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Synthesis and stereochemistry of some new spiro and polyspiro-1,3-dithiane derivatives

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ABSTRACT

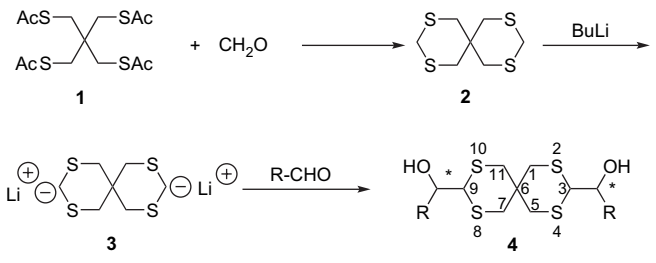
The synthesis of new spiro and trispiro compounds with 2,4,8,10-tetrathiaspiro[5.5]undecane and 7,11,18,21-tetrathia[5.2.2.5.2.2]heneicosane units is reported. The structural analysis was carried out by NMR investigations and the X-ray single crystal molecular structure determined for one of the compounds. The barriers for the flipping of the 1,3-dithiane units are determined by variable temperature NMR experiments.

1. Introduction

Six-membered ring spiranes and polyspiranes are intriguing targets in organic chemistry. Their stereochemistry is correlated with the helical chirality of the spiro[5.5]undecane skeleton.[1–4] The conformational analysis of six-membered ring spiranes was mainly carried out using NMR methods and revealed flexible or anancomeric structures in correlation with the substitution of the spirane skeleton.[1–6] The majority of the investigations of six-membered ring spiranes were focused on derivatives bearing 1,3-dioxane rings. The advantage of the investigations on spiro-1,3-dioxanes consisted of the fact that the stereochemistry of 1,3-dioxane system itself is well known[7–10] and spiro-1,3-dioxanes are appropriated for NMR investigations.[11]

The 1,3-dithiane derivatives are less studied[12] than the corresponding 1,3-dioxanes. Eliel[13] and Pihlaja[14] determined the A-values for some alkyl, aryl, and polar substituents located at different positions of the 1,3-dithiane ring. These investigations revealed for alkyl and aryl groups similar A-values with those found in the cyclohexane series, while for several polar groups located at position 2, the preference for the axial orientation was observed.

The literature data discuss few spiro-1,3-dithianes with 2,4,8,10-tetrathia[5.5]undecane skeleton. Maybe the reduced number of publications (compared to the very large number of papers concerning similar spiranes with oxygen atoms) can be explained by the difficulties encountered in the synthesis of these spiranes by the condensation reaction of carbonyl compounds with tetramercapto derivatives (tetrathiapentaerythritol) and the difficult access to the starting tetramercapto derivative itself. Only the paper of Backer and Evenhuis,[15] published in 1937, deals with the synthesis of 3,9-disubstituted-2,4,8,10-tetrathiaspiro[5.5]undecane derivatives by the direct thioacetalyzation reaction. The parent 2,4,8,10-tetrathia[5.5]undecane **2** (Scheme 1) was obtained by the reaction of the tetraacetylated derivative **1** with formaldehyde under acidic conditions.[16,17] Some spiro-1,3-dithianes (**4**), with chiral centers, were obtained via the reaction of double lithiated derivative **3** with various carbonyl compounds (substituted benzaldehydes, formylcalixarenes, and formylbenzocrown ethers)[16–18] as electrophiles (Scheme 1).



R=phenyl, calixarene-4'-yl, benzocrown-3'-yl

Scheme 1.

Compounds **4** exhibit complex stereochemistry due to the two chiral centers (*R* or *S* configurations at the secondary alcohols) and due to the chirality (*M* or *P* configuration) of the spirane skeleton. These compounds exhibit three diastereoisomers (d_1: *RPR*, *SMS*; d_2: *RMR*, *SPS*, and d_3: *SPR*, *RMS*). They were used for the synthesis of

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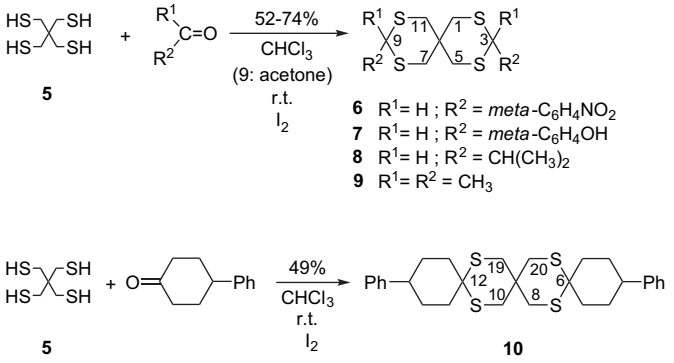
supramolecular structures with different guest molecules (e.g., C_{60}). The authors do not discuss the stereoisomerism of these derivatives but the NMR spectra (e.g., in S.I. of Ref. 16) show that the compounds were obtained and were investigated as mixtures of diastereoisomers. The axial chirality of spiro-bis-dithiepins was recently investigated.[19] No X-ray molecular structure for usual 2,4,8,10-tetrathiaspiro[5.5]undecane compounds were reported (except for 3,9-bis(dicyanomethylene)-2,4,8,10-tetrathiaspiro[5.5]-undecane, a derivative, which exhibits sp^2 carbon atoms in the 1,3-dithiane spirane unit).[20]

We considered it of interest to find an appropriate procedure for the direct synthesis of spiro compounds with 2,4,8,10-tetrathiaspiro[5.5]undecane skeleton and to investigate the stereochemistry and the properties of some 3,9-substituted derivatives of this tetrathiaspirane.

2. Results and discussions

New 3,9-substituted-2,4,8,10-tetrathiaspiro[5.5]undecane derivatives **6**–**9** and 7,11,18,21-tetrathiatrispiro[5.2.2.5.2.2]heneicosane **10** were obtained by the direct reaction of tetrathiapentaerythritol **5** with several carbonyl compounds (Scheme 2).



Scheme 2.

A recently published procedure[21] for the synthesis of the 1,3-dithiane ring based on I_2 catalysis was successfully adapted to the synthesis of spiranes with 2,4,8,10-tetrathiaspiro[5.5]undecane skeleton (yields 49–74%). The mechanism of this reaction is not yet well known. All the other essays of usual thioacetalization[22] reactions of the starting carbonyl compounds failed.

2.1. Structural aspects in solid state

The solid-state molecular structure for **6** was determined by single crystal X-ray diffractometry. The ORTEP diagram (Fig. 1) reveals the chair conformation for the 1,3-dithiane units. The aromatic rings are equatorial and exhibit a rotameric behavior close to that of the bisectional conformer. The angle between the aromatic ring and the best plane of the 1,3-dithiane ring is 26° 28′, while the angle between the aromatic rings is 52° 42′.

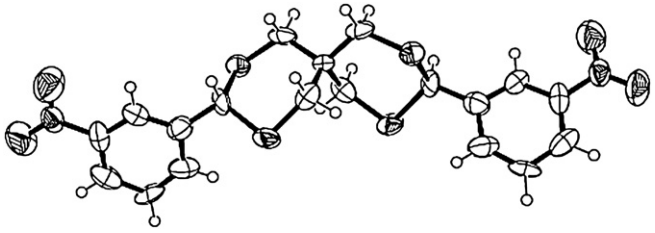


Figure 1. ORTEP diagram for compound **6**.

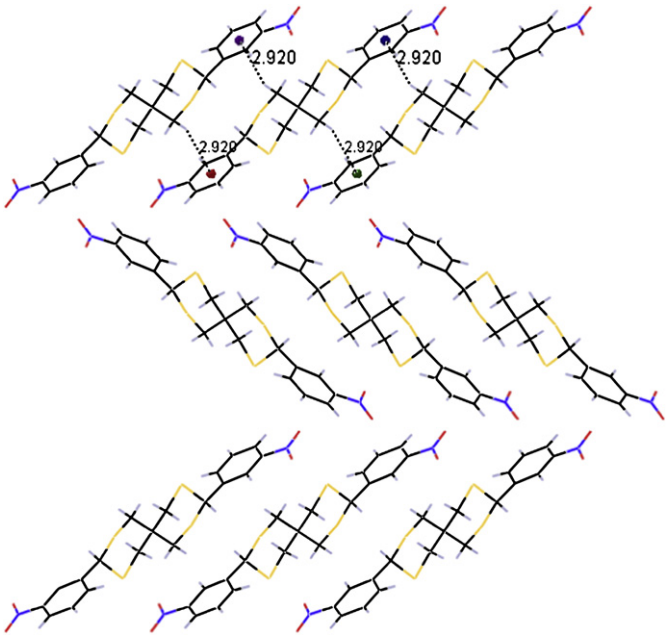


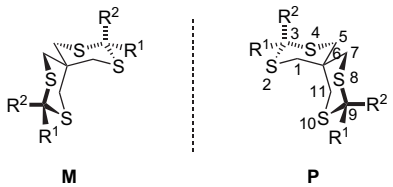
Figure 2. View of the lattice for **6** along the c crystallographic axis.

The lattice exhibits a *zigzag* arrangement of the molecules (Fig. 2). Each molecule exhibits four CH-π interactions. Two of them involve the axial proton of the *methylene inside* groups (positions 1 and 11) of the 1,3-dithiane units and the aromatic groups of two neighboring molecules. The other two interactions are located on the aromatic rings and involve the axial protons of the *methylene inside* groups of the 1,3-dithiane units of the same neighboring spirane molecules (the distance from the axial H atoms to the centroid of the aromatic rings is d=2.92 Å).

2.2. Structural aspects in solution

The stereochemistry of compounds **6**–**10** in solution was deduced from NMR investigations. Despite the lower difference between the energies of chair and TB (twist-boat) conformers ($\Delta G^0_{TB-chair}$=2.9 kcal/mol)[9] in 1,3-dithiane series than in the series of other six-membered rings (e.g., cyclohexane, $\Delta G^0_{TB-chair}$= 4.9 kcal/mol; 1,3-dioxane, $\Delta G^0_{TB-chair}$=5.7 kcal/mol)[9] the chair conformers are the main ones and in the further discussions only their contributions to the stereochemistry of the compounds are considered. The characteristic stereoisomers for **6**–**10** are similar with those found for the corresponding spiranes with 1,3-dioxane units.

Compound **6**–**8** exhibit anancomeric structures and the flipping of the 1,3-dithiane rings is shifted toward the conformers in which the larger substituents occupy the equatorial positions [R^2=*meta*-$C_6H_4NO_2$ (**6**); *meta*-C_6H_4OH (**7**); $-CH(CH_3)_2$ (**8**)]. Compounds **6**–**8** are chiral (due to the specific axial and helical chirality of spiro compounds with six-membered rings) and they are obtained as



1,11 inside, 5,7 outside (positions)

Scheme 3.

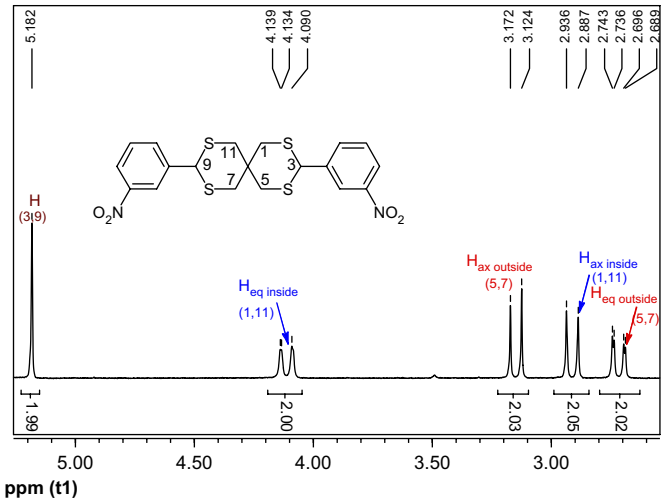


Figure 3. ^{1}H NMR spectrum ($CDCl_3$, rt, fragment) of compound **6**.

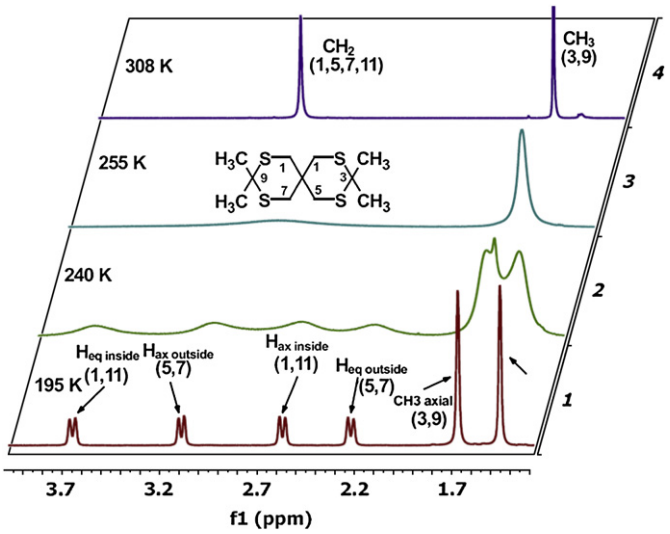


Figure 4. Variable temperature ^{1}H NMR experiments (CD_2Cl_2, fragments) for compound **9**.

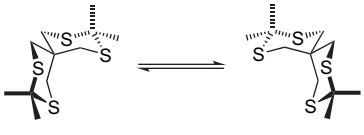
Table 1
NMR data (δ ppm) for compounds **6–8**

Compound	Solvent	Temperature (K)	δ (ppm)			
			CH_2 *inside*		CH_2 *outside*	
			Equatorial	Axial	Equatorial	Axial
6	$CDCl_3$	295	4.12	2.91	2.72	3.15
7	$CDCl_3$	295	4.17	2.93	2.66	3.34
8	$CDCl_3$	295	3.83	2.57	2.52	2.83
9	CD_2Cl_2	308	2.68			
9	CD_2Cl_2	195	3.67	2.59	2.24	3.11
10	CD_2Cl_2	295	3.04		2.91	
10	CD_2Cl_2	190	3.84	2.54	2.28	2.78

racemates (Scheme 3). The CH_2 groups of the spirane units are different in NMR. Positions 1 and 11 are oriented toward the other 1,3-dithiane ring and they are named *methylene inside*, while the other two CH_2 groups (positions 5 and 7) are oriented in opposite direction and they are named *methylene outside* groups. On the other hand, due to the anancomeric behavior of the compounds, the NMR spectra exhibit different signals for the axial and equatorial protons of the spirane units. The equatorial protons of the *methylene inside* groups are considerably more deshielded than those of the *methylene outside* positions (Fig. 3, Table 1). The assignment of the signals was carried out on the basis of NOESY or/and ROESY experiments.

The ^{1}H NMR pattern for the spirane units exhibits two AB (AX) systems (Fig. 3) with more deshielded equatorial protons for the *methylene inside* groups (they are the closest to the sulfur atoms of the neighboring heterocycle). The signals of the equatorial protons exhibit a further splitting due to the long range coupling ($^4J \approx 2$ Hz) possible as result of the W (*M*) arrangement of the bonds H_{eq}–$C^{1(11)}$–C^6–$C^{5(7)}$–H_{eq}.

Compound **9** is flexible and both 1,3-dithiane rings are flipping. The flipping of one of the heterocycles transforms one enantiomer of the compound into the other (*M*⇆*P*; Scheme 4).



Scheme 4.

The flexible behavior of the compound is proved by the NMR spectra. At rt, the ^{1}H NMR spectrum of **9** (Fig. 4) exhibits only two singlets; a more deshielded one (δ=2.96 ppm) for the protons of the heterocycles and another one (δ=1.67 ppm) for the protons of the methyl groups. The variable temperature NMR experiments (Fig. 4) show the obtaining of the (de)coalescences of the signals at lower temperatures (T=255 K) and the spectrum run at 195 K reveals the frozen structure.

The pattern of the NMR spectrum at 195 K for the protons of the spirane unit is similar with the spectra of the anancomeric compounds (Table 1, Figs. 3 and 4) while for the methyl groups at positions 3 and 9 the spectrum shows two singlets corresponding to the axial (δ_{ax}=1.69 ppm) and equatorial (δ_{eq}=1.48 ppm) orientations, respectively. On the basis of these experiments and using Eyring's equations[23] the barrier for the flipping of the 1,3-dithiane rings in **9** was calculated (Table 2).

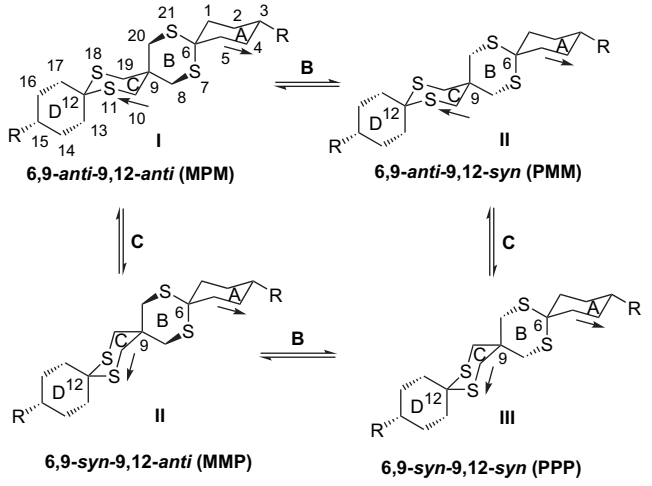
Compound **10** exhibits a semiflexible structure, the cyclohexane rings (A and D, Scheme 5) situated at the extremities of the polyspirane unit are anancomeric and show the substituents at positions 3 and 15 in equatorial orientations, while the heterocyclic middle part (rings B and C; Scheme 5) is flipping.

The trispirane is built up by merging three monospirane units (AB, BC, and CD). Spirane **10** is a semiflexible polyspirane (trispirane) with odd spirane units, which has similar groups at its extremities and exhibits six main conformers (3 diastereoisomers), which represent separable enantiomers (E^1: *PPP*⇆*MMP*⇆*MPM*; E^2: *MMM*⇆*PPM*⇆*PMP*; see Scheme 5 for E^1). The flipping of the 1,3-dithiane units transforms one diastereoisomer into the other. The transformation of a structure belonging to E^1 into a structure belonging to E^2 or vice versa is possible only if some bonds are broken and then they are rebuild in a new manner. The rt ^{1}H NMR spectrum of **10** (Fig. 5) exhibits for the protons of the heterocycles two singlets (positions 8,19 in one side and 10,20 on the other side are diastereotopic).

The variable temperature NMR experiments (Fig. 5) show at lower temperatures the coalescence of the signals (T=250 K) and at 190 K the spectrum corresponds to the frozen structure (Table 3). The spectrum exhibits for the protons of the heterocycles pattern similar to that recorded at rt for the anancomeric compounds **6–9**. Even if the four signals are well separated it is not possible to assign them to one diastereoisomer or to a mixture of frozen diastereoisomers. Despite this inconvenience, because the four groups are well separated the barrier for the flipping of the middle part of

Table 2
Flipping barriers calculated from the coalescence temperatures and the chemical shifts of the signals for the protons 3(9)-$CH_{3(ax)}$, 3(9)-$CH_{3(eq)}$, 1(11)-H_{ax}, 5(7)-H_{ax}, 1(11)-H_{eq}, and 5(7)-H_{eq} measured in the low temperature ^{1}H NMR spectra (CD_2Cl_2, 500 MHz) for compound **9**

Compd	Temperature (K)			$\Delta\delta$ (Hz)			$\Delta G^{\#}$ (kcal/mol)			Mean $\Delta G^{\#}$ value (kcal/mol)
	3(9)	1(11)	5(7)	3(9)	1(11)	5(7)	3(9)	1(11)	5(7)	
	$CH_{3(ax)}$, $CH_{3(eq)}$	H_{eq}, H_{ax}	H_{ax}, H_{eq}	$CH_{3(ax)}$, $CH_{3(eq)}$	H_{eq}, H_{ax}	H_{ax}, H_{eq}	$CH_{3(ax)}$, $CH_{3(eq)}$	H_{eq}, H_{ax}	H_{ax}, H_{eq}	
9	250	255	255	108.5	538.2	434	11.83	11.27	11.38	11.49±0.30



Scheme 5.

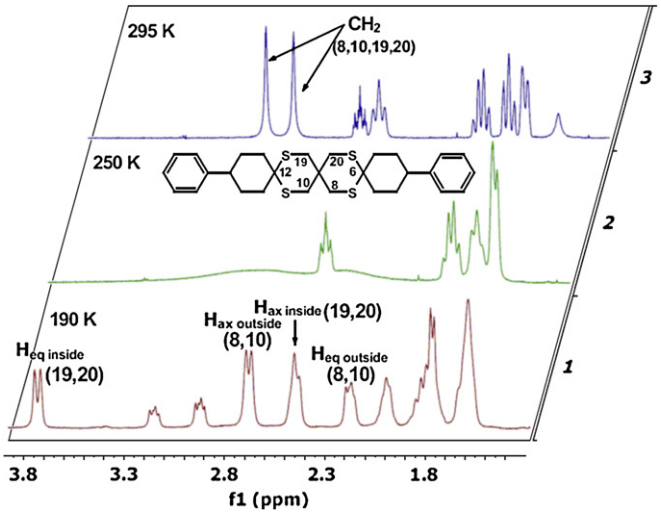


Figure 5. Variable temperature ^{1}H NMR experiments (CD_2Cl_2, fragments) for compound **10**.

the spirane could be estimated (Table 2). The measured barriers for the flipping of the 1,3-dithiane rings in the spiranes are somewhat larger than the value measured for flipping 1,3-dithiane ($\Delta G^{\#}$=10.3 kcal/mol).[24]

Table 3
Flipping barriers calculated from the coalescence temperatures and the chemical shifts of the signals of the protons 8(10)-H_{ax}, 19(20)-H_{ax}, 8(10)-H_{eq}, and 19(20)-H_{eq} measured in the low temperature ^{1}H NMR spectra (CD_2Cl_2, 500 MHz) for compound **10**

Compd	Temperature (K)		$\Delta\delta$ (Hz)		$\Delta G^{\#}$ (kcal/mol)		Mean $\Delta G^{\#}$ value (kcal/mol)
	19(20)	8(10)	19(20)	8(10)	19(20)	8(10)	
	H_{eq}, H_{ax}	H_{ax}, H_{eq}	H_{eq}, H_{ax}	H_{ax}, H_{eq}	H_{eq}, H_{ax}	H_{ax}, H_{eq}	
10	250	250	646.25	249.25	10.95	11.42	11.18±0.33

3. Conclusions

The efficient synthesis of some new spiro and trispiro-1,3-dithianes is reported. The first single crystal X-ray molecular structure for compounds with 2,4,8,10-tetrathiaspiro[5.5]undecane shows the chair conformation for the 1,3-dithiane rings and the *zigzag* disposition of the molecules in the lattice. The NMR studies reveal flexible, semiflexible, and anancomeric structures in correlation with the substituents located at the extremities of the spirane skeleton. The barriers ($\Delta G^{\#}$=10.95–11.83 kcal/mol) for the flipping of the heterocycles in the flexible and semiflexible compounds were calculated by variable temperature NMR experiments.

4. Experimental part

4.1. General information

Routine ^{1}H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra, COSY, HMQC, HMBC were recorded at rt in $CDCl_3$ on a Bruker 300 MHz spectrometer, using the solvent line as reference. Variable temperature NMR spectra and low temperature ROESY and NOESY were recorded on Bruker Avance DMX 500 spectrometer in CD_2Cl_2. Melting points were measured with a Kleinfeld melting point apparatus and are uncorrected. Mass spectra were recorded on ATI Unicam Automass, Micromass TofSpec E or a JEOL AX-500 spectrometer.

Thin layer chromatography (TLC) was conducted on silica gel 60 F_{254} TLC plates purchased from Merck. Preparative column (flash) chromatography was performed using PharmPrep 60 CC (40–63 μm) silica gel purchased from Merck.

The experimental conditions for the X-ray structure determination of compound **6** are as follows.[25]

The sample was studied on a Bruker AXS X8-APEX II with graphite monochromatized Mo Kα radiation for **6**. The structure was solved with SIR-97,[26] which reveals the non hydrogen atoms of the molecule. After anisotropic refinement, many hydrogen atoms may be found with a Fourier difference. The whole structure was refined with SHELXL97[27] by the full-matrix least-square techniques. Atomic scattering factors from International Tables for X-ray Crystallography (1992). ORTEP views were realized with PLATON98. The structural data was deposited at the Cambridge Crystallographic Data Center, deposition number is CCDC 678029 for **6**.

Chemicals were purchased from Aldrich, Merck or Acros and were used without further purification. Dimethylformamide was freshly distilled from CaH_2.

4.2. General procedure for the synthesis of 6–10

To a solution of aldehyde or ketone (1.2 mmol) and tetrathiapentaerythritol (100 mg, 0.5 mmol) in $CHCl_3$ (in acetone for derivative **9**) iodine (0.25 mmol) was added and the resulting mixture was stirred at rt. After completion of the reaction (TLC, hexane/dichloromethane=3:1) the mixture was quenched with aqueous $Na_2S_2O_3$. $CHCl_3$ was then added and the organic layer was washed twice with H_2O, dried over Na_2SO_4, and filtered. Evaporation of the solvent in vacuo gave the desired crude product. Further

purification was achieved by crystallization or separation by column chromatography (petroleum ether/dichloromethane).

Tetrathiapentaerythritol (**5**) was obtained by a modificated procedure described by Yang[28] for synthesis of SH groups. To a suspension of $LiAlH_4$ (100 mmol, 3.8 g) in 100 mL dry THF cooled with an ice bath, a solution of pentaerythrityl tetrathioacetate[16] (9.185 mmol, 3.38 g) in 75 mL dry THF was added. The reaction mixture was stirred under nitrogen atmosphere and the completion of the reaction was monitored by TLC. Water was carefully added in order to neutralize the excess of $LiAlH_4$, then the entire mixture was quenched in concentrated HCl (12 M) and stirred until a clear solution was obtained (pH=1). The mixture was extracted three times with dichloromethane (3×80 ml). The separated organic phase was dried over Na_2SO_4 and the solvent was then removed under reduced pressure. The crude product was crystallized from ethanol to give white crystals (mp 72.1–72.5 °C, yield: 1.49 g, 81%). ^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm 1.24 (t, J=8.7 Hz, 4H), 2.66 (d, J=8.7 Hz, 8H); ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm 30.3 (C-quaternary), 38.7 (CH_2).

4.2.1. 3,9-Bis(meta-nitrophenyl)-2,4,8,10-tetrathiaspiro-[5.5]undecane (**6**)

Yield: 52%; white crystals; mp=225–226.5 °C; purified by flash chromatography (silica, CH_2Cl_2/petroleum ether=1:1.25) R_f=0.30.

^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm 2.72 (dd, J=14.5, 2.1 Hz, 2H, H_{eq}-5, H_{eq}-7), 2.92 (d, J=14.5 Hz, 2H, H_{ax}-1, H_{ax}-11), 3.15 (d, J=14.5 Hz, 2H, H_{ax}-5, H_{ax}-7), 4.12 (dd, J=14.5, 2.1 Hz, 2H, 2H_{eq}-1, H_{eq}-11), 5.18 (s, 2H, H-3, H-9), 7.56 (t (overlapped dd), $J\approx J'$=8.1 Hz, 2H, H-5′, H-5″), 7.87–7.89 (m, 2H, H-6′, H-6″), 8.20 (ddd, 2H, J=8.1, 2.1, 0.9 Hz, H-4′, H-4″), 8.41 (t (overlapped dd), $J\approx J'$=2.1 Hz, 2H, H-2′, H-2″). ^{13}C NMR (75 MHz, CD_2Cl_2) δ/ppm 22.7 (C-6), 36.9 (CH_2-5, CH_2-7), 42.9 (CH_2-1, CH_2-11), 50.7 (CH-3, CH-9), 123.2, 123.7, 129.9, 134.1 (CH-tertiary aromatic carbon atoms), 140.0 (C-quaternary aromatic carbon), 148.5 (C–NO_2 quaternary aromatic carbon atom). MS (CI) m/z (%) 467 $[M+H]^+$. Anal. Calcd for $C_{19}H_{18}N_2O_4S_4$ (466): C, 48.91; H, 3.89; N, 6.00; S, 27.49. Found: C, 49.17; H, 3.77; N, 6.11; S, 27.31.

4.2.2. 3,9-Bis(meta-hydroxyphenyl)-2,4,8,10-tetrathiaspiro-[5.5]undecane (**7**)

Yield: 74%; pale yellow crystals; mp=234.5–235.3 °C; crystallized from chloroform.

^{1}H NMR (300 MHz, CD_3COCD_3) δ/ppm 2.66 (dd, J=14.4, 2.1 Hz, 2H, H_{eq}-5, H_{eq}-7), 2.93 (d, J=14.4 Hz, 2H, H_{ax}-1, H_{ax}-11), 3.34 (d, J=14.4 Hz, 2H, H_{ax}-5, H_{ax}-7), 4.17 (dd, J=14.4, 2.1 Hz, 2H, H_{eq}-1, H_{eq}-11), 5.24 (s, 2H, H-3, H-9), 6.78–6.81 (m, 2H, H-6′, H-6″), 6.96–7.03 (m, 4H, H-2′, H-2″, H-4′, H-4″), 7.18 (t (overlapped dd), $J\approx J'$=8.1 Hz, 2H, H-5′, H-5″), 8.71 (s, 1H, O*H*). ^{13}C NMR (75 MHz, CD_2Cl_2) δ/ppm 22.1 (C-6), 36.2 (CH_2-5, CH_2-7), 42.7 (CH_2-1, CH_2-11), 51.3 (CH-3, CH-9), 116.5, 117.2, 120.6, 131.6 (CH-tertiary aromatic carbon atoms), 142.1 (C-quaternary aromatic carbon), 159.4 (C–OH quaternary aromatic carbon atom). MS (CI) m/z (%) 409 $[M+H]^+$ (100), 437 $[M+C_2H_5]^+$ (24). Anal. Calcd for $C_{19}H_{20}O_2S_4$ (408): C, 55.85; H, 4.93; S, 31.39. Found: C, 55.59; H, 4.78; S, 31.62.

4.2.3. 3,9-Diisopropyl-2,4,8,10-tetrathiaspiro[5.5]undecane (**8**)

Yield: 57%; white crystals; mp=143.1–144.6 °C; purified by flash chromatography (silica, CH_2Cl_2/petroleum ether=1:1.25) R_f=0.30.

^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm 1.10 (d, J=6 Hz, 12H, [CH(C*H*$_3$)(C*H*$_3$)]), 2.07–2.09 (m, 2H, [C*H*(CH$_3$)(CH$_3$)]), 2.52 (dd, J=13.8, 2.4 Hz, H_{eq}-5, H_{eq}-7), 2.57 (d, J=13.8 Hz, 2H, H_{ax}-1, H_{ax}-11), 2.83 (d, J=13.8 Hz, 2H, H_{ax}-5, H_{ax}-7), 3.83 (dd, J=13.8, 2.4 Hz, H_{eq}-1, H_{eq}-11), 3.91 (d, J=5.4 Hz, 2H, H-3, H-9). ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm 20.2 (CH(*C*H$_3$)(CH$_3$)), 20.3 (CH(CH$_3$)(*C*H$_3$)), 28.4 (C-6), 32.9 (*C*H(CH$_3$)(CH$_3$)), 35.8 (CH_2-5, CH_2-7), 42.0 (CH_2-1, CH_2-11), 56.7 (CH-3, CH-9). MS (CI) m/z (%) 309 $[M+H]^+$ (100), 337 $[M+C_2H_5]^+$ (35). Anal. Calcd for $C_{13}H_{24}S_4$ (308): C, 50.60; H, 7.84; S, 41.56. Found: C, 50.71; H, 8.01; S, 41.28.

4.2.4. 3,3,9,9-Tetramethyl-2,4,8,10-tetrathiaspiro[5.5]undecane (**9**)

Yield: 69%; white crystals; mp=191.4–191.7 °C; crystallized from acetone.

^{1}H NMR (300 MHz, $CDCl_3$) δ/ppm 1.68 (s, 12H, H-3, H-9), 2.97 (s, 8H, H-1, H-5, H-7, H-11). ^{13}C NMR (75 MHz, $CDCl_3$) δ/ppm 25.6 (C-6), 30.1 (CH_3-3, CH_3-9), 36.4 (CH_2-5, CH_2-7), 42.5 (CH_2-1, CH_2-11). MS (EI, 70 eV) m/z (%) 280 $[M^+]$ (92), 237 (12.3), 206 (38), 191 (4), 173 (7), 141 (20), 132 (49), 117 (20), 99 (48), 85 (43), 74 (55), 59 (100), 45 (30), 41 (48). Anal. Calcd for $C_{11}H_{20}S_4$ (280): C, 47.09; H, 7.19; S, 45.72. Found: C, 46.99; H, 7.02; S, 45.99.

4.2.5. 3,15-Diphenyl-7,11,18,21-tetrathiatrispiro-[5.2.2.5.2.2]heneicosane (**10**)

Yield: 49%; white crystals; mp=242.8–243.7 °C; crystallized from ethanol.

^{1}H NMR (500 MHz, CD_2Cl_2) δ/ppm 1.76–1.77 (m, 4H, H_{eq}-2, H_{eq}-4, H_{eq}-14, H_{eq}-16), 1.82–1.86 (m, 4H, H_{ax}-1, H_{ax}-5, H_{ax}-13, H_{ax}-17), 1.95–2.01 (m, 4H, H_{ax}-2, H_{ax}-4, H_{ax}-14, H_{ax}-16), 2.46–2.51 (m, 4H, H_{eq}-1, H_{eq}-5, H_{eq}-13, H_{eq}-17), 2.55–2.61 (m, 2H, H-3, H-15), 2.91 (s, 4H, H-8, H-10), 3.05 (s, 4H, H-19, H-20), 7.19–7.22 (m, 2H, H-4′, H-4″), 7.25–7.27 (m, 4H, H-2′, H-2″), 7.30–7.33 (m, 4H, H-3′, H-3″). ^{13}C NMR (125 MHz, CD_2Cl_2) δ/ppm 26.2 (C-9), 30.4 (CH_2-2, CH_2-4, CH_2-14, CH_2-16), 35.0 (CH_2-8, CH_2-10, CH_2-19, CH_2-20), 38.2 (CH_2-1, CH_2-5, CH_2-13, CH_2-17), 44.5 (CH_2-3, CH_2-15), 51.1 (C-6, C-12), 126.6, 127.4, 128.9 (CH-tertiary aromatic carbon atom), 147.3 (C-quaternary aromatic carbon atom). MS (EI, 70 eV) m/z (%) 512 $[M^+]$ (81), 393 (10), 353 (20), 322 (16), 289 (21), 189 (20), 157 (70), 129 (53), 117 (42), 104 (45), 91 (100). Anal. Calcd for $C_{29}H_{36}S_4$ (512): C, 67.92; H, 7.08; S, 25.01. Found: C, 68.05; H, 7.22; S, 24.73.

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