JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

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Preparation of Highly Fluorescent Host–Guest Complexes with Tunable Color upon Encapsulation

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Supporting Information

ABSTRACT: Unlike previous coordinative host–guest systems, highly emissive host–guest complexes (up to Φ_F = 0.5) were successfully prepared upon encapsulation of various fluorescent dyes (e.g., BODIPY and coumarin derivatives) by a Pt(II)-linked coordination capsule in water. Picosecond time-resolved spectroscopy elucidates the photophysical behaviors of the obtained complexes. Notably, the emission color of the fluorescent guest within the capsule can be readily modulated upon pairwise encapsulation with planar aromatic molecules.

Host–guest chemistry in synthetic compounds has been greatly expanded since the emergence of coordination-driven molecular cages and capsules because of their structural variety, facile synthesis, relatively high stability, and efficient host–guest interactions.[1,2] The preparation of highly fluorescent coordination hosts and host–guest complexes shows great promise for the development of novel photofunctional supramolecules,[3,4] which attract much attention for wide-ranging applications in chemosensors, biological labels, and photoelectric materials.[5] However, to our surprise, coordinative host–guest complexes capable of displaying intense fluorescence have been scarcely reported, because the host frameworks effectively quench the guest emissions, owing to the heavy-atom effects of the indispensable transition metal hinges and/or host–guest charge-transfer interactions, in addition to the lack of guest-binding ability. The only two exceptions are a Pt(II)-linked coordination cage with a tetraazaporphine guest and a Fe(II)-linked coordination cage with perylene guests, but their fluorescence quantum yields (Φ_F) were recorded to be smaller than 0.2.[6] In addition, fine-tuning of the fluorescent colors of the encapsulated guests has not been accomplished even within covalent hosts. Since the first report of an M_2L_4 polyaromatic capsule in 2011,[7] we have been striving toward the preparation of fluorescent host–guest complexes by using various metal ions and fluorescent dyes for the host hinges and the guests, respectively. Here we report the quantitative preparation of highly emissive host–guest complexes in water by using a derivative of the coordination capsule. Photophysical properties of the host and host–guest complexes are elucidated by femtosecond time-resolved absorption and picosecond time-resolved fluorescence spectroscopy.[8] Furthermore, the emissive color of the fluorescent guest can be altered within the capsule through pairwise encapsulation.

Herein we employed M_2L_4 coordination capsule **1**, possessing a large cavity (~580 Å^3), formed quantitatively by Pt(II) ions and bent bispyridine ligands (Figure 1a).[9] While multiple anthracene fluorophores are incorporated into the ligand, the Pt(II) capsule and the Pd(II) analogue exhibit *no emission* ($\Phi_F < 10^{-3}$) from the host frameworks, much like other reported Pt(II) and Pd(II)-linked coordination cages.[2,10] Here, we selected BODIPY derivative **2**, coumarin 153 (**3**), and Nile red (**4**) as guests, well-known as hydrophobic fluorescent dyes (Figure 1b). Whereas highly emissive BODIPY derivatives have been widely utilized in various molecules and polymers,[11] to the best of our knowledge, host–guest and guest–guest interactions within synthetic molecular hosts have never been demonstrated. Pt(II)-linked capsule **1** containing one molecule of **2** emits strong green fluorescence with Φ_F = 0.5 and notably, the emissive color of the host–guest complex dramatically changes upon co-encapsulation with planar aromatic compounds such as anthracenes **5a**,**b**, phenanthrene (**6**), and pyrenes **7a**–**c**.

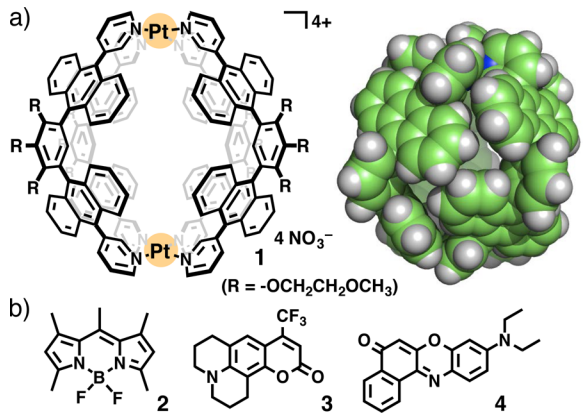

Figure 1. (a) M_2L_4 coordination capsule **1** and the space-filling representation of the crystal structure (substituents and counterions are omitted for clarity) and (b) fluorescent dyes **2**–**4** employed as guest molecules.

Received: June 15, 2015
Published: July 12, 2015

DOI: 10.1021/jacs.5b06195
J. Am. Chem. Soc. 2015, 137, 9266–9269

Quantitative encapsulation of fluorescent dyes **2**–**4** by capsule **1** was carried out in water through hydrophobic effect, and the structure of the resultant host–guest complexes was confirmed by NMR and MS analyses.[12] Stirring a suspension of **1** (0.39 μmol) and hydrophobic BODIPY derivative **2** (0.39 μmol) in D_2O (0.5 mL) at 80 °C for 1 h resulted in the formation of a **1**⊃**2** complex in quantitative yield. A ^{1}H NMR spectrum of the obtained orange solution showed new signals derived from the methyl protons of the encapsulated **2** at −0.98 and −1.06 ppm. The signals were significantly shifted upfield ($\Delta\delta_{max}$ = −3.57 ppm) as a result of magnetic shielding by the capsule framework (Figure 2c, left). In addition to NMR

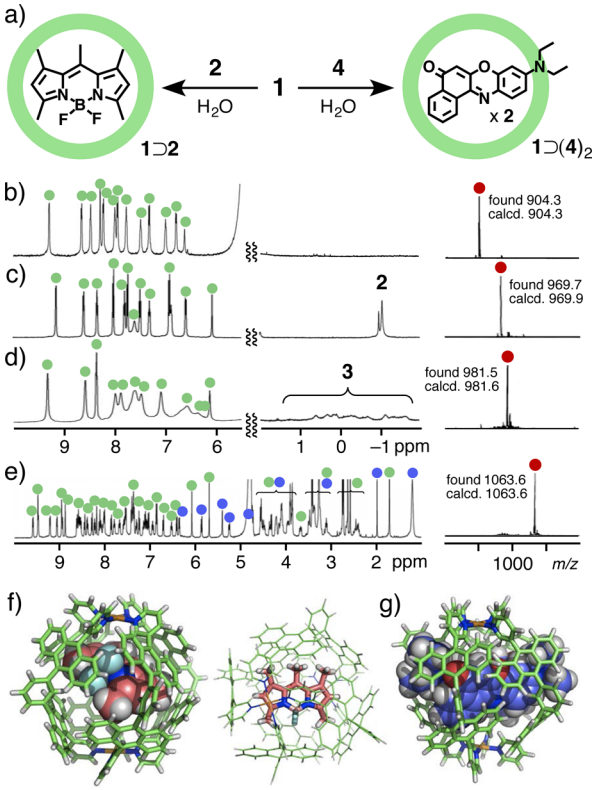

Figure 2. (a) Schematic representation of the selective formation of **1**⊃**2** and **1**⊃$(\mathbf{4})_2$. ^{1}H NMR (500 MHz, D_2O, r.t.) and ESI-TOF MS (H_2O, r.t., $[M]^{4+}$) spectra of (b) **1**, (c) **1**⊃**2**, (d) **1**⊃**3**, and (e) **1**⊃$(\mathbf{4})_2$ (green circle, **1**; blue circle, **4**). (f) X-ray crystal structure of **1**⊃**2** and (g) optimized structure of **1**⊃$(\mathbf{4})_2$ (substituents and counterions are omitted for clarity).

integration of the host/guest proton signals, the ESI-TOF MS measurement verified the 1:1 host–guest composition (e.g., m/z = 969.7 $[\mathbf{1}\supset\mathbf{2} - 4\cdot NO_3^-]^{4+}$; Figure 2c, right). No signal for the guest-free capsule was detected so that the host–guest complex is stable enough even under the MS conditions. Direct evidence of the host–guest structure was obtained from X-ray crystallographic analysis.[12] A crystal structure of **1**⊃**2** unambiguously revealed that one molecule of planar **2** rests between the two Pt(II) centers and is fully enclosed by the capsule shell (Figure 2f).

Using a similar procedure as was used for the **1**⊃**2** complex, coumarin derivative **3** with a CF_3 group was also encapsulated within capsule **1** to give a pale-yellow 1:1 host–guest complex, **1**⊃**3**, quantitatively in water at room temperature.[12,13] Although the ^{1}H NMR signals of the encapsulated **3** and the anthracene panels of **1** were significantly broadened (Figure 2d), ESI-TOF MS analysis clearly revealed the selective formation of the **1**⊃**3** complex. A single ^{19}F NMR signal of the guest was observed at −68.0 ppm. On the other hand, two molecules of hydrophobic Nile red (**4**) were quantitatively bound in the cavity of **1** at 80 °C to afford a purple solution of **1**⊃$(\mathbf{4})_2$. In the ^{1}H NMR spectrum, notably, the signals of the capsule were intricately split owing to desymmetrization of the capsule framework upon encapsulation of the relatively large guests (Figure 2e, left). The prominent peaks of the product found in the ESI-TOF MS spectrum established a 1:2 stoichiometry of the host–guest complex (Figure 2e, right).[12] The optimized structure of **1**⊃$(\mathbf{4})_2$ by force-field calculation[14] revealed that two molecules of **4** are covered by the distorted spherical shell of **1**, in which the diethylamino groups of **4** protrude slightly through the apertures of the capsule frameworks (Figure 2g).

Unlike typical coordination hosts, when M_2L_4 capsule **1** accommodates fluorescent dyes **2**–**4**, the resultant host–guest complexes turned out to be highly emissive. The UV–vis spectrum of the **1**⊃**2** complex in H_2O showed new absorption bands at 478 and 508 nm derived from the encapsulated **2** (Figure 3a). The bands were slightly shifted toward the red ($\Delta\lambda$ = 14 nm) with respect to those of free **2** in EtOH. In the **1**⊃**3** complex, the absorption band of **3** was partially overlapped with that of the anthracene moieties of **1** (320–430 nm). The purple solution of **1**⊃$(\mathbf{4})_2$ exhibited absorption bands in the range of 450–650 nm distinct from those of **1** (Figure 3a). The observed bands of **3** and **4** were also shifted by $\Delta\lambda \approx 30$ nm as compared with those of the free guests, due to their enclathration. The aqueous **1**⊃**2** complex emitted strong green fluorescence under ambient conditions. In the fluorescence spectrum, a sharp emission band was found at λ_{max} = 535 nm with high quantum yield (Φ_F = 0.48) upon irradiation at 495 nm (Figure 3b). It should be noted that more than 60% of the emission efficiency of free **2** remains even within the coordination capsule.[15] The **1**⊃**3** and **1**⊃$(\mathbf{4})_2$ complexes showed bluish-green fluorescence (λ_{max} = 509 nm, Φ_F = 0.25) and red fluorescence (λ_{max} = 636 nm, Φ_F = 0.32), respectively (Figure 3b). The guests **3** and **4** also retained their intrinsic emissivities of ∼60% within capsule **1**.[15] In sharp contrast, fluorescent hydrocarbon dyes, such as phenanthrene and pyrene with absorption bands around 400 nm, fully lost emissivity upon encapsulation within **1**, most likely owing to fast deactivation through energy transfer from the guest to the capsule.[15] This suggests that the absorption wavelength of the guests is one of the key factors in the present host–guest system.

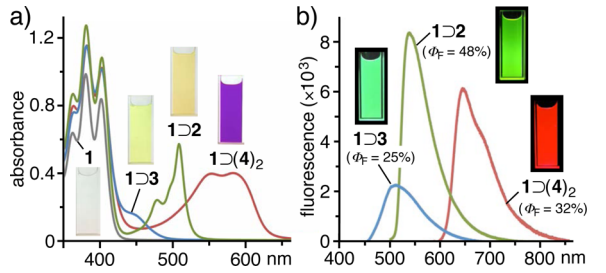

Figure 3. (a) UV–visible spectra (H_2O, 80 μM based on **1**, r.t.) of **1**, **1**⊃**2**, **1**⊃**3**, and **1**⊃$(\mathbf{4})_2$ and (b) their fluorescence spectra except for **1**. Excitation wavelengths: λ_{ex} = 495 nm for **1**⊃**2**, λ_{ex} = 423 nm for **1**⊃**3**, and λ_{ex} = 583 nm for **1**⊃$(\mathbf{4})_2$.

DOI: 10.1021/jacs.5b06195
J. Am. Chem. Soc. 2015, 137, 9266–9269

To understand the dynamics of emission of the guest within the coordination capsule, we performed time-resolved fluorescence measurements on aqueous solutions of **1** and **1⊃2** at room temperature. Following excitation of empty capsule **1** at 400 nm, approximately 90% of the fluorescence decays within the instrument response time of 30 ps, and the remaining 10% exhibited a fluorescence decay time of 4.3 ns (Supporting Information, Figure S38). In contrast to the emission from the empty capsule, long-lived fluorescence (7.4 ns) was observed at λ > 585 nm from **1⊃2** when the guest was directly excited at 525 nm (Figure 4a). The lifetime is comparable to that of free **2**

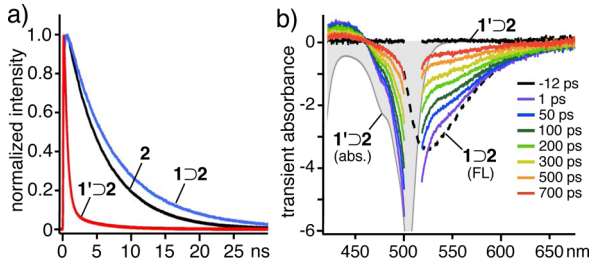

Figure 4. (a) Emission decay curves (λ_{ex} = 525 nm, λ_{det} > 585 nm) for **1⊃2** in H_2O, **2** in CH_3CN, and **1′⊃2** in H_2O/CH_3CN (9:1). (b) Time-resolved absorption spectra of **1′⊃2** following excitation of the guest at 510 nm.

(5.7 ns) in CH_3CN.[16] The long-lived emission of the encapsulated **2** indicates the existence of a stable excited state, which accounts for the bright fluorescence of the guest even within **1**. In contrast, rapid fluorescence quenching was found in the analogous host–guest complex that was prepared using Pd(II) ions, **1′⊃2**, in which the major emissive component (>90%) decays with a time constant of 0.35 ns.[17] In addition, transient absorption of **1′⊃2** was performed to elucidate the mechanism of the fluorescence quenching. As shown in Figure 4b, a transient bleach could be observed between 470 and 500 nm, and stimulated emission was observed between 540 and 700 nm. Both signals decreased simultaneously with a time-constant of 340 ps, indicating that the fluorescent excited state relaxes directly to the ground state.[18]

Finally, we demonstrated that the emissive features of fluorescent dye **2** can be altered upon pairwise encapsulation within capsule **1**. X-ray crystal analysis revealed that the **1⊃2** complex provides a planar interstice in the cavity, and therefore we envisioned that one additional molecule of a planar aromatic compound could be inserted into the space. When 9-methylanthracene (**5a**; 1 equiv) was suspended in an aqueous solution of **1⊃2** at 60 °C for 30 min, a ternary complex, **1⊃2·5a**, was formed in 74% yield (Figure 5a). The methyl signals of the co-encapsulated **2** and **5a** were desymmetrized and observed in the range of −0.24 to −1.64 ppm in the ^{1}H NMR spectrum due to the tight encapsulation (Figure 5b, left). The **1·2·5a** composition of the product was confirmed by ESI-TOF MS analysis (Figure 5b, right). The optimized structure of **1⊃2·5a** indicates that stacked heterodimer **2·5a** fully occupies the inner space of **1** (Figure 5c).[14] By employing other planar aromatics such as anthracene (**5b**), phenanthrene (**6**), pyrene (**7a**), 1-methylpyrene (**7b**), and 1-aminopyrene (**7c**), the corresponding ternary complexes were obtained in moderate to high yields (40–67%).[19]

It is worth noting that the color of the fluorescence of **1⊃2** was dramatically changed upon the formation of the ternary

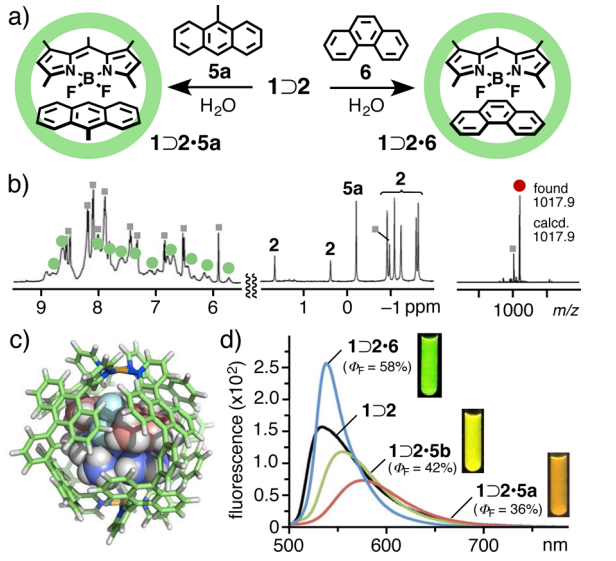

Figure 5. (a) Schematic representation of the formation of **1⊃2·5a** and **1⊃2·6**. (b) ^{1}H NMR (500 MHz, D_2O, r.t.) and ESI-TOF MS (H_2O, r.t., $[M]^{4+}$) spectra of **1⊃2·5a** (gray square, **1⊃(5a)$_2$**) and (c) the optimized structure of **1⊃2·5a** (substituents are omitted for clarity). (d) Fluorescence spectra (H_2O, λ_{ex} = 495 nm, r.t.) of **1⊃2·5a,b**, **1⊃2·6**, and **1⊃2**.

complexes. The aqueous solution of the 9-methylanthracene-embedded **1⊃2·5a** complex emitted orange fluorescence with a good quantum yield (Φ_F = 0.36) and showed a broad emission band around λ_{max} = 577 nm, which is greatly shifted toward the red ($\Delta\lambda$ = 42 nm) as compared with that of **1⊃2** (Figure 5d).[12] Within the capsule, interestingly, the emission color of guest **2** is sensitive to the identity of the co-encapsulated guest. The **1⊃2·5b** complex containing non-substituted anthracene exhibited strong yellow emission (Φ_F = 0.42 and λ_{max} = 554 nm). On the other hand, the phenanthrene-containing ternary complex, **1⊃2·6**, displayed strong green fluorescence (Φ_F = 0.58) with a sharp emission band at λ_{max} = 538 nm (Figure 5d). The emission intensity is 1.2 times higher than that of **1⊃2**. Insertion of pyrene derivatives **7a–c** could also modulate the fluorescent properties of **2** within the capsule (Supporting Information, Figure S32).[12] The aqueous solutions of **1⊃2·7a** and **1⊃2·7b** showed yellow and orange emissions (Φ_F = 0.48 and 0.36), respectively, in a manner similar to those of **1⊃2·5a,b**.[20]

There are many reports on pair-selective encapsulation of two substrates within supramolecular hosts for unusual chemical reactions.[21] We emphasize, however, that fine-tuning of the emission properties of fluorescent dyes upon pairwise encapsulation had not been achieved so far. BODIPY derivatives bearing simple alkyl substituents are known to be relatively insensitive to solvent polarity.[11] Indeed, mixtures of **2** and aromatic compounds such as **5a** and **6** in organic solvents (e.g., EtOH) showed a sharp emission band (λ_{max} = 522 nm) from **2** (Supporting Information, Figure S33), due to the absence of their intermolecular interactions. Therefore, the large, spherical cavity of coordination capsule **1** is essential for both the pairwise encapsulation of fluorescent dye **2** with guests **5–7** and the modulation of the emission color of **2** through tight intermolecular interactions between the co-encapsulated guests. The observed, unusual color changes most probably stem from the exclusive formation of excimer-like complexes in the confined nanospace of the capsule.

DOI: 10.1021/jacs.5b06195
J. Am. Chem. Soc. 2015, 137, 9266–9269

In summary, we have proven that highly emissive host−guest complexes are successfully prepared by simply mixing a Pt(II)-linked coordination capsule and various fluorescent dyes in water. The emission color of the host−guest complex containing a BODIPY derivative could be altered through pairwise encapsulation. The present non-covalent approach for the straightforward preparation of aqueous fluorescent nanocomposites capable of modulating the emission color *upon encapsulation* could lead to the development of new photofunctional sensing and labeling materials.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details and characterization data. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b06195.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through a Grant-in-Aid, "Soft Molecular Systems" and by "Support for Tokyotech Advanced Researchers (STAR)". We thank Dr. Kenji Yoza (Bruker AXS) for supporting X-ray crystallographic analysis.

■ REFERENCES

(1) Steed, J. W.; Atwood, J. L. *Supramolecular Chemistry*, 2nd ed.; Wiley: Chichester, UK, 2009.

(2) (a) Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853−908. (b) Hof, F.; Craig, S. L.; Nuckolls, C.; Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2002**, *41*, 1488−1508. (c) Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *Acc. Chem. Res.* **2009**, *42*, 1650−1659. (d) Yoshizawa, M.; Klosterman, J. K.; Fujita, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 3418−3438. (e) Wiester, M. J.; Ulmann, P. A.; Mirkin, C. A. *Angew. Chem., Int. Ed.* **2011**, *50*, 114−137. (f) Amouri, H.; Desmarets, C.; Moussa, J. *Chem. Rev.* **2012**, *112*, 2015−2041. (g) Han, M.; Engelhard, D. M.; Clever, G. H. *Chem. Soc. Rev.* **2014**, *43*, 1848−1860. (h) Castilla, A. M.; Ramsay, W. J.; Nitschke, J. R. *Acc. Chem. Res.* **2014**, *47*, 2063−2073.

(3) Fluorescent coordination cages and capsules: (a) Al-Rasbi, N. K.; Sabatini, C.; Barigelletti, F.; Ward, M. D. *Dalton Trans.* **2006**, 4769−4772. (b) Harano, K.; Hiraoka, S.; Shionoya, M. *J. Am. Chem. Soc.* **2007**, *129*, 5300−5301. (c) Ghosh, S.; Gole, B.; Bar, A. K.; Mukherjee, P. S. *Organometallics* **2009**, *28*, 4288−4296. (d) Wang, J.; He, C.; Wu, P.; Wang, J.; Duan, C. *J. Am. Chem. Soc.* **2011**, *133*, 12402−12405. (e) Wang, M.; Vajpayee, V.; Shanmugaraju, S.; Zheng, Y.-R.; Zhao, Z.; Kim, H.; Mukherjee, P. S.; Chi, K.-W.; Stang, P. J. *Inorg. Chem.* **2011**, *50*, 1506−1512. (f) Li, Z.; Kishi, N.; Yoza, K.; Akita, M.; Yoshizawa, M. *Chem. - Eur. J.* **2012**, *18*, 8358−8365. (g) Frischmann, P. D.; Kunz, V.; Würthner, F. *Angew. Chem., Int. Ed.* **2015**, *54*, 7285−7289.

(4) AIEE-active coordination cages: Yan, X.; Cook, T. R.; Wang, P.; Huang, F.; Stang, P. J. *Nat. Chem.* **2015**, *7*, 342−348.

(5) Xu, L.; Wang, Y.-X.; Yang, H.-B. *Dalton Trans.* **2015**, *44*, 867−890.

(6) (a) Ono, K.; Klosterman, J. K.; Yoshizawa, M.; Sekiguchi, K.; Tahara, T.; Fujita, M. *J. Am. Chem. Soc.* **2009**, *131*, 12526−12527. (b) Neelakandan, P. P.; Jiménez, A.; Nitschke, J. R. *Chem. Sci.* **2014**, *5*, 908−915.

(7) Kishi, N.; Li, Z.; Yoza, K.; Akita, M.; Yoshizawa, M. *J. Am. Chem. Soc.* **2011**, *133*, 11438−11441.

(8) (a) Hosoi, H.; Yamaguchi, S.; Tahara, T. *Chem. Lett.* **2005**, *34*, 618−619. (b) Klosterman, J. K.; Iwamura, M.; Tahara, T.; Fujita, M. *J. Am. Chem. Soc.* **2009**, *131*, 9478−9479.

(9) (a) Kishi, N.; Li, Z.; Sei, Y.; Akita, M.; Yoza, K.; Siegel, J. S.; Yoshizawa, M. *Chem. - Eur. J.* **2013**, *19*, 6313−6320. (b) Kishi, N.; Akita, M.; Yoshizawa, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 3604−3607. (c) Yamashina, M.; Sei, Y.; Akita, M.; Yoshizawa, M. *Nat. Commun.* **2014**, *5*, 4662.

(10) Debata, N. B.; Tripathy, D.; Chand, D. K. *Coord. Chem. Rev.* **2012**, *256*, 1831−1945.

(11) Loudet, A.; Burgess, K. *Chem. Rev.* **2007**, *107*, 4891−4932.

(12) See the Supporting Information. Orange single crystals were obtained by slow concentration of a H_2O/CH_3CN (9:1) solution of **1⊃2** at room temperature over 1 week.

(13) Electrostatic repulsions between the electronegative fluoride atoms of guests **2** and **3** probably suppress the encapsulation of two molecules of the guests within capsule **1**.

(14) The calculations were carried out by using *Materials Studio* (ver. 5.0; Accelrys Software Inc.: San Diego, CA, 2009).

(15) The fluorescence spectra of **2**, **3**, and **4** in EtOH showed intense emission bands at λ_{max} = 522 nm (Φ_F = 0.78), 530 nm (Φ_F = 0.49), and 640 nm (Φ_F = 0.54), respectively (Supporting Information, Figures S16−S18). 1:2 Host−guest complexes with fluorescent dyes such as anthracene, perylene, and 1,8-naphthalimide also displayed no emissive properties (Supporting Information, Figure S39).

(16) The Φ_F of **1⊃2** is lower than that of free **2**, despite the longer-lived emission, suggesting that the fluorescence of some fraction of the population is quenched within the time resolution of the experimental setup. This quenching is not directly observed by femtosecond transient absorption spectroscopy, indicating that other quenching processes may take place within 100 fs.

(17) The minor component (<10%) decays with a lifetime of 4.1 ns.

(18) While the usual mechanism for fluorescence quenching of guests within hosts is intersystem crossing to a long-lived triplet state, this result shows that the relaxation does not pass through any such state. The multiexponential decay of the emission suggests that multiple configurations of each species exist simultaneously in solution, with some very strongly quenching.

(19) The yields of the ternary complexes were estimated by UV−vis analysis: **1⊃2·5b** (67%), **1⊃2·6** (67%), **1⊃2·7a** (58%), **1⊃2·7b** (45%), and **1⊃2·7c** (40%).

(20) The co-encapsulation of 1-aminopyrene (**7c**) creating **1⊃2·7c** decreased the intense fluorescence of **2** (Φ_F = 0.10 and λ_{max} = 537 nm).

(21) (a) Kang, J.; Rebek, J., Jr. *Nature* **1997**, *385*, 50−52. (b) Chen, J.; Rebek, J., Jr. *Org. Lett.* **2002**, *4*, 327−329. (c) Marty, M.; Clyde-Watson, Z.; Twyman, L. J.; Nakash, M.; Sanders, J. K. M. *Chem. Commun.* **1998**, 2265−2266. (d) Yoshizawa, M.; Tamura, M.; Fujita, M. *Science* **2006**, *312*, 251−254. (f) Murase, T.; Horiuchi, S.; Fujita, M. *J. Am. Chem. Soc.* **2010**, *132*, 2866−2867.

DOI: 10.1021/jacs.5b06195
J. Am. Chem. Soc. 2015, 137, 9266−9269