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CAN-Mediated Oxidative Cyclodehydrogenation of Hexapyrrolylbenzenes

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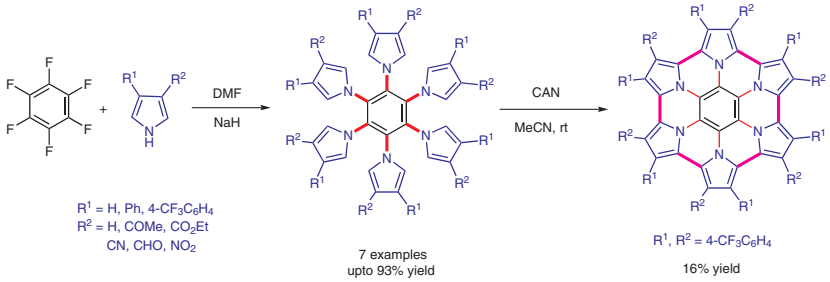

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Abstract An efficient method for ceric ammonium nitrate mediated synthesis of annularly fused hexapyrrolohexaazacoronene by oxidative cyclodehydrogenation has been reported. The photophysical properties of the representative hexaazacoronene has also been described.

Key words ceric ammonium nitrate, coronenes, azacoronene, hexapyrrolylbenzene, oxidative cyclodehydrogenation, MALDI-TOF

Development of π-conjugated organic molecules has gained huge attention in the recent times.[1] Two dimensional polycyclic aromatic hydrocarbons (PAHs),[2] for example chrysene, triphenylenes, coronene, and hexabenzocoronene (Figure 1), are known for their valuable utility in organic light-emitting diodes (OLEDs), organic field-effect transistors, and photovoltaic cells.[3] Heteroatom (N, B, Si, S, and P)-doped PAHs are novel materials that exhibit properties and functions altered from those of the parent PAHs.[4] It was observed that the replacement of a CH group by a nitrogen atom in PAHs can yield nitrogenated analogues such as compounds **I–IV**, which are *n*-type semiconductors, with enhanced electronic properties and which can be obtained by the Diels–Alder reaction of perylene as diene with diethyl azodicarboxylate and maleic anhydride as dienophile (Figure 2).[5]

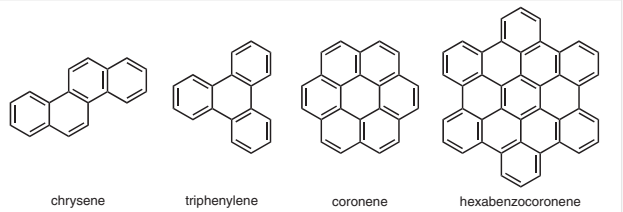

Figure 1 Two-dimensional π-conjugated PAHs

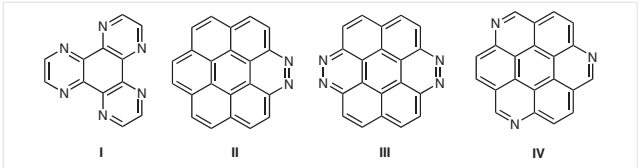

Figure 2 Hexaazatriphenylene and azacoronene derivatives

Although many heteroatom-doped structures have been developed, extended conjugations in a bigger scaffold resembling 'graphene-like' structures have been far less explored. Synthesis of such extended PAHs can provide opportunities to control the position and the distribution of the doped heteroatoms precisely, leading to generation of molecules that can allow structure–property relationships studies at different levels (atomic or molecular level).[6] Such studies are essential for developing novel organic materials with properties similar to or better than graphene. Development of a synthetic methodology will provide the much-needed bottom-up approach to design various interesting extended heteroatom-doped PAHs with control over π-conjugation, positions, and numbers of the heteroatoms and the substituents on scaffold.

The incorporation of nitrogen atoms into π-conjugated structures can be achieved by insertion of pyrrole rings in conjugation with the π-bonds. These structures, where the pyrrole ring becomes electron rich, have exhibited notable electronic and photophysical properties and such oligo- and polypyrroles are found to be conductive in their oxidized forms leading to multiple applications.[7,8]

In this context, various nitrogen-doped graphene molecules can be obtained by a series of pyrrole-fused azacoronenes via oxidative cyclodehydrogenation of the corresponding hexahetroaryl benzenes.[9] Notably, a method for the development of pyrrole-fused heteroaromatics bearing the fusion of two pyrrole rings is still unprecedented.[10] Ini-

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tial efforts have been made by Lacaze[11a] and Rapta[11b] for the synthesis of hexapyrrolohexaazacoronene but in 2007, Müllen et al. first designed and realized a novel family of annularly fused hexapyrrolohexaazacoronene (HPHAC) via oxidative cyclodehydrogenation of hexapyrrolylbenzene.[9a] Further oxidation of HPHAC revealed that the interior nitrogen atoms can be stabilized at higher oxidation states. While Müllen has elegantly substituted HPHACs with symmetrical pyrroles the generality of the method is not evident with respect to other electron-withdrawing and electron-donating substituents on the pyrrole core. In 2013, the same group synthesized other pyrrole-fused azacoronenes having six, five, four, and three pyrrole rings from the corresponding heteroarylbenezenes using $FeCl_3$ as an oxidant (Figure 3).[12]

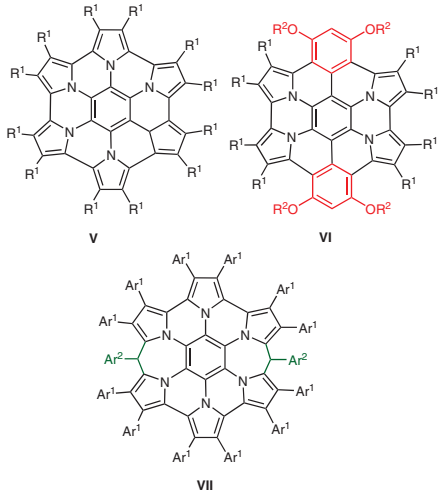
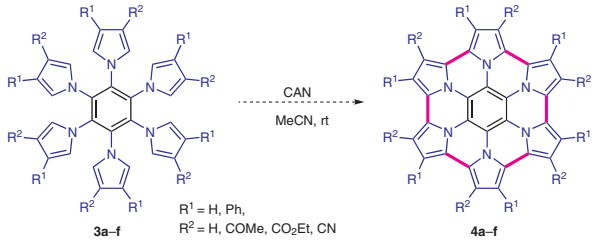


Figure 3 Pyrrole-fused azacoronenes

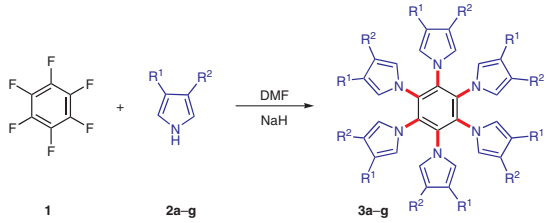
More recently, Stepien demonstrated the synthesis of expanded hexapyrrolohexaazacoronenes with broken exterior conjugation introduced by saturated methyl bridges.[13] The synthesis was carried out on substituted hexapyrrolyl benzenes via condensation followed by aromatization, *i.e.*, Lewis acid catalyzed bridging with *p*-nitrobenzaldehyde followed by oxidative cyclodehydrogenation to yield azacoronenes. Further, the peripheral bridges were aromatized through oxidative dehydrogenation. In addition, the method cannot be used for obtaining unsymmetrically substituted HPHACs. Thus, a method where various substituted hexapyrrolyl benzenes can be converted into the corresponding hexaazacoronenes will be indispensable to expand the library of PAHs for exploring interesting structure-based optoelectronic properties. We envisaged this could be achieved by installing pyrroles on perfluorobenzene by nucleophilic aromatic substitution followed by cyclodehydrogenation with an oxidant, resulting in extended fused polycyclic heteroaromatic systems.

While exploring the literature for the synthesis of coronenes and heterocoronenes, we were inspired by the work of Müllen and planned to synthesize annularly fused hexapyrrolohexaazacoronenes **4a–f** (Scheme 1). For this, we synthesized various symmetrical and unsymmetrical pyrroles, which were appended to all six position of the benzene ring. The starting hexapyrrolylbenzene **3a** was obtained by *ipso*/*para* nucleophilic substitution between hexafluorobenzene and pyrrolyl sodium salt as reported by Meijer.[14a] Other, hexapyrrolylbenzenes **3b–f** were also synthesized in good to moderate yields by same procedure (Table 1). The symmetrically substituted pyrrole **2b**, possessing two 4-$CF_3C_6H_4$ groups, on reacting with hexafluorobenzene gave product **3b** in 52% yield (entry 2). Unsymmetrical pyrroles with electron-withdrawing groups at C3 such as a methyl ketone, ethoxycarbonyl, aldehyde, or nitrile with a phenyl group at C4 gave substituted products **3c–f** in good yield (entries 3–6). Unfortunately, pyrrole **2g** with a nitro



Scheme 1 Cyclodehydrogenation of hexapyrrolylbenzenes **3** to afford hexapyrrolohexaazacoronenes **4**

Table 1 Synthesis of Hexapyrrolylbenzenes **3**[a]



Entry	**2**, **3**	R^1	R^2	Yield (%)
1	**a**	H	H	80
2	**b**	4-$CF_3C_6H_4$	4-$CF_3C_6H_4$	52
3	**c**	Ph	COMe	47
4	**d**	Ph	CO_2Et	93
5	**e**	Ph	CN	52
6	**f**	Ph	CHO	63
7	**g**	Ph	NO_2	0

[a] Reaction conditions: Hexafluorobenzene **1** (1.08 mmol), pyrrole 2 (7.09 mmol), and NaH (7.09 mmol) were taken in 1 mL DMF and stirred for 2 h at r.t.

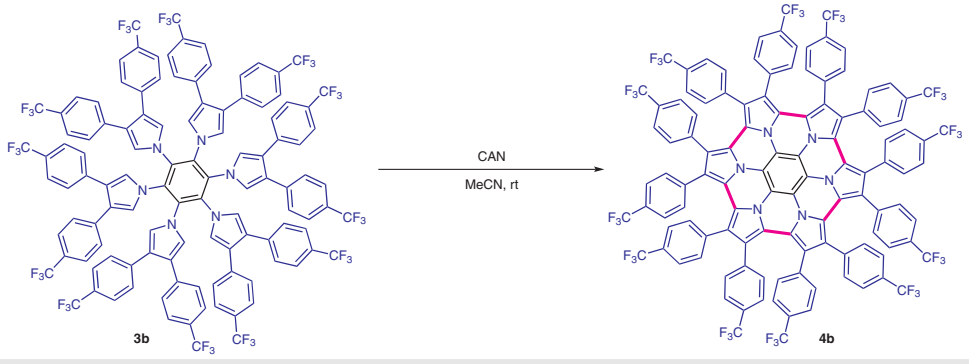
substituent at C3 and a phenyl group at C4 did not yield the substituted product with hexafluorobenzene, and unreacted starting material was recovered (entry 7).

The resulting hexapyrrolylbenzenes **3a–f** were characterized by MALDI-TOF mass spectrometry and ^{1}H NMR and ^{13}C NMR spectroscopy. It is important to note that unsymmetrically disubstituted hexapyrrolylbenzenes **3c–f** have been synthesized for the first time with yields in the range of 47–93% (Table 1) while monosubstituted hexapyrrolylbenzenes have been reported by Vègh et al.[14b] There was no specific trend in the reactivity of nucleophilic aromatic substitution of hexafluorobenzene with the different pyrroles.

After obtaining the various hexapyrrolylbenzenes, a suitable oxidation partner for the cyclodehydrogenation was sought. Various oxidizing agents, such as $FeCl_3$, $CuCl_2$ or $Cu(OTf)_2$ with $AlCl_3$, $Tl(CF_3CO_2)_3$, $MoCl_5$, CAN, $Pb(OAc)_4$, and $SbCl_5$, have been explored for the oxidative cyclization reaction. However, among these, only $FeCl_3$ has been shown to achieve cyclodehydrogenation of hexapyrrolylbenzene in moderate to good yield. Previously, our group has synthesized polycyclic aromatic and polycyclic heteroaromatic hydrocarbons through CAN-mediated oxidative cyclization.[15] Detailed mechanistic studies showed that C–C bond formation involved cation-radical intermediates. Extending this, we hypothesized that the key step for the synthesis of PAHs could be oxidative cyclodehydrogenation of the corresponding Scholl precursors by suitable oxidants. Since CAN is a one-electron oxidant with a high reduction potential (+1.61V vs NHE), we considered exploring this for the cyclodehydrogenation of hexapyrrolylbenzene.

In our first attempt to synthesize annularly fused hexapyrrolohexaazacoronenes (HPHAC), hexapyrrolylbenzene **3a** was oxidized by ceric(IV) ammonium nitrate (12.0 equiv) to afford a black powder (Scheme 1). MALDI-TOF mass spectrometric analysis of the product showed that it consisted of a complex mixture of partially cyclized nitrated compounds (peaks at *m/z* = 595.359, 641.374, 686.342, 730.353; see the Supporting Information). When the reaction was performed with hexapyrrolylbenzene **3b**, possessing 4-trifluoromethylphenyl substituents, we were delighted to see complete cyclization, yielding the desired product **4b** (Scheme 2). The pure product was obtained by column chromatography on silica gel with ethyl acetate/hexane as eluent. The isolated product was characterized by ^{1}H NMR and ^{13}C NMR spectroscopy, is further supported by MALDI-TOF mass spectrometric analysis (*m/z* calcd for M^+, $C_{114}H_{48}N_6F_{36}$: 2185.340; found: 2185.596). In the ^{1}H NMR spectrum of compound **4b**, two doublets were observed at δ = 7.66 (d, *J* = 7.4 Hz) and 7.58 (d, *J* = 7.8 Hz) due to the 4-trifluoromethylphenyl groups; whereas the signal (δ = 7.00–6.60) due to the C2 pyrrolyl protons was absent.

When the oxidation of other hexapyrrolylbenzenes **3c–f** with unsymmetrical 3,4-disubstituted pyrroles was performed it was observed that the oxidation of **3c** having the electron-withdrawing methyl ketone substituent on the pyrrole groups with CAN (12.0 equiv) afforded a black solid. MALDI-TOF mass spectrometry of this material gave an intense peak at *m/z* = 1054.223 and a low intensity peak at *m/z* = 1165.179, the latter corresponding to cyclized product **4c** (M^+, *m/z* = 1165.201). This implies that the isolated material is a mixture of desired cyclized product with unassigned side products. The mixture was soluble in deuterated chloroform, but ^{1}H NMR spectroscopy did not show any signals. Similarly, the oxidation of unsymmetrical hexapyrrolylbenzenes **3d** and **3e**, having ethoxycarbonyl and cyano groups, respectively, also gave black solids. For the material obtained from oxidation of **3d** MALDI-TOF mass spectrometric analysis showed peaks at *m/z* = 1151.397, 1183.348, 1243.376, 1344.365, out of which the peak at 1344.365 corresponds to the completely cyclized product **4d**. For the product obtained by oxidation of **3e** MALDI-TOF mass spectrometric analysis showed a high intensity peak at *m/z* = 1099.312 (*m/z* calcd for $C_{72}H_{30}N_{12}$: 1062.2716). This indicates that compounds **4c**, **4d**, and **4e** have been formed with other inseparable byproducts. In the oxidative cyclization reaction of **3f** with CAN (12.0 equiv), the starting material **3f** was completely consumed to give a brown material, which was purified by column chromatography. The ^{1}H NMR and ^{13}C NMR spectra did not show any resonances,



Scheme 2 Cyclodehydrogenation of hexapyrrolylbenzene **3b** to afford hexapyrrolohexaazacoronene **4b**

and MALDI-TOF mass spectrometry showed a peak at *m/z* = 983.970 (*m/z* calcd for $C_{72}H_{36}N_6O_6$: 1080.2696), indicating it to be an incompletely cyclized product. With these observations we conclude that this protocol is effective for obtaining symmetrically substituted hexaazacoronenes, however, for the unsymmetrically substituted hexaazacoronenes the reaction results in inseparable mixtures of products.

With pure hexapyrrolohexaazacoronene **4b**, we investigated its photophysical properties. As can be seen from the absorption spectra of **2b**, **3b**, and **4b** in dichloromethane (Figure 4), while no maximum was observed for **2b**, hexapyrrolylbenzene **3b** has an absorbance maximum at λ = 434 nm that is blue shifted to λ = 334 nm for the corresponding hexapyrrolohexaazacoronene **4b**. The most interesting observation was that exciting **4b** at its absorption maximum showed a significantly higher fluorescence emission at λ = 490 nm compared to **3b**. This clearly suggests the improved photophysical properties of such a scaffold compared to the hexapyrrolyl benzene that we believe will be useful in developing new dyes and other optoelectronic materials.

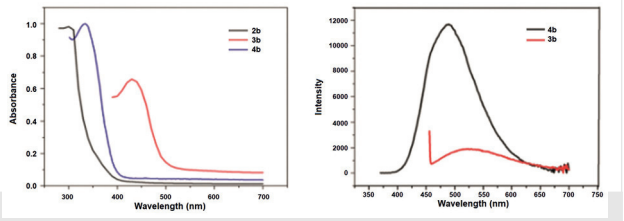


Figure 4 UV/Vis absorption spectrum for hexapyrrolohexaazacoronene and fluorescence spectrum of compound **4b** in dichloromethane

In summary, CAN with high redox potential in comparison with $FeCl_3$ has been explored for oxidative cyclodehydrogenation to synthesize annularly fused hexapyrrolohexaazacoronenes, and we have successfully demonstrated the synthesis of **4b**[16] and its characterization through ^{1}H NMR and ^{13}C NMR spectroscopy and MALDI-TOF mass spectrometry.

Funding Information

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Supporting Information

Supporting information for this article is available online at https://doi.org/10.1055/s-0040-1707822.

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(16) **1,2,3,4,5,6,7,8,9,10,11,12-Dodecakis[4-(trifluoromethyl)phenyl]-2*a*1,2*b*1,4*b*1,6*b*1,8*b*1,10*b*1-hexaazahexacyclopenta[*bc*,*ef*,*hi*,*kl*,*no*,*qr*]coronene (4b)**
Hexapyrrolylbenzene **3b** (1.0 equiv) was dissolved in dry acetonitrile (2 mL) and cerium(IV) ammonium nitrate (12.0 equiv) was added under nitrogen. The reaction immediately turned to black, and the progress of the reaction was monitored by TLC. After completion of the reaction (5 min), the reaction was quenched with water (5 mL) and extracted with EtOAc (3 × 10 mL). After drying and filtration, the combined extracts were concentrated under reduced pressure. The residue was purified by column chromatography on silica gel using EtOAc and hexane as eluent to afford **4b** as a brown solid; yield: 16%. MALDI-TOF-MS calcd for M^+, $C_{114}H_{48}N_{6O6}F_{36}$: 2185.340; found: 2185.596. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.66 (d, *J* = 7.4 Hz, 24 H), 7.58 (d, *J* = 7.8 Hz, 24 H). ^{13}C NMR (300 MHz, $CDCl_3$): δ = 168.9, 137.1, 132.5, 131.9, 131.3, 130.3, 125.8,125.4. ^{13}C NMR DEPT135 (101 MHz, $CDCl_3$): δ = 130.3, 126.1. ^{13}C NMR DEPT90 (75 MHz, $CDCl_3$): δ = 130.3, 126.1. ^{19}F NMR (282 MHz, $CDCl_3$): δ = –63.25. MALDI-TOF calcd for M^+, $C_{114}H_{48}F_{36}N_6$: 2185.340; found: 2185.956.