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Lateral Interactions in the Low-Density Region of Lipid Monolayers

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An approximate method to estimate the two-body total lateral energy profile for a two-dimensional system in the dilute concentration range is introduced. This profile is obtained from the phase diagram, Πa versus a, for lipid monolayers, where, Π is the force per unit length and a the available area per molecule. The potential energy profiles exhibit a shallow minimum of a few kT units, similar to the secondary minimum observed in colloids.

1. Introduction

The intermolecular total interaction for three-dimensional gases can be obtained directly or indirectly from many types of experimental data: transport and virial data, solid state data, and X-ray diffraction of gases (see Margenau and Kestner[1]). However, although the literature contains quite accurate methods for three-dimensional gases, there is a lack of this kind of information for two-dimensional systems. Accordingly, we introduce here an approximate method to estimate the total lateral energy profile for these systems in the low-density region.

The two-body total lateral energy interaction can be obtained in an easy and fast way, by determining the two parameters, α and β, from the curve Πa versus Π of the phase diagram surveyed with a Langmuir balance (Π being the lateral force exerted in the system per unit length, dyn·cm^{-1} and a the available area per molecule). This region has also to fulfill the condition that a be of the order of some units of r^2, where r is the intermolecular distance. This assures the existence of some pre-established molecular order and correspondingly the phase diagram will reflect the intermolecular interaction.

In some three-dimensional gases with high thermal velocity (low molecular weight) this happens at quite high pressures; this is not the case for two-dimensional lipid systems.

2. Theory

It is well-known that a system in thermodynamic equilibrium performs fluctuations in the number of its particles $\bar{N}$. For a two-dimensional system the fluctuation in particle number relative to a system without interparticle interaction (ideal gas) with the same number of particles, $\sigma_{\bar{N}}/\sigma_{\bar{N}}^{\text{ideal}}$, was given in ref 3, namely

$$\sigma_{\mathrm{R}} = \frac{\sigma_{\bar{N}}}{\sigma_{\bar{N}}^{\ \text{ideal}}} = \sqrt{-\frac{kT}{a^2\left(\frac{\partial \Pi}{\partial a}\right)_{\mathrm{T}}}} \tag{1}$$

where k is the Boltzmann constant and T the absolute temperature. The available area per molecule a and the derivative of the force with respect to this area $(\partial \Pi/\partial a)_T$ can be obtained from the phase diagram (Π vs a) obtained experimentally with a Langmuir balance (see Figure 1a,b).

The relation between the integral of the correlation function, ν, over a certain area $\vec{A}$ and σ_{R}, is given by (see for instance Landau and Lifshitz[2])

$$\int (\vec{r})\ \mathrm{d}\vec{A} = \sigma_{\mathrm{R}}^{\ 2} - 1 \tag{2}$$

As we are interested in intermolecular interactions, we chose the upper limit of the integral as being a, the available area per molecule. Also making the approximation of two-dimensional isotropy (this means to replace $\vec{r}$ by r and $\vec{A}$ by A in the former equation). Then eq 2 tranforms in

$$\int_0^a \nu(r)\ \mathrm{d}A = \sigma_{\mathrm{R}}^{\ 2} - 1 \tag{3}$$

Performing the derivative of eq 3 with respect to the upper limit of the integral a and from the definition of the primitive function of ν, we obtain

$$\nu = \mathrm{d}\sigma_{\mathrm{R}}^{\ 2}/\mathrm{d}a \tag{4}$$

For a slightly nonideal gas, the correlation function is given by (see for instance Landau and Lifshitz[2])

$$\nu(a) = \frac{1}{a}\left[\exp\left(-\frac{U(a)}{kT}\right) - 1\right] \tag{5}$$

where we have explicitly determined the dependence on a for the correlation function and the intermolecular interaction energy for each state of thermodynamic equilibrium. The use of eq 5 is justified because we will use data from the low-density region of the phase diagram.

From eqs 4 and 5, we obtain

$$\frac{U(a)}{kT} = -\ln\left(1 + a\,\frac{\mathrm{d}\sigma_{\mathrm{R}}^{\ 2}}{\mathrm{d}a}\right) \tag{6}$$

To avoid a numerical differentiation of σ_{R}^2, one utilizes

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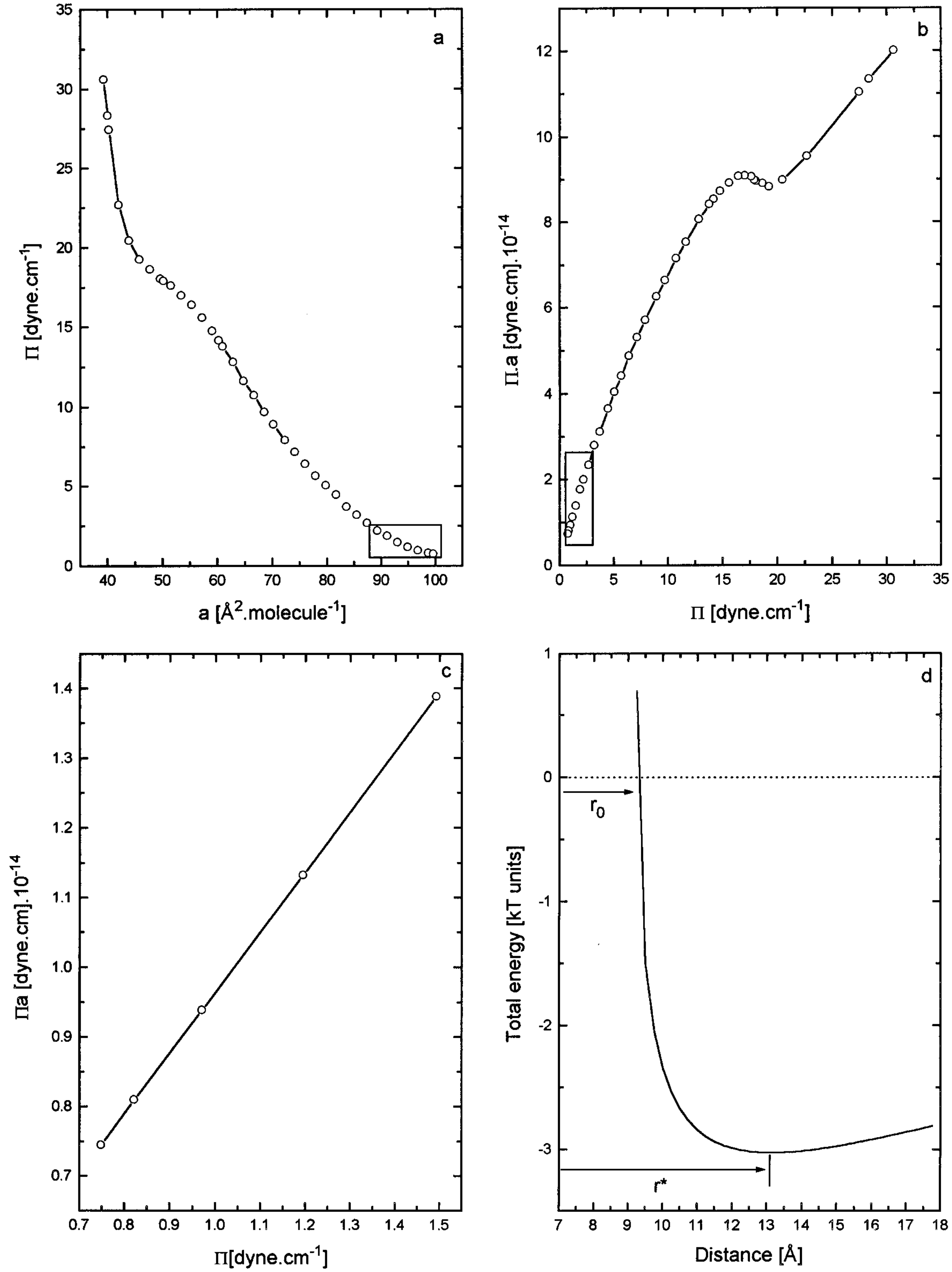

Figure 1. (a, b) Phase diagrams of the model lipid dimyristoylmethylphosphatidic acid, temperature 20 ° C, pH = 5.0. Data were extracted from ref 4. (c) Amplification of the box region shown in (b). (d) Total lateral energy profile for the lipid.

the experimental fact that in the low-density region Πa versus Π follows a linear relation (see Figures 1c and 2), namely

$$\Pi a = \alpha + \beta \Pi \tag{7}$$

From eqs 4, 6, and 7 we obtain

$$\frac{U(a)}{kT} = -\ln\left[1 + 2kT\left(\frac{\beta}{\alpha}\right)\left(1 - \frac{\beta}{a}\right)\frac{1}{a}\right] \tag{8}$$

The relation between the available molecular a and the mean intermolecular distance r is given by

$$r = a^{1/2} \tag{9}$$

Then using $a = r^2$ in eq 10, we obtain

$$\frac{U(r)}{kT} = -\ln\left[1 + 2kT\left(\frac{\beta}{\alpha}\right)\left(1 - \frac{\beta}{r^2}\right)\frac{1}{r^2}\right] \tag{10}$$

Correspondingly, the intermolecular total energy parameters r_0, r^*, and $U_{\min}$ (see Figure 1d) are given by

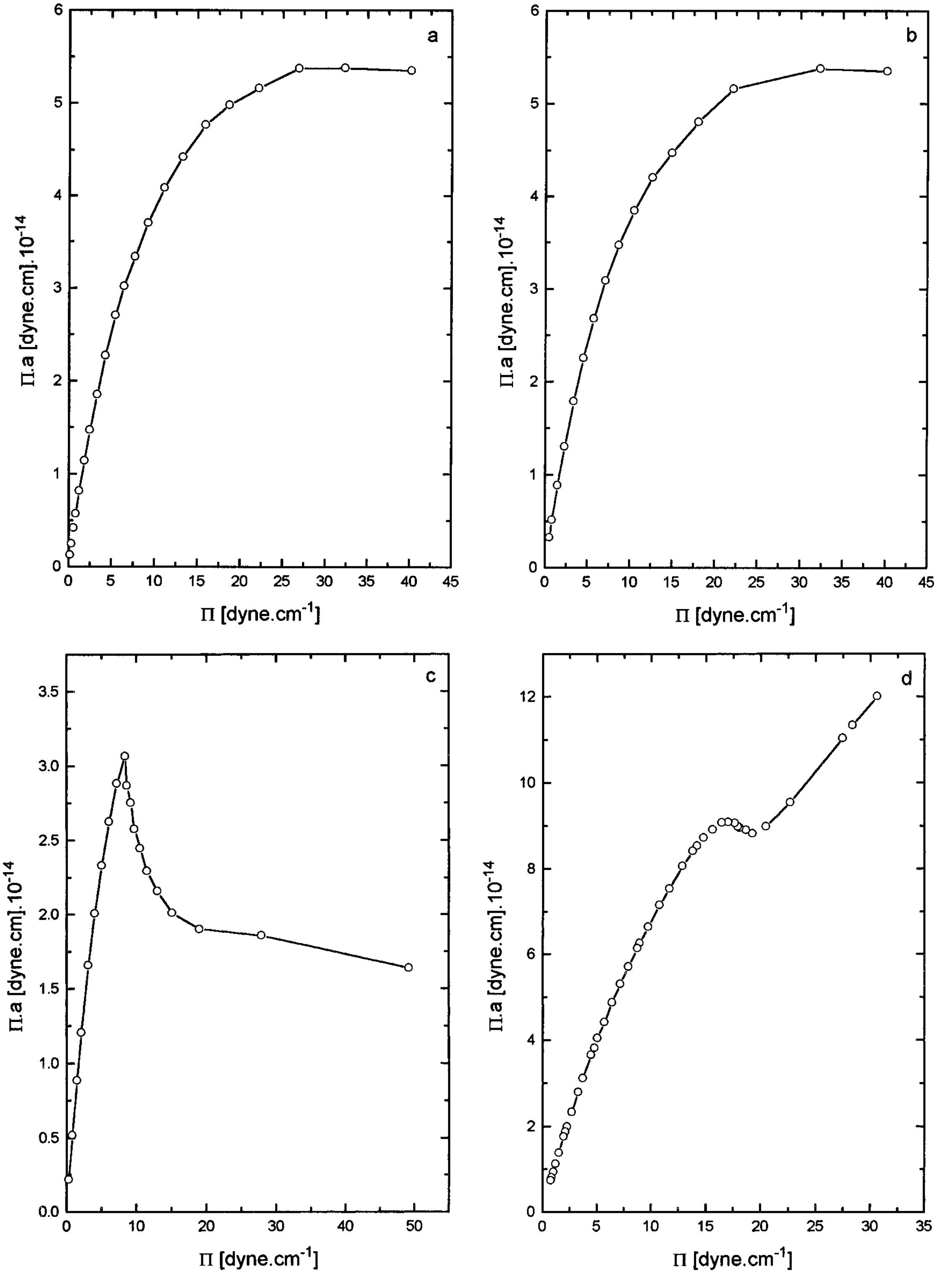

Figure 2. Phase diagram for the four lipids whose energy parameters are reported in Table 1: a–c, data extracted from ref 5; d, data from ref 4.

$$r_0 = \beta^{1/2} \tag{11}$$

$$r^* = (2\beta)^{1/2} \tag{12}$$

$$\frac{U_{\min}}{kT} = -\ln\left[1 + \frac{kT}{2\alpha}\right] \tag{13}$$

In Table 1 are reported the former parameters corresponding to four different lipids. Their energy profiles are shown in Figure 3.

Table 1. Energy Parameters[a]

	a	b	c	d
α (dyn cm/molecule) × 10^{-15}	1.23	3.82	3.71	1.03
β (cm^2/molecule) × 10^{-15}	5.50	4.00	3.92	8.61
r_0 (Å)	7.42	6.32	6.26	9.28
r^* (Å)	10.49	8.94	8.86	13.12
$U_{\min}$ (erg) × 10^{-14}	−11.67	−7.51	−7.61	−12.24

[a] Key: (a) dicapryl lecithin (C_{10}); (b) dimyristoyl lecithin (C_{14}); (c) dimpalmitoyl lecithin (C_{16}); (d) dimyristoylmethylphosphatidic acid.

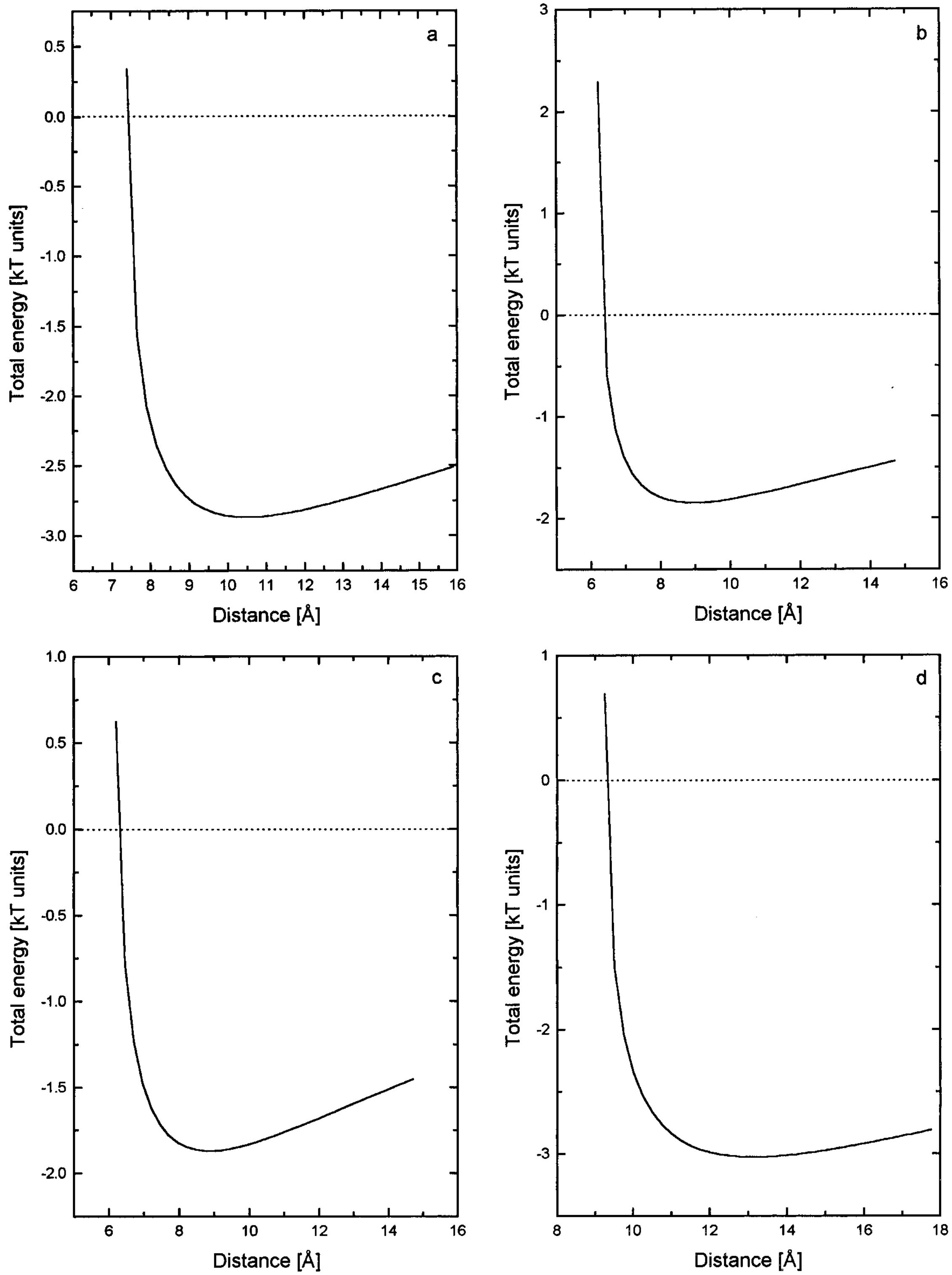

Figure 3. Total lateral energy profiles for the lipids.

3. Discussion

Fowler and Guggenheim[6] and Ross and Olivier,[7] when studying nonideal localized monolayers, introduced lateral interactions between adsorbate molecules in the adsorption isotherm and equation of state, respectively, although the profile of the energy versus distance was not given.

Mingins et al.[8] studying phospholipid interactions in monolayers presented measurements of interfacial potentials and concluded that the surface potentials and lateral pressures are independent of chain length and NaCl concentration, being therefore consequences of the headgroups.

Our obtained labile energy (some units of kT) is common to several physicochemical systems, such as colloid interactions in the DLVO theory,[9,10] giving rise to a form of lax flocculation. Under certain conditions it is generally agreed that, for a variety of phospholipids, the behavior

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of the bilayer system is similar to that of the respective monolayer. Accordingly, this low energy can be the explanation of the lateral translation of phospholipids in bilayers. This motion, determined by the spin label technique and expressed as a diffusion coefficient, has a value of $(1-2) \times 10^{-8}$ cm^2 s^{-1} at room temperature.[11−14]

The distances determined herein corresponding to the minimum energy are similar to the reported mean distance[15] between disordered headgroups in the molecular dynamics investigation of the structure of a fully hydrated gel-phase dipalmitoylphosphatidylcholine bilayer.

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