Volume 1 | Number 1 | Jan 2013 | Pages 1–100

ChemComm

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A double hetero[4]helicene composed of two phenothiazines: synthesis, structural properties, and its cationic states

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A novel double hetero[4]helicene consisting of two phenothiazines (1) has been synthesized. The racemization barrier of 1 is high enough to be optically separated. We successfully obtained the single crystal of the radical cation salt of 1·+, whose torsion angles was decreased compared to the neutral state.

Phenothiazine derivatives are an important class of π-electron donors because of their low oxidation potentials and high stability of oxidized species, and have been utilized as the redox-active units or spin sources in studies of organic mixes-valence systems and molecular magnetism. Until now, various kinds of phenothiazine oligomers connected through different bridging unit have been synthesized and the electronic properties depending on the bridging unit have been investigated.[1–4] Particularly, directly connected phenothiazine oligomers, which are the simplest multi-redox systems consisting of phenothiazines, have been of interest in the electronic and magnetic interactions among the phenothiazine units.[5–11] Another important feature of phenothiazines is the controllability of the structure by redox stimuli. Phenothiazine derivatives possess the bent structure along the S–N axis with the bending angle (denoted as θ_b) of typically 150–160°, and upon oxidation, the phenothiazine skeleton transforms to the more planar structure.[2,8] Therefore, phenothiazines are potential components of redox-active molecular machines.[12]

Recently, we reported a novel facile synthetic method of double heterohelicenes[13] by using tandem oxidation reaction of N-substituted heteroacenes.[14] In the report, we demonstrated the preparation of two kinds of double hetero[5]helicenes from 6,13-dihydro-6,13-diazapentacene and 13H-dibenzo[b,i]phenoxazine via cruciform heteroacene-dimers.
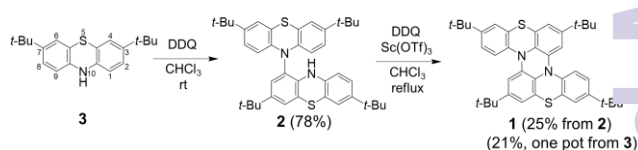
Scheme 1 Synthesis of phenothiazine dimers **1** and **2**.

This protocol is considered to be versatile approach to obtain double helicenes from other heteroacenes having a NH group. In this study, we applied this strategy to the construction of a novel double hetero[4]helicene by using phenothiazines as building blocks.

At first, phenothiazine-dimers were synthesized with a single C–N connection by the already reported dimerization reaction of phenothiazines using a mixture of dimethylsulfoxide (DMSO) and acetic anhydride as oxidant.[5] In this work, we used 3,7-di-*tert*-butylphenothiazine (**3**) as a starting material to prevent the reaction on the most reactive 3 and 7 positions, and
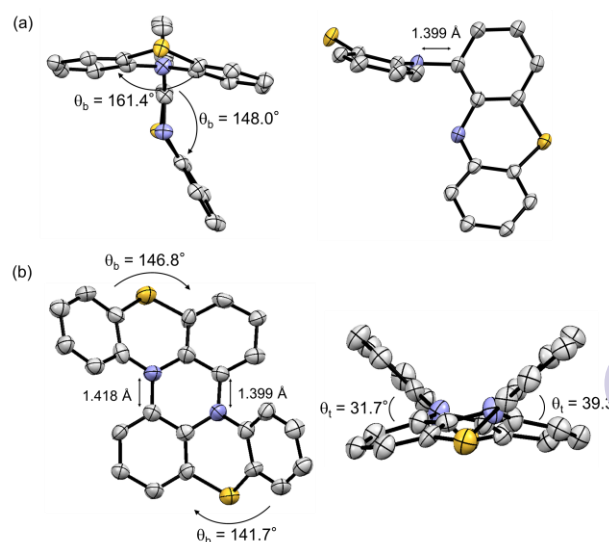

Fig. 1 X-ray structure of (a) **2** and (b) **1**. Thermal ellipsoids are set at 50% probability. The *t*Bu groups and hydrogen atoms were omitted for clarity.

obtained the desired 1,10'-dimer in 65% yield. However, this reaction requires long reaction time (about a week). Next, the dimerization of **3** was examined by DDQ oxidation according to our previous work.[14] This approach further improved the yield of **2** up to 78%, as well as short reaction time of several hours (Scheme 1). The oxidation of **2** by a combination of DDQ and Sc(OTf)$_3$ resulted in the intramolecular C–N bond formation and gave a doubly fused phenothiazine dimer **1**. Furthermore, **1** was also obtained in an one-pot manner by using the tandem oxidation of **3** with DDQ followed by DDQ/Sc(OTf)$_3$.

The structures of **2** and **1** were determined by the X-ray single crystal analysis (Fig. 1). In the crystal state, **2** took a cruciform structure similar to heteropentacene dimers,[14] although both of the phenothiazine units were bent along the S–N axes. As expected, **1** took a double hetero[4]helicene structure, and in a unit cell, two enantiomers ((P,P')- and (M,M')-isomers) existed by the ratio of 1:1. The torsion angles in the fjord regions (denoted as θ_t) were 31.7° and 39.3°, which were larger than those of carbo[5]helicene (ca.30°),[15] reflecting the bent structure of neutral phenothiazine molecule. The (P,P')- and (M,M')-isomers could interconvert via an achiral isomer (mesomer). Energy diagram of this interconversion was calculated by DFT calculations on the model compound **1'** without tBu groups at B3LYP/6-31G* level (Fig. S8).[16] The step with the highest barrier is the transformation from the chiral to achiral isomers, and the barrier height was calculated to be 118.0 kJ mol^{-1}. This value is remarkably higher than the calculated value of dibenzo[a,j]perylene, which corresponds to the all-carbon analogue of **1'** (41.5 kJ mol^{-1}, Fig. S9), due to the bent nature of phenothiazine.[17,18] Actually, we achieved optical resolution of **1** by HPLC using a chiral stationary phase. The obtained two fractions showed mirror-image circular dichroism (CD) spectra (Fig. 2). Spectral simulations based on time-dependent DFT (TD-DFT) calculations predicted the faster eluting fraction as (P,P')-isomer, and the slower as (M,M')-isomer, respectively (Fig. S20). The decay of the CD spectra of **1**
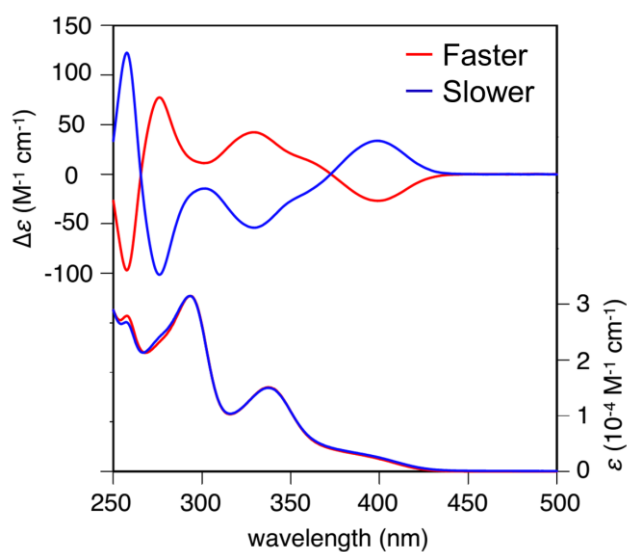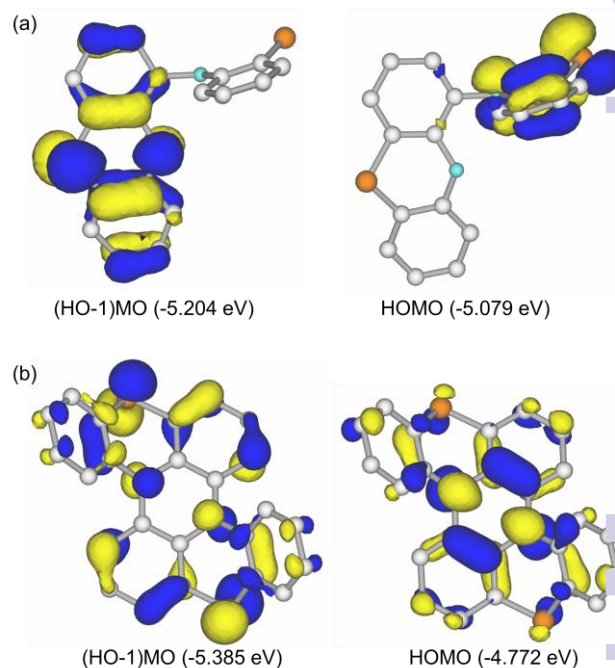

Fig. 3 Frontier Kohn–Sham MOs of (a) **2'** and (b) **1'** at B3LYP/6-31G* level.

obeyed first-order kinetics, and the racemization barrier was determined to be 112.8 kJ mol^{-1} by the Arrhenius plot of the rate constants at 30, 40, 50, and 60 °C (Fig. S7). This value was in good accordance with the theoretical calculations, and higher than that of the carbo[5]helicene (101 kJ mol^{-1}).[19] We also carried out the theoretical calculations for the analogues of **1** having O and Se instead of S atoms, and found that the analogue with heavier chalcogen atoms has larger torsions and the higher inversion barrier (Fig. S10-S11).

Because **1** and **2** are regarded as dual-electron donor molecules, herein we focus on HOMO and (HO-1)MO. For **2**, HOMO and (HO-1)MO were energetically close with an energy gap of 0.125 eV and completely localized on one side of the two phenothiazine units, resulted from their perpendicular connection (Fig. 3a). On the other hand, for **1'**, HOMO and (HO-1)MO were totally delocalized over the whole molecular skeleton, and the energy gap between these two MOs was increased to 0.613 eV (Fig. 3b).

Redox properties of **1** and **2** were investigated by cyclic voltammetry measurements (Fig. S13).[20] For **2**, the consecutive oxidation processes of $E_1 = 0.187$ V and $E_2 = 0.296$ V (vs ferrocene/ferrocenium) were observed, and the potential difference $\Delta E = E_2 - E_1$ was only 0.109 V, stemming from little electronic communication between two phenothiazine moieties of **2**. For **1**, on the other hand, the potentials of E_1 (0.023 V) and E_2 (0.655 V) markedly separated and ΔE was significantly increased to 0.632 V. This large ΔE value clearly indicates the increased electronic communication between two phenothiazine moieties in **1** by a ring-fusion. The E_1 value of **1** was lower than that of **2** by 0.164 V, suggesting the good electron donor property of **1**.
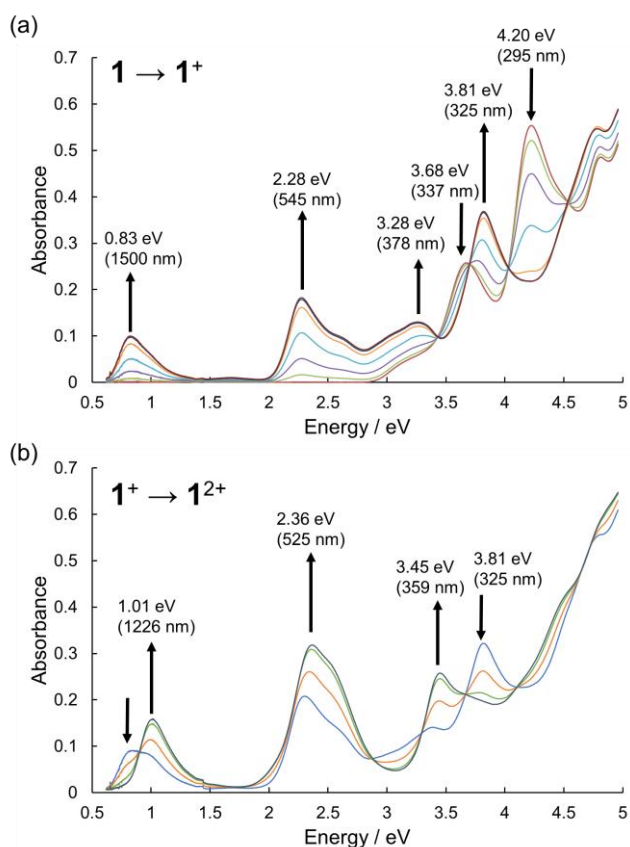

Fig. 2 CD and absorption spectra of the faster and the more slowly eluting enantiomers of **1** in CH$_2$Cl$_2$ at 298 K.

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Fig. 4 UV-Vis-NIR absorption spectra during the electrochemical oxidation of **1**. (a) **1** to **1**$^{+}$ and (b) **1**$^{+}$ to **1**$^{2+}$. The spectra were measured in CH$_2$Cl$_2$ with 0.1 M n-Bu$_4$NBF$_4$ at 298 K.

The UV-Vis-NIR absorption spectral changes of **1** during electrochemical oxidation were measured (Fig. 4). Upon oxidation, a low energy absorption band with a peak top at 0.83 eV (1500 nm) appeared, in addition to the band at 2.28 eV (545 nm) corresponding to the absorption of the radical cation of phenothiazines.[8,21] The low energy band in the NIR region could be ascribed to the charge-resonance band between two fused phenothiazine units, judging from the TD-DFT calculation of **1'**$^{+}$ (Fig. S16).[22] By applying higher voltage, the spectral shape was continuously changed with isosbestic points, according to the

simple 1 electron oxidation process from **1**$^{+}$ to **1**$^{2+}$ without any significant byproducts.

Motivated by the results of electrochemical measurement, we tried to isolate cation salts of **1** and **2** by chemical oxidation. The single crystals of a radical cation salt of **1**$^{+}$ was obtained as red-purple needles by slow evaporation of a CH$_2$Cl$_2$/hexane solution of **1** oxidized with 1 equiv. of tris(4-bromophenyl) aminium hexachloroantimonate (magic blue). The X-ray crystal analysis revealed the structure of **1**$^{+}$ (Fig. 5). The dihedral angles in the fjord regions of **1**$^{+}$ were smaller compared with those of the neutral **1**. This shrinkage of the helical pitches are ascribed to the increase of planarity of two phenothiazine units upon oxidation.[17,18] The average length of the two C-N bonds connecting two phenothiazine moieties also became shorter than that of **1**. In the crystal of **1**$^{+}$SbCl$_6^-$, a SbCl$_6^-$ anion existed on a saddle-shaped **1**$^{+}$, as shown in Fig. 5c. The radical cation **1**$^{+}$ is stable under ambient conditions both in solution and the solid state, and the absorption spectrum of the CH$_2$Cl$_2$ solution remained unchanged after 2 weeks under air and room light (Fig. S17). The ESR spectrum of **1**$^{+}$ in CH$_2$Cl$_2$ at 298 K showed a five-line splitting, which is mainly attributed to the hyperfine coupling interactions from two equivalent nitrogen nuclei ($|a_t|$ = 0.58 mT) (Fig. 6). This result indicates that the generated radical spin is equally delocalized over the two phenothiazine moieties. Oxidation of **1** with more than 2 equiv. of magic blue did not give the crystals of **1**$^{2+}$[SbCl$_6^-$]$_2$, because of the high second oxidation potential of **1** comparable to the formal potential of magic blue.[23] For **2**, the chemical oxidation with magic blue gave the crystals of doubly oxidized species **2**$^{2+}$[SbCl$_6^-$]$_2$, even when treated with 1 equiv. of oxidant because of the disproportionation reaction. The structure of **2**$^{2+}$ was also shown by the X-ray analysis (Fig. S14). The dication **2**$^{2+}$ maintained a cruciform orientation, and both the two phenothiazine moieties took more planarized structure compared to the neutral **2**.

In summary, we firstly synthesized the doubly fused phenothiazine dimer **1** with a double hetero[4]helicene structure by using the tandem oxidation of the phenothiazine derivative via the singly connected dimer **2**. Although double[4]helicenes usually racemize quickly, the enantiomers
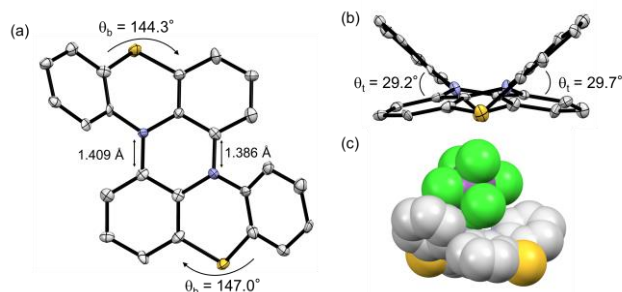

Fig. 5 X-ray structure of **1**$^{+}$SbCl$_6^-$. (a) Top view and (b) side view of **1**$^{+}$. (c) Space-filling representation of **1**$^{+}$SbCl$_6^-$. Thermal ellipsoids are set at 50% probability. The tBu groups and hydrogen atoms were omitted for clarity.
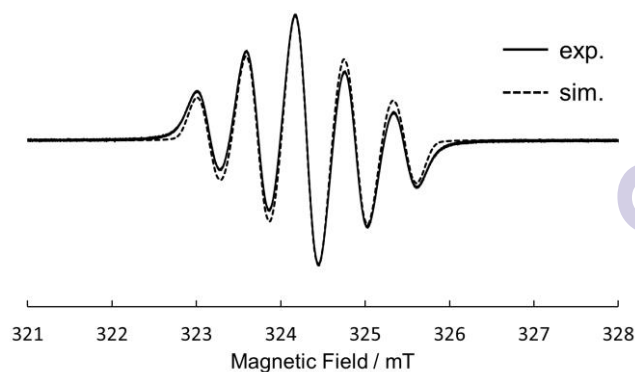

Fig. 6 ESR spectrum of **1**$^{+}$ (g = 2.0038) in CH$_2$Cl$_2$ at 298 K.

of **1** were much more stable toward racemization stemming from the highly bent structure of phenothiazine. Both of **1** and **2** exhibited good electron donor properties, and the chemical oxidation of these dimers gave the stable radical cations enough to be isolated. X-ray single-crystal analysis clarified the structures of **1**[.+] and **2**[2+]. The torsion angles in the fjord regions of **1**[.+] were found to be decreased compared with the neutral state. The generated spin of **1**[.+] was fully delocalized over the double[4]helicene skeleton. Further studies on analogues of **1** with other heteroatoms are currently under investigation.

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