

Line Tension and Line Activity in Mixed Monolayers Composed of Aliphatic and Terphenyl-Containing Surfactants

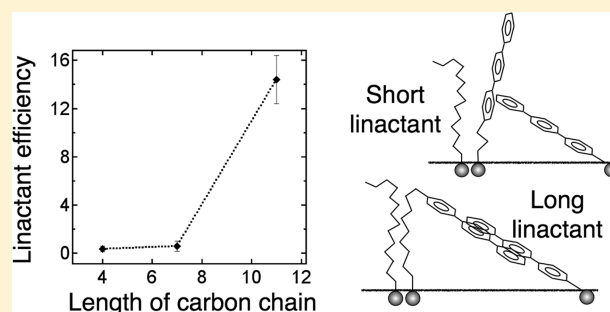
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Supporting Information

ABSTRACT: Custom-designed surfactants, known as “linactants”, have the ability to reduce the line tension between coexisting phases within mixed monolayers of chemically dissimilar compounds at the air–water interface. Thus far, linactants have been successfully identified for only one type of chemical dissimilarity, involving mixed monolayers of hydrocarbon and fluorocarbon surfactants. In the present work, we have pursued a more general interpretation of linactant compounds by extending the concept to a new system that is comprised of a mixture of aliphatic (pentadecanoic acid) and aromatic (*p*-terphenyl carboxylic acid) compounds. We found that the “bare” line tension between phases of this mixed monolayer was ~ 4 pN, and within the same order of magnitude as our previous measurement in mixed monolayers containing hydrocarbons and fluorocarbons. Furthermore, we examined a homologous series of potential linactant compounds possessing an aliphatic tail of variable length and a *p*-terphenyl block. We determined that linactants with longer tails were able to reduce the line tension more efficiently and effectively. In particular, the addition of only 0.14% of a linactant with an 11-carbon chain reduced the line tension by more than a factor of 2. We hypothesize that the efficiency of this particular linactant is associated with its long tail; this creates strong van der Waals interactions with the aliphatic chains and enables the tail to adopt conformations that facilitate π -stacking interactions with the aromatic compounds within the monolayer.



INTRODUCTION

Line tension between coexisting phases in surfactant/lipid monolayers and bilayers plays a pivotal role in various applications, including biosensor technology and artificial pulmonary surfactants.^{1–6} Furthermore, line tension has been implicated as a potential factor for the stabilization of lipid rafts within cellular domains.^{7,8} Understanding the physical phenomena that influence line tension and creating rational methods to control them remain as open and important scientific problems.

Historically, it was discovered serendipitously that impurities have the ability to lower the line tension between coexisting monolayer phases.^{9,10} More recently, we have pursued deliberate efforts to engineer molecules with the ability to reduce line tension between coexisting phases that occur due to specific types of chemical dissimilarity.¹¹ We refer to these molecules as “linactants”, as they are the two-dimensional analogues of surfactant compounds. Research to date has focused on developing linactants for binary mixtures of hydrocarbon and fluorocarbon surfactants, such as pentadecanoic acid (PDA) and perfluoroundecanoic acid (PFUDA). In these studies, the basic linactant structure consisted of a phosphonic acid headgroup attached to one or two hydrophobic tails, where the tails contained both fluorocarbon and

hydrocarbon blocks. Initial experiments established that one-tailed linactants were more efficient than two-tailed linactants, which had one purely hydrocarbon tail, and a second, longer tail with a hydrocarbon and fluorocarbon block.¹¹ Additional studies examined a homologous series of single-tailed linactants¹² and demonstrated that longer tail lengths and larger fluorocarbon blocks led to greater linactant efficiency. Further work by Malone et al. determined that these linactant compounds formed two-dimensional micellar structures in two-component mixtures with PFUDA.¹³

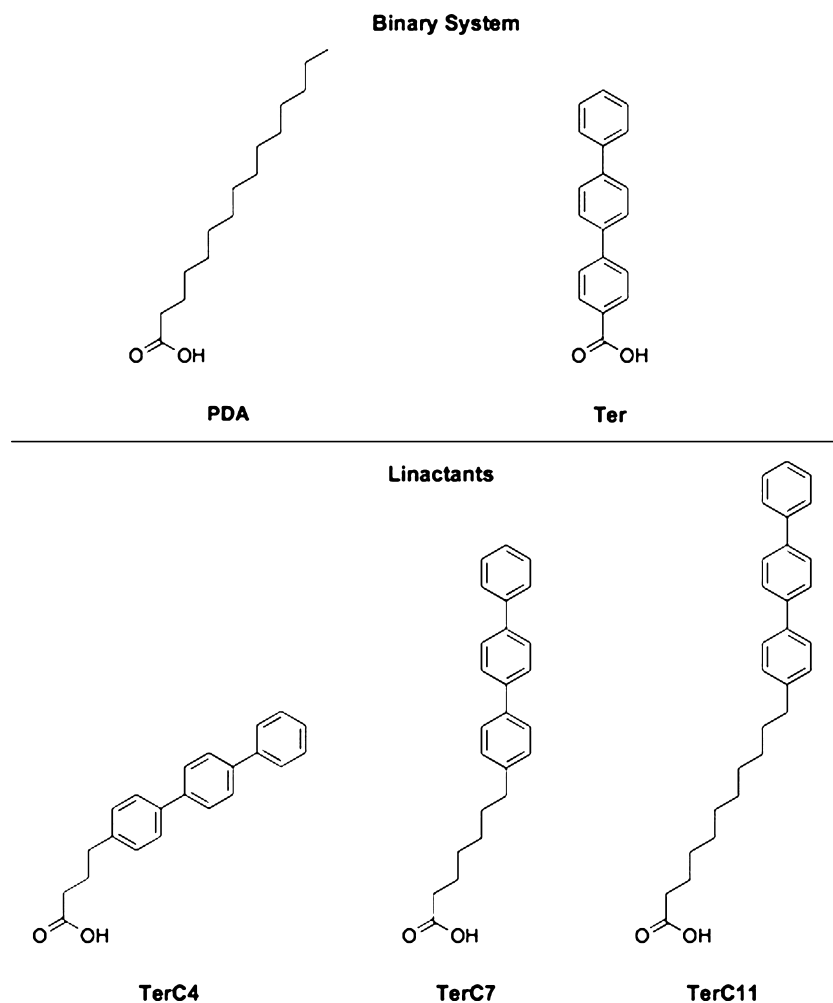
Recent theoretical studies have also focused on the ability of naturally occurring linactants to control the size of lipid rafts within the cell membrane. Akimov and co-workers considered the line tension at the interface between liquid ordered/liquid disordered phases, and estimated the line tension as a function of membrane thickness; they also explored the conditions that are required for raft formation and coalescence.^{14,15} Safran et al. studied the effect of “hybrid lipids”, such as 1-palmitoyl-2-oleoyl-*sn*-glycero-3-phosphocholine (POPC) and 1,2-dioleoyl-*sn*-glycero-3-phosphocholine (DOPC), on the cell membrane

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Scheme 1. Molecular Structure of the Carboxylic Acid Surfactants



and determined that these lipids could theoretically reduce the line tension within cell membranes.^{7,8} Marrink and co-workers extended this work using molecular dynamics simulations.¹⁶ Recent work by Yamamoto and Safran utilized a liquid crystal model to predict that hybrid lipids have the ability to reduce the line tension in “SHC” membranes composed of saturated lipids, hybrid lipids, and cholesterol.¹⁷ Additional studies have systematically examined how the degree of unsaturation within the unsaturated tail of the hybrid lipid tail affects the line tension in the system.¹⁸

Line tension has typically been studied in a canonical system consisting of a phospholipid/cholesterol mixture,^{19,20} with relatively few reports in other systems.^{9,21–23} Consequently, there is a poor understanding of the fundamental relationships between molecular structure/composition and line tension/activity. Notably, the Langmuir monolayer literature demonstrates that phase coexistence occurs readily as a consequence of various types of chemical dissimilarity, such as those between fluorocarbons and hydrocarbons,^{11,12} aromatic and aliphatic hydrocarbons,²⁴ saturated and unsaturated hydrocarbons,^{25,26} and saturated hydrocarbons of different lengths.²⁵ A more complete knowledge of line tension in such systems would greatly enhance our understanding of the connections between monolayer composition and quantitative values of line tension. Therefore, in an effort to study the effects of aromatic–aliphatic chemical dissimilarity, we considered the line tension of a

binary system composed of pentadecanoic acid and selected *p*-terphenyl carboxylic acid. Using our previous studies of hydrocarbon/fluorocarbon mixtures as a conceptual guide, compounds with connected aliphatic and aromatic blocks were designed as potential linactants. As described below, we found that linactants with short hydrocarbon blocks were ineffective; however, a compound whose tail contained a long hydrocarbon block was found to be the most effective and efficient within this series. We hypothesize that the longer tail increases the effectiveness of the linactant because it enables it to adopt multiple conformations, facilitating both van der Waals and π -stacking interactions.

■ MATERIALS AND METHODS

Materials. The structures of the carboxylic acids used to form monolayers are shown in Scheme 1. These compounds were either commercially available (PDA and Ter) or custom-synthesized in our laboratories (TerC4, TerC7, and TerC11). The details of the synthesis of the latter compounds are provided as Supporting Information. Stock solutions of the compounds were prepared by dissolving the individual surfactants in HPLC-grade tetrahydrofuran (THF, Sigma Aldrich) at concentrations ranging from 0.1 to 1 mg/mL. These solutions were then combined and gently mixed with a syringe to obtain the desired experimental compositions. The “base” two-component mixture used in the experiments described below consisted of 96% PDA and 4% Ter. We note that the monolayer must contain a large proportion of PDA for the PDA domains to be of a sufficient size for bola relaxation measurements. However, because the

experiments were performed far from the critical point, it is expected that the line tension has only a weak dependence on composition and temperature. As described below, small quantities of TerC4, TerC7, or TerC11 were added to this base mixture to evaluate their effectiveness as linactant compounds.

Brewster Angle Microscopy of Langmuir Monolayers. A custom built Langmuir trough was cleaned using HPLC grade ethanol and HPLC grade chloroform, and the trough was then filled with ultrapure water (Millipore Direct-Q UV3) and maintained at a temperature of 23 ± 2 °C. To determine the degree of surface contamination, we compressed the surface area of the trough using a mechanical barrier and ensured that the surface pressure remained at approximately 0 mN/m. The experimental solutions were then deposited drop-by-drop onto the clean water surface. The resulting monolayer was permitted to relax for 5 min to facilitate solvent evaporation, and was then compressed at a constant barrier speed of 20 mm/min until a surface pressure of 5 mN/m was reached. This surface pressure was maintained using feedback controlled by a LabView virtual instrument.

We manually sheared the monolayer using a stainless steel hypodermic needle, and obtained time sequences of images using a custom-built Brewster angle microscope (BAM) as the deformed monolayer structure relaxed to its equilibrium state. The BAM was mounted directly onto a motorized x - y translation stage controlled by a joystick, enabling us to follow specific areas of the monolayer despite the drift (i.e., convection) induced by the shearing process. Movies were recorded directly to a DVD at 30 frames per second; we ripped individual frames for analysis using DvDxPro and Final Cut Pro. The line tension was determined from measurements of domain relaxation as described below.

RESULTS AND DISCUSSION

Line Tension in Aromatic–Aliphatic Binary Monolayers. BAM images of all mixtures initially exhibited light-colored circular domains surrounded by a darker matrix; some are shown in Figure 1a. The contrast was consistent with

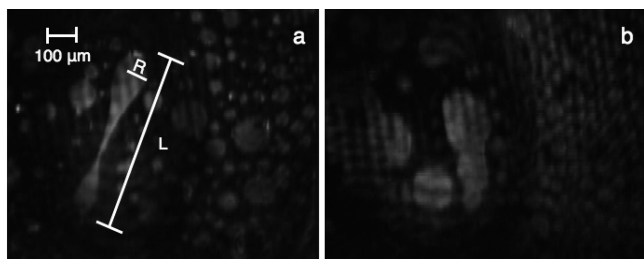


Figure 1. Images of the mixed monolayers after the application of shear: (a) within the base PDA–Ter system containing no linactant, and (b) the same system, but with the addition of 0.14% of terphenyl compound TerC11.

domains of a denser fluid (i.e., liquid or mesophase) surrounded by a matrix of a less dense fluid (liquid or two-dimensional vapor phase). The observations suggest that the denser fluid phase was very rich in PDA. As discussed below, upon addition of a relatively high concentration of linactant, the domain boundaries sometimes became irregular (Figure 1b), a qualitative indication of reduced line tension. To determine the line tension, we observed the relaxation dynamics of deformed circular domains, which formed structures known as “bolas” upon shearing. A typical bola is shown in Figure 1a. The bolas observed here typically consisted of two teardrop-shaped end points with characteristic radius, R , connected by a single thread. During relaxation, the thread shortened with time, and the domain eventually returned to a circular shape. The line tension of the system was the driving force for the relaxation

process, which was opposed in turn by dissipative forces. In this case, the dominant source of dissipation was the viscous drag associated with the subphase.²⁰ To determine the relaxation velocity, V , we measured the reduction in the end-to-end distance (L) of the bola as a function of time (i.e., $V = -dL/dt$).

Under the conditions of our experiments, the relaxation velocity of the bola could be quantitatively related to the line tension (λ) of the system by $V = 3\lambda/8\eta R$, where η is the viscosity of the subphase, and R is the radius of the disk-shaped ends.²⁰ Thus, by plotting a graph of V versus $1/R$, the line tension could be extracted from the slope of the curve. Figure 2

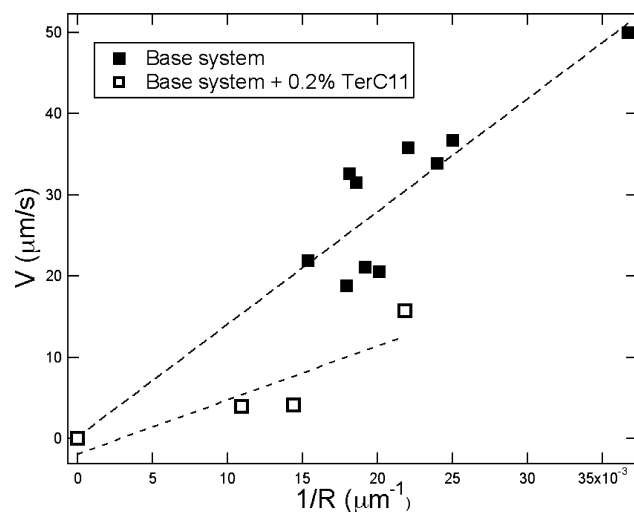


Figure 2. Bola relaxation velocity, V , versus the inverse radius of the bola end, $1/R$. The symbols are described within the legend. Straight lines indicate fits to these data.

shows representative V versus $1/R$ data for the base two-component system containing 96% PDA and 4% Ter, and data obtained upon the addition of 0.20% of TerC11 to the base system. Although both data sets displayed an approximately linear trend, the slope of the curve was notably reduced after the addition of the linactant compound, indicating a reduction in the line tension of the system.

The bola relaxation data for the two-component PDA–Ter system implied a line tension value of 3.7 ± 0.5 pN. By comparison, our previous measurement of line tension between coexisting phases in a fluorocarbon/hydrocarbon mixed monolayer (performed at similar compositions of the respective compounds) was on the order of 2 pN. The relative values of line tension in this case are somewhat surprising because conventional thermodynamic considerations would not suggest that aromatic/aliphatic chemical dissimilarity is significant, particularly in comparison with fluorocarbon/hydrocarbon dissimilarity.²⁷ To explore this phenomenon further, we used the UNIFAC model to compute activity coefficients for both the fluorocarbon/hydrocarbon and the aliphatic/aromatic mixtures.²⁸ We found that the fluorocarbon/hydrocarbon mixture yielded an activity coefficient that was nearly 2 orders of magnitude higher than that of the aliphatic/aromatic mixture, suggesting that, as intuitively expected, the fundamental interactions within the fluorocarbon/hydrocarbon system are dramatically more repulsive than those in the aromatic/aliphatic system. As a caution against a quantitative comparison, we note that the polar headgroups were not included in these calculations. Nevertheless, the fact that we

measure an aliphatic/aromatic line tension that is actually twice as large as the fluorocarbon/hydrocarbon line tension, when the activity coefficient data indicate that the former is actually expected to be dramatically smaller than the latter,²⁸ suggests that the two-dimensional environment is anomalous, and that the boundary between monolayer phases cannot simply be considered as a small section of the three-dimensional interface.

Linactants and Line-Tension Reduction. Notably, the addition of an effective linactant compound dramatically altered the structure of the bola, leading to irregular geometries as exhibited in Figure 1b; this increase in the perimeter of the relaxing domain was a qualitative indication that the line tension of the system had been reduced substantially. Furthermore, the average domain size was markedly smaller upon the addition of an effective linactant, an observation consistent with previous observations and theoretical predictions.^{10,11,20,22,29} As described above, the change of the slope of the V versus $1/R$ curves in Figure 2 was a quantitative indication of the reduction of line tension upon the addition of linactant compounds.

Within a base system consisting of 96% PDA and 4% Ter, linactants were added at concentrations ranging from 0.05% to 2.5%. The line tension was measured using the bola relaxation method described earlier, and these data are summarized in Figure 3. Broadly, the data follow the expected trend; the line

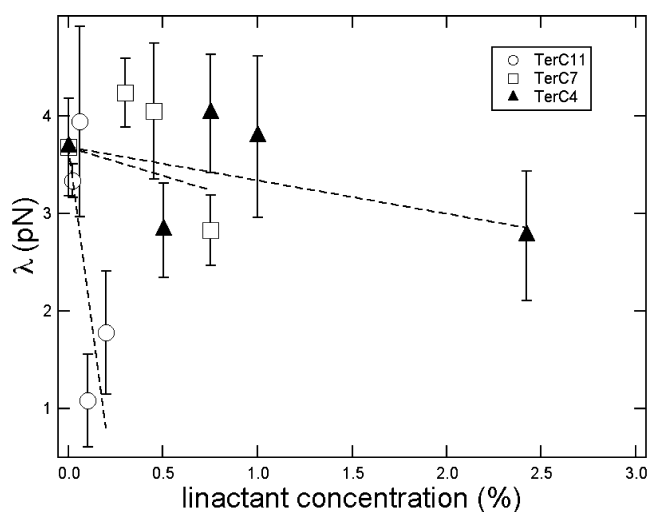


Figure 3. Line tension as a function of linactant concentration. “▲”, “□”, and “○” correspond to carbon chains containing 4 carbons, 7 carbons, and 11 carbons, respectively. Lines are drawn as described in the text. The error bars on each point represent the standard deviation obtained for the straight line fit to the V versus $1/R$ plot for each experimental condition.

tension decreased with increasing concentrations of linactant. Theoretically, the line tension would continue to decrease upon the addition of more linactant until essentially saturating at a limiting value at the critical aggregation concentration (CAC) of the linactant.¹² From Figure 3, it is apparent that the two linactants with shorter carbon chains, TerC4 and TerC7, induced a change in the line tension that was modest at best, even at relatively high concentrations. TerC11, on the other hand, which contained the longest aliphatic chain (10 methylene units), was the most efficient (largest slope) and most effective (greatest total line tension reduction) linactant. The previous most effective linactant, for example, reduced the

bare line tension of the relevant system to $\sim 70\%$ of its original value,¹² whereas TerC11 reduced the line tension to less than 50% of its original value.

The error in the measurements (see Figure 3) can be attributed to at least two factors. First, there is a variable density of domains across the monolayer. In turn, the bolas can be expected to relax relatively slowly in areas of high density, as their path might plausibly be obstructed by the presence of other domains. Second, bolas at higher linactant concentrations might be irregularly shaped, as mentioned earlier. Consequently, these bolas can be expected to exhibit slightly nonlinear relaxation dynamics.

TerC11 also exhibited a relatively high efficiency, which, by analogy with the traditional surfactant terminology, refers to the quantity of a linactant that is required to change the line tension by a certain amount.¹² In Figure 4, we show the

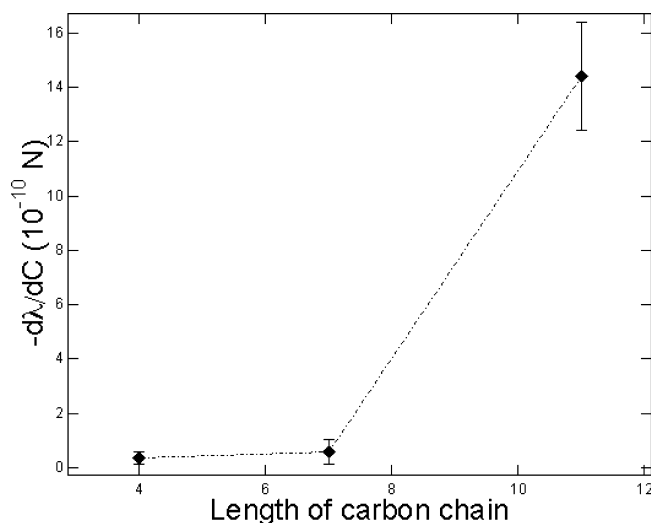


Figure 4. Linactant efficiency as a function of carbon chain length. The error bars represent the standard deviation for straight line fits to the equation $-d\lambda/dC$, using the data shown in Figure 3.

efficiency, $(-d\lambda/dC)$, of the three linactant compounds as a function of carbon chain length. To determine the efficiency, we held the intercept constant, and then fit lines through each data set, with appropriate weighting based on experimental uncertainties. From Figure 4, it is apparent that the largest linactant compound, TerC11, has the largest efficiency by far, while the remaining two compounds have essentially no statistically significant effect on the measured line tension. Previous work in our group examined the effect of a homologous series of linactants in fluorocarbon/hydrocarbon mixtures; the largest linactant efficiency in this series was approximately 13×10^{-10} N;¹² TerC11 has a similar efficiency of approximately 14×10^{-10} N, and is therefore as efficient as the most efficient fluorocarbon/hydrocarbon linactant.

Our earlier work established that a linactant's efficiency may be correlated to its characteristic cluster size in Langmuir–Blodgett films, and that a longer hydrophobic chain length leads to greater efficiency.¹² A similar argument is applicable in the present system. The hydrophobic component of pentadecanoic acid is long and aliphatic; conversely, the hydrophobic component of the pure terphenyl compound is short and aromatic. An ideal linactant would need respective components that are able to interact strongly with both of the dissimilar chemistries. The short hydrocarbon chains offer little

van der Waals contact with neighboring species within a film, and the short length of the hydrocarbon moiety in **TerC4** and **TerC7** can plausibly lead to a diminished capacity for these linactants to interact with the purely aliphatic compound in the film (i.e., **PDA**). In addition, C14 has a longer carbon chain than both of these linactants, which could lead to unfavorable interactions with the aromatic moieties on the shorter linactants, as shown in Figure 5a. The longer hydrocarbon

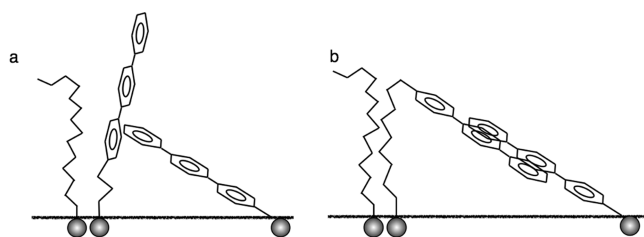


Figure 5. Illustration of the interaction of linactants with **PDA** and **Ter**. (a) The configuration of the binary system with **TerC4**. (b) The same binary system with **TerC11**.

moiety in **TerC11** affords a greater capacity for van der Waals interaction, thereby facilitating interactions of this molecule with both purely aliphatic and purely aromatic compounds at phase boundaries within the two-component system. Furthermore, the longer tail of **TerC11** could potentially enable it to adopt conformations that would facilitate interactions with both the aromatic and the aliphatic components of the monolayer. These interactions could include π -stacking between the aromatic components. We illustrate this concept in Figure 5b, where the long hydrocarbon chain in **TerC11** enables strong interactions with the aliphatic chains in **PDA**, and the aromatic moiety in **TerC11** enables strong interactions with the aromatic moiety of **Ter**.

CONCLUSIONS

We determined the line tension within a binary system composed of pentadecanoic acid (**PDA**) and *p*-terphenyl carboxylic acid (**Ter**) and obtained a value of approximately 4 pN. In addition, we tested the line activity of a homologous series of linactants composed of a hydrocarbon chain with variable length and a *p*-terphenyl tailgroup. We determined that the linactant compound with the longest hydrocarbon chain was the most efficient and effective linactant of the series. Consequently, we propose that the degree of linactant efficiency is directly linked to the length of the aliphatic chain. The long aliphatic chain in **TerC11** facilitates strong van der Waals interactions with the aliphatic chains of **PDA**; consequently, this linactant can interact strongly with both components of the binary system, as it is able to adopt multiple conformations.

ASSOCIATED CONTENT

Supporting Information

Experimental details of the synthesis of **TerC4**, **TerC7**, and **TerC11**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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