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Extension of Pyrrolopyrrole π-System: Approach to Constructing Hexacyclic Nitrogen-Containing Aromatic Systems

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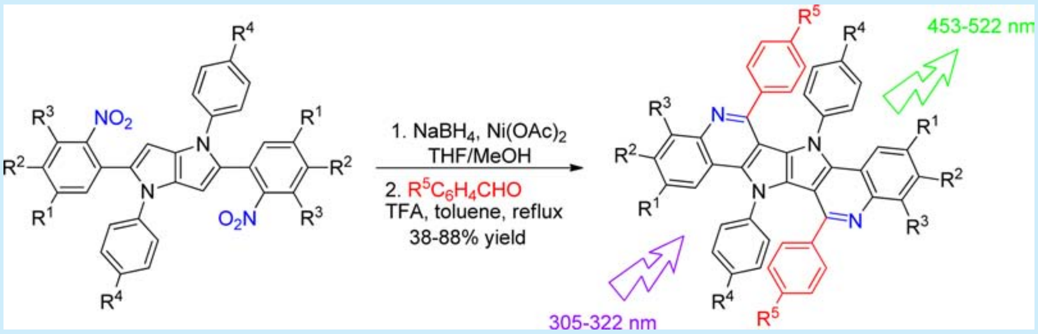
S *Supporting Information*



ABSTRACT: A facile three-step approach to synthesizing quinoline-fused pyrrolopyrroles is reported. The crucial step in this synthesis is the condensation of 2-aminophenyl substituted pyrrolopyrroles with aromatic aldehydes. The resulting hexacyclic ladder-type dyes strongly absorb UV radiation and exhibit fluorescence at 450−510 nm. The presence of pyridine-type and pyrrole-type nitrogen atoms is important for the electronic properties of this almost planar heterocycle. These heteroatoms, along with the addition of moderate electron-withdrawing and electron-accepting substituents, provide a means for fine-tuning of the emission characteristics of the polycyclic conjugates.

The recent explosion of the interest in ladder-type thiophene-based heterocycles[1] is a corollary of application-driven research encompassing, for example, N-type field-effect transistors,[2] nonlinear optical materials,[3] and mechanosensitive membrane probes.[4,5] The recent reports of new heteroacenes, such as dithieno[2,3-*d*:2′,3′-*d*′]-thieno[3,2-*b*:3′,2′-*b*′]dipyrrole,[6] dithienothieno[2,3-*d*;2′,3′-*d*′]-benzo[1,2-*b*:4,5-*b*′]dithiophenes,[7] and dibenzothiopheno[6,5-*b*:6′,5′-*f*]-thieno[3,2-*b*]thiophene[8] are a testimony for the potential importance of such conjugates. Moreover, the fundamental work by Bäuerle et al. not only proves their superior performance in different types of organic solar cells[9] but also shows that a long S,N-heteroacene, containing six[10] and ten units, respectively, can be feasibly prepared.[11]

This overwhelming presence of S-heteroacenes in the literature does not change the fact that analogous pyrrole-based heteroacenes have several distinct advantages over their analogs comprising thiophene and furan,[12] specifically, (1) pyrrole is a better electron-donor than thiophene and furan, which can lead to improved p-type organic semiconductors and (2) functionalization of nitrogen in pyrrole is possible (in contrast to oxygen in furan or sulfur in thiophene), which enables the addition of various groups for controlling polarity and solubility. Although indolo[3,2-*b*]indole scaffolds have been known for over 130 years,[13,14] the protocols for the preparation of such heterocyclic compounds are relatively scarce and limited. Most of the reported reactions involve the reduction of 2,2′-dinitrobenzil[15] and 2,2′-dinitrophenylacetylene,[15c,16] Cadogan cyclization of 2,2′-dinitrostilbene[17] or 2-nitrophenylindole,[18] and Sundberg cyclization of 2,2′-diazidostilbene.[19] Most of these methods suffer from low yields and tedious synthesis of the needed precursors. Moreover, they require relatively harsh conditions and almost nothing is known about their general applicability.

Conversely, the recent significant progress in the synthesis provides alternative venues toward indolo[3,2-*b*]indoles. Liu and co-workers found that self-condensation of methyl 2-aminobenzoate under basic conditions, followed by treatment of the resulting dibenzodiazocinedione with PCl_5 and hydrogenation of the obtained dichlorodibenzodiazocine in the presence of PtO_2 or zinc powder, leads to indolo[3,2-*b*]indoles with excellent yields.[20] Langer et al. developed a different approach based on 2-fold Pd-catalyzed cross coupling of 2-bromophenyl-3-bromoindoles.[21]

Limited access to indolo[3,2-*b*]indole is probably the major factor determining the low interest in this heterocyclic compound despite its immensely promising photophysical properties. Indolo[3,2-*b*]indoles absorb strongly in the UV spectral region and exhibit fluorescence quantum yields in the range of 30−50%.[21] Their HOMOs (Highest Occupied

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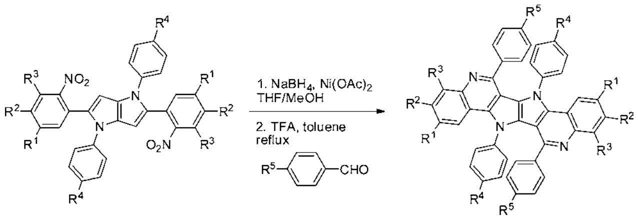
Molecular Orbitals) have some of the highest energy levels among all electron-rich heterocycles. Moreover, indolo[3,2-*b*]indole based polymers prove successful as electroluminescence layers in OLEDs (Organic Light Emitting Diodes)[22] and have promising nonlinear optical properties.[23]

Given the recent interest in both ladder-type[24] and linear *N*-heteroacences,[25] we explore the synthesis of hybrid heteroacenes possessing both pyridine- and pyrrole-type N-atoms. Accordingly, here we report an operationally simple three-step procedure for the preparation of 7,14-dihydroquinolino-[3″,4″:4′,5′]pyrrolo[2′,3′:4,5]pyrrolo[3,2-*c*]quinolines (QPPQ).

We recently discovered that tetraaryl-pyrrolo[3,2-*b*]pyrroles (TAPPs) can be efficiently synthesized in multicomponent reactions with aromatic aldehydes, aromatic amines, and diacetyl.[26] It allows us to hypothesize that 2,5-bis(2-nitrophenyl)-substituted TAPPs are feasible for the synthesis of heretofore unknown heteroanalogues of indolo[3,2-*b*]indoles. This strategy relies on the reduction of nitro groups, followed by condensation with aromatic aldehydes. It should lead to a Pictet−Spengler type of reaction, giving an easy access to QPPQ. This type of synthetic scheme is also used in the synthesis of phenanthridines and *π*-expanded phenanthridines.[27]

To test our hypothesis, we attempt the reduction of a variety of 2,5-bis(2-nitrophenyl)-substituted TAPPs possessing both electron-withdrawing and -donating moieties bonded to the benzene rings with the nitro groups (Table 1). Based on our previous work, we employ 4-*n*-alkylaryl substituents at the nitrogen atoms to secure good solubility of the expected products.[28] After short optimization of the reduction of NO_2 to NH_2 groups, we determine that $NaBH_4$ in combination with $NiCl_2$ or $Ni(OAc)_2$[29] is superior in comparison with palladium on charcoal catalyzed methods. The resulting bis(2-aminophenyl) substituted pyrrolo-[3,2-*b*]pyrroles appear to be relatively unstable; in particular, they are sensitive to light. Therefore, we use this material without any further purification. Subsequent condensation with aromatic aldehydes in boiling toluene, in the presence of catalytic amounts of trifluoroacetic acid,[27b] affords the desired QPPQs in moderately good yields. We select aldehydes containing both electron-withdrawing and -donating functional groups in order to establish the scope of this reaction and to investigate the relationship between structure and optical properties. Both electron-poor and -rich aldehydes efficiently participate in this reaction. The prepared compounds precipitate directly from the reaction mixture as light yellow crystals, and they are bench stable and show a high propensity for trapping solvent molecules in their crystal lattice. X-ray crystallography unambiguously confirms the structures, demonstrating that the azaindolo[3,2-*b*]azaindole core is perfectly planar, whereas external benzene fused rings are twisted by 10.81° and 11.09° from the plane determined by the azaindolo[3,2-*b*]azaindole scaffold (Figure 1). Aryl rings fixed to the azaindolo[3,2-*b*]azaindole core and pyridine rings are twisted by ca. 66°−72° and 55°−62°, respectively. Therefore, one can expect only moderate electronic coupling between the core and the substituents. The lengths of newly formed C−N bonds are 1.32 and 1.38 Å, with the shorter bond being adjacent to the cyanophenyl substituent, whereas the length of C−N bonds in unsubstituted pyridine is 1.37 Å. The unit cell of the $P2_1/c$ space group contains five molecules. It appears that the side alkyl chains play a crucial role in such an arrangement of **11** in the crystal lattice, as each alkyl chain interacts with the cyanophenyl substituent of the neighboring molecule. The distance between these two fragments is only 4.72 Å.

Table 1. Synthesis of Diquinolino[3,4-*b*:3′,4′-*f*]pyrrolo[3,2-*b*]pyrroles



TAPP	R^1	R^2	R^3	R^4	R^5	QPPQ (% yield)
1	H	H	OCH_3	C_6H_{13}	CN	**6** (54)
1	H	H	OCH_3	C_6H_{13}	CH_3	**7** (65)
1	H	H	OCH_3	C_6H_{13}	OCH_3	**8** (42)
2	H	H	H	C_8H_{17}	CN	**9** (38)
3	H	H	H	OCH_3	CN	**10** (60)
4	H	CF_3	H	C_4H_9	CN	**11** (63)
5	F	H	H	C_4H_9	OCH_3	**12** (88)

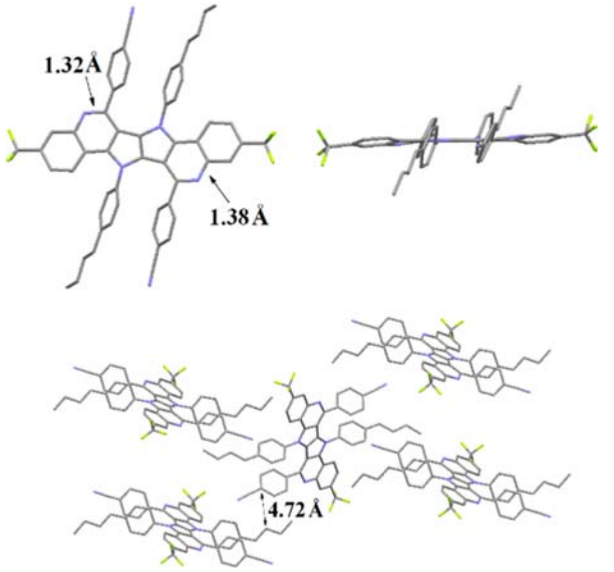


Figure 1. Molecular structure and packing of **11** in the crystal as determined from X-ray diffraction analysis. Hydrogen atoms are omitted for clarity.

To our knowledge, neither dihydroquinolino-[3″,4″:4′,5′]-pyrrolo[2′,3′:4,5]pyrrolo[3,2-*c*]quinolines nor dipyridino[3,4-*b*:3′,4′-*f*]pyrrolo[3,2-*b*]pyrroles have ever been reported.

The produced set of QPPQs provides a means for a systematic study of their spectroscopic properties. The centrosymmetric nature of new heterocycles, combined with the angular arrangement of fused rings, suggests that these compounds will not exhibit as significant bathochromic shifts in their absorption as the starting TAPPs. Accordingly, all QPPQs absorb in the UV region with a single strong band at 305−322 nm and a shoulder at around 360 nm (Table 2, Figure 2). Their fluorescence maxima, however, are in the 453−527 nm region, resulting in large Stokes shifts (of almost 14 000 cm^{-1} for **12**). We did not observe any apparent relationship between the structure (the character of the substituents) and the absorption maxima, which is in agreement with our expectation that the twists of the phenyl substituents

Table 2. Spectroscopic Properties of Diquinolino[3,4-*b*:3′,4′-*f*]pyrrolo[3,2-*b*]pyrroles Measured in $CHCl_3$

QPPQ	λ_{abs}^{max} (nm)	ε_{max} ($M^{-1}\,cm^{-1}$)	λ_{em}^{max} (nm)	Stokes shift (cm^{-1})	Φ[a] (%)
6	322	69 400	504	11 200	13
7	315	58 600	464	10 200	2.0
8	317	81 200	453	9500	4.2
9	314	65 000	510	12 200	14
10	315	45 700	513	12 300	7.4
11	318	68 500	499	11 400	14
12	305	59 100	527	13 800	19

[a] Fluorescence quantum yield measured with quinine sulfate as a reference.

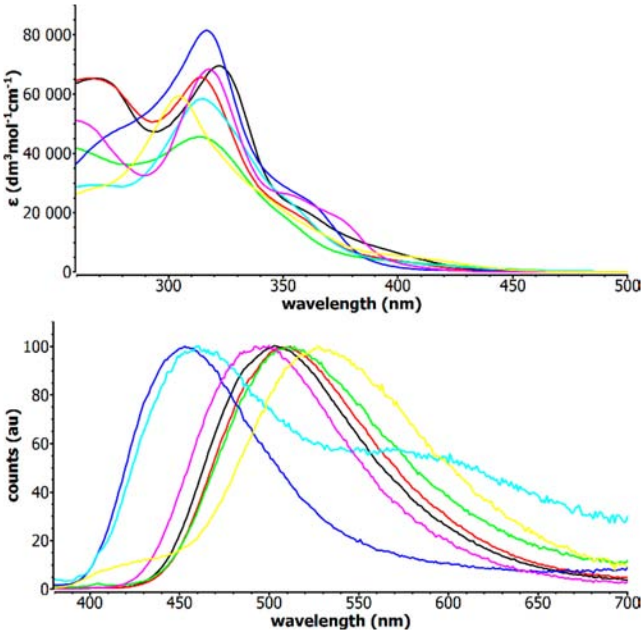


Figure 2. Absorption (top) and emission (bottom) spectra of **6** (black), **7** (cyan), **8** (blue), **9** (red), **10** (green), **11** (magenta), and **12** (yellow).

suppress the electronic communication in the ground state between these fragments and the core of the molecule. The values of the molar extinction coefficients are within a relatively narrow range of 59 000–69 000 $M^{-1}cm^{-1}$. Only two compounds deviate from this trend. Compound **8** is the only one that has a strong electron-donating group at R^5, while **10** is the only compound possessing a strong electron-donating group at R^4. Possibly, the presence of electron-donating groups at these positions has major influence on the oscillator strength of the $S_0 \rightarrow S_1$ transition. The comparison of the photophysical data for compounds **6**–**8** reveals that the electronic character of the substituent has no effect on the absorption maxima while the electron-withdrawing substituent (CN) caused a significant shift in the emission maxima (~50 nm, as compared with compound **8** possessing two 4-methoxyphenyl groups). This finding proves that the conformation of the excited state is more planar than that of the ground state, which allows the substituents to affect the core relatively strongly. It also signifies that in compounds **6**–**8** the whole core is electron-rich due the combined effect of the electron-rich pyrrole[3,2-*b*]pyrrole unit and two MeO groups. Furthermore, the effect of electron-donating groups would be amplified (due to the formation of push–pull system). In the case of such ladder-type heteroacenes, the effect of substituents bonded to the peripheral benzene ring seems to be crucial. The presence of electron-donating MeO groups amplifies the effect of the 4-cyanophenyl substituent. Conversely, if fluorine atoms are present, the 4-methoxyphenyl groups have a stronger effect on the photophysical properties (Table 2, Figure 2). As a result, compounds **7** and **8** emit at much shorter wavelengths than other QPPQs, which also leads to a smaller Stokes shift. On the other hand, the effect of *N*-aryl substituents is rather negligible (**10** vs **9**).[30]

Some of the prepared QPPQs are moderately fluorescent, with fluorescence quantum yields in the range of 2–19%. Compared with another ladder-type all-nitrogen system, namely diindolo-[2,3-*b*:2′,3′-*f*]pyrrolo[3,2-*b*]pyrroles,[28b] current diquinolino-[3,4-*b*:3′,4′-*f*]pyrrolo[3,2-*b*]pyrroles have weaker fluorescence, hypsochromically shifted absorption, and bathochromically shifted emission. An analogous diquinolino[2,3-*b*:2′,3′-*f*]-pyrrolo[3,2-*b*]pyrrole that is more linear[20b] has different optical characteristics; its absorption is bathochromically shifted and broader, displaying two bands at 380 nm and a broader one at 480 nm.

We employ cyclic voltammetry (CV) and differential pulse voltammetry (DPV) to investigate the electrochemical properties of **6**–**12**. None of the tested QPPQs exhibit well-defined reduction processes.

Compounds **6**, **8**, **9**, and **11**, however, display two reversible or quasi-reversible oxidation waves (Table 3, Figure 3). Com-

Table 3. Redox Potentials of Selected QPPQs Measured in 0.1M $TBAPF_6$ + CH_2Cl_2[a]

QPPQ	E_{ox1} (V)	E_{ox2} (V)	E_{HOMO} (eV)
6	0.67		−5.01
8	0.49	0.87	−4.83
9	0.64		−4.98
11	0.81		−5.17

[a] Potentials are given relative to Fc/Fc+.

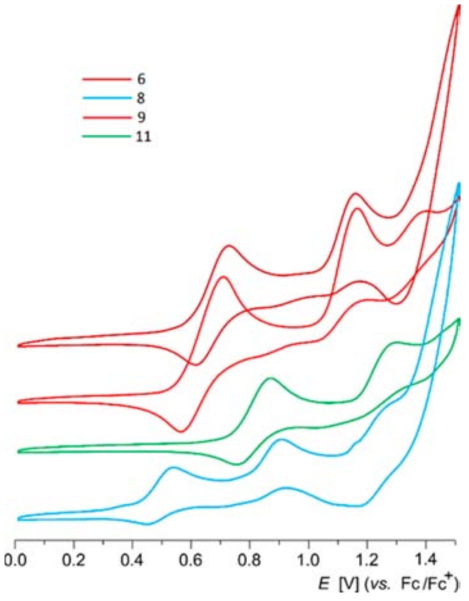


Figure 3. Cyclic voltammograms of selected QPPQs in 0.1 M $TBAPF_6$ + CH_2Cl_2, scan rate: 50 mV s^{-1}.

pounds **7**, **10**, and **12** exhibited only irreversible oxidation as determined by both CV and DPV experiments (Table S1, Figures S1, S2). Half-wave potentials $E_{1/2}^{\mathrm{ox}}$ of the tested compounds are in the range of 0.5−0.87 V vs ferrocene with compound **11** possessing the highest first oxidation potential due to the presence of strong electron-withdrawing substituents. For comparison, the electron-rich **8** has an $E_{1/2}^{\mathrm{ox}}$ that is lower by 0.32 V than in the case of **11**, whereas previously reported diindolopyrrolopyrroles[28b] have the first oxidation potential that is lower by ca. 0.6 V than that for structurally related QPPQs. The HOMO energy levels of compounds **6**, **8**, **9**, and **11** are estimated to be −5.16 to −4.84 eV, which is ca. 0.3 eV higher than values calculated for diindolopyrrolopyrroles. The difference in the photophysical properties resulting from fusion of an electron-poor quinoline moiety or an electron-rich indole fragment[28b] is well reflected.

In conclusion, we report a facile three-step approach to synthesizing π-extended aza-analogues of indolo[3,2-*b*]indoles. There is no need for chromatographic purification at any stage of this sequence of reactions, thus, allowing the preparation of these hexacyclic heterocycles with ease. The prepared hexacyclic ladder-type dyes display attractive optical properties, such as strong absorption in the UV region and a large Stokes shift. Interestingly, the hybrid nature of their electronic structures is responsible for tuning their fluorescence properties via electron-donating and -withdrawing substituents at the periphery. Furthermore, the electrochemical properties of QPPQs show that they are highly resistant toward reduction; however, they can be oxidized at potentials slightly more positive than those reported for diindolopyrrolopyrroles.[28b]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b03129.

> All experimental details, copies of ^{1}H NMR and ^{13}C NMR spectra for compounds **1**−**12**, X-ray diffraction data for compound **11** (PDF)
> Electrochemical results and crystallographic data (CIF)

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Notes

The authors declare no competing financial interest.

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