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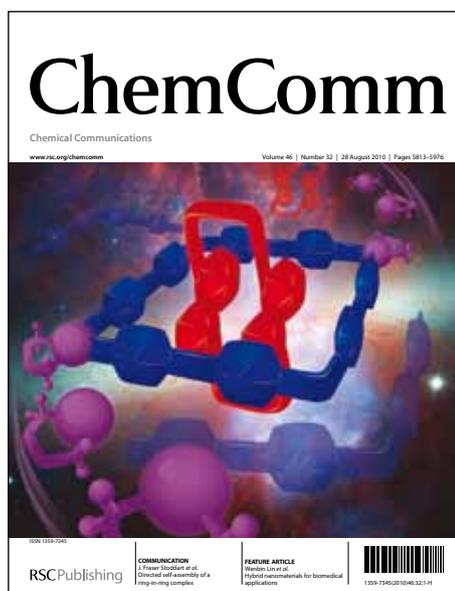
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ARTICLE TYPE

Water-Dispersible Nanospheres of Hydrogen-Bonded Supramolecular Polymers and Their Application for Mimicking Light-Harvesting System†

Hui-Qing Peng,[a,b] **Jiang-Fei Xu,**[a,b] **Yu-Zhe Chen,**[a] **Li-Zhu Wu,**[a] **Chen-Ho Tung**[a] **and Qing-Zheng Yang*[a]**

Water-dispersible nanospheres of hydrogen-bonded supramolecular polymers have been prepared for the first time by using miniemulsion method. Nanospheres containing
10 **chromophores with high fluorescence quantum yields were fabricated to mimic the natural light-harvesting system.**

Supramolecular polymers are arrays of small molecular-weight monomers connected through reversible non-covalent linkages, such as hydrogen bonds, hydrophobic interactions or other weak 15 interactions.[1] The highly directional quadruple hydrogen bonding units of ureidopyrimidinone (UPy) are among the most used building blocks in supramolecular polymer construction due to their high association constant and synthetic accessibility.[2] Impressive progress has been achieved with these supramolecular 20 polymers in fabrication of functional materials.[3] UPy-based monomers are typically polymerized in apolar organic solvents, because polar solvents, such as water, weaken or eliminate the hydrogen bonding pairing.[4] As a result, applications of UPy-based supramolecular polymers in life science or eco-friendly 25 materials have been little explored. Nanospheres are one of the most widely used shapes in nano materials due to their good dispersibility and low surface energy. Nanospheres of UPy-based supramolecular polymers generated in aqueous phase may find wide-ranging applications in areas such as biomaterials and 30 luminescent nanomaterials.

Supramolecular polymers share many properties with traditional polymers but are also capable of rapid and reversible polymerization/depolymerization.[5] The methods for preparation of polymer nanoparticles with a desired architecture may also be 35 suitable for supramolecular polymers.[6] Traditional polymers are fabricated as nanospheres by the miniemulsion method.[7] Homogeneous miniemulsions are easily formed by ultrosonication of a mixture of water and organic phase in the presence of a surfactant. The polymers aggregate into 40 nanospheres upon evaporation of the organic solvent. Inspired by such a method, we envisioned that miniemulsion could be utilized to prepare nanoparticles of hydrogen-bonded supramolecular polymers. Stable emulsified organic droplets may provide a hydrophobic environment to stabilize hydrogen-bonded 45 supramolecular polymers, which could aggregate into nanospheres. Here we report a highly efficient preparation of nanospheres of hydrogen-bonded supramolecular polymers in

water based on miniemulsion (Scheme 1). We prepared nanospheres of four types of UPy-based supramolecular polymers. 50 The supramolecular polymers containing chromophores with high fluorescence quantum yields form nanospheres for efficient light harvesting. To the best of our knowledge, this work is the first example of water-dispersible nanospheres of hydrogen-bonded supramolecular polymers.
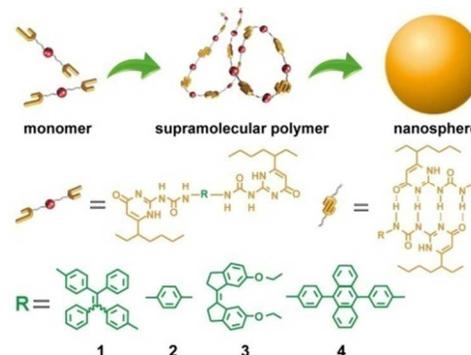
55 **Scheme 1** Chemical structures of monomer **1-4** and graphical representation for preparation of water-dispersible nanospheres of hydrogen-bonded supramolecular polymers.

We synthesized monomer **1-4** containing two UPy moieties 60 (supporting information). The formation of high-molecular-weight supramolecular polymers in chloroform from the monomers was confirmed by NMR spectroscopy and viscometry.[8] The ^1H NMR spectra of **1-4** in $CDCl_3$ clearly indicated dimerization of the UPy units, as the UPy N-H signals 65 showed a large downfield shift (10.0-13.5 ppm) (Supporting Information, Fig. S1). The viscosity measurements on $CHCl_3$ solution of **1-4** were consistent with the results of the NMR studies (Fig. S3). The double logarithmic plots of specific viscosity vs. concentration of **2** was linear with slope of 1.08 at 70 concentration <33 mM, indicating the presence of solutes with concentration-independent size (e.g.,oligomers). A slope of 3.11 was observed at >33mM indicating an increase in the degree of polymerization of **2** with concentration. Similar to **2**, a critical polymerization concentration was also observed at 100 mM for 75 **3**.[3b] In contrast to **2** and **3**, the slope of the graph for **1** and **4** was constant at 1.67 and 2.11, respectively, over the whole concentration range, indicating the propensity of **1** and **4** to polymerize even at low concentrations.
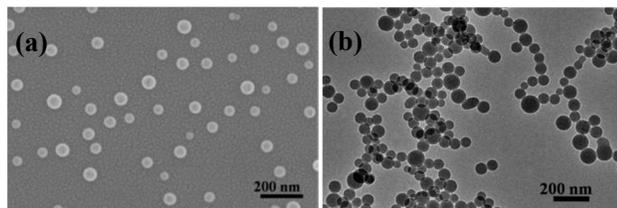
Fig. 1 (a) SEM and (b) TEM images of nanospheres prepared from supramolecular polymers of **1**.

We prepared nanospheres of hydrogen-bonded supramolecular polymers in water by miniemulsion method. 200 µL stock solution of **1-4** in CHCl₃ (25 mg/mL) was quickly added to aqueous solution of cetyl trimethyl ammonium bromide (CTAB) surfactant (10 mL, c_{CTAB} = 0.9 mM). We sonicated the resulting solution for 25 minutes to emulsify the organic phase. After three cycles of centrifuge-wash with water, we obtained stable water-dispersible nanospheres as confirmed by electron microscopy and dynamic light scattering (DLS). As illustrated in Fig. 1, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images indicated regular shape and uniform size of those well-dispersed nanospheres of **1** with an average diameter of ~60 nm. The average hydrodynamic diameter estimated from DLS was ~109 nm (Fig. S4). The size of nanospheres formed from **3** and **4** were similar to that from **1**, and **2** formed slightly larger nanospheres than **1** (Fig. S5, Table S1).
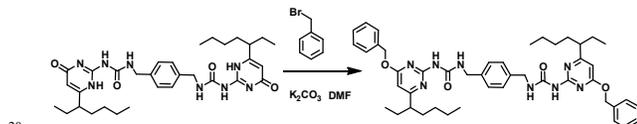
Scheme 2 Synthesis of compounds **benzyl 2**.

Because water lowers considerably the dimerization constant of UPy by competing with hydrogen-bond donor and acceptor sites of these units, the importance of hydrogen bonding in the formation of nanospheres from **1-4** is not obvious. The presence of peaks at 3212 and 3147 cm⁻¹ (Fig. S6) in the FTIR spectra of the nanospheres suggests the formation of the self-complementary hydrogen bonds.[2a] To further establish the importance of such self-complementary hydrogen bonding for the formation of the nanospheres, we synthesized derivatives of **2** and **4** (**benzyl 2** and **benzyl 4**, Scheme 2 and Scheme S1) in which one of the hydrogen-bonding acceptor sites was blocked.[9] The formation of our suparmolecular polymers is based on the UPy dimerization. The absence of the UPy N-H signals between 10.0 and 13.5 ppm in ¹H NMR spectrum suggests that the UPy dimers are not formed (Fig. S2). As a result, these derivatives did not assemble into supramolecular polymers. The aggregates formed from **benzyl 2** and **benzyl 4** under identical condition were disorderly (Fig. S7). Such results prove that supramolecular polymerization by dimerization of UPy moieties through the quadruple hydrogen bonding is the prerequisite for the formation of the nanospheres.

We speculated that the hydrogen bonding of the supramolecular polymers was protected by a hydrophobic microenvironment provided by emulsified organic droplets during preparation in water. As a result, the random-coil supramolecular polymers aggregate into nanospheres under the influence of hydrophobic interactions. It should be noted that our nanospheres made from supramolecular polymer have smaller size and better defined structures than most of these obtained from common covalent polymers by using the miniemulsion method,[7] which may reflect the dynamic character of supramolecular polymers. The dynamic formation and break of hydrogen bonds adjust the length and configuration of the polymers, which may lower the energy of the system especially the surface energy. Finally the polymers aggregate into the stable nanospheres with desired shape and size.

We studied the influence of surfactants and the concentration of monomers on properties of such nanospheres. Both anionic (e.g., Sodium dodecyl sulfate) and nonionic surfactant (e.g., Pluronic F-127) yielded nanospheres whose shape and size distribution were similar to those of the nanospheres prepared with CTAB as emulsifier, indicating that the method is not restricted to a particular surfactant type (Fig. S8). On the other hand, the average size of the nanospheres was sensitive to the initial monomer concentration. As the monomer concentration increased from 5 to 100 mg/mL, the hydrodynamic diameters measured by DLS increased from 49 nm to 237 nm (Fig. S9). This correlation enables us to fabricate nanospheres of different size by adjusting the monomer concentration.
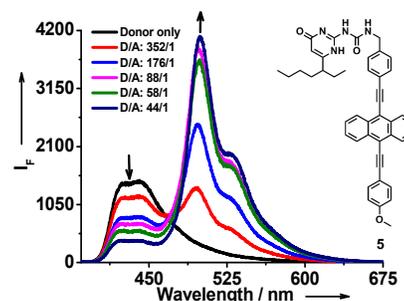
Fig. 2 Fluorescence spectra of nanospheres dispersed in water with different molar ratios between donor (D) and acceptor (A). [D] = 49.7 µM. [D] to [A] molar ratio is 352:1, 176:1, 88:1, 58:1, 44:1 from bottom to top. λ_{ex} = 375 nm. Inset: chemical structure of **5**.
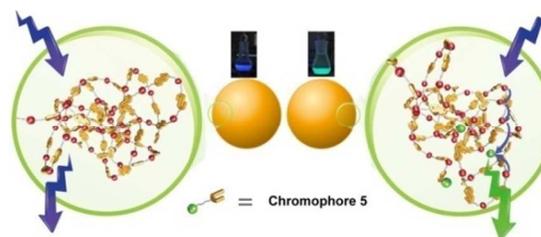
Fig. 3 Schematic illustrations of the energy transfer among chromophores densely organized in the nanospheres. Left: nanospheres prepared from supramolecular polymers of **4**. Right: nanospheres prepared from supramolecular copolymers of 88:1 of **4** to **5**. Inset: photographs of nanospheres in water under UV light (λ_{ex} = 365 nm)

To illustrate the utility of the described method we fabricated nanospheres to mimic the natural light-harvesting systems. Construction of artificial light-harvesting systems is important due to their potential applications in solar cells, photocatalysts and optical sensors.[10] Although impressive progress has been made using directed synthesis, the multiple steps needed to prepare complex architectures limit the reach of such approaches. Preparation of highly efficient antenna system by self-assembly from readily available building blocks can avoid such complex

synthesis and separation.[11] We chose green emissive chromophore 9-(4-methoxyphenylethynyl)-10-(4-UPy-phenylethynyl) anthracene (**5**) derivatized with a UPy moiety (Fig. 2) as the energy acceptor since its absorption has significant overlap with the emission of energy donor **4** (Fig. S10). We constructed light-harvesting system from the copolymer of **4** and **5** (Fig. 3). Because **5** contains a single UPy moiety, it terminates a supramolecular macrochain of chromophores **4**. The presence of **5** did not affect the shape and size distribution of the nanospheres within molar ratio of **4** to **5** from 352:1 to 44:1 (Fig. 4).
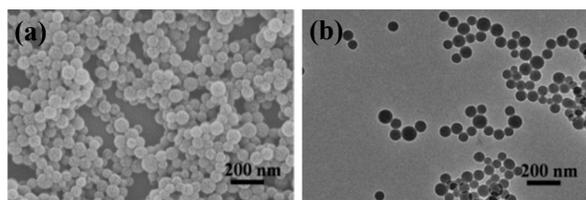
Fig. 4 (a) SEM and (b) TEM images of nanospheres prepared from supramolecular copolymers of 88:1 molar ratio of **4** to **5**.

The energy transfer from donor to acceptor was confirmed by steady state and time-resolved fluorescence spectroscopy. As shown in Fig. 2, an increase of the acceptor-to-donor molar ratio from 1/352 to 1/44 lowered the intensity of the donor emission at 430 nm while enhancing that of the acceptor at 496 nm when the donor was selectively excited at 375 nm. The excitation spectrum of the acceptor was nearly identical to the absorption spectrum of **4**, indicating that the donor contributed directly to the acceptor emission (Fig. S11). Time-resolved fluorescence measurements clearly show that the fluorescence decay of chromophore **4** accelerates after the co-assembly of acceptor **5**, indicating an efficient energy transfer (Fig. S12).

The change of fluorescence was easily visualized by a variation in the emission color from the bright blue emission of the donor to the bright green emission of the acceptor (Fig. 3), indicating that the unique optical properties of the nanosphere generated from small monomers could be tuned via convenient backbone copolymerization. Such fluorescent nanospheres may have potential applications for *in vitro* and *in vivo* fluorescence imaging.

To evaluate the light-harvesting ability of the system, we studied "antenna effect", a widely used empirical parameter, which is defined to determine the degree of the amplified acceptor emission assisted by the donor excitation.[11a, 11b] In our system, the antenna effect was calculated according to equation (1):

Antenna effect = $I_A (\lambda_{ex} = 375\ nm) / I_A (\lambda_{ex} = 445\ nm)$ (1)

where $I_A (\lambda_{ex} = 375\ nm)$ and $I_A (\lambda_{ex} = 445\ nm)$ are the fluorescence intensities of **5** upon exciting the donor at 375 nm and direct exciting the acceptor at 445 nm, respectively. With different molar ratio between donor and acceptor, the acceptor emission amplified significantly as the ratio of donor increased (Fig. S13, Table S2). A value of 11 fold emission enhancement was obtained for nanospheres of copolymers containing 44:1 molar ratio of donor to acceptor. With donor to acceptor ratios of 58:1, 88:1, and 176:1, the antenna effects resulted in 13, 20, and 29 fold enhancements of acceptor fluorescence, respectively. Eventually, the energy transfer was saturated at one acceptor per

352 donors, when the maximum acceptor emission amplification reached the factor of 35, which is much higher than other artificial light harvesting systems. [11a, 11b]

In summary, we described a highly efficient method to prepare water dispersible nanospheres of hydrogen-bonded supramolecular polymers with well-defined shape and size by miniemulsion method. This method is not restricted to a particular surfactant type. The size of the nanospheres was controlled by adjusting the monomer concentration in the precursor solution. We used this new method to construct brightly fluorescent light-harvesting nanospheres, from supramolecular copolymers containing energy donor and acceptor. In contrast to their covalent counterparts, nanospheres of supramolecular polymers are formed from low-molecular-weight molecules and their composition and functions are easily tunable. These features may offer great opportunities in bioapplications. Such an efficient fabrication of nanospheres of hydrogen-bonded supramolecuar polymers also opens up new opportunities for wide applications of UPy based supramolecular polymers in areas such as biomaterials and opto-electronic materials.

Notes and references

a Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190,China Fax: (+86) 10-62554670, E-mail: qzyang@mail.ipc.ac.cn
b University of the Chinese Academy of Sciences Beijing 100049, China
† Electronic Supplementary Information (ESI) available: Experimental details, ^{1}H NMR, specific viscosity, SEM, TEM, DLS, FT-IR, absorption and fluorescence measurements. See DOI: 10.1039/b000000x/

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