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Amidourea-Based Hydrogen-Bonded Heteroduplexes: Structure and Assembling Selectivity

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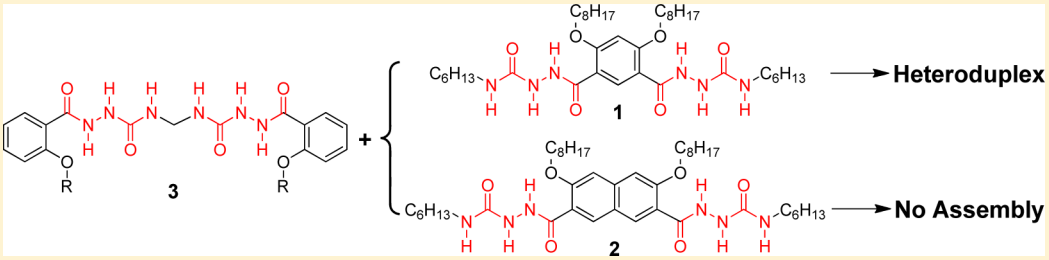
Supporting Information



ABSTRACT: A new class of multiply hydrogen-bonded heteroduplexes from readily available amidourea derivatives was designed, and their structures and selective assembling behaviors were investigated. Amidourea derivative **3** could selectively assemble with **1** to form a stable heteroduplex via eight intermolecular bifurcated hydrogen bonds, but could not assemble with **2** at all, because of their unique structures and the spacing effect, although **1** and **2** possessed the same hydrogen-bonding sequence. The high stability and selectivity will make the amidourea-based hydrogen-bonded heteroduplexes be potentially applicable in the design of well-defined supramolecular architectures and novel functional materials.

INTRODUCTION

Artificial molecular duplexes with high stability and selectivity are of great importance not only for the understanding of biological processes, but also in the design of new materials with specific structures and properties.[1] Multiple hydrogen-bonding modules with arrays of hydrogen-bond donors (D) and acceptors (A) are ideal for this mission.[2] During the past two decades, various hydrogen-bonded duplexes have been developed. Among known examples, the self-complementary ureidopyrimidone[3] and ureidodeazapterin[4] modules are of the most successful ones in wide research areas[5] due to their high affinity and synthetic accessibility. Another successful example is the aromatic oligoamide system designed by Gong et al.,[6] which could form homo and heteroduplexes conveniently by varying the hydrogen-bond sequence. In recent years, molecular duplexes based on the hydrazide motif were developed by Li et al.[7] and our group.[8] More recently, we also constructed a class of new homoduplexes based on the amidourea motif, which showed to be highly stable in $CDCl_3$.[9]

With increasing interest in supramolecular materials fabricated with multiple hydrogen-bonding modules, the development of new types of hydrogen-bonded duplexes that are of high association stability and selectivity represents a strong need. In principle, heteroduplexes are ideal tools to selectively assemble specific heterodimeric supramolecular architectures from diverse monomers. However, this kind of hydrogen-bonded heteroduplexes, especially those ones with high selectivity, available for use is still limited.[7,10] Herein we report the design, structure and selective assembling behavior of a new class of multiply hydrogen-bonded heteroduplexes from readily available amidourea derivatives **1**−**3** (Figure 1). It was demonstrated that the same hydrogen-bonding sequenced amidourea derivatives **1** and **2** with the only difference in spacers revealed completely distinct assembling properties with the complementary amidourea derivatives **3a**,**b**, because of the spacing effect, which thus led to the selective assembling behaviors among them.

RESULTS AND DISCUSSION

Design and Synthesis. Compounds **1**−**3** all possess two amidourea units. Amidourea derivatives **1** and **2** carry the same DDAADD hydrogen-bonding sequence but differ in the spacers, in which **1** takes phenylene as the spacer, while **2** contains naphthylene residue. And amidourea derivative **3** carries the ADDDDA hydrogen-bonding sequence with methylene as the spacer. In principle, the complementary DDAADD and ADDDDA hydrogen-bonding sequences are expected to lead to the formation of a new type of hydrogen-bonded heteroduplexes based on the amidourea motif (Figure 1). In compounds **1**−**3**, the alkoxy groups were all introduced

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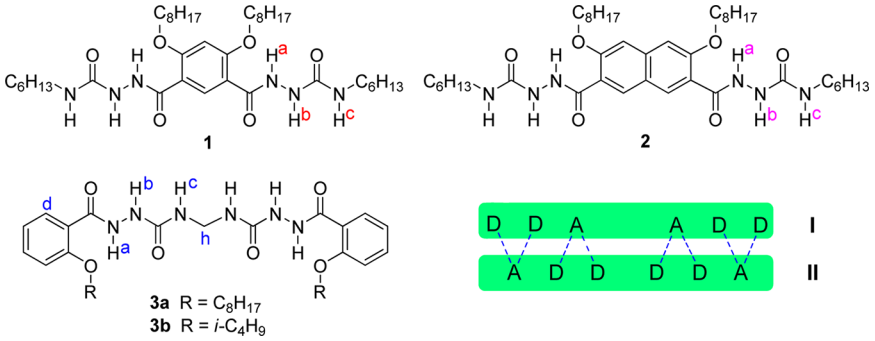
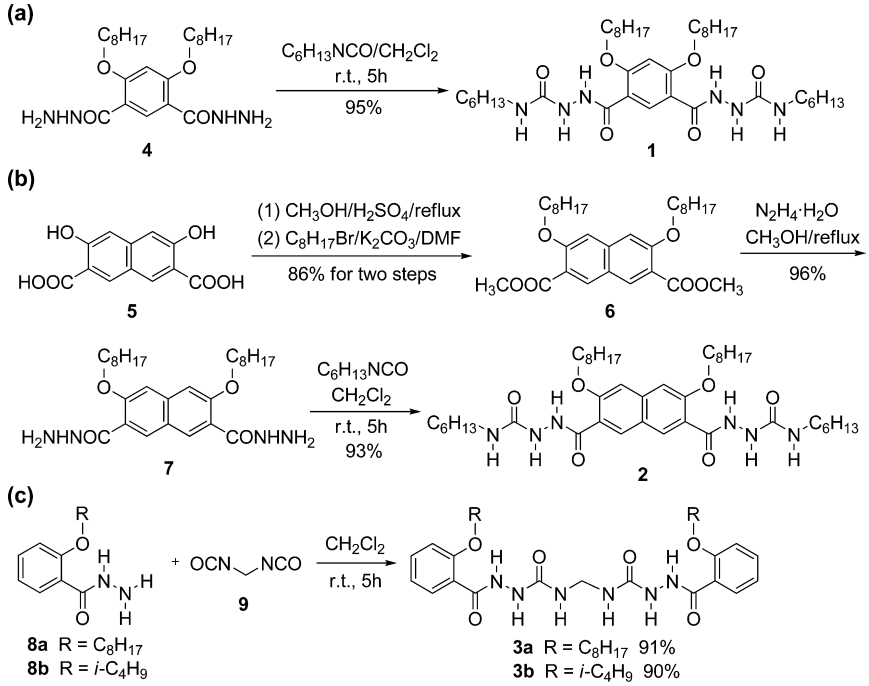


Figure 1. Chemical structures of amidourea derivatives **1**−**3** with proton-labeling scheme indicated and the designed binding motif of the hydrogen-bonded heteroduplexes.

Scheme 1. Synthesis of Compounds 1−3



for the formation of highly favorable S(6)-type intramolecular hydrogen bonds,[9,11] which could preorganize the amidourea groups and facilitate the monomer to complex with the complementary counterpart. As shown in Scheme 1a, compound **1** was conveniently synthesized in high yields by the reaction of the corresponding dihydrazide derivative **4** with hexyl isocyanate at room temperature. Compound **2** was obtained by the similar method from dihydrazide derivative **7** with hexyl isocyanate (Scheme 1b), and dihydrazide derivative **7** was synthesized from 3,6-dihydroxynaphthalene-2,7-dicarboxylic acid, which was prepared according to a literature procedure.[6e] Compounds **3a**,**b** were obtained easily by the reaction of the corresponding hydrazide derivatives **8a**,**b** and methylene diisocyanate **9** at room temperature (Scheme 1c), while **9** was prepared according to a literature procedure.[12]

Self-Assemblies of Monomers. With these amidourea derivatives in hand, we first examined the self-assembled property of each monomer respectively. For monomer **1**, its ^{1}H NMR study in $CDCl_3$ showed a large downfield shift of NH^a proton signal (9.52 ppm, at 5 mM, 298 K), which implied that NH^a proton was involved in strong intramolecular hydrogen bond. Substantial concentration-dependent chemical shift changes for protons NH^b and NH^c in the ^{1}H NMR dilution study[13] of **1** (from 5.0 to 0.5 mM) in $CDCl_3$ were then observed, indicating that their intermolecular hydrogen bonds formed. These observations suggested that **1** should self-assemble to form a hydrogen-bond-mediated supramolecular polymeric zipper structure (Figure 2). An association constant K_a of $(2.8 \pm 0.5) \times 10^2$ M^{-1} for chain extension of the aggregate $\mathbf{1}_n$ was also obtained by nonlinear regression analysis[14] of the chemical shift changes of NH^b proton. Similar to the results of **1**, ^{1}H NMR studies of monomer **2** in $CDCl_3$ indicated that it also self-assembled into a hydrogen-bond-mediated polymeric zipper structure (Figure 2). ^{1}H NMR dilution study[13] of **2** determined the association constant K_a for chain extension of the aggregate $\mathbf{2}_n$ to be $(1.1 \pm 0.1) \times 10^3$ M^{-1}. The fact that the association constant of $\mathbf{1}_n$ was smaller than that of $\mathbf{2}_n$ might be attributed to the steric hindrance[15] between every two adjacent hexyl groups in $\mathbf{1}_n$. For the monomers **3a** and **3b**, their ^{1}H NMR dilution studies (from 100.0 to 0.5 mM) in $CDCl_3$ showed that no significant chemical shift changes for the NH protons of **3a** or **3b** were found, indicating that their self-association was very weak.

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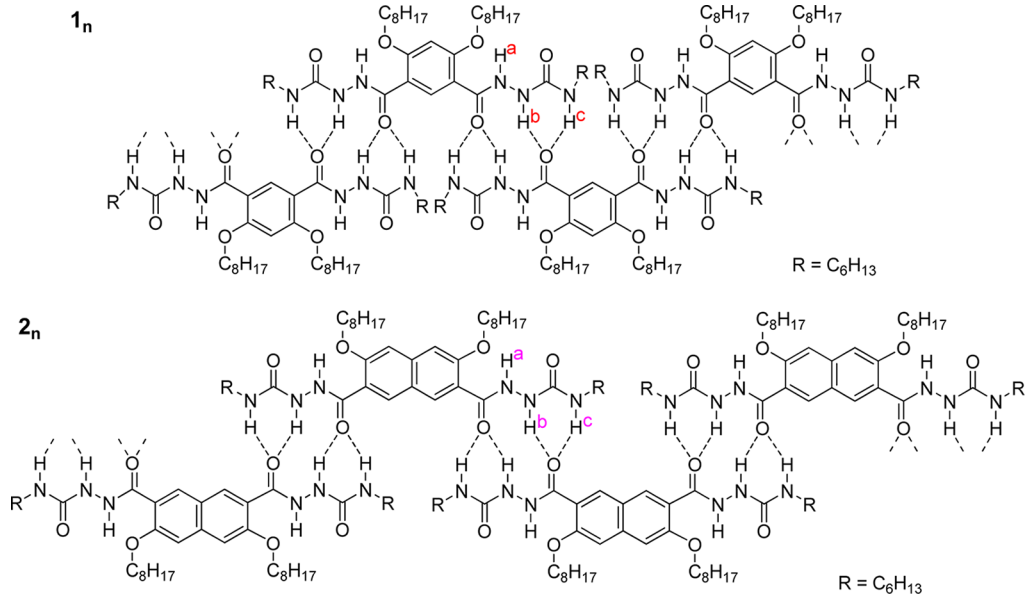

Figure 2. Representation of hydrogen-bond-mediated supramolecular polymeric zippers $\mathbf{1}_n$ and $\mathbf{2}_n$, and NH proton designations.

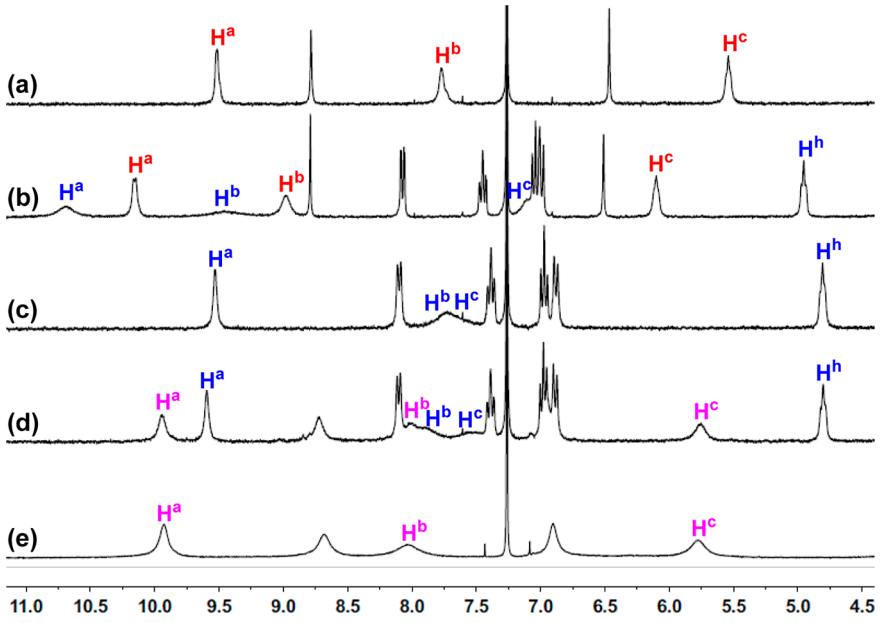

Figure 3. Stacked partial ^{1}H NMR spectra (300 MHz, 298 K) of (a) **1** (red), (b) **1** + **3a**, (c) **3a** (blue), (d) **2** + **3a**, (e) **2** (pink), each at 5 mM in $CDCl_3$.

These results are obviously different from those ones of monomers **1** and **2**.

Complexation Between Complementary Monomers. To test our design for the heteroduplexes, complexation between DDAADD-sequenced monomers **1**, **2** and ADDDDA-sequenced monomer **3** was investigated. Consequently, it was found that mixing equimolar amounts of **1** and **3a** (5 mM) in $CDCl_3$ led to substantial downfield changes of the chemical shifts for all the NH signals of **1** and NH^a, NH^b signals of **3a** (Figure 3), suggesting the formation of heteroduplex **1·3a**. The methylene proton H^h signal of **3a** also shifted downfield obviously, which could be rationalized by the proton H^h of **3a** within the deshielding zone of the aromatic ring of **1** upon complexation. But an unexpected upfield change for NH^c signal of **3a** was observed, which seemed a paradox to the formation of heteroduplex **1·3a**. To our surprise, when equimolar amounts of monomers **2** and **3a** (5 mM) were mixed in $CDCl_3$, no significant chemical shift changes for any NH signals of **2** or **3a**, or the methylene H^h signal of **3a** were found (Figure 3), which indicated that the complexation between **2** and **3a** was rather weak, and it was obviously different from that of **1·3a**.

How to explain these phenomena? We carefully examined the structures of these amidourea derivatives and found that **3a** might exist as the torsional conformer **3a′** rather than the linear conformer **3a** in $CDCl_3$ (Figure 4). Because of the formation of S(6)-type intramolecular hydrogen bond for NH^c in conformer **3a′**, and the rapid interconversion of these two conformers, NH^c proton (7.68 ppm, at 5 mM, 298 K) of **3a** displayed a broad and significant downfield signal as compared to the

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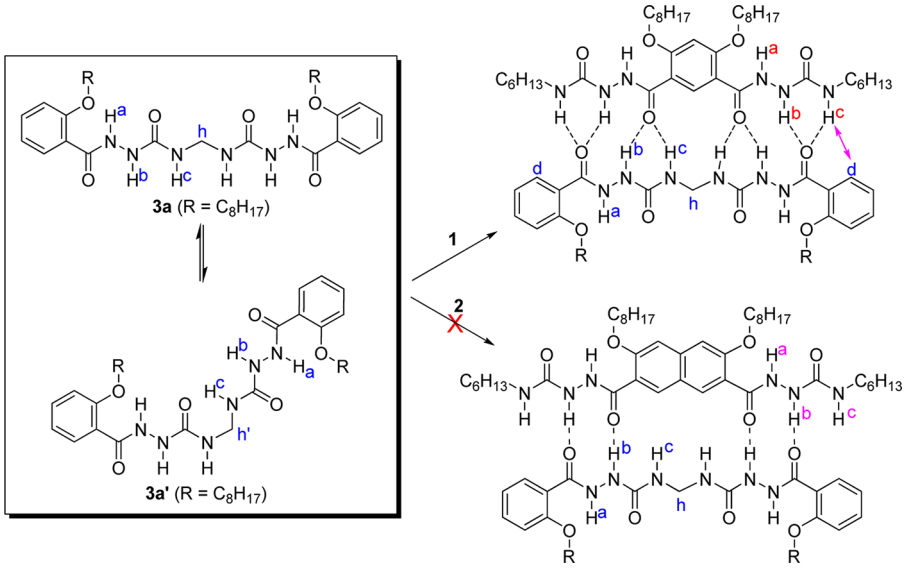

Figure 4. Isomerization of conformers **3a** and **3a′** and their selective assemblies with **1** to form heteroduplex **1·3a**. The intermolecular NOE contact highlighted with double headed arrows.

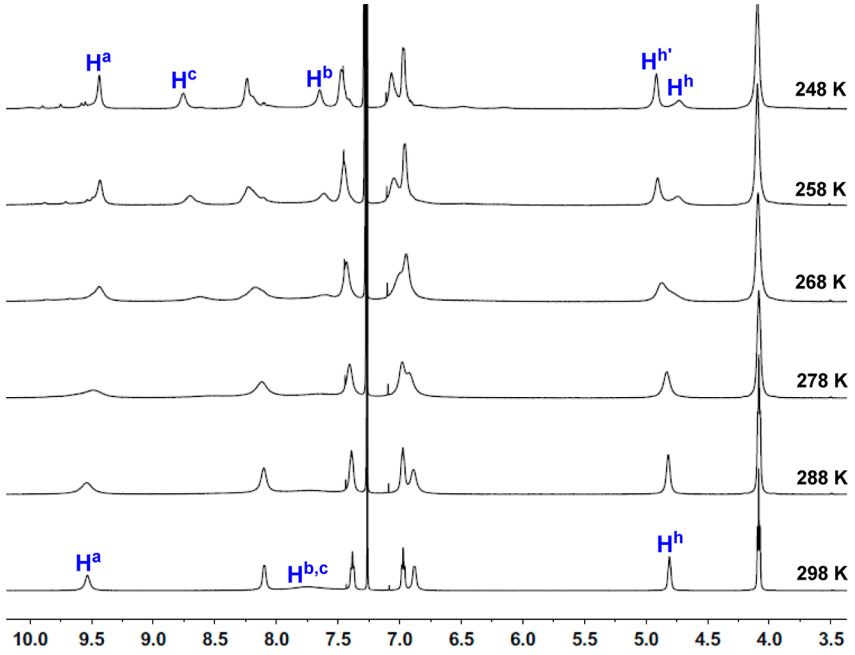

Figure 5. Stacked partial ^{1}H NMR spectra (600 MHz) of **3a** at different temperatures, 5 mM in $CDCl_3$.

corresponding NH^c proton of **1** and **2** (Figure 3). To investigate the conformational interconversion of **3a**, variable-temperature ^{1}H NMR study in $CDCl_3$ was performed (Figure 5). With the temperature lowering, the methylene H^h signal of **3a** gradually broadened and finally split into two peaks starting from 258 K, which indicated that the interconversion of the conformers was slowed on the NMR time scale at lower temperatures. And according to the integration of H^h and $H^{h'}$, the relative population of the two conformers **3a** and **3a′** was 1:2 at 248 K, which meant conformer **3a′** was the preferred conformation. During the temperature lowering, the chemical shifts of NH^a and NH^b protons both moved negligibly, because NH^a was involved in the intramolecular hydrogen bond, and NH^b was not involved in any hydrogen bonds. NH^c proton signal shifted downfield significantly and separated with H^b because of the formation of the intramolecular hydrogen bond during the conformer **3a** to **3a′** isomerization. The conformation of **3** was then studied by the density functional theory (DFT) calculation at the B3LYP/6-31+G(d,p) level.[13] It was revealed that the torsional conformer **3′** was more stable than the linear conformer **3** in the gas phase, and the difference in conformational energy was calculated to be −10 kJ/mol when the alkoxy groups were replaced with methoxy groups. Furthermore, a single crystal of compound **3b** was obtained for X-ray crystallographic analysis via slow evaporation from the mixed solvent of CH_2Cl_2/CH_3CN. As expected, the solid-state structure of **3b** (Figure 6) approximates to the torsional conformer **3b′**, in which the S(6)-type intramolecular hydrogen bond $NH^c\cdots O$ (N···O 3.09 Å, H···O 2.83 Å) was indeed formed. But there are still discrepancies between the crystal

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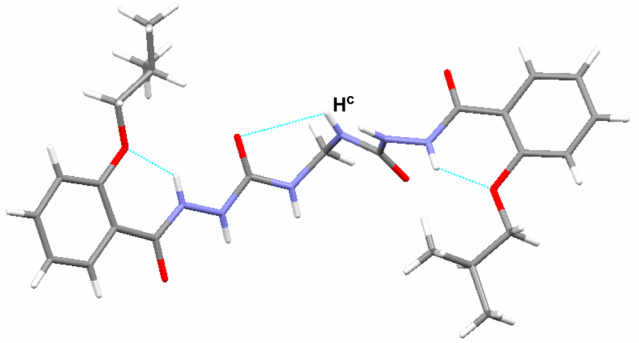

Figure 6. Crystal structure of **3b**, showing the intramolecular hydrogen bonds.

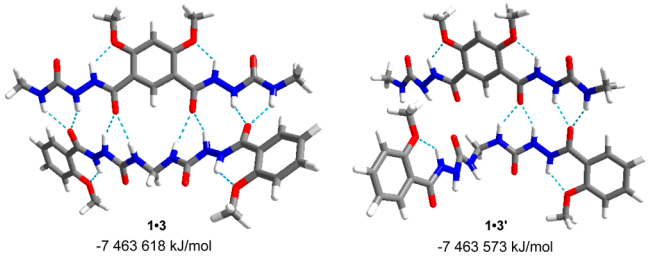

Figure 7. Optimized structure of heteroduplexes **1·3** and **1·3′**. All the side chains of monomers **1** and **3** are replaced with methyl groups for simplicity. The total energies were corrected with BSSE using counterpoise method.

structure and conformer **3b′**. The NH^c···O interaction in the crystal structure is only a weak interaction,[16] not the classical moderate S(6)-type intramolecular hydrogen bond. The amidourea groups in the crystal structure are not planar, and the two C−N−N−C dihedral angles are 8.01° and 86.58°, respectively. Compound **3b** further extended to form polymeric structure via 2-fold bifurcated hydrogen bonds at each knot in the solid state (Figure S26, Supporting Information). The complexation between monomers **1**, **2** and monomer **3b** in solution was also investigated. Consequently, it was found that ^{1}H NMR studies on 1:1 mixtures of **1** and **3b**, and **2** and **3b** (each at 5 mM in $CDCl_3$)[13] gave almost the same results as those of **1** and **3a**, and **2** and **3a**, respectively.

On the basis of the discovery above, the 1:1 mixing ^{1}H NMR results (Figure 3) would be elucidated reasonably. Adding compound **1** to **3** (1:1) in $CDCl_3$ could induce the torsional conformer **3′** to convert to the linear conformer **3**, which assembled with **1** to form the stable heteroduplex **1·3**. In this case, NH^c proton of **3** involving in the S(6)-type intramolecular hydrogen bond of conformer **3′** altered to form an intermolecular bifurcated hydrogen bond of heteroduplex **1·3**, and consequently NH^c proton signal of **3** shifted upfield upon complexation. While the other NH proton signals of **1** and **3** shifted downfield normally after heteroduplex **1·3** formed. The formation of heteroduplexes **1·3a** and **1·3b** was unequivocally evidenced by two-dimensional NMR spectra[13] (NOESY) of 1:1 mixtures of **1** and **3a**, and **1** and **3b** (each at 5 mM in $CDCl_3$), respectively. Cross-strand contacts between **1**-H^c and **3a**-H^d, and **1**-H^c and **3b**-H^d were observed, which were consistent with the heteroduplex structures. The formation of heteroduplex **1·3** was also evidenced by the mass spectrometry (APCI-MS), in which a peak of highest intensity corresponding to the heteroduplex (1333.18 for [**1·3a** + H]$^+$, 1220.81 for [**1·3b** + H]$^+$) was found.[13] The binding stability of **1·3** was then investigated by the ^{1}H NMR titration methods using **1** upon addition of **3a** or **3b** from 1:0 to 1:2 at 1.0 mM in $CDCl_3$. With the addition of **3a** or **3b**, the NH proton signals of **1** all shifted downfield gradually. A fit of the chemical shift data for NH^b proton to a 1:1 binding mode afforded apparent association constants K_a of $(1.6 \pm 0.1) \times 10^4$ M^{-1} for heteroduplex **1·3a** and $(1.5 \pm 0.2) \times 10^4$ M^{-1} for heteroduplex **1·3b**, respectively,[13,14] which indicated that heteroduplexes **1·3a** and **1·3b** had almost the same high stability without taking self-association into account. Furthermore, DFT calculation at the B3LYP/6-31+G(d,p) level was carried out to investigate the structure of heteroduplex **1·3** (Figure 7).[17] The total energy was estimated with consideration of the basis set superposition error (BSSE) correction using the counterpoise method. The optimized structure exhibited that heteroduplex **1·3** was stabilized by eight intermolecular bifurcated hydrogen bonds based on the amidourea motif.[9] The rigid **1** existed in a nearly planar conformation, whereas **3** adopted a twisted conformation in heteroduplex **1·3**. The heteroduplex composed of **1** and conformer **3′** (Figure 7) was also investigated by DFT calculation.[13] The optimized structure revealed that heteroduplex **1·3′** was combined by four intermolecular bifurcated hydrogen bonds between the two amidourea groups. Compared the BSSE corrected energies, the total energy of heteroduplex **1·3′** was larger than that of heteroduplex **1·3**, which indicated that heteroduplex **1·3** was more stable. The interaction energy of **1·3** and **1·3′** were calculated to be −182.0 and −88.7 kJ/mol, respectively. This is consistent with the fact that the number of hydrogen bonds in heteroduplex **1·3** is twice as in **1·3′**. We concluded that the lower energy of **1·3** is due to the contribution of the hydrogen bonds. From the other aspect, the 1:1 mixing ^{1}H NMR of **1** and **3** in $CDCl_3$ only showed one set of NH proton signals, which was more consistent with heteroduplex **1·3**. These results demonstrated that heteroduplex **1·3** via eight intermolecular hydrogen bonds was much more preferred and stable.

In contrast, although amidourea derivative **2** possessed the same DDAADD hydrogen-bonding sequence with **1**, it hardly complexed with **3** to form a heteroduplex based on the amidourea hydrogen-bonding motif,[9] due to the mismatched spacers between **2** and **3**. It seemed that **2** and **3** were likely to form a heteroduplex via the hydrazide-like quadruple hydrogen-bonding motif (Figure 4). But in fact, the 1:1 mixing ^{1}H NMR studies (Figure 3) of **2** and **3a**, and **2** and **3b** (each at 5 mM in $CDCl_3$) showed no significant chemical shift changes for any NH proton signals of **2** or **3**, or the methylene H^h signal of **3**, which indicated that the complexation between **2** and **3** was very weak. Considering that monomer **2** self-assembled into a relatively stable supramolecular polymeric zipper, and monomer **3** mainly existed as the torsional conformer **3′**, the assumed heteroduplex **2·3** might not be strong enough to self-assemble in $CDCl_3$. We also tried to investigate the binding stability of heteroduplex **2·3** by ^{1}H NMR titration studies using **2** upon addition of **3a** or **3b** from 1:0 to 1:2 at 1.0 mM in $CDCl_3$, but the chemical shift changes ($\Delta\delta \leq 0.03$ ppm) of all the NH protons of **2** were very small during the titration. As a result, the nonlinear regression analysis to yield any association constants for **2** and **3a**, or **2** and **3b** could not be finished, which also supported that monomers **2** and **3** could hardly assemble to form a heteroduplex. As another evidence, no intermolecular contacts were found in NOESY studies on 1:1 mixtures of **2** and **3a**, or **2** and **3b** (each at 5 mM in $CDCl_3$). Furthermore,

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the structure of the assumed heteroduplex **2·3** was studied by DFT calculation. The optimized structure (Figure 8) exhibited

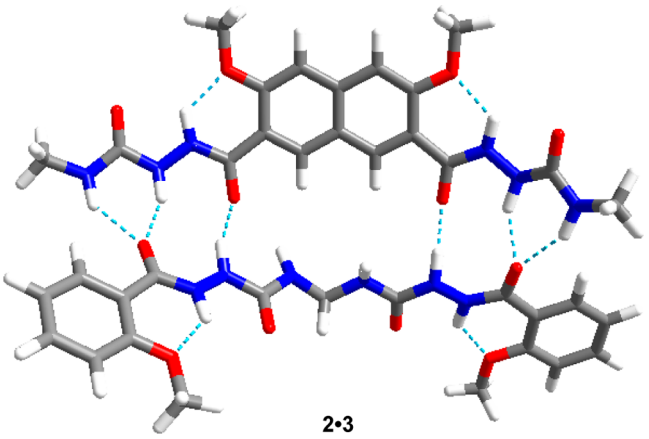

Figure 8. Optimized structure of the assumed heteroduplex **2·3**. All the side chains of monomers **2** and **3** are replaced with methyl groups for simplicity.

that the rigid **2** existed in a nearly planar conformation, while **3** adopted a twisted conformation in heteroduplex **2·3** similar to that in heteroduplex **1·3**. However, heteroduplex **2·3** was stabilized by six intermolecular hydrogen bonds, not the amidourea-based eight intermolecular hydrogen bonding mode. The result also demonstrated that heteroduplex **2·3** was much less stable than heteroduplex **1·3**. Therefore, although monomer **1** and **2** possessed the same hydrogen-bonding sequence, monomer **3** could selectively assemble with **1** to form a stable heteroduplex based on the amidourea motif, but could hardly assemble with **2**, because of their unique structures and the spacing effect.

Assembling Selectivity. To further investigate the selective assembling behavior of amidourea derivatives **1**, **2** and **3**, the competitive ^{1}H NMR experiments were also performed. When adding 1 equiv of **2** to a 1:1 mixture of **1** and **3b** (each at 5 mM in $CDCl_3$), the NH protons of **2**, **1** and **3b** all showed very small chemical shift changes ($\Delta\delta \leq 0.10$ ppm), which indicated that the presence of **2** inflicted insignificant impact on the binding affinity of heteroduplex **1·3b** (Figure 9). On the other hand, adding 1 equiv of **1** to a 1:1 mixture of **2** and **3b** (each at 5 mM in $CDCl_3$) led to large downfield chemical shift changes for all the NH protons of **1** and NH^a, NH^b protons of **3b**, and an obvious upfield change for NH^c proton of **3b** but only very small chemical shift changes for all the NH protons of **2** (Figure 10), which demonstrated that **3b** could selectively assemble with **1** between **1** and **2**, thereby leading to the high association specificity of heteroduplex **1·3b**. Likewise, the competitive ^{1}H NMR experiments of **1**, **2** and **3a** exhibited the similar results.[13]

CONCLUSION

In conclusion, we have shown a new class of multiply hydrogen-bonded heteroduplexes from readily available amidourea derivatives and investigated their structures and selective assembling behaviors. Although amidourea derivatives **1** and **2** possessed the same hydrogen-bonding sequence, **3** could selectively assemble with **1** to form a stable heteroduplex via eight intermolecular bifurcated hydrogen bonds, but not assemble with **2** at all, because of their unique structures and the spacing effect. The high association stability and specificity will render the amidourea-based hydrogen-bonded heteroduplexes potentially applicable in the construction of well-defined supramolecular systems and the design of novel functional materials.

EXPERIMENTAL SECTION

Compounds **4** and **8b**[8b] were synthesized previously. Compounds **5**,[6e] **8a**,[7] and **9**[12] were prepared according to literature procedures.

Compound 1. Hexyl isocyanate (0.53 g, 4.2 mmol) was added to a solution of compound **4** (0.90 g, 2.0 mmol) in CH_2Cl_2 (20 mL). The mixture was stirred at room temperature for 5 h. Then the solvent was evaporated under reduced pressure. The residue was recrystallized from hot acetonitrile to give the product (1.3 g, 95%) as a white solid: mp 209–210 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.51 (s, 2H), 8.78 (s, 1H), 7.77 (s, 2H), 6.47 (s, 1H), 5.54 (s, 2H), 4.17 (t, J = 6.7 Hz, 4H), 3.28–3.16 (m, 4H), 2.04–1.88 (m, 4H), 1.53–1.21 (m, 36H), 0.94–

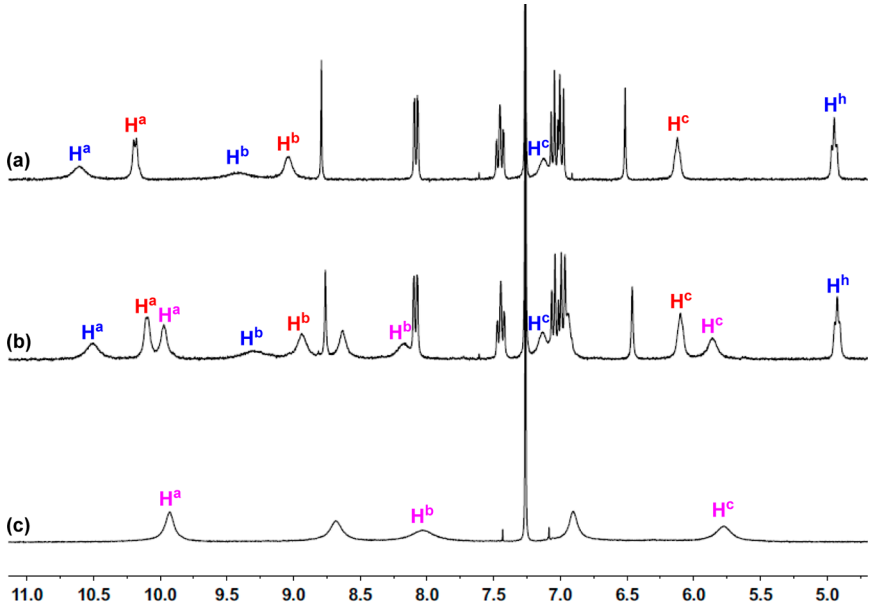

Figure 9. Stacked partial ^{1}H NMR spectra (300 MHz, 298 K) of (a) **1** (red) + **3b** (blue), (b) **1** + **3b** + **2**, (c) **2** (pink), each at 5 mM in $CDCl_3$.

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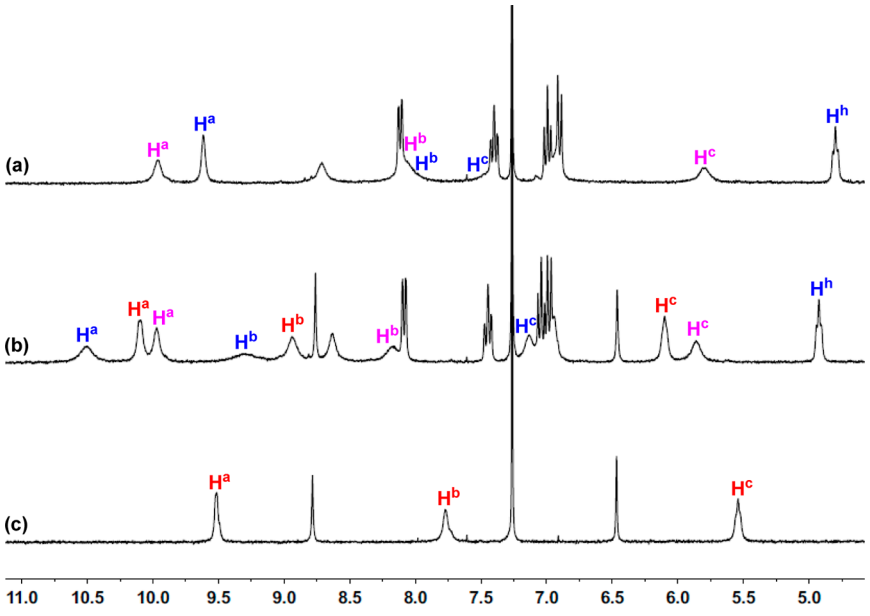

Figure 10. Stacked partial ^{1}H NMR spectra (300 MHz, 298 K) of (a) **2** (pink) + **3b** (blue), (b) **2** + **3b** + **1**, (c) **1** (red), each at 5 mM in $CDCl_3$.

0.79 (m, 12H); ^{1}H NMR (300 MHz, DMSO-d_6) δ 9.50 (d, J = 2.9 Hz, 2H), 8.30 (s, 1H), 8.10 (d, J = 2.9 Hz, 2H), 6.80 (s, 1H), 6.28 (t, J = 5.6 Hz, 2H), 4.24 (t, J = 6.3 Hz, 4H), 3.08−2.96 (m, 4H), 1.90−1.74 (m, 4H), 1.50−1.18 (m, 36H), 0.93−0.79 (m, 12H); APCI MS m/z 706.11 $[M + H]^+$. Anal. Calcd for $C_{38}H_{68}N_6O_6$: C 64.74, H 9.72, N 11.92. Found: C 64.52, H 9.65, N 12.04.

Compound 6. A mixture of compound **5** (2.5 g, 10.0 mmol) and concentrated sulfuric acid (5 mL) in methanol (100 mL) was refluxed under argon atmosphere for 24 h. After cooling to room temperature, the solution was poured into ice water (200 mL). The precipitate was filtered to give a yellow solid (2.6 g, 95%). A mixture of the above yellow solid (2.2 g, 8.0 mmol), 1-bromooctane (3.3 g, 16.8 mmol) and anhydrous K_2CO_3 (6.6 g, 48.0 mmol) in DMF (50 mL) was stirred for 24 h at 100 °C. After removal of K_2CO_3 by filtration, the solvent was evaporated under reduced pressure. The residue was dissolved in ethyl acetate and then was washed with dilute HCl and water. The organic phase was dried over anhydrous sodium sulfate. After removal of the solvent, the residue was purified by column chromatography (silica gel, ethyl acetate/petroleum ether 1:6 as eluent, v/v) to give the product (3.6 g, 90%) as a white solid: mp 56−57 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.27 (s, 2H), 7.03 (s, 2H), 4.10 (t, J = 6.5 Hz, 4H), 3.93 (s, 6H), 1.96−1.81 (m, 4H), 1.59−1.22 (m, 20H), 0.89 (t, J = 6.9 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.5, 157.4, 139.5, 133.9, 121.2, 120.2, 106.0, 68.8, 52.1, 31.8, 29.31, 29.27, 29.0, 26.0, 22.7, 14.1; ESI MS m/z 501.40 $[M + H]^+$. Anal. Calcd for $C_{30}H_{44}O_6$: C 71.97, H 8.86. Found: C 71.85, H 8.83.

Compound 7. To a solution of compound **6** (3.0 g, 6.0 mmol) in methanol (50 mL) was added hydrazine monohydrate (85%, 5 mL). The reaction mixture was then refluxed for 10 h. Upon cooling, a white solid precipitated from the solution. The product (2.9 g, 96%) was collected by filtration: mp 113−114 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.00 (s, 2H), 8.76 (s, 2H), 7.05 (s, 2H), 4.27−4.12 (m, 8H), 2.02−1.88 (m, 4H), 1.58−1.22 (m, 20H), 0.90 (t, J = 6.9 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.1, 156.1, 138.6, 135.1, 122.8, 119.8, 105.8, 69.3, 31.8, 29.25, 29.19, 29.0, 26.1, 22.6, 14.1; APCI MS m/z 501.76 $[M + H]^+$. Anal. Calcd for $C_{28}H_{44}N_4O_4$: C 67.17, H 8.86, N 11.19. Found: C 67.01, H 8.89, N 11.29.

Compound 2. Hexyl isocyanate (0.53 g, 4.2 mmol) was added to a solution of compound **7** (1.0 g, 2.0 mmol) in CH_2Cl_2 (20 mL). The mixture was stirred at room temperature for 5 h. Then the solvent was evaporated under reduced pressure. The residue was recrystallized from hot acetonitrile to give the product (1.4 g, 93%) as a white solid: mp 218−219 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.93 (s, 2H), 8.69 (s, 2H), 8.04 (br, 2H), 6.90 (s, 2H), 5.79 (br, 2H), 4.13 (s, 4H), 3.25 (s, 4H), 1.98 (s, 4H), 1.56−1.22 (m, 36H), 0.95−0.77 (m, 12H); ^{1}H NMR (300 MHz, DMSO-d_6) δ 9.77 (d, J = 2.5 Hz, 2H), 8.29 (s, 2H), 8.11 (d, J = 2.5 Hz, 2H), 7.43 (s, 2H), 6.26 (t, J = 5.6 Hz, 2H), 4.19 (t, J = 6.3 Hz, 4H), 3.12−2.98 (m, 4H), 1.91−1.76 (m, 4H), 1.53−1.20 (m, 36H), 0.94−0.81 (m, 12H); APCI MS m/z 756.17 $[M + H]^+$. Anal. Calcd for $C_{42}H_{70}N_6O_6$: C 66.81, H 9.34, N 11.13. Found: C 67.04, H 9.34, N 11.23.

General Procedure for Compounds 3a,b. A mixture of compound **8** (4.2 mmol) and methylene diisocyanate **9** (0.20 g, 2.0 mmol) in CH_2Cl_2 (20 mL) was stirred at room temperature for 5 h. Then the solvent was evaporated under reduced pressure. The residue was recrystallized from hot acetonitrile to give the product as a white solid.

Compound 3a. Yield: 91%; mp 108−109 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.53 (s, 2H), 8.10 (d, J = 7.2 Hz, 2H), 7.75 (br, 4H), 7.44−7.34 (m, 2H), 7.03−6.92 (m, 2H), 6.88 (d, J = 8.3 Hz, 2H), 4.81 (s, 2H), 4.09 (t, J = 6.9 Hz, 4H), 1.95−1.79 (m, 4H), 1.49−1.20 (m, 20H), 0.87 (t, J = 6.8 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.9, 159.0, 157.2, 133.2, 132.5, 120.9, 119.6, 112.2, 69.3, 45.9, 31.7, 29.2, 29.1, 28.9, 25.9, 22.6, 14.1; APCI MS m/z 627.95 $[M + H]^+$. Anal. Calcd for $C_{33}H_{50}N_6O_6$: C 63.24, H 8.04, N 13.41. Found: C 63.05, H 7.95, N 13.58.

Compound 3b. Yield: 90%; mp 185−186 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.55 (s, 2H), 8.11 (d, J = 7.4 Hz, 2H), 7.92 (br, 2H), 7.55 (br, 2H), 7.45−7.35 (m, 2H), 7.04−6.94 (m, 2H), 6.90 (d, J = 8.3 Hz, 2H), 4.80 (t, J = 6.1 Hz, 2H), 3.88 (d, J = 6.6 Hz, 4H), 2.30−2.12 (m, 2H), 1.05 (d, J = 6.7 Hz, 12H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 165.8, 158.9, 157.2, 133.3, 132.5, 121.0, 119.6, 112.2, 75.7, 46.0, 28.0, 19.4; APCI MS m/z 515.73 $[M + H]^+$. Anal. Calcd for $C_{25}H_{34}N_6O_6$: C 58.35, H 6.66, N 16.33. Found: C 58.22, H 6.61, N 16.45.

Theoretical Calculation. All the theoretical calculations were performed with density functional theory (DFT) at the B3LYP/6-31+G(d,p) level employing the Gaussian 09 software.[18] For all monomers and heteroduplexes, the geometries were completely optimized, which corresponded to the energy minimum. The total electronic energy of the hydrogen-bonded heteroduplex was the basis set superposition error (BSSE) corrected energy.[19]

Crystal Data for 3b. A single crystal of compound **3b** was obtained via slow evaporation from the mixed solvent of CH_2Cl_2/CH_3CN and then subjected to X-ray crystallographic analysis. The X-ray diffraction data were collected on a Rigaku Saturn X-ray diffractometer with graphite-monochromator Mo Kα radiation (λ = 0.71073 Å) at 173 K. Intensities were collected for absorption effects by using the multiscan technique SADABS. The structure was solved

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by direction methods and refined by a full matrix least-squares technique based on F^2, using SHELXL 97 program. All non-hydrogen atoms were refined anisotropically and H atoms were located from difference electron density maps. Crystal data: $C_{25}H_{34}N_6O_6$; M_r = 514.58; Triclinic; space group $P\bar{1}$; a = 8.2833(17) Å, b = 11.337(2) Å, c = 14.145(3) Å; α = 88.66(3)°; β = 84.99(3)°; γ = 80.94(3)°; V = 1306.6(5) Å^3; Z = 2; T = 173(2) K; 11890 reflections collected, 5928 unique; R_1 = 0.1392, wR_2 = 0.2236 [$I > 2\sigma(I)$]; R_1 = 0.2400, wR_2 = 0.2740 (all data).

■ ASSOCIATED CONTENT

Supporting Information

^{1}H NMR and ^{13}C NMR spectra of new compounds. Studies on the self-assemblies of $\mathbf{1}_n$, $\mathbf{2}_n$, heteroduplexes **1·3a** and **1·3b**. Conformational study of **3**. Competitive ^{1}H NMR experiments of **1**, **2** and **3a**. The X-ray crystallographic file (CIF) for **3b**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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