

Phosphorus Heterocycles

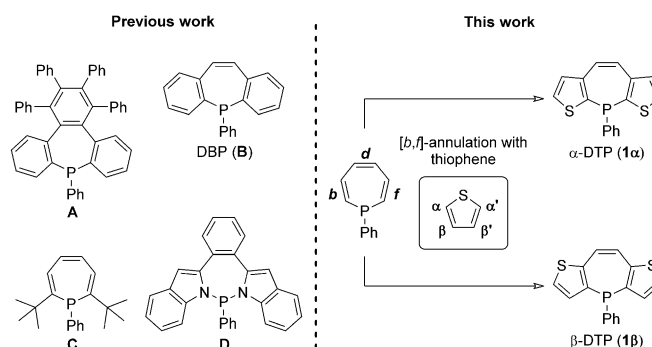
Isomeric Dithienophosphepines: The Impact of Ring Fusion on Electronic and Structural Properties

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Abstract: The synthesis and extensive experimental (X-ray crystallography, UV/Vis spectroscopy, cyclic voltammetry) and theoretical (DFT calculations) characterization of two isomeric dithieno[*b,f*]phosphepines (DTPs) are presented herein. The relative orientation of the phosphepine and the thiophene moieties has a decisive impact on the electronic and structural properties of these compounds. Moreover, the thiophene units allow for a facile subsequent functionalization through direct Pd-catalyzed C–H coupling, which renders DTPs highly promising building blocks for organophosphorus functional materials.

Heteroatoms are commonly implemented into π -conjugated scaffolds to achieve diverse organic materials with desirable optical and electronic properties.^[1] In this context, phosphorus holds a privileged position due to its versatile electronic nature and reactivity, which allows for efficient molecular property tuning.^[2]

For this reason, phospholes, the phosphorus-containing analogues of cyclopentadiene, have emerged as promising building blocks for organic materials with unique electronic and redox properties.^[2a,b,3] In contrast, the larger seven-membered phosphorus heterocycles, so-called phosphepines, have not been studied yet in detail. This is mainly due to synthetic challenges arising from the high thermodynamic instability of these compounds.^[4] As a matter of fact, early reports on the synthesis of unsubstituted phosphepines describe their rapid degradation already at room temperature.^[5] Stabilization can be achieved through steric shielding of the phosphorus center



Scheme 1. Schematic depiction of reported phosphepines (left) as well as isomeric dithieno[*b,f*]phosphepines (DTPs, right). The notations α - and β -DTP refer to which positions of the thiophenes are bridged by the phosphorus.

or annulation of the [*b,d,f*]-C=C double bonds (compounds **A–D**, Scheme 1, left).^[6] Especially the fusion of (hetero)aromatic rings to the [*b,f*]-bonds proved to be a desirable motif as the precursors for this strategy are easily made from simple starting materials.^[6b,d] Only recently, the annulation strategy was exploited to furnish dibenzo[*b,f*]phosphepines (DBPs, **B**)^[7] and diazaphosphepines (**D**),^[8] both showing remarkable stability. The bottleneck of this chemistry is the variety of derivatization that can be applied to these systems, which up to now required mostly the preinstallation of suitable functionalities and carrying them through the entire synthetic sequence.^[8] Thus, the realization of phosphepine-based small molecules that allow for π -expansion by post-functionalization methods is a desirable goal.

In this connection, thiophene-fused phosphepines are interesting synthetic targets due to the well-established rich chemistry of thiophenes allowing for regioselective functionalization.^[9] Several dithieno[*b,f*]phosphepines (DTPs) are in principle feasible, depending on the relative orientation of the fused heterocycles. Among these, we were particularly interested in the two symmetric isomers α -DTP (**1 α**) and β -DTP (**1 β** , Scheme 1, right). Both scaffolds have been reported previously, however, no photophysical and electrochemical investigations of **1 α** have been described.^[6b] Moreover, β -DTP was only isolated as pentavalent phosphine oxide.^[10] With this work, we therefore provide a reliable and scalable synthesis of trivalent and pentavalent DTPs and discuss the influence of the isomerically different ring fusions on the electronic and structural properties of these compounds. Additionally, we explored the possibilities of post-functionalization at the thiophene moieties to achieve novel π -expanded DTPs.

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For the realization of α -DTP and β -DTP we combined the strategy reported by Lammertsma and co-workers for DBP^[7] with the synthetic route towards thiophene-fused borepines described by Tovar and co-workers.^[11] In detail, DTPs were synthesized starting from isomeric (*Z*)-dithienylethenes^[12] **2** and **3** allowing for the incorporation of phosphorus at either the α - or the β -positions of the thiophene moieties (Scheme 2, left). Given that oxidation of trivalent phosphepines during chromatography is a known issue, borane adducts **4 α** and **4 β** were synthesized first in 46% and 69% yield, respectively, through a sequence of lithiation using *t*BuLi, ring closure through treatment with PPhCl₂, and protection of the phosphorus center with borane dimethylsulfide. Deprotection with 1,4-diazabicyclo[2.2.2]octane (DABCO) gave the desired DTPs **1 α** and **1 β** in yields of 96% and 91%, respectively. Additionally, the phosphorus center was further modified through treatment with H₂O₂ to afford the corresponding DTP oxides **5 α** and **5 β** in 82% and 93% yield, respectively. All DTP derivatives were prepared on a gram scale and handled under ambient conditions, however, slow oxidation of the parent DTPs **1 α** and **1 β** was observed during storage of the isolated solids at room temperature.

Single crystals of all DTP derivatives suitable for X-ray crystallography were obtained by slow liquid diffusion of *n*-pentane into CH₂Cl₂ solutions of the corresponding compounds at room temperature (Scheme 2, left). Owing to the nonplanar seven-membered rings, all derivatives adopt butterfly shaped structures with an average dihedral angle of 145° between the thiophene moieties, whereby **1 β** has the most bent structure (134°) and **5 β** the most flattened one (156°). Regarding the environment of the phosphorus center, the sum of C-P-C bond angles ($\Sigma_{\text{C-P-C}}$) ranges from 303.9° (**1 β**) to 319.1° (**5 α**), which is similar to the pyramidalizations of PPh₃ ($\Sigma_{\text{C-P-C}} = 308.4^\circ$)^[13] and PPh₃O ($\Sigma_{\text{C-P-C}} = 318.6^\circ$).^[14] Whereas the P-C_{phenyl} bond lengths of the DTP derivatives (P-C_{phenyl} 1.80–1.84 Å) lie in the same range as the P-C bond lengths of PPh₃O (1.80 Å)^[14] and PPh₃ (1.83 Å),^[13] the P-C_{ring} bonds are found to be slightly shorter with an average length of 1.789 Å throughout the series. In

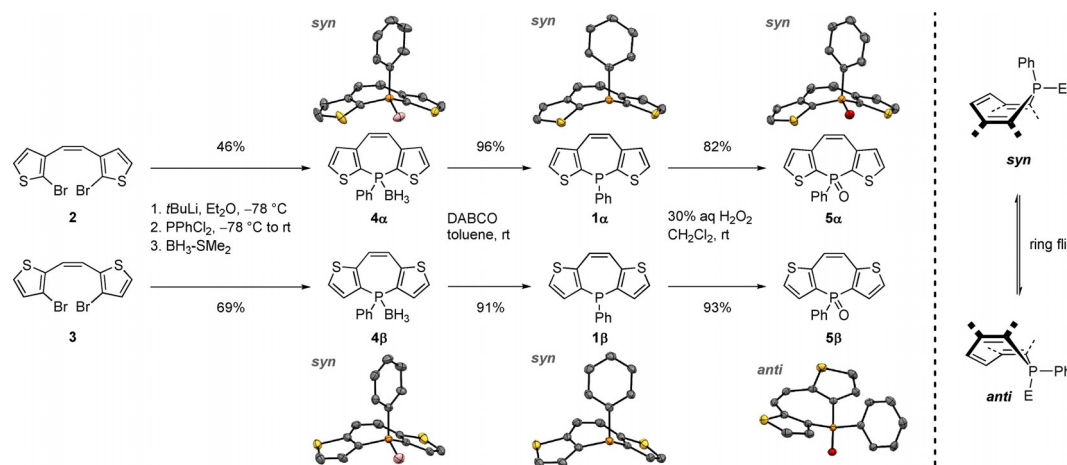
this connection, it is worth mentioning that the P-C_{ring} bonds in the α -isomers are on average slightly shorter by 0.016 Å than in the β -derivatives (Table S1, Supporting Information).

DTP oxide **5 β** adopts a different conformation than the other DTPs with its oxygen atom being oriented almost perpendicular to the DTP backbone (*anti* conformation). These features agree with those of the crystal structure reported for the same compound by Delouche et al.^[10] In contrast, the lone pairs, borane units, and oxo groups, respectively, are pointing in the same spatial direction as the thiophenes (*syn* conformation) in case of all other derivatives. It has been shown computationally that *syn* and *anti* conformations of phosphepines can interconvert through ring flip of the seven-membered ring with rather small activation barriers ≤ 5 kcal mol⁻¹ (Scheme 2, right).^[4b,15] Based on calculations performed at the B3LYP-D3/def2-TZVPD level of theory (Figure S39, Supporting Information), we found the *syn* conformation of **1 α** and **1 β** to be lower in energy by 3.6 and 5.7 kcal mol⁻¹, respectively, than the corresponding *anti* geometries. In case of the oxides **5 α** and **5 β** , this energy difference amounts to less than 1 kcal mol⁻¹. With such small energetic preferences in mind, it can be assumed that the observed conformations in the crystal structures are a result of packing effects.

A common packing motif or distinct intermolecular interactions were not observable in the solid state packing of DTPs **1**, **4**, and **5**, except for **1 β** showing S...S interactions with a distance of 3.6 Å (Figure S32, Supporting Information).

The electronic properties of DTPs **1** and **5** were investigated through UV/Vis absorption and fluorescence spectroscopy (in CH₂Cl₂) as well as cyclic voltammetry (in THF) and the results were corroborated by DFT calculations performed at the B3LYP-D3/def2-TZVPD level of theory.

The lowest-energy absorption wavelengths (λ_{max}) of the β -isomers are considerably red-shifted by 31–39 nm as compared with the α -derivatives (Figure 1, Table 1). The optical band gaps obtained from UV/Vis spectroscopy are in qualitative agreement with the calculated HOMO–LUMO gaps, which are found to be around 0.5 eV smaller for the β -DTPs (Figure 2).



Scheme 2. Synthesis of α - and β -DTPs starting from isomeric (*Z*)-dithienylethenes together with ORTEP plots of DTPs drawn at the 50% probability level (left). Hydrogen atoms are omitted for clarity. Conformational ring inversion of phosphepines (right, E = lone pair, BH₃, O).

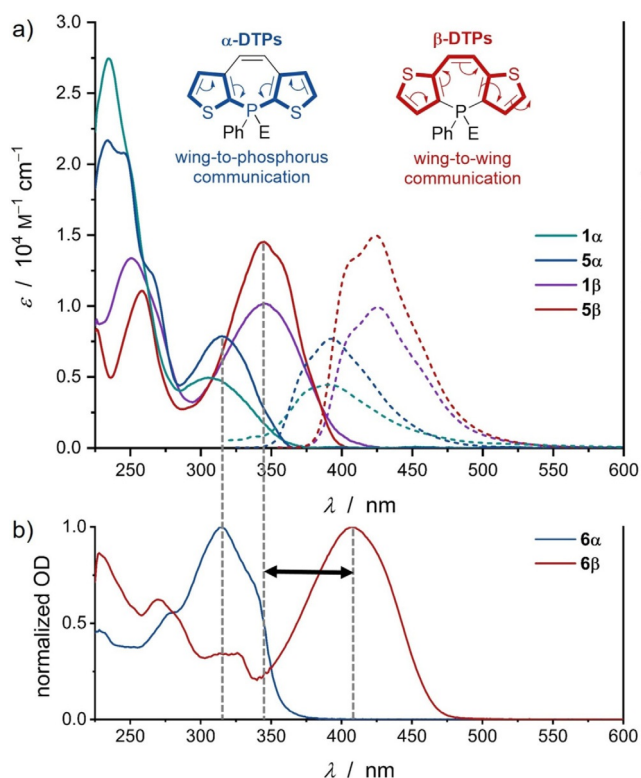


Figure 1. a) UV/Vis absorption (solid lines) and fluorescence spectra (dashed lines) of DTPs **1** and **5** recorded in CH₂Cl₂ at room temperature. The inset shows the different conjugation pathways within α- and β-isomers (E = lone pair, O). b) Normalized (with respect to the lowest energy absorption bands) UV/Vis absorption spectra of π-expanded DTPs **6** recorded in CH₂Cl₂ at rt.

These findings point to the presence of a longer effective conjugation pathway in the β-DTPs, as a result of the relative orientation of the thiophenes allowing for electronic communication between the outer α-positions through the [d]-bond of the seven-membered ring (wing-to-wing communication, Figure 1). It is worth mentioning that Tovar and co-workers have reported similar observations in isomeric dithieno[*b,f*]borpines (DTBs), however, the effect in this case was much less pronounced with a redshift of only 12 nm of the λ_{max} value of the β-isomer.^[11]

All DTPs feature weak ($\Phi_F < 5\%$) blue light fluorescence in solution (CH₂Cl₂). The fluorescence spectra are mirror-imaged

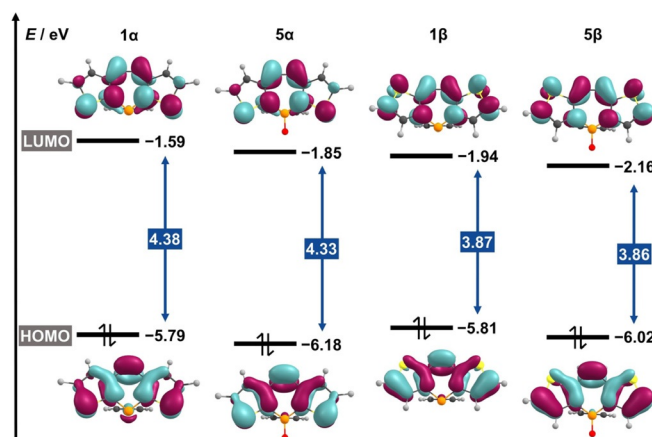


Figure 2. Kohn-Sham FMOs of isomeric DTPs **1** and **5** as obtained from DFT calculations at the B3LYP-D3/def2-TZVPD level of theory.

to the corresponding lowest-energy absorption bands with large Stokes shifts of approximately 80 nm (5500–7000 cm⁻¹). Recent studies have shown that dibenzannulated arsepines as well as other 8π-electron heteropines undergo planarization upon photoexcitation due to a gain of excited-state aromaticity (Baird's rule)^[16] resulting in unusually large Stokes shifts.^[17] Although computations suggest that phosphepines might behave similarly,^[17a] our experimental results provide no indication for such effect as the fluorescence of trivalent and penta-valent DTP derivatives is essentially the same.

The electrochemical data of DTPs **1** and **5** is summarized in Table 1. Anodic events were not observable within the electrochemical window (< 1.0 V) except for **1β**, which shows an irreversible oxidation at +0.67 V. All derivatives feature a reversible or quasi-reversible reduction between -2.2 and -2.8 V (vs. Fc/Fc⁺). Going from trivalent DTPs **1** to oxides **5** lowers the reduction potential by approximately 0.3 V. Regarding the influence of the relative orientation of thiophene and phosphepine it is discernible that the reduction potentials of the α-DTPs are cathodically shifted by 0.2 V as compared with their isomeric counterparts. In analogy to this observation, the calculated LUMO levels of **1α** and **5α** are higher in energy by 0.25–0.3 eV than those of their isomeric relatives (Figure 2). These trends can be explained by a higher electron density around the phosphorus center in the α-isomers. In detail, the

Table 1. UV/Vis spectroscopic, electrochemical, and theoretical data of DTPs **1**, **5**, and **6**.

Compound	λ _{max} [nm] ^[a]	ε [M ⁻¹ cm ⁻¹]	E _{gap} [eV] ^[b]	HOMO–LUMO gap [eV] ^[c]	λ _{em} [nm] ^[a]	Stokes shift [nm] ([cm ⁻¹]) ^[d]	Φ _F ^[e] [%]	E _{red,1} [V] ^[f]
1α	306	4900	4.05	4.38	390	84 (7050)	< 1	-2.74
5α	314	7800	3.95	4.33	392	78 (6340)	2	-2.40
1β	345	10200	3.59	3.87	425	80 (5460)	< 1	-2.52
5β	345	14500	3.59	3.86	424	79 (5400)	5	-2.22
6α	314	–	3.95	–	424	110 (8260)	1	-2.16
6β	407	–	3.05	–	479	72 (3690)	13	-1.93

[a] Measured in CH₂Cl₂ at room temperature. [b] Optical band gap calculated using $E_{\text{gap}} = h \cdot c \cdot \lambda_{\text{max}}^{-1}$. [c] Obtained from DFT calculations performed at the B3LYP-D3/def2-TZVPD level of theory. [d] Calculated as $\lambda_{\text{em}} - \lambda_{\text{max}}$. [e] Fluorescence quantum yields. [f] Half-wave potentials were obtained from CV measurements in 0.1 M solutions of nBu₄NPF₆ in THF (scan rate 0.1 V s⁻¹, vs. Fc/Fc⁺).

ring fusion in the latter facilitates the delocalization of electron density from the electron-rich thiophenes towards phosphorus (wing-to-phosphorus communication, Figure 1), which consequently renders their reductions more difficult.

Additional support for the observed conjugation pathways is provided by the frontier molecular orbitals (FMOs, Figure 2). In case of α -DTPs **1a** and **5a**, the orbitals are mostly concentrated on the central ring and on the sulfur atoms, which reflects the strong wing-to-phosphorus conjugation. In contrast, the orbital coefficients at the outer α -positions at thiophene are noticeably larger in β -DTPs **1b** and **5b**, which is in agreement with wing-to-wing communication.

With DTPs **1**, **4**, and **5** in hand, we targeted the functionalization of the thiophene moieties. In this connection, the introduction of functional groups at the α -positions of the thiophenes was probed first. Given the fact that DTPs possess a phosphine-like reactivity rendering them susceptible towards oxidation, our efforts were focused on the borane adducts **4** and phosphine oxides **5**. In principle, two reaction pathways are feasible, that is, first, electrophilic aromatic substitution and, second, metalation followed by quenching with suitable electrophiles. Unfortunately, both routes showed to be unsuitable for our DTPs with the exception of borane adduct **4b**, which allowed for the introduction of bromines and formyl groups at the α -position of thiophene through treatment with *t*BuLi and subsequent quenching with elemental bromine and DMF, respectively (compounds **S1** and **S2** in the Supporting Information). Although both functionalities should in principle allow for subsequent derivatization, we did not pursue this approach any further and turned our attention towards more straightforward methods such as direct oxidative cross-couplings. Very recently, Delouche et al. reported on the direct Pd-catalyzed arylation of **5b**,^[10] however, we found that this approach is not applicable to the corresponding α -isomer. Instead, we were able to introduce phenylethynyl units through direct C–H functionalization of thiophene. Suitable conditions (Pd₂(dba)₃, PivOH, Cs₂CO₃, Et₃N, Ag₂O in DME at 100 °C)^[9a] were adapted from Jie et al. and afforded the desired ethynylated DTP oxides **6a** and **6b** in over 40% yield (Scheme 3).

The influence of the π -expansion through ethynylation was investigated through UV/Vis spectroscopy (Figure 1, Table 1). Strikingly, α -derivative **6a** has the same λ_{max} value (314 nm) as unfunctionalized **5a**. This observation is comprehensible remembering that the outer α -positions in the α -DTPs are cross-conjugated, which prevents efficient communication of the phenylethynyl substituents in **6a**. Turning to β -isomer **6b**, a

strong bathochromic shift of the lowest-energy absorption band of 62 nm is observed as compared to **5b**. In this case, the acetylenes are conjugated through the olefinic backbone, which leads to an effectively expanded π -system.

Similar to their unfunctionalized counterparts, **6** show fluorescence in solution (CH₂Cl₂) with Stokes shifts > 70 nm (3700–8300 cm⁻¹, Figure S37, Supporting Information). Noteworthy, the fluorescence quantum yield of **6a** ($\Phi_{\text{F}}=1\%$) was found to be as low as for the unfunctionalized DTPs, whereas the fluorescence of **6b** was significantly stronger with $\Phi_{\text{F}}=13\%$. Cyclic voltammetry measurements revealed that the first reduction potentials of **6** are lowered roughly equally by 0.2 V as compared to **5**. Thus, the significantly redshifted absorption of the β -isomer is most likely to be ascribed to a more pronounced increase of the energy of its HOMO. With the different electronic structures of α - and β -DTPs in mind, the coupling of different acetylenic groups offers great possibilities for target-oriented molecular property tuning.

In summary, we presented a reliable and scalable synthetic route towards a series of two isomeric dithieno[*b,f*]phosphines, that is, α - and β -DTPs. Comprehensive experimental and theoretical investigations revealed the different electronic nature of the isomeric DTPs regarding the relative orientation of phosphine and thiophene moieties. In particular, wing-to-phosphorus communication turned out to be the preferred conjugation pathway in α -DTPs, whereas wing-to-wing communication was found to be dominant in β -DTPs. Finally, we showed that it is possible to introduce acetylenes through direct C–H functionalization at thiophene, which is a promising strategy for the synthesis of novel functional materials based on the DTP scaffold.

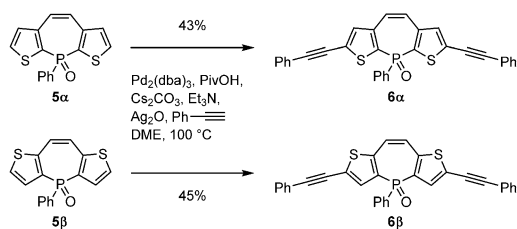
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Conflict of interest

The authors declare no conflict of interest.

Keywords: cross-coupling · phosphine oxides · phosphorus heterocycles · ring fusion · thiophene



Scheme 3. Functionalization of DTP oxides **5** through direct Pd-catalyzed C–H coupling.

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