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Cyril Poriel,* Joëlle Rault-Berthelot,* Sébastien Thiery, Cassandre Quinton, Olivier Jeannin, Urelle Biapo, Denis Tondelier, Bernard Geffroy

Since the last 30 years, the fantastic emergence of organic electronics is assignable to the design, the synthesis and the study of thousands of organic semi-conductors (OSCs) with specific properties fitting with the different electronic devices.\textsuperscript{11,14} Since the discovery of the 'host/guest concept' in Phosphorescent Organic Light Emitting Diodes (PhOLEDs),\textsuperscript{15} the design of OSCs usable as host materials for blue emitting phosphors has been an intense research field worldwide.\textsuperscript{16} In addition to its high thermal/morphological stability and its high triplet energy (E\textsubscript{T}), an ideal host should also possess a bipolar character with HOMO and LUMO energy levels adapted to the Fermi levels of the electrodes.\textsuperscript{17-19} However, there is a certain antimony between a high E\textsubscript{T} (essential to insure efficient energy transfers) and a short HOMO/LUMO gap (essential to insure efficient charge injection) and the best trade-off should be found for the ideal host. If the nature of the linkage\textsuperscript{10} between the electron rich and the electron poor units is of key importance to control the E\textsubscript{T} as well as the HOMO/LUMO gap, their intrinsic properties remain nevertheless the most important characteristics. In this context, the widely known electron rich carbazole fragment has led to impressive breakthroughs and is nowadays an important building block in organic electronics.\textsuperscript{11,12} Around the molecular structure of carbazole, many other carbazole-like fragments have been developed in the recent years sometimes surpassing the performance of the carbazole fragment in electronics. Thus, indolocarbazole (IC),\textsuperscript{13} phenylacridine (PA)\textsuperscript{14-16} and more recently indoloacridine (IA)\textsuperscript{17} are nowadays key building blocks, widely used in all organic electronic devices.

Scheme 1: Synthesis of SQPTZ-F and SQPTZ-TXO\textsubscript{2}
SQPTZ-F and SQPTZ-TXO\textsubscript{2} were readily obtained through a short and highly efficient synthetic approach by coupling the halogeno-aryl 10-(2-bromophenyl)-10H-phenothiazine 1, obtained from the copper catalysed Goldberg coupling of phenothiazine and 2-bromoisodibenzene (Scheme 1), with either 9-fluorenone (for SQPTZ-F) or 9H-thioxanthene-9-one-10,10-dioxide (for SQPTZ-TXO\textsubscript{2}) as the basis. The corresponding fluorenol 2 and thioxanthenol 3 respectively obtained were not isolated and were involved in an intramolecular electrophilic substitution to provide the two targets SQPTZ-TXO\textsubscript{2} and SQPTZ-F with good yields. These short and efficient synthetic approaches allow a gram-scale preparation, key feature for electronic applications. X-ray diffraction data (Figure 1) show that SQPTZ-F crystallizes in a monoclinic system, P\textsubscript{2}\textsubscript{1}/a, revealing an asymmetric unit containing two molecules (Mo1/Mo2, see Fig. S1-S4/S7-S10 in SI) whereas SQPTZ-TXO\textsubscript{2} crystallizes in a triclinic system P\textsubscript{1} with also two molecules (Mo1/Mo2, see Fig. S13-S16/S19-S22 in SI). The very large value of the molecular radius of each molecule...
oxidation waves have been assigned to two.

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formed by electrochemical studies with the phenothiazine and the acridine backbones, atom highlighting the strong steric congestion between the short intramolecular C/C distance of ca 3.0 Å is especially detected between the two carbons in β position of the nitrogen atom highlighting the strong steric congestion between the phenothiazine and the acridine backbones.

Figure 1. Molecular structures of SQPTZ-TXO (top) and SQPTZ-F (bottom) exemplified by one molecule (Mol 1) with extreme values of the different parameters for the 2 molecules present in the asymmetric unit.

The electron rich character of the QPTZ fragment is the most important feature and has been investigated by cyclic voltammetry (Figure 2). In oxidation, the two compounds remarkably present two reversible single electron oxidation processes with peak potentials E1/2 vs SCE recorded at 0.89/1.61 V for SQPTZ-F and at 1.0/1.64 V for SQPTZ-TXO. As TXO and F monieties are oxidised through irreversible processes, these two oxidation waves have been assigned to two single electron transfers involving the QPTZ core. Thus, the first oxidation of the QPTZ fragment remarkably occurs at a less anodic potential than that of the PA (E1/2 ~ 1.11 V in SPA-TXO)[17] and that of the IA core (E1/2 ~ 1.33 V for SIA-TXO and 1.19 V for SIA-F).[14] This strong electron rich character finds hence its origin in the electron donating behaviour of the intracyclic sulphur atom, which fully drives the HOMO energy level of these dyes (Figure 4). Another important feature deserves to be stressed out. Indeed, the reversibility of the two first oxidation waves clearly shows the efficient delocalization of the charges within the QPTZ core, which is not the case for the structurally analogues based on the IA or on the PA core (Figure 2-right).[14, 17] Thus, the sulphur atom has a significant impact on the electrochemical properties not only in terms of potential but also in the stability of the cationic species. From the onset potential pointed at 0.9 V, we determined the HOMO energy level of SQPTZ-TXO at -5.3 eV, significantly higher than that of SPA-TXO (-5.42 eV) and SIA-TXO (-5.61 eV). Similarly, the HOMO energy level of SQPTZ-F (-5.16 eV) is more than 0.3 eV higher than that of SIA-F (-5.48 eV) confirming the strong electron-rich nature of the QPTZ fragment.[14] One can also note that the HOMO energy level of SQPTZ-F is higher than that of SQPTZ-TXO, translating the non-negligible influence of the acceptor unit on the HOMO level via the spiro bridge. Thus, the HOMO energy levels of QPTZ based molecules are high and should favour the hole injection within an electronic device.

In reduction, neither SQPTZ-F nor SQPTZ-TXO present any distinguishable reduction wave before the accessible limit of the present electrolytic solution (see Fig. S33 in SI). We determined their LUMO energy levels from the onset potential of their reduction at -1.85 and -2.06 eV for SQPTZ-F and SQPTZ-TXO, highlighting the stronger electron-poor character of TXO compared to that of F in accordance with the above mentioned results on HOMO energies. The electrochemical gaps (ΔEg) were found to be 3.31 eV for SQPTZ-F and 3.24 eV for SQPTZ-TXO. Thus, SQPTZ-TXO possesses a ΔEg significantly contracted by 0.20/0.3 eV compared to that of the PA and IA counterparts (ΔEg SPA-TXO = 3.43 eV, ΔEg SIA-TXO = 3.56 eV) due to its high HOMO energy level. As the same gap contraction is detected between SIA-F and SQPTZ-F (3.60 vs 3.31 eV resp.), this clearly highlights the strong impact of the QPTZ fragment to contract the gap, independently of the spiro-connected unit. Geometry optimization of the two compounds was performed using density functional theory (DFT, B3LYP/6-31G(d)). The HOMO and LUMO levels follow the same tendencies as those obtained by electrochemical studies with notably a higher HOMO energy level for SQPTZ-F (-5.03 eV) than for SQPTZ-TXO (-5.30 eV). The HOMO levels are spread on the QPTZ fragment (Figure 4), confirming a first electron transfer from this core. The calculated LUMO levels are respectively lying at ~0.92 and ~1.17 eV for SQPTZ-F and SQPTZ-TXO and are spread out on the fluorene of SQPTZ-F and on the TXO of SQPTZ-TXO (Figure 4). There is hence a complete electronic separation between the HOMO and the LUMO, which will have important repercussions on the photophysical processes (see below). This orbital separation is a key point to gather within a single dye the HOMO/LUMO energy levels of the constituting building blocks, a short π-conjugation pathway and a high ΔEg.

Absorption spectra of SQPTZ-TXO and SQPTZ-F are presented in Figure 3A. SQPTZ-F presents an UV-vis spectrum with maxima recorded at 262, 296 and 308 similar to that of its...
building unit fluorene (265, 290, 301 nm) at the exception of the long tail observed between 320 and 360 nm. In the light of TD-DFT, the main absorption band centred at 308 nm is assigned to a transition with two contributions (HOMO/LUMO+4 and HOMO/LUMO+5, f=0.117, see Fig. S37 in SI) implying only the QPTZ fragment, the one at 296 nm is attributed to fluorene-fluorene transition (HOMO-1/LUMO, f=0.067), and the large high energy band at 262 nm to phenyl-phenyl transitions. More importantly, the low energy tail is noticeably large due to the flexibility induced by the presence of the sulphur atom within the QPTZ fragment and is assigned to HOMO/LUMO+1 and HOMO/LUMO+2 transitions (Figure 4-left). Indeed, the calculated absorption spectrum shows that the first excited state corresponds to an HOMO-LUMO transition but with a very weak oscillator strength (f= 0.0002), not detectable experimentally. This is a crucial point in the D-spiro-A design, which finds its origin in the spatial separation of HOMO and LUMO levels (HOMO delocalized on the QPTZ core and LUMO on the fluorene core) leading to through-space forbidden transitions. Oppositely, the HOMO/LUMO+1 and HOMO/LUMO+2 transitions possess oscillator strengths of ca 0.02, being ca 100 times more probable than the HOMO/LUMO transition (Figure 4-left). These transitions involve almost exclusively the QPTZ core which hence governs the optical gap ∆Eopt of SQPTZ-F (ca 3.3/3.4 eV). Despite an almost identical ∆Eopt, the absorption spectrum of SQPTZ-TOXO is slightly different in the low energy region with a broader tail. As observed for SQPTZ-F, the HOMO/LUMO transition of SQPTZ-TOXO possesses a very weak oscillator strength (f=0.003, Figure 4-right) due to the spatial separation of HOMO (centred on QPTZ) and LUMO (centred on TOXO) and is not experimentally observed. Thus, the main low-energy transition is an HOMO/LUMO+1 transition (f= 0.042, see Fig. S39 in SI). There is nevertheless a significant difference between SQPTZ-F and SQPTZ-TOXO, which is linked to the different localization of the LUMO+1 orbital: on the QPTZ core for the former and on the TOXO core for the latter. This difference confers to the HOMO/LUMO+1 transition of SQPTZ-TOXO a notable charge transfer character, which is not the case for SQPTZ-F (see solvatochromic experiments Figure 3D).

SQPTZ-TOXO and SQPTZ-F display almost no fluorescence and the emission spectra were recorded in absence of oxygen (under argon, Figure 3B). Thus, the emission of SQPTZ-F and that of SQPTZ-TOXO appear very similar with a main large and unresolved band at 421 nm. The quantum yields (QY), measured in presence of oxygen, appear very low (QY < 0.05 for both). Thus, QPTZ fragment, due to the insertion of the intracyclic sulphur atom, is very weakly fluorescent in opposition to the IA core, which is highly fluorescent (QY=0.4).17 This feature can be assigned to internal heavy atom effects as recently shown for phenothiazinyl dyes and highlights the significant impact of the sulphur atom on the electronic properties of the QPTZ fragment.18 Solvatochromic experiments allow a deeper understanding of the photophysical properties through the determination of the polarity of the excited states (Figure 3, bottom-right). Indeed, the emission maximum of SQPTZ-F in polar MeCN is recorded at 425 nm, being only very weakly shifted by 4 nm, compared to that in apolar cyclohexane (421 nm), in accordance with a transition occurring with only one fragment involved, namely QPTZ. SQPTZ-TOXO displays a very different behaviour with an impressive red shift of 98 nm between cyclohexane (421 nm) and MeCN (516 nm) highlighting a strong photoinduced Intramolecular Charge Transfer (ICT) character due to the different localization of the HOMO and LUMO+1 levels. Δμ values of 6.05 D and 21.51 D have been evaluated using the Lippert-Mataga formalism (the dipole moments at the ground state obtained through DFT calculations were: 1.6 and 5.1 D for SQPTZ-F and SQPTZ-TOXO, see Fig. 27-29 in SI), translating the different polarity of the two dyes at the excited state (μ=7.5 and 26.6 D resp.). Thus, the strong solvatochromic effect and the corresponding high μ* observed for SQPTZ-TOXO are indicative of a significant photoinduced ICT whereas the negligible solvatochromic effect and the corresponding low μ* observed for SQPTZ-F are indicative of a very weak photoinduced ICT. Thus, the acceptor unit can drastically change the electronic properties of QPTZ based dyes.

Figure 3. Optical properties of SQPTZ-F (black line) and SQPTZ-TOXO (blue line): A: UV-vis absorption spectra (cyclohexane), B: Emission spectra (cyclohexane) at rt under argon (λex=315 nm), C: Emission spectra at 77K (2-MeTHF, λex=315 nm), D: Emission spectra in cyclohexane and acetonitrile.

SQPTZ-TOXO and SQPTZ-F display almost no fluorescence and the emission spectra were recorded in absence of oxygen (under argon, Figure 3B). Thus, the emission of SQPTZ-F and that of SQPTZ-TOXO appear very similar with a main large and unresolved band at 421 nm. The quantum yields (QY), measured in presence of oxygen, appear very low (QY < 0.05 for both). Thus, QPTZ fragment, due to the insertion of the intracyclic sulphur atom, is very weakly fluorescent in opposition to the IA core, which is highly fluorescent (QY=0.4).17 This feature can be assigned to internal heavy atom effects as recently shown for phenothiazinyl dyes and highlights the significant impact of the sulphur atom on the electronic properties of the QPTZ fragment.18 Solvatochromic experiments allow a deeper understanding of the photophysical properties through the determination of the polarity of the excited states (Figure 3, bottom-right). Indeed, the emission maximum of SQPTZ-F in polar MeCN is recorded at 425 nm, being only very weakly shifted by 4 nm, compared to that in apolar cyclohexane (421 nm), in accordance with a transition occurring with only one fragment involved, namely QPTZ. SQPTZ-TOXO displays a very different behaviour with an impressive red shift of 98 nm between cyclohexane (421 nm) and MeCN (516 nm) highlighting a strong photoinduced Intramolecular Charge Transfer (ICT) character due to the different localization of the HOMO and LUMO+1 levels. Δμ values of 6.05 D and 21.51 D have been evaluated using the Lippert-Mataga formalism (the dipole moments at the ground state obtained through DFT calculations were: 1.6 and 5.1 D for SQPTZ-F and SQPTZ-TOXO, see Fig. 27-29 in SI), translating the different polarity of the two dyes at the excited state (μ=7.5 and 26.6 D resp.). Thus, the strong solvatochromic effect and the corresponding high μ* observed for SQPTZ-TOXO are indicative of a significant photoinduced ICT whereas the negligible solvatochromic effect and the corresponding low μ* observed for SQPTZ-F are indicative of a very weak photoinduced ICT. Thus, the acceptor unit can drastically change the electronic properties of QPTZ based dyes.

Figure 4. The first calculated electronic transitions of SQPTZ-F (Left) and SQPTZ-TOXO (Right) by TD-DFT B3LYP/6-31G(d), shown with an isovalue of 0.04 [e bohr−3].

The phosphorescent spectra (Figure 3C), recorded at 77K, appear large and weakly structured and contrarily to the fluorescence spectra, are relatively intense. As the fluorescence of the two molecules is low, the intersystem crossing (ISC) between S1 and T1 is fast and the phosphorescence contribution at 77K is very intense. This is a remarkable characteristic of the QPTZ fragment, which results from the incorporation of the sulphur atom which enhances the ISC by vibronic spin-orbit coupling.19 The transition of highest energy presents a maximum at 459 nm for SQPTZ-F and 454 nm for SQPTZ-TOXO giving respective triplet energy E3 of 2.70 and 2.73 eV. QPTZ based compounds possess hence an E3 of ca 2.7 eV, smaller than those of PA (3.08 eV for SPA-TOXO and 3.02 eV for SPA-F) and IA analogues (2.93 eV SIA-TOXO and 2.87 eV for SIA-F) indicating a different localization of the triplet exciton in IA, PA and QPTZ.
based molecules. In summary, thanks to the QPTZ fragment, the two dyes possess an HOMO/LUMO gap relatively small as well as an \( E_g \) high enough to be used with the blue Flrpic phosphor (\( E_g = 2.62 \) eV\cite{23}). This combination appears appealing for the future design of host materials based on this fragment.

The potential of the QPTZ fragment in electronics has been finally evaluated using SQPTZ-F as host in a blue PhOLED (10% Flrpic). The performance of these devices has been compared to those of structurally related SIA and SPA analogues with exactly the same device architecture. Indeed, in order to accurately compare the performance of the hosts, the device architecture should be strictly identical (see PhOLED architecture in SI). Thus, SQPTZ-F displays a very high EQE of 15.8% at \( J=10 \) mA/cm\(^2\) with corresponding Current Efficiency (CE) of 32.8 cd.A\(^{-1}\) and Power Efficiency (PE) of 21.7 lm.W\(^{-1}\) (see Fig. S40 in SI). These performances are ca 50% higher than those recorded with the IA counterpart SIA-F (EQE of 10.7% at \( J=10 \) mA/cm\(^2\) with corresponding CE of 24.2 cd.A\(^{-1}\) and PE of 13.3 lm.W\(^{-1}\)) (see Fig. S42 in SI). In addition, the turn on voltage \( V_{on} \) (at 1 cd.m\(^{-2}\)) of SQPTZ-F based device appears to be very low, 2.7 V, for a blue PhOLED and significantly lower than that of SIA-F recorded at 3.5 V. This feature clearly translates a better charge injection within the SQPTZ-F Flrpic emitting layer than within the SIA-F/Flrpic one. Similarly, SQPTZ-TXO emits light at a low voltage of 2.8 V and displays a very high EQE of 15.8% (10 mA/cm\(^2\)) with corresponding CE and PE of 33.1 cd.A\(^{-1}\) and 17.6 lm.W\(^{-1}\) (see Fig. S41 in SI), clearly highlighting that these very high performances are induced by the QPTZ fragment. The electroluminescent spectra of all devices (see Fig. S40-41 in SI) are identical, exclusively showing the emission of the blue dopant at 472 and 496 nm close to the photoluminescence of pure Flrpic (468/495 nm in solution in CH\(_2\)Cl\(_2\)), indicating efficient energy transfers.\cite{23} It is also important to mention that SQPTZ-F and SQPTZ-TXO displays a better performance and a lower turn on voltage than structurally related IA and PA compounds reported in literature. Thus, SIA-TXO\(_\text{2}\) (EQE of 12.7 % at 10 mA.cm\(^{-2}\)) with corresponding CE of 27.7 cd.A\(^{-1}\), PE of 14.5 lm.W\(^{-1}\) and a \( V_{on} \) of 2.9 V\cite{17} and SPA-TXO\(_\text{2}\) (EQE of 11.4% at 10 mA.cm\(^{-2}\)) with CE of 28.4 cd.A\(^{-1}\), LE of 14.4 lm.W\(^{-1}\) and a \( V_{on} \) of 2.9 V\cite{15} both display a lower performance and a higher \( V_{on} \) than that exposed above. Thus, switching from IA or PA core to QPTZ allows a strong EQE increase as well as a decrease of the \( V_{on} \). Some recent universal hosts based on the indolocarbazole backbone, namely diphenyl-indolocarbazole (EQE=10.4%) and phenylpyridine-indolocarbazole (EQE=13.4%)\cite{10} also display lower performance for Flrpic based devices than those reported herein, indicating the strong potential of the QPTZ core in electronics.

In summary, this work reports the first example of a new molecular fragment, namely QPTZ, used in electronics. The QPTZ fragment can be easily synthesized, presents a high HOMO level, -5.2/5.3 eV and a moderate \( E_g \) value of ca 2.7 eV. This combination leads to high-efficiency blue PhOLEDs displaying higher performance (increase by 50%) than those reported with the PA and IA analogues. This preliminary result highlights the potential of this fragment in the field of PhOLEDs. We believe that the future development of QPTZ based materials is appealing for other organic devices and can advance the field of organic semi-conducting materials.

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Keywords: Quinolophenothiazine - PhOLED - organic semi-conductors-spiro compounds


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Organic Semi-conductors

Cyril Poriel,* Joëlle Rault-Berthelot,* Sébastien Thiery, Olivier Jeannin, Urelle Biapo, Denis Tondelier, Bernard Geffroy

We report a novel electron-rich fragment for organic electronic applications, namely the quinolophenothiazine (QPTZ). The sulphur atom of QPTZ fragment plays a major role in the electronic properties (increasing the HOMO energy level, modulate the spin-orbit coupling…) and leads to highly efficient blue Phosphorescent Organic Light Emitting diode, indicating the strong potential of this new molecular fragment in organic electronics.