New cyclen-cored dendrimers functionalized with pyrene: Synthesis characterization, optical and photophysical properties

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ABSTRACT

New cyclen (1,4,7,10-teraazacyclododecane) cored dendrimers up to the second generation, functionalized with 4, 8 and 16 pyrene units, respectively, were synthesized following a convergent procedure. All new compounds were characterized by NMR spectroscopies and ESI or MALDI TOF mass spectrometry. The optical and photophysical properties of the new dendrimers were studied in THF solution. Absorption spectra showed the typical absorption bands of pyrene moieties. In the fluorescence spectra, monomer as well as excimer emission were observed for all compounds. An increased proportion of excimer emission was observed in the dendrimer of the highest generation.

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Introduction

Dendrimers are macromolecules presenting a well-defined structure which have been extensively studied in the last decades due to the large amount of potential applications in materials and biological science.[1–7] Among them, photoactive dendrimers, able to give light harvesting, changing the initial wavelength of the incident light like the antennas of photosystems do during the photosynthesis, are presenting a special interest.[8–10] Specific photophysical properties, such as excimer and exciplex formation, charge transfer (CT) or resonance energy transfer (RET), are observed in photoactive dendrimers, depending on the nature of the different types of chromophore placed in their structures. The incorporation of photoactive metals in dendrimers have been achieved through the incorporation of porphyrin or bipyridine based ligands and have found applications in sensors, catalysis or nanomaterials for drug delivery.[11–13]

Other metals were incorporated at the core of dendrimers by means of coordination with aza-macrocycles. This kind of ligand is very effective due to its chelating effect.[14,15] Moreover, the ability of complexation of aza-macrocycles towards various metal ions have been reviewed.[11,16] Among them, 1,4,7,10-teraazacyclododecane (cyclen), has shown good coordination ability for a large range of metals.[17–20] This has lead to various applications in ion sensing, ion carriers and medical diagnosis.[14,21–28] Dendrons have been appended to a cyclen core[14,29–32] and sensitization of lanthanide

complexed with cyclen based ligands have been observed from various chromophores.[33–35]

In our research group we have been focusing on pyrene as chromophore, studying its ability to transfer energy to chromophores such as porphyrins and fullerenes.[33,36] The special interest in pyrene emission is due to its ability to form excimers. Dendrimers built with numerous pyrene units at the periphery are therefore presenting various types of photophysical processes.[37] A linear dependence between the excimer formation and the generation number has been previously reported for a series of pyrene labeled dendrimers.[38] Since only a few reports about energy transfer from pyrene to lanthanides are available,[39–42] we have designed novel series of cyclen cored dendrimers with an increasing number of pyrene units at the periphery. In this work, we are presenting the synthesis as well as the optical and photophysical properties of the free cyclen dendrimers with 4, 8 and 16 pyrene units, respectively.
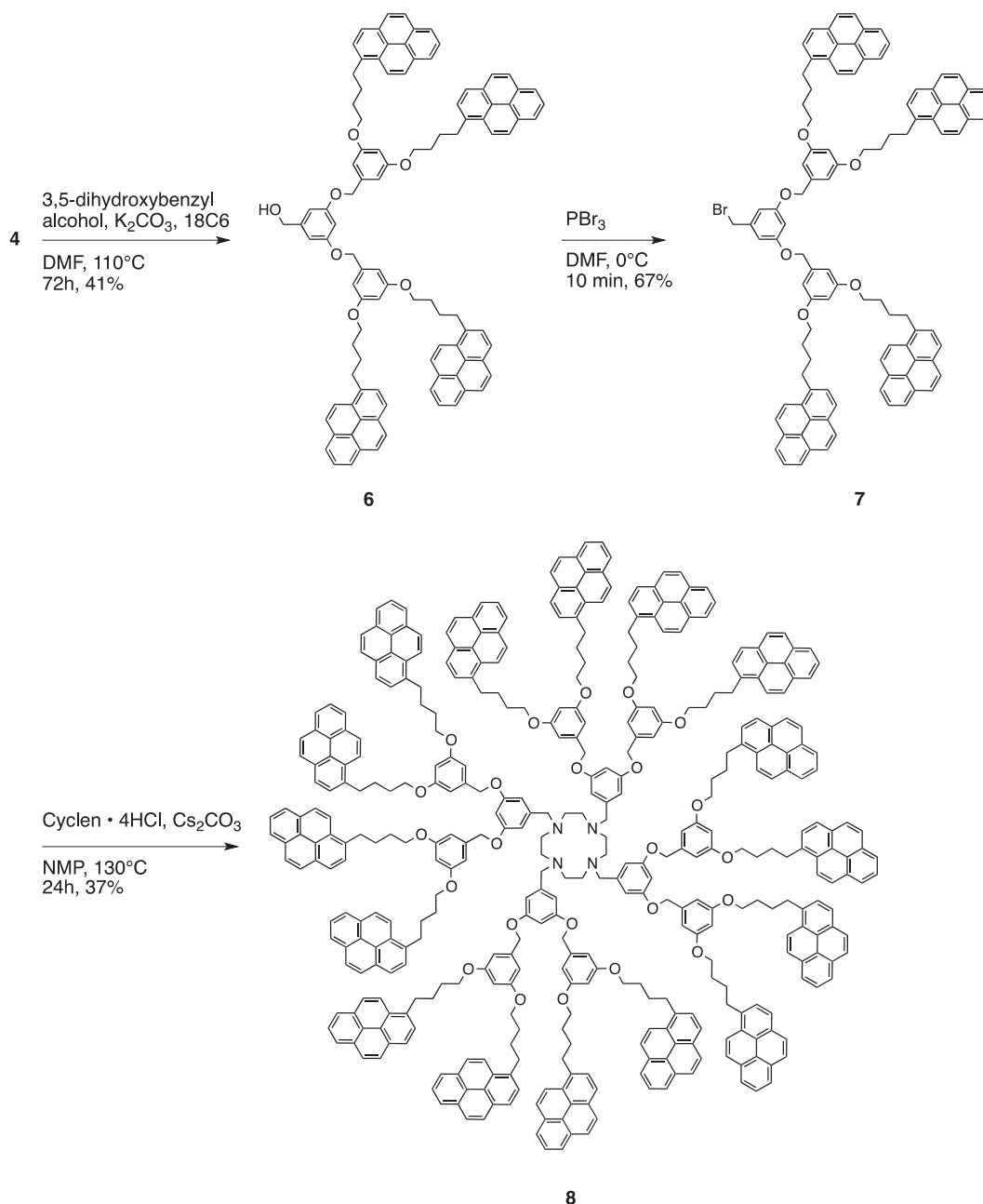
Results and discussion

Synthesis of the dendrimers

The synthesis of the cyclen-cored dendrimer of the zero generation (**2**) and first generation dendrimer (**5**) are illustrated in Scheme 1. Firstly, bromination of 1-pyrenebutanol was carried out in the presence of CBr_4 and PPh_3 in anhydrous THF to give the corresponding 1-(4-bromobutyl)pyrene **1**.[11] Afterwards, **1** was reacted with cyclen (1,4,7,10-tetraazacyclododecane) tetrahydrochloride salt to afford the desired compound **2**. For the

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Scheme 1. Synthesis of compound **2** and first generation dendrimer **5**.

synthesis of the first generation dendrimer **5**, the brominated intermediate **1** was reacted in the presence of 3,5-dihydroxybenzyl alcohol and a catalytic amount of 18-crown-6 in anhydrous acetone to give the first generation alcohol **3**. Bromination of **3** in the presence of PBr$_3$ in DMF at 0 °C lead to the corresponding brominated dendron **4**.[43] Finally, **4** was reacted with cyclen tetrahydrochloride salt using Cs$_2$CO$_3$ as base and NMP as solvent to obtain the desired first generation dendrimer **5** in moderate yield.

The second generation dendrimer **8** was prepared similarly, using the convergent approach as depicted in Scheme 2. The brominated first generation dendron **4** was reacted in the presence of 3,5-dihydroxybenzyl alcohol, potassium carbonate and a catalytic amount of 18-Crown-6 in DMF to obtain the second generation benzyl alcohol **6**. This compound was brominated to give the corresponding alkyl bromide **7**, using the same reaction conditions employed for the bromination of compound **3**. Brominated

dendron **7** was further reacted in the presence of cyclen tetrahydrochloride salt using Cs$_2$CO$_3$ as base and NMP as solvent to give the second generation dendrimer **8** in moderate yield.

Characterization of the dendrimers

All obtained dendrimers were fully characterized by ^{1}H and ^{13}C NMR spectroscopies and the structures were confirmed by ESI or MALDI-TOF mass spectrometry. In the ^{1}H NMR spectrum of the cyclen-cored dendrimer of generation zero (**2**), a broad singlet at 2.61 ppm indicating the presence of the aliphatic protons CH$_2$-N- of the cyclen core was seen. The ^{13}C NMR of compound **2** showed signal at 51.7 ppm attributed to the carbon of the cyclen, which indicated a full substitution of the four nitrogen atoms of the cyclen core. The MALDI-TOF spectrum of **2** exhibited a molecular ion peak at C$_{88}$H$_{84}$N$_4$ [M]$^+$ m/z = 1197.67 g/mol, which is very close to the calculated value (m/z = 1197.76 g/mol). This confirmed that

Scheme 2. Synthesis of the second generation dendrimer **8**.

the obtained compound was substituted in the four nitrogen atoms of the cyclen core. In the ^{1}H NMR spectrum of the first generation dendrimer **5**, a broad singlet at 2.58 ppm indicated the presence of the aliphatic protons of the cyclen core. Moreover, all the signals corresponding to the first generation of the parent dendron were present and up-field shifted due to the effect of the nitrogen atom. The ^{13}C NMR spectrum of **5** showed a signal at 50.0 ppm for the carbons of the cyclen core, which are equivalent by symmetry. The ESI spectra exhibited a molecular ion peak [M+2H]$^+$ m/z = 1355.66 g/mol, corresponding to the first generation dendrimer **5**, which is very close to the calculated value $C_{196}H_{172}N_4O_8$ [M+2H]$^+$ m/z = 1355.66 g/mol, and confirmed the structure of the macromolecule. The ^{1}H NMR spectrum of the second generation dendrimer **8** showed similarity to the spectrum of compound **5**. Moreover the signal observed at 3.36 ppm is attributed to the CH_2N benzylic protons, which confirms that the Fréchet type dendrons are linked to the cyclen core. The structure of **8** was

confirmed by MALDI-TOF mass spectrometry; the molecular ion peak was observed at m/z = 5739.35 g/mol. The obtained molecular weight value is very close to that calculated of the dendrimer **8** [M]$^+$ m/z = 5739.63 g/mol, which confirmed the structure of the obtained macromolecule.

Optical and photophysical properties of the dendrimers

The optical and photophysical properties of the obtained dendrimers were studied by absorption and fluorescence spectroscopy in chloroform solutions. Firstly, the molar extinction coefficients (ε) of the compounds were determined by preparing a series of solutions of dendrimers **2**, **5** and **8** at different concentrations; the obtained results are summarized in Table 1. A linear correlation between the molar extinction coefficient values at 345 nm and the number of pyrene units present in the dendrimer was observed.

Table 1
Extinction coefficients, quantum yields and ratio between the monomer and excimer emission of dendrimers **2**, **5** and **8**.

Compound	ε (M^{-1} cm^{-1})	Φ (λ_{ex} = 344 nm)[a]	I_E/I_M
2	120,400	0.41	2.0
5	269,100	0.51	6.5
8	532,500	0.51	9.2

Measurements were done in chloroform.
  [a] Quantum yields were determined relative to pyrene (Φ = 0.32) in cyclohexane.

The absorption spectra of the dendrimers are shown in Fig. 1. In all spectra, two well-structured absorption bands were observed at 278 and 345 nm due to the $S_0 \rightarrow S_3$ and $S_0 \rightarrow S_2$ transitions of the pyrene groups, respectively. The band due to the $S_0 \rightarrow S_1$ transition of pyrene should appear at 370 nm, but it can be seen only at very high concentration since this transition is forbidden by symmetry. Therefore, for practical purposes fluorescence spectra were recorded exciting at the wavelength of the second transition.

The fluorescence spectra of the obtained dendrimers were acquired in chloroform solution with excitation at 344 nm at room temperature. All measurements were performed at the same concentration of pyrene units (1.25×10^{-6} M), corresponding to an absorbance of about 0.04 at 345 nm. The fluorescence spectra of dendrimers **2**, **5** and **8** normalized at 377 nm are shown in Fig. 2. All dendrimers exhibited a monomer emission band between 377 and 396 nm, followed by a broad excimer emission band centered at 480 nm, arising from intramolecular pyrene-pyrene interactions in the dendrimers. It was noticeable that the intensity of the excimer emission band was significantly higher when the number of peripheral pyrene units present in the dendrimer increased. This is due to the presence of intramolecular pyrene-pyrene interactions in these constructs. To quantify this phenomenon the ratio of the excimer emission intensity (I_E) and monomer emission intensity (I_M) was calculated for all these systems and the results are summarized in Table 1. In the second generation dendrimer **8** the intensity of excimer emission appeared 4.6 times stronger than in the zero generation dendrimer **2**. This ratio showed a similar trend as previously reported for similar compounds.[38] The solutions had a concentration in the order of 10^{-6} M for the pyrene unit; thereby demonstrating that the I_E/I_M ratio was independent from the concentration of the dendrimer, the pyrene-pyrene interactions are exclusively intramolecular and no intermolecular processes are involved.

Stokes shift values were calculated for dendrimers **2**, **5** and **8**. It was found that they behaved similarly with Stokes shift values of about 30 nm. It is evident that in all cases the geometry of the
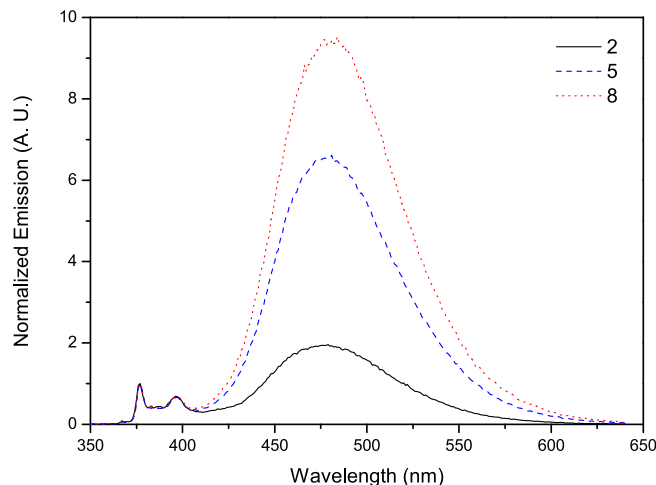

Fig. 1. Absorption spectra of dendrimers **2**, **5** and **8** in chloroform solution.

Fig. 2. Emission spectra of dendrimers **2**, **5** and **8** in chloroform solution.

dendrimer in the ground state differs from that in the excited state. The quantum yields of the obtained dendrimers **2**, **5** and **8** were determined by using a solution of pyrene in THF as reference. All the solutions were degassed with argon for 30 min since pyrene is very sensitive to the oxygen quenching. The quantum yields were calculated using the procedure previously described by Fery-Forgue and Lavabre.[44] The obtained results are summarized in Table 1. The quantum yields of the first and second generation dendrimers (**5** and **8**) are higher than that of the zero generation dendrimer **2**. These results seems to indicate that nitrogen atom of the zero generation dendrimer is slightly affecting the fluorescence emission of the construct.

Conclusion

A novel series of Frechet type dendrimers bearing a cyclen core and peripheral pyrene groups were synthesized. These dendrimers were fully characterized by ^{1}H and ^{13}C NMR spectroscopies and the structures were confirmed by ESI or MALDI-TOF mass spectrometry. The optical and photophysical properties of these compounds were studied by absorption and fluorescence spectroscopy. The intensity of the absorbance increases linearly with the number of pyrenes present in the dendrimers. Concerning the emission, these dendrimers are presenting high quantum yields with increased proportion of the excimer band as the generation augments. Cyclen (1,4,7,10-teraazacyclododecane) is an interesting center for photoactive dendrimers since it is silent in the absorption and emission spectrum but can interact with the dendrons or complex metals and modify the photophysical properties of the dendrimers.

A. Supplementary material

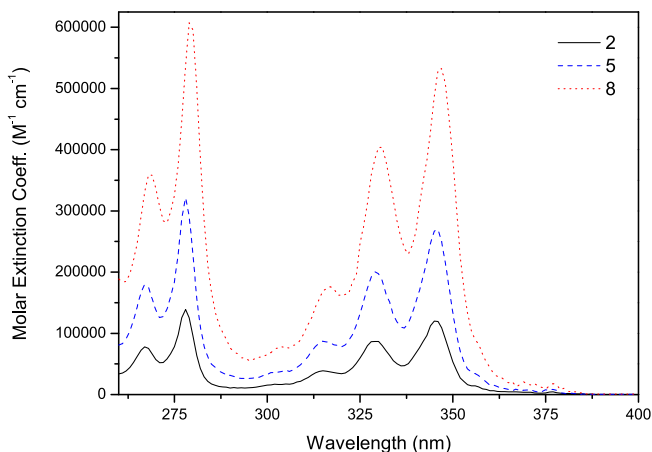Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetlet.2017.02.054.

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