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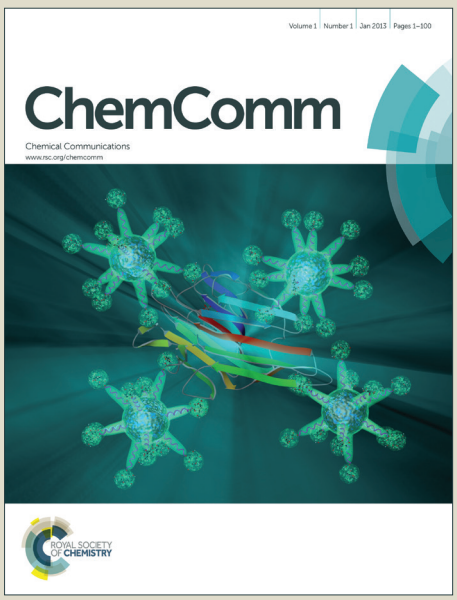

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COMMUNICATION

A novel fluorescent probe for paraquat and cyanide in water based on pillar[5]arene/10-methylacridinium iodide molecular recognition

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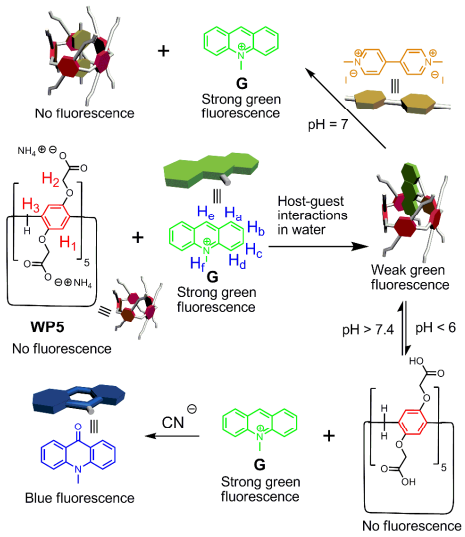
A novel fluorescent probe for paraquat and cyanide in water based on pillar[5]arene/10-methylacridinium iodide molecular recognition was reported.

There are always two sides for everything, such as paraquat (*N*,*N*'-dimethyl-4,4'-bipyridinium salt)[1] and cyanide,[2] which bring human progress and pollution, even death. Paraquat, one of the non-selective, effective, and quick acting herbicides, its high toxicity poses considerable risks to human health, animals, and the environment. Cyanide is another extremely harmful anion, it can be absorbed through the lung, gastrointestinal tract, and skin, leading to vomiting, convulsions, loss of consciousness, and eventual death.

The recognition and sensing of these two analytes have emerged as an important objective in the supramolecular community.[3] In recent years, a number of well-designed synthetic fluorescent probes specific for paraquat or cyanide have been constructed.[4] However, they were not able to respond to both paraquat and cyanide with two different sets of fluorescent signals. Many of them were even carried out in organic solvents, which limited their practical applications.[5] Thus, constructing a simple and practical probe which is capable of responding to paraquat and cyanide with distinct fluorescent signals in water is still an unmet challenge.

Pillararenes[6,7] are a new generation of macrocyclic hosts for supramolecular chemistry after crown ethers, cyclodextrins, calixarenes, and cucurbiturils.[8,9] Their repeating units are connected by methylene bridges at the *para*-positions, forming a special rigid pillar-like architecture, which is different from the basket-shaped structure of *meta*-bridged calixarenes. Herein, we report the establishment of new molecular recognition between water-soluble pillar[5]arene **WP5**[10] and 10-methylacridinium iodide **G** (Scheme 1) and its application in the fluorescent detection of paraquat and cyanide in water. The aim of our work is to develop a single fluorescent probe based on the complexation between **WP5** and **G** (known to be strongly fluorescent) which can detect paraquat and cyanide with different fluorescent signal patterns in water. The present paper reports the recognition properties of **WP5** with **G** and paraquat, the guest-displacement process for fluorescent sensing to paraquat, and the pH-controllable release of **G** for the determination of the cyanide anion based on a nucleophilic attack reaction on **G** in water.



Scheme 1. Chemical structures of **WP5**, **G**, and paraquat, and the illustration of the fluorescent detection of paraquat and cyanide.

WP5 and **G** were prepared according to previously reported methods.[10,11] The complexation of **WP5** with **G** was first studied by ^{1}H NMR experiments (Fig. S13, ESI†). When 1.00 equiv of **WP5** was added into a D_2O solution of **G** (10.0 mM), all the signals related to the protons on **G** shifted upfield significantly. Additionally, extensive broadening occurred due to the complexation dynamics. The reason is that the protons located within the cavity of **WP5** were shielded by the electron-rich cyclic structure upon forming a threaded structure between **WP5** and **G**. On the other hand, the protons on **WP5** also exhibited slight chemical shift changes. A mole ratio plot for the complexation between **WP5** and **G** showed that the stoichiometry of the complex between **WP5** and **G** was 1 : 1 (Fig. S6, ESI†). From the 2D NOESY spectrum (Fig. S3, ESI†) of a mixture of 10.0 mM **WP5** and **G** in D_2O, correlations were observed between protons H_a–H_f of **G** and proton H_1 on **WP5**, suggesting that **G** was threaded into the cavity of **WP5**. Therefore, we concluded that when **G** was mixed with **WP5**, it penetrated the cavity of **WP5**, forming a 1 : 1 inclusion [2]complex **WP5**⊃**G**. We speculated that the formation of the complex between **WP5** and **G** was mainly driven by multiple electrostatic interactions between the carboxylate anionic groups on **WP5** and the cationic 9-pyridinium unit of the **G** guest, hydrophobic interactions, and

π–π stacking interactions between the benzene rings on the host **WP5** and the acridinium ring on the guest **G** in aqueous solution. The binding affinity of this host–guest system can be attributed to the cooperativity of these noncovalent interactions.

Further evidence for the formation of host–guest complex **WP5⊃G** was obtained from UV-vis absorption spectroscopy (Fig. S10. ESI†). A broad absorption band above 370 nm corresponding to the charge-transfer interaction between electron-rich **WP5** and electron-deficient **G** was observed. Moreover, upon gradual addition of **WP5** to **G**, a notable red shift occurred, indicating the formation of a typical charge-transfer complex. Fluorescence titration of **WP5** with **G** was also carried out at room temperature in water. As shown in Fig. 1a, the quenching of the fluorescence intensity of **G** was found to be significant upon the gradual addition of **WP5**, proving the formation of a strong supramolecular complex. The quenching of fluorescence is ascribed to photo-induced electron transfer from the anionic carboxylate groups of **WP5** to the excited state of **G**.

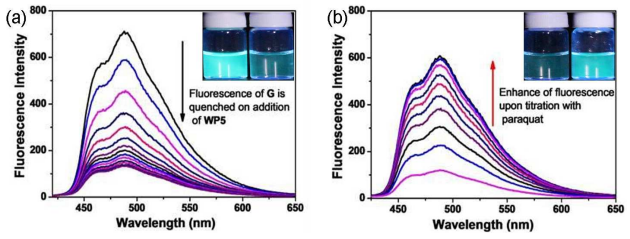


Fig. 1 (a) The changes in fluorescence intensity of **G** (3.00 μM) upon the titration of **WP5** (0.00–11.0 equiv) in water (λ_{ex} = 360 nm, λ_{em} = 490 nm; slits, 3 nm/3 nm). The inset photographs show the corresponding fluorescence quenching in water on excitation at 365 nm using a UV lamp at 298 K. (b) Recovery of the fluorescence of a solution of **WP5** (33.0 μM) and **G** (3.00 μM) upon the titration with paraquat (0.00–390 μM) in water (λ_{ex} = 360 nm, λ_{em} = 490 nm; slits, 3 nm/3 nm). The inset photographs show the corresponding fluorescence enhancement in water on excitation at 365 nm using a UV lamp at 298 K.

Our starting point was to design a proper non-fluorescent host–guest system that allows for the effective "turn-on" fluorescence for sensing paraquat. The host in this target host–guest system should show a large difference in binding constants for **G** and paraquat. The ability of **G** to form a 1 : 1 complex with **WP5** was assessed by ^{1}H NMR titration of **G** into **WP5** in water and the association constant (K_a) of **WP5⊃G** was calculated to be (1.28 ± 0.42) × 10^2 M^{-1} in water using a nonlinear curve-fitting analysis (Figs. S5 and S6, ESI†). Meanwhile, the K_a value of **WP5**⊃paraquat was measured by a ^{1}H NMR titration experiment to be (1.32 ± 0.25) × 10^5 M^{-1} (Figs. S8 and S9, ESI†). Therefore, the K_a value of **WP5**⊃paraquat is about 1000 times higher than that of **WP5⊃G**. Hence, based on the different binding abilities, fluorescence titration was carried out to realize the detection of paraquat in water. With such consideration in mind, we initially studied the fluorescence titration of **WP5⊃G** with paraquat (Fig. 1b). This new supramolecular ensemble **WP5⊃G** was a non-fluorescent complex with highly solubility in water. When this non-fluorescent complex was treated with paraquat in water, the expected increase in the fluorescence intensity was observed. It means that in the presence of paraquat, the fluorescence dye **G** slipped out of the cavity of **WP5** which was rethreaded by paraquat with a higher association constant. The underlying optical changes were ascribed to the formation of a **WP5**⊃paraquat complex, which is more stable than **WP5⊃G**. Moreover, the "turn-on" fluorescence changes produced by the addition of paraquat were easily visualized by the naked eye using a simple UV-lamp (Fig. 1b).

As known from our previous report,[4c] an anionic water-soluble pillar[6]arene analogue reduced the toxicity of paraquat efficiently based on the concept of host–guest chemistry. Here **WP5** also forms a stable host–guest complex with paraquat in water. Therefore, the host–guest complex **WP5⊃G** not only acts as a fluorescent chemosensor for the detection of paraquat but also may have potential application as a toxicide.

It is well-known that anionic carboxylate groups and neutral carboxylic groups can be interconverted by changing the solution pH. We then tested the switchable property of the complex **WP5⊃G** by acid/base treatment. The solubility of **WP5** with ten carboxylate groups in water was decreased by the addition of an aqueous HCl solution, leading to the precipitation of the macrocyclic host and the disassembly of the complex **WP5⊃G**. This was easily observed by the naked eye; a white precipitate appeared after the aqueous HCl solution was added. Then, after the addition of NaOH, the white precipitate disappeared, indicating the recovery of the host–guest complex. ^{1}H NMR provided convincing evidence for the pH-responsive complexation between **WP5** and **G** (Fig. S14, ESI†). When the solution pH was adjusted from 7.4 to 6.0, the chemical shifts corresponding to protons of **G** almost returned to their uncomplexed values and the signals of the protons of **WP5** disappeared (Figs. 14b and 14c, ESI†), indicating that the complexation of **G** and **WP5** was totally quenched. After the solution pH was recovered to 7.4, all the signals of the protons of host and guest came back (Figs. 14b–14d, ESI†), suggesting that the complexation between **G** and **WP5** was recovered.

It is well known that nucleophilic addition of cyanide at the 9-position of **G** can be used to fabricate cyanide-selective chemosensors.[4a,12] Furthermore, compound **G** has a high fluorescence quantum yield and also exhibits very good solubility in water, which make it feasible for practical applications. Therefore, based on the successful pH control of the complexation between **WP5** and **G** and the acid-induced release of **G** in water, we used the host–guest complex **WP5⊃G** as a fluorescent chemosensor to detect cyanide in aqueous solution. The binding pattern of **G** and cyanide was examined by a ^{1}H NMR titration experiment (Fig. S15, ESI†). Upon addition of KCN to a DMSO-d_6 solution of **G**, the ^{1}H NMR signal attributed to H_e disappeared, indicating that nucleophilic addition of cyanide at the 9-position of **G** occurred and the **G–**CN^- adduct formed. The ^{1}H NMR signals corresponding to all protons of **G** remained essentially unchanged when more than 1.0 equiv of KCN was introduced into the solution, further suggesting the production of the stable **G–**CN^- adduct. In addition, the formation of **G–**CN^- adduct was confirmed by mass spectrometric analysis (Fig. S11, ESI†), in good agreement with the aforementioned design concept and previous reports.[4a]

We next investigated the concentration-dependent changes in the fluorescence spectra upon incubation of **G** (3.00 μM) with CN^-. As shown in Fig. 2, free **G** exhibits a green emission at 490 nm. With the addition of CN^-, the emission at 490 nm decreased sharply, followed by the appearance and the increase of a new emission band at 430 nm. This indicated that the chemical reaction between cyanide and **G** interrupted the conjugation. The emission changed and resulted in an obvious fluorescence color change from green to blue as well as a well-defined isoemissive point at 400 nm. Essentially, these changes in the fluorescence spectrum stopped and the ratio of the emission intensities at 430 nm and 490 nm (I_{430}/I_{490}) became constant when the amount of

CN^- reached 20.0 equiv. In fact, in the presence of 20.0 equiv of CN^-, a ca. 51-fold enhancement in the ratiometric value of I_{430}/I_{490} was achieved with respect to the cyanide-free solution. In addition, the probe is stable and displays the best response for CN^- in a pH region of 3–11 (Fig. S12, ESI†). These results indicated that **G** reacts with CN^- and allows CN^- detection in a wide range of pH values.

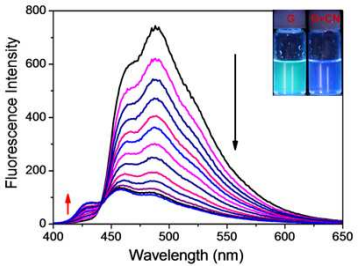


Fig. 2 Fluorescence titration spectra of **G** (3.00 μM) in Tris-HCl buffer (10.0 mM, pH = 6.0) upon the gradual addition of CN^- (λ_{ex} = 360 nm, λ_{em} = 490 nm; slits, 3 nm/3 nm). The inset photographs show the corresponding fluorescence intensity color changes of **G** upon the gradual addition of CN^- on excitation at 365 nm using a UV lamp at 298 K.

In summary, a new multi-functional fluorescent chemosensor based on the host–guest complexation between **WP5** and **G** in water was constructed. This non-fluorescent complex served as a fluorescence "turn-on" probe to detect paraquat because of the much higher binding constant of **WP5**⊃paraquat than that of **WP5**⊃**G**. This molecular recognition had not only different binding strengths for paraquat and **G** but also pH-responsiveness. The assembly and disassembly processes were reversibly controlled by changing the solution pH. Meanwhile, a ratiometric fluorescent probe was developed based on the addition of nucleophilic cyanide to the 9-position of **G** for the determination of CN^- in water. We expect that this design strategy of multi-functional fluorescent chemosensors based on host–guest interactions can be extended for other practical applications.

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Notes and references

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† Electronic Supplementary Information (ESI) available: Synthetic procedures, characterizations, determination of association constants, UV-vis data and other materials. See DOI: 10.1039/c0xx00000x.

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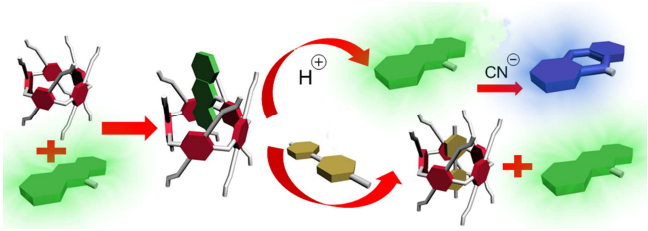

Text:

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