

## RESEARCH ARTICLE

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## Room temperature synthesis of perylene diimides facilitated by high amic acid solubility†

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A novel protocol for the synthesis of perylene diimides (PDIs), by reacting perylene dianhydride (PDA) with aliphatic amines is reported. Full conversions were obtained at temperatures between 20 and 60 °C, using DBU as the base in DMF or DMSO. A “green” synthesis of PDIs, that runs at higher temperatures, was developed using K<sub>2</sub>CO<sub>3</sub> in DMSO. The reaction sequence for the imidization process, *via* perylene amic acid intermediates (PAAs), has been confirmed experimentally aided by the synthesis and full characterization of stable model amic acid salts and amic esters. Kinetic studies, using absorption spectroscopy, have established that PDI formation proceeds *via* fast amic acid formation, followed by a slow conversion to imides. Solubility of the intermediate PAA salts is found to be low and rate-limiting. Based on this finding, quantitative PDI synthesis at room temperature was achieved by diluting the reaction mixture with water, the solvent in which PAA salts have better solubility. Thus, the otherwise harsh synthesis of PDIs has been transformed into an extremely convenient functional group tolerant and highly efficient reaction that runs at room temperature.

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## Introduction

Perylene-3,4,9,10-tetracarboxylic acid derivatives (PTCAs) form a class of organic dyes and pigments, from which perylene-3,4,9,10-tetracarboxylic diimides (PDIs) are the most abundantly used representatives.<sup>1</sup> These compounds have very benign optical properties, which has resulted in large scale application of PDIs as dyes and pigments.<sup>2</sup> Moreover, PDIs are well-suited for utilization as functional materials, mostly in the optoelectronic domain.<sup>3</sup> Current research efforts are focussed on the use of PDIs as non-fullerene acceptors in photovoltaics,<sup>4</sup> light harvesting antenna molecules,<sup>5</sup> electrode materials in batteries,<sup>6</sup> fluorescent probes<sup>7</sup> and photocatalysts for the dehalogenation of aromatic compounds.<sup>8</sup>

Despite this long history and intense interest by scientists from a wide range of disciplines, the synthesis of PDIs is generally performed under harsh conditions, with limited functional group tolerance.<sup>9</sup> PDIs are routinely synthesised by the

“Langhals method”, reacting perylene-3,4,9,10-tetracarboxylic dianhydride (PDA) with primary amines in molten imidazole at 140–180 °C, using zinc acetate as a catalyst.<sup>10</sup> This method has been the gold standard for decades and has proven itself to be very reliable and universally applicable. Nevertheless, a milder, greener and more user-friendly synthesis would be desirable, in order to make more PDIs accessible to a larger scientific audience.

The harsh conditions in the “Langhals method” appear to originate from either the low reactivity of the amic acid intermediates, the low solubility of starting compounds and intermediates, or both. The more soluble bay-halogenated PDAs generally undergo imidization reactions at milder conditions, typically using organic acids as catalyst and (co)solvent,<sup>11</sup> while the imidization of 4-substituted naphthyl anhydrides proceeds at even milder conditions,<sup>12</sup> typically in refluxing ethanol. These observations suggest that solubility is the major driver for applying harsh reaction conditions in the current PDI syntheses.

Greener methods for PDI synthesis have been reported recently, notably a solvent-less method using a twin screw extruder<sup>13</sup> and a method in which water at high temperatures and elevated pressure is used.<sup>14</sup> Both methods work particularly well for aliphatic amines and are definitely green(er). Still these reactions require high temperatures, which limits functional group tolerance. Interestingly, when using water at milder temperatures, around 60 °C, PDIs are not formed in significant quantities. Instead, perylene-3,4-dicarboxylic acid

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†Electronic supplementary information (ESI) available: Extra figures, schemes and tables to support the main text. Procedure for kinetic measurements and modelling. Absorption and emission spectra and fluorescence quantum yields of all new compounds. <sup>1</sup>H and <sup>13</sup>C NMR spectra of all synthesized compounds. Mass spectra of all the new compounds. See DOI: 10.1039/d1qo01723c



monoanhydride-9,10-dicarboxylic acid monoimides (PMAMIs) are the major reaction products.<sup>15</sup> Most likely, anhydride ring opening by hydroxide ions,<sup>16</sup> resulting in the formation of adjacent dicarboxylates on the perylene scaffold is responsible for the observed PMAMI formation.<sup>17–19</sup> It should be mentioned nevertheless, that partial hydrolysis of PDA to perylene-3,4-dicarboxylic monoanhydride-9,10-dicarboxylates, followed by a selective imidization at the anhydride position is a highly beneficial reaction that has been exploited for efficient syntheses of aliphatic PMAMIs and *N*-desymmetrized PDIs.<sup>20</sup>

In contrast to imidization, esterification of PDA has been achieved at mild reaction conditions,<sup>21</sup> even at room temperature,<sup>22</sup> see Scheme 1. In the first step of this reaction an alcohol opens the anhydride in the presence of the strong base DBU. The perylene-3,9-dicarboxylic acid-4,10-dicarboxylic dialkyl esters **2** resulting from the first reaction step are highly soluble and subsequently react with an alkyl halide in a slower rate-determining step to produce perylene-3,4,9,10-tetracarboxylic tetra-alkyl esters (PTEs **3**) in almost quantitative yields. Interestingly, in a variation of this reaction, the synthesis of an imide at room temperature, postulated to proceed *via* an amic acid, has been reported. Although the reported synthetic procedure, exploiting a 3-day aminolysis reaction, may not be the most practical one, this finding suggests that PDI synthesis at mild reaction conditions is a realistic option.<sup>22</sup>

Additional information suggesting that PDI synthesis at low temperatures is feasible, comes from mechanistic studies on naphthalene-1,8-dicarboxylic amic acid (NMAA)<sup>23</sup> and naphthalene-1,3,4,8-tetracarboxylic diamic acid (NDAA).<sup>24</sup> NMAA has been synthesised by a reaction of naphthalene-1,8-dicarboxylic anhydride (NMA) with butyl amine at low temperatures.<sup>25</sup> At high pH values in water, NMAA forms the corresponding imide, naphthalene-1,8-dicarboxylic imide (NMI), while at low pH values the anhydride NMA is formed. These reactions are reversible and already proceeds at appreciable rates at temperatures as low as 30 °C. These studies suggest that formation of PDIs from PDA *via* corresponding amic acids may take place at low temperatures and high pH values, provided that a suitable polar solvent is identified. This may not

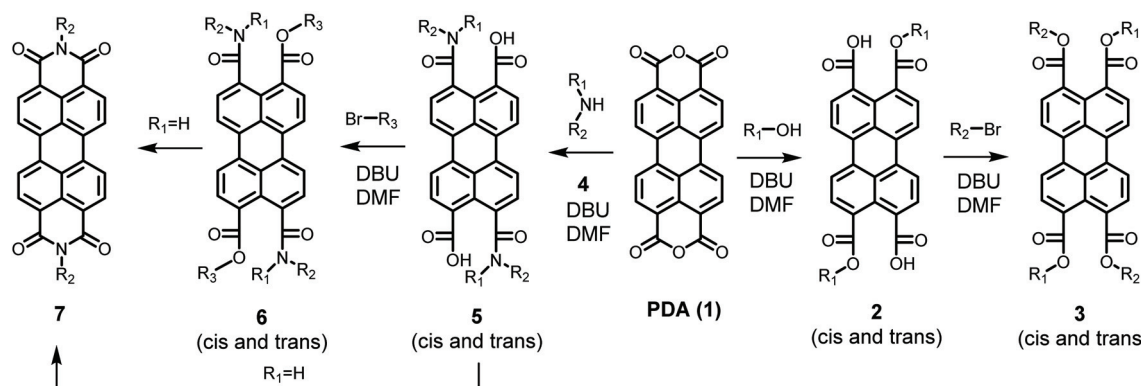
be a trivial event in the light of the low solubility of most PTCA derivatives. Also it should be mentioned that the chemistry of PTCAs may differ from those of the corresponding naphthalene derivatives in other aspects than solubility. For example perylene-3,4,9,10-tetracarboxylic acid chloride has never been prepared<sup>10b</sup> whereas the analogous naphthyl-1,8-di<sup>26</sup> and 1,3,4,8-tetracid chlorides<sup>27</sup> are readily available by conventional means.

In this work we report the synthesis of PDIs by reacting PDA with primary aliphatic amines at low temperatures, in a manner analogous to the synthesis of PTEs depicted in Scheme 1. Reaction conditions for the imidization of PDA under “standard” conditions, with DBU as the base in the solvent DMF, were optimized. In addition an entirely Green synthesis of PDIs, using DMSO and K<sub>2</sub>CO<sub>3</sub>, was developed. To identify the reactive intermediates formed during the imidization reaction, stable model amic acids have been synthesised by the reaction of PDA with secondary amines. The (photo) physical properties of these compounds were determined and their spectra were compared with those of the reaction intermediates to support the proposed mechanism of imide formation. A kinetic model of the imidization reactions has been constructed and tested by monitoring imidization reactions in real time. Based on the mechanistic insights obtained from these experiments the reaction conditions were optimized further to achieve quantitative imide formation at room temperature.

## Results and discussion

### General reaction and proposed reaction mechanism

When secondary amines were reacted with PDA **1**, using the synthetic protocol for the synthesis of PTEs, perylene-3,4,9,10-tetracarboxylic-diamic esters PDAE **6** were formed *via* perylene-3,4,9,10-tetracarboxylic-diamic acid PDAA **5**, see Scheme 1. Both compounds have been isolated and fully characterized, *vide infra*. When primary amines were employed, using the same procedure, however, PDIs **7** were obtained in appreciable yields. The fact that PDIs are formed is not surprising as such,



**Scheme 1** Room temperature synthesis of PTEs (**3**) PDAAEs (**5**), PDAEs (**6**) and PDIs (**7**).



since amic acids and amic esters are known to react further to form imides. The observation that this reaction takes place at room temperature already was surprising to us and clearly indicates that PDI synthesis can be performed at very mild conditions.

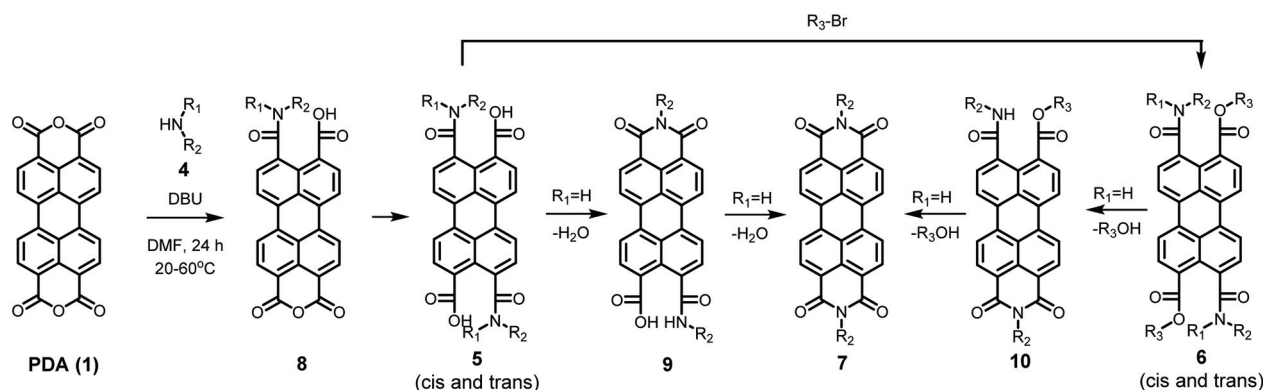
Next, it is worthwhile to establish whether alkylation of amic acids, *i.e.* amic ester formation, is a prerequisite for efficient imide formation. Reactions from amic esters to imides have been reported in the context of polyimide formation. This work, however, involved the synthesis of five-membered phthalimides and these imidization reaction have been performed by “brute force”. To the best of our knowledge, neither the temperature nor the solvent dependence of such reactions have been explored.<sup>28</sup> In another work the alkylation of a perylene-3,4-monoamic acid has been reported. This reaction resulted in a double alkylation at the carboxylate and the amide nitrogen,<sup>29</sup> but imide formation was not reported.

Whether the imide formation using our original procedure proceeds *via* the amic acid **5**, the amic ester **6**, or possibly both has been investigated by reacting **1** with 2-ethyl-hexyl amine **4b**, in the presence and in the absence of butyl bromide. For both reactions PDI **7b** was isolated, in yields of 60% and 25%, respectively, see Table 2 entries 3 and 4. This outcome demonstrated convincingly that addition of an alkylating reagent sig-

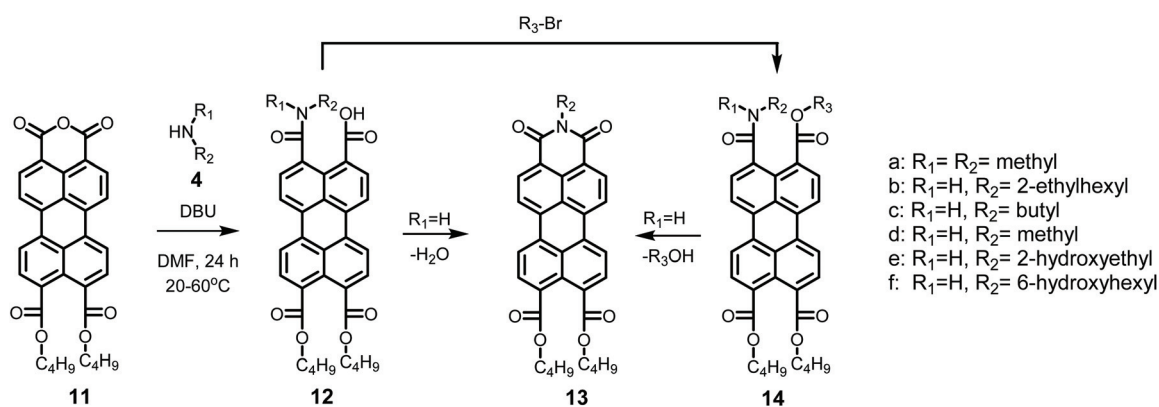
nificantly increased the yield of PDI **7b**, and thereby proofs that imidization *via* PDAE **6** is the faster route to form PDIs.<sup>30</sup>

Although significantly higher yields have been obtained by adding an alkylating reagent, we decided to further develop mild imidization reactions without the use of alkylating reagents. This choice has been made because alkylation requires an extra reaction step, uses a highly reactive alkylating reagent and thereby severely limits functional group tolerance. As for the reaction without an alkylating reagent, the imide formation itself already has a conversion around 50%,<sup>31</sup> and that is a good starting point for obtaining satisfactory yields after optimizing the reaction conditions. It should be noted that the use of alkylating reagents for highly unreactive systems, such as electron deficient or sterically hindered amines, is still a viable option.

The detailed reaction schemes for the imidization reactions, starting from PDA **1** or model compound perylene-3,4-dicarboxylic anhydride-9,10-dicarboxylic dibutyl ester PMADE **11**,<sup>32</sup> are depicted in Schemes 2 and 3. The imidization reaction of PMADE **11** is included in this work, because this reaction proceeds *via* a single amic acid intermediate compound **12**, and yields reaction products, perylene-3,4-dicarboxylic monoimide-9,10-dicarboxylic diesters (PMIDEs **13**), that are soluble in common organic solvents. The more complex imidi-



Scheme 2 Imidization reaction starting from PDA (**1**) including all anticipated intermediates.



Scheme 3 Imidization reaction starting from PMADE (**11**) including all anticipated intermediates.



zation of PDA (**1**) proceeds through four intermediates; compound **8**, *cis*- and *trans*-**5** and compound **9**. In addition, the resulting PDIs **7** generally are not soluble in organic solvents, which prevents easy identification of the reaction product(s).

### Synthesis and characterization of model amic acids

In order to validate the reaction mechanism depicted in Schemes 2 and 3, the potassium salts of the amic acids **12a**, **5a** and **9a** were synthesised and characterised. These compounds are model compounds for the intermediate amic acid salts in the imidization reaction. Potassium salts were synthesised, because these compounds are easier to isolate and characterise than the corresponding DBU salts. It has been reported that hydrolysis of structurally similar amic acids yield anhydrides under acidic conditions.<sup>23,29</sup> Under basic conditions amic acids derived from primary amines form imides, but this reaction is blocked for amic acids derived from secondary amines. Therefore amic acids salts **K12a**, **K<sub>2</sub>5a** and **K9a** are expected to be stable under basic conditions.

At room temperature the formation of the amic acid salt **K12a** from PMADE **11** proceeds within 60 minutes, as the pale reaction mixture, in which PMADE **11** is sparsely soluble, is converted to a bright orange solution. Isolation of compound **K12a** was achieved by precipitation, using water-free conditions, see entry 1, Table 3. Formation of the perylene monoamide triester **14a**, a thermally and hydrolytically stable compound, was accomplished by adding butylbromide to the reaction mixture. This reaction is highly efficient and without any purification efforts compound **14a** was isolated in 86% yield, see entry 2 in Table 3. Compounds **K12a** and **14a** were characterised by NMR, absorption and emission spectroscopy and mass spectrometry. These techniques provided solid proof of the molecular structure of these compounds, see ESI.† With the successful synthesis and characterization of compounds **K12a** and **14a** it has been proven that the amic acid **12** in an intermediate in the imidization of PMADE **11**, which strongly supports the validity of Scheme 3. Also, the synthesis and spectral characterization of **K12a** facilitates the identification of other perylene monoamic acid diesters salts of **12**.

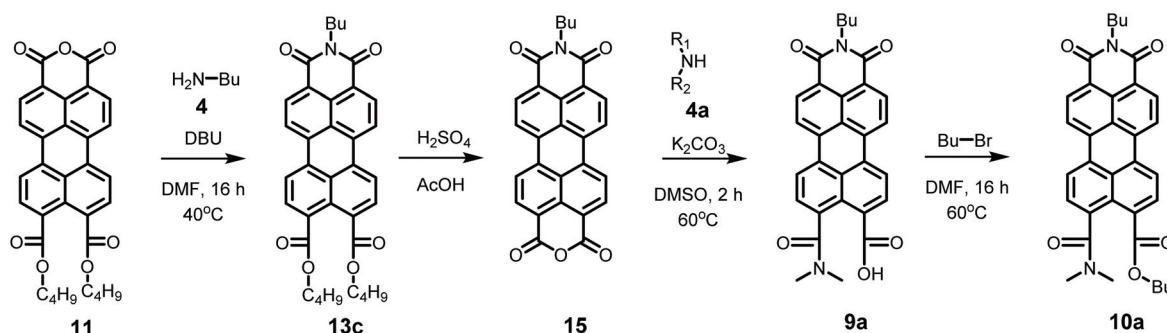
When PDA **1** is reacted with dimethylamine **4a** soluble amic acids are formed even faster. The initial reaction mixture, a red suspension, is transformed to a deep orange viscous liquid

within 20 minutes. Amic acid salt **K<sub>2</sub>5a** was isolated by precipitation in dry acetone, see entry 1, Table 2. The dibasic salt **K<sub>2</sub>5a** is soluble in polar solvents, including water, and exhibits an absorption spectrum that is very similar to that of PTE **3** and perylene-3,4,9,10-tetracarboxylate.<sup>16</sup> When butylbromide was added after formation of PDAA **5a**, PDAAE **6a** was obtained in 76% yield, virtually free of contaminants, see Table 2, entry 2 and Fig. S1 and S2† in the ESI.† The *cis* and *trans* regioisomers of compound **6a** were not distinguishable in the <sup>1</sup>H NMR spectrum. Broadening of the resonances of the aromatic protons is the sole indication of the presence of two isomers, a result that is in line with the <sup>1</sup>H NMR spectrum reported for a similar amic acid,<sup>33</sup> see Fig. S1.† The <sup>13</sup>C NMR spectrum, however, clearly revealed the formation of two isomers by the presence of two amide and two carboxylate carbons. Also the number of aromatic carbons atoms in the <sup>13</sup>C NMR spectrum exceeds the 10 expected for either the *cis* or the *trans* isomer, see Fig. S2.† The successful isolation of compounds **K<sub>2</sub>5a** and **6a** confirms that diamic acid salt of **5** is an intermediate in the imidization of PDA and supports the reaction mechanism in Scheme 2.

Model compounds **K9a** and **10a** were synthesized according to Scheme 4. This synthesis starts with the imidization of compound **11** using our mild imidization protocol and produced **13c** in almost quantitative yield. Cleavage of the ester functionalities in concentrated sulphuric acid gave compound **15** in high yield.<sup>34</sup> Ring opening, using dimethylamine **4a**, yielded model compound **K9a**, that was isolated *via* an anhydrous precipitation. The hydrolytically stable and highly soluble compound **10a** was obtained from **K9a *in situ*, by addition of bromobutane. The identity of compounds **10a** and **K9a** was unambiguously proven by NMR spectroscopy and mass spectrometry, see ESI.†**

To provide proof of the intermittency of compound **9** in the imidization reaction we have reacted compound **15** with butylamine under standard conditions (DBU, DMF) to form compound **9c** *in situ*, see Scheme S1.† The conversion of this compound to PDI **7c** was followed by absorption spectroscopy, *vide infra*, and this experiment has confirmed the intermediacy of compound **9c** in Scheme 2.

The absorption and emission spectra of the amic acid salts **K<sub>2</sub>5a**, **K9a**, **K12a** were recorded in water, DMF and ethanol, see Fig. S14 and S16,† while the spectra of the corresponding apolar model compounds **6a**, **10a** and **14a** were recorded in



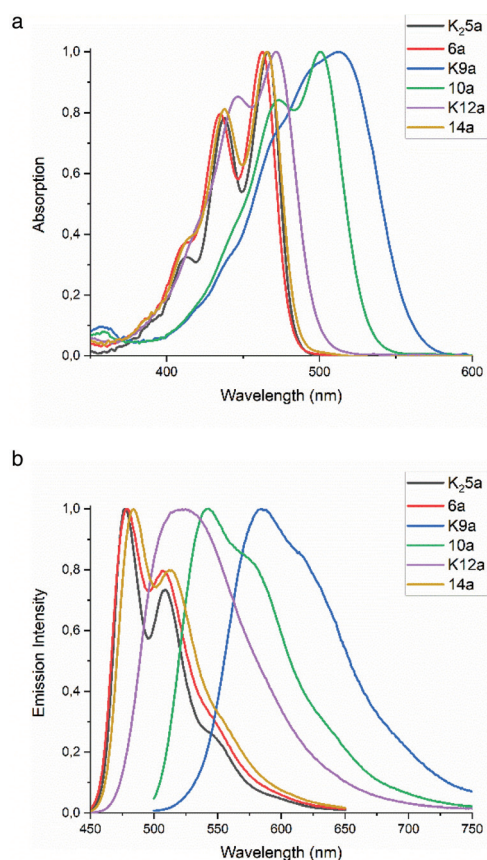
**Scheme 4** Synthesis of model compounds **K9a** and **10a**.





ethanol and chloroform, see Fig. S15.† The spectra of all compounds in the common solvent EtOH are presented in Fig. 1, while photo physical data are presented in Table S3.† The absorption spectra of compounds **3**, **13c** and **7c** in chloroform are depicted in Fig. S3.† The spectra in this Figure serve as a point of reference, for the spectra expected for molecularly dissolved perylene diamic acids, perylene monoamic acid monoi-mides and perylene diimides, respectively.

The absorption spectra in ethanol of diamic acid salt **K<sub>2</sub>5a**, diamic ester **6a** and the diester monoamic ester **14a** resemble that of tetraester **3**, with a clear vibronic structure and absorption maxima around 470 and 440 nm. Substitution of a butyl ester by a dimethyl amide (**3** to **14a**, **6a**) resulted in ~2 nm blue shifts per substitution, whereas substitution of an amic ester by an amic acid salt (**6a**, **14a** to **12a**, **5a**) resulted in ~3 nm red shifts per substitution. The absorption of the monoamic ester diester **10a** is 32 nm red shifted as compared to tetraester **3**, see also Fig. S3.† The absorption spectra of the amic acid salts **K12a** and **K9a** are red shifted and show a diminished vibrational structure, as compared to their amic ester analogues. Amic acids, obtained after protonation of their potassium salts, exhibit blue shifted absorption spectra, but are too unstable for full characterisation, see Fig. 8, S12 and S13.†



**Fig. 1** (a) Normalized UV-Vis absorption and (b) normalized fluorescence emission spectra of compounds **3**, **K<sub>2</sub>5a**, **6a**, **K9a**, **10a**, **K12a** and **14a** in ethanol.

The emission spectra of PTE **3** and compounds **6a**, **9a** and **14a** are very similar. In all cases the emission spectra are mirror images of the absorption spectra and fluorescence quantum yields  $\Phi_F$  are around 0.85. The emission spectra of the amic acid salts **K12a** and **K9a** show diminished vibrational structure and quantum yields  $\Phi_F$  of 0.96 and 0.65, respectively.

Since the amic acid salts of **5** and **9** are intermediates in the PDI synthesis, it is worthwhile to investigate the (photo) physical data of compounds **K<sub>2</sub>5a** and **K9a** in different solvents, see Table 1. Surprisingly, these amic acid salts have poor solubility in DMF, the solvent used for the imide formation, while solubility in water is much higher. Fluorescence quantum yields of compound **K<sub>2</sub>5a** are very high in water and ethanol, which indicates that this dianionic compound is molecularly dissolved. In DMF, however, the fluorescence quantum yield is a meagre 0.16. For compound **K9a** the structure-less absorption and emission spectra, as compared to those of compound **10a** and **13c**, may be indicative for aggregate formation. Fluorescence quantum yields are high in ethanol, but in DMF and water quantum yields of 0.14 and 0.19 reflect substantial quenching. Solutions of **K9a** in water form a strong foam layer after shaking, which indicates that this compound acts as a surfactant and presumably forms micelles. The corresponding DBU salts of **5a** and **9a** have not been isolated, but spectra from diluted reaction mixtures containing these DBU salts have been recorded. Absorption and emission spectra as well as fluorescence quantum yields taken from these reaction mixtures closely resemble those of the corresponding potassium salts.

To determine the relative rates of the reaction steps in the imidization process, we have reacted PDA **1** with butyl amine **4c** at room temperature and monitored the reaction by sampling the reaction mixture at regular intervals. Subsequently, these samples were diluted and analysed by absorption spectroscopy. Highly fluorescent yellow solutions were obtained after 20 minutes of reaction, both in water and chloroform, as seen in Fig. S4.† This result indicates that all PDA had reacted, and that all reaction products are soluble, both in water and chloroform. The absorption and emission spectra of the reaction product closely resembled those of diamic acid salt **K<sub>2</sub>5a**, indicating that the reaction product is the DBU salt of **5c**. Amic acid formation using  $K_2CO_3$  in DMSO, proceeded at a similar rate.

**Table 1** Spectral data of amic acid salts **K<sub>2</sub>5a** and **K9a** in different solvents

Compound	Solvent	$\lambda_{abs}$	$\lambda_{em}$	$\Phi_F$
<b>K<sub>2</sub>5a</b>	DMF	475, 443	487	0.16
<b>K<sub>2</sub>5a</b>	EtOH	466, 438	477.5, 509	0.93
<b>K<sub>2</sub>5a</b>	Water <sup>a</sup>	463, 435	475, 505	1.0
<b>K9a</b>	DMF	521	581	0.14
<b>K9a</b>	EtOH	513	584	0.65
<b>K9a</b>	Water <sup>a</sup>	505	591	0.19

<sup>a</sup> 0.01 M  $K_2CO_3$ .



Upon heating the reaction to 60 °C, the amount of diamic acid salt **5c** slowly decreased. It is anticipated that the DBU salt of **9c** is formed. However, this compound has not been identified in the absorption spectra. Poor solubility of compound **9c** in chloroform, the solvent used for dilution, along with the presence of considerable quantities of compounds **5c** and **7c**, may be the reason for this. The formation of PDI **7c**, however, is clearly visible when the imidization reaction is performed, see Fig. S4.<sup>†</sup><sup>35</sup>

In summary, these preliminary studies of the reaction of PDA **1** with butylamine **4c**, revealed a fast formation of diamic acid **5c** in 15–20 minutes at room temperature. At prolonged reaction times and elevated temperatures, typically a few hours at 60 °C, the concentration of diamic acid **5** decreased and monoamic acid monoimide **9c** was formed (but not detected). Subsequently the formation of PDI **7c** has been observed. It was concluded that the fast ring opening reactions, forming amic acid **5c**, and the subsequent slow imidization processes, forming intermediate **9c** and eventually the PDI **7c**, are decoupled processes that take place at markedly different time scales.

### Reaction optimization by variation of reaction conditions

After validation of Scheme 3 and the establishment of the relative rates of the reaction steps, the imidization reaction was optimized by changing the reaction parameters. The reaction of PDA **1** with 2-ethyl-hexyl amine **4b** was chosen for this purpose, because the product of this reaction, PDI **7b**, is highly soluble in chloroform and conveniently characterised by NMR spectroscopy. Isolation of the reaction product was extremely convenient; pouring the reaction mixture in water, filtering the precipitate and washing the product with dilute base to remove water-soluble amic acids, yielded pure PDI.<sup>36</sup>

Using the standard conditions (4 molar equivalents of amine and DBU and DMF as the solvent), increasing the reaction yields was achieved by increasing the temperature to 60 °C or the reaction time to 7 days, see entries 5 and S1<sup>†</sup> in Tables 2 and S1.<sup>†</sup> From a practical point of view the elevated temperature is preferred. In the original work by Langhals,<sup>10</sup> Zinc Acetate Zn(OAc)<sub>2</sub> was used to catalyse the reaction. In our experiments Zn(OAc)<sub>2</sub> leads to higher yields at room temperature, but addition of this compound no longer has a pronounced effect at elevated temperatures, see entries 2 and 3 in Table S1.<sup>†</sup> Therefore, and also because we want to keep the reactions clean and simple, we refrain from the addition of Zn(OAc)<sub>2</sub>. In summary, the optimized imidization proceeds at 60 °C, achieves quantitative yields and takes approximately 24 hours.

Our next objective is to convert the mild, convenient and efficient imidization reaction into a green(er) and more sustainable process.<sup>37</sup> This has been accomplished by substitution of the solvent DMF and the base DBU by greener alternatives. Substitution of toxic DMF by DMSO, a non-toxic solvent with similar physical properties, did not affect the reaction yields (entry 6, Table 2). With regard to the substitution of DBU by organic bases, it was observed that DBU is distinctly

the best base for this reaction, as was the case for the PTE formation as well.<sup>38</sup> Reaction with TEA or DIPEA, resulted in significantly lower yields, typically around 20–25% after 24 hours at 60 °C, entry S4, Table S1.<sup>†</sup> Since most organic bases have toxicity issues similar to those of DBU, substitution of DBU by organic bases was not explored further. Finally, the use of the non-toxic inorganic base K<sub>2</sub>CO<sub>3</sub> in combination with DMSO, was investigated. At 60 °C, significantly lower yield were observed than with DBU as a base, see entry S5, Table S1.<sup>†</sup> By raising the reaction temperature to 100 °C, however, the decreased reaction rate was fully compensated for and the reaction gave quantitative yields, see entry 7 in Table 2. This result demonstrates that an entirely green and sustainable process for the imidization of PDA has been developed. Apart from starting material PDA **1**, the amine **4b** and the reaction product PDI **7b**, all inherent to this reaction, the solvent and other reactant are non-toxic and environmentally benign.

Next, imidization reactions of PDA **1** were undertaken using the amines **4c–4f**. The PDIs obtained by these reactions bear small alkyl chains (**7c–7d**), or hydroxyalkyl chains (**7e–7f**) and only the PDIs **7c** and **7f** are sparsely soluble in chloroform.<sup>39</sup> With butylamine **4c**, the room temperature reaction was incomplete, but the yield of **7c**, (48%) was considerably higher than that of **7b** (25%). By increasing the reaction temperature to 60 °C, the reaction yielded **7c** in quantitative yield, both in DMF and DMSO. Using the green conditions, DMSO as a solvent and K<sub>2</sub>CO<sub>3</sub> as a base, quantitative yields were obtained at 100 °C, see entries 5–7 and S6 in Tables 2 and S1.<sup>†</sup> In order to make the DMSO/K<sub>2</sub>CO<sub>3</sub> reaction entirely green, the excess of amine was limited to 10%. After facilitating the amic acid formation, by stirring one hour at room temperature, the reaction mixture was heated to 100 °C and PDI **7c** was isolated in quantitative yield, see entry 8 Table 2. With this modification only minute amounts of unreacted amine are present in the final reaction mixture. This procedure of forming the amic acid at room temperature prior to imidization at higher temperatures, may also be extremely suited for working with volatile or expensive amines.

In the synthesis of **7d**, methylamine **4d** dissolved in methanol was used as a reactant. The room temperature reaction yielded **7d** in 89% yield. When the reaction was stirred at room temperature for 1 hour, to ensure amic acid formation and prevent evaporation of the amine, quantitative yields were obtained for the DBU reactions at 60 °C as well as the K<sub>2</sub>CO<sub>3</sub> reaction at 100 °C, see entries 5, 7 and S7 in Tables 2 and S1.<sup>†</sup><sup>19</sup> For the reaction with 6-amino-1-hexanol **4f**, the yield of the DMF/DBU reaction was 66% at room temperature. Quantitative yields are obtained by raising the temperature to 60 °C, while the K<sub>2</sub>CO<sub>3</sub> reaction gave quantitative yields at 100 °C, see entries 5, 7 and S8 in Tables 2 and S1.<sup>†</sup>

The imidization reaction with ethanolamine **4e** proceeded much faster and quantitative conversion at room temperature was achieved after 8 hours already. When this reaction was sampled and diluted in water, the resulting absorption spectra clearly showed that amic acid formation and imidization both take place at room temperature and that amic acid



**Table 2** Formation of PDIs **7** from the reaction of PDA **1** with different amines, using various reaction conditions

Entry	Perylene anhydride	Reagents	Base	Solvent	Reaction conditions	Yield, in %
1	PDA ( <b>1</b> ) 0.5 mmol	<b>4a</b> 2 mmol	K <sub>2</sub> CO <sub>3</sub> 2 mmol	DMSO 4 ml	24 h RT	<b>K<sub>2</sub>5a</b> 66%
2	PDA ( <b>1</b> ) 0.5 mmol	<b>4a</b> 2 mmol BuBr, 2 mmol	DBU 2 mmol	DMF 4 ml	24 h RT	<b>6a</b> 76%
3	PDA ( <b>1</b> ) 0.5 mmol	<b>4b</b> 2 mmol	DBU 2 mmol	DMF 4 ml	24 h RT	<b>7b</b> 25%
4	PDA ( <b>1</b> ) 0.5 mmol	<b>4b</b> 2 mmol BuBr, 4 mmol	DBU 2 mmol	DMF 4 ml	24 h RT	<b>7b</b> 60%
5	PDA ( <b>1</b> ) 0.5 mmol	<b>4b, 4c, 4d<sup>a</sup>, 4f</b> 2 mmol	DBU 2 mmol	DMF 4 ml	24 h 60 °C	<b>7b, 7c, 7d, 7f</b> >97%
6	PDA ( <b>1</b> ) 0.5 mmol	<b>4b, 4c</b> 2 mmol	DBU 2 mmol	DMSO 4 ml	24 h 60 °C	<b>4b, 4c</b> >97%
7	PDA ( <b>1</b> ) 0.5 mmol	<b>4b, 4c, 4d<sup>a</sup>, 4e<sup>b</sup>, 4f</b> 2 mmol	K <sub>2</sub> CO <sub>3</sub> 2 mmol	DMSO 4 ml	24 h 100 °C	<b>7b, 7c, 7d, 7e, 7f</b> >97%
8	PDA ( <b>1</b> ) 0.5 mmol	<b>4b, 4c</b> 1.1 mmol	K <sub>2</sub> CO <sub>3</sub> 2 mmol	DMSO 4 ml	24 h 100 °C	<b>7b</b> 93% <b>7c</b> >97%
9	PDA ( <b>1</b> ) 0.5 mmol	<b>4e</b> 2 mmol	DBU 2 mmol	DMF 4 ml	8 h RT	<b>7e</b> >97%
10	PDA ( <b>1</b> ) 0.5 mmol	<b>4b<sup>c</sup>, 4c, 4d, 4f</b> 2 mmol	DBU 2 mmol	DMSO 4 ml Water <sup>d</sup> , 4 ml	24 h RT	<b>7b, 7c, 7d</b> >97% <b>4f</b> 90%

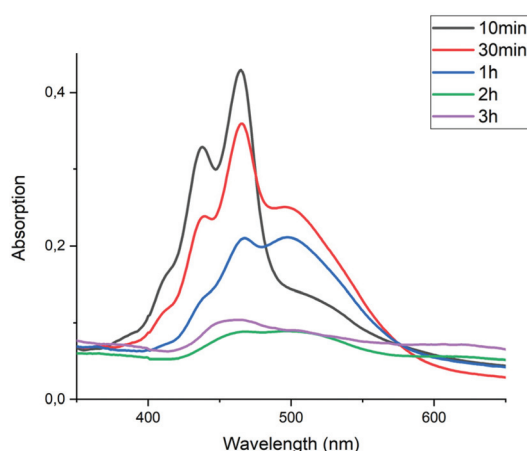
<sup>a</sup> First hour kept at room temperature. <sup>b</sup> At 80 °C. <sup>c</sup> 2 ml of water added. <sup>d</sup> Water was added to the reaction after half an hour.

formation and imidization are no longer decoupled. The initial rise in the concentration of amic acid **5e** is reversed within 20 minutes and a broad structure-less red-shifted absorption emerges, which closely resembles that of compound **9a**, see Fig. 2 and S16.† Also, a purple precipitate originating from PDI **7e** is formed upon diluting the reaction mixture in water early in the reaction. For the same reaction in DMSO, using K<sub>2</sub>CO<sub>3</sub> as the base, amic acid formation took

place within 20 minutes, but imidization was not observed at room temperature, see Fig. S6.† For this reaction quantitative yields were obtained at 80 °C, see entries 7 and 9, Table 2.

The mild imidization reaction with model compound PMADE **11** and the aliphatic amines **4b–4f** was also examined. Reactions were performed at room temperature and yields, after purification by column chromatography are displayed in Table 3. Purity and identity of compounds **13b–f** were conveniently proven by NMR spectroscopy. From the reported yields in Table 3 it is concluded that in all cases the reaction yields are well over 50% at room temperature, and that ethanolamine **4e** is the most reactive amine. These room temperature yields correlate well with those obtained for the bis-imides and may be indicative for the reactivity of the amines in the imidization of perylene anhydrides. By increasing the reaction temperatures to 40 °C, quantitative yields can be obtained overnight, as demonstrated with the synthesis of compound **13c**, *vide supra*.

In summary, the reactions of PDA **1** with all aliphatic amines are very convenient and quantitative yields are obtained with DBU in DMF or DMSO at 60 °C and with K<sub>2</sub>CO<sub>3</sub> in DMSO at 100 °C. Quantitative PDI formation resulted in a convenient workup in which the filtrate is transparent, virtually colourless and free from PTCA derivatives. These results indicate that these reaction conditions are universally applicable for aliphatic amines. For all reactions the ring opening by the amines is fast while the imidization from the amic acid intermediates is rate-determining. Therefore, differences in amine reactivity must be due to differences in rates of imidization of the respective amic acids.



**Fig. 2** UV-Vis spectra of the reaction of PDA (**1**) with ethanolamine (**4e**) in DMF using DBU as the base. Spectra were taken from samples of the reaction mixture diluted in water. The baseline is lifted due to the presence of insoluble PDA **1** and/or PDI **7e**. Absorptions do not accurately scale with concentrations in the reaction mixture due to sampling from a heterogeneous reaction mixture.



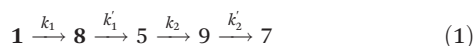
**Table 3** Reaction of amines **4a–4f** with PMADE **11**

Entry	Perylene anhydride	Reagents	Base	Solvent	Reaction conditions	Yield, in %
1	PMADE ( <b>11</b> ) 0.19 mmol	<b>4a</b> 0.38 mmol	K <sub>2</sub> CO <sub>3</sub> 0.38 mmol	DMSO 2 ml	24 h RT	<b>K12a</b> 61%
2	PMADE ( <b>11</b> ) 0.19 mmol	<b>4a</b> 0.38 mmol BuBr, 0.76 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>14a</b> 86%
3	PMADE ( <b>11</b> ) 0.19 mmol	<b>4b</b> 0.38 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>13b</b> 55%
4	PMADE ( <b>11</b> ) 0.19 mmol	<b>4c</b> 0.38 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>13c</b> 65%
5	PMADE ( <b>11</b> ) 0.19 mmol	<b>4d</b> 0.38 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>13d</b> 75%
6	PMADE ( <b>11</b> ) 0.19 mmol	<b>4e</b> 0.38 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>13e</b> 80%
7	PMADE ( <b>11</b> ) 0.19 mmol	<b>4f</b> 0.38 mmol	DBU 0.38 mmol	DMF 2 ml	24 h RT	<b>13f</b> 75%

### Reaction kinetics; modelling and measuring

Based on the reaction sequence for the imidization of PDA in Scheme 2, a kinetic model has been constructed. With this kinetic model the reaction mechanism can be validated and the rate constants for the different reaction steps determined. Furthermore, this model may also help to understand why our novel synthetic approach produces PDIs at room temperature already. In addition, factors that limit the rate of the imidization step, can be identified and potentially resolved to make the process even faster at mild and green conditions.

The imidization of PDA consists of 4 reaction steps, two consecutive second-order amic acid forming ring opening reactions, followed by two intramolecular consecutive first-order imidization reactions, see eqn (1). These consecutive reaction steps are identical by mechanism and their rate constants should have near-identical values, *i.e.*  $k_1 \approx k'_1$  and  $k_2 \approx k'_2$ . It should also be noted that the stable amic acids salts **K<sub>2</sub>5a** and **K9a**, have been synthesised and characterized, which facilitated easy identification of analogous amic acid intermediates.



Bimolecular ring opening reactions to form amic acids are fast, *vide supra*, and we have observed that these ring opening reactions are generally decoupled from the slower unimolecular imidization reactions. Therefore, both reactions, the amic acid formation from **1** to **5** and the imidization from **5** to **7**, will be described separately.

The first part of the reaction, from PDA to diamic acid **5**, is treated in detail in the ESI.† In deriving the kinetic equations, we assume that compound **1** is insoluble, whereas compound **8** will be somewhat soluble. Therefore, the conversion from PDA **1** to compound **8** is the rate-limiting step in this sequence. Accumulation of compound **8**, whose spectroscopic signature in molecular solutions is expected to be close to that of compound **9**, apart from a ~4 nm blue shift,<sup>20b</sup> is not anticipated. The rate of consumption of compound **1** and the rate of formation of compound **5** according to eqn (S3) and (S8),† are identical and depicted in Fig. S7.† Experimental data, shown

in Fig. S3 and S6,† do not resemble those in Fig. S7,† most likely because the data used for constructing Fig. S3 and S6,† were obtained from sampling inhomogeneous reaction mixtures.

Compounds **5** and **9**, participating in the second part of the reaction, are partly soluble in the reaction medium, as indicated by the deep red colour that is developed throughout the reaction. Eqn (2)–(4) describe the rates of the individual reaction steps.

$$\frac{d[5]}{dt} = -2k_2[5] \quad (2)$$

$$\frac{d[9]}{dt} = 2k_2[5] - k'_2[9] \quad (3)$$

$$\frac{d[7]}{dt} = k'_2[9] \quad (4)$$

Solutions for eqn (2)–(4) are given by eqn (5)–(7).<sup>40</sup>

$$[5] = [5]_0 \exp^{-2k_2 t} \quad (5)$$

$$[9] = \frac{2k_2[5]_0}{k'_2 - 2k_2} (\exp^{-2k_2 t} - \exp^{-k'_2 t}) \quad (6)$$

$$[7] = [5]_0 \left\{ 1 + \frac{1}{k'_2 - 2k_2} [k'_2 \exp^{-2k_2 t} - 2k_2 \exp^{-k'_2 t}] \right\} \quad (7)$$

The kinetic model for the imidization of PMADE **11** or PMAMI **15**, in which the same reaction rate constants  $k_1$  and  $k_2$  are employed, is described in the ESI (eqn (S9)–(S15)).†

A graphical representation of the composition of the reaction mixture, according to eqn (5)–(7), is given in Fig. 3. The decay of the diamic acid **5** follows first order kinetics, the amic acid monoimide **9** is an intermediate whose concentration builds up to nearly 50% and subsequently declines, while the formation of PDI **7** distinctly lags behind the disappearance of compound **5**. Experimental data, to support our kinetic model have not been obtained so far. Qualitatively the consumption of compound **5c** and formation of compound **7c** have been demonstrated but detection, let alone quantification of the amount of compound **9c** has not been achieved.





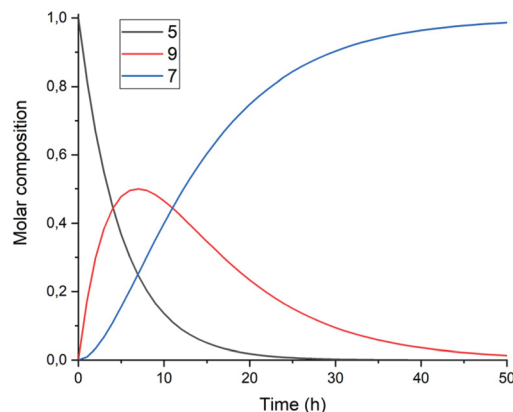


Fig. 3 Consumption of diamic acid **5**, formation and disappearance of reaction intermediate **9** and formation of PDI **7** according to eqn (5)–(7).

It should be noted that the amic acid salts of compounds **5** and especially **9** have limited solubility in DMF and DMSO and form aggregates and precipitates at the high concentrations used for the standard reactions. Thus solubility and possibly the type of aggregation of the amic acid salts of **5** and **9**,<sup>41</sup> will govern the rate of the imidization reaction. The solubility and aggregation behaviour of these salts depends on the reaction temperature, the solvent, the substituent  $R_2$  and the counter ions. Therefore, we anticipate that these are the major factors that determine rates of imide formation.

To test the hypothesis that solubility of amic acid salts limits the rate of imidization reaction, we decided to perform the second stage of this reaction in a highly diluted medium. The imidization reaction with butylamine **4c** at room temperature was conducted under standard conditions (DMF, DBU) for 30 minutes, until the formation of the diamic acid **5c** was completed. At this stage the reaction mixture was a thick orange slurry, a clear indication that the amic acid salts derived from compound **5c** did not fully dissolve. By strongly diluting the reaction mixture with DMF, reaching concentrations in the  $10^{-5}$  molar range,<sup>42</sup> the remainder of the reaction at room temperature was followed *in situ* by absorption spectroscopy, see Fig. 4.<sup>43</sup> While the normal reaction reaches 48% conversion in 24 hours, the diluted reaction reaches this conversion in approximately 6 hours and achieves a near-quantitative conversion in 24 hours. The diamic acid salt of **5c**, absorbing at 438 and 466 nm, is consumed swiftly, and a broad absorption (extending up to 600 nm), which closely resembles the absorption of model compound **K9a**, emerges. In time this broad absorption, which originates from the salt of compound **9c**, builds up and disappears, while eventually PDI **7c**, with distinct absorptions at 488 and 524 nm, is formed. At the end of the reaction a clear, brightly fluorescent solution that contains PDI **7c** is obtained. The good solubility of PDI **7c** in DMF is really surprising, although it is obvious that these solutions are oversaturated.<sup>44</sup>

In Fig. 5, the composition of the reaction mixture as a function of time is displayed. For determining the composition of

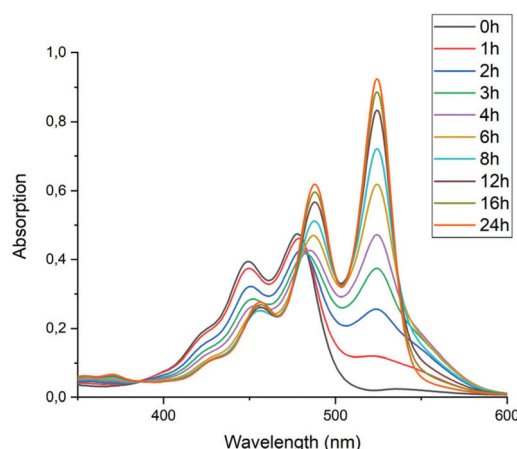


Fig. 4 Absorption spectra as a function of time of the reaction of the DBU salt of diamic acid **5c** in DMF at room temperature (20 °C) at concentrations around  $10^{-5}$  M.

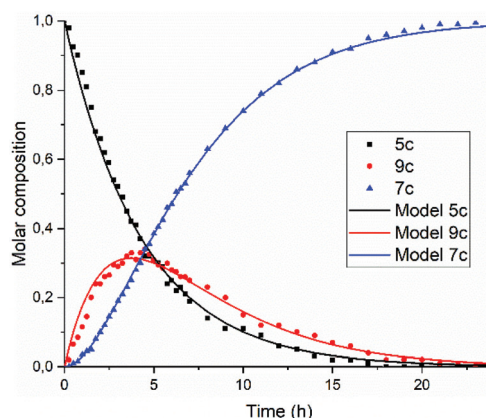


Fig. 5 Composition of the reaction mixture obtained from the data displayed in Fig. 5. Solid lines represent the fitting curves obtained using eqn (5)–(7). The solid squares, circles and triangles are concentrations of compounds **5c**, **9c** and **7c**, respectively obtained by analysing the absorption spectra.

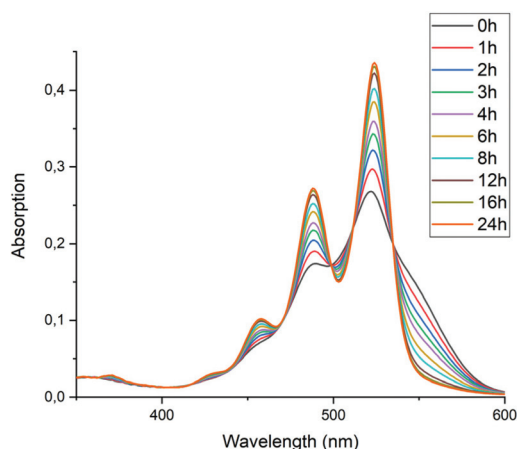
the reaction mixture, it was assumed that the spectrum taken at  $t = 0$  is that of the DBU salt of **5c** and that the spectrum taken after 24 hours is from **7c**. Relative concentrations of **5c** and **7c** were determined by manual fitting of the absorption spectra. The remaining absorption spectrum, obtained by subtracting the contributions from compounds **5c** and **7c**, is assigned to reaction intermediate **9c**. The fitting was done such that the absorption spectra of compound **9c** were consistent throughout the series, and closely resembled the spectra that we have previously obtained from compound **K9a**, see Fig. S14.† Using this procedure, determining the concentration of PDI **7c** is fairly consistent and reliable. However, for determining  $[5c]$  and  $[9c]$  independently this procedure is not suited.<sup>45</sup>

The experimental data in Fig. 5 resemble those predicted by our model depicted in Fig. 3, qualitatively; the monotonic

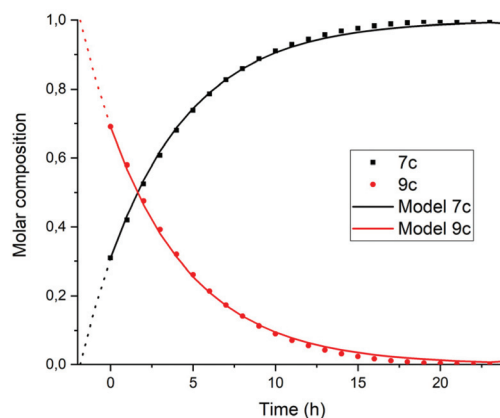


decrease of compound **5c**, the delayed formation of compound **7c** and the intermediate formation of compound **9c** are clearly visible. The curve fitting of the data in Fig. 5 was accomplished by using values for the rate constants  $k_2$  and  $k'_2$  of  $3 \times 10^{-5} \text{ s}^{-1}$  and  $8 \times 10^{-5} \text{ s}^{-1}$ , respectively. The blue curve for the formation of PDI **7** was constructed by taking identical values for  $k_2$  and  $k'_2$  of  $5 \times 10^{-5} \text{ s}^{-1}$ . We anticipate that these seemingly different values for the rate constants  $k_2$  and  $k'_2$  are artefacts that emerged because the concentrations of diamic acid **5c** and the monoamic acid **9c** could not be determined independently.

To find out if this assumption is correct, the rate constant  $k_2$  was determined independently by monitoring the reaction from compound **9c** to **7c**. To this end, monoanhydride **15** was reacted with butylamine **4c** under standard conditions for 30 minutes to form compound **9c** quantitatively, see Scheme S1.† After dilution with DMF, the conversion from intermediate **9c** to PDI **7c** by a first order process was monitored, see Fig. 6 and 7. In Fig. 6 three isosbestic points at 499, 512 and 535 nm are observed, which proofs that **9c** is converted to **7c** directly. The rate constant  $k'_2$  was determined to be  $5 \times 10^{-5} \text{ s}^{-1}$ , as demonstrated in Fig. 7. In addition this reaction rate constant was also determined from the reaction of monoamic acid diester **12c** to PMIDE **13c**, see Fig. S9 and S10.† The imidization rate constant for this reaction had the same value,  $5 \times 10^{-5} \text{ s}^{-1}$ . Combining these results it is obvious that the rate constants  $k_2/k'_2$  for the transformation of an amic acid to an imide on the perylene scaffold has a value of  $5 \times 10^{-5} \text{ s}^{-1}$  and is not significantly affected by the substituent(s) at the opposing *peri*-position(s). It is also concluded that kinetic measurements, starting from compound **5c** are not appropriate for determining  $k_2$  and  $k'_2$  independently. With the assumption that  $k_2 = k'_2$ , however, the reaction rate constant can be determined from such kinetic measurements. To investigate the stability of amic acids under acidic conditions,

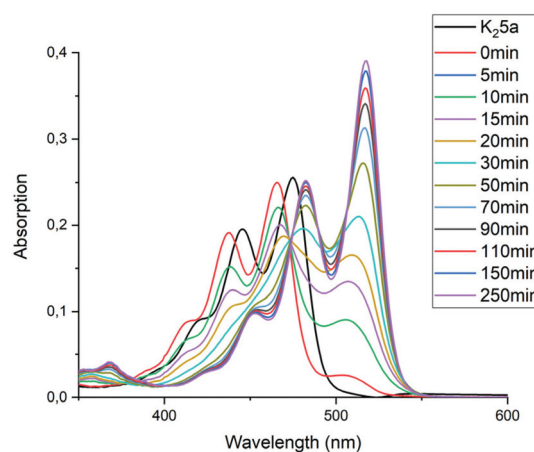


**Fig. 6** Absorption spectra as a function of time of the reaction of the DBU salt of amic acid monoimide **9c** in DMF at concentrations around  $5 \times 10^{-6} \text{ M}$ . The starting solution at  $t = 0$  already contains traces of the product **7c**. The sharp isosbestic points, at 499, 512 and 535 nm, clearly indicate the presence of only two compounds; **9c** and **7c**.



**Fig. 7** Composition of the reaction mixture obtained from the data displayed in Fig. 6. Solid lines represent the theoretical fitting curves obtained using a first-order decay obtained using eqn (S11) and (S12).†

dilute solutions of the model amic acid salts **K<sub>2</sub>5a**, **K<sub>9</sub>a** and **K<sub>12</sub>a** in DMF were acidified with HCl. In line with the reported behaviour of naphthyl-1,8-dicarboxylic amic acids, perylene amic acids were highly unstable.<sup>46</sup> Protonation was visible by a distinct 9 nm blue shift in the absorption spectrum and formation of **5a** was immediately followed by the appearance of an absorption around 505 nm, see Fig. 8. After 30 minutes the spectrum of PDA **1**, the end product of the acid decomposition process, became visible and the reaction was finished within 5 hours. From this experiment, the spectrum of the so far undetected monoamic acid monoanhydride **8a** was obtained, by subtracting the spectra of compounds **5a** and **1** from those of the reaction mixture, in a procedure similar to the one used to analyse the imidization of compound **5c**, see Fig. S11.† It appears that compound **8a** is molecularly dissolved, as its



**Fig. 8** Absorption spectra of compound **K<sub>2</sub>5a** (black) in DMF and **5a** (red), formed after acidification with 1 drop 1 N HCl. In the time-dependent absorption spectra the reaction from **5a** ( $\lambda_{\text{max}} = 466$  and  $438 \text{ nm}$ ) via compound **8a** to compound **1** ( $\lambda_{\text{max}} = 517.5$  and  $482 \text{ nm}$ ) is visible. Please note that the first spectrum after acidification already contains traces of compound **8a**.

absorption spectrum exhibits weak vibrational structure and is neither broadened nor red shifted.<sup>47</sup> Similar experiments, monitoring the acid catalysed anhydride formation from amid acids **9a** and **12a** are depicted in Fig. S12 and S13.† For these reactions clear and unambiguous isosbestic points were observed, due to the absence of reaction intermediates. PDA, PMAMI and PMADE, formed by amic acid hydrolysis, were molecularly dissolved in DMF and formed highly fluorescent oversaturated solutions. Rate constants for these reactions were not determined, because pH values, on which these reaction rates depend, have not been determined.

Finally it should be noted that fast anhydride formation from amic acids, implies that workup of reaction products in the PDI synthesis must be performed under basic conditions, until all amic acids are removed. Otherwise anhydrides are formed that cannot be removed.

### Room temperature imidization

The dilution experiments depicted in Fig. 4–7 have demonstrated that imidizations of PDA proceed at room temperature and have low activation barriers for imide formation. The overall reaction rate under standard conditions is limited by the solubility of the intermediate amic acid salts of **5** and **9**. At high dilution<sup>48</sup> the imide formation for the DBU reaction in DMF is strongly accelerated, with a rate constants  $k_2$  around  $5 \times 10^{-5} \text{ s}^{-1}$ . This allows the reaction to proceed to a >97% conversion in 24 hours at room temperature. It appears, from visual inspection of the reaction mixtures, that the DBU salts of the amic acids **5** and **9** have better solubility, as compared to the potassium salts, and this increased solubility may be the cause of the apparent DBU catalysis of the imidization reaction.

Our findings, that the rate of imidization is limited by the solubility of the amic acid salts **5** and **9**, and that dilution has a highly beneficial effect on the overall reaction rate, can be readily exploited for improving the synthesis of PDIs. Taking into account that amic acids **5** and **9** have higher solubility in water (as compared to DMF and DMSO) and that for imidization of NMA and NDA water is an excellent solvent, dilution with water appears to be a viable option to increase the imidization rate even further.

When the synthesis of PDI **7c** was started employing the normal reaction protocol (DBU in DMSO) quantitative formation of PDAA **5c** was achieved within an hour at room temperature. Subsequently, one equivalent of water (4 ml) was added, resulting in instantaneous dissolution of the DBU salt of **5c** to form a deep red solution.<sup>49</sup> After 24 hours of reaction at room temperature, PDI **7c** was obtained in quantitative yield, entry 10 Table 1. It should be noted that this reaction has a 50% yield without water addition. Water is the ideal solvent to add, because in our synthetic protocol water should be added anyway for separating the solid product from the reaction mixture. For amines **4b**, **4d** and **4f**, the same procedure, adding water after amic acid formation was examined. For the formation of **7d**, imide formation was quantitative as well, while for the formation of **7f**, the yield was high, 90%, but not quantitative. For the formation of **7b**, we only added 2 mL of water

because the long hydrophobic 2 ethyl hexyl tails limit water solubility. The yield for this reaction was quantitative.<sup>50</sup>

These results imply that aliphatic PDIs can be synthesised in quantitative yields at room temperature, without (**7e**) or with the addition of water (**7b–d**). When stable aliphatic amines, such as **4b–f** are used, synthesis at 60–100 °C is a reliable and practical option. As it has been reported that PDI synthesis with amino acids under Langhals conditions does not affect the stereochemistry of the appended amino acid,<sup>51</sup> the 60–100 °C “high temperature” synthesis is appropriate for these compounds as well. However, when temperature sensitive amines are used, imidization at room temperature will be the preferred route.

## Discussion

In this work, we have demonstrated that imidization of PDA, contrary to previous experience, is a process that is conveniently and efficiently performed at moderate temperatures, if need be at room temperature. The first step of the process, formation of diamic acid, is facile and fast in DMF or DMSO with all bases that we have explored. Conditions for PDAA synthesis found in the literature are generally harsh,<sup>33</sup> but structurally similar amic acids, such as 1,8-naphthyl-dicarboxylic amic acids and 1,3,4,8-naphthyl-tetracarboxylic diamic acids, have been synthesised under much milder conditions.<sup>25</sup> Also the formation of compound **2**, the ester analogue of perylene diamic acid **5**, is a process that runs at extremely mild conditions. Therefore the observation that amic acid formation is the easy step in the imide synthesis is not very surprising and in line with our expectations.

Imide formation from amic acids, on the other hand, is anticipated to be much more difficult to achieve. It is reasonable to assume that limited solubility of PTCA derivatives is a major factor necessitating the high temperatures in the conventional PDI syntheses, since imidization from more soluble analogous (di)anhydride substrates is reported at lower temperatures.<sup>11,12</sup> The activation barrier for the imidization step has been largely unexplored, since all PDI forming reactions have been performed far above room temperature. In contrast to the data obtained from synthetic sources, mechanistic research on the reactivity of 1,8-naphthyl-dicarboxylic amic acids in water indicates that the activation barriers for analogous imidization reactions are low. The conversion from naphthyl amic acids to naphthyl imides is a process that takes place reversibly at temperatures as low as 30 °C. These data suggest that in water, a solvent in which PTCA derivatives tend to be poorly soluble, imidization is a process with a low activation barrier. So if polar solvents in which perylene amic acids are soluble can be found, imidization reactions of PDA may proceed at low temperatures.

Our experiments, in which diamic acid salts of **5** were fully dissolved in DMF at high dilution, gave full conversion to PDI **7** at room temperature. This proves that amic acid salt solubility is the major rate limiting factor for the imization of PDA.



Absorption spectra taken at high dilution have clearly demonstrated that all reaction products and intermediates are visible. The diamic acid salts of **5** and even PDI **7** are molecularly dissolved, but monoimide amic acid salts of **9** still forms aggregates at these high dilutions. This finding suggests that the solubility of compound **9** is the major factor limiting the imidization rate. Since we have observed that the solubility of compound **5** is also limited under the standard reaction conditions, the solubility of this compound may be rate limiting as well. For amic acid salts of **5** and **9** it has been observed that potassium salts are less soluble than DBU salts and this solubility difference correlates with a lower reactivity of the reactions when  $K_2CO_3$  is used. Another case where high solubility and high reactivity are correlated is the unusual fast reaction of ethanolamine **4e** with PDA under standard conditions. The more intense red colour of the reaction mixture observed in this synthesis obviously reflects a higher solubility of the intermediate amic acid salts. Once more, the rate for this reaction is higher when DBU is used as the base. Based on these observations, we conclude that the rate enhancing effect of DBU primarily originates from the higher solubility of the DBU amic acid salts in the reaction medium.

For optimal results, in terms of materials used and rate of the reaction, the bimolecular amic acid formation from PDA is best performed at high concentrations, using only a small excess of amine in as little solvent as possible. For this reaction DMF and DMSO are the only useful solvents identified so far. The second step, the unimolecular imide formation, is limited by the solubility of the amic acid salts and therefore dilution with an appropriate polar solvent is required to speed up this part of the reaction. Enhancing the yield has been proven by strongly diluting the reaction mixture with DMSO or DMF. By adding just one equivalent amount of water the same result, *i.e.* quantitative PDI formation at room temperature, was obtained as well. The use of water in this respect is extremely beneficial, as water is green, cheap and is already used for precipitating the reaction product PDI **7** out of the solution. Further reaction optimization along these lines will be the subject of coming research in our group.

Looking ahead further, attractive opportunity emerge in broadening the scope of the mild imidization reactions. For example in terms of the amines and anhydrides used as starting compounds. It is known from literature that aromatic amines are less nucleophilic and generally have lower yields in imidization reactions.<sup>10,13,14</sup> Preliminary results of reactions on PMADE **11** have shown that at elevated temperatures aromatic imides can be formed.<sup>52</sup> Reactions of NDI with butyl amine demonstrated the formation of dibutyl NDI at room temperature already. In the literature this reaction is reported in DMF or acetic acid at temperatures above 100 °C.<sup>53</sup> Attaching delicate and sensitive (bio)molecules, such as amino terminated nucleic acids and proteins, to strongly fluorescent perylene anhydride moieties like compound **11** is another attractive prospect of our novel synthetic procedure. Very mild reaction conditions can be employed, which is advantageous in view of the high value and limited stability of  $NH_2$ -termi-

nated biomolecules. An additional advantage of the mild imidization protocol is that every step of the process can be monitored and examined in great detail using absorption spectroscopy. This facilitates optimization of the reaction by tuning the individual reaction steps.

## Conclusions

The imidization of PDA **1** has been converted from a harsh “molten imidazole” process, performed at 140–180 °C, into a highly practical, efficient process that runs at strongly decreased temperatures. When using primary aliphatic amines, DBU and either DMF or DMSO as the solvent, full conversion within 24 hours is achieved in the temperature range between 20–60 °C. By using  $K_2CO_3$  in DMSO, a truly green and user-friendly synthesis has been developed at reaction temperatures between 80–100 °C.

The reaction sequence for the imidization process *via* various amic acid intermediates, as displayed in Scheme 2, has been confirmed experimentally, aided by the synthesis and full characterization of stable model amic acid salts and amic esters. The formation of diamic acid salts is a fast process that is completed within 30 minutes. Conversion from amic acids to imides is rate determining, due to the low solubility of the intermediate amic acid salts. Diluting the reaction mixture after amic acid formation, strongly increases the reaction rates. The reaction rate constant for the imidization process in DMF was determined to be  $5 \times 10^{-5} \text{ s}^{-1}$  at 20 °C. An improved synthesis, that yields quantitative conversion at room temperature, was developed by adding water after amic acid is formed. An equivalent amount of water is enough to solubilise these amic acids and run the reaction to completion.

Finally, the convenience of the novel synthetic protocol needs to be emphasized. A protective atmosphere, special equipment and advanced synthetic skills are no longer required. When run at the proper temperature, full conversion is obtained and work-up comes down to product precipitation in water followed by a simple filtration. Current research efforts are focussed on broadening the scope of our synthetic protocol by exploring the synthesis of aromatic PDIs and the use of delicate, temperature sensitive amines.

## Experimental

Perylene-3,4-dicarboxylic monoanhydride-9,10-dicarboxylic dibutyl ester (**11**) was synthesized according to literature procedures.<sup>32a</sup> All other reagents utilized in the syntheses were used as received from the manufacturers, unless otherwise stated. The solvents used were of reagent grade. PDA (**1**), 97% purity, was obtained from Sigma Aldrich.

### Instrumentation and characterization

The NMR spectra were recorded with 400 MHz pulsed Fourier transform NMR spectrometer in  $CDCl_3$ , DMSO- $d_6$  or MeOH- $d_4$





at room temperature. The chemical shift values are given in ppm and J values in Hz. High-resolution mass spectra were collected on an AccuTOF GCv 4G, JMS-T100GCV, Mass spectrometer (JEOL, Japan). The FD/FI probe (FD/FI) was equipped with an FD Emitter, Carbotec (Germany), FD 10  $\mu\text{m}$ . Typical measurement conditions were as follow: Current rate 51.2 mA  $\text{min}^{-1}$  over 1.2 min; Counter electrode  $-10$  kV; Ion source 37 V. The samples were prepared in dichloromethane. Absorption measurements were performed using a PerkinElmer Lambda 365 UV-Vis spectrophotometer. Photoluminescence studies were done in Jobin Horiba SPEX Fluorolog 111 Spectrofluorometer. For quantum yield measurements, the formula for optically dilute solutions was used.<sup>54</sup> Fluorescence quantum yields were determined by the comparative method using perylene-3,4,9,10-tetracarboxylic tetrabutylester ( $\Phi_F = 0.95$  in  $\text{CH}_2\text{Cl}_2$ ) and  $N,N'$ -di(1-hexylheptyl)peryene-3,4,9,10-tetracarboxy bisimide ( $\Phi_F = 0.99$  in  $\text{CHCl}_3$ ) and perylene-3,4,9,10-tetracarboxylic tetrapotassium salt ( $\Phi_F = 1.0$  in water) as reference compounds.<sup>16</sup> Melting points (uncorrected) were recorded on a Gallenkamp melting point apparatus.

Kinetic measurements were performed on the formation of imides from amic acids at low concentrations in 3 mL quartz cuvettes with a 10 mm pathway. Reactions from the anhydrides **1**, **11** or **15** to the amic acid salts of **5c**, **12c** and **9c** were performed at room temperature (20 °C) at the smaller scale (200 or 100 mg starting compound) in DMF using DBU as the base at the conditions specified in the synthetic section. For the synthesis of **9c**, 100 mg of **15**, 2.0 equivalents of DBU and amine in 2 mL DMF were used. After 1 hour of reaction a droplet of the reaction mixture was diluted with DMF and a few droplets of this solution were added to a cuvette placed in a dual beam spectrophotometer. Absorption spectra were taken at room temperature every 5 minutes over a period of 24 hours.

## Synthesis

**Perylene-3,4,9,10-tetracarboxylic acid 3,9-dimethylamide dipotassium salt (and its 3,10 isomer) K<sub>2</sub>5a.** In a 50 mL round bottom flask equipped with a magnetic stirring bar, PDA **1** (200 mg, 0.51 mmol),  $\text{K}_2\text{CO}_3$  (564 mg, 4.08 mmol) and dimethylamine hydrochloride (**4a**, 166 mg, 2.09 mmol) were suspended in 4 mL DMSO. The suspension was stirred for 2 hours at 60 °C. The reaction mixture was cooled to room temperature. Methanol (10 mL) was added under vigorous stirring and subsequently, acetone (200 mL) was added. The precipitate was filtered off and washed with acetone. The yellow solid was dissolved in methanol (20 mL) and filtered to remove the remaining  $\text{K}_2\text{CO}_3$ . The organic solvent was removed from the filtrate by rotary evaporation. This yielded a yellow solid that was dried in a vacuum oven.

Yield: 188 mg, 0.34 mmol, 66%. Mp >350 °C.  $^1\text{H}$  NMR ( $\text{MeOH}-d_4$ , 400 MHz): 8.40 (2H,  $J = 8$  Hz, d), 8.38 (2H,  $J = 8$  Hz, d), 7.79 (2H,  $J = 8$  Hz, d), 7.51 (2H,  $J = 8$  Hz, d), 3.10 (6H, s), 3.05 (6H, s). MS (ESI):  $[\text{M}]^{2-}$  Calculated for  $\text{C}_{28}\text{H}_{20}\text{N}_2\text{O}_6$ , 240.0666; found: 240.0668  $[\text{KM}]^-$  Calculated for  $\text{C}_{28}\text{H}_{20}\text{KN}_2\text{O}_6$ ; 519.0964; found: 519.0965.

**Perylene-3,4,9,10-tetracarboxylic acid 3,9-dimethylamide 4,10-dibutyl ester and perylene-3,4,9,10-tetracarboxylic acid 3,10-dimethylamide 4,9 dibutyl ester 6a.** In a 50 mL round bottom flask equipped with a magnetic stirring bar, PDA **1** (200 mg, 0.51 mmol), DBU (621 mg, 4.08 mmol) and dimethylamine hydrochloride (**4a**, 166 mg, 2.04 mmol) were suspended in 4 mL DMF. The suspension was stirred for 1 hours at 60 °C. 1-bromobutane (699 mg, 5.10 mmol) was added and the reaction mixture was left to stir for 18 hours at 60 °C. The mixture was cooled to room temperature. Water (40 mL) was added under strong stirring, which caused precipitation of the crude product. The reaction product was filtered and the obtained solid was washed extensively with water, until almost no colour was observed in the filtrate, yielding an orange solid that was dried in a vacuum oven.

Yield: 230 mg, 0.39 mmol, 76%. Mp = 190–198 °C.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.24 (4H, m), 7.86 (4H,  $J = 8$  Hz, d), 7.52 (2H,  $J = 8$  Hz, d), 4.33 (4H,  $J = 8$  Hz, t), 4.15 (6H, s), 3.12 (6H, s), 1.82 (4H,  $J = 8$  Hz, quin), 1.52 (4H, m), 1.01 (6H,  $J = 8$  Hz, t).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 172.13, 172.09, 169.04, 169.02, 133.60, 133.29, 132.73, 131.12, 130.43, 129.44, 129.28, 128.82, 128.32, 127.81, 127.66, 120.97, 120.80, 120.75, 77.04, 76.72, 65.37, 39.80, 35.06, 30.68, 19.30, 13.83. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{36}\text{H}_{38}\text{N}_2\text{O}_6$ , 594.2730; found: 594.2764,  $[\text{M}_2]^+$  Calculated for  $\text{C}_{72}\text{H}_{77}\text{N}_4\text{O}_{12}$  1188.5460; found: 1188.5600.

**Perylene-3,4,9,10-tetracarboxylic acid diimides 7.** Standard reactions were performed using 200 mg of PDA. Under optimal conditions larger scale reactions for synthetic purposes were performed, using up to 5 grams of PDA. Reaction yields were independent of the scale.

In a 50 mL round bottom flask equipped with a magnetic stirring bar, PDA **1** (200 mg, 0.51 mmol), base (DBU or  $\text{K}_2\text{CO}_3$ , 2.04 mmol) and amine **4** (2.04 mmol) were suspended in 4 mL solvent. Reactions with methylamine **4d** used a 40% solution in MeOH and were stirred for one hour at RT prior to heating. The suspension was stirred for 24 hours at the desired temperature. The reaction mixture was cooled to room temperature. Water (40 mL) was added under strong stirring, which caused a precipitation of the crude product. The precipitate was left to settle for a maximum of 24 hours. The reaction product was filtered and the obtained solid was washed extensively with 0.01 M  $\text{K}_2\text{CO}_3$  until almost no color was observed in the filtrate and subsequently with water. When the reaction involved the more hydrophobic amine **4b**, the filtrate was washed two more times with dilute HCl (1 M, 10 mL) and two more times with demineralized water (25 mL). The solid was dried in a vacuum oven.

**DBU/DMSO water addition.** After addition of the reagents, the suspension was stirred for 1 hour at room temperature. Subsequently 4 mL of water was added (2 mL for the synthesis of **7b**) and the reaction mixture was stirred for another 23 hours at room temperature. Workup as described above.

**$N,N'$ -Di(2-ethylhexyl) perylene-3,4,9,10-tetracarboxylic acid diimide 7b.** DBU/DMF method, RT, from 200 mg PDA: Purple solid, yield 79 mg, 0.13 mmol, 25%.

DBU/DMF method, 60 °C, from 1.00 g (2.55 mmol) PDA: Purple solid, yield 1.534 g, 2.50 mmol, 98%.



$K_2CO_3$ /DMSO method, 100 °C, from 1.00 g (2.55 mmol) PDA: Purple solid, yield 1.548 g, 2.52 mmol, 99%.

DBU/DMSO water addition, from 200 mg PDA: Purple solid, yield 307 mg, 0.50 mmol, 98%.

$^1H$  NMR ( $\delta_H$ [ppm],  $CDCl_3$ , 400 MHz): 8.61 (4H,  $J$  = 8 Hz, d), 8.52 (4H,  $J$  = 8 Hz, d), 4.14 (4H, m), 1.97 (2H, m), 1.42–1.32 (18H, m), 0.96 (6H,  $J$  = 8 Hz, t), 0.90 (6H,  $J$  = 8 Hz, t).  $^{13}C$  NMR ( $\delta_C$ [ppm],  $CDCl_3$ , 101 MHz): 163.70, 134.44, 131.35, 126.30, 123.25, 122.98, 44.34, 37.96, 30.77, 28.71, 24.08, 23.08, 14.10, 10.64.

***N,N'*-Dibutyl perylene-3,4,9,10-tetracarboxylic acid diimide 7c.** DBU/DMF method, RT, from 200 mg PDA: Purple solid, yield 123 mg, 0.24 mmol, 48%.

DBU/DMF method, 60 °C, from 1.00 g (2.55 mmol) PDA: Purple solid, yield 1.249 g, 2.49 mmol, 98%.

$K_2CO_3$ /DMSO method, 100 °C, from 1.00 g (2.55 mmol) PDA: Purple solid, yield 1.239 g, 2.47 mmol, 97%.

DBU/DMSO water addition, from 200 mg PDA: Purple solid, yield 249 mg, 0.50 mmol, 98%.

$^1H$  NMR ( $\delta_H$ [ppm],  $CDCl_3$ , 400 MHz):  $\delta$  8.74 (4H,  $J$  = 8 Hz, d), 8.67 (4H,  $J$  = 8 Hz, d), 4.23 (4H,  $J$  = 8 Hz, t), 1.74 (4H,  $J$  = 8 Hz, quin), 1.47 (4H,  $J$  = 8 Hz, sex), 0.99 (6H,  $J$  = 8 Hz, t).

***N,N'*-Dimethyl perylene-3,4,9,10-tetracarboxylic Diimide 7d.** DBU/DMF method, RT, from 200 mg PDA: Red solid, yield 180 mg, 0.43 mmol, 84%.

DBU/DMF method, RT, from 200 mg PDA: Red solid, yield 210 mg, 0.50 mmol, 98%.

$K_2CO_3$ /DMSO method, 100 °C, from 200 mg PDA: Red solid, yield 207 mg, 0.49 mmol, 92%.

DBU/DMSO water addition, from 200 mg PDA: Red solid, yield 214 mg, 0.51 mmol, 100%.

$^1H$  NMR ( $\delta_H$ [ppm],  $D_2SO_4$ , 400 MHz): 9.15 (4H,  $J$  = 8 Hz, d), 9.10 (4H,  $J$  = 8 Hz, d), 3.93 (6H, s). FTIR: 742, 808, 850, 863, 1021, 1053, 1127, 1156, 1184, 1237, 1284, 1326, 1358, 1400, 1446, 1507, 1578, 1594, 1659, 1698.

***N,N'*-Di-(2-hydroxyethyl) perylene-3,4,9,10-tetracarboxylic acid diimide 7e.** DBU/DMF method, RT, 1.00 g (2.55 mmol) PDA: Dark purple solid, yield 1.196 g, 2.40 mmol, 98%.

$K_2CO_3$ /DMSO method, 80 °C, 1.00 g (2.55 mmol) PDA: Dark purple solid, yield 1.177 g, 2.36 mmol, 97%.

$^1H$  NMR ( $\delta_H$ [ppm],  $D_2SO_4$ , 400 MHz): 9.21–9.07 (8H, m), 5.64 (4H,  $J$  = 8 Hz, t), 4.85 (4H,  $J$  = 8 Hz, t).

***N,N'*-Di-(6-hydroxyhexyl) perylene-3,4,9,10-tetracarboxylic acid diimide 7f.** DBU/DMF method, RT, 200 mg PDA: Purple solid, yield 199 mg, 0.34 mmol, 66%.

DMF/DBU method, 60 °C, 200 mg PDA: Purple solid, yield 297 mg, 0.50 mmol, 97%.

$K_2CO_3$ /DMSO method, 100 °C, 200 mg PDA: Purple solid, yield 296 mg, 0.50 mmol, 97%.

DBU/DMSO water addition, 200 mg PDA: Purple solid, yield 270 mg, 0.46 mmol, 90%.

$^1H$  NMR ( $CDCl_3$ , 400 MHz): 8.77 (4H,  $J$  = 8 Hz, d), 8.72 (4H,  $J$  = 8 Hz, d), 4.37 (4H,  $J$  = 8 Hz, t), 4.25 (4H,  $J$  = 8 Hz, t), 8.69 (8H, m), 1.50 (8H, m).

***N*-Butyl perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9-dimethylamide potassium salt K9a.** In a 25 mL round bottom

flask equipped with a magnetic stirring bar, PMAMI 15 (50 mg, 0.11 mmol),  $K_2CO_3$  (650 mg, 0.47 mmol) and dimethylamine hydrochloride (4a, 20 mg, 0.25 mmol) were suspended in 1 mL DMSO. The suspension was stirred for 2 hours at 60 °C. The mixture was cooled to room temperature. Methanol (1 mL) was added under vigorous stirring and subsequently 20 mL of a 1 : 1 acetone/petroleum ether mixture was added. The precipitate is filtered off and washed with acetone/petroleum ether. The purple solid was dissolved in ethanol (5 mL) and filtered to remove the remaining  $K_2CO_3$ . The organic solvent was removed from the filtrate by rotary evaporation. This yielded a yellow solid that was dried in a vacuum oven.

Yield: 42 mg, 0.08 mmol, 73%. Mp >350 °C.  $^1H$  NMR (MeOD, 400 MHz): 8.59–8.45 (6H, m), 7.88 (1H,  $J$  = 8 Hz, d), 7.59 (1H,  $J$  = 4 Hz, d), 4.16 (2H,  $J$  = 8 Hz, t), 3.13 (3H, s), 3.10 (3H, s), 1.73 (2H,  $J$  = 8 Hz, quin), 1.47 (2H,  $J$  = 8 Hz, sex), 1.02 (3H,  $J$  = 8 Hz, t). MS (ESI):  $[M]^-$  Calculated for  $C_{28}H_{20}N_2O_6$ , 240.0666; found: 240.0668  $[KM]^-$  Calculated for  $C_{30}H_{23}N_2O_5$ , 491.1612; found: 491.1598.

***N*-Butyl perylene-3,4,9,10-tetracarboxylic acid 3,4-butyliimide 9-dimethylamide 10-butylester 10a.** In a 25 mL round bottom flask equipped with a magnetic stirring bar, PMAMI 15 (50 mg, 0.11 mmol), DBU (680 mg, 0.45 mmol) and dimethylamine hydrochloride 4a (20 mg, 0.25 mmol) were suspended in 1 mL DMF. The suspension was stirred for 1 hours at 60 °C. 1-bromobutane (153 mg, 1.12 mmol) was added and the reaction mixture was left to stir for 3 hours at 60 °C. The mixture was cooled to room temperature. Water (10 mL) was added under strong stirring, which caused precipitation of the crude product. The suspension was transferred to a separation funnel and chloroform (10 mL) was added. The organic layer was collected, and washed two times with salt solution (10 mL, 2 M NaCl). The organic layer was collected and dried on  $Na_2SO_4$ . After filtration, the organic solvent was removed by rotary evaporation, yielding a red solid.

Yield: 53 mg, 0.097 mmol, 77%. Mp = 153–154 °C.  $^1H$  NMR ( $CDCl_3$ , 400 MHz): 8.63 (2H,  $J$  = 8 Hz, d), 8.46 (4H, m), 7.95 (1H,  $J$  = 8 Hz, d), 7.63 (1H,  $J$  = 8 Hz, d), 4.35 (2H,  $J$  = 8 Hz, t), 4.22 (2H,  $J$  = 8 Hz, t), 3.18 (3H, s), 3.13 (3H, s), 1.84 (2H, m), 1.75 (2H, m), 1.47 (2H, m), 1.01 (6H, m).  $^{13}C$  NMR ( $CDCl_3$ , 101 MHz): 168.56, 163.38, 163.34, 135.33, 135.14, 132.43, 131.51, 131.01, 130.90, 129.92, 129.22, 127.84, 125.48, 122.68, 122.44, 121.55, 121.31, 121.22, 120.94, 65.74, 40.24, 39.84, 35.12, 30.67, 30.20, 20.44, 19.31, 13.87, 13.85. MS (FD):  $[M]^+$  Calculated for  $C_{34}H_{32}N_2O_5$ , 548.2311; found: 548.2326,  $[M_2]^+$  Calculated for  $C_{68}H_{62}N_4O_{10}$ , 1096.4622; found: 1096.4767.

**Perylene-3,4,9,10-tetracarboxylic acid 3-dimethylamide 9,10-dibutylester potassium salt K12a.** In a 25 mL round bottom flask equipped with a magnetic stirring bar, PMADE 11 (50 mg, 0.096 mmol),  $K_2CO_3$  (56 mg, 0.40 mmol) and dimethylamine hydrochloride (4a, 17 mg, 0.21 mmol) were suspended in 1 mL DMSO. The suspension was stirred for 2 hours at 60 °C. The mixture was cooled to room temperature. While vigorously stirring, methanol (1 mL) was added.



Subsequently, 20 mL of a 1:1 acetone/petroleum ether mixture was added. The resulting yellow precipitate was left to settle and filtered off. The yellow solid was dissolved in ethanol (5 mL) and filtered to remove the remaining  $\text{K}_2\text{CO}_3$ . The organic solvent was removed from the filtrate by rotary evaporation. This yielded a yellow solid that was dried in a vacuum oven.

Yield: 35 mg, 0.063 mmol, 61%. Mp  $>350^\circ\text{C}$ .  $^1\text{H}$  NMR (MeOD, 400 MHz): 8.40 (2H,  $J = 8$  Hz, d), 8.36 (2H,  $J = 4$  Hz, d), 7.76 (2H,  $J = 8$  Hz, d), 7.81 (1H,  $J = 8$  Hz, d), 7.51 (1H,  $J = 8$  Hz, d), 4.30 (4H,  $J = 8$  Hz, t), 3.12 (3H, s), 3.08 (3H, s), 1.78 (4H,  $J = 8$  Hz, quin), 1.52 (4H,  $J = 8$  Hz, sex), 1.01 (6H,  $J = 8$  Hz, t). MS: (ESI):  $[\text{M}]^-$  Calculated for  $\text{C}_{34}\text{H}_{32}\text{NO}_7$ , 566.2148; found: 566.2165,  $[\text{KM}_2]^-$  Calculated for  $\text{C}_{68}\text{H}_{62}\text{KN}_2\text{O}_{14}$ , 1171.4000; found: 1171.3961.

**Perylene-3,4,9,10-tetracarboxylic acid-3,4-monoimide-9,10-dibutylesters 13.** In a 25 mL round bottom flask equipped with a magnetic stirring bar, PMADE **11**, (100 mg, 0.19 mmol), DBU (58 mg, 0.38 mmol) and amine (**4**, 0.38 mmol) were suspended in 2 mL DMF. The reaction mixture was stirred at room temperature for 24 hours. Afterwards the clear solution was poured in a sodium bicarbonate solution (20 mL, 1 M) and left for at least 30 minutes. The resulting suspension was filtered on a paper filter and the solid was washed with water until the filtrate was colorless. The solid was dried in a vacuum oven and the product was dissolved in DCM and subsequently purified using normal phase column chromatography ( $\text{SiO}_2/\text{DCM}/\text{MeOH}$ ).

**N-(2-Ethylhexyl)perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9,10-dibutylester 13b.** Column chromatography on silica/0.5% MeOH in DCM yielded a red waxy solid.

Yield: 66 mg, 0.10 mmol 55%. Mp =  $178^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.41 (2H, d, 8 Hz), 8.20 (2H, d, 4 Hz), 8.17 (2H, d, 4 Hz), 7.97 (2H,  $J = 8$  Hz, d), 4.36 (4H,  $J = 8$  Hz, t), 4.11 (2H, m), 1.96 (1H,  $J = 8$  Hz, sep), 1.82 (4H,  $J = 8$  Hz, quin), 1.53 (4H,  $J = 8$  Hz, sex), 1.42–1.32 (8H, m), 1.02 (6H,  $J = 8$  Hz, t), 0.96 (3H,  $J = 8$  Hz, t), 0.90 (3H,  $J = 8$  Hz, t).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 168.20, 163.78, 135.06, 131.86, 131.78, 131.18, 130.15, 129.04, 128.93, 128.83, 125.67, 122.37, 121.95, 121.60, 77.31, 76.99, 76.67, 65.54, 44.18, 37.97, 30.78, 30.62, 28.71, 24.09, 23.08, 19.25, 14.09, 13.79, 10.64. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{40}\text{H}_{43}\text{NO}_6$ , 633.3090; found: 633.3073.

**N-Butyl perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9,10-dibutylester 13c.** Column chromatography on silica/0.5% MeOH in DCM yielded a red waxy solid. Yield: 71 mg, 0.12 mmol, 65%. Mp =  $265^\circ\text{C}$ .

Synthesis for compound **15**, performed at  $40^\circ\text{C}$  overnight (16 h) starting from 200 mg (0.38 mmol) **11**: Yield: 215 mg, 0.37 mmol, 97% red solid. Traces of PDI **7c** are visible in the NMR spectrum of the crude reaction product, presumably originating from PDA contaminant in the starting material. Yield after column chromatography, 204 mg, 0.35 mmol, 92%.

$^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.17 (2H,  $J = 8$  Hz, d), 7.91 (2H,  $J = 8$  Hz, d), 7.84 (4H, m), 4.36 (4H,  $J = 8$  Hz, t), 4.12 (2H,  $J = 8$  Hz, t), 1.82 (4H,  $J = 8$  Hz, quin), 1.74 (2H,  $J = 8$  Hz, quin), 1.52 (6H, m), 1.03 (9H, m).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 168.12,

163.15, 134.61, 131.67, 131.47, 130.73, 129.97, 128.81, 128.47, 128.44, 125.21, 122.14, 121.67, 121.27, 77.33, 77.01, 76.70, 65.56, 40.26, 30.64, 30.17, 20.43, 19.28, 13.86, 13.82. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{38}\text{H}_{39}\text{NO}_7$ , 577.2464; found: 577.2443.

**N-Methyl perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9,10-dibutylester 13d.** Column chromatography on silica/1.0% MeOH in DCM yielded a red waxy solid.

Yield: 77 mg, 0.14 mmol, 75%. Mp =  $263^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.32 (2H,  $J = 8$  Hz, d), 8.11 (2H,  $J = 8$  Hz, d), 8.07 (2H,  $J = 8$  Hz, d), 7.93 (2H,  $J = 8$  Hz, d), 4.35 (4H,  $J = 8$  Hz, t), 3.50 (3H, s), 1.81 (4H,  $J = 8$  Hz, quin), 1.51 (4H,  $J = 8$  Hz, sex), 1.01 (6H,  $J = 8$  Hz, t).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 168.15, 163.53, 135.09, 131.83, 131.69, 131.02, 130.13, 128.96, 128.66, 128.63, 125.52, 122.37, 121.63, 121.48, 77.30, 76.99, 76.67, 65.57, 30.61, 26.98, 19.25, 13.79. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{33}\text{H}_{29}\text{NO}_6$ , 535.1995; found: 535.1983.

**N-(2-Hydroxyethyl)perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9,10-dibutylester 13e.** Column chromatography on silica/0.5 to 2.5% MeOH in DCM yielded a red waxy solid.

Yield: 82 mg, 0.14 mmol, 80%. Mp =  $305^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 7.92 (2H,  $J = 8$  Hz, d), 7.69 (2H,  $J = 8$  Hz, d), 7.59 (2H,  $J = 8$  Hz, d), 4.36–4.31 (6H, m), 4.03 (2H,  $J = 4$  Hz, t), 2.89 (br, 1H), 1.84 (4H,  $J = 8$  Hz, quin), 1.54 (4H,  $J = 8$  Hz, sex), 1.04 (6H,  $J = 8$  Hz, t).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 168.00, 163.73, 134.40, 131.68, 130.84, 130.63, 129.84, 128.46, 127.95, 127.95, 124.61, 122.12, 120.99, 120.98, 77.33, 77.01, 76.69, 65.62, 61.27, 42.72, 30.63, 19.28, 13.84. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{34}\text{H}_{31}\text{NO}_7$ , 565.2101; found: 565.2100.

**N-(6-Hydroxhexyl)perylene-3,4,9,10-tetracarboxylic acid 3,4-imide 9,10-dibutylester 13f.** Column chromatography on silica/0.5 to 2% MeOH in DCM yielded a red waxy solid.

Yield: 88 mg, 0.14 mmol, 75%. Mp =  $195^\circ\text{C}$ .  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.09 (2H,  $J = 8$  Hz, d), 7.84 (2H,  $J = 8$  Hz, d), 7.80 (2H,  $J = 8$  Hz, d), 7.75 (2H,  $J = 8$  Hz, d), 4.36 (4H,  $J = 8$  Hz, t), 4.08 (2H,  $J = 8$  Hz, t), 3.86 (2H,  $J = 8$  Hz, t), 1.83 (6H, m), 1.76 (2H, m), 1.64 (2H, m), 1.52 (6H, m), 1.03 (6H,  $J = 8$  Hz, t).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 168.11, 163.11, 134.57, 103.66, 129.96, 128.74, 128.37, 128.30, 125.06, 122.17, 121.47, 121.19, 65.58, 62.70, 40.22, 32.56, 30.64, 27.88, 26.64, 25.22, 19.28, 13.83. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{38}\text{H}_{39}\text{NO}_7$ , 621.2727; found: 621.2703.

**Perylene-3,4,9,10-tetracarboxylic acid 3-dimethylamide 4,9,10-tributylester 14a.** In a 25 mL round bottom flask equipped with a magnetic stirring bar, PMADE **11** (100 mg, 0.19 mmol), DBU (117 mg, 0.77 mmol) and dimethylamine hydrochloride (**4a**, 31 mg, 0.38 mmol) were suspended in 2 mL DMF. The suspension was stirred for 1 hours at  $60^\circ\text{C}$ . 1-bromobutane (131 mg, 0.96 mmol) was added and the reaction mixture was left to stir for 18 hours at  $60^\circ\text{C}$ . The mixture was cooled to room temperature. Water (40 mL) was added under strong stirring, which caused a precipitation of the crude product. The reaction product was filtered and the obtained solid was washed extensively with water, until almost no colour was observed in the filtrate, yielding a yellow solid that was dried in a vacuum oven.





Yield: 103 mg, 0.17 mmol, 86%. Mp = 123–127 °C.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.06 (4H, m), 7.92 (2H, m), 7.90 (1H,  $J = 8$  Hz, d), 7.75 (1H,  $J = 8$  Hz, d), 7.42 (1H, d), 4.34 (6H,  $J = 8$  Hz, t), 3.15 (3H, s), 3.13 (3H, s), 1.87–1.76 (6H, m), 1.57–1.48 (6H, m), 1.05–0.99 (9H, m).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ , 101 MHz): 171.92, 168.90, 168.65, 134.11, 133.22, 133.07, 132.63, 130.92, 130.41, 130.31, 130.00, 129.68, 129.31, 128.89, 128.83, 128.69, 128.43, 127.75, 121.42, 121.33, 120.95, 120.68, 65.49, 65.23, 39.80, 35.08, 30.66, 19.29, 13.80. MS (FD):  $[\text{M}]^+$  Calculated for  $\text{C}_{38}\text{H}_{41}\text{NO}_7$ , 623.2883; found: 623.2886.

**N-(2-Butyl)perylene-3,4,9,10-tetracarboxylic acid 3,4-anhydride 9,10-imide 15.** Concentrated sulphuric acid (7 mL) was added to a 50 mL round bottom flask, closed off with a drying tube charged with calcium chloride. **13c** (298 mg, 0.517 mmol) was then dissolved by stirring at room temperature for a few minutes. The mixture was left to stir at room temperature overnight. The strongly acidic mixture was slowly poured on ice. After the ice melted, the obtained suspension was filtered washed with water and dried by air and further dried in a vacuum oven. This yielded a red solid.

Yield: 215 mg, 93%.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 400 MHz): 8.81 (8H, m), 4.26 (2H,  $J = 8$  Hz, t), 1.76 (2H,  $J = 8$  Hz, quin), 1.49 (2H,  $J = 8$  Hz, sex), 1.00 (3H,  $J = 8$  Hz, t).

## Conflicts of interest

There are no conflicts to declare.

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- 44 PDA, PDIs and PMAMIs are virtually insoluble in DMF. When these compounds are formed in situ by reaction in DMF, oversaturated solutions are formed. These compound are molecularly dissolved and highly fluorescent, but precipitate in due time.
- 45 Extracting the relative concentrations of **5c**, **9c** and **7c** from the absorption spectra has been performed manually in a few independent runs. In all cases the relative concentration of **7c** was consistent. The relative concentrations of **5c** and **9c**, on the other hand, showed a larger variation between the different runs.
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