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Extra hydrogen bonding interactions by peripheral indole groups stabilize benzene-1,3,5-tricarboxamide helical assemblies

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Benzene-1,3,5-tricarboxamide monomers derived from alkyl esters of tryptophan (BTA Trp) self-assemble into helices with an inner threefold hydrogen bond network surrounded by a second network involving the indole N-H groups. As a consequence of this extra stabilization of its helical assemblies, BTA Trp forms more viscous solutions than a range of ester and alkyl BTAs.

The bottom-up assembly of small synthetic molecules provides an efficient strategy for the construction of artificial helices and their implementation in chirality-based applications.[1] In this context benzene-1,3,5-tricarboxamide (BTA)[2] molecules constitute an iconic class of monomers given their ability to predictably form helical assemblies with a preferred handedness, and their utility as asymmetric catalysts,[3] circularly-polarized light emitters[4] and chiral templates.[5] Stacks of BTA molecules in the form of a threefold hydrogen bonded helix connecting the amide units has been characterized in the crystalline state[6] in the liquid-crystalline state,[7] in gel[8] and in solution.[2a,9] An important challenge for imparting these supramolecular polymers with further functionality is to introduce functional groups in their side chains without destabilizing the helices. Comparatively to BTAs bearing alkyl chains (alkyl BTAs), a significant destabilization of the assemblies has been reported for BTAs endowed with short ethylene glycol chains[10] or derived from α-amino esters (ester BTAs).[11]

In the case of ester BTAs, the hydrogen bond competing nature of the ester group is reflected by the possible formation of a dimeric structure in which the N-H moieties are bound to the ester C=O, instead of amide C=O in the case of helical BTA stacks.[11c-e] Moreover, the nature of the substituent attached to the amino-ester α-carbon significantly influences the assembly properties of ester BTAs. Previous studies revealed that stereoelectronic[11d] and conformational effects[11e] can strongly shift the assembly of ester BTAs from dimers to stacks. Also, weak non-covalent interactions involving the side chains of the BTAs derived from L-phenylalanine[11a, 11c, 11e, 11f] or L-methionine[6e, 11c, 11e] help stabilize the helical assemblies in apolar solvents. Nevertheless, these helices are less stable, by at least one order of magnitude, than alkyl BTAs.[11e]

Much effort has been devoted towards the stabilization of α-helical peptides and mimetics[12] and of the collagen triple helix,[13] which can be achieved by chemical mutation of a particular amino-acid, amongst other possible strategies. Moreover, the helical conformation of synthetic covalent polymers such as poly(isocyanide)s[14] and poly(acetylene)s[15] can be stabilized by means of hydrogen bonding interactions involving the polymer side chains. Such a toolbox for the stabilization of artificial supramolecular helices by strong interactions between peripheral groups is currently lacking.[16] Taking into consideration the possible array of interactions involving the indole moiety,[17] we became interested in the self-assembly properties of BTA monomers derived from tryptophan alkyl esters (BTA Trp). We report herein that BTA Trp monomers, thanks to additional hydrogen bonding interactions provided by the indole groups, self-assemble into remarkably stable supramolecular helices in apolar solvents.

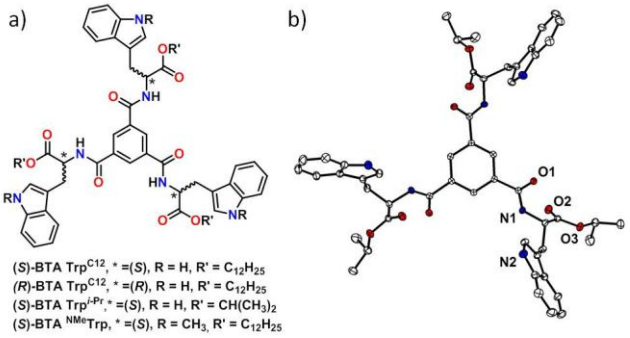


Chart 1 (a) Chemical structures of the BTA monomers investigated in this study. (b) ORTEP representation of an isolated molecule of **(*S*)-BTA Trp^{i-Pr}** together with heteroatom labels.

BTA Trp monomers (Chart 1) with dodecyl (**BTA Trp^{C12}**) or isopropyl (**BTA Trp^{i-Pr}**) ester chains have been prepared *via* conventional synthetic procedures and have been isolated in pure form according to ^{1}H NMR, ^{13}C NMR, High-Resolution Mass Spectrometry and Fourier-Transform Infrared (FT-IR) analyses (ESI†). Chiral HPLC analyses certify that both **(*S*)-BTA Trp^{C12}** and **(*S*)-BTA Trp^{i-Pr}** are enantiopure (*de*> 99%, *ee*> 99%). **(*S*)-BTA ^{NMe}Trp** has been synthesized from *N*-methyl (*S*)-tryptophan with the purpose of determining the influence of the indole N-H group on the self-assembly properties of BTA Trp monomers.

Crystals of **(*S*)-BTA Trp^{i-Pr}** have been obtained by cooling of a concentrated solution in CH_3CN. **(*S*)-BTA Trp^{i-Pr}** crystallizes in the hexagonal $P6_3$ space group, a view of the isolated molecule is shown in Chart 1.

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† Electronic Supplementary Information (ESI) available: Chart S1, general procedures, supplementary figures (Figs. S1-S9), Table S1, and synthetic procedures. See DOI: 10.1039/x0xx00000x

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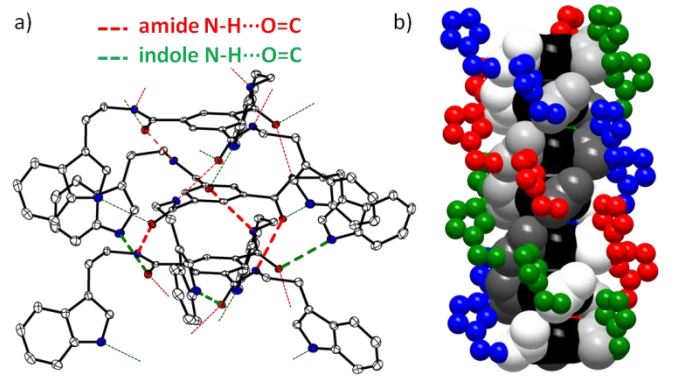


Fig. 1 X-ray structure of **(*S*)-BTA Trp$^{i\text{-Pr}}$**. (a) ORTEP representation of a trimer of **(*S*)-BTA Trp$^{i\text{-Pr}}$** with the two types of hydrogen bonds present in the helical polymer shown in green (indole/amide) and red (amide/amide). The ester side chains (CO_2*i*-Pr) and hydrogen atoms are omitted for clarity. The six hydrogen bonds connecting the lower monomer pair are shown with a thicker dotted line. Selected distances (Å): N1···O1: 2.89(1), N2···O1: 2.84(1). Selected angles (°): N1-H1A···O1: 162(1), N2-H2···O2: 139(1). (b) Diagram of a hexamer of **(*S*)-BTA Trp$^{i\text{-Pr}}$** highlighting the inner helical threefold hydrogen bond network (O, C, NH helical strands shown with different shades of grey, BTA ring in black) surrounded by the second helical network involving the indole moiety (CH, CH_2, N ring corresponding to different strands are shown in blue, red and green). The amide C=O are common to both hydrogen bond networks.

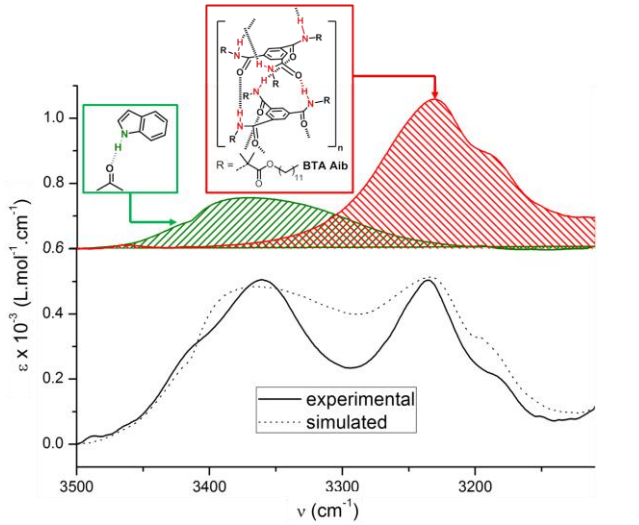


Fig. 2 FT-IR spectrum of **(*S*)-BTA Trp^{C12}** in MCH (10^{-2} mol.L^{-1}, 293 K), zoom on the N-H region (see the C=O region in Fig. S1b). The FT-IR spectra of the models (indole in acetone, 5×10^{-3} mol.L^{-1}, and **BTA Aib** in MCH, 10^{-2} mol.L^{-1}) are shown with an offset of 600 L.mol^{-1}.cm^{-1}. The simulated spectrum is obtained by addition of the FT-IR spectra of indole (×3) and of **BTA Aib**.

Examining the packing arrangement in the crystal shows that **(*S*)-BTA Trp$^{i\text{-Pr}}$** molecules stack upon each other and form supramolecular helices by means of a double hydrogen bond network: **(i)** an inner helical network involving the amide functions only (see the red dotted lines in Fig. 1a and the strands colored with different shades of grey in Fig. 1b) similar to the one observed in the crystalline structures of other alkyl and ester BTAs.[6] The distance (N1···O1: 2.89(1)Å) and angle (N1-H1A···O1: 162(1)°) related to hydrogen bonds, the aromatic-amide dihedral angle (40(1)°) and the distance between the central arenes (3.54(1) Å) match those found for BTAs reported in the literature (see compiled structural data in Table S1). The refinement of the Flack x parameter, equal to 0.00(17), ascertains the absolute configuration of the structure, *i.e.* **(*S*)-BTA Trp$^{i\text{-Pr}}$** assembles into right-handed helices which is in agreement with the handedness of helices found for other ester BTAs having (*S*)-configuration.[6d, 6e] **(ii)** an outer hydrogen bond network involving the indole N-H groups and the amide C=O (see the green dotted lines in Fig. 1a and the red, green and blue colored strands in Fig. 1b). The N···O distance (2.84(1) Å) is consistent with that found for indole N-H group of Trp residues involved in hydrogen bonding interactions in peptides and proteins.[17b] The NH···O angle of only 139(1)° is likely due to the bifurcated nature of the hydrogen bond since the acceptor, the amide C=O, is already engaged in the inner hydrogen bond network. The two threefold hydrogen bonded helices, which adopt opposite handedness, are emphasized in Fig. 1b. Importantly, the additional interaction provided by the amino ester side chain allows each consecutive monomer inside the stacks to be maintained by six hydrogen bonds (Fig. 1a), compared to three in previously reported BTA structures, thus potentially strengthening the overall assembly (*vide infra*).

A set of experiments has been carried out in order to probe whether this unusual type of helices with a double hydrogen bond network also exists in solution. **(*S*)-BTA Trp^{C12}** has been selected for the solution studies given its good solubility in apolar solvents. Firstly, the FT-IR spectra of **(*S*)-BTA Trp^{C12}** in methylcyclohexane (MCH) and in solid state have been compared to that of solid **(*S*)-BTA Trp$^{i\text{-Pr}}$**. The three FT-IR spectra exhibit the same bands in the N-H and C=O regions which suggests that **(*S*)-BTA Trp^{C12}** and **(*S*)-BTA Trp$^{i\text{-Pr}}$** form the same type of self-assemblies (Fig. S1). Then, the nature of these bands have been definitively established by using **BTA Aib**[11e] in MCH and indole in acetone as models of the inner and outer hydrogen bonding interactions, respectively, found in the structure of **(*S*)-BTA Trp$^{i\text{-Pr}}$**. Thus, the bands with absorption maxima at ν= 3361 cm^{-1} and ν= 3235 cm^{-1} correspond to indole N-H and amide N-H groups, respectively, both hydrogen bonded to amide C=O (Fig. 2). As a matter of comparison, free indole and amide N-H bands both exhibit maxima at *ca.* ν= 3440 cm^{-1} (Fig. S2a). The simulated FT-IR spectrum, obtained by combining those of the models, resembles the experimental one except that the indole N-H band is broader which is likely due to a less directional hydrogen bonding interaction for indole in acetone relatively to the same interaction taking place in the helical structure of **(*S*)-BTA Trp^{C12}**. The absorption maxima corresponding to ester band (ν= 1742 cm^{-1}, free) and amide I band (ν= 1633 cm^{-1}, bonded) are also consistent with **(*S*)-BTA Trp^{C12}** adopting a similar hydrogen bond network in solution than **(*S*)-BTA Trp$^{i\text{-Pr}}$** in the crystalline state (Fig. S2b).

The Small-Angle Neutron Scattering (SANS) analysis of **(*S*)-BTA Trp^{C12}** in C_7D_8 (4.4×10^{-3} mol.L^{-1}) shows a q^{-1} dependency of the scattered intensity at low q values which is characteristic of the presence of rigid one-dimensional objects (Fig. 3).‡ The data extracted from the fit indicate that these objects are very long cylinders (L>1000 Å, DP_w>275) with a radius of 12.9 Å which is close to the one of the isolated molecule in its fully extended conformation (17 Å).§ This analysis thus

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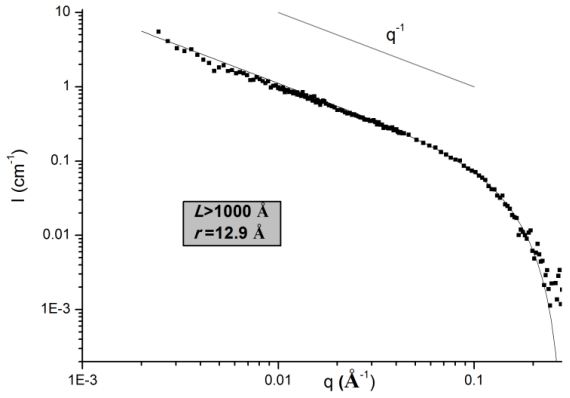


Fig. 3 SANS analysis (●) of **(*S*)-BTA Trp^{C12}** in C_7D_8 (5.61 g.cm^{-3}, 4.4×10^{-3} mol.L^{-1}, 293 K). The curve was fitted (—) according the form factor for rigid rods of infinite length with a circular cross section and a uniform scattering length density (*L* =length, *r* =radius).

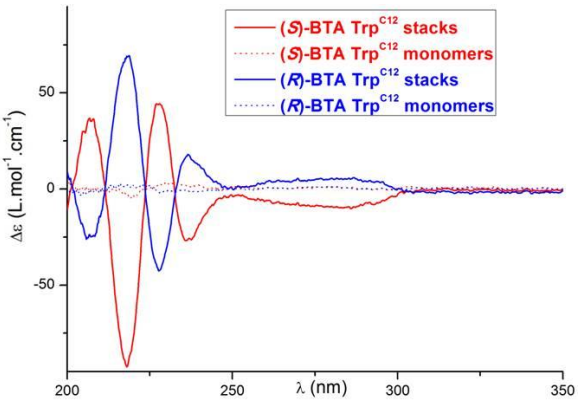


Fig. 4 CD spectra at 293 K of **(*S*)-BTA Trp^{C12}** (10^{-4} mol.L^{-1}, MCH, stacks), **(*S*)-BTA Trp^{C12}** (10^{-3} mol.L^{-1}, EtOH, monomers), **(*R*)-BTA Trp^{C12}** (10^{-4} mol.L^{-1}, MCH, stacks) and **(*R*)-BTA Trp^{C12}** (10^{-3} mol.L^{-1}, EtOH, monomers). For the corresponding UV-Vis absorption spectra see Fig. S4.

corroborates the presence in solution of supramolecular polymers with a single molecule of **(*S*)-BTA Trp^{C12}** in the cross-section.

The chiral nature of the polymers formed by self-assembly of **(*S*)-BTA Trp^{C12}** monomers was probed by Circular Dichroism (CD) spectroscopy (10^{-4} mol.L^{-1}, MCH, Fig. 4).[§§] In contrast to monomers, assemblies of **(*S*)-BTA Trp^{C12}** display a set of intense CD signals with a negative Cotton effect centered at *ca.* 280 nm and two successive bisignated CD signals (λ^-= 237 nm/λ^+= 227 nm and λ^-= 218 nm/λ^+= 207 nm). The well-structured and intense CD band at 280 nm is related to the longer wavelength absorption maxima of the indole unit. CD spectra of previously studied BTA assemblies usually display a single (broad) CD signal in the 200-250 nm region, as it is the case for the BTA derived from the dodecyl ester of L-Phenylalanine (see the overlaid spectra in Fig. S5).[11c] This corroborates that, in **(*S*)-BTA Trp^{C12}** assemblies, the indole side chains are located in a well-defined chiral environment. As expected, **(*S*)-BTA Trp^{C12}** and **(*R*)-BTA Trp^{C12}** feature mirror-image CD spectra reflecting the opposite handedness of their helical assemblies.

This full set of analyses (FT-IR, SANS and CD) demonstrates the ability of **(*S*)-BTA Trp^{C12}** monomers to assemble into long, one-dimensional helical stacks in solution similar to the ones reported for other BTA assemblies but with additional hydrogen bonding interactions involving the indole moieties of

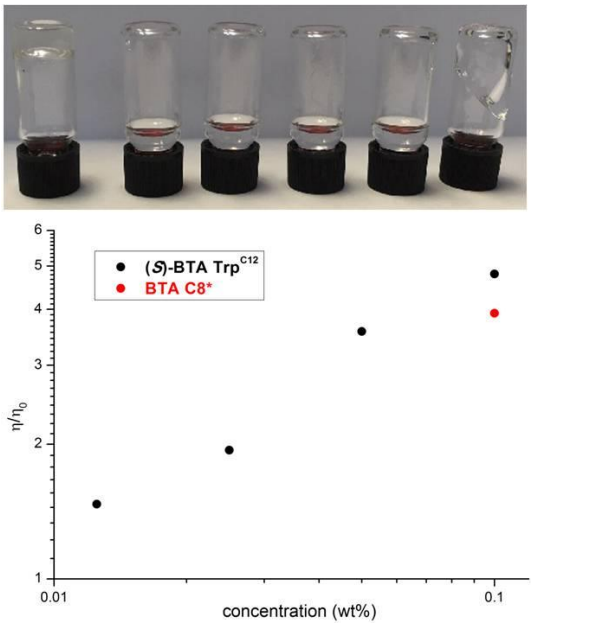


Fig. 5 Top: Pictures of 2×10^{-2} mol.L^{-1} toluene solutions of various ester and alkyl BTAs 2 minutes after inverting the vials. From left to right: **(*S*)-BTA Trp^{C12}**, **(*S*)-BTA ^{NMe}Trp**, **(*S*)-BTA Met**, **BTA Aib**, **BTA C8** and **BTA C8***. **(*S*)-BTA Met**: BTA derived from the dodecyl ester of L-methionine, **BTA C8**: BTA endowed with thee octyl side chains. **BTA C8***: BTA endowed with two octyl side chains and one (*S*)-1-methylheptyl side chain. See Chart S1 for the chemical structures of these BTAs. Bottom: Relative viscosity of **(*S*)-BTA Trp^{C12}** and **BTA C8*** solutions in toluene versus concentration (293 K).

the side chain. FT-IR (Fig. S6) and CD (Fig. S7) analyses in MCH indicate that at room temperature the helical assemblies are identical over several order of magnitudes of concentrations (2×10^{-2} mol.L^{-1}–2.0×10^{-6} mol.L^{-1}). Variable-temperature CD and UV-Vis analyses (Fig. S8) have then been performed to probe the thermal stability of the helical assemblies under very diluted conditions (2.0×10^{-6} mol.L^{-1}). The transition occurs between helical stacks (with a double hydrogen bond network) and monomers at a remarkably elevated temperature (≈ 360 K).[18] It infers that these assemblies are more stable, by at least one order of magnitude, than those formed by the other ester BTA assemblies[11e] and are at least as stable as alkyl BTAs investigated to date.[7b, 19] The importance of the extra hydrogen bonds in stabilizing the helical assemblies of **(*S*)-BTA Trp^{C12}** is further supported by the fact that **(*S*)-BTA ^{NMe}Trp**, which lacks the indole N-H group, does not form long assemblies in MCH (Fig. S9).

Finally, we have examined whether the high stability of these helical assemblies, explained at the molecular scale by the six hydrogen bonds connecting adjacent BTA monomers within the stacks, translated into an improved property at the macromolecular level. With this aim in mind, we have prepared 2×10^{-2} mol.L^{-1} toluene solutions of **(*S*)-BTA Trp^{C12}**, of **(*S*)-BTA ^{NMe}Trp** and of a set of ester BTAs and alkyl BTAs previously-found to form helical assemblies in solution. From all of these samples, only **(*S*)-BTA Trp^{C12}** forms a self-standing gel for more than 2 minutes after inverting the tube (Fig. 5 top). The solution of **(*S*)-BTA Trp^{C12}** is notably more viscous than that of **BTA C8***, an alkyl BTA with one optically pure 1-methylheptyl chain.[7b] The solution containing **(*S*)-BTA ^{NMe}Trp** is fluid as anticipated for the presence of short species only. The high viscosity of **(*S*)-BTA Trp^{C12}** was confirmed under more

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diluted conditions (7.9×10^{-4} mol.L^{-1}, Fig.5 bottom). The high viscosity of **(*S*)-BTA Trp^{C12}** means that the overlap concentration is below 0.1 wt%, which yields a lower estimate for degree of polymerization of the stacks: DPn>290 at a concentration of 0.1 wt%.[20]

In this study, we brought to light the ability of the peripheral indole N-H groups to stabilize helical BTA assemblies through hydrogen bonding interactions with the amide C=O. Without these additional interactions, the presence of ester C=O as a hydrogen bond acceptor would actually have destabilized the formation of supramolecular polymers under the same conditions. As a consequence of this extra stabilization, helical assemblies of BTA Trp are very long and remain stable at low concentrations and high temperatures. In BTA Trp, the supramolecular chirality is expressed at two levels, the inner and outer hydrogen bond networks, and this may offer the opportunity to amplify the chirality to a greater extent compared to classical BTAs. Studies towards this goal are underway in our laboratory as well as the implementation of these assemblies as scaffolds for asymmetric catalysis.

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Conflicts of interest

There are no conflicts to declare.

Notes and references

‡ **(*S*)-BTA Trp^{C12}** adopts a similar supramolecular structure in toluene and MCH as indicated by the virtually identical FT-IR spectra obtained in these solvents (Fig. S3).

§ As obtained by geometry optimization using molecular mechanic method (MM3) with the software Scigress (Fujitsu).

§§ **(*S*)-BTA Trp^{C12}** is fully assembled down to 2.0×10^{-6} mol.L^{-1} at 293 K in MCH as demonstrated by FT-IR and CD analyses performed at various concentrations (Figs. S6 and S7, respectively).

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