacted with pure water 2. In some cases the diffusion path in one or both phases passes through the two-phase region of the phase diagram, e.g., cd in Figure 2.2, indicating that local supersaturation can develop, in this case in the aqueous phase, even though both initial compositions are in single-phase regions. They suggested that spontaneous emulsification would occur in these supersaturated regions and showed that this method successfully predicted both when emulsification would occur and in



**FIGURE 2.2** Diffusion path in a typical alcohol (1) – water (2) – oil (3) system indicating spontaneous emulsification (SE) in the aqueous phase.

which phase(s) for several oil/water/alcohol systems. As Figure 2.2 suggests, spontaneous emulsification is favored when the solute, here the alcohol, diffuses into the phase in which it is more soluble. The reader is referred to previous reviews for further discussion of spontaneous emulsification produced by this mechanism in oil/water/alcohol systems and in oil/water/surfactant systems with the surfactant initially located in the aqueous phase (8,17,18). The emulsions formed were more stable in the surfactant systems, as one would expect.

The review articles just cited describe situations where oil and the water–surfactant mixtures, some of which were dispersions of the lamellar liquid crystalline phase, were contacted without application of external mixing, and where the resulting emulsification was visible, either with the naked eye or using optical microscopy. However, stable “mini-emulsions” having much smaller droplets some 100 nm in diameter were formed when toluene or styrene was added with gentle stirring to water containing 10 mM SDS and 20 mM n-hexadecanol (19). The water/surfactant/alcohol mixture had previously been stirred vigorously at 65 °C, then cooled to 40 °C where an alcohol-rich birefringent phase had formed as a dispersion in an aqueous micellar solution. The added oil penetrated the alcohol-rich phase, presumably causing local supersaturation leading to nucleation of oil droplets containing dissolved hexadecanol. As this extraction of alcohol into oil droplets increased the SDS/alcohol ratio in the birefringent phase, the lamellar structure could eventually no longer be maintained, leaving an oil-in-water emulsion. Emulsification was truly spontaneous as shown by experiments with no stirring, which, however, produced larger drops and a turbid emulsion. Evidently, application of gentle stirring separated the growing oil droplets while they were still surrounded by the birefringent phase, thereby minimizing coalescence and maintaining droplet size near 100 nm. In later sections related phenomena also yielding small droplets and involving dynamics of appearance and/or disappearance of birefringent phases will be described for situations where the surfactant is initially dissolved in oil or an oil-containing phase.

It should perhaps be mentioned that it is not necessary to have both oil and water present for spontaneous emulsification to occur. For instance, Chen et al. (20) observed spontaneous formation of nonspherical drops of liquid within the lamellar liquid crystalline phase during dissolution in water at 35 °C of an 85/15 mixture by weight of the pure nonionic surfactant C<sub>12</sub>E<sub>8</sub> and n-decanol. Spontaneously formed multiple emulsions of water and isotropic surfactant-containing liquid phases (micellar solutions or sponge phase) were observed during dissolution of some commercial nonionic surfactants, which are mixtures of many species; mixtures of pure nonionic surfactants; and mixtures of pure C<sub>12</sub>E<sub>4</sub> with SDS (21).

## 2.4 LOCAL SUPERSATURATION: NANOPARTICLE FORMATION

Minehan and Messing (22) contacted solutions of partially hydrolyzed tetraethoxysilane in ethanol with aqueous NH<sub>4</sub>OH solutions. Local supersaturation produced spontaneous emulsification in the aqueous phase. The drops were subsequently gelled to yield silica particles, which in some cases had diameters of order 100 nm.

In recent years there has been considerable interest in using nanoparticles (NPs) of biodegradable polymers such as polylactide and poly (D,L-lactide-co-glycolide) for drug delivery (e.g., 23–26). Among methods investigated for preparing such NPs are those in which a solution of the polymer and drug in an organic solvent is contacted with water containing polyvinyl alcohol (PVA) or a surfactant with gentle stirring. As water is a poor solvent for the polymer, it has been suggested that diffusion of solvent into the aqueous phase creates a region of local supersaturation where a polymer-rich phase nucleates as “protonanoparticles,” which are stabilized by the PVA or surfactant (24). Later the remaining solvent is removed to yield the desired NPs, whose diameters are typically of order 100 nm although in some cases even smaller.

Some data on phase behavior such as cloud point curves have been published for a few of these systems (25). However, the present author is not aware of a system where sufficient quantitative information on phase behavior is available to clearly locate diffusion paths, although plausible phase diagrams where local supersaturation would be expected can be constructed. Moreover, some workers add the water rapidly, others slowly, and in at least one system NP size was not significantly affected by the rate of addition (26). In any case it seems clear that system composition is shifted by addition of water in such a way that new polymer-rich phase nucleates, i.e., the protonanoparticles are not the same phase as the original polymer solution in the solvent but instead are a phase with a much higher polymer content immersed in a water-rich continuous phase, which is a poor solvent for the polymer. That they remain small is the result of stabilization by PVA or surfactant immediately after nucleation, a process similar in concept but not in detail to the mini-emulsion formation process described above.

## 2.5 LOCAL SUPERSATURATION: SELF-EMULSIFICATION

The remainder of this paper will deal mainly with “self-emulsification” of oils, which is basically spontaneous emulsification of a phase containing oil, one or more surfactants, and frequently an active ingredient such as a pesticide or drug when it is brought into contact with a relatively large quantity of water, usually with gentle mixing. As in the mini-emulsion case, emulsification is spontaneous, but mixing speeds up the rate at which the initial phases are contacted and can significantly influence the final drop size distribution. Sometimes it is desirable to dissolve water in the oil phase to form a microemulsion before mixing with excess water. In any case the objective is generally to obtain a dispersion of “small” oil droplets in water, small meaning

diameters of order 1  $\mu\text{m}$  in some cases but 100 nm or even smaller in others. The latter are sometimes called mini-emulsions, as indicated above, or nanoemulsions.

Self-emulsification of oil is of interest in the use of various products such as *emulsifiable concentrates* of agricultural chemicals (27,28), soluble oils for machining, and bath oils and other personal care products. It has also been investigated for drug delivery (29–31). Self-emulsification of water in an oil phase is also possible although it seems not to be widely used.

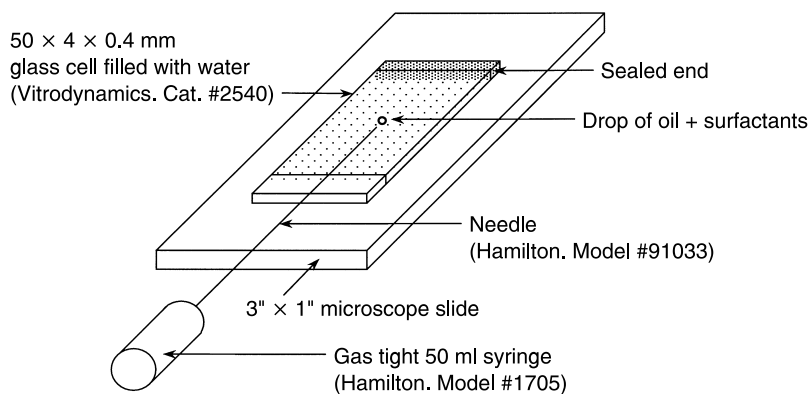
The mechanism of self-emulsification has been poorly understood prior to work of the past several years, which is reviewed below. Previously, Lee and Tadros (32) found that the occurrence of low interfacial tensions could not fully explain the emulsification phenomena they observed. Self-emulsification was also sometimes attributed to formation of intermediate liquid crystalline phases near the surface of contact between oil and water phases (33,34), although the precise role of the liquid crystal was not made clear by these authors. Accordingly, selection of surfactants for self-emulsification and determination of the minimum surfactant concentration needed has been largely empirical.

## 2.6 SELF-EMULSIFICATION PRODUCED BY PREFERENTIAL DIFFUSION OF SOME SPECIES INTO WATER

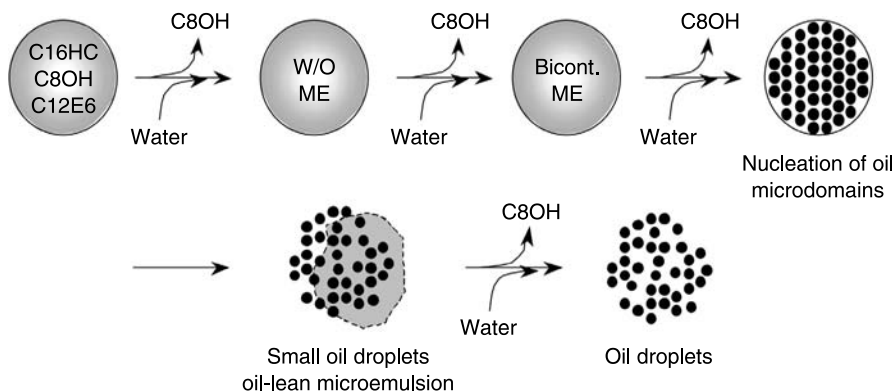
One way to produce self-emulsification is to start with a surfactant or surfactant mixture in the initial oil phase that is rather lipophilic, favoring formation of oil-continuous microemulsions. The surfactant or mixture is chosen so that on contact with water diffusion and/or chemical reaction occur which make the surfactant more hydrophilic, favoring water-continuous microemulsions. As these have much less ability to solubilize oil, some oil nucleates due to local supersaturation and forms small drops. Provided that coalescence can be controlled, the desired emulsion with small oil drops is obtained.

Specific features of the inversion process just described depend on the equilibrium phase behavior and dynamics of phase transformation for the system being considered. For example, Rang and Miller (35) used videomicroscopy to study spontaneous emulsification in water at 30 °C of individual drops some 100  $\mu\text{m}$  in diameter which contained n-hexadecane, n-octanol, and the pure linear alcohol ethoxylate  $\text{C}_{12}\text{E}_6$ . A thin hypodermic needle was used to inject an oil drop into water contained in a rectangular capillary cell approximately 400  $\mu\text{m}$  thick (see Figure 2.3). Spontaneous emulsification yielding only small oil droplets was observed when the initial weight ratio of alcohol to hydrocarbon was greater than that (approximately 1/9) in the excess oil phase in equilibrium with a microemulsion and water at 30 °C, i.e., above the ratio existing at the phase inversion temperature (PIT), and when surfactant concentration exceeded 15 wt%.

The mechanism of emulsification is shown schematically in Figure 2.4. Initially water diffused rapidly into the oil phase, converting it to an oil-continuous microemulsion. Although little surfactant left the drop because its solubility was very low – near the CMC – for conditions above the PIT, the solubility of octanol was high enough for it to diffuse gradually into the aqueous phase following injection. As a result, the ratio of alcohol to surfactant in the films covering the microemulsion droplets decreased, making them more hydrophilic and leading to an increased capability of the microemulsion to solubilize water and a decreased capability to solubilize oil. Eventually, the microemulsion was no longer able to solubilize all the oil present, and oil droplets nucleated. Moreover, the microemulsion itself inverted to become water-continuous and miscible with water, so that the final state was oil droplets dispersed in an aqueous phase, the size distribution of the droplets depending largely on their rate of coalescence. When surfactant content of the initial drop was less than 15 wt%, coalescence was rapid and several large drops were



**FIGURE 2.3** Schematic illustration of contacting experiment where a small drop of oil is injected into water.

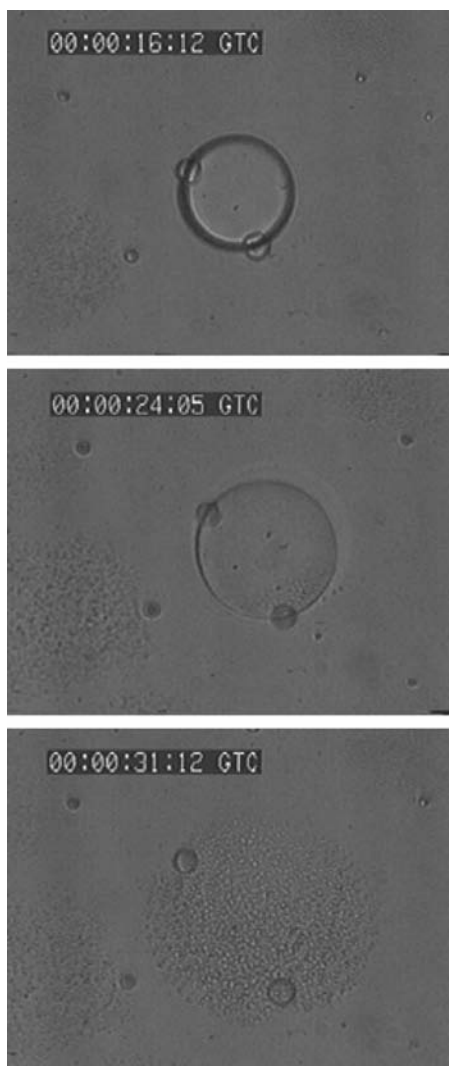


**FIGURE 2.4** Schematic behavior showing spontaneous emulsification process for drops of hydrocarbon/ alcohol/surfactant contacting water.

observed. However, for initial surfactant concentrations exceeding 15 wt%, coalescence was relatively slow, and the droplets remained small. A series of video frames showing the emulsification process in a system with 20 wt% surfactant is shown in [Figure 2.5](#) (35). The higher surfactant concentrations yielded droplets with more hydrophilic surfactant films, which are well known to promote stability of oil-in-water emulsions.

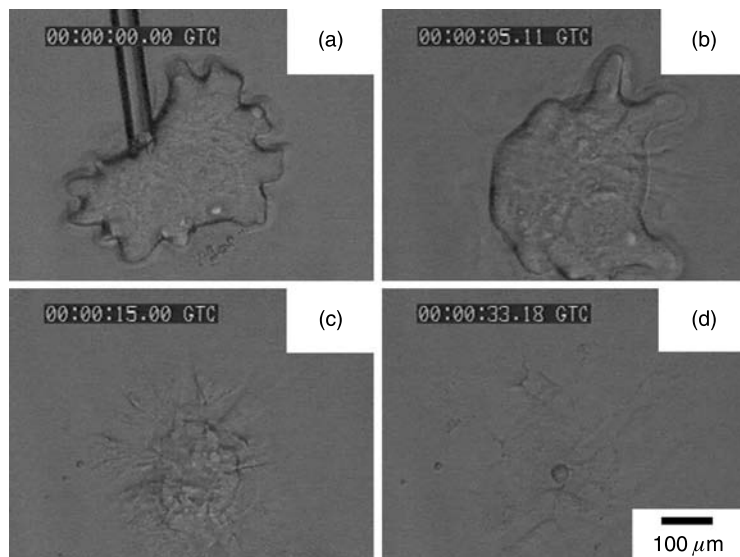
No intermediate liquid crystalline phases were formed for the conditions of Figure 2.5. However, an intermediate lamellar phase *was* seen for a system where the injected drops were mixtures of n-decane, tetradecyldimethylamine oxide ( $C_{14}$ DMAO), and n-heptanol (36). Here too the initial ratio of alcohol to hydrocarbon had to be above that in the excess oil phase at the PIT to obtain satisfactory results. Emulsions with small oil droplets were observed for initial drops containing only 5 wt% surfactant in this system, apparently because the lamellar phase, which formed before oil nucleation began, reduced the rate of coalescence of the droplets. Nevertheless, both the liquid crystal and the microemulsion eventually became miscible with water as they lost alcohol by its diffusion into the aqueous phase, so that the final state was an oil-in-water emulsion.





**FIGURE 2.5** Video frames showing spontaneous emulsification of an oil drop with an initial composition of 20 wt%  $C_{12}E_6$  and 80 wt% of a 90/10 mixture by weight of hexadecane and octanol. Behavior at approximately 16, 24, and 31 s after drop injection is shown. The initial drop is approximately 60  $\mu\text{m}$  in diameter. The two small drops at its periphery did not influence the emulsification process.

It should be emphasized that *all* the oil initially present in both these systems was converted to microemulsion and/or liquid crystal. Hence the oil drops in the final emulsion were formed by nucleation during the inversion process. Extensive equilibrium phase behavior was obtained for both of these systems. That is, the mechanisms described above for the two surfactants were confirmed using a combination of videomicroscopy observations and phase behavior. For example, results of the combined techniques showed that no liquid crystal would form in the nonionic surfactant system for several compositions where satisfactory emulsification occurred.



**FIGURE 2.6** Video frames for a drop with proportions 60/30/10 by weight of n-octane/AOT/water injected into water at 30 °C. Times are as indicated in the upper part of the frame (h:min:sec:frame).

## 2.7 SELF-EMULSIFICATION WITH AN ANIONIC SURFACTANT

Ionic surfactants may also be used for self-emulsification. Aside from providing greater flexibility in surfactant choice, the electrical repulsion between drops in an emulsion formed with an ionic surfactant may contribute to emulsion stability. Greiner and Evans (37) observed spontaneous formation of an oil-in-water (o/w) emulsion with small droplets when a water-in-oil (w/o) microemulsion containing a potassium rosinate surfactant was contacted with water. Nishimi and Miller (38) investigated self-emulsification of alkanes containing the anionic surfactant Aerosol OT (AOT; sodium bis(2-ethylhexyl) sulfosuccinate). This surfactant was chosen because, unlike many anionic surfactants, it has appreciable solubility in hydrocarbons and forms oil-continuous microemulsions even in the absence of alcohol co-surfactants. Moreover, considerable information on its equilibrium phase behavior is available in the literature. Behavior of this well-defined ternary system is described in the following paragraphs although the basic cause of inversion leading to emulsification, i.e., reduction in ionic strength for an initially lipophilic system, was the same in both Refs. 37 and 38.

Figure 2.6 presents a series of video frames showing the behavior observed when a drop containing proportions 60/30/10 by weight of n-octane/AOT/water was injected into water at 30 °C. Upon injection the drop became cloudy and highly nonspherical. In addition, its surface appeared rough and exhibited numerous “bulges” (Figure 2.6(a,b)), which grew rapidly outward and then just as rapidly shrank, leaving behind in the aqueous phase small oil droplets (diameters of order 1 μm) and possibly some vesicles or particles of the lamellar phase. The droplets moved radially outward over the lower part of the cell’s 400 μm thickness (Figure 2.6(b–d)). At the same time, oil which had not been emulsified and remained in the upper part of the cell experienced a radially inward flow to form a drop which was larger than the emitted droplets but much smaller

than the initial drop (Figure 2.6(c,d)). This drop remained at the end of the experiment along with many small oil droplets but no visible particles of the lamellar phase.

Similar behavior was seen whenever initial water content in the drop was 10 wt% or lower and AOT concentration exceeded 25 wt%, but virtually no emulsification occurred for lower AOT concentrations. Emulsification also occurred when the 10 wt% water in the drop of Figure 2.6 was replaced by the same amount of NaCl solution. Indeed, when the solution contained 0.75 wt% NaCl, emulsification was observed even when AOT concentration was reduced to 20 wt%. However, when salt-free octane drops containing 30 wt% AOT and 10 wt% water were injected into a 0.5 wt% NaCl solution, emulsification was minimal.

These results can be understood by recognizing that surfactant films containing AOT have spontaneous curvature favoring a w/o configuration at high ionic strength and an o/w configuration at low ionic strength. In the experiment of Figure 2.6 ionic strength inside the drop decreased as water diffused in and AOT out, causing inversion via the lamellar liquid crystalline phase and nucleation of oil droplets. The decrease in ionic strength was even larger for drops which contained NaCl. But when salt-free drops were injected into sufficiently concentrated salt solutions, inversion and hence spontaneous emulsification did not occur.

As noted above, a small amount of the original oil was not converted to droplets. The reason is that the w/o microemulsion present initially or formed immediately after injection did not invert continuously to an o/w microemulsion as with the systems containing short-chain alcohols discussed above. Instead it was converted to a lamellar phase which itself was subsequently transformed to an o/w microemulsion. The lamellar phase was able to solubilize considerable oil but had a somewhat higher surfactant-to-oil ratio than the w/o microemulsion (see Ref. 38 for references on and discussion of phase behavior). As a result, nearly all of the surfactant was converted to the lamellar phase but not all of the oil.

The higher initial AOT concentrations which produced emulsification also produced lower interfacial tensions. Hence, when drops with high AOT concentrations rose to the upper surface of the cell after injection owing to their low density, gravity caused much more flattening than for drops containing less AOT, producing a generally radial outward flow during which diffusion caused inversion via the lamellar liquid crystalline phase and emulsification. Not all of the oil was converted to the lamellar phase, however, as indicated previously. The later retraction of this oil, which had not been emulsified (Figure 2.6c), was probably the result of an increase in interfacial tension caused by a decrease in AOT concentration in the oil. With the higher tension and smaller volume of this remaining oil, gravity no longer dominated interfacial effects and free energy was minimized by formation of a nearly spherical drop. The retraction in the upper part of the cell to form this drop produced the outward flow of the oil droplets in the lower part seen in Figure 2.6(c,d).

It is noteworthy that the basic inversion mechanism for ionic surfactants involving a decrease in ionic strength makes possible nearly complete emulsification in a ternary oil–water–surfactant system as in Figure 2.6. In contrast, complete or nearly complete emulsification was not observed for ternary *n*-hexadecane/water/ $C_{12}E_6$  (or  $C_{12}E_4$ ) systems. Because there is no analog to the ionic strength effect for nonionic surfactants, their phase behavior did not permit complete conversion of an oil–surfactant mixture to another phase which later became supersaturated in oil.

Dicharry et al. (39) obtained complete dispersion of oil as small droplets for a mixture of a cationic and a nonionic surfactant in their study of cutting fluid formation. They started with microemulsions – perhaps in some cases containing dispersed lamellar phase – having equal amounts of oil and water, 10% surfactant, and various amounts of dissolved monoethanolamine borate (MEAB). Although the water added contained some dissolved calcium and magnesium, ionic strength was reported to nevertheless decrease owing to dilution of the MEAB solution,

so that inversion leading to emulsification occurred as in the AOT experiments described above. Some stirring was applied during water addition, and nearly monodisperse drops having diameters of order 100 nm were obtained. Contributing to the absence of larger oil drops was that, in contrast to the AOT experiment, no bulk oil phase was present initially and thus all the drops in the final emulsion must have nucleated as small droplets during inversion.

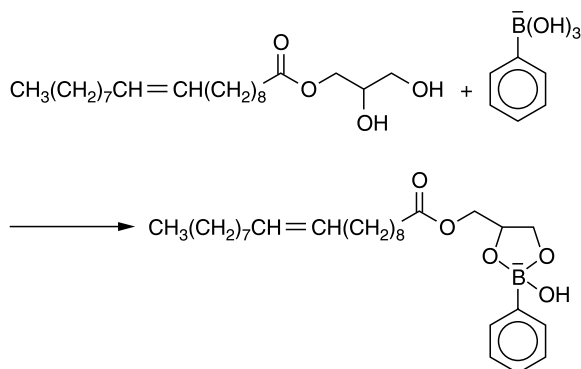
## 2.8 SELF-EMULSIFICATION PRODUCED BY CHEMICAL REACTION OF SURFACTANTS

As demonstrated above, inversion of a w/o to an o/w microemulsion can lead to spontaneous emulsification of oil. The inversion occurs because the surfactant film experiences changes in composition and/or environment which effect a reversal in spontaneous curvature. In the systems discussed above diffusion brought about these changes. For nonionic surfactants a reduction in temperature can produce similar effects, the phase inversion temperature (PIT) method of emulsification (40–42). Of interest in this section, however, are chemical reactions which convert lipophilic to hydrophilic surfactants and thereby cause inversion. For example, reaction might produce ionization of an uncharged amphiphilic compound or convert a double-chain to a single-chain surfactant.

Perhaps the simplest reactions which cause self-emulsification are those where ionization of fatty acids, amines, or other amphiphilic compounds dissolved in an oil phase occurs when the oil contacts an aqueous phase having a suitable pH. It has long been known that contacting oil containing a dissolved fatty acid with an alkaline solution produces spontaneous emulsification (1,43), which is often accompanied by interfacial turbulence generated by interfacial tension gradients (44). Emulsification has been attributed to this turbulence, to the occurrence of transient negative interfacial tensions, or both. Raney (45) observed spontaneous emulsification using videomicroscopy when n-decane/oleic acid/2-pentanol mixtures were contacted by comparable volumes of aqueous solutions containing different amounts of NaOH and NaCl. Information on equilibrium phase behavior was available for this system (46). For a composition where the equilibrium state was an oil-in-water microemulsion in equilibrium with excess oil, spontaneous emulsification was observed in the aqueous phase at some distance from the surface of contact and thus clearly due to local supersaturation. Similarly, spontaneous emulsification produced by local supersaturation was seen in the oil phase for a composition where the equilibrium state was a water-in-oil microemulsion in equilibrium with excess brine. For a composition where a bicontinuous microemulsion was present with both excess oil and excess brine at equilibrium, interfacial turbulence featuring vigorous roll cells was seen on initial contact between oil and aqueous phases along with emulsification of drops of an intermediate microemulsion phase in the oil. Some lamellar liquid crystal was formed as well, and soon continuous layers of both microemulsion and liquid crystal developed near the initial surface of contact, while the roll cells disappeared. The initial interfacial turbulence likely contributed to the emulsification, but the phase dispersed was not one of those initially present but the microemulsion phase, which formed at the initial interface due to mass transfer.

Nishimi and Miller (47) investigated self-emulsification produced by other types of reactions which convert lipophilic to hydrophilic surfactants. In one case a drop containing 5 wt% C<sub>12</sub>E<sub>8</sub>, 5 wt% monoolein, and 90 wt% n-dodecane was injected into Tris buffer solution (pH = 10.4) containing 0.05 wt% phenylboronic acid at 40 °C. The reaction converted the rather lipophilic monoglyceride into a much more hydrophilic ionic surfactant, thereby producing local

supersaturation and extensive, though not complete, emulsification (Scheme 2.1).



Separate experiments showed that the PIT was approximately 35 °C for the same proportions of nonionic surfactant, monoglyceride, and hydrocarbon in the absence of phenylboronic acid. Hence the system was slightly lipophilic in its initial state but rapidly inverted to hydrophilic conditions as a result of the reaction. No emulsification was seen when a similar drop was injected into the buffer solution without added phenylboronic acid.

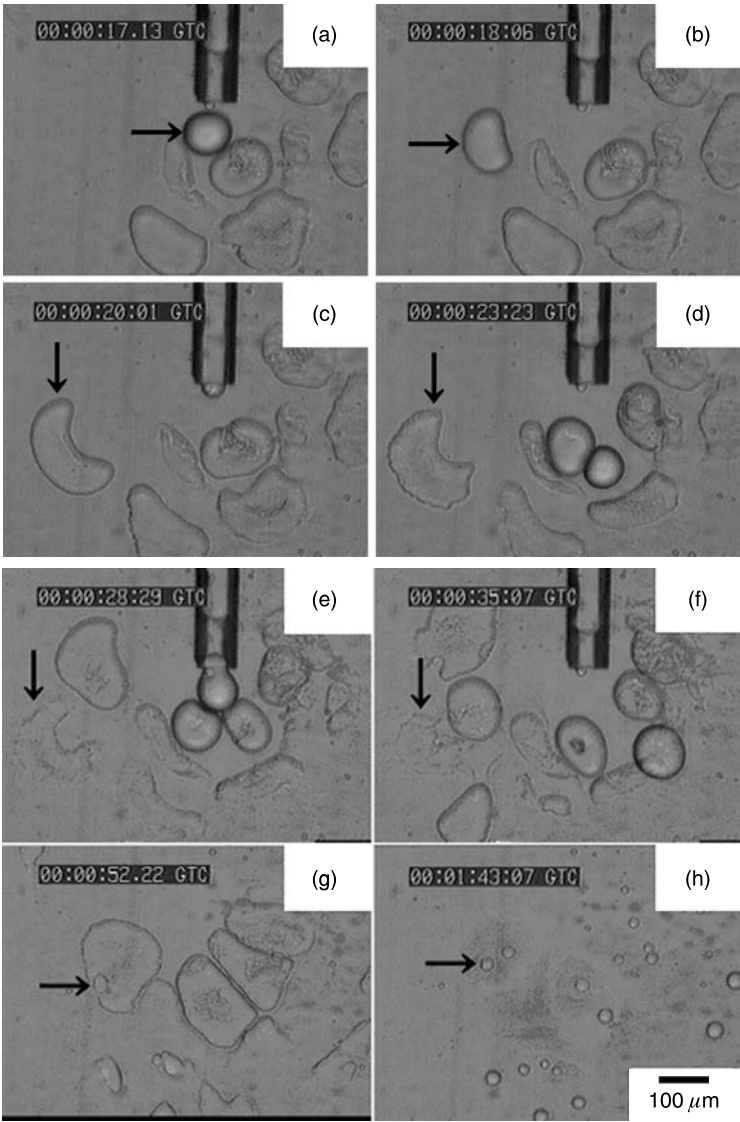
Self-emulsification yielding nearly all small droplets was observed when drops containing 10 wt% C<sub>12</sub>E<sub>4</sub>, 10 wt% of the calcium salt of a commercial dodecylbenzene sulfonic acid, and 80 wt% n-octane were injected into water containing 0.5 wt% of the sodium salt of EDTA at 50 °C (Figure 2.7). As is well known, this EDTA salt complexes calcium ions, simultaneously releasing sodium ions. The PIT was found to be approximately 45 °C for the same oil phase and water containing no EDTA. Thus, at 50 °C the system was again slightly lipophilic initially but inverted when EDTA complexed calcium ions, thereby converting double-chain calcium sulfonates to more hydrophilic single-chain sodium sulfonates. No emulsification was seen in the absence of EDTA.

Finally, self-emulsification was observed after several minutes when a drop of ethyl oleate, a nontoxic oil, containing 5 wt% of the zwitterionic phospholipid DOPC (1,2-dioleoylglycero-3-phosphorylcholine) was injected into an aqueous phase maintained at pH 9 by a borate buffer and containing 5000 units per gram of the enzyme phospholipase A<sub>2</sub>. This enzyme catalyzed splitting of the double-chain phospholipid into two single-chain and hence more hydrophilic surfactants, the corresponding lysolecithin and oleic acid. In addition, much of the acid was ionized since the aqueous phase was alkaline.

## 2.9 SELF-EMULSIFICATION FOR COMPOSITIONS NEAR THE PHASE INVERSION TEMPERATURE

In the systems of the preceding three sections self-emulsification of oil occurred because diffusion and/or chemical reaction caused spontaneous curvature of the surfactant films at oil–water interfaces in a microemulsion to change from that favoring a w/o microstructure to that favoring o/w. During this process the associated decrease in the ability to solubilize oil produced local supersaturation leading to nucleation of small oil droplets.

However, self-emulsification of oil has also been observed in some systems where the above explanation seems inadequate. That is, the transformation from an oil-rich isotropic phase to an oil-in-water emulsion appears to be due primarily to an increase in the water-to-oil ratio (WOR) rather than to a change in spontaneous curvature. The existence of two types of inversion

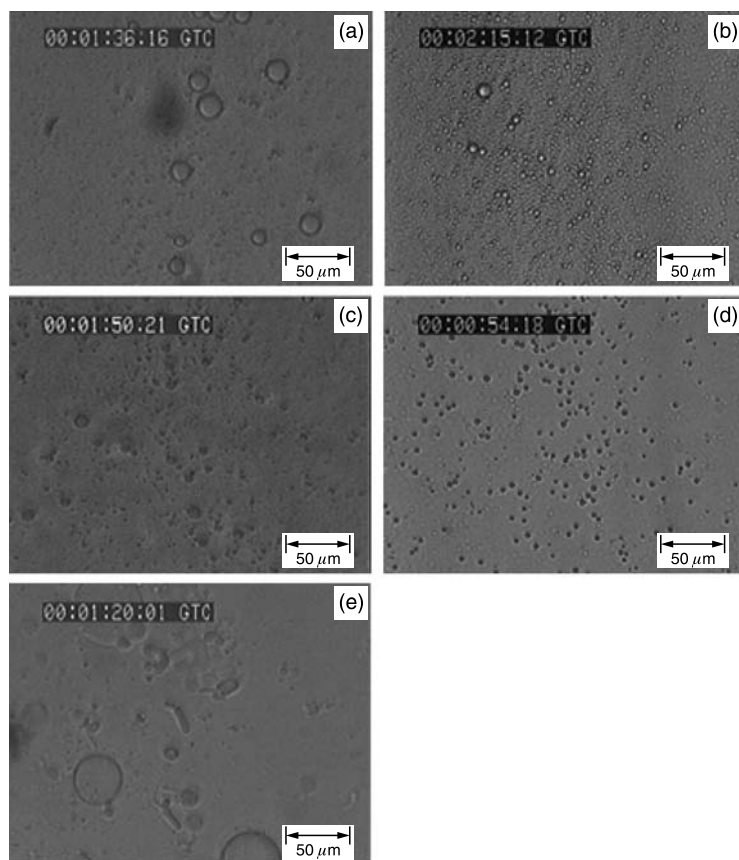


**FIGURE 2.7** Video frames showing spontaneous formation and exit from the micropipette of drops consisting of 10 wt% C<sub>12</sub>E<sub>4</sub>, 10 wt% Ninate 401, and 80 wt% n-octane in contact with water containing 0.5 wt% of the sodium salt of EDTA at 50 °C. The arrows show behavior of a single drop as nearly all of it is emulsified. Times are indicated as (h:min:sec:frame).

processes produced respectively by changes in spontaneous curvature and WOR is well known for conventional emulsions (48). However, in such cases inversion caused by variation in WOR has been studied mainly for systems where the surfactant is either rather hydrophilic or rather lipophilic and not near the balanced condition where spontaneous curvature is zero. The self-emulsification phenomena described next occurred for systems near this balanced condition.

Rang and Miller (49) investigated emulsification systematically for the system n-hexadecane/oleyl alcohol/ $C_{12}E_6$ /water, where the alcohol is nearly insoluble in water. Complete emulsification to form small oil droplets was seen only when initial surfactant concentration was at least 20 wt% and when the hexadecane/oleyl alcohol ratio in the injected drop was between 95/5 and 90/10 by weight. Phase behavior studies suggested that the higher surfactant concentrations were necessary in order for the drop to be completely converted to the lamellar phase as it took up water following injection. Approximately 10 wt% water was required. As yet more water entered the drop, a microemulsion phase formed as well. One or both of these phases eventually became super-saturated in oil, and spontaneous emulsification occurred. Complete conversion to the lamellar phase assured that all oil droplets would be formed by nucleation, i.e., that no larger drops of the original oil phase remained. It is noteworthy that, according to the phase behavior experiments, the minimum surfactant concentration in this oil-rich lamellar phase occurred near the balanced condition or PIT where spontaneous curvature was small, as would be expected.

Figure 2.8 illustrates the effect of hexadecane/oleyl alcohol ratio on the size of droplets formed with 25 wt% surfactant present. The condition that this ratio be within the range cited



**FIGURE 2.8** Video frames showing drop size distribution for self-emulsification of oil drops initially containing 25 wt%  $C_{12}E_6$  and having various hexadecane/oleyl alcohol ratios by weight: (a) 97/3, (b) 95/5, (c) 93/7, (d) 90/10, and (e) 87/13.

above is basically a requirement that it be near that corresponding to the PIT. Because for these conditions both oleyl alcohol and  $C_{12}E_6$  have low solubility in water, little diffusion into the aqueous phase occurs with the result that there is little change in spontaneous curvature. Hence, unlike the situation in a similar system with octanol discussed above, inversion to an oil-in-water microemulsion does not occur for initial states considerably more lipophilic than the PIT, as shown in Figure 2.8e where particles of the lamellar phase are present along with some oil drops in the final state. Pautot et al. (50) recently reported interesting observations of the mechanism by which particles of the lamellar phase are formed and subsequently ejected into water when oil containing a lipophilic surfactant (phospholipid) contacts water.

Emulsification also occurred more quickly for the system containing oleyl alcohol than for that with octanol. In fact, it was not possible to observe details of the emulsification process. The reason is that the initial state was near the PIT and intermediate phases formed immediately on injection. In contrast, no emulsification or intermediate phase formation occurred for the octanol system until sufficient alcohol had diffused from the injected drop into the surrounding water.

The stability of the emulsions so formed was studied using turbidity measurements in a gently stirred system (49). The most stable emulsion was found when the injected drop had a hexadecane/oleyl alcohol ratio of 90/10 by weight and surfactant concentration was 20 wt%. Droplets having diameters of a few microns were observed in the videomicroscopy experiments for this composition when there was no stirring. Of course, smaller droplets not visible with the optical microscope might also have been present. However, droplet diameter as measured by light scattering for the emulsion formed in the stability experiment was only  $60 \pm 20$  nm. Possibly the mixing dispersed small droplets as they nucleated, thereby limiting coalescence. Equilibrium phase behavior indicated that the composition of the dilute emulsion was in or very close to a three-phase region consisting of oil, a dilute surfactant solution, and the lamellar liquid crystalline phase. If the lamellar phase was indeed present, it could form a protective coating around the small oil droplets and provide the enhanced stability observed. This enhanced stability near the PIT contrasts sharply with results of most studies of emulsion stability, which have found that emulsions are least stable near the PIT. The difference is that in this system the lamellar phase is present even at relatively low surfactant concentrations near the PIT when comparable amounts of oil and water are present (49), whereas only microemulsions are present at low surfactant concentrations in systems which have been studied and exhibit unstable emulsions near the PIT. The existence of the lamellar phase at low surfactant concentrations seems also to be the case for the systems discussed in the following paragraphs and is likely necessary for successful self-emulsification for systems near the PIT.

Forgiarini et al. (51), who conducted an independent investigation emphasizing the conditions and mechanisms of nanoemulsion formation, reported that oil droplets with diameters of 50 nm were formed when n-decane containing approximately 20 wt% of a commercial nonionic surfactant (Brij 30) was injected into water under conditions of gentle stirring. As this commercial surfactant, which has an average composition of  $C_{12}E_4$ , contains various species with a range of ethylene oxide chain lengths, it can be viewed as a mixture of hydrophilic and lipophilic components. Thus, it is similar to the system described above where the hydrophilic component was  $C_{12}E_6$  and the lipophilic component oleyl alcohol. Other similarities exist in that Forgiarini et al. (51) also had an initial surfactant concentration of 20–25% in the oil when the smallest oil droplets were formed. Moreover, they found that their system was near the PIT and that on addition of water the initial mixture would first be completely converted to the lamellar phase and ultimately to a final emulsion whose composition was clearly in the three-phase region containing oil, a surfactant solution, and the lamellar liquid crystal. They noted in this and subsequent work that the liquid crystal stabilized the emulsion with respect to coalescence. Nevertheless,



drop size increased with time owing to Ostwald ripening (52). The same group formed stable nanoemulsions by cooling (PIT method), apparently for conditions where no liquid crystal was present (42). Evidently nucleation occurred at a temperature low enough that surfactant films on the drops were sufficient to minimize coalescence.

Mohlin et al. (53) studied self-emulsification at 60 °C of alkyl ketene dimer containing a mixture of a nonionic surfactant and calcium dodecylbenzene sulfonate. Here too compositions of the mixtures yielding nanoemulsions were near the PIT, the system was stirred during the emulsification process, and stability was enhanced because the lamellar phase was present and apparently coated the oil droplets in the final state. It is not clear whether significant dissociation of the calcium sulfonate occurred. If so, the ionic surfactant formed would modify spontaneous curvature to favor oil-in-water emulsions.

Shahidzadeh et al. (54) presented intriguing phase contrast microscopy results on self-emulsification of n-hexadecane drops containing mixtures of C<sub>12</sub>E<sub>5</sub> and n-dodecanol. They observed that the lamellar phase formed as vesicles within the oil phase upon contact with water and that these vesicles “exploded” when they reached the oil–water interface, apparently dispersing oil drops with diameters of order 1 μm into the aqueous phase. They considered that when such behavior occurred, complete transformation of the original oil phase to the lamellar phase was not required to obtain only small oil drops in the final emulsion although phase behavior showing the minimum surfactant content of the lamellar phase was not provided. In any case the authors were able to produce emulsification with only 5–10% surfactant in the oil, in contrast to the work described in the preceding paragraphs where typical concentrations were of order 20%. It may be that, since both surfactant and alcohol had straight hydrocarbon chains of the same length, their lamellar phase was more coherent than those in the other systems and hence dispersed more oil when it exploded. It is noteworthy that the same group observed similar explosions in experiments in which dispersions of the lamellar phase of AOT in water were contacted with oil (55).

Lopez-Montilla et al. (2) also observed phenomena resembling explosions when a drop of n-hexadecane containing Brij 30 was contacted with a drop of water. Some explosions were seen before the lamellar phase became visible. However, as the observations were made at relatively low magnification, it seems possible that some liquid crystal formed at the interface on initial contact and may have been involved in the explosive phenomena.

All of the systems reported to yield nanoemulsions were subjected to modest stirring during the emulsification process. It seems unlikely that shear stresses generated by such stirring was sufficient to break up oil into nanodroplets (although homogenizers which *can* generate nanodroplets exist). It seems more likely the stirring helped disperse nanodroplets formed by nucleation before substantial coarsening could occur due to coalescence or possibly Ostwald ripening, the rate of which can be enhanced for droplets in contact. Further investigation of the effect of stirring is desirable. Nevertheless, the above results suggest that nanoemulsions do form spontaneously but may exist only transiently, especially in the absence of stirring.

## 2.10 SUMMARY

The results summarized above have helped clarify the mechanism of self-emulsification of oils yielding small droplets. One method is to start with oil containing a surfactant or surfactant mixture which forms interfaces whose spontaneous curvature favors water-in-oil microemulsions. When suitable mixtures of this type contact water, diffusion and/or chemical reaction causes inversion to conditions where spontaneous curvature favors oil-in-water microemulsions. During inversion the microemulsion becomes unable to solubilize all the oil present with the result that oil

droplets nucleate. Self-emulsification is possible without formation of the lamellar liquid crystal during inversion, but the lamellar phase can coat the small droplets and prevent coalescence from generating large drops. Higher surfactant concentrations may also be able to minimize coalescence but with the disadvantage of added expense.

Self-emulsification of surfactant/oil mixtures or microemulsions near the balanced condition or PIT seems to occur in some systems with little change in spontaneous curvature but with a large increase in water-to-oil ratio (WOR). Conventional emulsions are known to invert with changing WOR, but such behavior has not been studied extensively near the PIT. In the self-emulsification studies described above, formation of the lamellar liquid crystalline during addition of water seems to be essential, both because oil incorporated into the lamellar phase must renucleate as small droplets if an oil phase is to be present in the final state and because striking phenomena involving ejection of oil have been observed when the anisotropic lamellar phase is swollen by uptake of water.

Emulsions having nanosize droplets can form spontaneously, but gentle stirring seems to be required during the process to prevent coarsening, even when the droplets are coated by the lamellar phase.

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