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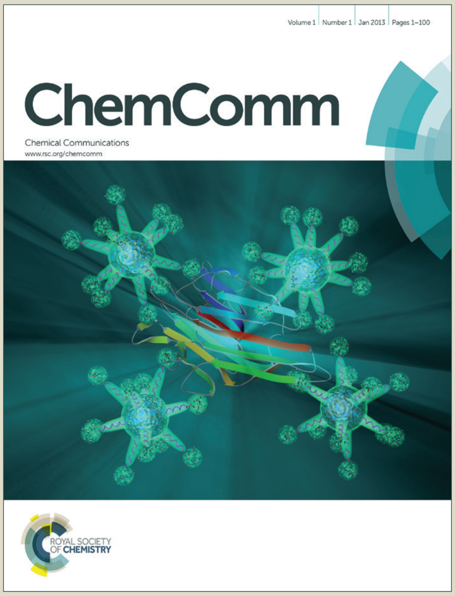

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Vesicles Composed of One Simple Single-Tailed Surfactant †

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Na Du,‡ Ruiying Song,‡ Xiaoyu Zhu, Wanguo Hou,* Haiping Li and Renjie Zhang

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Novel vesicles formed spontaneously from the micelle solution of DTAB, a single-tailed surfactant (STS), under the mediation of a rough glass surface (RGS) without any additives. The obtained STS vesicles displayed good stability upon long-term storage, high temperatures, and freeze-thawing after the removal of RGS.

Vesicles are organized amphiphilic molecular assemblies consisting of unilamellar or multilamellar closed bilayers.[1] These assemblies have attracted much interest over the past several decades because of their substantial value for biomimicry,[2a] biopharmaceutics,[2b] drug encapsulation and delivery,[2c] the synthesis of nanoparticles,[2d] and microreactors.[2e] Based on the concept of molecular packing parameter proposed by Israelachvili et al.,[3] vesicles can form spontaneously from amphiphilic molecules whose packing parameter (P) is between 0.5 and 1, where $P = v_0/al_0$, v_0 is the surfactant tail volume, l_0 is the tail length, and a is the occupied area per amphiphile at the aggregate surface. Simple single-tailed surfactants (STS) such as dodecyltrimethylammonium bromide (DTAB) are typically considered to be unable to form vesicles in water in the absence of co-surfactants or additives, because their P values obtained from experimental a values at gas-liquid interfaces[4] are not in the range of 0.5-1. Indeed, almost all of the vesicles reported in the literature are composed of "non-simple" amphiphiles,[5] such as amphiphilic block copolymers,[5a] surfactants with double tails,[5b] and mixtures of catanionic,[5c] cationic/cationic,[5d] nonionic/ionic,[5e] zwitterionic/anionic[5f] and single-chain/perfluorinated surfactants.[5g] A few reports[6] have revealed the spontaneous formation of vesicles from small molecular ionic surfactants with a single tail in aqueous solutions in the absence of co-surfactants; however, in these studies the researchers either introduced ionic liquids,[6a] or employed single-chain surfactants with special structures and conformations.[6b] Even in tertiary-level textbooks, it is typically stated that small molecular surfactants with a single tail are unable to form vesicles in water in the absence of a co-surfactant.[7]

Herein, we report that novel vesicles composed of only one single-tailed surfactant. The STS vesicles formed spontaneously from the cationic surfactant DTAB micelle aqueous solutions with the mediation of a rough glass surface (RGS), in the absence of co-surfactants or other additives. It has been reported that the spontaneous formation of vesicles can be induced via the variation of environmental factors,[8] such as the pH,[8a] temperature[8b] and salinity,[8c] and via the addition of organic additives[8d] or heavy metal ions.[8e] In contrast with these methods, the facile RGS-mediated route developed in this study does not require the introduction of new components into the surfactant system.

Hanczyc et al.[9] reported that negatively charged clay mineral particles could catalyze the formation of vesicles from fatty acids, yielding composites of clay particles encapsulated in vesicles. We found that positively charged layered double hydroxides (LDHs) particles could induce the spontaneous formation of vesicles in mixtures of zwitterionic/anionic[10a] or catanionic surfactants,[10b] producing composites consisting of LDHs particles encapsulated in vesicles. Differently, in this work individual vesicles rather than composites were formed from the simple STS solution under the mediation of the RGS. More importantly, the so-obtained STS vesicles were stable upon long-term storage, high temperatures, and freeze-thawing after the RGS had been removed. This work improves the understanding of the nature of vesicle systems.

The RGS used was obtained from a microscope slide corroded by hydrofluoric acid (ESI, Experimental details). The surface of glass is very rough, where numerous pits and islands are located (ESI, Fig. S1). The size and depth of the pits are ~50 nm and 3.5 nm, respectively, and the width of the islands is ~10 nm. Thus, the features on the RGS consist of curved surfaces with a curvature radius of ~91 nm.

After the corroded glass plate was immersed in the DTAB micelle solution (20 mmol/L) at 25 ± 0.5 °C (ESI, Experimental details), significant formation of vesicles with an average size of ~70 nm was observed by negative−staining (NS) and freeze−fracture (FF) TEM (Figs. 1 a, b), indicating STS vesicles can be formed with the mediation of RGS from the STS micelle solution.

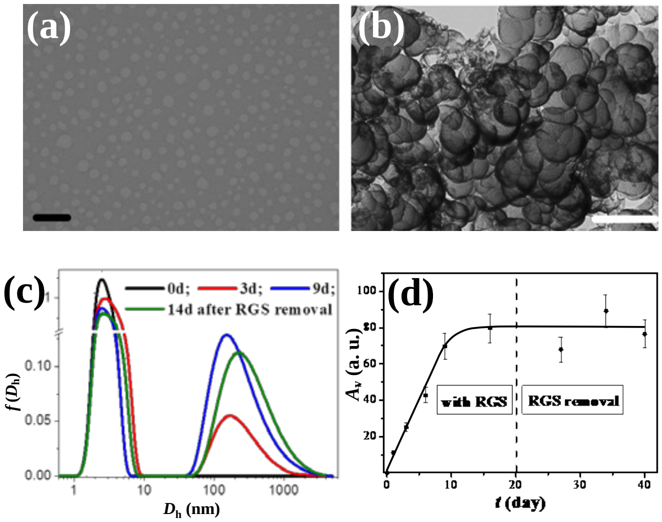

Fig. 1 (a) Negative-stain and (b) freeze-fracture TEM images of vesicles in DTAB solutions. RGS-mediated time is 9 d, scale bar: 200 nm. (c) Hydrodynamic diameter distributions in DTAB systems at different RGS-mediated time, and at 14 d after the removal of RGS. (d) Variation of vesicle peak area versus time for DTAB solutions.

The dynamic light scattering (DLS) data confirmed the RGS-mediated formation of vesicles in the simple STS solution (Fig. 1c). Before the addition of the corroded glass plate, the DLS plot exhibited a single peak at a hydrodynamic diameter (D_h) of ~3 nm; this is a typical value for a micellar system. After the corroded glass plate was added to the STS solution, the intensity of the micelle peak decreased, and a new peak around D_h 200 nm was observed, corresponding to the formation of vesicles. The most probable vesicle diameter (~200 nm) was higher than the vesicle sizes (~70 nm) obtained from the TEM images. This possibly arises from the momentary adhesion of vesicles.

Similar test using smooth (uncorroded) glass plate was performed under the same conditions, and no vesicles were observed using either TEM or DLS, demonstrating that the roughness of the solid surface played a key role in the formation of the vesicles. In addition, to investigate the possibility that substances leaching from the corroded glass plate could have induced the vesicle formation, we prepared the surfactant solution using ultrapure water in which the corroded glass plate had been soaked for 6 days; no vesicle aggregates were detected in this system by TEM or DLS. These verification tests proved that the formation of the vesicles in the STS solution was induced solely by the RGS.

Upon analyzing the hydrodynamic diameter distribution, the variation of the area of vesicle peak (A_v) versus time (t) provides approximate information on the kinetics of the RGS-mediated vesicle formation. Results are shown in Fig. 1d for an initial 20 days with RGS mediation, and a subsequent 20 days with the RGS removed. Under the mediation of the RGS, the A_v increased initially, and then reached an equilibrium value, which indicated that the STS vesicles formed gradually in the micelle solution until the equilibrium between the vesicle and micelle phases was reached. No significant change in A_v was observed after the removal of RGS, demonstrating that no notable change occurred in the vesicle phase. NS-TEM observations also showed that the vesicles remained stable over a storage period of 20 days at room temperature (ESI, Fig. S2). In fact, the obtained STS vesicle solution has been stable at room temperature approximately six months after the initial experiment till now.

The thermal and freeze-thaw stabilities of the STS vesicle system were also investigated. To examine its thermal stability, the STS vesicle system was placed in a thermostatic bath at 80 °C for 2 h. The NS-TEM and DLS experiments showed that the vesicles still remained in the system (Figs. 2a, and S3 in ESI). To examine its freeze-thaw stability, the STS vesicle system was frozen at –20 °C for 2 h, and then the frozen sample thawed at ambient temperature of ~25 °C. Vesicles were observed clearly by NS-TEM and detected by DLS after thawing (Figs. 2b, and S3 in ESI). According to the above results, we can conclude that the STS vesicles exhibit high stability, similar to some of the conventional vesicle systems.

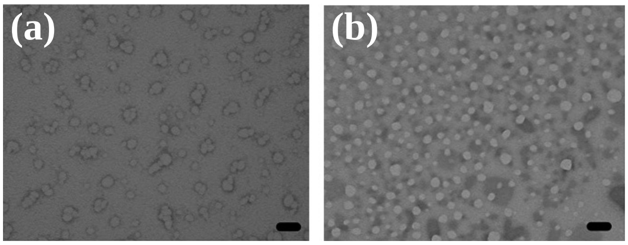

Fig. 2 Negative-stain TEM images of DTAB vesicle solution, after (a) thermal treatment at 80 °C for 2 h, and (b) freezing at –20°C for 2 h and subsequent thawing. Scale bar: 200 nm.

The microenvironment of the STS vesicles was examined using the fluorescence of pyrene as an extrinsic probe. The fluorescence emission spectra of pyrene in the STS solution showed five vibronic peaks (Fig. S4 in ESI). The I_1/I_3 ratio of pyrene fluorescence, that is, the ratio of the intensity of the first vibrational peak (at 374 nm) to that of the third peak (at 385 nm), is very sensitive to the polarity of the microenvironment in which the pyrene is located.[11] The I_1/I_3 value for the DTAB vesicle system was 1.42, while that of the DTAB micelle solution was 1.45 before the corroded glass plate addition. Such close agreement between the I_1/I_3 values for the vesicle and micelle solutions reveals that the micropolarity experienced by the probing molecules is the same in the vesicle bilayers as in the micelles. This result is consistent with that of conventional vesicle systems reported previously.[12]

We propose a possible mechanism for the RGS-mediated formation of vesicles, as shown in Fig. 3. As a corroded glass plate is immersed into the surfactant solution, the surfactant micelles and molecules are adsorbed on the curved surfaces of the glass under the influence of electrostatic interaction, hydrogen bonding, and van der Waals forces, forming curved bilayers.[13] Under the forces imposed by shaking, the curved bilayers are detached from the glass surface. These bilayers close to form vesicles subsequently, to decrease the interfacial energy of the aggregates. With the repetition of this process, the micelle phase is gradually transformed into a vesicle phase, until the equilibrium is achieved between the two phases.

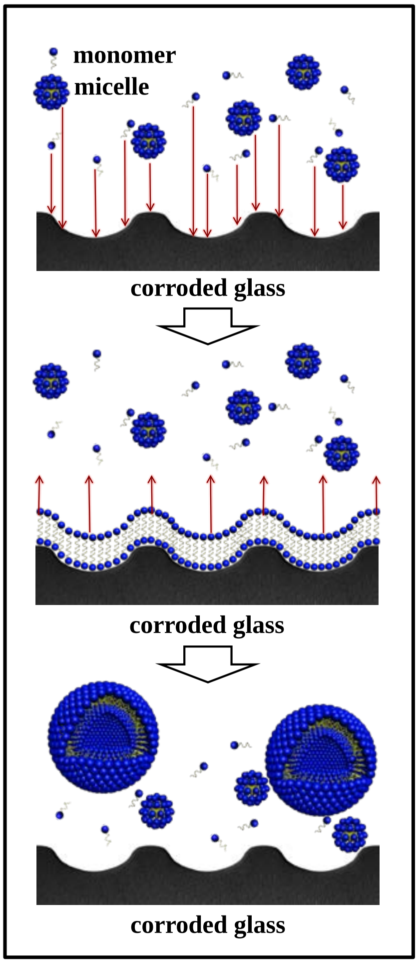

Fig. 3 Schematic illustration of the RGS-mediated vesicle formation.

The concept of molecular packing parameter[3] has been widely applied to explain how the molecular structure of a surfactant controls the shape and size of the resulting aggregate, providing intuitive insight into the self-assembly phenomena. As a general rule, spherical micelles are favored when $P \le 1/3$, cylindrical micelles when $1/3 \le P \le 1/2$, and bilayers or vesicles are energetically the most favorable when $1/2 \le P \le 1$.[14] The l_0 and v_0 values of DTAB are 1.67 nm and 0.35 nm^3,[3,15] respectively. The *a* value reported in the literature[4] for DTAB at gas-liquid interfaces is ~0.49–1.23 nm^2; its related *P* value is therefore ~0.43–0.17. This *P* value would suggest that spherical micelles are favored for the surfactant. However, using the Hartree-Fock method in Gauss View 3.0 to determine the energy-minimized structure, the intrinsic area of the head group (or the cross-sectional area of the nonhydrated head group) of DTAB was obtained as ~0.20 nm^2, lower than the previously reported *a* value at gas-liquid interfaces. The higher experimental *a* value is due to the hydration of the head groups and the electrostatic repulsion between the head groups. Calculated from the intrinsic *a* value, the intrinsic *P* value of DTAB is ~1.05, indicating the possibility of the formation of vesicles. In fact, surfactant molecules can exhibit much lower values of *a* at solid-liquid interfaces than at gas-liquid interfaces. The *a* value for DTAB at silica-water interfaces has been reported previously as ~0.28–0.33 nm^2,[4b, 16] yielding a *P* value of ~0.75–0.64. This is likely because the interaction of the solid surface with the surfactant molecules decreases the hydration of the surfactant head groups, and obstructs the electrostatic repulsion between the head groups. This effect of RGS on DTAB molecules alters the *P* value to be in the range of 1/2–1 for the STS assemblies on the RGS. Thus, the observation in the present report, of RGS-mediated formation of STS vesicles, is consistent with the concept of molecular packing parameter. It is surprising that such obtained STS vesicles can be stable. We extended the strategy of RGS-mediated formation of vesicles to other STSs, including cetyltrimethylammonium bromide (CTAB) and lauryl sulfobetaine (LSB). Similar results were obtained (Fig. S5 in ESI), indicating the strategy is general.

In conclusion, we report for the first time that vesicles can form from a solution of STS micelles, under the mediation of the RGS in the absence of co-surfactants or any other additives. The roughness of the glass surface plays a key role in the STS vesicle formation. The obtained STS vesicles show good stability towards long-term storage (at least 6 months at room temperature), high temperatures (80 °C for 2 h), and freeze-thawing (–20 °C for 2 h to approximately 25 °C). We propose a possible mechanism for the RGS-mediated formation of the STS vesicles, where the STS micelles and molecules are adsorbed on the RGS to form curved bilayers, and the curved bilayers detach from the RGS and close to form vesicles subsequently. Further research is needed to fully understand this phenomenon; many essential questions concerning the nature of STS vesicles remain to be addressed.

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Notes and references

Key Laboratory of Colloid and Interface Chemistry (Ministry of Education), Shandong University, Jinan 250100, P.R. China. E-mail: wghou@sdu.edu.cn

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‡ N. Du and R. Song contributed equally.

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