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STUDIES OF AMPHIPHILES WITH CRYPTAND HEADGROUP AT THE AIR-WATER INTERFACE

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Two laterally nonsymmetric cryptands have been derivatized by reacting with acid chlorides of different alkyl chain lengths to form a new generation of triple-tailed amphiphiles. When selectively allowed to react these cryptands can form single-tailed amphiphiles. The cryptand cavity can accommodate a Cu(II) ion forming yet another set of cryptand based amphiphiles. These amphiphiles form robust monolayers at the air-water interface and can be deposited onto a number of substrates such as glass, ITO-coated glass and fluorite. They form Y-type Langmuir-Blodgett films. A nucleic acid base such as thymine can be attached to the cryptand headgroup affording molecular recognition studies at the air-water interface.

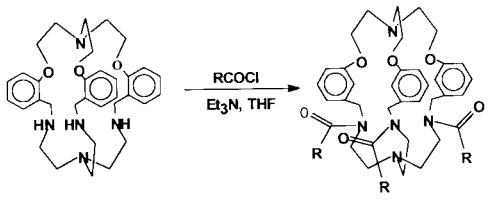
Key Words : Cryptands; Amphiphiles; Monolayers; Langmuir-Blodgett Films; Molecular Recognition

1 Introduction

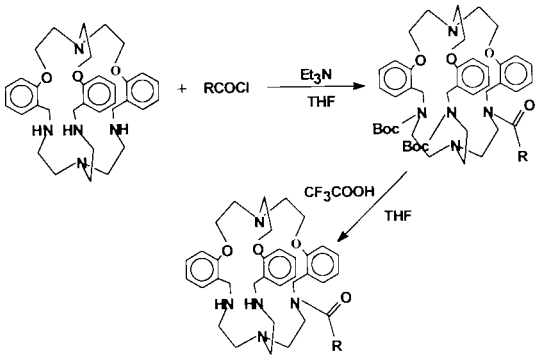
Amphiphilic molecules are crucial to life starting from forming cell walls to translocation of biomolecules *in vivo*. They are known to form a great variety of supramolecular structures such as micelles, vesicles, monolayers, bilayers, multilayer rods, and so on. The LB technique[1] is one of the most effective ways of depositing extremely thin films of amphiphiles with precise molecular dimension and high structural order. This technique has assumed great importance in recent years[2-5] with the demand for materials with tailored interfacial properties. Thus, the quest for new microbiosensors[6] has brought the need for highly selective as well as sensitive organic molecules in the form of thin layers which can be incorporated into electronic, optical or electrochemical devices. In this situation, amphiphilic molecules with signalling capability alongwith metal ions for signal transduction can be very useful. The LB films can be useful in metal-mediated charge-separation, in understanding molecular interactions on biological cell surfaces, and in developing novel 2D nanostructures composed of multiple chemical species[7]. A large number of synthetic amphiphiles with both acyclic as well as cyclic headgroups and one or more hydrophobic tails with different chemical structures have been reported[8-14]. The cyclic headgroups include crown ethers, calixarenes, phthalocyanins, polypyrrols, fullerenes, cyclodextrin, etc. Cryptands are an important ingredient of supramolecular chemistry[15]. These molecules can host different types of guests depending upon the structure and the nature of the donor atoms giving rise to interesting systems. Herein, the discussion is centered on our studies of cryptand based surfactants at the air-water interface in a Langmuir trough. The ultimate aim of these studies is forming stable LB films with cryptand based smart materials. It is therefore, necessary to first probe the stability of monolayers of cryptand based amphiphiles and in the present article we describe our results on these aspects of supramolecular chemistry.

2 Synthesis of the Amphiphiles

The cryptand headgroup can be synthesized[16] by coupling two podand units under moderate dilution at 5° C. The three secondary amino groups readily react with acid chlorides of different chain lengths affording triple-tailed amphiphiles in high yields (Scheme 1). The three amino groups in the parent cryptand have different pK_a values[17] which make it possible to have single-tailed amphiphiles as shown in Scheme 2. The triple-tailed surfactants described[18] here are collected in Fig. 1 while the single-tailed surfactants are shown in Fig. 2. Each amphiphile could be easily purified through recrystallization from ethanol several times before use. Satisfactory elemental analyses were obtained and each amphiphile showed a clean mass spectrum showing the molecular ion peak as 100% pointing to the high stability of the compounds.



Scheme I



Scheme II

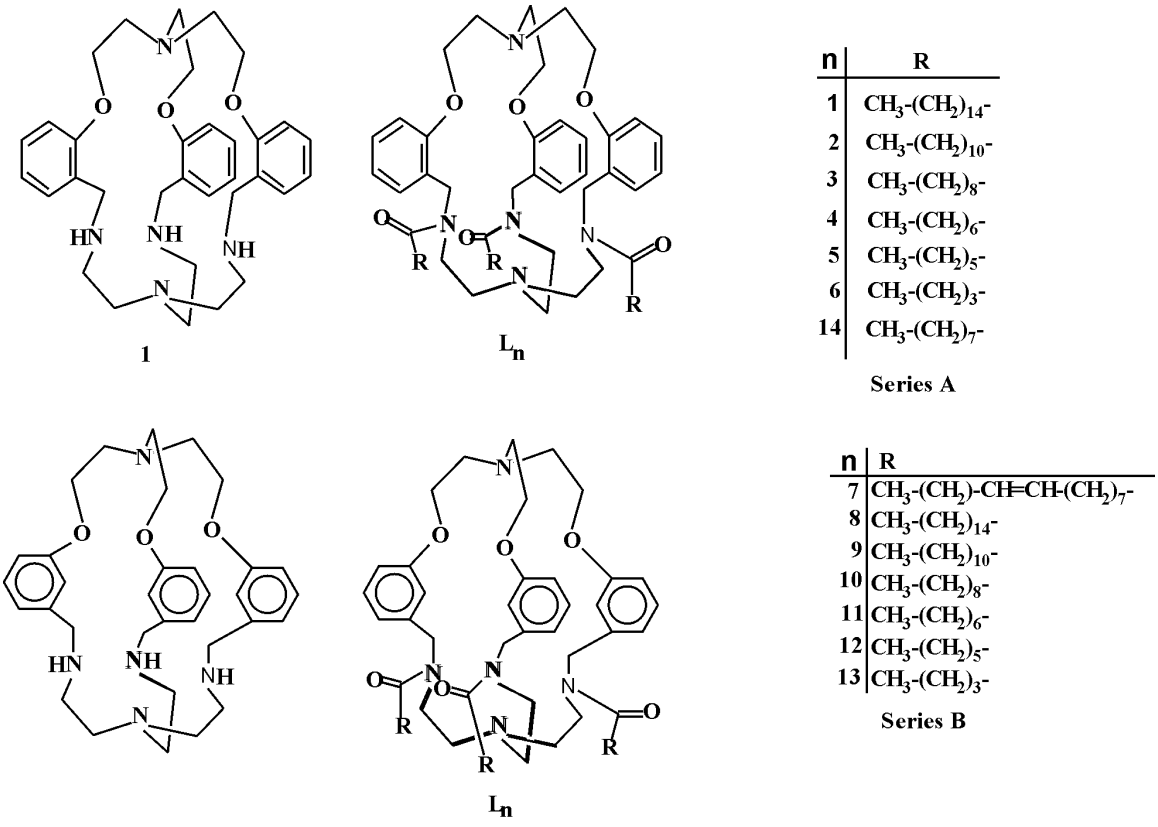
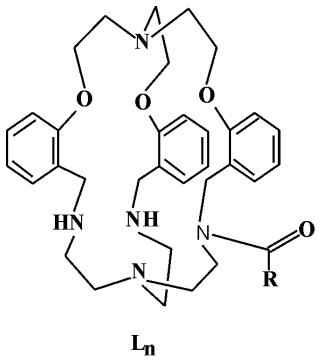


Fig. 1. Triple-tailed amphiphiles with two different cryptand headgroups



L_n

n	R
15	$CH_3(CH)_{15}$-
16	$CH_3(CH)_{16}$-
17	$CH_3(CH)_{17}$-

Fig. 2. Single-tailed amphiphiles

Cu(II)-complexed amphiphile could be prepared by reacting an amphiphile with a Cu(II) salt such as cupric perchlorate or cupric nitrate in methanol to obtain the desired product as a greenish-blue solid. Inclusion of the metal ion inside the cavity was ascertained by spectroscopic measurements as well as mass spectral data.

3 Studies at the Air-Water Interface

The pattern of the isotherms for the triple-tailed amphiphiles either as metal-free or Cu(II)-complexed are illustrated in Fig. 3. The area per molecule shrinks while going from the metal-free amphiphiles to the corresponding Cu(II)-complexed one (Fig. 4). This, however, is expected from our previous experiences with the cryptands. The X-ray crystallographic studies reveal that the donor nitrogen atoms of the cryptand move inwards by a small extent with respect to the free cryptand. The extent of shrinkage is more when the hydrophobic chains are longer. As the hydrophobic chain length increases, the monolayer can sustain higher surface pressure due to better packing of the amphiphiles. Again, the monolayers of the complexed amphiphiles can sustain higher pressure compared to their uncomplexed counterparts. Comparing the radius of the cryptand headgroup in the amphiphiles with that of the cryptand[16] itself leads to the fact that the pseudo three-fold axis passing through the bridged nitrogen atoms of the cryptand is perpendicular to the water surface. This result reflects the association tendencies and orientations of the hydrocarbon chains. The stability of the monolayers is found to be dependent upon the length of the hydrophobic chains. The stability decreases monotonically with the decrease in chain length (Fig. 5). In Fig. 5, a typical scale presenting the ratio between the area of the monolayer determined at time *t* (at a constant surface pressure Π), A(t), and at time t=0, A(0), was used. The

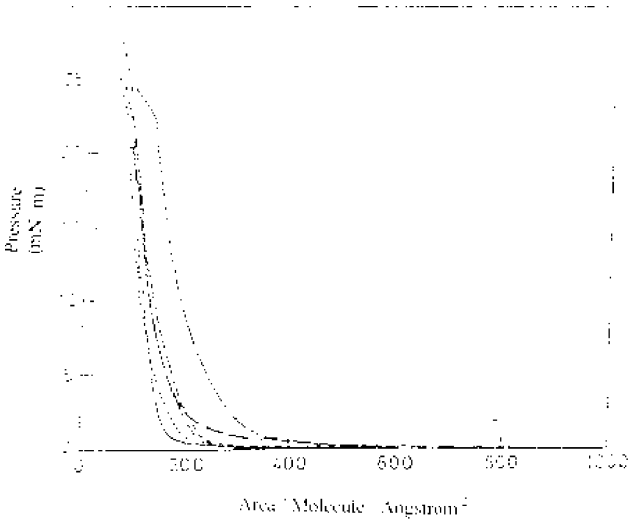


Fig. 3. Pressure-area isotherm for L_1-L_6 (Series A amphiphiles) at 298 K. The Series B amphiphiles show similar isotherms

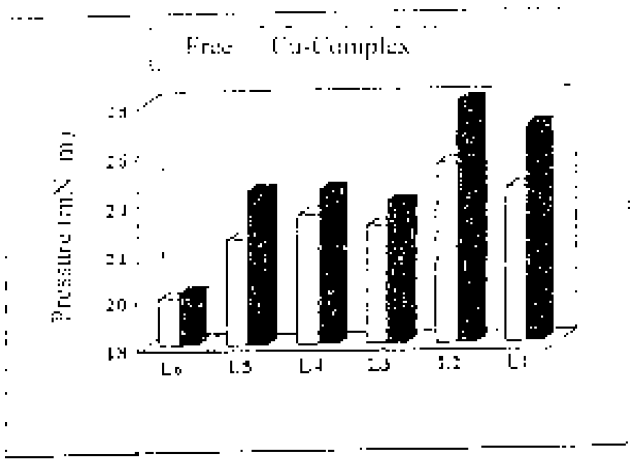


Fig. 4. Comparison of maximum surface pressure (mN/m) sustained by the amphiphiles

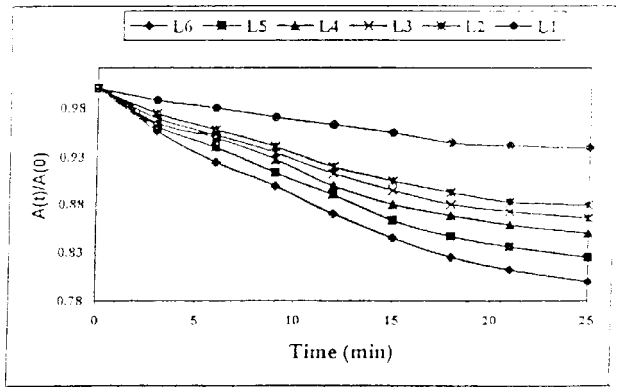


Fig. 5. Comparison of the stability of the monolayer at the air-water interface for the amphiphiles L_1- L_6

amphiphiles with palmitoyl groups are able to sustain a pressure of 25 mN/m for over 30 min without any significant area loss whereas the one with valeroyl group is the least stable showing the area loss of about 15% at the same pressure. When the headgroup is changed to a more rigid cryptand (Series B), the isotherms do not change to any significant extent except for the fact that they are able to sustain higher surface pressure compared to the corresponding Series A amphiphiles. They still orient themselves in the monolayer such that the pseudo threefold axis is perpendicular to the water surface. The effect of sub-phase pH (2.5, 4.7, 7.9, 9.5) on the area/molecule as well as the stability of the monolayers are negligible. However, at low pH values, the monolayers could sustain more than 50 mN/m of surface pressure due to protonation of the secondary amino nitrogens. None of the surfactants (Series A and B; free or Cu(II)-complexed) shows any width of the hysterisis curve (Fig. 6) on repeated compression and expansion which exclude multi-layering or collapsing of the film[19]. In other words, these amphiphiles form robust monolayers capable of withstanding repeated compression and expansion without any major change in the monolayer structure. Under our experimental conditions, palmitic acid (used as control) also showed no hysterisis. The speed of compression also had no observable effect. Besides, the isotherms obtained in the quasi-static mode (i.e., compression of 20 cm^2/min and waiting for 2 min) are the same as that of the continuous one. Both these observations are attributable to the well-behaved amphiphiles. The Cu(II)-complexed surfactants show no changes in the formation or stability of the monolayer either in pure water or in 0.1 M $CuSO_4$ sub-phase because once Cu(II) ion enters the cavity of the cryptand, it forms a stable complex[20].

Interestingly, the monolayers formed by the single-tailed amphiphiles $\mathbf{L_{15}}$-$\mathbf{L_{17}}$ can sustain a surface pressure of 45 mN/m or more (Fig. 7) which is significantly higher compared to those obtained with the triple-tailed amphiphiles with the same chain length. With the pseudo three-fold symmetry of the cryptand headgroup, the three alkyl chains attached cannot pack in an interdigitizing fashion. The crystal packing studies[14] on them also showed that the hydrophobic chains are not aligned. We have not been able to obtain any of the present set of amphiphiles in single crystal form. However, with one hydrophobic chain attached to the cryptand unit, the chains can align in an interdigitizing fashion and thus in the monolayer, the individual molecules can pack efficiently and give a rigid film. The molecular radii of the amphiphiles calculated from the isotherms lie in the range, 8.0-8.5 Å while the distance between the bridgehead nitrogens of the cryptand is ~6.6 Å as found from X-ray crystallography[19]. This suggests that the pseudo three-fold axis passing through the bridgehead nitrogens of the cryptand is slightly tilted with respect to the water surface.

4 Mixed Monolayers

We have studied the behaviour of the mixed Langmuir monolayers. The surface pressure (Π) vs. area per molecule (Å) isotherm for mixed cryptand based amphiphiles + stearic acid (SA) was investigated under-steady state conditions at the air-water interface. These

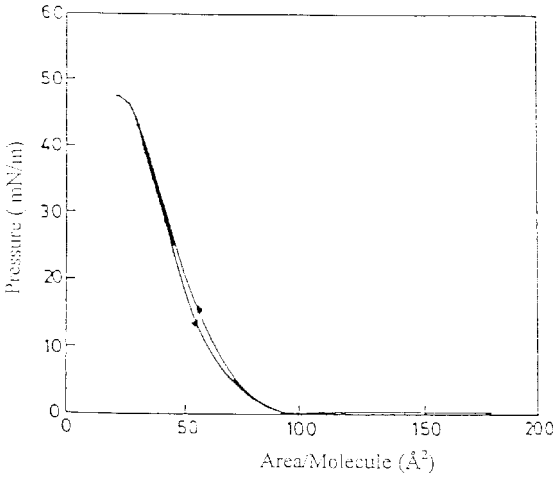


Fig. 6. Representative successive compression and expansion cycles (hysterisis) with a monolayer of $\mathbf{L_2}$

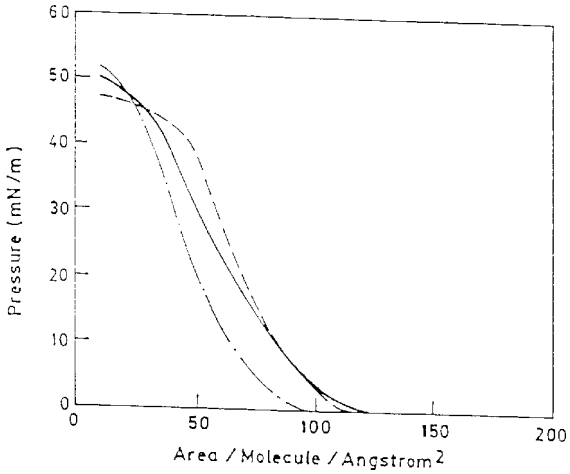


Fig. 7. Pressure-area isotherms for the single-tailed amphiphiles $\mathbf{L_{15}}$-$\mathbf{L_{17}}$ at 298 K

studies provide much insight into existing interactions between the constituents of the mixed monolayer. Such studied are important from the perspective of incorporating compounds with desirable properties in supramolecular LB films to satisfy specialized needs such as high photorefractivity, photoconductivity, large nonlinear responses and so on which are deemed to be important in the design of molecular devices. In the present studies, mixed monolayer have been obtained at several ratios. For two component systems of non-interacting molecules, the average area per molecule of the mixed system (A_{12}) is given by a relation[21] suggested by several workers :

$$A_{12} = N_1A_1 + N_2A_2$$

Where N_1, A_1 and N_2, A_2 are the mole fractions and the area per molecule at zero pressure of the first and second components respectively. A_{12} is the average area per molecule at zero pressure of the mixed monolayer of the two-component system. The pressure-area isotherms of the mixed monolayer has the following characteristics:

i) when mixed with stearic acid, the minimum pressure sustained by the surfactants increases, ii) the shape of the isotherm becomes steeper in nature, and iii) with increase in stearic acid concentration in the spreading solution, the limiting area per molecule decrease monotonically. The experimental data for Series A amphiphiles are shown in Fig. 8. The data show positive deviation from the ideal behaviour indicating that at all composition of the mixture, the experimentally obtained area per molecule of the mixed system is greater than sum of the areas of the pure components. This suggests[22] the existence of a repulsive interaction between SA and the surfactants. The Series B amphiphiles as well as all the single-tailed amphiphiles behave in a similar manner. Therefore, stearic acid does not interact with these surfactants; they merely occupy the void space available that result from the large size of the cryptand headgroup.

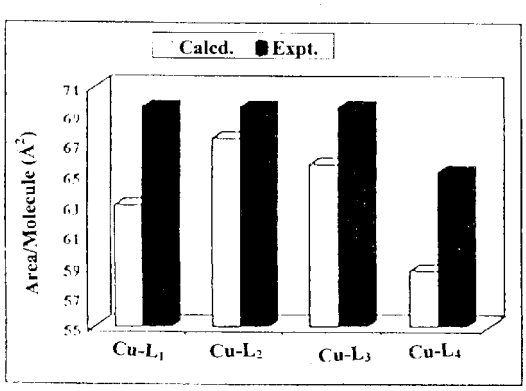


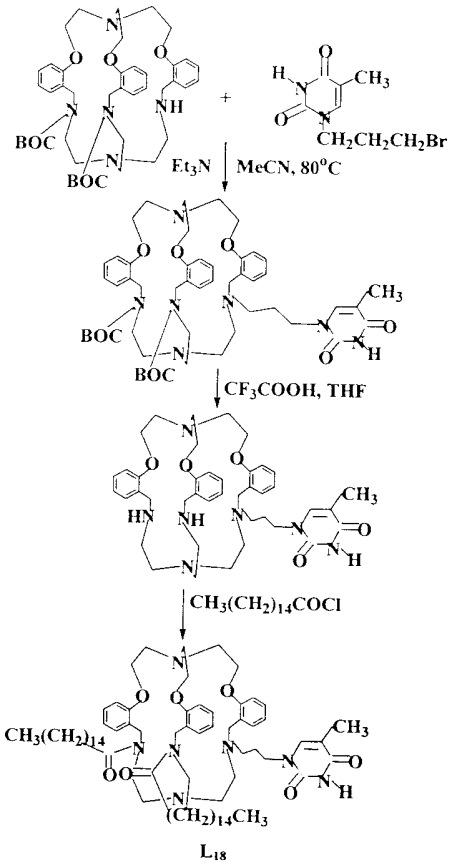
Fig. 8. Comparison of average area per molecule (exp. & calcd.) of Cu(II)-complexed surfactants and stearic acid mixture (1:1) at 15 mN/m surface pressure

5 Formation of LB Films

The LB films of the triple-tailed amphiphiles could be transferred onto a number of substrates such as glass, quartz, ITO-coated glass, and fluorite. Deposition takes place at each downward as well as the upward movement of the arm. The transfer ratio for the upward and downward dipping was comparable to each other suggesting Y-type deposition of the LB films. When the glass surface is untreated, the transfer ratio varies from 60-80%. However, if the glass is precoated with stearic acid (10 layers), the transfer ratio can reach up to 95%. Typically, 50 layers can be transferred without encountering any problem. When the substrate is fluorite, the transfer ratio is found in the range, 60-70%. Scanning electron microscopic studies on the LB films show that the free amphiphiles make inhomogeneous films. In contrast, the Cu(II)-complexed amphiphiles make films showing distinct edges with ordered aggregates. The single-tailed amphiphiles can be transferred onto glass pre-coated with stearic acid (10 layers) although the transfer ratio for the upward and downward dip do not reach beyond 60%. The amphiphiles might behave better when they are further derivatized with different groups of interest or different substrates are chosen. Efforts are on along these lines with the ultimate aim of having stable Langmuir-Blodgett films with desired interfacial properties.

6 Studies on Molecular Recognition at the Air-Water Interface

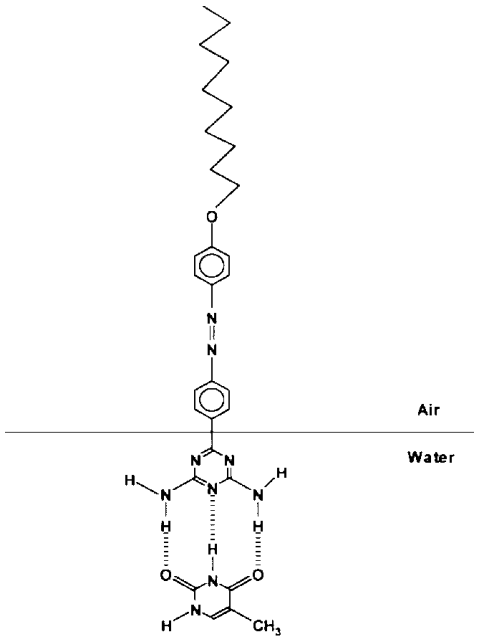
The single-tailed amphiphiles are excellent candidates for attachment of different groups of interest. Presently, we have attached a thymine moiety (Scheme III) to study molecular recognition in aqueous medium. Molecular recognition relies upon the complementarity of size, shape and intermolecular forces[23]. Hydrogen-bonding is a highly directional secondary valence force compared to other non-covalent interactions such as electrostatic, van der Waals and hydrophobic forces. It plays decisive roles in biological molecular recognition such as replication of nucleic acid, maintenance of the tertiary structure of proteins, and substrate recognition of enzymes. Intensive efforts have been made recently[24-27] to develop organic host molecules that specifically binds substrates by complementary H-



Scheme III

bonding. Unlike biological molecular recognition, most of the artificial systems are not effective in aqueous medium due to interference from strong H-bonding nature of water. However, molecules at the air-water interface behave very differently [28] compared to their behaviour in the bulk water. First of all, then interface introduces a directionality in the molecular interactions and causes a particular orientation of the molecules. Secondly, the average separation of the molecules at the interface is generally much smaller than in bulk solution. The high local concentration increase the probability of forming desired entitites through intermolecular bonds. Shimomura and coworkers[29] investigated the binding of aqueous nucleosides to a cytosine-functionalized monolayer (Scheme 4). Kitano and Ringsdorf[30] have found that the pressure-area isotherm of an adenine functionalized amphiphile expands when thymine is present in the aqueous sub-phase due to formation of the complemetary A-T type pair at the interface.

The amphiphile $\mathbf{L}_{18}$ gives a well-behaved isotherm in pure water as the sub-phase. The isotherm is expanded[31] by about 20% when adenine is present in



Scheme IV

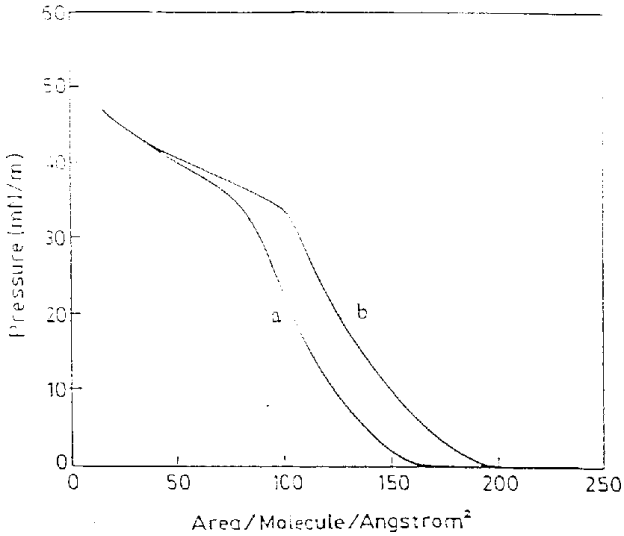


Fig. 9. Pressure-area isotherms for $\mathbf{L}_{18}$ at 298 K (a) with pure water as sub-phase and (b) adenine (0.1 M) in pure water as sub-phase

the sub-phase (Fig. 9) due to the formation of A-T base pair at the interface. also , no change in the maximum sustainable pressure was observed signifying the base-pair association had no effect on the orientations as well as packing behaviour of the amphiphiles. Such an expansion does not take place if any other nucleic acid base is present in the sub-phase.

7 Conclusion

In conclusion, cryptand based amphiphilic molecules form robust monolayers at the air-water interface. These monolayers can be transferred onto different substrates and the Cu(II)-complexed amphiphiles form well defined aggregates in the LB films. The cryptand headgroup can be selectively derivatized with groups of interest leading to cryptand based smart amphiphiles molecules. Our present research efforts are on along these lines.

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