

Letter

Acid/Base-Controllable FRET and Self-Assembling Systems Fabricated by Rhodamine B Functionalized Pillar[5]arene-Based Host—Guest Recognition Motifs

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Supporting Information

ABSTRACT: A novel supramolecular Föster resonance energy transfer (FRET) system was fabricated by utilizing rhodamine B (**RB**) functionalized pillar[5]arene (**EtP5-RB**) and cyanomodified boron dipyrromethene (**BDP-CN**) based on their host–guest recognition at 5.0×10^{-5} M, which could be turned "on" and "off" by adding trifluoroacetic acid (TFA) and triethylamine (TEA), respectively. At a higher concentration (1.0×10^{-4} M) in acetone, **EtP5-RB** self-assembled into vesicles while **EtP5-RBH** self-assembled into nanoribbons. After the addition of **BDP-CN**, both **EtP5-RB**-**BDP-CN** and **EtP5-RBH**-**BDP-CN** self-assembled into nanoparticles, which caused the fluorescence of the host–guest complexes to be quenched.

S upramolecular fluorescent systems based on both of the host-guest recognition and various electron- or energy-transfer mechanisms, such as photoinduced electron transfer (PET),¹ Föster resonance energy transfer (FRET),² and triplet-triplet energy transfer (TTET),³ have stimulated tremendous interest in recent years due to their promising applications in numerous fields, including fluorescent probes,^{1b,c,e} chemosensors,^{1h} molecular devices,^{1d,g,2c,d,3b} and biological applications,^{1a,2a} etc. The host-guest recognition plays a significant role in the construction of advanced supramolecular fluorescent systems as a result of their intriguing binding abilities, facile tunable functionality, and abundant stimuli responsiveness.¹⁻³ For instance, the supramolecular fluorescent systems based on the host-guest recognition can be controlled via a variety of external stimulations, such as acid/base,^{1b,g,3b} redox,^{1c,e} light,^{1d,2b,d} and metal ion^{1a,e,f,h,2c} by tuning the formation/ dissociation of the host-guest complexes.

As a new generation of macrocyclic hosts, pillar[*n*] arenes were synthesized by Ogoshi et al. in 2008 for the first time.⁴ Since then, due to the accessible one-step synthesis, convenient tunable functionalization, unique symmetric pillar-shaped structures, and intriguing host—guest binding properties, pillararenes have been widely explored in the construction of numerous supramolecular systems, such as supramolecular polymers,⁵ controlled release systems,⁶ transmembrane channels,⁷ and porous materials.⁸ In addition, pillararene-based fluorescent systems have also attracted considerable attention owing to their promising applications in cell diagnostic imaging,⁹ controlled release systems,¹⁰ and chemosensors.¹¹ However, the investigation of pillararene-based supramolecular fluorescent systems via elec-



tron or energy transfer is still a great challenge, and only few examples without stimuli-responsiveness have been reported to date. $^{\rm 12}$

On the other hand, there are many stimuli-responsive compounds, such as dithienylethene (DTE) derivatives, ^{1d,2a,d,13} azobenzene (AB) compounds, ^{1d,2a,5a} spiropyrane (SP) compounds, ^{1d,2a} and rhodamine B (RB), ¹⁴ that have been widely utilized in fabricating functional molecular systems. Among them, RB, which is well-known for the acid/base or metal ion-controllable spirolactam \leftrightarrow opened amide reversible transformation, was widely utilized in ratiometric fluorescent probes ^{14a,b,d} and molecular logic gates; ^{14c} however, it was rarely investigated in supramolecular fluorescent systems based on the host–guest recognition. ¹⁵ Furthermore, to the best of our knowledge, the research of fabricating FRET-based supramolecular fluorescent systems upon the modification of RB moiety onto the pillararenes has not been reported so far.

Herein, we fabricated an acid/base-controllable FRET system via **RB** functionalized pillar[5]arene-based host-guest recognition. A novel functionalized pillar[5]arene which was modified with **RB** was synthesized by adopting click reaction to conjugate the **RB** moiety to the pillar[5]arene. Based on the host-guest interactions between the **RB** functionalized pillar[5]arene (**EtP5-RB**) and the cyano-modified boron dipyrromethene (**BDP-CN**), the FRET process between **EtP5-RB** and **BDP-CN** could be turned "on" and "off" by adding trifluoroacetic acid (TFA) and triethylamine (TEA), respectively (Scheme 1).

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Scheme 1. Top: Structures and Cartoon Representations of EtP5-RB, BDP-CN, the Protonated EtP5-RB (EtP5-RBH), and EtP5. Bottom: Cartoon Representations of Acid/Base Responsive FRET and the Self-Assemblies of EtP5-RB, EtP5-RBH, EtP5-RBDP-CN, and EtP5-RBH⊃BDP-CN



It is well-known that pillar [5] arene could associate with nitrile guests in CDCl₃; in contrast, the investigation of the host–guest chemistry between pillar[5] arenes and nitrile guests in other solvents such as acetone- d_6 has been rarely reported.^{5b} To confirm the formation of the host-guest complexes between EtP5-RB and BDP-CN as well as EtP5-RBH and BDP-CN in acetone- d_{6} , partial ¹H NMR spectra were first investigated by using BDP-CN as a guest compound and EtP5 as a model host compound. As shown in Figure S10, compared with the free **BDP-CN** (Figure S10c), the peaks of protons H_{1-4} on **BDP-CN** shifted upfield significantly ($\Delta \delta = -2.99, -3.24, -2.88$, and -2.16 ppm for H₁, H₂, H₃, and H₄, respectively) and became broad as a consequence of complexation dynamics after the addition of EtP5 (Figure S10b). Meanwhile, the peaks of protons H_{a-d} on **EtP5** shifted downfield slightly ($\Delta \delta = 0.07, 0.09, 0.11,$ and 0.03 ppm for H_a, H_b, H_c, and H_d, respectively). Second, 2D NOESY NMR spectrum of EtP5 and BDP-CN in acetone-d₆ was also carried out to prove the formation of a host-guest complex (Figure S14). Nuclear overhauser effect (NOE) correlations were observed between protons H_a and H_1 , H_2 , H_3 (B, F, and D points, Figure S14), H_b, H_d and H₁, H₂, H₃ (A, C, and E points, Figure S14). Third, in the ¹H NMR titration experiments in acetone- d_{6} , two sets of peaks were clearly observed for H₁₋₃ on BDP-CN, indicating the slow-exchange complexation on the

NMR time scale between EtP5 and BDP-CN (Figures S8 and S9). The association constant (K_a) of EtP5⊃BDP-CN was calculated to be $3.56 \times 10^2 \text{ M}^{-1}$ by using the ¹H NMR single point method.¹⁶ In addition, from the UV–vis absorption titration experiments in acetone, Job plots of both complexes EtP5-RB⊃BDP-CN and EtP5-RB→BDP-CN showed a 1:1 stoichiometry (Figures S15 and S16).^{12b} These results confirmed that the cyano moiety of BDP-CN could be threaded into the electron-rich cavities of EtP5, EtP5-RB, and EtP5-RBH in acetone.^{5b} However, there was no complexation for EtP5 and BDP-CN in DMSO- d_6 , the polarity of which was very high so that the electron-rich cavity of EtP5 could not complex with BDP-CN but DMSO- d_6 instead (Figures S12 and S13).^{5b}

In order to investigate the acid/base responsiveness, the UVvis absorptions of EtP5-RB, BDP-CN, and EtP5-RB⊃BDP-CN under different conditions were studied in acetone (Figure 1).



Figure 1. UV-vis absorption spectra changes of (a) **EtP5-RB** and (b) **BDP-CN** and **EtP5-RB** \supset **BDP-CN**, by adding TFA/TEA (1.0 × 10⁻⁵ M in acetone, 298 K). Photographs: **Etp5-RB** (No. 1), **EtP5-RB** + TFA (No. 2), **EtP5-RB** + TFA + TEA (No. 3), **BDP-CN** (No. 4), **EtP5-RB** \supset **BDP-CN** (No. 5), **EtP5-RB** \supset **BDP-CN** + TFA (No. 6) and **EtP5-RB** \supset **BDP-CN** + TFA + TEA (No. 7).

No absorption of EtP5-RB in the visible spectral region was observed (Figure 1a); in contrast, upon addition of TFA, a new absorption band at 554 nm was observed and the color of EtP5-RB changed from colorless to red (the inset photographs in Figure 1a), which was attributed to the absorption of protonated **RB** moiety due to forming into a π electron conjugated system. Furthermore, the absorption band at 554 nm disappeared upon the addition of TEA and the color changed from red to colorless (the inset photographs in Figure 1a) due to forming into a spirolactam of the RB moiety whose π electron conjugated system was destroyed.¹⁴ Similarly, the maximum absorption wavelength of BDP-CN and EtP5-RB⊃BDP-CN in the visible spectral region was 497 and 498 nm, respectively. Upon the addition of TFA into EtP5-RB>BDP-CN, a new absorption band appeared at 554 nm, which was the absorption of the opened amide form of RB (Figure 1b). However, the absorption band disappeared again when excess TEA was added (Figure 1b). Moreover, the changes of colors of EtP5-RB⊃BDP-CN in acid or base conditions could be clearly visualized by the naked eye (the inset photographs in Figure 1b). Therefore, the absorption of EtP5-RB and EtP5-RB⊃BDP-CN at 554 nm could be turned "on" and "off" by the spirolactam \leftrightarrow opened amide transformation of the RB moiety.

Then, the concentration-dependent fluorescent emission spectra of EtP5-RBH⊃BDP-CN (molar ratio was 1:1) were conducted to investigate the FRET between EtP5-RBH and BDP-CN upon excitation at 460 nm in acetone (Figures S20 and S21). With increasing concentration, the luminescence intensity of BDP-CN increased first and then was intensely quenched while the luminescence intensity of EtP5-RBH gradually increased. When the concentration of both EtP5-RBH and



Figure 2. (a) Fluorescence changes of **BDP-CN** and **EtP5-RBH** by adding **EtP5-RBH** to the acetone solution of **BDP-CN** (5.0×10^{-5} M, 298 K) from 0.0 to 1.5 equiv upon excitation at 460 nm. The inset picture was the amplified fluorescence changes of **EtP5-RBH** under the same conditions. (b) Maximum emission intensity changes of **EtP5-RBH** under the same condition as (a). (c) Fluorescence changes of **EtP5-RB**⊃**BDP-CN** (5.0×10^{-5} M, molar ratio was 1:1, 298 K) at 591 nm upon addition of TFA/TEA, respectively. The inset photographs show the corresponding fluorescence changes of **EtP5-RB**→**BDP-CN** under the same conditions. (d) Corresponding color changes of **EtP5-RB**→**BDP-CN** under the same conditions as (a).

BDP-CN was 5.0×10^{-5} M, the emission intensity of **EtP5-RBH** reached the highest value. Herein, according to the integral intensities of uncomplexed and complexed BDP-CN, respectively (Figure S9), the concentration of the host-guest complex was calculated to be approximately 1.6×10^{-5} M at which there was FRET occurring, and the emission intensity of EtP5-RBH was highest. However, when the concentration of EtP5-RBH and **BDP-CN** was higher than 5.0×10^{-5} M, the luminescence intensity of EtP5-RBH decreased intensely (Figure S21). It was speculated that EtP5-RBH>BDP-CN aggregated and selfassembled at a higher concentration, which caused its fluorescence to be quenched.¹⁷ In addition, although there was no complexation between EtP5-RBH and BDP without CN moiety, the FRET still occurred between them (Figure S31), which was in accordance with the experiment results in DMSO (Figures S26, S27, and S30 and Table S3). It is noteworthy that the FRET efficiency $(\Phi_{\rm ET})$ was enhanced by formatting of the host-guest complex between EtP5-RBH and BDP-CN, which could ensure the efficient distance between the donor (BDP-CN) and acceptor (EtP5-RBH) for FRET (Tables S3 and S4).^{2,14b}

To further confirm the FRET process between BDP-CN and EtP5-RBH, fluorescence titration experiments were conducted in acetone (Figure 2). As shown in Figure 2a,b, with the addition of EtP5-RBH from 0.0 to 1.5 equiv, the emission intensity of BDP-CN at 521 nm decreased significantly while the emission intensity of EtP5-RBH at 591 nm increased slightly upon excitation at 460 nm, which proved that the FRET process occurred between EtP5-RBH and BDP-CN. When the molar ratio of EtP5-RBH was 1:1, the fluorescence emission intensity of EtP5-RBH reached the highest value ($\Phi_{ET} = 71.1\%$). Moreover, the corresponding fluorescence changes of EtP5-RBH > BDP-CN could be clearly visualized by the naked eye (Figure 2d). In addition, the acid/base responsiveness of the FRET in EtP5-RB⊃BDP-CN was also investigated (Figure 2c). Upon excitation at 460 nm, the maximum fluorescence emission wavelength of EtP5-RB⊃BDP-CN was at 521 nm, which was the fluorescence emission of BDP-CN, while upon addition of TFA a new emission band appeared at 591 nm, which was the fluorescence emission of EtP5-RBH as a result of the FRET between EtP5-RBH and BDP-CN. Meanwhile, the corresponding fluorescent color of EtP5-RBH \supset BDP-CN changed from green to yellow (Figure 2c). Moreover, upon addition of TEA to the system the emission band at 591 nm disappeared because the π electron conjugated system of RB moiety was destroyed by TEA and the corresponding fluorescent color of EtP5-RBH \supset BDP-CN returned from yellow to green (Figure 2c).¹⁴ Therefore, the FRET process could be turned "on" and "off" over several cycles upon the addition of TFA/TEA, respectively.

Finally, in order to verify the self-assembling behaviors of **EtP5-RB**, **EtP5-RBH**, **EtP5-RB** \supset **BDP-CN**, and **EtP5-RBH** \supset **BDP-CN** at a higher concentration (1.0 × 10⁻⁴ M) in acetone, scanning electron microscope (SEM), transmission electron microscope (TEM), and dynamic laser scattering (DLS) were investigated (Figure 3 and Figures S33 and S34). The TEM



Figure 3. (a, b): TEM images of **EtP5-RB** $(1.0 \times 10^{-4} \text{ M})$. (d, e): TEM images of **EtP5-RBH** $(1.0 \times 10^{-4} \text{ M})$ and **EtP5-RBH** \supset **BDP-CN** $(1.0 \times 10^{-4} \text{ M})$, respectively. (c, f): DLS study of **EtP5-RB** $(1.0 \times 10^{-4} \text{ M})$ and **EtP5-RBH** \supset **BDP-CN** $(1.0 \times 10^{-4} \text{ M})$, respectively.

images revealed that the aggregates of **EtP5-RB** were vesicles (Figure 3a,b), which was further supported by SEM image (Figure S33). The average diameter of the vesicles was approximately 150 nm supported by TEM and DLS results (Figure 3a-c).¹⁷ However, by addition of TFA, the aggregates of **EtP5-RBH** were nanosheet assemblies (Figure 3d). Moreover, after the addition of **BDP-CN**, both of the aggregates of **EtP5**-

RB \supset **BDP-CN** and **EtP5-RBH** \supset **BDP-CN** were spherical assemblies approximately 200 nm in diameter (Figure 3e and Figure S34), which were consistent with the DLS results (Figure 3f). As we know, in acetone, the pillar[5]arene had a good solubility but the solubility of **RB** and **RBH** was poor. It was speculated that **EtP5-RB**, **EtP5-RBH**, **EtP5-RB** \supset **BDP-CN**, and **EtP5-RBH** \supset **BDP-CN** self-assembled in acetone at a higher concentration as a result of the difference in solubility and the π - π interactions of the moieties in the hosts or host-guest complexes.¹⁷ Similarly, **EtP5-RBH** and **EtP5-RBH** \supset **BDP-CN** self-assembled into nanosheets and nanoparticles in CHCl₃, respectively (Figure S35). In contrast, **EtP5-RB** and **EtP5-RB** \supset **BDP-CN** self-assemble in CHCl₃ because each moiety of the host and guest (**EtP5**, **RB** and **BDP**) had good solubility in CHCl₃ (Figure S35).

In conclusion, a novel supramolecular FRET system was constructed via a RB functionalized pillar[5]arene-based hostguest recognition motif. An efficient FRET process ocurred in EtP5-RBH \supset BDP-CN at 5.0 × 10⁻⁵ M, which could be turned "on" and "off" over several cycles upon the addition of TFA/ TEA, respectively. At a higher concentration in acetone $(1.0 \times$ 10^{-4} M), EtP5-RB self-assembled into vesicles with the average diameter of 150 nm, while EtP5-RBH self-assembled into nanosheets. Moreover, after the addition of BDP-CN, both of EtP5-RB⊃BDP-CN and EtP5-RBH⊃BDP-CN self-assembled into nanoparticles with an average diameter of 200 nm, which caused the fluorescence emission of the host-guest complexes to be quenched. Therefore, we developed a new pathway for fabricating acid/base-controllable FRET and self-assembling systems based on the host-guest recognition of EtP5-RB/EtP5-RBH with BDP-CN. These research results will be significant for designing novel molecular sensors and devices.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.7b03612.

Syntheses, NMR data, MALDI-TOF MS spectra, 2D NOESY NMR data, UV-vis absorption spectra, fluorescence emission spectra, SEM result, TEM results, and other materials (PDF)

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Notes

The authors declare no competing financial interest.

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