Inorganic Chemistry Communications 43 (2014) 15–18

Contents lists available at ScienceDirect

Inorganic Chemistry Communications

journal homepage: www.elsevier.com/locate/inoche

Interfacial response of a novel gemini metallo-surfactant to ionic guest species

Gina E. Jaggernauth, Richard A. Fairman *

Department of Chemistry, The University of the West Indies, St. Augustine, Trinidad and Tobago

ARTICLE INFO

Article history:
Received 9 November 2012
Accepted 1 February 2014
Available online 14 February 2014

Keywords:
Diamsar
Ion selective response
Langmuir isotherms

ABSTRACT

The surface properties of a novel metallosurfactant with twin dodecyl aza-crown aliphatic tails (**L3**) were studied by surface pressure isotherms on aqueous subphases of selected Group I and Group II metals. Mean molecular areas of the headgroup at the monolayer interface (gas phase) are observed to decrease in response to aqueous phase complexation of **L3** by metal ions in the order Ca^{2+}, Li^{+}, Mg^{2+}, Na^{+}, Ba^{2+} and K^{+}. The surface-tension derived critical micelle concentration of **L3** at 25 °C was 0.072 mM, while atomic force microscopy of aggregates observed after preparing Langmuir Blodgett multilayers on mica confirmed the formation of vesicles of up to 100 nm diameter as opposed to wormlike micelles formed by the monomeric analogs.

A common approach to the molecular engineering of surfactant molecules is that of a dimeric or gemini construct, where variations of the spacer [1], aliphatic tail [2] and headgroup [3] together afford access to unique physicochemical properties [4–7], interfacial phenomena [8], or even cytotoxicity [9–11]. Typically, the spacer unit has dual and competing functions: to connect monomeric amphiphiles at a critical minimum distance for both headgroups to behave as one in condensed mesophase, while keeping the centers of like charge optimally distant to exert wider influence on the negatively charged surfaces of, for example, cellular membranes [12]. In this report, we describe the synthesis, surface and aggregation behavior of a novel gemini-type metallosurfactant, **L3**, in which a bulky and highly-charged cobalt(III)sarcophagine acts as both spacer group and center of extensive headgroup charge density. Additionally, **L3** bears a metal coordinating aza-oxa crown ether functionality and is therefore likely to respond to different metal ions with configurational changes at interfacial regions and through varying modes of aggregation in bulk solution [13]. We also anticipate that the added crown functionality will confer enhanced antimicrobial activity of the amphiphile in analogous manner to natural [14] and synthetic macrocyclic ionophores [15]. Our investigations of the solution properties with surface tension, Langmuir surface pressure measurements and atomic force microscopy are herein described.

Compound **L3** was prepared by overnight condensation of the appropriate cobalt(III)diamsar acid chloride [16] and unsymmetrically functionalized diaza-18-crown-6 precursor amine [17], each prepared as cited, at room temperature in the presence of K_2HPO_4. The condensation products were separated by ion exchange chromatography, **L3** being eluted from the column by dilute hydrochloric acid as an orange hydrochloride salt. The generally low, un-optimized yield (7%), can be attributed to the hydrolysis of the amide during workup from the aqueous acid and also by the large numbers of coordinated solvent molecules in the precursor amine which reduce available acid chloride. However, all complexes were satisfactorily characterized by NMR, IR, and mass spectral analysis as described in the supplementary data. We include studies of the precursor organic amine without the cobalt cage appended (**L1**) and the single tail analog (**L2**) for comparison of monomeric vs gemini surfactant properties (Fig. 1).

Despite its size, the crown and cage functionalities in **L3** result in high amphiphilicity, evident from its solubility in aqueous and organic solvents such as water, methanol and chloroform. The critical micelle concentration (cmc) was measured by surface tension measurements (Fig. 2) at 25 °C with ultrapure water (18.2 MΩ). The break-point in the graph of surface tension versus log surfactant concentration gives a cmc of 0.072 mM and the lowest surface tension of 37 mN m^{-1} for **L3**. Corresponding cmc values for **L1** and **L2** (2.45 and 1.07 mM) accentuate the trend of significantly lower cmc values for geminis (34 times lower for **L3**) relative to their monomeric analogs. Differences in bulk aggregation behavior due to the twin tail-group of **L3** were evaluated by coating a mica substrate four times using the computer controlled dipping accessory and performing tapping-mode atomic force microscopy after drying the substrate at room temperature. In contrast to the 2–3 nm wide wormlike micelles observed for the monomeric ligand **L2** [17], gemini **L3** forms spherical vesicles as large as 100 nm in diameter (Fig. 3). Such a marked difference in morphology is consistent with an increased surfactant packing parameter [18,19] (volume/area × length) as the effective hydrophobic volume is significantly increased by twin-tails being attached to the single headgroup in **L3**.

Estimates of the mean molecular areas (**mma**) of **L1**–**L3** were extracted from the Langmuir isotherms of monolayers on either a pure

---

* Corresponding author.
E-mail address: Richard.Fairman@sta.uwi.edu (R.A. Fairman).

http://dx.doi.org/10.1016/j.inoche.2014.02.006
1387-7003/© 2014 Elsevier B.V. All Rights Reserved

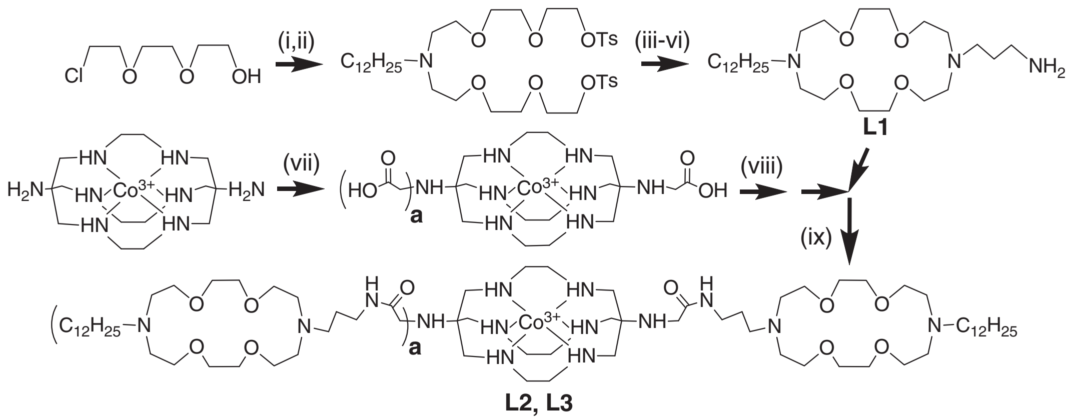

Fig. 1. Synthesis of double-tailed amphiphile **L3** (a = 1), precursors **L2** (a = 0), and **L1**. (i) $C_{12}H_{25}NH_2$, DMF, K_2CO_3, 4d (ii) p-TsCl, NaOH/THF, 0 °C, (iii) $BzNH_2$, MeCN, Na_2CO_3, 3d (iv) H_2, Pd/C, 50 °C, 8 h, (v) CH_2CHCN, 12 h, (vi) = (iv), (vii) CH_2ClCO_2H, Sephadex CM C25, (viii) $SOCl_2$, 3 h, (ix) K_2HPO_4, RT, 12 h.

water subphase or above solutions of different alkali/alkaline earth metal chlorides. Whereas typical cationic-surfactant response to added electrolytes is small [20] and ascribed to interactions between counterions and the Stern layer at the interface [21], the π–A isotherms of **L3** show large responses to cations even at 1 mmol added electrolyte. For example, among the group I metals, the maximal surface pressure is reduced by as much as 50% with Na^+ (Fig. 4), while the sharper K^+ curvature suggests even higher sensitivity of the ligand host to this ion. A similar pattern obtains for Ca^{2+} and Mg^{2+}, with Ba^{2+} evidently better at reducing both the maximum surface pressure and **mma** (Fig. 5).

Such high susceptibility implies dominant configurational-change contributions to the surface tension differences, which we ascribe to the influence of guest cation complexation since the counterion of all the added electrolytes is invariant. We develop schematically in Fig. 6, a model of these changes based on the affinity and coordination modes that obtain for crown macrocycles with cations of varying size and charge. In general, the metal radius that best matches the cavity size of the crown module is strongly coordinated [22], but mismatched dimensions can also yield strong binding through a variety of sandwich-type coordination modes [23]. First, we invoke the former to account for strong binding among the group I metals and the latter to account for the effectiveness of the group II ions at reducing the **mma** of the interfacial segments. Next, we consider that since free crowns align parallel to the interface in compressed monolayers [23], metal encapsulation and attendant increases in solubility of this component will reduce molecular separation at the interface as the crown is further immersed in the subphase. Lastly, we posit an adverse effect on molecular separation where the crown–ion complex is close to the bulky cobalt-cage appendage, due to strong electrostatic repulsion.

Treating **L1**–**L3** within this framework, we note a dramatic response of the monomeric precursor **L1** to Mg^{2+} ions and an enhancement of this behavior with the added cage headgroup in **L2**, but the gemini metallosurfactant **L3** is striking in opposition: all interactions result in a reduced **mma**, and the effect is the largest for K^+ and Ba^{2+} in their respective groups (Fig. 7). Since **L3** bears two macrocyclic rings, the possibility of either inter- or intra-molecular coordination with the larger cations is germane. However, applying our model to the **mma** changes across the series **L1**–**L3** (Table 1) affords distinction between the two modes based on the observed effects on the surface pressure:

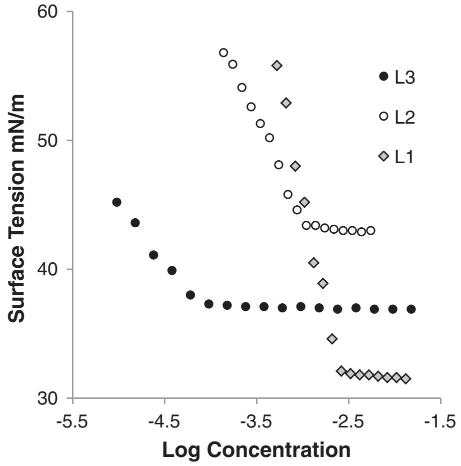

Fig. 2. Critical micelle concentration of L1, L2 and L3 by surface tension measurements.

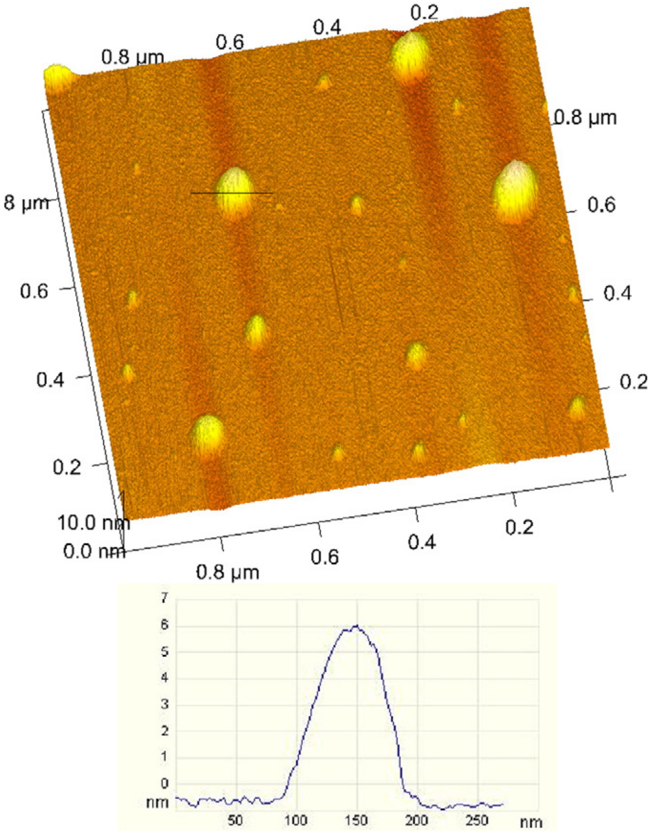

Fig. 3. Atomic force microscopy of **L3** vesicles deposited on mica substrate.

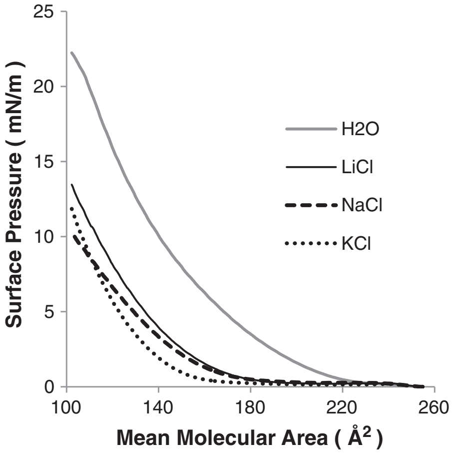

Fig. 4. π–A isotherms for **L3** monolayer above aqueous group I ions in subphase.

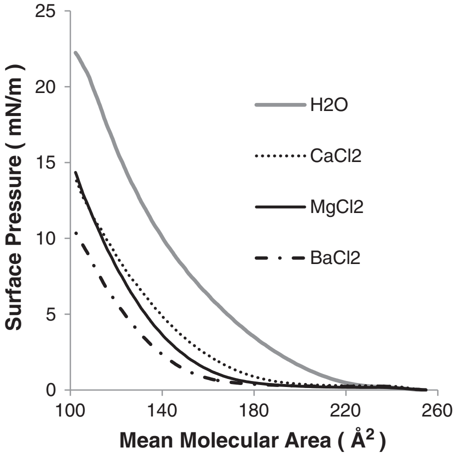

Fig. 5. π–A isotherms for **L3** monolayer above aqueous group II ions in subphase.

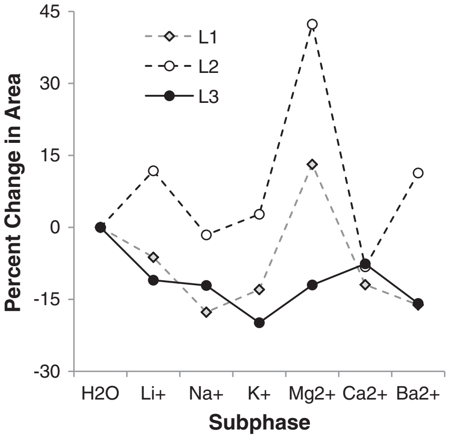

Fig. 7. Percent change in mean molecular area with various cations for **L1**–**L3**.

the **mma** values are only moderately reduced by inter-molecular complexation, as confirmed by experiment, while intra-molecular binding with two endogenous macrocyclic rings would be expected to reduce the **mma** by at least 50% as the lipophilic segments are brought to their minimum separation distance in this alternative binding mode. Our results therefore support an intermolecular coordination for the largest cations.

The synthesis, amphiphilic properties and ion-selective interfacial response of a new gemini metallosurfactant with a crown ether functionality between the lipophilic tails are described. In concert, the crown and cobalt cage affect metal and coordination-mode discrimination among group I and II ions, which is modeled according to conformational changes of **L3** at the interface, and supported by monolayer compression studies. A low cmc value for **L3** in aqueous solution exemplifies the observed trends of decreasing cmc in going from a monomeric to a dimeric surfactant, and AFM images of its aggregates support the Tanford relation [19] between lipophilic volume, critical packing parameter and observed aggregate morphology.

Acknowledgments

This work was supported by the Research and Publication Fund of the University of the West Indies (UWI), St. Augustine. The authors are grateful to Dr. Leonette Cox (UWI) for providing Atomic Force Microscopy.

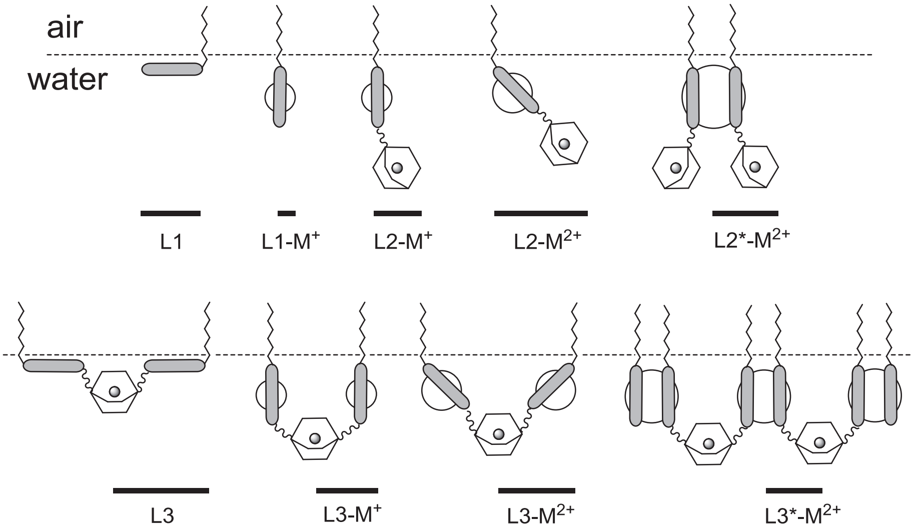

Fig. 6. Proposed changes in surface area by metal ion binding at the air–water interface: row 1 for single-tailed ligands, row 2 for double-tailed ligand **L3**. Guest cation radii increase left to right and solid bars depict effective radius of the host–guest complex.

Table 1
Mean molecular areas of amphiphiles and percent change with metal ions in subphase.

Ion in subphase	Radius	Mean molecular area (Å^2 ± 2.6)/percent change					
	(pm)	L1		L2		L3	
H_2O	–	59.4	0	153.5	0	181.7	0
Li^+	76	55.7	−6.2	171.6	11.8	161.7	−11.0
Na^+	102	48.9	−17.7	151.1	−1.6	159.7	−12.1
K^+	138	51.7	−13.0	157.7	2.7	145.6	−19.9
Mg^{2+}	72	67.2	13.1	218.5	42.3	159.9	−12.0
Ca^{2+}	100	52.3	−12.0	140.9	−8.2	167.9	−7.6
Ba^{2+}	135	49.8	−16.2	170.9	11.3	152.9	−15.9

References

[1] A.K. Tiwari, M. Sonu, S.K. Sowmiya, Saha, Micellization behavior of gemini surfactants with hydroxyl substituted spacers in water and water–organic solvent mixed media: the spacer effect, J. Mol. Liq. 167 (2012) 18–27.

[2] J. Bowers, K.E. Amos, D.W. Bruce, R.K. Heenan, Surface and aggregation behavior of aqueous solutions of Ru(II) Metallosurfactants: 4. effect of chain number and orientation on the aggregation of [Ru(bipy)2(bipy')]Cl2 complexes, Langmuir 21 (2005) 5696–5706.

[3] Q. Zhang, Z. Gao, F. Xu, S. Tai, X. Liu, S. Mo, F. Niu, Surface tension and aggregation properties of novel cationic gemini surfactants with diethylammonium headgroups and a diamido spacer, Langmuir 28 (2012) 11979–11987.

[4] L. Casal-Dujat, M. Rodrigues, A. Yague, A.C. Calpena, D.B. Amabilino, J. Gonzalez-Linares, M. Borras, L. Perez-Garcia, Gemini imidazolium amphiphiles for the synthesis, stabilization, and drug delivery from gold nanoparticles, Langmuir 28 (2012) 2368–2381.

[5] Y. Han, Y. Wang, Aggregation behavior of gemini surfactants and their interaction with macromolecules in aqueous solution, Phys. Chem. Chem. Phys. 13 (2011) 1939–1956.

[6] C. Ma, L. Han, Z. Jiang, Z. Huang, J. Feng, Y. Yao, S. Che, Growth of mesoporous silica film with vertical channels on substrate using gemini surfactants, Chem. Mater. 23 (2011) 3583–3586.

[7] G.P. Sorenson, K.L. Coppage, M.K. Mahanthappa, Unusually stable aqueous lyotropic gyroid phases from gemini dicarboxylate surfactants, J. Am. Chem. Soc. 133 (2011) 14928–14931.

[8] Z. Jiang, X. Li, G. Yang, L. Cheng, B. Cai, Y. Yang, J. Dong, pH-Responsive surface activity and solubilization with novel pyrrolidone-based gemini surfactants, Langmuir 28 (2012) 7174–7181.

[9] J. Hoque, P. Akkapeddi, V. Yarlagadda, D.S.S.M. Uppu, P. Kumar, J. Haldar, Cleavable cationic antibacterial amphiphiles: synthesis, mechanism of action, and cytotoxicities, Langmuir 28 (2012) 12225–12234.

[10] K. Kuperkar, J. Modi, K. Patel, Surface-active properties and antimicrobial study of conventional cationic and synthesized symmetrical gemini surfactants, J. Surfactant Deterg. 15 (2012) 107–115.

[11] V.G. Sanchez, C.J. Giudici, A.R. Bassi, M.C. Murguia, Synthesis, surface-active properties, and anthelmintic activities of new cationic gemini surfactants against the gastrointestinal nematode, *Heligmosomoides polygyrus* bakeri, in vitro, J. Surfactant Deterg. 15 (2012) 463–470.

[12] C. Peetla, V. Labhasetwar, Effect of molecular structure of cationic surfactants on biophysical interactions of surfactant-modified nanoparticles with a model membrane and cellular uptake, Langmuir 25 (2009) 2369–2377.

[13] G.W. Gokel, N. Barkey, Transport of chloride ion through phospholipid bilayers mediated by synthetic ionophores, New J. Chem. 33 (2009) 947–963.

[14] J.M. Blondeau, Macrocyclic antibiotics: a novel class of drug for the treatment of *Clostridium difficile* infection, Expert. Rev. Clin. Pharmacol. 5 (2012) 9–11.

[15] I.N. Pantcheva, R. Zhorova, M.I. Mitewa, W.S. Sheldick, Divalent metal complexes of the monovalent polyether ionophorous antibiotic monensin, Monogr. Ser. Int. Conf. Coord. Bioinorg. Chem. 9 (2009) 257–268.

[16] P.S. Donnelly, J.M. Harrowfield, B.W. Skelton, A.H. White, Carboxymethylation of cage amines: control of alkylation by metal ion coordination, Inorg. Chem. 39 (2000) 5817–5830.

[17] G.E. Jaggernauth, R.A. Fairman, Synthesis and characterization of an amphiphilic cobalt cage complex with aza-crown spacer, Inorg. Chem. Commun. 14 (2011) 79–82.

[18] R. Nagarajan, Molecular packing parameter and surfactant self-assembly: the neglected role of the surfactant tail, Langmuir 18 (2002) 31–38.

[19] C. Tanford, The Hydrophobic Effect: Formation of Micelles and Biological Membranes, 2nd ed. Wiley, 1980.

[20] Y. Jiang, Z. Xu, J. Luan, P. Liu, W. Qiao, Z. Li, Effect of ionic strength on the interfacial and bulk properties of unsymmetrical bolaamphiphiles, J. Surfactant Deterg. 11 (2008) 73–78.

[21] Z. Adamczyk, G. Para, P. Warszynski, Influence of ionic strength on surface tension of cetyltrimethylammonium bromide, Langmuir 15 (1999) 8383–8387.

[22] L.F. Lindoy, The Chemistry of Macrocyclic Ligand Complexes, Cambridge University Press, 1992.

[23] G.R.J.M. Klein, A.J. Sandee, F.G.A. Peters, S.J. van d.G., M.C. Feiters, R.J.M. Nolte, Aggregation of a crown ether-based copper amphiphile as a mimic for the superstructure of hemocyanin, J. Chem. Soc. Dalton Trans. (2001) 3056–3064.