

## TECHNICAL APPLICATIONS OF COLLOID SCIENCE

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### ABSTRACT

Colloidal dimensions play a role in many applications. In preparing dispersed systems, condensation methods lead to finer and more uniform dispersions than dispersion methods. In technical preparation of dispersions a two step condensation-dispersion procedure is frequently followed. Among the examples treated in more detail are emulsion polymerization leading to isodispersed latices, and "throw-away dispersions" as encountered in washing. In applications often a state of thixotropy or weak flocculation is desirable. Special attention is given to painting, electro-deposition and drilling muds. In some applications coagulation or coalescence is essential e.g. in natural crude oil emulsions, in coal washeries, using sensitized flocculation and in froth flotation.

## I. INTRODUCTION

I have chosen this subject for my lecture in order to be able to stress once more, in how many, often quite dissimilar, fields colloid science is applied, or rather in how many applications colloidal dimensions and colloidal phenomena are important. Also for those who occupy themselves with pure research and with education it is essential to be aware of the broad applicability of colloid and surface science.

Some obvious cases where the *dispersed state is desirable* are: milk, latex, many paints, inks and laquers, mayonnaise, photographic "emulsions", dirt suspended by soap, but also soap micelles as such, and solutions of polymers and biopolymers. Living organisms make and use dispersed systems. Blood is an outstanding example. One may consider the individual cell itself to be a colloidal particle and wonder why cells usually have dimensions between 1 and 10  $\mu\text{m}$ , and why elephants are not unicellular. The answer, of course, is that diffusion is a quick enough transport mechanism in water over distances of the order of one micron but much too slow for larger distances. That is why larger (and higher) organisms are multicellular and why they need circulation systems. Many organisms grow colloidal fibers. They have been used by man and have stood model for a very large industry.

Most of the above examples deal with dispersions in liquid. Dispersions in gases, aerosols, are also applied, e.g. for camouflage, for protection of orchards against frost damage by radiation, and in fluidized bed reactors.

The *dispersed state*, however, is *not always desirable*. In most macroscopic phase separations, in liquid-liquid extractions, in water and air purification by sedimentation and/or filtration, a stable state of fine dispersion is a drawback. In the preparation of polymers by emulsion polymerization, in latex based paints, the colloidal state, essential in the early stages, has to be destroyed towards the end of the process. Foams and emulsions are

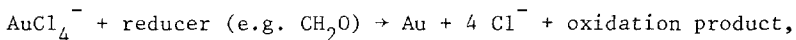
often a nuisance. They have to be broken or their formation has to be prevented.

I could continue giving other examples but I will rather select a relatively small number of typical applications and treat these a little more in depth.

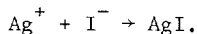
## II. PREPARATION OF STABLE DISPERSIONS

It is customary to divide methods for preparation of colloidal dispersions into *dispersion methods* and *condensation methods* [1]. In the dispersion methods coarse material is subjected to milling, grinding or other methods of comminution, until the desired degree of fineness is reached. The presence of a stabilizing agent is essential to prevent the fine particles from forming agglomerates. The stabilizing agent may be either an ionic species that is sufficiently strongly adsorbed or a large adsorbable molecule or a combination of both (polyion). In the condensation methods the particles are allowed to grow, starting from an atomic, ionic or molecular solution (or from the gasphase) until the desired size is reached. Again a stabilizing agent must be present. Good examples are:

the preparation of a gold sol by the reduction of a chloroaurate solution;



and the preparation of a silver iodide sol from solutions of  $\text{AgNO}_3$  and  $\text{KI}$ ;



The gold sol is stabilized by adsorption of negative ions (e.g. chlorogold complexes, citrate or  $\text{OH}^-$ ). In the case of the silver iodide a small excess of  $\text{Ag}^+$  or  $\text{I}^-$  provides the stabilizing charge.

It is often stressed that the condensation methods allow finer, more isodispersed, particles to be obtained and most laboratory

methods for the preparation of lyophobic sols are based on condensation. In technical applications, however, dispersion methods are more commonly used than condensation methods, with the preparation of photographic emulsions and emulsion polymerization as the outstanding exceptions. Dispersed paints and dyes, most pharmaceutical, cosmetic and agricultural emulsions and suspensions, suspensions used in froth flotation, drilling muds, fluorescent light tubes, magnetic tapes and composite multiphase materials are all made via dispersion methods.

This, however, does not imply that in the dispersion methods one starts with very coarse bulk crystals. No, the material to be milled is often prepared by a condensation method from low molecular weight starting materials, but the condensation is allowed to go on beyond the degree of subdivision eventually required. The reason for such a two step, condensation-dispersion, procedure is that after the condensation, ageing and thermal treatments give the necessary control of magnetic properties, color or fluorescence of the particles, after which the final dispersion is prepared by milling in the presence of the stabilizing agent.

### Examples

#### 1. PHOTOGRAPHIC EMULSIONS

As mentioned above *photographic emulsions* [2] (an unfortunate misnomer, given the suspension character of the system) are formed by condensation. Solutions of silver nitrate and alkali halide in gelatin are mixed and a very fine dispersion of silver halide is formed. The gelatin serves both as the stabilizing agent (protective colloid) and as the gel that immobilizes the system.

Washing away of the alkali nitrate, addition of sensitizer and dyes and carefully controlled Ostwald ripening to obtain good sensitivity are essential steps in the process.

## 2. EMULSION POLYMERIZATION

In *emulsion polymerization* [3] the latex particles are formed by condensation starting from molecularly distributed monomer(s). The monomers may originally be present as relatively coarse emulsion droplets, or be dissolved in water. The essential first steps, the formation of free radicals from the initiator and the addition of the first few monomers take place in the aqueous phase. The growing polymer becomes insoluble, separates from the solution and forms the latex particles. The size of these particles is determined by the number of latex nuclei formed and the time during which they grow. An isodisperse latex may be expected when all the nuclei are formed at a very early stage, or if instead of allowing spontaneous nucleation the system is seeded with a large number of small latex particles. Agglomeration must of course be prevented by sufficiently strong stabilization either by the action of suitable soaps or other amphipathic substances or by the electric charge on the polymers themselves.

It may not be superfluous to point out why *isodispersed systems* [4] are obtained, if all nucleation takes place at an early stage of the process. Growth of the nuclei requires diffusion of the monomers to the latex particles (or diffusion of other low molecular weight building stones in other cases such as Au atoms to the growing particles in a gold sol), followed by addition of monomers to the growing polymer molecules (or precipitation, crystallization of the small building blocks on the growing particle).

Each of these steps may be rate limiting.

- a. If the diffusion is rate limiting the flux of small molecules,  $J$ , towards each particle can be found, using a reasoning analogous to Smoluchowski's derivation [5] of the rate of coagulation, which also applies to diffusion controlled reactions [6]. A concentration gradient which soon reaches a stationary state, develops around each particle. Assuming spherical symmetry this flux in the stationary state is

$$J = D 4\pi r^2 \frac{dc}{dr} \quad (1)$$

where  $c$  is the concentration of the small molecules,  $r$  the distance from the center of the particle and  $D$  the mutual diffusion coefficient between particle and small molecules.  $D$  is equal to

$$D = D_p + D_m = D_m \left(1 + \frac{b}{a}\right) \quad (2)$$

$p$  and  $m$  refer to particle and monomer (small molecules) respectively,  $b$  is the radius of the monomer and  $a$  that of the particle. Since the diffusion is considered to be rate limiting the concentration  $c$  at the particle surface,  $c_a$ , must be zero or at least very low. If the diffusion is not rate limiting,  $c_a$  must be equal to the monomer activity in the swollen particle. It will be constant or slowly changing with time and may have any value between zero and the concentration far from the particle, which we shall call  $c_\infty$ . Integrating eq. (1) we find

$$J = 4\pi D a (c_\infty - c_a) \approx 4\pi D a c_\infty \quad (3)$$

The rate of growth of the particle radius  $a$  is then

$$\frac{da}{dt} = \frac{J}{4\pi a^2} \bar{V} = D_m c_\infty \bar{V} \left(\frac{1}{a} + \frac{b}{a^2}\right) \quad (4)$$

where  $\bar{V}$  is the partial molar volume of the polymerized monomer in the particle.

If the growth is not very fast (e.g.  $da/dt \leq 1 \text{ \AA s}^{-1}$ ) and realistic values for  $D_m$ ,  $\bar{V}$  and  $a$  are chosen,  $c_\infty$  must be extremely small (e.g.  $10^{-9} \text{ g cm}^{-3}$ ). Then, however, the supply of  $m$  would be soon exhausted and reasonable concentrations of particles of acceptable size can only be obtained if the low concentration,  $c_\infty$ , is continuously replenished by slow production of  $m$  [4].

Integration of eq. (4) leads to

$$\frac{1}{2}(a^2 - a_0^2) - b(a - a_0) + b^2 \ln \frac{a+b}{a_0+b} = D_m c_{\infty} \bar{V} t \quad (5)$$

After a given time  $t$  the variation in radius of the particle  $da$  can be compared to the variation  $da_0$  at  $t = 0$ .

This is found to be

$$\frac{da}{da_0} = \frac{a_0}{a} \frac{1 + b/a}{1 + b/a_0} \quad (6)$$

showing that the distribution of radii becomes narrower with time. On growing, the particles get more and more isodispersed.

- b. If, however, the rate of growth of the particles is limited by the rate of polymerization (or crystallization or precipitation) the increase in particle volume with time is

$$\frac{d(4\pi a^3/3)}{dt} = s\bar{V} \quad (7)$$

where  $s$  is the amount of monomer polymerizing per unit time and per particle.  $s$  may be proportional to  $a^3$  (number of growing radicals per unit volume is constant) or proportional to  $a^2$  (constant number of growing radicals per unit surface area) or independent of  $a$  (constant, presumably low - 1 or 0.5 - number of growing chains per particle).

If  $s$  is constant, eq. (7) can be integrated over  $t$  and differentiated by  $a_0$ . We find then:

$$\frac{da}{da_0} = \frac{a_0^2}{a^2} \quad (8)$$

The narrowing of the particle size distribution with time is still more pronounced than when diffusion is rate limiting. Similarly proportionality between  $s$  and  $a^2$  leads to  $da/da_0 = 1$  and with growing  $a$  the distribution becomes relatively narrower.

Only if  $s$  is proportional to  $a^3$ ,  $da/da_0 = a/a_0$ , with just no relative change in the distribution on growth.

In all these cases it is essential that all particles grow during the same time, which is equivalent to the requirement that all nucleation takes place at a very early stage.

*Vanderhoff* et al. [7] have pointed out already in 1956 that, as long as the growth rate is proportional to a smaller power than the third of the radius the particle, size distribution is self sharpening. From experiments with a mixture of two polystyrene latices of different size they found the rate of volume growth to be proportional to the radius to the power 2.5. This might be interpreted as due to a constant number of growing chains per unit area, plus some extra ones, but not so many as to make the number proportional to the particle volume.

### 3. DISPERSED PIGMENTS AND DYESTUFFS

*Dispersed pigments and dyestuffs* [8] are prepared by milling the coarsely divided solids in the liquid dispersion medium in the presence of a stabilizer. The milling leads to a fairly wide size distribution, often limited at the top side by continuing the milling until the requirement that all (a very large fraction of) the particles are below a given size is satisfied. At the lower end the size is limited because milling of any type becomes less effective when smaller particles must be broken. Since the process is applied to a great variety of solvents (varying from water to extremely non-polar hydrocarbons) and a great variety of solids, a wide choice of stabilizers must be available. A stabilizer must satisfy three requirements, viz.

- a. it must be soluble in the medium,
- b. it must be adsorbed on the particles and
- c. it must cause a sufficiently large repulsion between the particles.



In a number of cases, when the medium is water or a fairly polar organic solvent, small inorganic ions, in particular potential determining ions, or detergent ions satisfy these requirements. In these cases the repulsion is electrostatic in nature. More often than not, electrical stabilization is not practical (ionic strength too high, medium not polar enough) and then stabilizers must contain a fairly large group (often a long chain) which is soluble in the medium and causes so called "steric" or "entropic" repulsion and an anchorgroup, which has a strong tendency to be adsorbed on the particles but which, on the other hand, should not cause the stabilizer to become insoluble. The preparation and selection of such stabilizers is still more a highly developed art than a deductive science.

When polyelectrolytes (among them gums and proteins) are used as stabilizers we probably have cases of mixed electrical and steric stabilization.

In technical applications it is frequently desirable that dispersions are not completely stabilized, but that they do retain a certain thixotropy, which is a sign of weak flocculation. This is particularly obvious in the case of paints. If the pigment particles in a paint are completely stabilized, on standing a very dense sediment will be formed at the bottom of the can, which can only be redispersed with difficulty. A small degree of thixotropy will prevent the sedimentation, but still allow the paint to behave as a freely mobile liquid during the application. The thixotropy also helps to keep the paint film from flowing down a vertical surface in the time between application and drying (hardening).

#### 4. EMULSIONS

*Emulsions* [9] are applied in many cases. They can be easily prepared by stirring the two liquids together and subjecting the coarse emulsion to high shear, because a sufficiently elongated

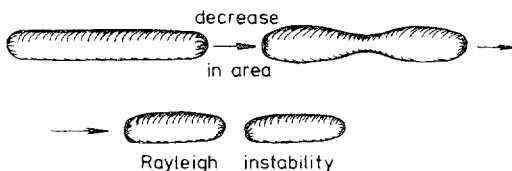


Fig. 1. Illustrating the breaking of an elongated drop by Rayleigh instability.

drop will break spontaneously into two or more smaller ones under decrease of the total interfacial area as illustrated in Fig. 1. A stabilizer is essential to prevent reaggregation (coalescence), and it depends on the nature of the stabilizer and to a lesser extent on the phase volume, whether oil (general designation for a water insoluble organic liquid) in water or water in oil emulsions are obtained. We leave liquid metal emulsions (e.g. Hg in  $H_2O$ ) out of consideration.

Emulsions prepared by stirring are usually fairly coarse and heterodisperse. Homogenizing produces finer emulsions, but still the droplet diameter does not fall below a few tenths of a micron and the droplet size distribution remains wide. Moreover, making fine emulsions by this method requires large amounts of energy. So called *spontaneous emulsification*, in which emulsions are formed with little or no mechanical energy applied, are therefore often an attractive proposition. A number of mechanisms, leading to fluctuations that grow spontaneously, may contribute individually or collectively to spontaneous emulsification. Diffusion of material across the phase boundary is one of these mechanisms. It may cause density instability and Benard convection cells, which may entrain droplets of one phase into the other. The turbulent motions may be enhanced by changes of interfacial tension along the interface caused by concentration gradients. A temporary, local, negative interfacial tension would also cause the surface area to increase and be a mechanism for spontaneous emulsification.

Certain agricultural chemicals are sold in the form of such *self emulsifiable concentrates*. They consist as a rule of the

active substance dissolved in kerosene, to which an oil soluble surfactant or mixture of surfactants, which is also to some extent water soluble, has been added.

A closely related phenomenon is presented by the *micro-emulsions*, formed spontaneously from a mixture of water, oil, a fairly polar surfactant and a higher alcohol or amine. Here, indeed the original two phase mixture may have a negative interfacial tension, but the large interfacial area requires so many surfactant molecules, that their concentration is substantially reduced and the interfacial tension brought back to a positive value. The particle size of microemulsions is very small, of the order of a few hundred Ångströms, and they appear to be rather isodisperse.

## 5. WASHING

In *washing* [10] solid and liquid soil particles should be dispersed and emulsified and be prevented from redeposition during the washing and rinsing process. The washing solution must easily wet the objects (or subjects) to be cleaned. This requires spreading and is promoted by a low surface tension. The stabilizer, in becoming adsorbed, is the cause of a repulsion between soil particle and skin, fabric, glass, ceramic etc. as illustrated in Fig. 2. This repulsion may lead to peptization but often some

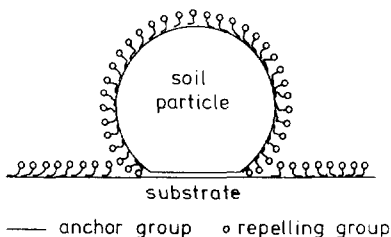


Fig. 2. Adsorption of stabilizer tends to separate soil and substrate.

additional mechanic action is required. Water is the usual medium, but dry cleaning in chlorinated hydrocarbons forms a well known alternative.

Given the great variety of soil (oil, coal, denatured proteins etc., etc.) a very general type of stabilizer is required. Fortunately the highly polar nature of water allows the use of amphipolar detergents, the non polar half acting as anchor group, not on account of a special attraction to soil and fabric, but because it is squeezed out of the water. The stabilizing group may be ionic (classical soaps and its synthetic anionic and cationic variants) or non-ionic, in particular polyethylene oxide.

Whereas the suspensions and emulsions treated in the examples 1-4 are prepared to be used, the dispersions made in washing are intended to be thrown away. An analogous case of "throw away emulsions" is the cleaning up of oil spills by dispersion. Here the use of oil soluble, rather than water soluble surfactants appears to be the correct strategy to avoid loss of active material, and wave and windaction rather than spontaneous emulsification should cause the dispersion of the oil.

The use of "dopes" (= suspension stabilizers) in motoroil [11], in order to keep carbon and other products of incomplete combustion suspended as very fine particles, rather than allowing them to agglomerate and cause wear of engine surfaces is another example of throw away dispersions. Recently, moreover, the suspension of large quantities of coal in oil has obtained a great deal of interest as a way to substitute cheap coal for expensive oil in fuels.

### III. APPLICATIONS OF DISPERSIONS

The reasons for using stable dispersions may be quite varied. In milk and other foodstuffs the high interfacial area and the small particle size promote digestibility. In blood the small particles may pass through the capillaries without clogging them.

Moreover oxygen exchange between erythrocytes and plasma requires only very short diffusion pathways. In painting and writing the ease in bringing colored material in a desired pattern to a surface is the essential asset and in drilling muds it is the peculiar rheological behavior of suspensions.

On the other hand, from Perrin's time on, isodisperse systems have been powerful tools in the hands of pure scientists. Perrin himself [12] used redispersed natural latex, or carefully fractionated mastix emulsions to derive Avogadro's constant from Brownian phenomena. Various isodisperse systems were used in conjunction with theoretical work on light scattering [13] and, recently, synthetic latices allowed a critical test of an extension of Smoluchowski's theory of collision frequencies [14].

One of the simplest applications is the *latex dipping process*, in which a smooth, non porous mold, either preheated or covered with a thin layer of a coagulant, is dipped in a concentrated (e.g. 60%) latex. After retraction from the latex bath the adhering layer can be coalesced, dried and vulcanized by the application of moderate heat.

Another simple process is *slip casting* of ceramics. Here a stable aqueous suspension is poured into a porous mold (e.g. plaster of Paris), which takes up part of the water, thus concentrating and rigidifying the suspension, which then acquires sufficient strength for further handling.

In applying a *paint* layer, the suspension or emulsion must be quite fluid during the application by brushing or spraying, but must rigidify soon after, to prevent sagging. The final strength is then obtained by further evaporation of solvent and by polymerization and crosslinking reactions, in which coalescence of oil or latex particles may have an essential role.

The preparation of *magnetic tapes* starting from a suspension of the magnetic particles poses a particularly tough colloid problem since magnetic forces are strong and far reaching, so that a fairly long range and strong repulsion, necessarily based on

adsorbed molecules, must help to combat formation of large aggregates, which would spoil the degree of resolution of the signal.

A more sophisticated way of applying layers of small particles, usually, but not exclusively from emulsion or latex paints, is *electrodeposition* [15]. In this most interesting process, highly concentrated layers of stable particles are deposited by d.c. on a metal or metallized surface. The high electrical resistance of a compact layer of particles tends to make the thickness of the layer rather uniform, even in recesses which are not easily reached by spraying or brushing. The electrolysis products, causing a shift in pH or simply an increase in ionic strength, will then promote coagulation of the deposit, the whole process combining the advantages of a dense sediment, which can be only produced from a stable suspension (or emulsion), and good adherence based on coagulation. Of course, the strength of the layer may be further increased by additional heat treatment.

In *drilling muds* [16] a number of properties must be combined. They must be fluid and have a high heat capacity to cool the drilling bit. They must have a high density to withstand the pressure in the formation. This high density and a high rate of flow help to carry the chips loosened by the drilling to the surface. If the drilling is interrupted, as it must be from time to time, the mud must gel in order to prevent accumulation of the chips and the suspended particles at the bottom of the hole. Finally the excess pressure in the mud column over the contents of the formation pushes the mud into the formation. The clay particles in the mud must then plaster out and form a virtually impermeable lining on the wall of the hole. The combination of these divergent properties requires the mud to be a thixotropic suspension with low viscosity when kept in motion but forming rather quickly a weak gel on standing. The addition of some surfactant and a relatively high pH are often essential to obtain the required rheological behavior.

A general remark, to apply to nearly all applications of suspensions, is that the rheology is important, that the systems should certainly not be grossly flocculated, but colloidal stability with a small degree of thixotropy (sometimes called "weak flocculation") is the favored state.

#### IV. COAGULATION OF DISPERSIONS

As mentioned in the introduction it is often necessary to destroy the dispersed state by inducing coagulation and/or coalescence. One has the classical examples of making cheese, butter or cottage cheese, the clarification of beer, or the coagulation of natural rubber latex.

A very large scale example is found in the demulsification and separation of *natural petroleum emulsions* [9]. A sizable fraction of all crude oil is produced in the form of emulsions of the water in oil type. Before further processing and even before transport the water content has to be brought down below 1%. Although such emulsions as a rule are not very stable, a variety of methods is used to accelerate the separation, among them the addition of chemicals which counteract the natural emulsifiers (e.g. surfactants which - if present alone - would promote oil-in-water emulsions). Passage through water wettable filter beds on which the water droplets collect and coalesce and electrical demulsification are other methods. The electric field acts in this case not so much by causing electrodeposition of the water droplets as by polarizing them so that their mutual attraction causes coalescence.

Another major area in which suspensions are destroyed is that of *coal washeries* [17]. Coal as produced from the mine usually contains clay or claylike material and fine coal dust. If these are separated from the larger lumps of coal by washing with water a nasty black suspension is produced, which should not be discharged into public waters, and which, if left to itself, takes a long time

to separate by sedimentation. The application of sensitized flocculation will solve the problem. Sensitized flocculation involves the addition of a small concentration of a polymer, usually a poly-electrolyte which may form bridges because molecules get adsorbed with two anchor groups on two different particles. Agglomerates are formed, big enough to settle rapidly, with enough mutual adherence to include all, also the very small, particles and open enough to allow rapid filtration. The precipitate then contains enough coal to be of value as fuel and the remaining water is clear and not unduely contaminated by chemicals.

This sensitized flocculation [18], discovered long ago (about 1900) as a relative rarity in systems showing protective action at higher polymer concentration, may well become one of the most attractive methods for destroying the stability of suspensions, on account of the small amounts of agent required, and of the openness and good coherence of the flocs. Clarification of sewage and other waste waters may be based upon the same principles.

*Soil improvement* by partially saponified polyacrylamide is another application of sensitizing action.

*Froth flotation* [19], the process in which yearly millions of tons of minerals are separated and concentrated, may be regarded as heterocoagulation between fine mineral particles and gas bubbles. Variants of the same technique have been used to remove other particulate materials from suspension and fairly recently the use of small bubbles [20] (diameter about 50  $\mu$ ) has allowed the efficient removal of bacteria and particles of colloidal dimensions. Particles adhere to a water/gas interface when they are hydrophobic. Some kinds of particles are inherently hydrophobic, but more often hydrophobicity is introduced by the adsorption of amphipolar solutes on the particles.

Since this adsorption may be selective, flotation can be used to collect one particular kind of particles from a mixture. Selective flotation of course requires the suspension of particles to be non-flocculated or if it is flocculated, the particles should



be fairly large, so that the floccules formed are continuously broken up into individual particles by the agitation. Flotation is a rate process and can only be successful if sufficient time is allowed for the particles to become attached to the gas bubbles before these have reached the foam layer floating on the suspension. There is also a thermodynamic condition [21] which must be satisfied for particle bubble attachment to occur. This is the requirement of a finite contact angle  $\theta$ .

Fig. 3 shows two particles, A and B, attached to a bubble, particle A being very hydrophobic and having a large contact angle  $\theta_A$ , whereas particle B is less hydrophobic and has a small contact angle. Particle A will adhere more strongly to the bubble than particle B. Young's equation (9) gives the relation between the contact angles and the respective interfacial tensions ( $\gamma_{SL}$ ,  $\gamma_{SG}$  and  $\gamma_{LG}$ ):

$$\gamma_{LG} \cos \theta = \gamma_{SG} - \gamma_{SL} \quad (9)$$

If the particle is originally hydrophilic ( $\theta = 0$ ) and the amphipolar solute (the collector) is added, the three interfacial tensions will be modified by adsorption according to the Gibbs adsorption equation,

$$\gamma = \gamma^0 - \int_{c=0}^{c \text{ final}} \Gamma d\mu_{\text{solute}} \quad (10)$$

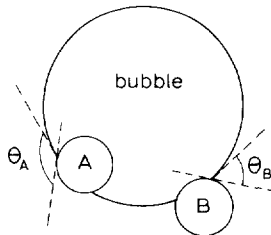


Fig. 3. Particles with large ( $\theta_A$ ) and small ( $\theta_B$ ) contact angles respectively.

An increase of the contact angle  $\theta$  (a decrease of  $\cos \theta$ ) can only be obtained in case  $\gamma_{SG}$  is decreased more than  $\gamma_{SL}$ , or if:

$$\int \Gamma_{SG} d\mu_{\text{solute}} > \int \Gamma_{SL} d\mu_{\text{solute}} \quad (11)$$

or

$$\int (\Gamma_{SG} - \Gamma_{SL}) d\mu_{\text{solute}} > 0 \quad (12)$$

Thus, an essential requirement for flotation is that the adsorption of the collector on the solid/gas surface is larger than or occurs at lower concentrations than the adsorption at the solid/liquid interface. The point is stressed because it is sometimes forgotten that the substance causing the hydrophobicity has to reach the solid/gas interface and stay there.

Finally when the material to be floated has accumulated in the foam, the next step in the process must be separation of the foam from the bulk and breaking of the foam.

The above may remind us that the flotation process really applies the whole bag of tricks of surface and colloid science, such as stability vs. flocculation, play with contact angles, breaking of foams and considerations of frequencies of collisions between bubbles and particles.

By discussing a few rather divergent cases of application of colloid science and by showing how often they are based upon the fundamentals of our science, I hope to have strengthened the conviction that ours is a field in which fundamental and applied science often go hand in hand.

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