

Listeria-like Motion of Oil Droplets

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Self-propelling movement of oil droplets associated with formation of giant vesicles on/in the surface of an oil droplet at the site opposite that of the direction of motion was observed. Fluorescence microscopic study using a synthesized fluorescent indicator confirmed that formation of the vesicular molecule occurred through the coupling reaction between a reactive lipophile and a micellar amphiphile in an aqueous dispersion.

Recently, autonomous motion of molecular aggregates in a nano- and microscale has drawn much attention as a dynamic model of protein complexes and even of living cells.¹ Several pathogenic bacteria, such as *Listeria monocytogenes*, propel themselves by polymerizing actin, which is contained in the host cell, at their tail edge.² In this study, we describe the self-propelled motion of a reactive oil droplet that forms giant vesicles at its tail edge. The movement of this oil droplet resembles the self-propelled motion of such bacteria.

When an oily liquid (ca. 1 μ L) of 3-(*n*-octyloxy)benzaldehyde (**1**, in Figure 1a) was added to ca. 75 μ L of 20 mM aqueous micellar solution³ of 10-(4-aminophenoxy)decyltrimethylammonium bromide (**2**, in Figure 1a), oil droplets were observed in the dispersion under a phase-contrast microscope (IX70, Olympus, Japan). While some droplets were adhered to the surface of glass substrate, other droplets whose sizes were in range of 50–120 μ m, swam autonomously, with giant vesicles trailing behind (Figures 2a and 2b). Initially, these droplets moved along one direction (maximum speed ca. 11 μ m/s); the rate of the self-propelled swimming motion then decreased and the swimming droplet made frequent turns (see Supporting Information). Note that the inner aqueous particles inside the swimming droplets demonstrated convective movement. The rate of convection was found to be related to that of the self-propelled swimming droplet (Figures 2c and 2d). Namely, the stroboscopic micrographs (Figure 2c, exposure time = 1 s) indicate that the directional swimming motion was associated with a pair of convection of aqueous particles and that the inner convection flow temporarily stopped at the turning point of the swimming motion (Figure 2d). The observed phenomenon is summarized in Figure 2e.

The oil droplets adhering on the surface of glass substrates also generated giant vesicles and slithered around on the glass slides. This slithering continued about for 1 h. However, all of the emulsion droplets in the dispersion eventually fixed on the substrate and did not move any more after 2 h after the preparation. Accompanied with the generation of vesicles, all the oil droplets turned out to be shrunken.

Conversion of **1** to vesicular amphiphile **3** in the aqueous

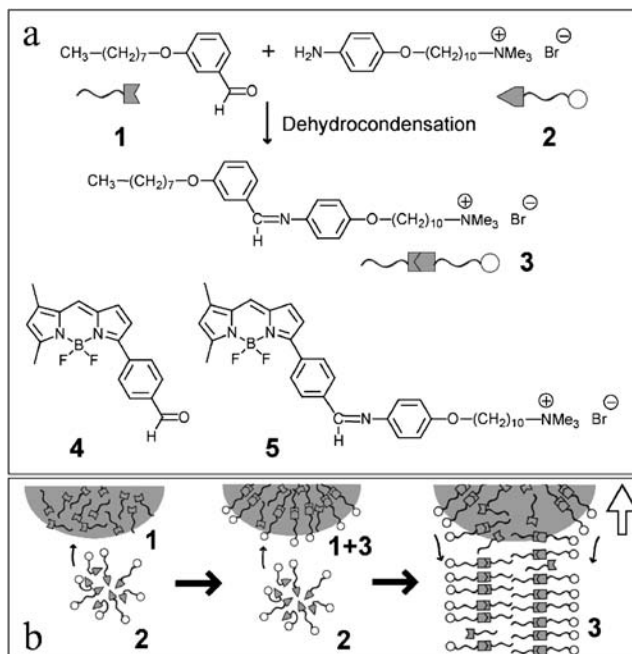


Figure 1. (a) Schematic illustration of dehydrocondensation of lipophile **1** and fluorescent indicator **4** with surfactant **2**, producing amphiphilic azomethine derivatives **3** and **5**. (b) Representative image of the autonomous swimming of oil emulsion droplet of **1** in micellar solution of **2**, propelled by generation of the membrane of vesicular amphiphile **3**.

dispersion of [1]/[2] = 20/20 (mM) was evaluated by ¹H NMR spectroscopy (see Supporting Information), and it turned out that the conversion yield of **1** to product **3** was only ca. 1% at 2 h and 50% after 5 days (see Supporting Information). Therefore, it was necessary to clarify that the trailing giant vesicles were composed of vesicular amphiphile **3** (Figure 1b).⁴ We thus focused on a fluorescent probe method that directly informs us the state of this emulsion system at the microscopic level under a fluorescent microscope.

Among fluorophores, 4,4-difluoro-4-bora-3a,4a-diaza-s-indacene (BODIPY) with its high fluorescent quantum yield is useful because its fluorescent color can be varied by chemical modification.⁵ Moreover, some BODIPY derivatives, of which fluorescence intensity or wavelength is switched by complexation with a cation or by protonation, have also been reported.⁶ We synthesized a BODIPY derivative (**4**, in Figure 1a) with a formyl group linked directly to the phenyl ring as a reaction-sensitive fluorescence indicator. This indicator can monitor the progress

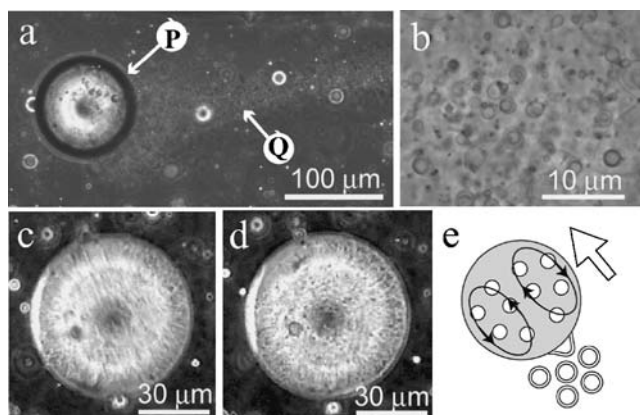


Figure 2. (a) Phase-contrast microscopic images on self-propelled motion of an oil emulsion droplet (site P) with a trail of giant vesicles (site Q). (b) Phase-contrast micrograph of a group of giant vesicles in the trail [site Q in (a)]. Stroboscopic micrographs (exposure time = 1 s) of the oil droplet including a couple of convection of water particles during the directional swimming motion (c); traces indicate that water particles are moving as a pair of convection, and at a turning point (d); stopped water particles are seen (see Supporting Information).⁹ Dynamics are schematically illustrated in (e).

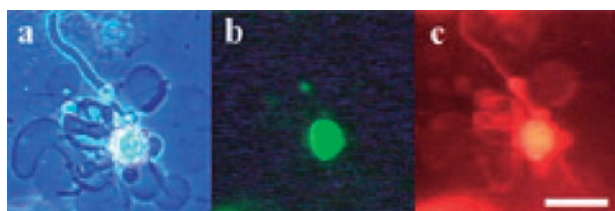


Figure 3. Microscopic images of membrane formation at an oil droplet of **1** containing 5 mol % of green-fluorescent indicator **4** one hour after addition of amphiphile **2**. (a) Phase-contrast microscopic image; (b and c) fluorescence microscopic image with two filter units [(b) λ_{ex} , 460–490 nm; λ_{em} , 515–550 nm; (c) λ_{ex} , 520–550 nm; λ_{em} , >580 nm]. The scale bar corresponds to 10 μm . Since an exposure time (ca. 1 s) was needed for capturing the fluorescence images, we recorded the fluorescence image of immobilized or slowly moving droplets in the same batch as we found the moving ones therein.

of the local imine-formation reaction, associated with the formation of giant vesicles because the formyl group is dehydrocondensed with an amino residue of the substrate **2** to afford azomethine derivative **5** (see Supporting Information). The absorption and fluorescence spectra of **4** showed its absorption and emission maxima at 528 and 556 nm, respectively, whereas the absorption and fluorescence maxima of several azomethine BODIPY derivatives shifted to the range of 535–537 and 568–570 nm, respectively (see Supporting Information).

The reaction-sensitive fluorescence indicator **4** was applied to monitor the formation of a vesicular amphiphile through imine coupling. To an emulsion of oil droplets of **1** containing 5 mol % of the indicator **4** was added an aqueous micellar solution (20 mM) of **2**. As imine formation proceeded, membranes began to grow from the oil droplets. The progress of membrane

formation was monitored by phase-contrast and fluorescence microscopes (Figure 3). When a band-pass filter (λ_{em} : 515–550 nm) was used, only the droplets glittered green. On the other hand, the growing vesicles and emulsion droplets glittered red through a cut-off filter (λ_{em} : >580 nm). This observation clearly indicates that the vesicular amphiphile **3** (and **5**) was, indeed, produced in/on the oil droplets by way of imine coupling between **1** (and **4**) and **2**.

Investigations of triggering and sustaining mechanisms of the self-propelled motion of the emulsion droplets tailing giant vesicles in this system is now in progress with regard to following factors: (i) the chemical Marangoni effect⁷ and (ii) the symmetry-breaking jet.⁸ It is probable that the formed thin film of **3** around the surface of the droplet is stripped off at an inlet position of the convection, releasing vesicles at the opposite side. This would be the reason why the oil droplet moves in one direction associated with the flow pattern of convection inside of the running oil droplet (Figure 2e). Although the detailed mechanism remains elusive, this is the first experimental system made of simple organic molecules that exhibits self-propelled motion that is coupled with chemical formation of the membrane molecule.

This work was supported by Grant-in-Aid for Center of Excellence (“Research Center for Integrated Science”) from the Ministry of Education, Culture, Sports, Science and Technology. T.T. is supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists (No. 08289).

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- 3 Dynamic light-scattering experiments (NIKKISO Microtrac UPA150) at room temperature ($23 \pm 1^\circ\text{C}$) revealed that, in a micellar solution (20 mM) of **2**, micelles with average diameters of 5 nm (standard deviation = 1 nm) formed in water.
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- 9 Supporting Information is available electronically on the CSJ-Journal Web site, <http://www.csj.jp/journals/chem-lett/index.html>.