Supramolecular Chemistry

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Quadruple π Stack of Two Perylene Bisimide Tweezers: A Bimolecular Complex with Kinetic Stability**

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Self-assembly has become an attractive approach towards functional materials.[1–5] However, to match with covalent chemistry, self-assembly processes have to be developed from reversible thermodynamic regimes to systems of kinetic stability. Generally, the weak supramolecular interactions such as hydrogen-bonding[6] and π–π stacking[7,8] rarely provide sufficient binding strength to lock particular structures in a desired architecture. Accordingly, examples of kinetically stable supramolecular structures are given either for large but structurally less defined aggregates[9–11] or discrete self-assemblies that are attainable by using multiple intermolecular interactions[12–14] or stronger metal ion–ligand interactions,[15–18] the latter represent a borderline case between covalent and noncovalent chemistry. In our recent work on perylene bisimide (PBI) dyes,[19,20] we realized that PBI-PBI interactions are stronger than those of any other π–π stacking interactions reported for other π scaffolds, for example, hexabenzocoronenes, phthalocyanines, phenylacetylene macrocycles, and naphthalene bisimides.[21] Thus, we envisioned that the formation of discrete well-defined and kinetically persistent PBI aggregates might be feasible for self-assemblies of rather modest size.

In the past years, molecular tweezers[22,23] have been used to form thermodynamically stable assemblies by means of aromatic π–π interaction or hydrophobic effect.[24–30] However, to the best of our knowledge, kinetically stable tweezer assemblies are barely known and no molecular tweezers of PBI dyes have been reported to date. Herein, we present a novel tweezer-type PBI dyad with two PBI units attached at a diphenylacetylene (DPA) backbone which self-assembles into hitherto unprecedented kinetically stable dimer aggregates (Figure 1).

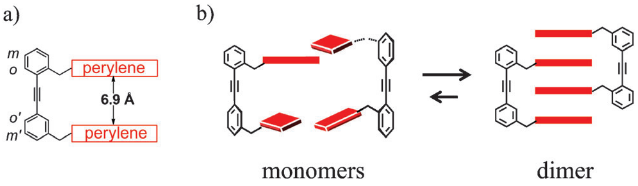
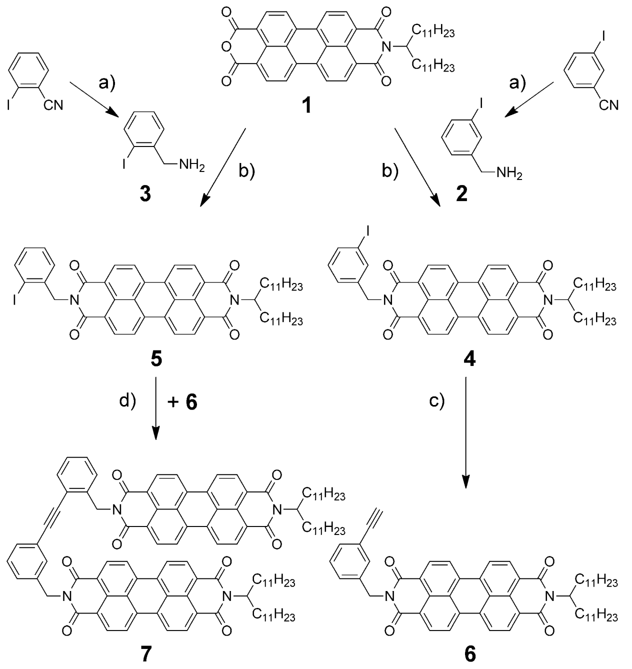


Figure 1. a) The designed PBI dyad building block and b) the self-assembly process of monomers into a dimer. Note that the dimer structure shown here is an idealized cartoon. For a force-field calculated dimer structure, see the Supporting Information (Figure S6).

The target tweezer-type PBI dyad **7** was synthesized according to the route outlined in Scheme 1 (for details see the Supporting Information). It contains long "swallow-tail" alkyl chains attached at the imide terminals of PBI units[31] to provide sufficient solubility in chlorinated solvents like $CHCl_3$ and CCl_4, and a methylene linking group between the PBI units and DPA backbone to ensure the proper orientation of PBI π systems, while being short enough to preserve rigidity and spacing constraints of a tweezer architecture.



Scheme 1. Synthesis of PBI dyad **7**: a) BH_3·THF, dry THF, 0 °C, 24 h, 58 % for **2** and 45 % for **3**. b) Imidazole, 140 °C, 4 h, 65 % for **4** and 61 % for **5**. c) Trimethylsilylacetylene (TMSA), $Pd(PPh_3)_2Cl_2$, CuI, CH_2Cl_2/NEt_3 (ν:ν = 3:1), 40 °C, 3 h; tetra-*n*-butylammonium fluoride (TBAF), THF, RT, 10 minutes, 89 % over two steps. d) $Pd(PPh_3)_2Cl_2$, CuI, THF/NH(*i*Pr)$_2$ (ν:ν = 5:1), 40 °C, 18 h, 57 %.

Because of unavoidable homo-coupling of PBI **6**,[32] it was not possible to isolate the pure PBI dyad **7** by conventional column chromatography. The material isolated after two successive chromatographic separations of crude product on a silica gel column with chloroform as an eluent still contained

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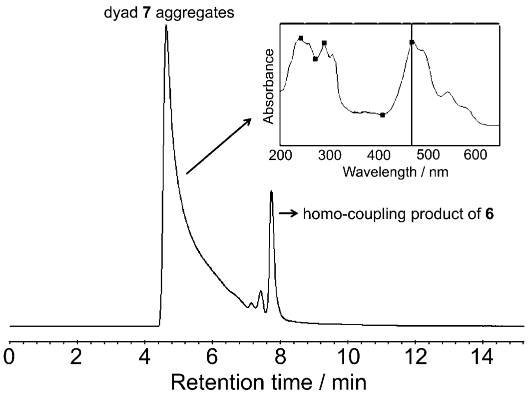

Figure 2. Semi-preparative HPLC separation of the reaction mixture containing PBI dyad **7** and homo-coupling byproduct. The stock solution was concentrated in chloroform and a solvent mixture of $CHCl_3$/MeOH (v:v = 100:1) was used as an eluent. The inset shows the in situ absorption spectrum of the first fraction.

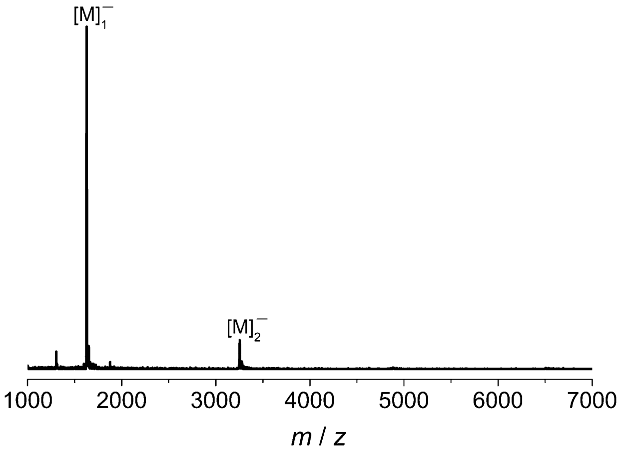

Figure 3. MALDI-TOF mass spectrum (linear mode) of PBI dyad **7**. The peaks corresponding to monomer and dimer species are marked with $[M]_1^-$ and $[M]_2^-$, respectively. 2-[(2*E*)-3-(4-*tert*-butylphenyl)-2-methylprop-2-enylidene]malononitrile (DCTB) was used as a matrix.

significant amounts (ca. 15%) of the homo-coupling byproduct of PBI **6**. Complete purification of dyad **7** could, however, be achieved by semi-preparative HPLC (Figure 2) at the highest flow rate of 9.9 mL min^{-1} from a concentrated stock solution of the product mixture in $CHCl_3$ obtained after column chromatography. The first fraction with a retention time of 4.5–6 minutes was collected and fully characterized as pure dyad **7** by ^1H and ^{13}C NMR spectroscopy (see Figures S1–S3 in the Supporting Information), MALDI-TOF mass spectrometry and elemental analysis.

It was noted that the freshly eluted solution of this fraction has a red color which gradually turned bright yellow. Such color changes of the solution are typical for a dissociation of PBI aggregates into PBI monomers.[33] Analytical HPLC studies with diode array detection corroborate that this fraction indeed possesses the characteristic absorption profile of dyad **7** aggregates (inset of Figure 2, see also Figure S4 in the Supporting Information). This finding indicates that under the applied HPLC conditions dyad **7** prevails in a kinetically trapped aggregated state, whilst the impurities exist as monomer or in dynamic equilibrium with respective aggregates. The long tail of the first HPLC fraction can, therefore, be attributed to the partial disassembly of dyad **7** aggregates while passing through the HPLC column. It is worth to mention that when a slower flow rate (less than 6 mL min^{-1}) and/or a diluted stock solution was used, the first fraction did not appear and dyad **7** was thus chromatographically inseparable from the homo-coupling byproduct.

The impressive finding that aggregates of PBI dyad **7** survive HPLC separation with eluent of 1 vol% MeOH in $CHCl_3$ is suggestive of strong and uniform aggregate formation of dyad **7**. On the account of high stability, mass spectrometry is a promising tool for assessing the aggregate composition of dyad **7**. Among different mass spectrometry techniques, matrix-assisted laser desorption/ionization (MALDI) is one of the relatively soft ionization methods that has been widely applied to monitor noncovalent self-assemblies and in particular π–π stacked species.[34–38] MALDI-TOF mass spectra were recorded from a sample of dyad **7** (10^{-4} M in CCl_4). As demonstrated in Figure 3, besides the first peak with an m/z value of 1627 confirming the molecular mass of dyad **7** molecule, there is an apparent signal at $m/z = 3254$ corresponding to the dimer of dyad **7**. It is noteworthy that no further peak at multiples of the $m/z = 1627$ parent ion value assignable to larger aggregates can be perceived, implying that dimer complexes are the only present aggregates of dyad **7** (which complies with the fact that a single aggregate species could be identified by analytical HPLC and separated by semi-preparative HPLC). For the same solution as used for MALDI-TOF studies, that is, a 10^{-4} M solution of dyad **7** in CCl_4, dynamic light-scattering (DLS) measurements were performed. The observed signal also corroborates the presence of very small assemblies with a diameter of less than 3 nm, which is in the range of the measurement limit of the light-scattering instrument (Figure S5).[39,40] Such a dimension clearly confirms the absence of large aggregate species of dyad **7** beyond dimers. Moreover, molecular modeling studies performed with MacroModel using MM3* force-field calculations support the viability of a dimer structure (for details see the Supporting Information and Figure S6).[41]

It is rather uncommon that π–π stacked dye aggregates can survive the HPLC separation and mass spectrometry measurements. This reflects that the noncovalently self-assembled dyad **7** dimer features a high degree of persistence comparable to the strength of a covalent bond. To quantitatively assess the activation parameters for the dissociation of dyad **7** dimer in solution, we designed kinetic experiments[42] to monitor the time-dependent absorption changes when a small amount of concentrated solution containing dyad **7** dimers was dispersed into a thousand times larger volume of pure chloroform (Figure 4). At a final concentration of 10^{-5} M, dyad **7** molecules have a strong thermodynamic driving force (ΔG) to be molecularly dissolved in the good solvating solvent $CHCl_3$, which is recognized from the, for PBI monomers characteristic, well-resolved vibronic progressions between 450 and 550 nm of the final absorption spectra at

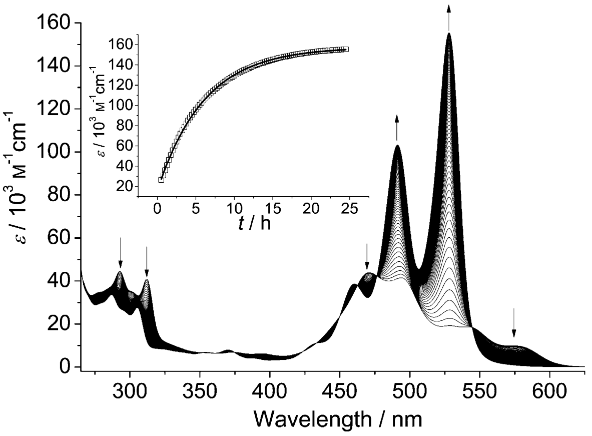

Figure 4. Recorded absorption spectral changes at time intervals of 15 minutes for 24 h when 3 μL of dyad **7** stock solution at 10^{-2} M in $CHCl_3$ was added into 3 mL of pure $CHCl_3$ solvent at 298 K. Arrows indicate the absorption changes with time. Inset: A plot of the absorbance at 521 nm versus time and the best fitting to a simple mono-exponential equation.

10^{-5} M concentration. Accompanied with the pronounced PBI absorption enhancement, the DPA backbone of dyad **7** shows a blue-shifted absorption with weaker intensity at around 300 nm. It can be interpreted in terms of DPA deplanarization synchronous to the PBI disaggregation process. This observation indicates the freeze of the DPA structure in dimers of dyad **7** in contrast to its free rotatability in the monomeric state.[43]

The absorption variations recorded in time intervals of 15 minutes (Figure 4) share several well-defined isosbestic points at 545, 477, 463, 450, and 266 nm, indicative of the disassembly process between only two explicit species, that is, the dimer and monomer of dyad **7**. Thus, the dimer dissociation process can be regarded as a first-order fragmentation reaction. If we assume that at time $t = 0$ h, the dimer concentration $c_{M_2}(0)$ is equal to a, and after a time interval of t hours, the dimer concentration $c_{M_2}(t)$ changes to $(a{-}x)$ and the monomer concentration will be accordingly $c_M(t) = 2x$, the following Equations (1) and (2) apply.

$$M_2 \xrightarrow{k_1} 2\,M \tag{1}$$

$$\begin{array}{lll} t = 0 & c_{M_2}(0) = a & c_M(0) = 0 \\ t = t & c_{M_2}(t) = a{-}x & c_M(t) = 2x \end{array} \tag{2}$$

Considering a dead time of $t^0 = t{-}t'$ between the ideal time t and recorded time t' and setting a constant value [Eq. (3)]

$$C = \left(\frac{\varepsilon_{M_2}}{2} - \varepsilon_M\right)\exp(-k_1 t^0) \tag{3}$$

we can obtain Equation (4),

$$\varepsilon(t') = \varepsilon_M + \left(\frac{\varepsilon_{M_2}}{2} - \varepsilon_M\right)\exp(-k_1 t^0)\exp(-k_1 t') = \varepsilon_M + C\exp(-k_1 t') \tag{4}$$

where ε_{M_2} and ε_M are the absorption coefficients of dimer and monomer, respectively (for detailed deduction of Equation (4) see the Supporting Information). Fitting the measured absorption coefficient $\varepsilon(t')$ values at 528 nm against the time t' provides exactly an exponential function, from which the rate constant k_1 can be acquired (inset of Figure 4). The measured $\varepsilon(t')$ values at different wavelengths fit very well into Equation (4) with a correlation coefficient better than 0.999 (see Table S1). From the fitting curves, reasonable ε_M and C values can be directly obtained. The ε_M values correspond well to the absorption of a molecule bearing two isolated PBI dyes[30] (≅monomer M), whereas the C values show the correct positive or negative signs with regard to the absorption relationship of $\varepsilon_{M_2}/2$ and ε_M at different wavelengths. More importantly, all the fittings generate quite similar k_1 values that were averaged to obtain a rate constant value of 0.16 h^{-1} for the dissociation process of dyad **7** dimer and a corresponding half time of $t_{1/2} = 4.31$ h.

At different temperatures from 298 to 323 K, the same kinetic experiments were repeated and thus a series of k_1 values could be acquired (Table S2 in Supporting Information). Based on these temperature-dependent k_1 values the activation parameters $\Delta H^{\ddagger} = 81.4 \pm 0.8$ kJ mol^{-1} and $\Delta S^{\ddagger} = -55.3 \pm 2.5$ J mol^{-1}K^{-1} can be obtained from the plot of $\ln(k_1/T)$ against $1/T$ by applying the Eyring Equation (5) (Figure 5).[42]

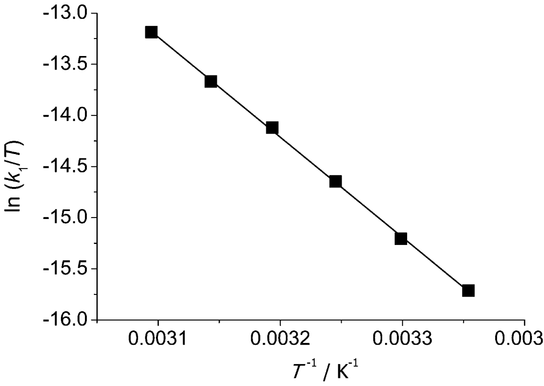

Figure 5. Eyring plot for the temperature dependence of the disassembly rate constant k_1 of the dyad **7** dimer in $CHCl_3$.

$$\ln\frac{k_1}{T} = -\frac{\Delta H^{\ddagger}}{R}\frac{1}{T} + \ln\frac{k_B}{h} + \frac{\Delta S^{\ddagger}}{R} \tag{5}$$

The Gibbs activation energy of disassembly $\Delta G^{\ddagger} = 97.9 \pm 0.8$ kJ mol^{-1} and disassembly activation energy $E_a = 83.8 \pm 0.8$ kJ mol^{-1} of dyad **7** dimer in chloroform at room temperature results according to the Equations (6) and (7), respectively.

$$\Delta G^{\ddagger} = \Delta H^{\ddagger} - T\Delta S^{\ddagger} \tag{6}$$

$$E_a = \Delta H^{\ddagger} + RT \tag{7}$$

For comparison, the activation energy E_a of quadruply hydrogen-bonded 2-ureido-4[1*H*]-pyrimidinone dimers in $CHCl_3$ is reported to be 70 ± 2 kJ mol^{-1}.[12] Dyad **7** dimer is stabilized by triple PBI π–π interaction and thus possesses a higher activation energy in the same solvent. Accordingly, the interlocked self-assembly of tweezer-type dyad **7** provides a method to produce kinetically stable π stacks, presumably resulting from the multiple cooperative π–π interactions, a concept analog to the multiple cooperative hydrogen bonds that has been applied for noncovalent synthesis of kinetically stable hydrogen-bonded complex assemblies.[12–14] This is indeed a quite remarkable result if we consider that chloroform and other halogenated solvents are the best ones for solvation of aromatic compounds and concomitantly lead to the smallest aggregation constants among the solvents applied, which has been experimentally verified for PBI dyes in our recent work.[19] Therefore, even larger activation energies are given for the disassembly of dyad **7** in other solvents[44] and accordingly the chosen diphenylacetylene tether scaffold should be suitable to form kinetically stable quadruple π stacks also for other dyes under proper experimental conditions (solvent, temperature). In our opinion, such self-assembled π stacks should be most adequate precursors for many applications ranging from artificial photosynthesis[45] up to organic electronics and photovoltaics,[46] where high supramolecular order is beneficial but has hitherto only been achieved by little defined processes such as thermal annealing or solvent-vapor treatment of the materials.

We have introduced discrete PBI quadruple π stacks by DPA backbone-supported dimerization of tweezer-type PBI dyad **7** and demonstrated for the first time that such small dye aggregates can exhibit high kinetic stability at ambient conditions. The activation energy of dissociation $E_a = 83.8 \pm 0.8\,\mathrm{kJ\,mol^{-1}}$ is even higher than that of quadruple hydrogen bonding,[12] which holds great promise for the construction of an entirely new generation of kinetically stable functional dye aggregates by appropriate backbone-controlled self-assembly. Such persistent supramolecular species are of considerable interest for the elucidation of functional properties of dye aggregates by sophisticated spectroscopic techniques such as single-molecule spectroscopy. They may also bridge the gap to natural photosystems (which can be likewise considered as kinetically trapped assemblies) and hence open new avenues for the design of functional materials for organic electronics and photovoltaics.

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