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Macromolecular Adsorption: A Brief Introduction

Martinus A. Cohen Stuart Laboratory for Physical Chemistry and
Colloid Science, Wageningen Agricultural University,
Wageningen, The Netherlands

I. BIOLOGICAL MACROMOLECULES

The primary structure of many biological macromolecules is simply that of a linear chain of monomers. In this respect, they do not differ from most synthetic polymers. Behind the chemical simplicity, however, rather complex and specific behavior may be hidden. For example, the secondary and tertiary structures of proteins often play an essential role in their specific biological function. For such molecules it may seem impossible to develop a universal description as is now well established for synthetic polymers.

However, one may wonder whether this has been attempted. Some of the concepts fruitfully introduced in polymer physics may be quite relevant for understanding the behavior of, say, globular proteins. It is the purpose of this chapter to discuss polymers at interfaces from a physical chemists' point of view, highlighting processes and central concepts rather than specific systems. Effects of conformational entropy, internal cohesion, electrostatic interactions, and intermolecular interactions on adsorbed layers will be considered, and processes like transport, attachment, unfolding and trapping will be discussed.

As said, most biological polymers are chemically more complex than homopolymers and have a copolymer character that cannot be ignored. However, considering the entire plenitude of phenomena that various classes of copolymers can display would by far exceed the limits of this introductory presentation. We will therefore not explicitly discuss copolymers.

II. MACROMOLECULES ARE SOFT PARTICLES

Around the bonds that connect the atoms in the main chain of a linear polymer, some rotation is usually possible. This gives the polymer a certain degree of flexibility, which is usually enough to allow the molecule to assume a large number of shapes or *conformations*. With this large number of conformations, a conformation entropy is associated. In the absence of external forces, the chain will wiggle because of thermal motion, and assume an average, approximately spherical *coil* shape with a characteristic size R dependent on the number of monomers N per chain (i.e., the length of the chain). This dependence can be generally expressed as a power law: $R \sim N^{\nu}$. The conformational entropy gives the coil a certain elastic resistance to deformations such as squeezing and stretching. This resilience is rather weak: the molecules can be considered "soft spheres."

The characteristic size R of the coil depends strongly on the solvent [1,2] but it can always be written as a power law of the chain length N: $R \sim N^{\alpha}$. *Good solvents* tend to keep the individual monomers separate. In such a solvent, most shapes permitted by bond rotation are energetically equivalent.

If the monomers would not occupy any volume (i.e., the chain is infinitely thin, this is called an *ideal chain* analogously to ideal gases) one could describe the chain in terms of a random walk (diffusion-like) process. However, because monomers do have a volume, walks that lead to overlap between monomers must be excluded. The proper description is therefore that of a *self-avoiding walk.* The characteristic size R of such a structure is known to scale as $N^{3/5}(\alpha = 3/5)$, and such molecules are denoted as *swollen coils.* The monomer-monomer repulsion also ensures that the molecules do not cluster but form a homogeneous solution. At higher concentration, however, this repulsion is not enough to keep the coils apart; as soon as they fill the entire solution volume, they begin to interpenetrate, thus forming a transient network. This situation is now commonly referred to as "semidilute" solution.

In less good solvents, there is, effectively, an attraction between the monomers. As long as this attraction is very weak, the coil may somewhat contract, but it remains swollen. At a certain point, the attraction becomes strong enough to compensate the effect of the excluded volume of the monomers. This is called the θ point or θ temperature. The behavior of the coil around the θ point is equivalent to that of an ideal chain, for which random walk statistics apply and one can prove the $R \sim N^{1/2}(\alpha = 1/2)$; this is called the Gaussian coil because the density of monomers inside the coil is a Gaussian function of the distance to the center [2].

Should the solvent become even worse, the entropy can no longer maintain the open, dilute structure of the coil and the molecule collapses to a compact *globule.* Inside this globule, the monomer density is essentially constant and therefore the mass must scale as R^3 so that $R \sim N^{1/3}(\upsilon = 1/3)$. Of course, monomer-monomer attraction will not only occur between monomers within the same chain, but also between monomers on different chains. Hence, in poor solvents there is a concentration where the molecules accumulate into a dense phase and we have phase separation.

As a parameter that describes the strength of the monomer interaction it is customary to use the so-called Flory-Huggins parameter χ, which is essentially an excess Gibbs energy of monomer-solvent contacts (with respect to monomer-monomer and solvent-solvent contacts) normalized by kT. In good solvents, χ is close to zero, at the θ point it equals 0.5, and for poor solvents, $\chi > 0.5$. In many texts, the parameter $\upsilon = 1 - 2\chi$ is used. It measures the strength of the monomer-monomer interaction relative to that at the θ point and is called the *excluded volume* parameter. Its value is zero at the θ point, positive in better solvents and negative in worse solvents (Fig. 1).

In poor solvents, where the molecules collapse into globules, deformation is not only counteracted by the conformational entropy, but also by the fact that the number of (unfavorable) monomer-solvent contacts increases at the

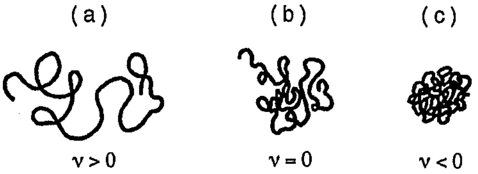

FIG. 1 Polymer molecules in solution under (a) good, (b) θ, and (c) poor solvent conditions.

expense of (favorable) monomer-monomer contacts, just as for a droplet of an inmiscible liquid in some liquid medium. One may therefore assign a certain *interfacial tension* γ to the molecules of order $kT\upsilon^2$. This means that collapsed macromolecules are also deformable, but to an extent dictated by the surface tension (υ^2) rather than the conformational entropy. In other words, they become "harder" as $|\upsilon|$ increases [3].

As is well known, protein molecules are rather compact. This compact structure is stabilized by hydrophobic attractions between lipophilic amino acids which tend to accumulate inside the globular structure of the molecule because water is a poor solvent for them. In this sense, there is a clear parallel with simple homopolymers in a poor solvent. As one approaches the temperature where the hydrophobic interactions become too weak to keep the globule together, the particles become "softer" (get lower surface tension) and unfolding becomes increasingly easier. Therefore one can consider the denaturation temperature of the protein as a kind of θ temperature. Of course, the important difference between proteins and simple polymers in a poor solvent is that the former are copolymers: they have sufficient hydrophilic monomers on their external surface to suppress the accumulation of molecules into a macroscopic phase. A detailed discussion of protein structure can be found in Chapter 2.

III. ADSORPTION AND PARTICLE DEFORMATION

Adsorption of a polymer occurs whenever its monomers are attracted sufficiently strongly by a surface. Therefore, on the one hand, the molecules attempt to maximize their favorable monomer-surface interactions by spreading out to a large extent. For each polymer-surface contact established, a solvent molecule is detached and the net Gibbs energy of contact formation is therefore $u_p - u_s$. For convenience, the parameter $\chi_s = (u_p - u_s)/kT$ has been introduced as a measure of adsorption affinity. On the other hand, there is a penalty in the form of the resistance to deformation. For the Gaussian or swollen coil, this resistance is weak. In the case of weak attraction, the polymer is deformed into a "pancake" of thickness D, where D scales as

$(\varepsilon/kT)^{-\alpha/(1-\alpha)}$, where ε is the adsorption energy per monomer [1]. For the Gaussian coil, one may argue that the Gibbs energy increase due to entropy loss ($-TS$) upon adsorption is, per monomer unit, of order $\ln(\omega^b/\omega^s)$, where ω^b and ω^s are the orientational degrees of freedom per monomer in the bulk (b) and in the surface (s), respectively. This entropic contribution is small, typically around 0.5 kT, and must be balanced by an equal adsorption energy ε for appreciable adsorption to occur. Values of 1 kT for ε are quite common; this is enough to completely squeeze the chains into an essentially flat structure [4] (Fig. 2a).

Hence, already at moderate adsorption strength per monomer, large polymers can make an appreciable number of contacts with the surface and will, therefore, adhere tenaciously. As a consequence, the surface will be fully covered before any free polymer in the equilibrium solution is detected. In other words, the adsorption has a strongly *high affinity* character. When the molecules start to crowd on the surface, they begin to interpenetrate, thus forming a more or less homogeneous layer on the surface with a high monomer concentration (Fig. 2b). Since, in good solvents, the monomers repel each other, the Gibbs energy of adsorption increases in this stage, eventually bringing the system to equilibrium. The homogeneity of the adsorbed layer allows us to consider it as a polymer solution with a concentration which only varies normal to the surface, the so-called density profile [4]. In Sec. V we will explain how one can calculate this profile theoretically from known solution properties of the polymer and from the adsorption energy.

For the globular polymer molecule (Fig. 2c), deformation leads to exposure of more monomers to the solvent. In other words, work must be done against the interfacial tension. Therefore, globular polymers adsorb in a way analogous to the spreading of liquid droplets [5]. The driving force is, again, given by the low polymer-substrate interfacial tension (proportional to χ_s), but the resistance is a measure of the monomer-monomer attraction as given by χ. Large deformation will occur as soon as $\chi_x = \chi^2$. For a strongly deformed polymer, the monomer-monomer contacts are so few that one can no longer speak of a surface tension; this occurs when the thickness becomes of order ξ_t, the thermal blob size given by $-1/\nu$ [3,5].

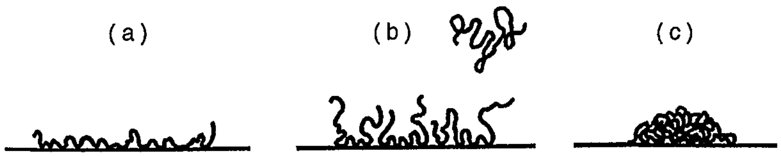

FIG. 2 Polymers on a surface: (a, b) good solvent conditions; (c) poor solvent conditions.

IV. FORMATION OF AN ADSORBED LAYER

When a bare surface is exposed to a solution of adsorbing macromolecules, an adsorbed layer will form. Each adsorbing molecule must pass through the following steps:

1. Transport toward the surface by convection and diffusion
2. Attachment
3. Spreading

In the following, we shall assume that the formation of the polymer layer takes place under well-defined hydrodynamic conditions, so that the first step (transport) can be treated simply by solving the convective diffusion equation. Analysis shows that most of the process takes place under steady-state conditions where a fixed concentration gradient drives the process. This leads to an adsorption rate [6]

$$\frac{d\Gamma}{dt} = k(c^b - c^s) \tag{1}$$

where c^s is the concentration of polymer in the immediate neighborhood of the surface, often referred to as the subsurface concentration, c^b is the bulk concentration, and k is a rate coefficient depending on diffusion coefficient and hydrodynamic conditions. Expressions for k in various flow geometries have been given by Adamczyk et al. [7]. The value of the *subsurface concentration* c^s depends on what happens near the surface, i.e., on the attachment process. In general, one can treat this as a first-order reaction. For the forward rate,

$$\left.\frac{d\Gamma}{dt}\right|_{+} = Kc^s \tag{2}$$

Of course, the rate constant K will decrease with increasing coverage Γ, because fewer and fewer surface sites are available for the polymer to attach to. However, even on a bare surface, it may be lowered by some repulsive barrier (e.g., electrostatic repulsion).

As the coverage increases, so does the rate of *desorption*. Eventually, the system should come to its equilibrium condition, and the rates of adsorption and desorption should become equal. This implies for the net attachment rate, i.e., the sum of forward and backward rates:

$$\frac{d\Gamma}{dt} = K(c^s - c^{eq}) \tag{3}$$

where c^{eq} is the equilibrium concentration corresponding to the value of Γ

at some moment during adsorption. The function $c^{eq}(\Gamma)$ is the inverse adsorption isotherm. Combining (1), (2), and (3), one obtains

$$\frac{d\Gamma}{dt} = \frac{c^b - c^{eq}}{1/k + 1/K} \tag{4}$$

Provided the attachment barrier is negligible ($K^{-1} = 0$) and the adsorbed layer entirely relaxed one can use this equation to deduce the adsorption rate from the equilibrium isotherm, and vice versa.

For example, the high-affinity adsorption isotherm so characteristic for most polymers implies that $c^{eq} \simeq 0$ up to almost saturation, so that $d\Gamma/dt = kc^b$, and Γ must increase linearly in time with a slope k up to almost saturation; this is easily verified in a well-controlled experiment [8]. Since the rate of adsorption cannot increase beyond kc^b, this is called the limiting flux J_0. Lower rates are indicative for adsorption barriers. One can also use the equation to describe desorption into pure solvent by putting $c^b = 0$ so that $d\Gamma/dt = -kc^{eq}(\Gamma)$ [9].

In order to develop this further and predict (starting from the same assumptions) adsorption and desorption rates, the function $c^{eq}(\Gamma)$ and, hence, an equilibrium adsorption theory is required. This will be considered in the following section.

V. THE HOMOGENEOUS LAYER IN EQUILIBRIUM

Developing a general theory for an arbitrary kind of polymer on an arbitrary surface is of course a hopeless task. We therefore shall have to limit ourselves to a tractable case, which nevertheless brings out essential features. We shall consider an ideally plane and homogeneous surface in contact with a solution of a simple, uncharged homopolymer. The polymer is homodisperse: all the polymer molecules have the same molar mass. (This limitation can be overcome, however [10].) The monomer units interact with sites on the surface with a net energy $-kT\chi_s$ which may be negative (attraction) or positive (repulsion); see Sec. III. As pointed out above, polymers in θ or good solvents form a layer of interpenetrated molecules, the density ϕ of which varies only normal to the surface. We now shall try to calculate this density profile $\phi(z)$.

One particularly transparent way to arrive at a theoretical description is the mean-field approach. On a crowded surface with many polymers, there are many interactions between the chains. In any statistical theory of adsorption, all these interactions have to be considered. However, this is obviously very complicated. In a mean-field theory, these interactions are replaced by interactions between a single chain and an average environment, called the "field" that originates from the presence of all the other chains.

Hence, each monomer at a distance z from the surface just “feels” a potential (Gibbs energy) given by the average density at and around z. This reduces the problem to one of a chain in an external, z-dependent field. Of course, the strength of the field at z is a function of the monomer density at z. To a reasonable approximation, one can ignore the interactions of the chain with itself. We then have the case of a Gaussian chain in an external field, which can be treated with random walk statistics and leads to an expression for the density profile and, hence to a field. Of course, this field must be the same as that which was initially imposed: it must be self-consistent, hence the term *self-consistent field* theory [4,11,12].

The first step in the calculation of ϕ at position z is to realize that a monomer finding itself at z (so that it contributes to $\phi(z)$) must be somewhere in a polymer chain. It therefore has to be the end point of *two* random walks (in the field), starting from either end of the chain, and ending exactly at z. Hence, we can write $\phi(z)$ in terms of the product of (1) the end point probabilities $g(z, s)$ and $g(z, N - s)$ (with respect to the same probabilities in the solution far from the wall) for the two walks that make up a chain of length N, (namely s steps from one end and $N - s$ steps from the other) and (2) the density of s-monomers in the bulk solution ϕ^b/N [4]:

$$\phi(z, s) = \frac{\phi^b}{N} \{g(z, s)g(z, N - s)\} \tag{5}$$

We now have to find the function $g(z, s)$ by considering the random-walk-in-a-field problem. This is equivalent to solving the diffusion equation

$$\lambda \frac{d^2 g}{dz^2} = ug + \frac{dg}{ds} \tag{6}$$

where λ is the fraction of bonds normal to the interface and ug represents the effect of the external field u on g. Equations of this type occur frequently. One example is the motion of elementary particles as described by Schrödinger’s equation. The general solution is written as

$$g(z, s) = \sum_i g_i(z)^{\varepsilon_i s} \tag{7}$$

where ε_i is the eigenvalue of the ith term. Note that the solution is factorized into a z- and s-dependent part. Short random walks will be rather different from long ones, and therefore $g(z, s)$ and $g(z, N - s)$ are also different for small values of s or $N - s$, i.e., near the end points. However, as the walks become longer, they will visit the same z again and again, and eventually the z-dependence of g becomes more or less independent of s. In terms of the Schrödinger equation, we expect stationary solutions for long time and a spectrum of well-separated stationary eigenfunctions. The assumption that is therefore usually made at this point is that only the first term in the series of Eq. (7) is important; this is equivalent to supposing that the system is in its "ground state" (this is called the ground state approximation or GSA [4]. Hence,

$$g(z, s) = g(z)e^{\varepsilon s} \tag{8}$$

Here, ε can be seen as the free energy per monomer in the ground state. Using this we can rewrite (5) as

$$\phi(z, s) = \frac{\phi^b}{N} g^2 e^{\varepsilon N} \tag{9}$$

Summing this over s gives

$$\phi(z) = N\phi(z, s) = \phi^b g^2 e^{\varepsilon N} \tag{10}$$

We note that in the solution far from the wall we must have $g(z) = 1$, giving

$$\varepsilon = -\frac{\ln(\phi_b)}{N} \tag{11}$$

The "potential" u can be considered as the extra reversible work needed to bring one monomer from the solution to the adsorbed layer, which is in good solvents well approximated by $\phi(z)$. Inserting this into (6) one obtains, for the case of an attracting wall (and using the boundary condition that $\phi(z)$ has a negative slope at the wall),

$$\phi(z) = \frac{\varepsilon}{\sinh^2(z + D/d)} \tag{12}$$

where D is a constant related to the adsorption energy per monomer, and d equals $\sqrt{\lambda/\varepsilon}$ [13]. For the adsorption isotherm in the region of the semiplateau one deduces by integration:

$$\Gamma = \frac{2\lambda}{d}\left\{\coth\left(\frac{D}{d-1}\right)\right\} \approx 2\lambda\left(\frac{1}{D} - \frac{1}{d}\right) \tag{13}$$

Note that the adsorbed amount is linear in ε, hence to $(\ln(\phi_b)/N)^{1/2}$; it is not really constant but increases very slowly with the polymer concentration. This modest increase in Γ comes from the growth of the dilute periphery of the layer with concentration and with molecular weight. Of course, the approximations introduced can be avoided if one solves the basic equations numerically. Then, end effects and short chains are no longer neglected. This has been done in great detail by Scheutjens and Fleer [11].

Further analysis has shown that good agreement between numerical results and analytical theory can be obtained when the expansion Eq. (7) is not truncated after the first term but after the second term; there is a second function $g_2(z)$ which has almost the same eigenvalue as g_1 but describes walks that *do not touch the wall.* In quantum mechanical terms, the spectrum is degenerate. Just as g_1^2 corresponds to chains which have at least two attached monomers (thereby forming loops), g_2^2 relates to conformations that do not touch the wall (free chains), and the cross product $g_1 g_2$ to chains that start on the surface and end in the solution (tails). Taking these three contributions into account, excellent agreement between numerical and analytical solutions can be established [4,13–15].

VI. ADSORPTION AND DESORPTION RATES

The function $\Gamma(c^{\mathrm{eq}})$ being available, we can invert it to $c^{\mathrm{eq}}(\Gamma)$ and insert it into Eq. (4). One sees immediately that, provided k is a constant and other resistances do not occur ($K^{-1} = 0$), we obtain a straightforward differential equation for $\Gamma(t)$. As pointed out, Γ is predicted to increase proportionally to t, the slope being given by k. As soon as the semiplateau is reached, c^{eq} increases very rapidly (roughly as $e^{N(\Gamma-\Gamma_{\mathrm{ov}})}$, where Γ_{ov} is the coverage where molecules start to overlap), $c^b - c^{\mathrm{eq}}$ drops rapidly, and $d\Gamma/dt$ becomes very small. Hence $\Gamma(t)$ has a second part where it rises very slowly (Fig. 3).

In the same way, we can analyze the case of desorption. Now, $c^b = 0$ is imposed. Initially, Γ decreases, as c^{eq} has the finite value c^0, but as Γ decreases, c^{eq} must become very small because of the high-affinity character of $\Gamma(c)$ (Fig. 3). Hence, $d\Gamma/dt$ also becomes very small. We can now use Eq. (12); to a very good approximation, $\Gamma \sim \log c$. If this is the case, one can show that Γ must decay logarithmically [9]:

$$\Gamma = \Gamma_0 \left\{1 - p \ln\left(1 + \frac{t}{\tau}\right)\right\} \tag{14}$$

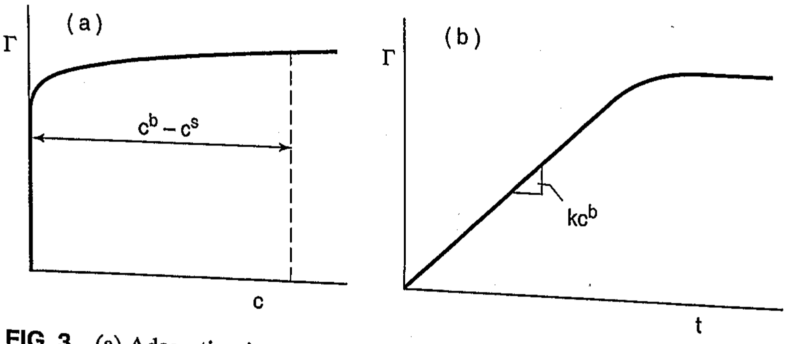

FIG. 3 (a) Adsorption isotherm $\Gamma(c)$; (b) corresponding kinetic curve $\Gamma(t)$.

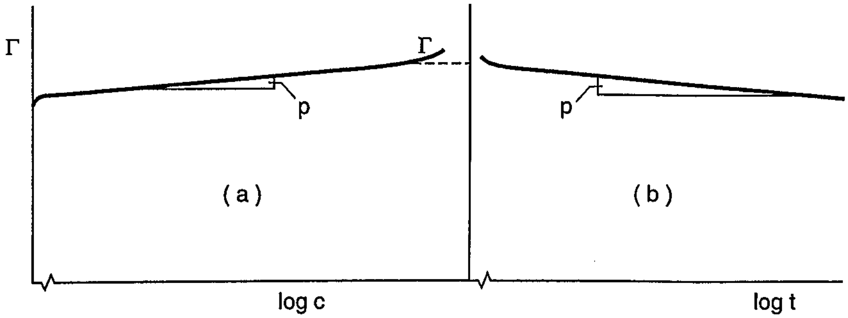

FIG. 4 (a) Adsorption isotherm Γ(log *c*); (b) corresponding desorption curve. Note that the slope of Γ(log *c*) is the same as the one for Γ(log *t*) but with a minus sign.

where p is a small coefficient of order $1/N$ and τ equals p/kc^0 (Fig. 4). This results teaches us that per decade in time a constant (small) amount $p\Gamma_0$ is desorbed, say 1% of the initial value. Hence, the time needed for desorption increases exponentially with the amount to be desorbed. It follows that, in a practical sense, long chains desorb too slowly for any rate to be measured, which is in agreement with the experimental observation that adsorbed polymer layers cannot simply be removed by rinsing with the solvent they were prepared from [9]. Yet, one should realize that this does not imply that densities and conformations at the surface cannot relax!

VII. STRUCTURE OF ADSORBED LAYERS

As pointed out, isolated random coil polymers tend to become strongly compressed normal to the surface. However, as soon as crowding occurs, the driving force for the spreading decreases because entirely free surface is no longer available. More polymer can adsorb, but the molecules must protrude into the solution and form loops and loose ends (“tails”). Hence, the dilute periphery of the adsorbed layer grows in the normal direction.

The protrusions, in particular the tails, have a pronounced effect on solvent flow along the surface. Despite their very low density they are able to suppress flow velocities near the surface very strongly, just as a few trees on an open field break the wind [4,16]. As a consequence, the surface apparently bears a considerable stagnant layer of solvent, the thickness of which is called the *hydrodynamic layer thickness* δ_h. Measurements and calculations show that δ_h is very small at low coverage (chains spread out) but increases enormously as soon as saturation is approached, and that the maximum layer thickness observed becomes strongly dependent on molecular weight. This is clearly shown by the (theoretical) curves given in Fig.

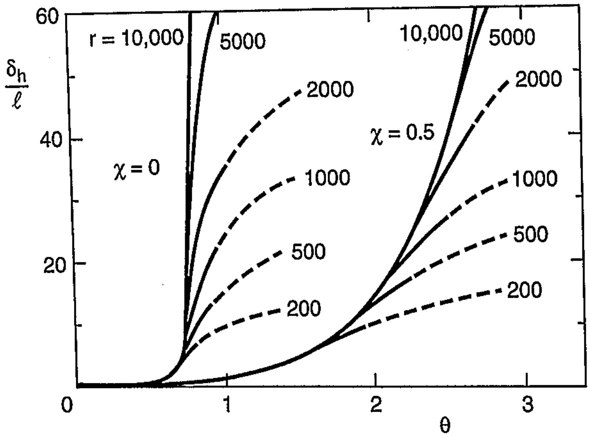

FIG. 5 Hydrodynamic layer thickness δ_h as a function of coverage θ, for various molar masses (here indicated by the number of chain segments r). The curves on the left are for $\chi = 0$, those on the right for $\chi = 0.5$, a Θ solvent. These curves are obtained by a theoretical based on flow perturbation in a (theoretically calculated) density profile [4].

5 [16]. In some systems, particularly for good solvents, a dependency of Γ on molecular weight could not be detected, yet δ increased strongly with increasing M: the few dominating tails hardly contribute to the adsorbed mass [17]. This corresponds quite well with what we see in Fig. 5 for good solvents: δ may increase very strongly with r while θ is virtually constant.

Turning this around, one concludes that very minor desorption of molecules from a saturated layer must show up in a strong decrease of δ_h; this idea has been exploited to verify the desorption rate equation [9]. Data are shown in Fig. 6 for *static* thickness measurements (at finite c^b) and for the *dynamic* case ($c^b = 0$).

VIII. POLYMER MIXTURES: PREFERENCE AND EXCHANGE

It is often stated that polymers adsorb irreversibly, implying that a molecule, once adsorbed, cannot leave the surface anymore. This is a very misleading idea. It has been observed for many systems that an adsorbed polymer molecule can readily desorb if another molecule (even when identical to the leaving one) takes its place so that Γ does not need to decrease. In other words, *exchange* with molecules in solution occurs frequently. This may have various consequences.

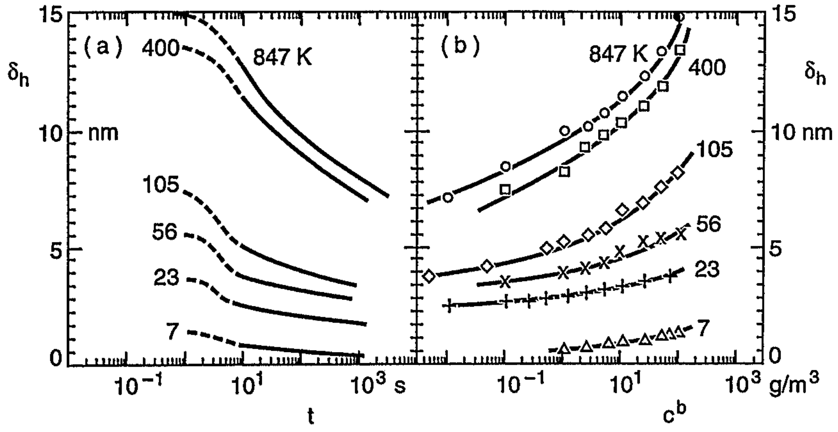

FIG. 6 (a) Decrease of layer thickness as a function of log t during a kinetic desorption experiment (the layer is continuously flushed with pure solvent); (b) increase of layer thickness as a function of log c in a static thickness measurement (fixed c for each point). Note the similarity in slope and shape between $\delta_h(\log t)$ and $\delta_h(\log c)$, just as between $\Gamma(\log t)$ and $\Gamma(\log c)$ in Fig. 4.

When the solution contains more than one solute component, exchange may lead to a change in the composition of the adsorbed layer. Most commercial polymers are far from pure components, as they contain a large variation in chain lengths so that one may anticipate shifts in the average chain length on the surface. Such *polydispersity effects* have indeed been observed in many systems [4,18,19]. In dilute solutions, there is a clear driving force for preferential adsorption of long chains. Each long chain (of length N) that adsorbs at the expense of an equal mass of short chains (of length n) liberates on average N/n chains, which leads to a small net gain in translational entropy of order $kT(N/n - 1)$. Since exchange can even be observed in the absence of a net driving force, we should not be surprised to see exchange occur between chemically identical short and long chains. For an entire distribution of chain lengths (as is the usual case) one can show that the surface chain length shifts gradually to higher values as the polymer concentration in solution is increased; the amount of available surface area as compared to the solution volume is then a crucial parameter determining the final distribution of each fraction in the polymer sample over the solution and the surface [10,20]. How this exchange process proceeds and what its rate is will be discussed in the following section.

Chemically different polymer molecules have often an even more pronounced tendency for exchange. In this case the driving force is a lowering of the Gibbs energy of the interfacial contact. Since the adsorbed mass in equilibrium depends only logarithmically on the bulk concentration of a component, whereas the polymer-surface interaction is linear in the surface composition, a large concentration difference is needed to offset a difference in surface energy [4,21]. Therefore, simple experiments of sequential adsorption may quickly tell which of a given monomer pair adsorbs most strongly.

The limiting case of exchange between chemically different species is displacement of a polymer by a small molecule. This may even occur when the small displacer molecule adsorbs just a bit stronger than the monomer unit but is present in large amounts [22–24]. A simple case is the adsorption of a polymer from its own "monomer." Theory predicts that this will not occur as there is no change in surface contact energy, hence no driving force for spreading and adsorption. Diluting the displacer will eventually restore the situation of adsorption; this happens at a sharply defined *critical displacer concentration.* Thermodynamic analysis allows us to determine the adsorption energy per monomer unit from this critical displacer concentration [22,23].

Occurrence of exchange is also well documented for proteins. When a solution of a protein is exposed to a surface, adsorbed molecules may again spontaneously exchange with molecules from the solution. It has been found for some cases that as a result of adsorption followed by desorption one finds molecules in the solution which have undergone irreversible changes in conformation. Exchange between different proteins occurs frequently in mixtures and is known as the "Vroman effect" [25].

IX. SPREADING: EXPERIMENTAL EVIDENCE

In Sec. III we argued that macromolecular adsorption is always accompanied by deformation or *spreading* of the molecules. In our analysis of the rate of the adsorption process we totally ignored this spreading process. In other words, we considered adsorption processes where spreading occurs very fast as compared to the experimental time scale. As a result, no information on the rate of the spreading process could be obtained. What if this is not so? Qualitatively, one consequence is immediately seen.

If the molecules need a certain time τ_s to spread, we can compare that to the time τ_d required to deposit molecules to the surface. If the deposition is slow ($\tau_s < \tau_d$), each molecule can unfold and spread before it is surrounded by other molecules. The adsorbed amount will correspond to a thin layer and therefore be low. In the reverse case, fast supply ($\tau_s > \tau_d$), the molecules are enclosed by neighbors before they had time to unfold. The layer will therefore be thicker and Γ higher. The two cases are sketched in Fig. 7.

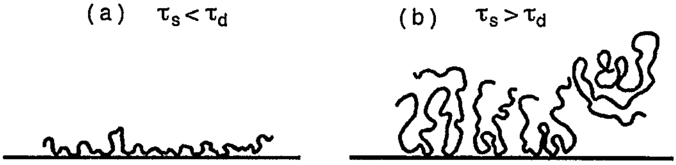

FIG. 7 Adsorbed layers obtained at (a) fast and (b) slow spreading.

In order to develop this more quantitatively, we need to specify the occupied area as a function of time. Let us suppose that one single time scale τ_s dominates the spreading process, i.e.,

$$a = a_0 + \alpha(1 - e^{-t/\tau_s}) \tag{15}$$

where a_0 is the size of the molecule upon first attachment and α denotes the extra surface occupied at full spreading. In addition, we need to specify the relation between the rate of attachment and the coverage. We simply suppose that this rate is proportional to the unoccupied area β. We now have two parallel processes, supply and spreading, which are coupled by the instantaneous value of β. This leads to a differential equation for the adsorbed mass versus time, which now becomes a function of the limiting flux J_0 [26,27]. If no desorption occurs (so that spreading stops as soon as $\beta = 0$), one gets a family of $\Gamma(t)$ curves with increasing saturation plateaus as J_0 increases. This allows us to determine the spreading rate constant. An experimental example is given in Fig. 8 for the adsorption of the protein savinase [27].

Desorption may also occur, in which case some molecules may increase their occupied area at the expense of others; this could be called "competitive spreading." If this occurs, one expects that at high supply rates many molecules are packed on the surface. As they begin to spread, some molecules are "kicked off" the surface and the coverage decreases spontaneously: the $\Gamma(t)$ curve has an overshoot. At lower supply rates, the spreading process can keep up with the supply, and the overshoot disappears. Such behavior is seen, e.g., for the protein savinase on silica (Fig. 9) [28].

Effects as discussed here occur frequently for proteins, but not for most of the swollen polymers, although one case for a polyelectrolyte has been reported. This seems to indicate that the spreading rate is strongly decreased by the high density in the protein globules, probably as a result of strong friction within the molecule as it is being deformed. Swollen polymers do not have much internal friction. However, their spreading rate may be slowed down because monomers must detach and reattach to the surface, and this requires an activation energy which is equivalent to friction with

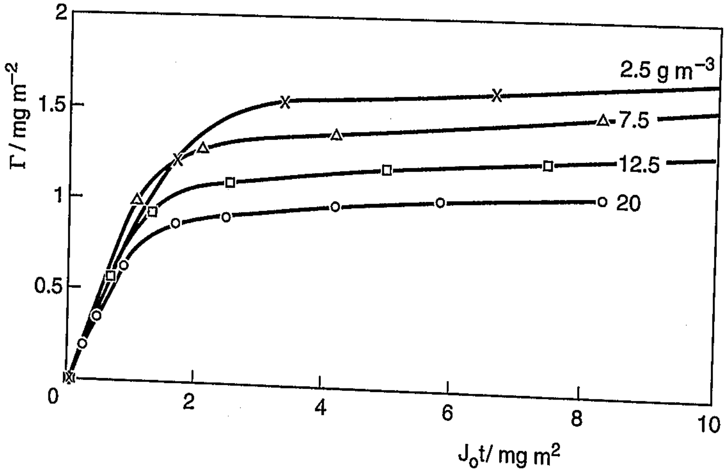

FIG. 8 Adsorption kinetics of savinase at various concentrations, hence various supply rates (limiting flux) $J_0 = kc^b$. The time axis has been renormalized by J_0 to make the initial slopes all equal to unity [27].

the substrate. Alternatively, competition with surrounding molecules may play a role.

That surrounding molecules do so is deduced from exchange experiments between two polymeric species where the detected rate of desorption of one species reveals the rate of spreading of the other (Fig. 10) [29,30]. Most observations have shown that this process has two stages: (1) the invading chain attaches rapidly to the surface; (2) the displaced polymer molecules

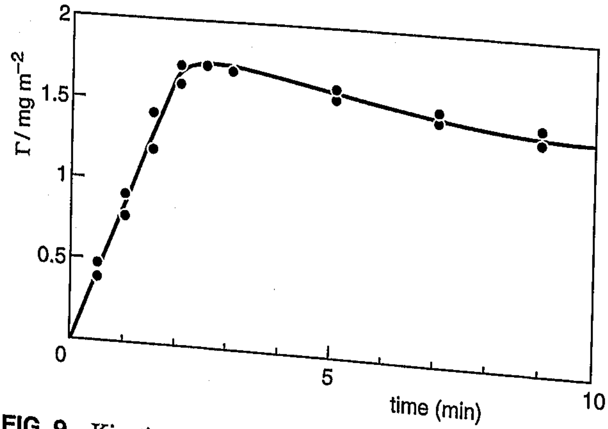

FIG. 9 Kinetic curve for the adsorption of savinase, showing an overshoot [28].

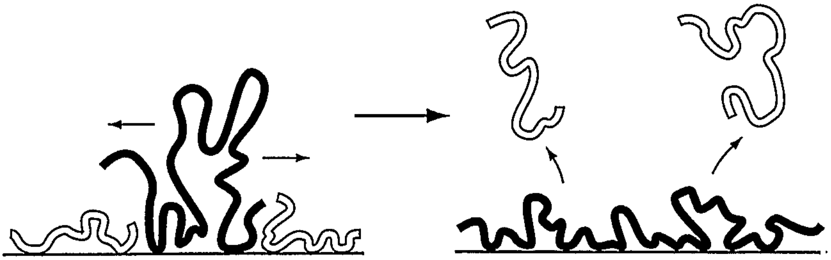

FIG. 10 Desorption of molecules induced by a spreading process: the detected rate of desorption reveals the rate of spreading.

leave the surface more slowly. In fact, in many cases one can stop the supply of displacing polymer without interrupting the desorption process: the displacer is already "stored" on the surface. In our view, desorption then follows as a result of competitive spreading, where the invading chain increases its occupied area at the expense of the leaving species. Detailed studies on several systems have shown that the rate of competitive spreading depends on (1) stiffness of the invading chain and (2) its net adsorption energy. This seems plausible, as both increase the friction between the polymer and the substrate.

X. TRAPPING

Granick [31] has emphasized the importance of topological effects in dense layers of flexible polymers. Just as in concentrated solutions, long chains tend to become entangled, and this hampers translational diffusion very strongly. Hence, instead of displacement by spreading (as described above) an incoming polymer can also *trap* chains that are already on the surface. The trapped chain must escape "from under" the invading chain which may involve a kind of slithering motion (reptation) that could be very slow indeed.

This trapping phenomenon has been investigated in more detail with a system consisting of two rather similar polysaccharides. These were first sequentially supplied to the surface in order to allow displacement and/or trapping to occur. Then the solvent was changed such that the first polymer was encouraged to leave the substrate. Desorption was allowed to take place. Finally, the composition of the adsorbed layer was analyzed. The experiment was repeated for several lengths of the displacer polymer. Surprisingly, both displacement and trapping were observed. When the second polymer was shorter than the first one, displacement did not occur but substantial trapping

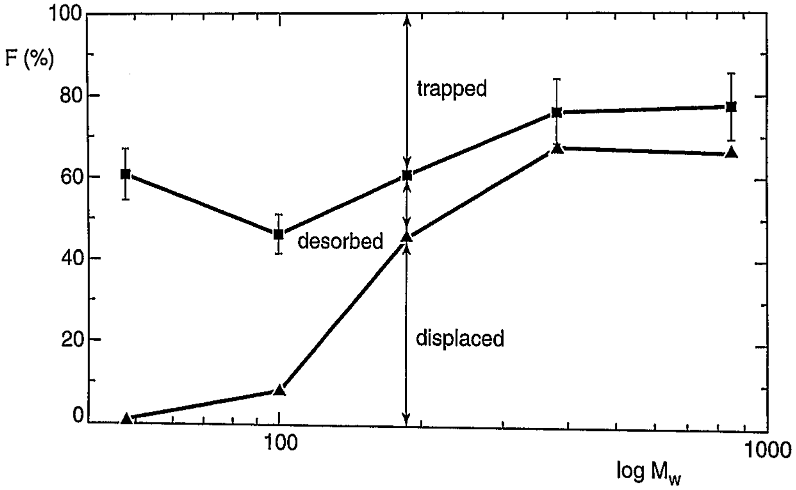

FIG. 11 Fraction of initially adsorbed polymer that is displaced, desorbed, and trapped, as a function of displacer/trapper chain length. System: carboxypullulan adsorbed on polystyrene from water, trapped by uncharged pullulan [32].

was seen. Increasing the displacer's chain length led to substantial displacement (up to about 80%) and much less trapping (Fig. 11) [32].

XI. POLYELECTROLYTES AND POLYAMPHOLYTES

So far we have not said anything about electrostatic effects. Yet many water-soluble macromolecules, particularly those of biological origin, carry charges. A simple case is that of a water-soluble homopolymer with a fixed fraction of equally charged monomers. If these charges arise from strong dissociating groups, they will remain charged over the entire pH range; this is called a *quenched polyelectrolyte*. The opposite case, where the charge arises from reversible proton transfer and is thus pH dependent, is the *annealed* case [33]. Another case of importance, certainly in the context of biological matter, is that of polyampholytes, which carry both positive and negative groups.

Polyelectrolytes tend to swell due to essentially two electrostatic effects: the chains become locally more rigid and the effective excluded volume increases. Very long polymers will still have a swollen coil shape, but short ones may eventually become rodlike. Polymers in poor solvents, which would be collapsed in their neutral state, may swell dramatically as soon as they acquire enough charges; there are well-documented cases for annealed polyelectrolytes which behave in this way (e.g., polymethacrylic acid) [34].

Polyampholytes behave differently. If their net charge is around zero, they tend to contract, because the formation of ion pairs between positive and negative groups leads again to an increase of entropy which drives the association. Synthetic polyampholytes therefore tend to be poorly soluble. Adding salt may improve the solubility and narrow the pH range in which there is phase separation ("salting in") because the entropy gain of the ions becomes less. Hence, it may be misleading to consider only the *net* charge on a molecule. At larger distances (of order κ^{-1}, the *Debye length*) the local variations in charge become "invisible" and only the net charge is important.

Surfaces may be classified in roughly the same way. Many inorganic surfaces consist of metal (hydr)oxides and can be considered as annealed surfaces that get their charge (density σ_s) from reversible proton transfer reactions. Various insoluble salts behave likewise, but they get their charge from other adsorbing ions. Most of these annealed surfaces are amphoteric and have a point where their net charge is zero; this is the point of zero charge (pzc) [35]. Quenched surfaces are obtained if strongly dissociating groups are chemically attached to a surface; a typical example is the surface of polymer latex particles with sulfate groups. The behavior of polyelectrolytes and polyampholytes is complicated because both the electrostatic and the nonelectrostatic (short range) interactions may contribute and all sorts of patterns may arise.

In order to appreciate the role of electrostatics, we first discuss *pure electrosorption* of a simple polyelectrolyte on a surface with opposite, quenched charge, from a solution of very low ionic strength [4]. In its neutral state, the polymer experiences no attraction from this surface, and adsorption does not take place. A small amount of charge suffices to induce substantial adsorption up to a point where the charge on the surface and that on the polymer are just equal. Beyond that *charge compensation* point, only little more charged polymer can adsorb (for entropic reasons the net charge of surface + polymer need not be zero) up to a certain extent of overcompensation [36,37]. Beyond this value of σ_p the adsorption process can be considered as a kind of ion exchange process, where the macroion takes the place of many small counterions at the surface [38]. Clearly, the driving force for this process is the large entropy gain (at low ionic strength) due to the liberation of the small ions. We should therefore expect that the adsorbed amount comes close to charge stoichiometry. Hence, if the charge density σ_p on the polymer increases further, less and less polymer is needed to reach the same overcompensation: the adsorption decreases with increasing σ_p. A curve of Γ versus σ_p is obtained with a pronounced maximum located at the compensation point (Fig. 12) [38]. This pattern is rather general and occurs for many polyelectrolytes. If there are additional, nonelec-

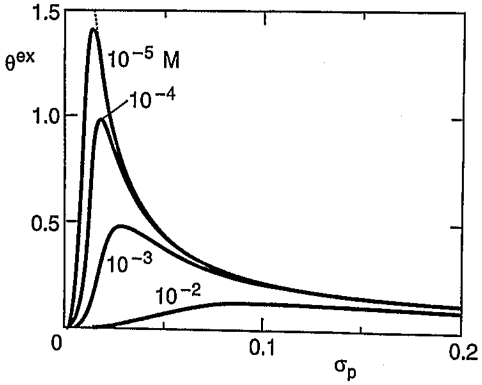

FIG. 12 Adsorption θ^{ex} of a polyelectrolyte on a surface with fixed charge, as a function of polymer charge density σ_p [38].

trostatic interactions contributing to the adsorption the adsorbed amounts at low σ_p will be increased, particularly those around $\sigma_p = 0$.

An experimental case of pure electrosorption (for an annealed polyelectrolyte) has been reported recently (Fig. 13) [39]. In this case, the amphoteric nature of the annealed surface played a crucial role. On the basis of net charge, electrosorption would not be expected to occur beyond the pzc of the surface, where polymer and surface carry the same charge, because there would be no net attraction between the polymer and the surface. Yet, adsorption occurs well into that range. This can only mean that the polymer is able to find and attach to sites of opposite charge: it sees the heterogeneity

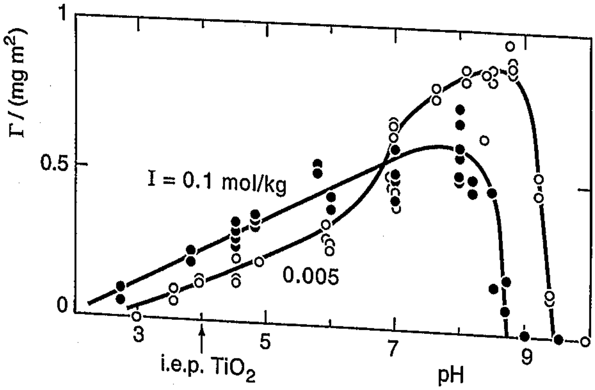

FIG. 13 Adsorption vs. pH of PDMAEMA on TiO_2 at two different ionic strengths [39].

of the surface. That nonelectrostatic forces are responsible for this effect could be excluded because the polymer was unable to adsorb in its uncharged form.

When we have electrosorption of a quenched polyelectrolyte on an annealed surface, the polymer structure remains unaffected by pH. The system then behaves as a capacitor with a fixed capacitance so that charge and potential are linearly related as are (by Nernst's law) potential and pH. As a result, the adsorption is simply linear in pH [39]. In many cases, both polymer and surface can adjust their charge. Provided the pzc of the surface is well separated from the p*K* of the polyelectrolyte, we can observe a combined pattern [40].

At this point, we should consider the question to what extent polyelectrolyte adsorption is reversible. Adsorption of polyelectrolytes is a self-killing process: the accumulation of charged polymer leads to a high electrostatic potential which will repel new incoming molecules. Even if these molecules could anchor under strong short-range interactions (complexation, hydrophobic interaction) they may not be able to reach the surface. If this occurs, the adsorbed amount is kinetically limited, rather than the outcome of a free energy balance. Lowering σ_p (pH shift) or adding salt may then lower the kinetic barrier and promote adsorption, but subsequently restoring the original conditions does *not* restore the corresponding adsorption. In other words, adsorption hysteresis occurs under cycling the pH or the ionic strength. This is analogous to the aggregation of charged colloidal particles which can be very effectively enhanced by adding salt or bringing the system into the pzc, but often cannot be undone by restoring the conditions under which the dispersion was stable. Kinetic barriers due to electrostatic repulsion for flexible polyelectrolytes were recently considered theoretically [41]; examples of experimental systems are numerous in the literature. We give one example in Fig. 14.

Polyampholytes are attracted to almost any charged surface. As with the amphoteric surface, they can find (short-range) electrostatic attraction even when the net surface charge is repulsive. This has been shown theoretically and experimentally for synthetic polyampholytes [42,43]. Should nonelectrostatic interactions also be present, then adsorption is even more likely to occur, unless a very strong barrier prohibits the attachment of the polymer. Hence, proteins in their pzc are likely to adsorb to almost any substrate and certainly to hydrophobic substrates.

Adding electrolyte will reduce all effects due to charges and therefore we should expect to eventually obtain a case of pseudoneutrality [4]. How adsorption depends on ionic strength therefore depends in the first place on the level of adsorption in the absence of any charge. If this is high, one may anticipate salt to enhance adsorption; if this is low or zero, then one must

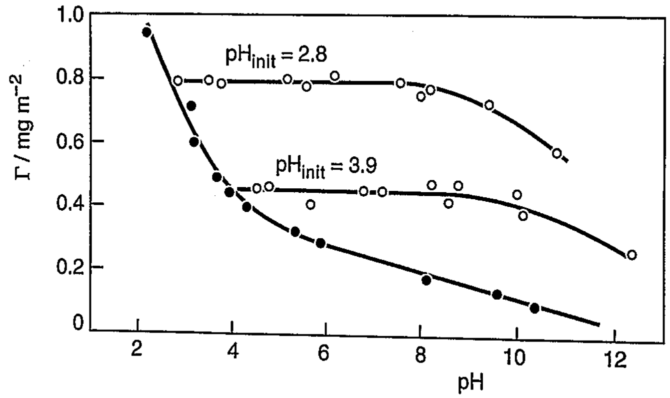

FIG. 14 Polyelectrolyte adsorption hysteresis upon cycling pH: adsorption of carboxy methyl cellulose on titanium dioxide (TiO_2, rutile) particles from aqueous electrolyte solution. Closed symbols: adsorption was measured at fixed pH; open symbols: adsorption took place at low pH (2.8 and 3.9, respectively) but was determined after increasing the pH [40].

expect lower adsorption [4,37]. In some subtle cases there is a weak maximum because screening of lateral interactions occurs before extensive ion competition for surface sites comes into play [39,44].

XII. CONCLUDING REMARKS

The adsorption process of a macromolecule is a complex process in which transport in solution, attachment barriers, and shape relaxations together determine the final outcome. In particular, shape relaxations are difficult to study directly, but recent research has shed much light on the factors that control the rate of these surface processes. With the help of these insights, it may soon become feasible to construct a theory for the adsorption of biopolymers.

REFERENCES

1. P. G. de Gennes, *Scaling Concepts in Polymer Physics*. Cornell University Press, Ithaca, NY, 1979.
2. H. Yamakawa, *Modern Theory of Polymer Solutions*. Harper & Row, 1971.
3. I. M. Lifschitz, A. Yu. Grosberg, and A. R. Khoklov, Structure of a polymer globule formed by saturating bonds. *Zh. Exp. Teor. Fyz.* *71*:1634–1643 (1976).
4. G. J. Fleer, M. A. Cohen Stuart, J. M. H. M. Scheutjens, T. Cosgrove, and B. Vincent, *Polymers at Interfaces*. Chapman & Hall, London, 1993.

5. A. Johner and J. F. Joanny, Polymer adsorption in a poor solvent. J. Phys. II *1*:181–194 (1991).
6. M. A. Cohen Stuart and G. J. Fleer, Adsorbed polymers in nonequilibrium situations. Ann. Rev. Mat. Sci. *26*:463–500 (1996).
7. Z. Adamczyk, T. Dabros, J. Czarnecki, and T. G. M. van de Ven, Particle transfer to solid surfaces. Adv. Colloid Interface Sci. *19*:183–252 (1983).
8. J. C. Dijt, M. A. Cohen Stuart, J. E. Hofman, and G. J. Fleer, Kinetics of polymer adsorption in stagnation point flow. Colloids Surfaces *51*:141–158 (1990).
9. J. C. Dijt, M. A. Cohen Stuart, and G. J. Fleer, Kinetics of polymer adsorption and desorption in capillary flow. Macromolecules *25*:5416–5423 (1992).
10. G. J. Fleer, Multicomponent polymer adsorption. A useful approximation based upon ground-state solutions. Colloids Surf. A: Physicochem. Eng. Aspects *104*:271–284 (1995).
11. J. M. H. M. Scheutjens and G. J. Fleer, Statistical theory of the adsorption of chain molecules. I: Partition function, segment density distribution and adsorption isotherms. J. Phys. Chem. *83*:1619–1635 (1979); II: Train, loop, tail size distribution *84*:178–190 (1980).
12. P. G. de Gennes, Polymer solutions near an interface. I: Adsorption and depletion layers. Macromolecules *14*:1637–1644 (1981); II: Interaction between two plates carrying adsorbed polymer layers *15*:492–500 (1982).
13. G. J. Fleer, Ground state description of the adsorption of homodisperse and polydisperse polymers. Macromol. Symp. *113*:177–196 (1997).
14. J. M. H. M. Scheutjens, G. J. Fleer, and M. A. Cohen Stuart, End effects in polymer adsorption: a tale of tails. Colloids Surf. *21*:285–306 (1986).
15. A. N. Semenov, J. Bonet-Avalos, A. Johner, and J. F. Joanny, Adsorption of polymer solutions onto a flat surface. Macromolecules *29*:2179–2196 (1996).
16. M. A. Cohen Stuart, F. H. W. H. Waajen, T. Cosgrove, T. L. Crowley, and B. Vincent, Hydrodynamic thickness of adsorbed polymer layers. Macromolecules *17*:1825–1830 (1984).
17. C. W. Hoogendam, C. J. W. Peters, A. de Keizer, M. A. Cohen Stuart, and B. H. Bijsterbosch, Layer thickness of adsorbed CMC on hematite. J. Colloid Interface Sci. (submitted).
18. M. A. Cohen Stuart, J. M. H. M. Scheutjens, and G. J. Fleer, Polydispersity effects and the interpretation of polymer adsorption isotherms. J. Pol. Sci. Pol. Phys Ed. *18*:559–573 (1980).
19. J. M. H. Scheutjens and G. J. Fleer, Some implications of recent polymer adsorption theory, in *The Effect of Polymers on Dispersion Properties*, (Th. F. Tadros, ed.), Academic Press, London, 1982, pp. 145–168.
20. S. P. F. M. Roefs, J. M. H. M. Scheutjens, and F. A. M. Leermakers, Adsorption theory for polydisperse polymers. Macromolecules *27*:4810–4816 (1994).
21. D. C. Leonhardt, H. E. Johnson, and S. Granick, Adsorption isotope effect for protio- and deuteropolystyrene at a single surface. Macromolecules *23*: 685 (1990).

22. M. A. Cohen Stuart, G. J. Fleer, and J. M. H. M. Scheutjens, Displacement of polymers. I: theory. Segmental adsorption energy from polymer desorption in binary solvents. J. Colloid Interface Sci. *97*:515–525 (1984).
23. G. P. van der Beek, M. A. Cohen Stuart, G. J. Fleer, and J. E. Hofman, A chromatographic method for the determination of segmental adsorption energies of polymers. Polystyrene on silica. Langmuir *5*:1180–1186 (1989).
24. G. P. van der Beek, M. A. Cohen Stuart, G. J. Fleer, and J. E. Hofman, Segmental adsorption energies for polymers on silica and alumina. Macromolecules *24*:6600–6611 (1991).
25. L. Vroman and A. L. Adams. Adsorption of proteins out of plasma and solutions in narrow spaces. J. Colloid Interface Sci. *111*:391 (1986).
26. E. Pefferkorn and A. Elaissari, Adsorption-desorption processes in charged polymer-colloid systems. Structural relaxation of adsorbed macromolecules. J. Colloid Interface Sci. *138*:187 (1990).
27. M. C. P. van Eijk and M. A. Cohen Stuart, Polymer adsorption kinetics: effects of supply rate. Langmuir *13*:5447 (1997).
28. J. Buijs, P. A. W. van den Berg, J. W. Th. Lichtenbelt, W. Norde, and J. Lyklema, Adsorption dynamics of IgG and its F(ab$'$)$_2$ and Fc fragments studied by reflectometry. J. Colloid Interface Sci. *178*:594–605 (1996); M. C. L. Maste, Proteolytic stability in colloidal systems. Ph.D. thesis, Wageningen University, 1996.
29. J. C. Dijt, M. A. Cohen Stuart, and G. J. Fleer, Surface exchange kinetics of chemically different polymers. Macromolecules *27*:3229–3237 (1994).
30. H. E. Johnson and S. Granick, Exchange kinetics between the adsorbed state and free solution: PMMA in CCl_4. Macromolecules *23*:3367–3374 (1990).
31. H. E. Johnson, J. F. Douglas, and S. Granick, Regimes of polymer adsorption desorption kinetics. Phys Rev. Lett. *70*:3267 (1990).
32. A. Krabi and M. A. Cohen Stuart, Sequential adsorption of polymer—displacement or trapping? Macromolecules, in press (1990).
33. I. Borukhov, D. Andelman, and H. Orland, Polymer solutions between charged surfaces, Europhys. Lett. *32*:499 (1995).
34. J. C. Leyte and M. Mandel. Potentiometric behavior of poly(methacrylic acid). J. Pol. Sci. A2 (1964), 1879–1891.
35. J. Lyklema, *Fundamentals of Interface and Colloid Science*, Vol. II, Chap. 3, Academic Press, London, 1995.
36. M. R. Böhmer, O. A. Evers, and J. M. H. M. Scheutjens, Weak polyelectrolytes between two surfaces: adsorption and stabilization. Macromolecules *23*: 2288–2301 (1990).
37. H. G. M. van de Steeg, M. A. Cohen Stuart, A. de Keizer, and B. H. Bijsterbosch, Polyelectrolyte adsorption: a subtle balance of forces. Langmuir *8*: 2538–2546 (1992).
38. M. A. Cohen Stuart, Polyelectrolytes on solid surfaces, in *Short and Long Chains at Interfaces*, Proc. 30th Rencontres de Moriond (J. Daillant, P. Guenoun, C. Marques, P. Muller, and J. Trân Thanh Vân, eds.), Editions Frontières, 1995, pp. 3–12.

39. N. G. Hoogeveen, M. A. Cohen Stuart, and G. J. Fleer, Polyelectrolyte adsorption on oxides. I: Kinetics and adsorbed amounts. J. Colloid Interface Sci. *182*:133–145 (1996).
40. C. W. Hoogendam, A. de Keizer, M. A. Cohen Stuart, B. H. Bijsterbosch, and J. G. Batelaan, Adsorption mechanisms of carboxymethylcelluloses on mineral surfaces. Langmuir (submitted).
41. M. A. Cohen Stuart, C. W. Hoogendam, and A. de Keizer, Kinetics of polyelectrolyte adsorption. J. Phys. Condensed Matter, in press (1997).
42. J. F. Joanny, Adsorption of a polyampholyte chain. J. Phys. France II *4*:1281–1288 (1994).
43. S. Neyret, L. Ouali, F. Candau, and E. Pefferkorn, Adsorption of polyampholytes on PS latex. Effect on the colloid stability. J. Colloid Interface Sci. *176*:86–94 (1995).
44. B. C. Bonekamp, Adsorption of Polylysins at Solid-Liquid Interfaces, Ph.D. thesis, Wageningen University, 1984.