Pergamon

Tetrahedron Letters 42 (2001) 8619–8624

TETRAHEDRON LETTERS

First synthesis and electronic properties of (hetero)aryl bridged and directly linked redox active phenothiazinyl dyads and triads

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Received 27 August 2001; revised 1 October 2001; accepted 3 October 2001

Abstract—Phenothiazinyl dyads and triads with variable functionalization can be synthesized in good yields by Suzuki coupling with suitable phenothiazinyl boronates. In addition, the structure of the phenylated phenothiazine (**6**) has been corroborated by an X-ray structure analysis. According to cyclic voltammetry these oligofunctional heterocyclic oligomers are strongly electronically coupled and represent suitable functional units for novel redox active molecular wires. © 2001 Elsevier Science Ltd. All rights reserved.

Phenothiazines[1] are an interesting class of electron-rich tricyclic nitrogen–sulfur heterocycles with a low oxidation potential and a high propensity to form stable radical cations. Besides their physiological activities,[2] more recently, due to reversible oxidations giving rise to characteristic, deep colored radical cation absorptions,[1,3] phenothiazine derivatives have become attractive spectroscopic probes in molecular and supramolecular arrangements for photoinduced electron transfer (PET) studies[4] and as material scientific[5] motifs. Recently, we have communicated a straightforward access to a variety of functionalized 3-mono- and 3,7-dialkynylated phenothiazines **1** and **2** as well as dumbbell-shaped butadiynyl-bridged and alkynyl-bridged diphenothiazinyl compounds **3** and **4** that are interesting building blocks for redox active oligomers (Fig. 1).[6,7]

The prospect of integrating strongly coupled redox fragments into conjugated chains could constitute a so far unknown class of redox addressable molecular wires, in particular, for a redox manipulation of single molecules with nanoscopic scanning techniques.[8,9] According to cyclic voltammetry in dumbbell-shaped phenothiazinyl dyads **3** and **4**,[6] the alkynyl bridges ensure only a fairly weak electronic communication between heterocyclic cores.[10] To circumvent this shortcoming the transposition of biaryl syntheses to the electron-rich phenothiazinyl fragment could establish a direct connectivity of the electrophores. Here, we communicate the syntheses, structure and first cyclic voltammetry measurements of directly linked phenothiazinyl dyads and triads with flexible substitution.

Synthetically, the exploitation of cross-coupling methodologies opens flexible strategies to various functionalizations. In particular, the Suzuki coupling[11] offers a broadly applicable methodology for biaryl synthesis with a maximum functional group tolerance. Although quite a number of substituted phenothiazines have been prepared, due to the electron-rich nature of phenothiazines and the sometimes tedious access to suitable halogen derivatives, the synthesis of 3- and 3,7-arylated representatives are almost unknown. However, the reaction of the monobrominated phenothiazines **5**[12] under standard Suzuki coupling conditions with

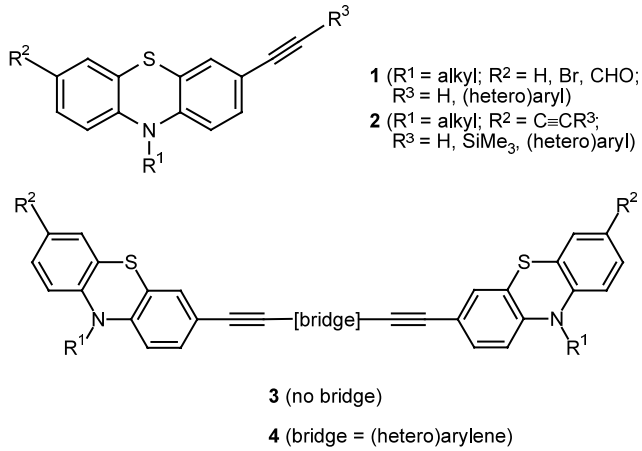

Figure 1.

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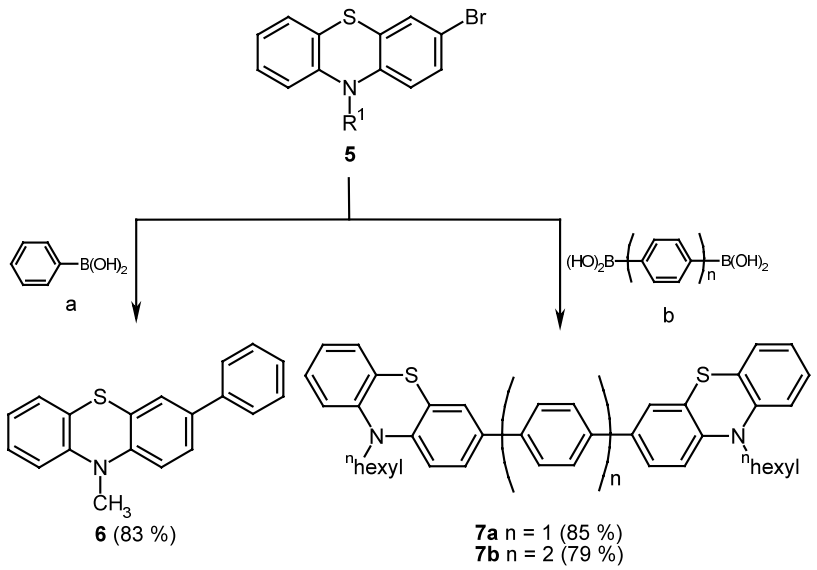
PII: S0040-4039(01)01848-2



Scheme 1. *Reagents and conditions*: (a) 2% $Pd(PPh_3)_2Cl_2$, 1 equiv. K_2CO_3, DME/H_2O (2:1), reflux, 3 h; (b) 5% $Pd(PPh_3)_4$, 5 equiv. $NaHCO_3$, DME/H_2O (2:1), reflux, 12 h.

commercially available aryl boronic and diboronic acids give the desired phenyl substituted **6** or phenylene and biphenylene bridged derivatives **7** in good yields (Scheme 1).[13]

The X-ray crystal structure analysis of **6**[14] (Fig. 2) clearly shows the expected butterfly conformation[1] of the phenothiazine core with dihedral angles of 35.11° (C6–N1–C7–C12) and 31.72° (C6–C1–S1–C12). The dihedral angle of the phenyl ring with the mean plane of the adjacent phenothiazinyl benzo moiety shows the typical biphenyl torsion of 36.96° (C9–C10–C14–C15). Furthermore, the *N*-methyl group adopts a pseudo-equatorial arrangement.

A more flexible synthetic access to dumbbell-shaped phenothiazinyl dyads and even triads can be realized upon coupling phenothiazinyl boronic acids or esters. Therefore, we have transposed a recently described procedure for the preparation of boronic esters by reacting even electron-rich aryl bromides with tetramethyl dioxoborolane under palladium catalysis.[15] Starting from the bromo phenothiazines **5**[12] and **8**[16] the desired 3-mono- and 3,7-bisborylated compounds **9** and **10** are formed in good yields (Scheme 2).[17]

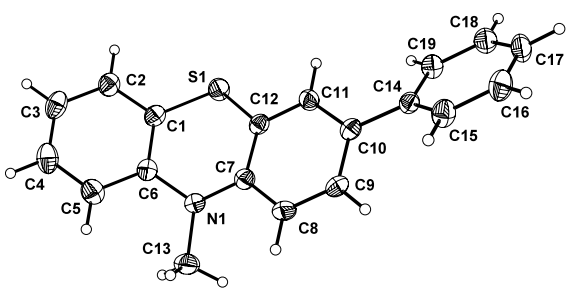


Figure 2.

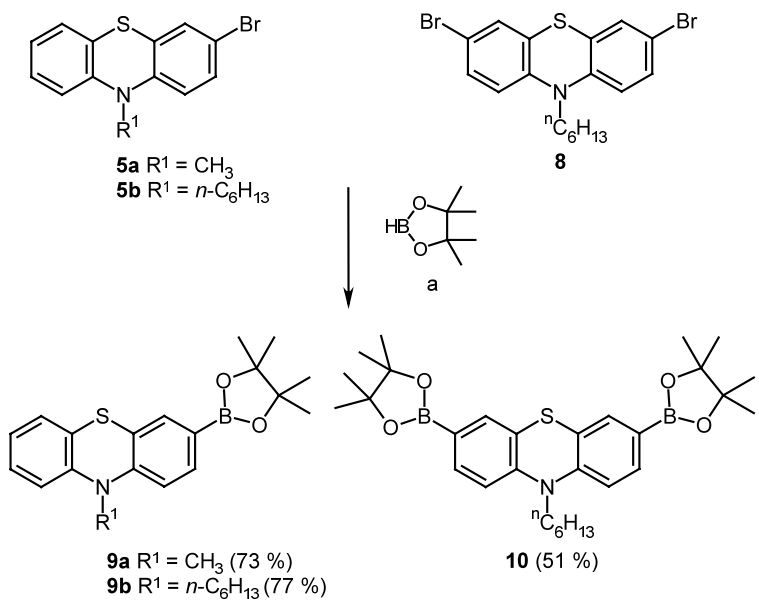
With the boronic esters **9** in hand, the Suzuki coupling with 2,5-diiodo thiophene, **5** or the bromo aldehyde **12** functionalized phenothiazinyl dumbbells like **11** and **13** can be obtained in a straightforward convergent fashion and in good yields as yellow resins or solids (Scheme 3).[18]

Applying the cross-coupling protocol to the bis(boronic ester) **10** with the bromide **5** and **12** as electrophilic coupling partner or to the pair **9** and 3,7-dibromo phenothiazine (**14**),[16] we finally are able to synthesize phenothiazinyl triads **15**[19] with a flexible substitution pattern and in good yields (Scheme 4).

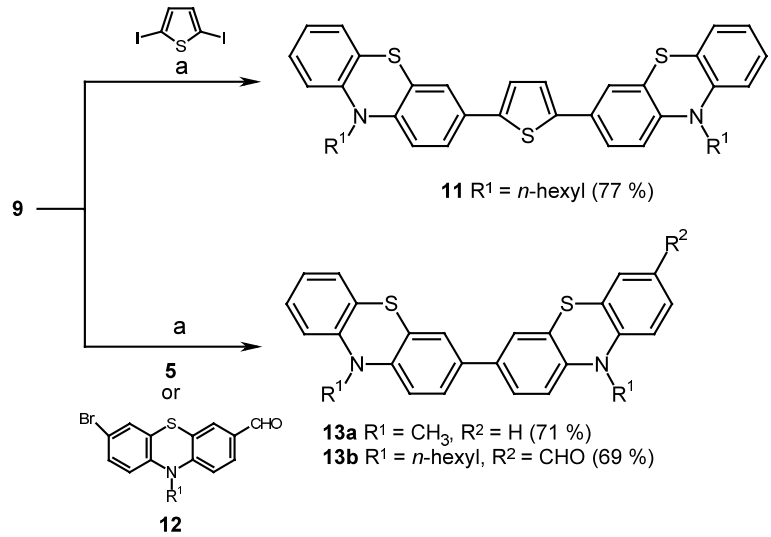
Electronically, all these dumbbell-shaped bridged or directly linked phenothiazine dyads and triads reveal some interesting features (Table 1). The longest wavelength absorption bands in the UV/vis spectra appear between 346 (**13a**) and 404 nm (**15b**) and arise from π–π* transitions within the extended π-system. They are significantly less intensive than the strong absorptions within the phenothiazine core appearing between 265 and 280 nm.[20] Formyl substitution (**13b**, **15b**) causes a red shift of approximately 2800–3700 cm^{-1} as a consequence of an enhanced push–pull character of the transition. Most remarkably, however, is the strong red shift by altering the conjugating bridge from phenylene (**7a**) to thienylene (**11**) due to the higher polarizability and reduced conformational biases of thiophene.

In the emission spectra pronounced Stokes shifts ($\Delta\tilde{\nu}$ = 5300–8400 cm^{-1}) can be found for all dumbbells. Interestingly, the phenylene (**7a**) and biphenylene (**7b**) bridged phenothiazine dyads fluoresce with higher quantum yields (Φ_f = 27 and 36%) for the spontaneous emission upon irradiation of the longest wavelength absorption band in comparison to the thienylene bridged or directly linked dyads and triads.

According to cyclic voltammetry two or three reversible anodic oxidations can be found for the dyads (**11**, **13a**)



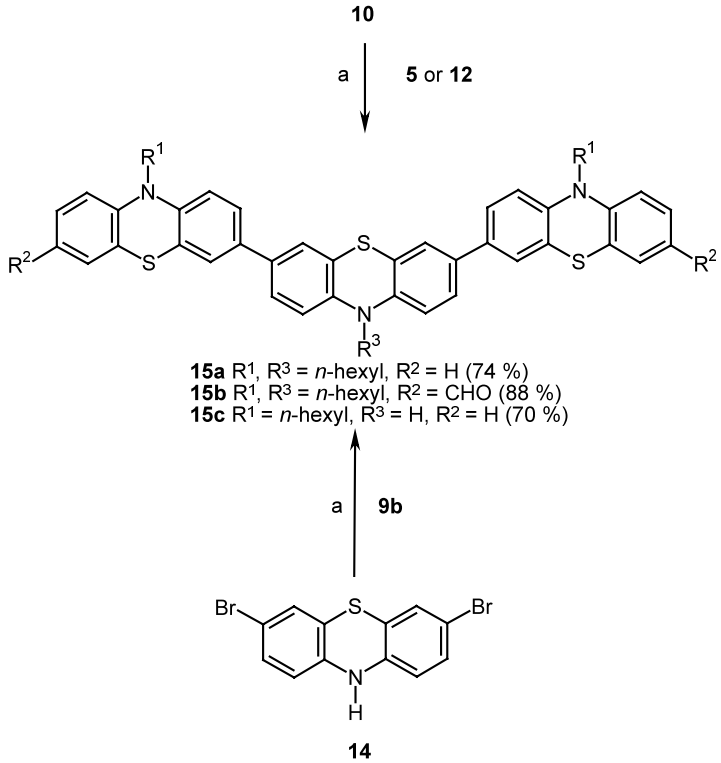
Scheme 2. *Reagents and conditions*: (a) 3% $Pd(PPh_3)_2Cl_2$, NEt_3, dioxane, reflux, 2 days.



Scheme 3. *Reagents and conditions*: (a) 5% $Pd(PPh_3)_4$, 6 equiv. $NaHCO_3$, DME/H_2O (2:1), reflux, 2.5–48 h.

and the triad (**15a**, Fig. 3), respectively. In comparison to *N*-hexyl phenothiazine ($E^{0/+1}=728$ mV), the first reversible one-electron oxidations are significantly shifted cathodically (**11**: $E^{0/+1}=644$ mV; **13a**: $E^{0/+1}=697$ mV; **15a**: $E^{0/+1}=610$ mV) indicating that another electron-rich phenothiazinyl moiety is in proximal conjugation to the first one. Therefore, the second oxidation occurs at higher potentials (**11**: $E^{+1/+2}=737$ mV; **13a**: $E^{+1/+2}=856$ mV; **15a**: $E^{+1/+2}=715$ mV). This can be interpreted as a strong electronic coupling between the phenothiazinyl units as a consequence of an extended delocalization of the initially formed radical cation as also reflected in the magnitude of the semiquinone formation constants $K_{SEM}=38$ (**11**), 495 (**13a**), and 60 (**15a**). In the case of the triad **15a** even the third oxidation potential can be detected arising from the oxidation of the dication ($E^{+2/+3}=837$ mV). The phenylene- and biphenylene-bridged dyads **7** only display a very weak electronic coupling (**7a**: $E^{0/+1}=697$ mV; $E^{+1/+2}=728$ mV; **7b**: $E^{0/+1}=691$ mV; $E^{+1/+2}=717$ mV), which can be attributed to an increased electrophor distance.

In conclusion, we could show that bridged and directly linked phenothiazine dyads and triads with flexible functionality can be easily synthesized by applying the Suzuki arylation to bromo phenothiazinyl derivatives and novel borylated building blocks. Both electronic spectra and cyclic voltammetry reveal a strong electronic coupling between the redox active phenothiazinyl cores. Thus, these novel functionalized oligomers are good candidates as functional units in redox addressable molecular wires. Further studies directed towards higher oligomer syntheses, their molecular self assembly, as well as the investigation of their electronic structure and photophysical behavior are currently underway.



Scheme 4. *Reagents and conditions*: (a) 5% $Pd(PPh_3)_4$, 6 equiv. K_2CO_3, DME/H_2O (2:1), reflux, 18–48 h.

Table 1. UV/vis and fluorescence data, and fluorescence quantum yields of bridged and directly linked *N*-alkyl phenothiazine dyads and triads in trichloromethane

	Absorption λ_{max} (nm)	Emission λ_{max} (nm)	Stokes shift[a] $\Delta\tilde{\nu}$ (cm^{-1})	Quantum yield Φ_f[b] (%)
7a	348sh	471	7500	27
7b	341sh	477	8400	36
11	390	490	5300	17
13a	346sh	458	7100	10
13b	397	555	7200	18
15a	363sh	471	6300	15
15b	404	556	6800	17

[a] Difference of longest (absorption) and shortest (emission) wavelength maxima (cm^{-1}).
[b] Perylene as a standard.

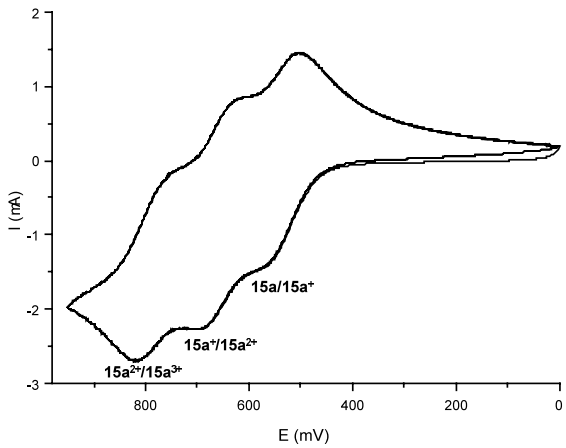


Figure 3. Cyclic voltammogram of **15a** in the anodic region (CH_2Cl_2, 20°C, scan rate = 100 mV/s, supporting electrolyte: $^nBu_4N^+PF_6^-$; Pt working electrode, Pt wire counter electrode, Ag/AgCl reference electrode).

Acknowledgements

The financial support of the Deutsche Forschungsgemeinschaft (SFB 486) and the Fonds der Chemischen Industrie is gratefully acknowledged. The authors wish to thank Ms. Birgit Bischoff-Förstner for kindly recording the fluorescence spectra.

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10. Compound **9** (Ref. 6) has been misinterpreted and shows only a weak electronic coupling ($\Delta E = 0.082$ V). The corrected electrochemical data will be soon published elsewhere.
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13. **Synthesis of 6**: A degassed solution of 292 mg (1.00 mmol) of **5**, 134 mg (1.10 mmol) of phenyl boronic acid, 11 mg (0.02 mmol) of $Pd(PPh_3)_2Cl_2$ and 138 mg (1.10 mmol) of K_2CO_3 in 8 mL of dry DME and 4 mL of water was heated to reflux temperature under nitrogen for 3 h. After cooling to rt the reaction mixture was diluted with 100 mL of diethyl ether. Twofold extraction of the organic layer with 50 mL of water, drying of the organic phase with magnesium sulfate and evaporation of the solvents furnished 240 mg (83%) of **6** as colorless crystals. Mp 126–127°C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 3.38 (s, 3H), 6.83 (m, 2H), 6.93 (m, 1H), 7.15 (d, $J = 7.5$ Hz, 2H), 7.19–7.31 (m, 1H), 7.37–7.42 (m, 4H), 7.52 (d, $J = 7.3$ Hz, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 35.3 (CH_3), 114.1 (CH), 114.2 (CH), 122.5 (CH), 123.1 ($C_{quat.}$), 123.8 ($C_{quat.}$), 125.6 (CH), 126.1 (CH), 126.5 (CH), 126.9 (CH), 127.2 (CH), 127.5 (CH), 128.8 (CH), 135.6 ($C_{quat.}$), 140.0 ($C_{quat.}$), 145.1 ($C_{quat.}$), 145.6 ($C_{quat.}$). MS (70 eV, m/z (%)): 289 (M^+, 100), 274 (M^+-CH_3, 59). Anal. calcd for $C_{19}H_{15}NS$ (289.4): C, 78.86; H, 5.22; N, 4.84; S, 11.08. Found: C, 78.60; H, 5.26; N, 4.80; S, 11.05.
14. Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC–167503 (**6**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-1223/336-033; e-mail: deposit@ccdc.cam.ac.uk) or as supporting information of this article.
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17. All new compounds have been characterized spectroscopically and by correct elemental analysis or HRMS (oils).
18. **Synthesis of 11**: A degassed solution of 384 mg (0.94 mmol) of **9b**, 150 mg (0.45 mmol) of 2,5-diiodo thiophene, 31 mg (0.03 mmol) of $Pd(PPh_3)_4$ and 225 mg (2.7 mmol) of $NaHCO_3$ in a mixture of 7 mL of DME and 3 mL of water was heated to reflux temperature under nitrogen for 12 h. Workup similar to that for compound **6** furnished 222 mg (77%) of **11** as a yellow resin. ^{1}H NMR (CD_2Cl_2, 300 MHz): δ 0.79 (m, 6H), 1.18–1.24 (m, 8H), 1.35 (m, 4H), 1.71 (m, 4H), 3.77 (t, $J = 7.0$ Hz, 4H), 6.76–6.85 (m, 6H), 7.03–7.11 (m, 6H), 7.27–7.32 (m, 4H). ^{13}C NMR (CD_2Cl_2, 75 MHz): δ 13.8 (CH_3), 22.7 (CH_2), 26.6 (CH_2), 26.9 (CH_2), 31.5 (CH_2), 47.6 (CH_2), 115.5 (CH), 115.6 (CH), 122.5 (CH), 123.2 (CH), 124.0 (CH), 124.1 ($C_{quat.}$), 124.5 (CH), 125.3 ($C_{quat.}$), 127.3 (CH), 127.4 (CH), 128.7 ($C_{quat.}$), 141.9 ($C_{quat.}$), 144.6 ($C_{quat.}$), 145.0 ($C_{quat.}$). MS (70 eV, m/z (%)): 646 (M^+, 100), 561 ($M^+-C_6H_{13}$, 21), 476 ($M^+-2C_6H_{13}$, 21). Anal. calcd for $C_{40}H_{42}N_2S_3$ (646.9): C, 74.26; H, 6.54; N, 4.33; S, 14.87. Found: C, 74.28; H, 6.98; N, 4.11; S, 14.21.
19. **Synthesis of 15a**: A degassed solution of 155 mg (0.29 mmol) of **10**, 220 mg (0.61 mmol) of **5b**, 18 mg (0.02 mmol) of $Pd(PPh_3)_4$ and 80 mg (0.58 mmol) of K_2CO_3 in a mixture of 7 mL of DME and 3 mL of water was heated to reflux temperature under nitrogen for 2 days. Workup similar to that for compound **6** furnished 182 mg (74%) of **15a** as a yellow resin. ^{1}H NMR (CD_2Cl_2,

300 MHz): δ 0.89 (m, 9H), 1.32 (m, 12H), 1.45 (m, 6H), 1.80 (m, 6H), 3.86 (m, 6H), 6.88–6.94 (m, 8H), 7.12–7.19 (m, 4H), 7.31–7.34 (m, 8H). ^{13}C NMR (CD_2Cl_2, 75 MHz): δ 13.8 (CH_3), 22.7 (CH_2), 26.7 (CH_2), 26.9 (CH_2), 31.6 (CH_2), 47.5 (CH_2), 47.6 (CH_2), 115.5 (CH), 115.6 (CH), 115.65 (CH), 122.4 (CH), 124.4 ($C_{quat.}$), 124.7 ($C_{quat.}$), 124.9 (CH), 124.95 (CH), 125.2 (CH), 125.25 (CH), 127.3 (CH), 134.1 ($C_{quat.}$), 134.2 ($C_{quat.}$), 144.1 ($C_{quat.}$), 144.3 ($C_{quat.}$), 145.2 ($C_{quat.}$). MS (70 eV, m/z (%)): 845 (M^+, 100), 760 (M^+–C_6H_{13}, 15), 590 (M^+–$3C_6H_{13}$, 15), 422 (M^{2+}, 10). Anal. calcd for $C_{54}H_{59}N_3S_3$ (846.3): C, 76.64; H, 7.03; N, 4.96; S, 11.36. Found: C, 76.55; H, 7.33; N, 4.79; S, 10.78.

20. According to ZINDO/CI calculations with INDO/1 parameters using the Quantum CAChe 3.0 Program, Oxford Molecular Group, 1997.