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Metal ion templated self-assembly of crown ether functionalized perylene bisimide dyes†

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Two new perylene bisimide (PBI) derivatives possessing crown ether receptors at the 1,7 bay-positions and solubilizing ionic imide substituents were synthesized and their self-assembly properties in the presence of different metal ions were studied, revealing highly selective barium ion templated self-assembly of 15-crown-5 functionalized PBI into H-type dimer aggregates.

Metal ion templated self-assembly of heterocyclic π-systems is of importance in nature as demonstrated, for instance, by the potassium ion dependent formation of G-quartets in the telomeric sequences of nucleic acids.[1] Synthetic efforts to utilize metal ions for the control of self-assembly processes of π-systems have been made as well and most often relied on the binding of metal ions to crown ether functionalized dyes. Among the outstanding examples are the formation of helical nanofibers of crown ether functionalized phthalocyanines,[2] the formation of hexagonal columnar liquid crystalline phases of crown ether functionalized tapered dendrons,[3] and the formation of fluorescent dye aggregates of crown ether functionalized naphthalene bisimides[4] upon addition of suitable metal ions. However, the metal ion templated self-assembly of crown ether functionalized perylene bisimide (PBI) dyes[5] has been barely investigated despite the widespread interest for this class of outstanding fluorophores[6] in supramolecular architectures[7] and organic semiconductors.[8] The most relevant article in this regard has been published only very recently by Müllen and co-workers, describing a crown ether bearing dibenzocoronene bisimide, the latter can formally be considered as a core-extended perylene bisimide. This molecule was shown to bind Pb^{2+} or K^+ ion to form the respective 1:2 (ligand/metal ion) complexes in solution[9] which leads, however, to the dissociation of the π-stacks. Nevertheless, despite the destabilization of the π-stacks by metal ions in this example, both metal free and metal containing thermotropic mesophases could be observed for the bulk materials.[9] Here we show the opposite case, i.e. that the metal ion templating approach can be utilized to self-assemble crown ether appended PBI dyes in solution into aggregates. The obtained aggregates are indeed particularly interesting because they are of exclusive dimeric size (Fig. 1). Creation of such small aggregates of distinctive size has been proven to be rather difficult[10] due to the isodesmic or even cooperative growth of PBI dyes into extended columnar stacks.[11,12]
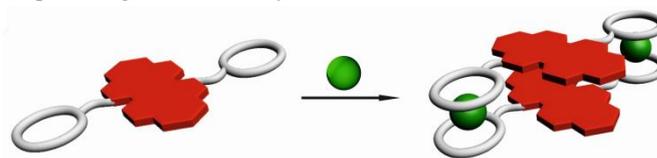

Fig. 1 Schematic illustration of metal ion templated formation of PBI dimers (red: PBI core, grey: crown ether, green: metal ion).

Because solubility issues are of particular significance for PBI dye self-assembly, we have decided to abjure the most obvious approach, i.e. attaching crown ether substituents at the imide positions,[5a] and instead to functionalize those positions with solubilizing ammonium ionic side chains[13] for polar solvents, whilst attaching the crown ether substituents at the 1,7 bay-positions as receptors. Based on the aforementioned design principles, we have conceived the PBI derivatives **1a** and **1b** and synthesized them starting from regioisomerically pure dibromoperylene bisanhydride **2**, the latter was prepared using literature procedures,[14] in three steps according to the route depicted in Scheme 1. The imidization of bisanhydride **2** with dimethylethylenediamine in a solvent mixture of DMF and dioxane afforded the corresponding perylene bisimide **3**. Subsequent nucleophilic substitution reaction of **3** with commercially available racemic 2-hydroxymethyl-15-crown-5 (**4a**) and 2-hydroxymethyl-18-crown-6 (**4b**) gave the respective PBI derivatives **5a** and **5b**. Finally, the methylation of **5a** and **5b** with iodomethane in toluene afforded the target crown ether functionalized ionic PBIs **1a** and **1b** in good to excellent yields. As racemates of the chiral crown ethers were applied, these PBIs contain stereoisomers that were not separated and used as synthesized for further investigations. The new bis-crown PBIs **1a** and **1b** as well as the precursors **3** and **5a/5b** were properly characterized by ^{1}H and ^{13}C NMR spectroscopy and high-resolution mass spectrometry (HRMS). For the detailed synthetic procedures and characterization data see ESI†.
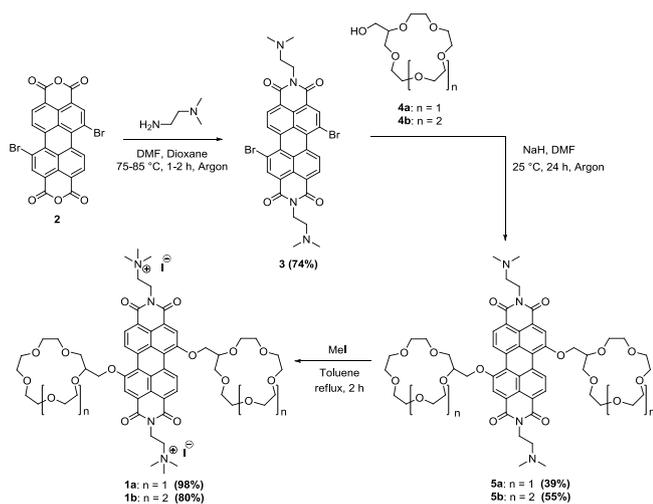
Scheme 1 Synthetic route to crown ether functionalized perylene bisimides **1a** and **1b**. DMF = dimethylformamide, THF = tetrahydrofuran.

We have studied the self-assembly properties of PBIs **1a** and **1b** by UV/Vis and fluorescence spectroscopy in acetonitrile in the presence of different alkali and alkaline earth metal ions. UV/Vis spectrum of PBI **1a** in acetonitrile ($c = 1.06$ x 10^{-5} M) in the absence of metal ions shows an absorption maximum at 566 nm with an extinction coefficient of $\varepsilon = 46600$ M^{-1} cm^{-1} (Fig. 2a, black line).
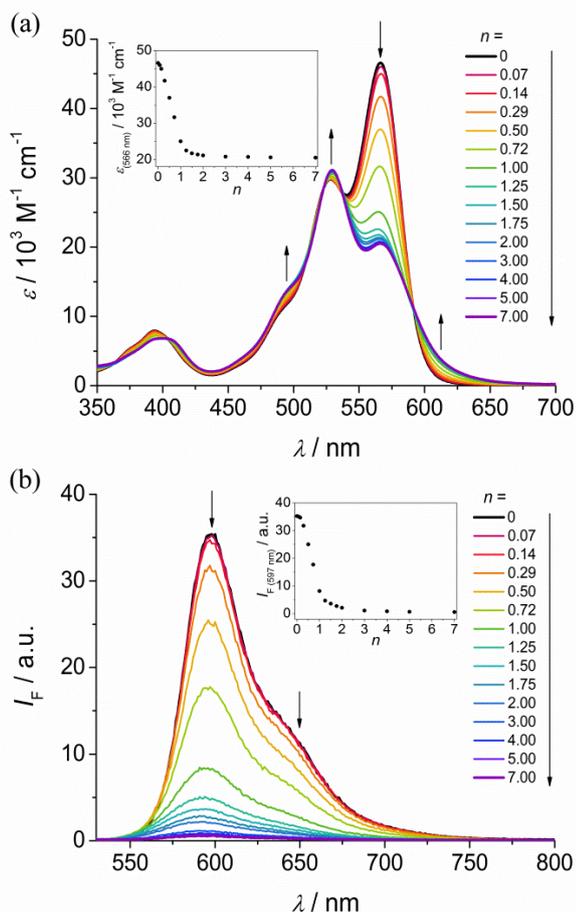
Fig. 2 (a) UV/Vis absorption and (b) emission ($\lambda_{ex} = 505$ nm) spectra of PBI **1a** in acetonitrile ($c = 1.06$ x 10^{-5} M) on addition of Ba(ClO$_4$)$_2$ in acetonitrile (0 – 7.48 x 10^{-5} M, 0 – 7 equiv). Insets: plot of (a) absorption at 566 nm and (b) fluorescence intensity at 597 nm against the molar ratio of Ba(ClO$_4$)$_2$/PBI **1a** (n).

This PBI derivative exhibits a fluorescence maximum at 598 nm (λ_{ex} = 505 nm) and a fluorescence quantum yield of $\Phi = 0.73$ in acetonitrile (Fig. 2b, black line). Upon addition of increasing amounts of Ba(ClO$_4$)$_2$ (in acetonitrile, 0 – 7 equiv) the absorption maximum of PBI **1a** at 566 nm decreased gradually with a concomitant blue-shift of about 36 nm and signal broadening. These are characteristic spectral signatures for the formation of cofacially stacked PBI aggregates with H-type excitonic coupling.[15] The plot of extinction coefficient at 566 nm against the molar ratio of Ba^{2+}/PBI **1a** clearly shows that the extinction of PBI **1a** decreased strongly upon addition of up to 1 equivalent of Ba^{2+} ion, while further addition of this metal ion (up to 7 equiv) has no significant effect (Fig. 2a, inset). This is indicative of a 1:1 stoichiometry of PBI **1a** and Ba^{2+} ion in the formed H-type aggregates. Similar results are obtained by fluorescence titration of PBI **1a** with Ba^{2+} ion in acetonitrile. On addition of up to 1 equivalent of Ba^{2+} the fluorescence intensity (at 597 nm) decreased very strongly (Fig. 2b), which again suggests the formation of H-type aggregates with a 1:1 stoichiometry of the chromophore and metal ion.

We have also studied the self-assembly behaviour of PBI **1a** in the presence of other metal ions. Fluorescence titration experiments of **1a** were performed in acetonitrile at a concentration of 10^{-5} M with different cations (Na$^+$, K$^+$, Rb$^+$, Mg^{2+} and Ca^{2+}). In contrast to Ba^{2+}, these metal ions effect very little or no changes in the fluorescence spectra of PBI **1a** (Fig. 3).
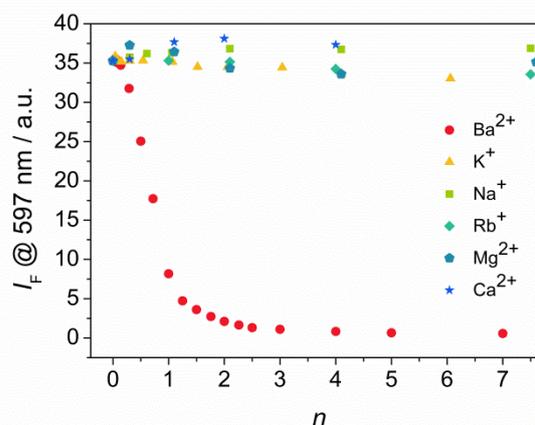
Fig. 3 Fluorescence titration plots of PBI **1a** in acetonitrile ($c = 1.01$ x 10^{-5} M) with Ba^{2+}, K$^+$, Na$^+$, Rb$^+$, Mg^{2+} and Ca^{2+}.

These results underline high selectivity of Ba^{2+} to template the self-assembly of PBI **1a** equipped with 15-crown-5 receptor. The reluctance of Na$^+$, Rb$^+$, Mg^{2+} and Ca^{2+} ions to bind with the receptors in PBI **1a** could be explained in terms of their atomic radii.[16] However, despite similar atomic radii of K$^+$ and Ba^{2+} ions and the fact that both are known to form sandwich-like complexes with 15-crown-5 derivatives,[17] K$^+$ ion does not template the self-assembly of PBI **1a** as virtually no changes in emission spectra are observed with this cation in the given concentration range. This might be due to lower stability of PBI **1a**/K$^+$ complex caused by mono-cationic nature of potassium ion.

To explore whether the size of crown ether receptor has any influence on the templated self-assembly, 18-crown-6 functionalized PBI **1b** was studied by UV/Vis and fluorescence spectroscopy in acetonitrile in the presence of different metal ions. PBI **1b** ($c = 1.10$ x 10^{-6} M) in the absence of metal ions shows an absorption maximum at 566 nm and a fluorescence maximum at 595 nm (λ_{ex} = 520 nm) with a quantum yield of $\Phi = 0.82$. The addition of up to 7 equivalents of different metal ions (Na$^+$, K$^+$, Cs$^+$ and Ba^{2+}) to acetonitrile solutions of PBI **1b** ($c = 1.01$ x 10^{-5} M) does not lead to any

significant changes of absorption and emission spectra of this PBI derivative (Fig. S2-S5, ESI†). This clearly indicates that these metal ions do not exert any templating effect on the self-assembly of 18-crown-6 functionalized PBI **1b**, and hence the size of the receptors plays a prominent role in metal ion templated self-assembly of PBIs. To gain more information on the binding process of Ba^{2+} ion to PBI **1a** the changes in absorption are plotted against the concentration of Ba^{2+} ions (data are taken from Fig. 2a). This plot reveals a sigmoidal shape (Fig. 4), which is generally regarded as a criterion for cooperativity.[18] The data can be fitted very satisfactorily to the Hill equation[19], yielding a Hill coefficient of $n_H = 2.8$ and a binding constant of $K_1 = 1.51 \times 10^5 \pm 4.23 \times 10^3 \ M^{-1}$ (for details see ESI†). A Hill coefficient larger than 1 indicates a positive cooperative binding process.[19,20] This implies that the second Ba^{2+} binding event is supported by the first one for bis-crown ether functionalized PBI **1a**. In such a situation only two species are present in significant amounts during the whole titration experiments: Non-complexed PBI **1a** and the [2+2] complex. The Hill coefficient has also been described as an "interaction coefficient" reflecting the extent of cooperativity, where the maximum value is equal to the number of binding sites.[18] A value of $n_H > 2$ rules out the formation of a [1+1] complex species. Therefore, the observed Hill coefficient of $n_H = 2.8$ suggests the formation of a [2+2] sandwich-type complex, in which each Ba^{2+} ion coordinates to two PBI **1a** molecules as depicted in Figure 1.
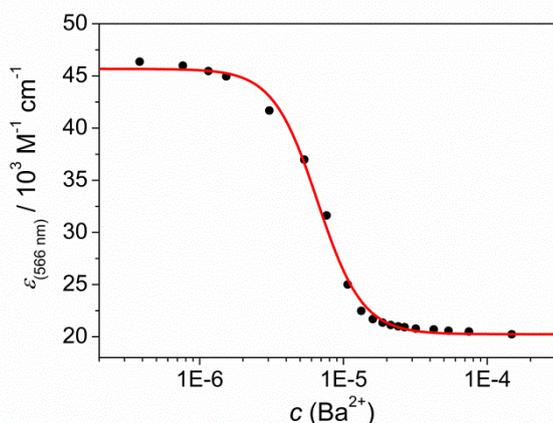

Fig. 4. Plot of ε (at 566 nm) of PBI **1a** versus concentration of Ba^{2+} and fit of the data points to the Hill equation. Black circles represent the experimental data obtained from UV/Vis spectra and the red line is the fitting curve.

To explore whether other oligomeric species are involved, additional titration experiments were performed at higher concentrations of PBI **1a** (10^{-4} M). Similar results, as obtained for low concentration of 1.06×10^{-5} M, were found for the titration profiles as well as for binding properties (Fig. S1, ESI†). Thus, the formation of larger oligomeric species can be excluded.

Our absorption and fluorescence titration studies have clearly revealed that Ba^{2+} selectively templates the self-assembly of 15-crown-5 functionalized PBI **1a**. To gain more insight into the Ba^{2+} templated self-assembly process, in particular to estimate the thermodynamic binding parameters, we performed isothermal titration calorimetry (ITC)[21] experiments. In these experiments, the release of heat upon injections of Ba^{2+} solution are recorded as a function of time (for details see ESI†). The corresponding binding isotherm obtained from the plot of heat of formation per mole of injected Ba^{2+} against the molar ratio of Ba^{2+} to receptor PBI **1a** provides information on the change of enthalpy (ΔH) upon binding and the stoichiometry (n) of Ba^{2+} and PBI **1a** in the formed complex (Fig. S6, ESI†). The ITC experiments revealed an exothermic self-

assembly process with an enthalpy (ΔH) in the range of -113 to -129 kJ/mol and a 1:1 stoichiometry of the formed complex (Fig. S6, ESI†). This stoichiometry is in perfect agreement with that obtained from absorption and fluorescence titration experiments (Fig. 2).

To gain some structural information of [2+2] dimer species of PBI **1a** and Ba^{2+}, we performed ^1H NMR titration experiments (for details see ESI†). ^1H NMR spectrum of PBI **1a** without Ba^{2+} displays sharp signals both for aliphatic and aromatic protons. Upon addition of Ba^{2+} ions (0 – 2.0 equiv) to a solution of PBI **1a** in deuterated acetonitrile ($c = 1.0 \times 10^{-4}$ M) the signals became significantly broader, which can be taken as an indication for the dynamic equilibria between complexed and non-complexed PBIs (Fig. S7, ESI†).[10,22] In the absence of Ba^{2+} ions three signals in the aromatic region (9.8 – 8.4 ppm) are observed for the six perylene core protons as expected for this symmetric molecule. Interestingly, at a 1:1 ratio we see the presence of two species which are non-complexed PBI **1a** and newly formed [2+2] complex. This result corroborates our conclusion from UV/Vis data analysis by the Hill equation, i.e. cooperative self-assembly of [2+2] complex. On addition of more than 1.0 equivalent of Ba^{2+} ions each of these aromatic signals is splitted in several nicely resolved signals with significant high-field shift (Fig. S8, ESI†). These changes in NMR spectra can be explained in terms of the formation of PBI **1a**/Ba^{2+} dimer complexes. On the one hand, in such dimers the perylene protons will experience aromatic shielding effect and thus shift to higher field. On the other hand, the interconversion of the atropoenantiomers (*P* and *M*) of this core substituted PBI will be restricted in these confined dimers which should lead to signal splitting of the perylene protons due to formation of *P,P* (or *M,M*) and *P,M* (or *M,P*) diastereomers.[23,24] Moreover, each of these diastereomers can have two different conformations (*syn*- and *anti*-conformer) in regard to the relative orientation of the crown ether units in two PBI molecules (Fig. S9, ESI†).[25] All these possible stereoisomers of dimeric PBI **1a**/Ba^{2+} complex coexist in the NMR time scale, and thus ultimately lead to the splitting of each of the three aromatic proton signals of monomeric PBI **1a** into several high-field shifted signals.[26] Thus, the results of NMR studies unambiguously confirm the formation of [2+2] dimer complex of PBI **1a** and Ba^{2+} ion.

In conclusion, we have synthesized hitherto unknown at bay position with crown ether receptor functionalized perylene bisimide dyes. Metal ion templated self-assembly of these novel PBIs has been shown to be dependent on the size of the crown ether receptor as well as on the nature of the metal ions. Thus, among different alkali and alkaline earth metal ions applied in this study only Ba^{2+} ion selectively templates the self-assembly of 15-crown-5 functionalized PBI **1a** into dimeric PBI/Ba^{2+} complexes through positive homotropic cooperative binding process. As the fluorescence of PBI **1a** is efficiently and selectively quenched by Ba^{2+}, this PBI dye can also be considered as a "turn-off" chemosensor for barium ions.

Notes and references

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26 It is to note that the stereoisomers of PBI **1a** due to the stereogenic center in crown ether units may also contribute to the complexity of the ^{1}H NMR spectra.

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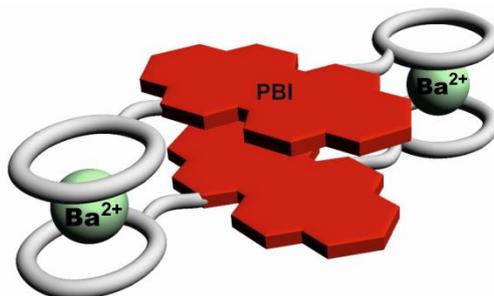
Barium ion (Ba^{2+}) templated self-assembly of perylene bisimide (PBI) functionalized with 15-crown-5 receptors leads selectively to dimer species.

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