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Design and Sensing Properties of a Self-Assembled Supramolecular Oligomer

Steffen Bähring, Luis Martín-Gomis, Gunnar Olsen, Kent A. Nielsen, Dong Sub Kim, Troels Duedal, Ángela Sastre-Santos, Jan O. Jeppesen, and Jonathan L. Sessler

Abstract: Supramolecular polymers are a class of macromolecules stabilized by weak non-covalent interactions. These self-assembled aggregates typically undergo stimuli-induced reversible assembly and disassembly. They thus hold great promise as so-called functional materials. In this work, we present the design, synthesis, and responsive behavior of a short supramolecular oligomeric system based on two hetero-complementary subunits. These “monomers” consist of a tetra(thio)fulvalene-functionalized calix[4]pyrrole (TTF-C[4]P) and a glycol diester-linked bis-2,5,7-trinitrodicyanomethylenefluorene-4-carboxylate (TNDCF), respectively. We show that when mixed in organic solvents, such as CHCl₃, CH₂Cl₂, CHCl₃, Cl₂, and methylcyclohexane, supramolecular aggregation takes place to produce short oligomers stabilized by hydrogen bonding and donor–acceptor charge transfer (CT) interactions. The self-associated materials were characterized by ¹H NMR and UV/Vis/NIR absorption spectroscopy, as well as by concentration- and temperature-dependent absorption spectroscopy and dynamic light scattering (DLS) analyses of both the monomeric and oligomerized species. The self-associated system produced from TTF-C[4]P and TNDCF exhibits a concentration-dependent aggregation behavior typical of supramolecular polymers. Further support for the proposed self-assembly came from theoretical calculations. The fluorescence emitting properties of TNDCF are quenched under conditions that promote the formation of supramolecular aggregates containing TTF-C[4]P and TNDCF. This quenching effect has been utilized as a probe for the detection of substrates in the form of anions (i.e., chloride) and nitroaromatic explosives (i.e., 1,3,5-trinitrobenzene). Specifically, the addition of these substrates to mixtures of TTF-C[4]P and TNDCF produced a fluorescence “turn-on” response.

Introduction

Non-covalent interactions play a key role in stabilizing biological materials.[1] In nature, different building blocks self-assemble in 3D supramolecular structures with the aid of multiple non-covalent interactions, including hydrogen bonding, solvatochromic effects, π-π donor-acceptor interactions, or metal-ligand complexation.[2] This affords supramolecular structures with a large number of specific functions. Many of these systems are responsive to subtle changes in the local and external environment.[3] For example, the majority of proteins or enzymes,[4] and even some lipid bilayers,[5] recognize specific substrates, which act as chemical triggers that induce conformational changes in the biomolecule or ensemble thus regulating the specific function of the system.[6,7] In many cases, the natural systems in question respond to different stimuli.[8] This salient feature endows them with the capacity to modulate their behavior in a differential manner depending on the external stimulus to which they are exposed. Mimicking this multi-input and controlled output behavior using synthetic constructs represents a considerable challenge. Recently, we have reported several electron-rich tetra(thio)fulvalene–calix[4]pyrrole (TTF-C[4]Ps) that interact with hetero-complementary monomers, such as 3,5-dinitrophenyl-derivatized guests, to form supramolecular polymeric structures.[9] The complexation relies on the 1,3-alternate conformation[7] of TTF-C[4]P, which exits in a double-sided tweezer-like conformation.[8] These self-assembled systems were found capable of responding to two or more different stimuli, namely, competing electron-deficient guests and anionic salts. We have also previously reported the strong supramolecular complexation of TTF-C[4]P 1 and 2,5,7-trinitrodicyanomethylenefluorene (TNDCF) derivatives by hydrogen bonding and charge-transfer (CT)-mediated interactions.[9] For example, methyl-2,5,7-trinitrodicyanomethylene-
fluorene-4-carboxylate (Figure 1, MTNDMFC; 2) was reported to complex with 1 in a 2:1 stoichiometry, with complexation constants of $K_1 = 1.2 \times 10^3 \text{ M}^{-1}$ and $K_2 = 5.2 \times 10^2 \text{ M}^{-1}$ (CH$_2$Cl$_2$ at 295 K) and a visual color change from yellow (1) to brown (2) [10].

Results and Discussion

The bidentate guest oxybis(ethane-2,1-diy) di-2,5,7-trinitrodicyanomethylene-fluorene-4-carboxylate (TNDCF; 3) was synthesized in two steps as outlined in Scheme 1, from 2,5,7-trinitrofluorenone-4-carboxylic acid chloride [11] (4). Condensation of the acid chloride 4 with diethylene glycol in the presence of 4-(dimethylamino)pyridine (DMAP), afforded 3-oxapentane-1,5-diy bis(2,5,7-trinitrofluorenone-4-carboxylate (5) in 37% yield. A Knoevenagel condensation of the fluoroenes with dicyanomethane gave in 79% yield the final product TNDCF dimer 3.

In order to gain insight into the underlying interactions that might lead to self-assembly, the complexation behavior of TTF-C[4]P 1 and the model TNDCF monomer, MTNDMFC 2, were investigated through density functional theory (DFT) calculations using Gaussian 09 [12] in CHCl$_3$ as polarizable continuum model [13] (PCM). The structure and properties (geometry, CT interaction, and excitation) of 1, 2, and the 2:1 complex, 2\textsubscript{C}1, were analyzed through full geometry optimizations, single-point calculations, and natural bond orbital [14] (NBO) analyses. The calculations were performed using the M05-2X/6-31G [15] level of theory. In the case of the 2\textsubscript{C}1 complex, four discrete binding conformations (cf. Supporting Information) were sampled by molecular mechanics in the Merck molecular force field [16] (MMFF) and the resulting five lowest energies of each conformation were geometry-optimized using DFT calculations. Single-point energy calculations of the four resulting conformations led to the conclusion that the lowest-energy conformation is the one in which the pyrrole NH protons interact with the 6- and 8-nitro groups of 3 (See Figures 2 and 3, as well as the Supporting Information). This conformation was selected as best representing complex 2\textsubscript{C}1 in the subsequent calculations. For the uncomplexed receptor 1 (Figure 2), the four HOMOs (highest-occupied molecular orbital) are predominantly localized on the four individual TTF units. Parts of the HOMOs are partially mixed. The two LUMOs (lowest-unoccupied molecular orbital) of 2 are characterized by a nodal plane running through the middle. The orbitals are distributed throughout the conjugated system, with greater density being present on the dicyanomethylene moiety. Upon complexation,
Figure 3. Molecular mechanics geometry optimized structures of the proposed oligomeric assembly of (13), and the model complex 2·1.\cite{18}

As an initial test of whether equimolar quantities of TTF-
C(4)IP 1 and TNDCF dimer 3 would self-associate to create an
globular structure, 1H NMR spectroscopic studies were car-
rried out at 298 K in CDCl3. As shown in Figure 4, when 1 mm
CDCl3 solutions of 1 and 3 (Figure 4A and B) are mixed (Fig-
ure 4C) a broadening of the signals corresponding to both 1\cite{19}
and 3 is seen. The aromatic signals corresponding to 3 are also
shifted to higher field (e.g., by Δδ = 0.23 ppm in the case of
the TNDCF proton labeled as H8, see Figure 5). These upfield shifts are consistent with the electron-deficient
TNDCF moieties of 3 being located within the TTF arms of re-
ceptor 1. The pyrrole NH protons of 1, on the other hand,
become broadened and shifted to lower field upon mixing with 3. This is expected for a complex (or complexes) in which
hydrogen-bonding interactions involving the pyrrole NH pro-
tons play a stabilizing role.

Figure 4. Partial 1H NMR spectra (400 MHz, CDCl3, 298 K) of A) TTF-C(4)IP 1 (1 mM), B) TNDCF 3 (1 mM), and C) supramolecular aggregate (1-3), pro-
duced from an equimolar mixture of 1 and 3 (both 1 mM). The spectral re-
gions between 3 ppm and 3.5 ppm, as well as between 4.9 ppm and 6.9 ppm,
contain no signals and are not shown. Note: The intensity scales for the two
spectral regions displayed in this figure have been adjusted for clarity.

Further evidence for the interaction of TTF-C(4)IP 1 with
TNDCF 3 came from two-dimensional NMR spectroscopic anal-
yses. Figure 5 shows the 2D NOESY-NMR spectrum of an equi-
molar mixture of 1 and 3 (7 mM each in CDCl3 at 298 K). Of
note is the observation of coupling between the meso-CH3
protons, as well as the thiopropyl hydrogen atoms, of receptor
1 with the aromatic protons of 3.

The absorption and emission features of the CT complex
produced upon mixing 1 and 3 allowed determination of the
binding stoichiometry of the presumed supramolecular aggre-
gates (1 and 3), as well as the corresponding binding con-
stants. Adding increasing quantities of 3 to a solution of 1 in

CH3CICH2Cl leads to an enhancement in the spectral intensity

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across the whole UV/VIS/NIR spectral region. Broad bands with absorption maxima at 757 nm and 1230 nm are identifiable within this increase (see Figure 6). Figure 7 shows two Job plot analyses, in which the normalized absorbance of the CT complex, measured at 1200 nm, is plotted versus mole fraction of 3, at total concentrations ([1] + [3]) of 30 μM (Figure 7, squares) and 200 μM (Figure 7, circles). Both plots are consistent with the dominant formation of a complex with 1:1 binding stoichiometry (maximum at X ≈ 0.5). However, at lower concentrations, a broadening in the curve and a slight shift in the maximum is seen, which is consistent with the formation of some complexes with net 1:2 stoichiometry. No evidence was seen for the formation of complexes with 2:1 stoichiometry under any of the tested experimental conditions, a finding ascribed to the cooperative binding behavior seen for TTF-C[4]P, as noted in previous studies.

Using standard absorption-based titration techniques, a value expected for the formation of oligomeric/polymeric aggregates.

These absorption-based binding analyses were complemented by fluorescence quenching studies (Figure 8). Here, it was appreciated that the various CT interactions between the TTF donor groups of 1 and the electron-accepting TNDCF moieties present in 3 would lead to a quenching of the inherent fluorescence of the 2,5,7-trinitro-9-dicyanomethylenfluorene fluorophore. Indeed, when a solution of 3 in CH₂Cl₂ was titrated with increasing quantities of 1, a gradual decrease in the fluorescence intensity of the TNDCF moiety present in 3 (23 μM) recorded at 520 nm during the course of the titration shown in A). Panel C shows the relative fluorescence of 3 (23 μM and 100 μM) recorded at 520 nm upon treating with increasing equiv of 1.

\[ F_0 \frac{F - F'}{F_0} = \frac{1}{A} + \left( \frac{1}{K_{A|G}} \right) \]  (1)
By monitoring the change in intensity of the fluorescence maximum at 520 nm as a function of the concentration of 1 (Figure 8A), and fitting the data to the Benesi–Hildebrand equation, a binding constant of $2.6 \times 10^4 \text{M}^{-1}$ was obtained, when the concentration of 3 was kept at 23 $\mu\text{M}$ (Figure 8B).

An ostensibly similar value of $3.8 \times 10^4 \text{M}^{-1}$ was obtained in an analogous experiment in which the concentration of 3 was kept constant at 100 $\mu\text{M}$ (see the Supporting Information). It is worth noting that, when one equivalent of 1 is added, the quenching effect is greater at 100 $\mu\text{M}$ (97% of TNDCF fluorescence quenched) than that registered at 23 $\mu\text{M}$ (53%) (Figure 8C). This is in agreement with the concentration-dependent aggregation behavior inferred from the UV/Vis spectroscopic studies above. At low concentrations, oligomeric species are not favored and discrete 1:2 complexes (in which receptor 1 binds two molecules of 3) are favored. This leads to a greater number of fluorescent TNDCF moieties being present “free” in an unbound form. Consequently, at lower concentrations, the extent of quenching is relatively low.

Supramolecular aggregate characterization

The supramolecular aggregates were characterized by DLS and concentration- and temperature-dependent absorption spectroscopic measurements. Figure 9 shows the size and distribution profile of the species formed from 1 (9.3 $\text{mM}$ CHCl$_3$, Figure 9, light grey circles) and from an equimolar mixture of 1 and 3 (141 $\text{mM}$ in methylcyclohexane, Figure 9 dark grey circles). From an inspection of this figure, it can be appreciated that a 1:1 mixture of 1 and 3 affords aggregates with a Gaussian distribution and a hydrodynamic radius of approximately 90 nm under the conditions of the analysis. On this basis, we conclude that mixing 1 and 3 can afford self-associated entities, including possibly a supramolecular oligomer.

Self-associated supramolecular aggregates typically display concentration-dependent behavior. Therefore, in order to understand the supramolecular nature of the complex(es) formed upon mixing 1 and 3, a number of solution-phase studies were carried out. Firstly, a solution containing equimolar concentrations of 1 and 3 (CH$_2$Cl$_2$:CHCl$_3$:CHI, 0.20 $\text{mM}$ in each component) was gradually diluted, while absorption spectroscopy was used to monitor the decrease in the intensity of the CT band arising from the interaction between 1 and 3 (Figure 10A). The absorption coefficient, monitored as a function of total concentration, can be fit to a concentration-dependent isodesmic model derived from hetero-complementary monomers (Eq. (2)), in which $K$ is the equilibrium constant, $C_i$ is the total concentration of the two components, and $e_{\text{mon}}$ and $e_{\text{agg}}$ are the extinction coefficients of the monomers and the aggregated species, respectively.

$$e(C_i) = \frac{K e_{\text{agg}} + 1 - \sqrt{2KC_i + T}}{KC_i} (e_{\text{mon}} - e_{\text{agg}}) + e_{\text{agg}} \tag{2}$$

The molar fraction of the aggregated species, $\alpha_{\text{agg}}$, can be calculated [Eq. (3)] from the apparent absorption coefficients of the solution $e(C_i)$ and the absorption coefficients of the monomers $e_{\text{mon}}$ and aggregate $e_{\text{agg}}$. In Equation (2) these are extinction coefficients.

$$\alpha_{\text{agg}} \approx \frac{e(C_i) - e_{\text{mon}}}{e_{\text{agg}} - e_{\text{mon}}} \tag{3}$$

Using the absorption coefficient $e$ at 1100 nm as an input for Equation (2) allowed an equilibrium constant of $K = 1.76 \times 10^4 \text{M}^{-1}$ ($R^2 = 0.999$) to be calculated. This value is in good...
agreement with the binding constant obtained from the absorption spectroscopic titration experiments discussed above. Using the equilibrium constant from Equation (2), we were then able to determine the number averaged degree of polymerization DPn (Figure 10 C) by use of Equation (4).

$$DP_n = \frac{K_C}{-1 + \sqrt{2KC_T + 1}}$$  (4)

The number averaged degree of polymerization supports the conclusion that modest aggregation occurs at the relatively low concentrations used in the present experiments (e.g., DPn = 2.4 at C = 4.0 x 10^{-4} M).

Temperature-dependent absorption spectroscopic measurements were also used to investigate the supramolecular aggregation process. While some modifications to the standard concentration-dependent isodesmic model were required to allow it to be applied to the present hetero-complementary system (vide supra), the temperature-dependent model may be applied directly. The temperature-dependent isodesmic model expresses the apparent absorption coefficient of the mixture, $\varepsilon(T)$, at a certain wavelength as a function of the temperature, $T$, the absorption coefficients of the monomer, $\varepsilon_{mon}$, and the aggregate species, $\varepsilon_{agg}$, the melting temperature of the assembly, $T_m$, the ideal gas constant, $R$, and the molar enthalpy of assembly formation $\Delta H^o$:

$$\varepsilon(T) = \frac{1}{1 + \exp\left(-0.9088\frac{\Delta H^o - T_mK_eC_T}{\pi\mu}\right)}(\varepsilon_{agg} - \varepsilon_{mon}) + \varepsilon_{mon}$$  (5)

In terms of experiment, a solution consisting of an equimolar mixture of 1 and 3 (C = 125 mM) in CDCl3 at 354 K and then gradually cooled to 250 K while measuring the absorbance at 525 nm. The absorbance intensity at 525 nm versus temperature was fitted to Equation (5) (see also Figure 11 A and Supporting Information) to provide the melting temperature $T_m$ of 296.0 K and the molar enthalpy $\Delta H^o$ of -44.5 kJ mol^{-1} and -107 J mol^{-1} K^{-1}, respectively. On this basis, we conclude that formation of the oligomeric species is thermally favored (exoergic), but entropically unfavored.

Chemoresponsive analysis

The supramolecular oligomers formed from 1 and 3 are expected to be dual-analyte-responsive materials. Specifically, complete or partial de-aggregation was expected when the self-assembled oligomers were exposed to nitroaromatic compounds or anionic substrates as shown schematically in Figure 12. Fluorescence-based sensing of key analytes, such as nitroaromatic explosives[20c] (i.e., 2,4,6-trinitrotoluene (TNT) and TNB), as well as halides (i.e., chloride and bromide anions)[26] are attractive objectives, in light of current environmentally and safety concerns[21]. TTF-C4IP 1 has been previously shown to form complexes with those particular analytes[20c,28]. In the present case, the addition of five molar equivalents of TNB to a 0.5 mM solution of the aggregated complex (1-3), results in a slight increase in the absorption intensity throughout the visible spectral region (400 nm to 1100 nm), as well as a hypsochromic shift (747 nm) in the absorption maximum, initially located at 757 nm (Figure 13). These spectral changes are rationalized in terms of competition between TNB and the TNDCC moieties for the electron-rich clath formed by the TTF arms of 1. Since it is a monomeric entity, binding of TNB results in a disruption of the aggregated structure with the concomitant formation of discrete TNB<sub>C1</sub> complexes. These complexes, as well as somewhat analogous 3<sub>C1</sub> complexes, have been previously characterized in dichloromethane. The TNB<sub>C1</sub> complexes display similar absorption profiles, ascribed to CT interactions between TTF units and electron-acceptor nitroaromatic substrates, as does 3<sub>C1</sub>, although they are characterized by
The effect of TNB addition to a mixture of 1 and 3 was tested at three different total concentrations (4.0 μM, 40 μM and 200 μM in CH₃CICH₂Cl; Table 1). Addition of TNB to a 4.0 μM total concentration of 1 and 3 resulted in no appreciable increase in the fluorescence intensity (Figure 14 A and B). On the other hand, when the total concentration of 1 and 3 was increased to 40 μM and 200 μM, TNB addition served to increase the fluorescence intensity by 35% and 80%, respectively (Figure 14 C–F). These findings are fully consistent with the concentration-dependent nature of the aggregation process. At low concentrations (e.g., 40 μM) the self-association is not favored and discrete 3·C₁ complexes with inherent fluorescence dominate. On the other hand, as the concentration of the co-monomers increases (e.g., to 40 μM and 200 μM), the effect of TNB becomes apparent, since the aggregate is formed in the absence of this competitor but not in its presence.

<table>
<thead>
<tr>
<th>C, [μM]</th>
<th>Analyte</th>
<th>Fluorescence increase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>TNB</td>
<td>–</td>
</tr>
<tr>
<td>4.0</td>
<td>TEACl</td>
<td>20[29]</td>
</tr>
<tr>
<td>40</td>
<td>TNB</td>
<td>35</td>
</tr>
<tr>
<td>40</td>
<td>TEACl</td>
<td>74</td>
</tr>
<tr>
<td>200</td>
<td>TNB</td>
<td>80[29]</td>
</tr>
<tr>
<td>200</td>
<td>TEACl</td>
<td>245</td>
</tr>
</tbody>
</table>

(a) Saturation in the fluorescence increase curve did not occur.

It was also found that addition of two molar equivalents of chloride anions (as the corresponding tetraethylammonium salt, TEACl) to a 0.5 mM solution of oligomer (1·3), (298 K, CH₃CICH₂Cl) observed upon titrating with the test analyte TNB and TEACl. The TNB-mediated rupture of the supramolecular aggregates results in release of the ditopic TNDCF entity when TNB is added to the original 0.4 mM solution of (1·3). This is rationalized in terms of a chloride-induced conformational change of 1 to its cone-like conformation, a form that is unable to interact appreciably with planar electron-deficient species, such as the ditopic TNDCF entity 3. As a result, and in contrast to what is seen under conditions of TNB competition, the intensity of the broad CT band(s) decreases.

Further evidence that the addition of TEACl to CDCl₃ solutions of oligomer (1·3), led to dissociation came from ¹H NMR spectroscopic measurements. As can be seen from an inspection of Figure 15, the addition of 0.5 equivalents of TEACl (0.50 mM, Figure 15 C) to a solution of the aggregate results in a downfield shift of the protons attributed to 3 (Δδ = 0.06–0.25 ppm), as well as a large downfield shift in the NH proton resonances (to δ = 10.93 ppm).

Because the supramolecular association between 1 and 3 depends on the chemical environment, we considered that it might allow for the creation of a new class of concentration-sensitive assays. Operationally, this spectral change provides a fluorescence displacement assay[29] which allows for the optical sensing of the analytes in question.

Figure 12. Graphical representation of the proposed disruption of the supramolecular oligomer in the presence of TNB (left) or chloride ion (right) and the release of fluorophore 3.

Figure 13. Absorption spectra (CH₃CICH₂Cl, 298 K) of the supramolecular aggregate (1·3), recorded at 0.4 mM total concentration (black line) and following the addition of TNB (5 equiv, dashed line) or TEACl (2 equiv, grey line). Insert shows a zoom of the hypochromic displacement that occurs when TNB is added to the original 0.4 mM solution of (1·3).

The supramolecular association between 1 and 3, was lost at 308 nm in CH₃CICH₂Cl. This is also true for discrete 3·C₁ complexes, which contain “free” TNDCF subunits. The fluorescence of 3 is quenched in the aggregated species, presumably as the result of CT interactions serving to deactivate the excited state. Because of the inherent fluorescence of 3, it was expected that TNB-induced deaggregation of (1·3), would result in a net increase in the overall fluorescence intensity. Operationally, this spectral change provides a fluorescence displacement assay[29] which allows for the optical sensing of the analytes in question.

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Figure 14. Fluorescence spectroscopic study (298 K, CH$_2$Cl$_2$) of the supramolecular ensemble (1:3)$_n$ and its interactions with TNB. A) Fluorescence emission spectra of (1:3)$_n$ (4.0 µM) at recorded in the presence of TNB (increasing concentrations between 0–70 µM). B) Plot of the fluorescence intensity at 520 nm of the supramolecular aggregate (1:3)$_n$ (4.0 µM) versus TNB concentration. C) Fluorescence emission spectra of the supramolecular ensemble (1:3)$_n$ (40 µM) recorded in the presence of TNB (increasing concentrations between 0–1.0 mM). D) Plot of the fluorescence intensity at 520 nm of the supramolecular aggregate (1:3)$_n$ (40 µM) versus TNB concentration. E) Fluorescence emission spectra of the supramolecular aggregate (1:3)$_n$ (200 µM) recorded in the presence of increasing concentrations of TNB (0–5.0 mM). F) Plot of the fluorescence intensity at 520 nm of the supramolecular aggregate (1:3)$_n$ (200 µM) versus TNB concentration.

Figure 15. Partial $^1$H NMR spectra (400 MHz, 298 K, CDCl$_3$) of the supramolecular ensemble (1:3)$_n$, recorded at a 1.0 mM total concentration in the absence and presence of certain additives. A) Supramolecular ensemble (1:3)$_n$ (1.00 mM) and 1 molar equiv of TNB (1.00 mM). B) Supramolecular ensemble (1:3)$_n$ (1.00 mM). C) Supramolecular ensemble (1:3)$_n$ (1.00 mM) and 0.5 molar equiv TEACl (0.50 mM).

In summary, we have designed and synthesized a new TNDCF-based compound 3, and used it as hetero-complementary monomer, together with TTF-CIP 1, to afford supramolecular dynamic oligomers, (1:3)$_n$. These self-associated aggregates exhibit concentration-dependent behavior and show dual-analyte chemoresponsive performance, when they are exposed to TNB or chloride anions, respectively. This chemoresponsive-sensing behavior is evidenced by an increase in the fluorescence emission, although the underlying mechanisms are different in the case of these two analytes. Supramolecular ensembles such as

**Conclusion**

In summary, we have designed and synthesized a new TNDCF-based compound 3, and used it as hetero-complementary monomer, together with TTF-CIP 1, to afford supramolecular dynamic oligomers, (1:3)$_n$. These self-associated aggregates exhibit concentration-dependent behavior and show dual-analyte chemoresponsive performance, when they are exposed to TNB or chloride anions, respectively. This chemoresponsive-sensing behavior is evidenced by an increase in the fluorescence emission, although the underlying mechanisms are different in the case of these two analytes. Supramolecular ensembles such as
those described here are attractive as possible sensors for the detection of nitroaromatic explosives and anions. In particular, the concentration-dependent behavior of the supramolecular oligmeric system may provide an increased sensitivity towards analytes as compared to analogous single-component sensors. From a structural perspective, the present study sets the stage for the creation of more complex systems in which polytopic, as opposed to ditopic, electron-deficient guests are combined with electron-rich receptor(s), the size, shape, and electronic features of which might differ from those of 1. This, in turn, is expected to allow for the construction of new and more complex supramolecular ensembles.

Experimental Section

General methods: All chemicals were purchased from Sigma–Aldrich and used as received unless indicated otherwise. Compounds 1\[^{1}\text{(a)}\] 2\[^{1}\text{(a)}\] and 5\[^{1}\text{(b)}\] were synthesized according to literature procedures. All reactions were carried out under an atmosphere of anhydrous argon. CH\textsubscript{2}Cl\textsubscript{2} was distilled immediately prior to use and, if necessary, stored over molecular sieves (4 Å). Anhydrous dimethylformamide (DMF) was stored over molecular sieves (4 Å) for a minimum of three days prior to use. Melting points (m.p.) were determined with a Büchi melting point apparatus and are uncorrected.

1D and 2D NMR spectra were recorded with a Bruker AVANCE III 400 MHz spectrometer or a Varian Direct Drive 600 MHz spectrometer; \[^{1}\text{H}^\text{NMR spectra were recorded at 300 MHz (223 K) or 400 MHz (298 K) and }^{13}\text{C NMR spectra were recorded at 75 MHz (223 K). The NMR samples were dissolved in deuterated solvents purchased from Cambridge Isotope Labs or Sigma-Aldrich, and TMS or the residual solvent were used as internal standard. Solvent signals were assigned according to Núñez-Máñez et al.\[^{20}\] IR spectra were recorded with a Perkin–Elmer 580 spectrophotometer. Matrix-assisted laser-desorption/ionization (MALDI) mass spectrometry was performed with a Bruker Reflex III (MALDI-TOF) utilizing a diethanol matrix. Absorption spectroscopic measurements were performed on a Varian Cary 5000 spectrophotometer or a Shimadzu UV-1601PC spectrophotometer. Fluorescence emission spectroscopy was measured on a Perkin–Elmer LS 55 Fluorescence spectrometer. Dynamic light scattering (DLS) measurements were performed on an ALV-7004 autocorrelator mounted on an ALV-CGS-4F goniometer platform. All samples were filtered through a 0.2 μm polytetrafluoroethylene filter prior to measurements. All correlation functions are fitted with a CONTIN algorithm.\[^{11}\]

Synthesis of 3-oxapentane-1,5-diyl bis[2,5,7-trinitrofluorenone-4-carboxylate] (9): A mixture of compound 5 (50 mg, 0.06 mmol) and dicyanomethane (80 mg, 1.21 mmol) were dissolved in anhydrous DMF (2 mL) and the reaction mixture was stirred at 70 °C under argon. After 14 h, the reaction mixture was diluted with toluene (10 mL) and washed with brine (2 × 10 mL) and H\textsubscript{2}O (10 mL). The organic layer was concentrated in vacuo to give a beige solid, which, after washing with Et\textsubscript{2}O (2 × 5 mL) gave TNDCF dimer 3 (44 mg, 79 %) as a beige solid (m.p. > 200 °C). \[^{1}\text{H}^\text{NMR (300 MHz, CDCl\textsubscript{3}; CDCl\textsubscript{3}, 223 K): } \delta = 3.87 \text{ (t, } J = 4.7 \text{ Hz, } 4 \text{H; CH}_2\text{O}), \texttt{5.95} \text{ (t, } J = 4.7 \text{ Hz, } 4 \text{H; COOCH}_2\text{), } 8.73 \text{ (d, } J = 2.2 \text{ Hz, } 2 \text{H; Ar-H}), \texttt{8.82} \text{ (d, } J = 2.1 \text{ Hz, } 2 \text{H; Ar-H}), \texttt{8.85} \text{ (d, } J = 2.2 \text{ Hz, } 2 \text{H; Ar-H}), \texttt{8.94} \text{ ppm (d, } J = 2.1 \text{ Hz, } 2 \text{H; Ar-H); }^{13}\text{C NMR (75 MHz, CDCl\textsubscript{3}; CDCl\textsubscript{3}, 223 K): } \delta = 65.9, 68.4, 121.6, 122.3, 125.1, 130.5, 131.9, 137.7, 138.7, 143.5, 144.6, 149.3, 149.5, 164.1, 164.6 \text{ ppm; HRMS (MALDI-TOF, dithranol): } \text{m/z: calcd for C}_{192}\text{H}_{119}\text{O}_{19}: 788.0476 \text{ [M+]; found 788.0470; IR (KBr) } \nu = 3089, 2954, 2931, 2856, 1737, 1720, 1617, 1594, 1542, 1346 \text{ cm}^{-1}.\]

Synthesis of 3-oxapentane-1,5-diyl bis[2,5,7-trinitrofluorenone-4-carboxylate] (3): A mixture of compound 5 (50 mg, 0.06 mmol) and dicyanomethane (80 mg, 1.21 mmol) were dissolved in anhydrous DMF (2 mL) and the reaction mixture was stirred at 70 °C under argon. After 14 h, the reaction mixture was diluted with toluene (10 mL) and washed with brine (2 × 10 mL) and H\textsubscript{2}O (10 mL). The organic layer was concentrated in vacuo to give a beige solid, which, after washing with Et\textsubscript{2}O (2 × 5 mL) gave TNDCF dimer 3 (44 mg, 79 %) as a beige solid (m.p. > 200 °C). \[^{1}\text{H}^\text{NMR (300 MHz, CDCl\textsubscript{3}; CDCl\textsubscript{3}, 223 K): } \delta = 3.87 \text{ (t, } J = 4.6 \text{ Hz, } 4 \text{H; CH}_2\text{O}), \texttt{5.95} \text{ (t, } J = 4.6 \text{ Hz, } 4 \text{H; COOCH}_2\text{), } 8.73 \text{ (d, } J = 2.0 \text{ Hz, } 2 \text{H; Ar-H}), \texttt{8.82} \text{ (d, } J = 2.0 \text{ Hz, } 2 \text{H; Ar-H}), \texttt{8.94} \text{ ppm (d, } J = 2.0 \text{ Hz, } 2 \text{H; Ar-H); }^{13}\text{C NMR (75 MHz, CDCl\textsubscript{3}; CDCl\textsubscript{3}, 223 K): } \delta = 66.0, 68.4, 111.3, 111.3, 122.7, 123.6, 124.4, 129.9, 132.2, 136.7, 137.5, 138.6, 140.3, 146.7, 148.6, 149.0, 153.1, 163.8 \text{ ppm; HRMS (ESI): } \text{m/z: calcd for C}_{184}\text{H}_{119}\text{N}_{19}O_{19}: 884.0700 \text{ [M+]; found 884.0726; IR (KBr) } \nu = 3118, 2966, 2232, 1737, 1615, 1602, 1586, 1536, 1349 \text{ cm}^{-1}.\]

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[10] The complexion between 1 and 2 was further investigated by absorption spectroscopy (CH2Cl2/CHCl3 at 238 nm). The absorption band that arises at 750 nm was analysed with the Adair binding isotherm (G. S. Adair, J. Biol. Chem. 1925, 63, 529–545) to give complexion constants of K1 = 3.9·1014·M−1 and K2 = 1.2·1013·M−2 (see the Supporting Information). To our knowledge, these are the highest reported values for correlative association constants in a 1:2 host-guest complex involving TTF-C4P1.

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Explosive fluorescence: The hetero-complementary monomeric subunits, tetrathiafulvalene–calix[4]pyrrole (TTF-C[4]P) and bis-2,5,7-trinitrodicyanomethylenefluorene-4-carboxylate (TND CF), assemble to form oligomeric structures at higher concentrations. Dual-analyte-responsive behavior is seen, with de-aggregation of the supramolecular oligomers and a corresponding increase in the fluorescence intensity being seen in the presence of 1,3,5-trinitrobenzene (TNB) or Cl\(^-\) anions.