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Detection of alkali and alkaline earth metal ions using birefringence of hyperswollen lamellar phase†

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Chemical sensors have targeted various substances. Most sensors electrically amplify signals. Here, we propose a visual detection system that uses a hyperswollen lamellar phase and detects targets in a solution without electric amplification. Amphiphiles with an oligo(ethylene glycol) chain can catch alkali and alkaline earth metal ions and amplify to macroscopic birefringence.

Introduction

Chemical sensors have been applied to various substances, from simple ions to complicated bacteria. They have employed various detection methods: chromatography,¹ flame reaction,² fluorescent detection,³ precipitation reaction,⁴ conductivity detection,⁵ and discoloration.⁶ Fluorescent detection, the most widely used method for biology, diagnosis, and environmental chemistry benefits from the substrate-specific interactions between fluorescent molecules and the target substances: alkali metal ions,⁷ alkaline earth metal ions,⁸ protons,⁹ and nucleic acids.¹⁰ This method detects target substances by converting the interactions to fluorescent changes, which can be quantitatively detected as electric signals. Because each probe molecule reacts with its target substance at a molar ratio of one to one and diffuses three-dimensionally, we cannot detect the substance without any amplification processes that require electric power sources and devices: lasers, detectors, and fluorescence microscopes.¹¹

As the detection methods without electric supplies, pH-test papers and gas detector tubes have been used.^{12–14} In these methods, we can visually observe the color change of the detector in response to the small number of targets because the probe molecules are immobilized to the substrates like filter papers and silica gels. The two-dimensional immobilization of the probe molecules can prevent signal attenuation caused by diffusion. However, it is not easy to prevent the diffusion of the probe molecules in the liquid phase. To visually detect the small number of targets in a solution without electric amplification, the self-assembly of the probe molecules should be effective in amplifying their small molecular deformation into large changes in the molecular assembled structures.

Liquid crystals can amplify signals through molecular cooperative behavior.^{15–19} They show texture changes in polarized optical microscopy when a certain chemical exists. To avoid using microscopies, we focused on the hyperswollen lamellar (HL) phase, a highly-diluted lyotropic liquid crystalline phase. The HL phase consists of the several-nanometers-thickness bilayers that keep several-hundred-nanometer intervals. The HL phase can visually display centimeter-sized typical birefringence textures without any microscopes due to their

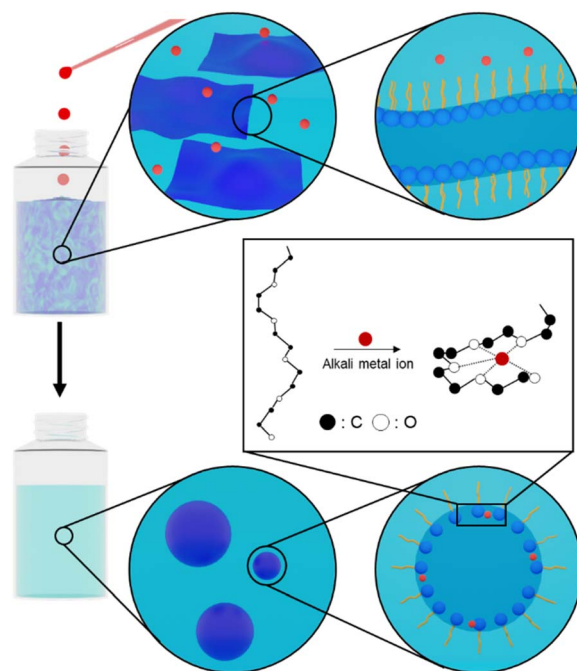


Fig. 1 Schematic illustration of the present detection method with the deformation of the HL phase. The metal ions (red dots) bind with the oligo ethylene glycol moieties (blue parts) of the amphiphiles. The complexation breaks the bilayers, and the birefringence disappears.

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transparency and long correlation length.^{20–24} *In vivo*, chemicals are detected in cell membranes consisting of bilayers and proteins. The signals are transferred and amplified by a second messenger after the target substance binds with a receptor on a nerve cell. The bilayers in HL phases could also immobilize the probe molecules. The HL phase can probably amplify the change of the probe molecules induced by the interactions with the target. The added target substance binds with the probe molecules in the bilayers. The complexation breaks the bilayers, and the HL phase disappears. We can detect it through the disappearance of birefringence.

Fluorescent detection of alkali metals is possible by using a crown ether as a probe.²⁵ The oligo(ethylene glycol) moiety of a crown ether attached to a chromophore strongly interacts with alkali metal ions, and the chromophore emits fluorescent light.^{26,27} Some organic solutions of a commercially available surfactant Brij L4 with an oligo(ethylene glycol) group show HL phases.²³ Here we demonstrate a visual detection system using HL phases of amphiphilic compounds with an oligo(ethylene glycol) chain whose self-assembled structures sensitively respond to the addition of alkali metal ions, as shown in Fig. 1.^{28,29} We confirm the texture change of the HL phase with the addition of alkali and alkaline earth metal ions.

Experimental

Chemicals

Heptane, methanol, lithium chloride, sodium chloride, potassium chloride, calcium chloride, barium chloride, lithium hydroxide, sodium hydroxide, potassium hydroxide, sodium carbonate, sodium hydrogen carbonate, and sodium nitrate were purchased from Wako Pure Chemical Industries Co. Brij L4 was purchased from Merck KGaA. The water with a resistivity of 18.2 M Ω cm was obtained from a water purifier (Direct-Q UV, Millipore Co).

Stability test

The HL phase solution consists of decane (4.8×10^{-3} M), Brij L4 (1.5×10^{-4} M) and deionized water (5.6×10^{-4} M). The target salts were added to the decane solution (40 mL). After sonication, we confirmed the birefringence of the solution at 25 °C. As long as the birefringence was maintained, we added target compounds. We defined the concentration at which birefringence disappears as a critical concentration (C_c).

Results and discussion

The organic solutions of Brij L4, a mixture containing tetraethyleneglycol monododecyl ether ($C_{12}E_4$) as the main component, exhibit HL phases when a small amount of water is added, as shown in Fig. S1.†²³ We can check if the solutions show the birefringence using polarizing films, as shown in Fig. 2a.²² The polarized photograph of the decane solution of Brij L4 (1.5×10^{-4} M) and water (5.6×10^{-4} M) shows a texture typical of HL phases originating from their birefringence, as shown in Fig. 2b. When we added sodium chloride (NaCl, $>1.9 \times 10^{-5}$ M)

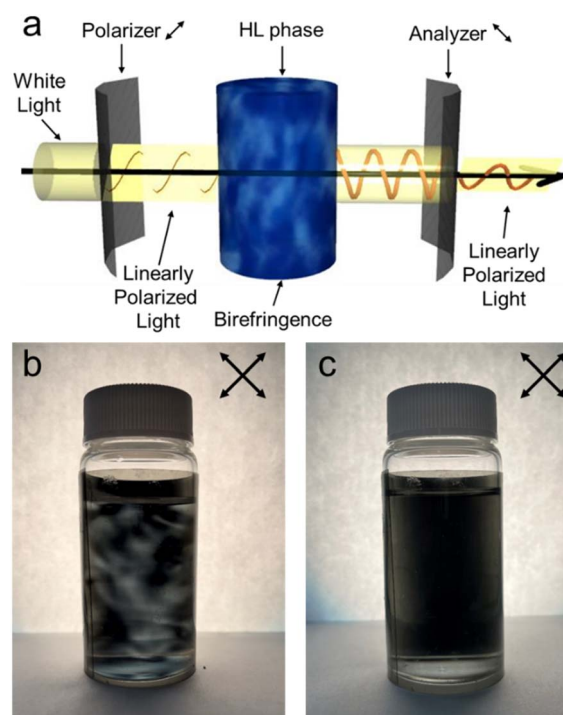


Fig. 2 Observation of birefringence. (a) The optical system to observe the birefringence using a polarizing film wrapped around a vessel white tilted at 45°. Polarized photographs of decane solution of water (5.6×10^{-4} M) and Brij L4 (1.5×10^{-4} M) (b) without additives and (c) with NaCl (1.9×10^{-5} M).

to the decane solution showing an HL phase (40 mL), the HL phase disappeared, as shown in Fig. 2c. Even when we added hydrogen chloride (HCl, 6.1×10^{-5} M) to the decane solution, the solution kept showing the HL phase maintained, as shown in Fig. S2.† It indicates that the main factor is Na^+ ions. Adding Na^+ ions should destabilize the HL phases due to the interactions between oligo(ethylene glycol) chains of Brij L4 and Na^+ ions, as shown in Fig. 1. The interactions probably affect the single-molecular shape of Brij L4 and the intermolecular interactions between Brij L4 molecules.^{30,31} They could be important for the stability of the HL phase.³²

We should examine if the destabilization should occur by adding different cations. When we added some other chloride salts to the decane solution of Brij L4 that shows an HL phase (40 mL), as shown in Table 1, lithium chloride (LiCl, $>3.0 \times 10^{-5}$ M), sodium chloride (NaCl, $>1.9 \times 10^{-5}$ M), potassium chloride (KCl, $>3.2 \times 10^{-5}$ M), calcium chloride (CaCl_2 , $>9.0 \times 10^{-6}$ M) and barium chloride (BaCl_2 , $>5.9 \times 10^{-6}$ M) destabilized the HL phase, as shown in Fig. S3.† The molar ratio required for destabilizing the HL phase (critical concentration, C_c) depends on the type of cations. It seems to come from the association constant of the oligo(ethylene glycol) chain and cations. It depends on the combination of the length of the oligo(ethylene glycol) chain and the ionic diameter of the cations.²⁶ It also depends on the charge density of cations.³³ Although Na^+ and Ca^{2+} ions are almost the same sizes, Ca^{2+} ions interact more strongly with the oligo(ethylene glycol) chains than Na^+ ions.

Table 1 C_c of alkali and alkaline earth metal chloride

	LiCl	NaCl	KCl	CaCl ₂	BaCl ₂
C_c [M]	3.0×10^{-5}	1.9×10^{-5}	3.2×10^{-5}	9.0×10^{-6}	5.9×10^{-6}
Cation radius [pm]	60	95	133	99	135

Table 2 C_c of alkali metal hydroxide and chlorides

	LiOH	NaOH	KOH	LiCl	NaCl	KCl
C_c [M]	1.1×10^{-5}	4.9×10^{-6}	9.2×10^{-6}	3.0×10^{-5}	1.9×10^{-5}	3.2×10^{-5}

Table 3 C_c of sodium compounds

	NaOH	Na ₂ CO ₃	NaHCO ₃	NaCl	NaNO ₃
C_c [M]	4.9×10^{-6}	2.2×10^{-6}	1.3×10^{-5}	1.9×10^{-5}	3.8×10^{-5}
[Na ⁺] [M]	4.9×10^{-6}	4.4×10^{-6}	1.3×10^{-5}	1.9×10^{-5}	3.8×10^{-5}

We added alkali metal hydroxides to the decane solution (40 mL), showing an HL phase, as shown in Table 2. The addition of lithium hydroxide (LiOH, $>1.1 \times 10^{-5}$ M), sodium hydroxide (NaOH, $>4.9 \times 10^{-6}$ M), and potassium hydroxide (KOH, $>9.2 \times 10^{-6}$ M) also destabilized the HL phase, as shown in Fig. S4.† The solubilities of calcium hydroxide (Ca(OH)₂) and barium hydroxide (Ba(OH)₂) are too low to be applied to the same tests. Among the three alkali metal ions, Na⁺ ion is the most effective. The critical concentrations of alkali hydroxide salts to Brij L4 are about one-third that of alkali chloride salts. These results imply that the anions also play important roles in the disturbance of HL phases.

We measured the effect of the anion by adding various sodium compounds to the decane solution (40 mL), as shown in Table 3. The data shows that the effect of the sodium compounds on the stability of the HL phase depends on the type of anions. As mentioned above, the main factor of the additives is cations. Cations make complexes with the oligo(ethylene glycol) chain, and the bilayers in the HL phases change their stabilities. The effect of the anions would be secondary. We came up with several scenarios. Acidity constant, size, pH, charge density and salting out could be effective. We found that the order of the critical concentrations is consistent with that of the salting-out effects of the anions, *i.e.*, the Hofmeister series: OH⁻ \approx CO₃²⁻ > HCO₃⁻ > Cl⁻ > NO₃⁻.^{34–37} These results indicate that the bilayers destabilized by the association of oligo(ethylene glycol) chains and metal ions are salted-out in the presence of anions.

Conclusions

We have confirmed that the present system can detect the existence of alkali and alkaline earth metal ions by observing the birefringence of the HL phase. The addition of alkali and alkaline earth metal compounds destabilized the HL phase. The association of oligo(ethylene glycol) chains and cations and the

salting-out-like effect of anions probably originate the destabilization. The critical concentration seems to depend on the diameter and charge density of cations. Anions should be the second factor of destabilization; anions might induce undesired interactions between the complexes of oligo(ethylene glycol) chains and cations like salting-out. We have successfully detected the presence of the alkali and alkaline earth metal ions; however, it is still difficult to identify which ions exist. This method could apply to detecting various materials by choosing the appropriate probes, though it cannot apply to no-water and extreme pH conditions. In principle, the detection limit can be arbitrarily controlled by appropriately setting the initial HL phase stability.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- 1 C. E. Dent, *Biochem. J.*, 1947, **41**, 240–253.
- 2 A. R. Clark, *J. Chem. Educ.*, 1935, **12**, 242–243.
- 3 A. H. Coons and K. H. Melvin, *J. Exp. Med.*, 1950, **91**, 1–13.
- 4 M. Arnac and G. Verboom, *Anal. Chem.*, 1974, **46**, 2059–2061.
- 5 J. S. Fritz, D. T. Gjerde and R. M. Becker, *Anal. Chem.*, 1980, **52**, 1519–1522.
- 6 R. Ishida, H. Narita and K. Tonosaki, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 1751–1754.
- 7 A. Minta and R. Y. Tsien, *J. Biol. Chem.*, 1989, **264**, 19449–19457.
- 8 H. Komatsu, N. Iwasawa, D. Citterio, Y. Suzuki, T. Kubota, K. Tokuno, Y. Kitamura, K. Oka and K. Suzuki, *J. Am. Chem. Soc.*, 2004, **126**, 16353–16360.
- 9 J. Han and K. Burgess, *Chem. Rev.*, 2010, **110**, 2709–2728.
- 10 G. Patonay, J. Salon, J. Sowell and L. Strekowski, *Molecules*, 2004, **9**, 40–49.

- 11 Y.-H. Shin, M. T. Gutierrez-Wing and J.-W. Choi, *J. Electrochem. Soc.*, 2021, **168**, 017502.
- 12 E. W. Rice, *Ind. Eng. Chem.*, 1912, **4**, 229.
- 13 A. B. Lamb and C. R. Hoover, *US Pat.*, US1321062A, 1918.
- 14 K. Kawamura, K. Miyazawa and L. Kent, *Appl. Chem.*, 2021, **1**, 14–41.
- 15 H. Eimura, D. S. Miller, X. Wang, N. L. Abbott and T. Kato, *Chem. Mater.*, 2016, **28**, 1170–1178.
- 16 Y. Wang, Q. Hu, T. Tian, Y. Gao and L. Yu, *Colloids Surf., B*, 2016, **147**, 100–105.
- 17 P. Popov, L. W. Honaker, E. E. Kooijman, E. K. Mann and A. I. Jákli, *Sens. Bio-Sens. Res.*, 2016, **8**, 31–35.
- 18 J. Shen, F. J. He, L. C. Chen, L. Ding, H. L. Liu, Y. Wang and X. L. Xiong, *Microchim. Acta*, 2017, **184**, 3137–3144.
- 19 Y. Han, K. Pacheco, C. W. M. Bastiaansen, D. J. Broer and R. P. Sijbesma, *J. Am. Chem. Soc.*, 2010, **132**, 2961–2967.
- 20 F. C. Larche, J. Appell, G. Porte, P. Bassereau and J. Marignan, *Phys. Rev. Lett.*, 1986, **56**, 1700–1703.
- 21 R. Strey, R. Schomäcker, D. Roux, F. Nallet and U. Olsson, *J. Chem. Soc. Faraday. Trans.*, 1990, **86**, 2253–2261.
- 22 K. Sasaki, T. Okue, T. Nakai, Y. Uchida and N. Nishiyama, *Langmuir*, 2021, **37**, 5872–5877.
- 23 K. Sasaki, T. Okue, Y. Shu, K. Miyake, Y. Uchida and N. Nishiyama, *Dalton Trans.*, 2021, **50**, 10394–10399.
- 24 K. Sasaki, K. Miyake, Y. Uchida and N. Nishiyama, *ACS Appl. Nano Mater.*, 2022, **5**, 4998–5005.
- 25 C. J. Pedersen, *J. Am. Chem. Soc.*, 1967, **89**, 7017–7036.
- 26 J. Yin, Y. Hu and J. Yoon, *Chem. Soc. Rev.*, 2015, **44**, 4619–4644.
- 27 D. E. Fenton, J. M. Parker and P. V. Wright, *Polymer*, 1973, **14**, 589.
- 28 T. Kato, *Science*, 2002, **295**, 2414–2418.
- 29 M. Yoshio, T. Mukai, K. Kanie, M. Yoshizawa, H. Ohno and T. Kato, *Adv. Mater.*, 2002, **14**, 351–354.
- 30 S. Yanagida, K. Takahashi and M. Okahara, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 3111–3120.
- 31 S. Yanagida, K. Takahashi and M. Okahara, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 1294–1299.
- 32 Y. Uchida, T. Nishizawa, T. Omiya, Y. Hirota and N. Nishiyama, *J. Am. Chem. Soc.*, 2016, **138**, 1103–1105.
- 33 Y. Tian, W. Chen, Z. Zhao, L. Xu and B. Tong, *J. Mol. Model.*, 2020, **26**, 67.
- 34 M. Randall and C. F. Failey, *Chem. Rev.*, 1927, **4**, 285–290.
- 35 P. Lo Nostro and B. W. Ninham, *Chem. Rev.*, 2012, **112**, 2286–2322.
- 36 A. M. Hyde, S. L. Zultanski, J. H. Waldman, Y.-L. Zhong, M. Shevlin and F. Peng, *Org. Process Res. Dev.*, 2017, **21**, 1355–1370.
- 37 K. P. Gregory, G. R. Elliott, H. Robertson, A. Kumar, E. J. Wanless, G. B. Webber, V. S. J. Craig, G. G. Andersson and A. J. Page, *Phys. Chem. Chem. Phys.*, 2022, **24**, 12682–12718.