DOI 10.1007/s10593-017-2086-9

Chemistry of Heterocyclic Compounds **2017**, *53*(5), 518–525

Thia-Diels–Alder reactions of hetaryl thioketones with nonactivated 1,3-dienes leading to 3,6-dihydro-2*H*-pyrans: evidence for a diradical mechanism

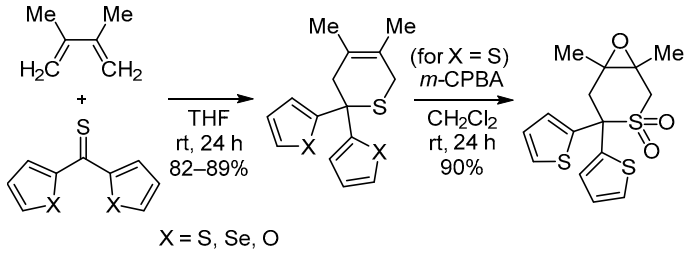
Grzegorz Mlostoń[1]*, Paulina Grzelak[1], Anthony Linden[2], Heinz Heimgartner[2]

[1] *Department of Organic and Applied Chemistry, University of Łódź, 12 Tamka, Łódź PL-91-403, Poland; e-mail: gmloston@uni.lodz.pl*

[2] *Department of Chemistry, University of Zurich, 190 Winterthurerstrasse, Zurich CH-8057, Switzerland e-mail: heinz.heimgartner@chem.uzh.ch*

Published in Khimiya Geterotsiklicheskikh Soedinenii, 2017, *53*(5), 518–525

Submitted December 21, 2016
Accepted February 21, 2017



Dihetaryl thioketones possessing thiophen-2-yl and selenophen-2-yl rings react as "superdienophilic" reagents with nonactivated 1,3-dienes such as 2,3-dimethylbuta-1,3-diene, cyclopentadiene, and mixtures of isomeric hexa-2,4-dienes to produce the expected 2*H*-thiopyrans in moderate to excellent yields. In the latter case, the corresponding *cis*-2,2-dihetaryl-3,6-dimethyl-3,6-dihydro-2*H*-thiopyrans are formed as the sole products in a stereoconvergent thia-Diels–Alder reaction. A stepwise mechanism *via* delocalized diradical intermediates is postulated to rationalize the observed reaction course. Treatment of 4,5-dimethyl-2,2-di(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran with excess of *m*-CPBA at room temperature leads to the oxidation of the C=C bond and the sulfur atom in the six-membered ring.

Keywords: cyclic sulfones, 3,6-dihydro-2*H*-thiopyrans, thioketones, reaction mechanisms, thia-Diels–Alder reactions.

The thia-Diels–Alder reactions constitute an important group of hetero-Diels–Alder reactions and can be used to synthesize six-membered sulfur-containing compounds.[1] These chemical transformations arouse special interest for preparation of 3,6-dihydro-2*H*-thiopyrans, which are known as relevant components of natural and biologically active products.[2] In general, thia-Diels–Alder reactions can be performed with thiabutadienes[3] or thiadienophiles as starting materials. In the latter case, activated thioesters,[4] dithioesters,[4,5] and thioamides,[6] as well as thiourea derivatives,[7] are known as prone dienophiles in reactions with nonactivated 1,3-dienes. In addition, application of some aromatic thioketones as heterodienophiles is also described,[8] but reactions with simple enolizable, aliphatic thioketones are rarely reported, as their handling is difficult.[9a]

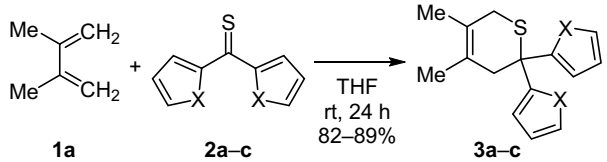
Nevertheless, the reaction of thioacetone with 2,3-dimethylbuta-1,3-diene (**1a**) was reported to afford the expected cycloadduct.[9b] On the other hand, hexafluorothioacetone reacts easily with compound **1a** and some other 1,3-dienes.[10a] The analogous reactions were observed with α,α,α-trifluorothioacetophenone and α,α,α-trifluorothioacetone.[10b] Various 3,6-dihydro-2*H*-thiopyrans have been prepared *via* the reaction of *in situ* generated thioketones bearing an electron-withdrawing group and 2,3-dimethyl-1,3-butadiene (**1a**).[11] Furthermore, several thia-Diels–Alder reactions of adamantanethione with substituted buta-1,3-dienes were reported.[12] Alkyl trimethylsilyl as well as phenyl trimethylsilyl thioketones undergo the (4+2) cycloaddition with diene **1a**, and the obtained 2-silylated 3,6-dihydro-2*H*-thiopyrans have been converted into 2*H*-thiopyrans by treatment with *m*-chloroperbenzoic acid (*m*-CPBA).[13] The relatively stable diaryl thioketones react efficiently with diverse 1,3-dienes[14] and on the basis of kinetic measurements have been named as "superdienophiles" by Sauer.[15] In a recent study, the volume parameters of the thiobenzophenone reaction with isoprene were determined, and authors concluded that a concerted reaction mechanism is plausible.[16]

In addition to the aforementioned, asymmetric thia-Diels–Alder reactions of activated dithioesters[17] as well as aryl and hetaryl thioketones[18] with *in situ* generated chiral trienamines were presented. In the first case, Jørgensen, according to DFT calculations, suggested a stepwise mechanism involving zwitterionic intermediates.[17] On the other hand, in the case of hetaryl thioketones and activated 1,3-dienes (i.e., trienamines), a stepwise reaction mechanism *via* diradical intermediates was proposed.[18] The goal of the present study was to examine thia-Diels–Alder reactions of nonactivated dienes with a series of dihetaryl and hetaryl phenyl thioketones, which have been used as heterodienophiles only in a single study.[18]

Symmetric and nonsymmetric dihetaryl thioketones exploited in this study were obtained from the corresponding ketones by thionation with Lawesson's reagent (LR).[19] The already reported method, which relies on heating a mixture of the ketone and LR in $PhCH_3$, was improved by applying microwave irradiation.[20] In that case, the reaction times were drastically reduced to two minutes, and the desired thioketones were obtained in moderate to high yields. However, in contrast to the reported data,[21] the desired thiofluorenone could not be obtained, instead the formation of bisfluorenylidene was observed.

In a typical experiment, a solution of 2,3-dimethylbuta-1,3-diene (**1a**) (2 mmol) and di(thiophen-2-yl)methanethione (**2a**) (1 mmol) in THF was stirred at room temperature for 24 h (Scheme 1). After chromatographic purification, the sole product **3a** was obtained as a solid material in 82% yield. The ^{1}H NMR spectrum confirmed the presence of the expected 4,5-dimethyl-2,2-di(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran (**3a**), and the structure was further proven by ^{13}C NMR and IR spectra and elemental analysis. Similarly, reactions of diene **1a** with di(selenophen-2-yl)methanethione (**2b**) and di(furan-2-yl)methanethione (**2c**) led to the desired 2*H*-thiopyrans **3b**,**c** in 89 and 85% yields, respectively. However, the attempted (4+2) cycloaddition of di(*N*-methylpyrrol-2-yl) thioketone and reactant **1a** was unsuccessful, and the thioketone was recovered from the reaction mixture.

Scheme 1



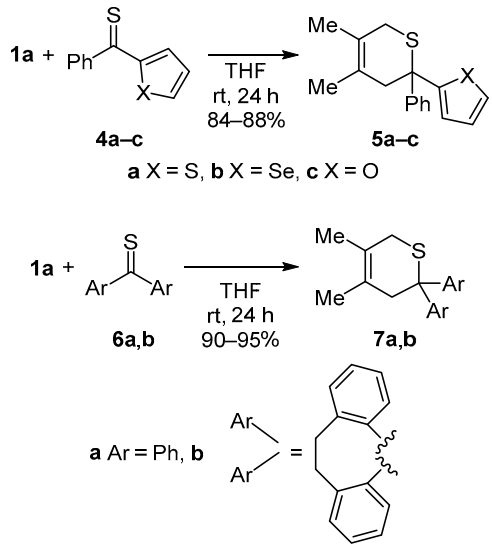
1a **2a–c** **3a–c**

a X = S, **b** X = Se, **c** X = O

In another series of experiments, hetaryl phenyl thioketones **4a–c** were used in the reaction with 1,3-diene **1a** leading solely to products **5a–c** in 84–88% yield. Furthermore, thiobenzophenone (**6a**) and thiodibenzosuberone (**6b**) were converted into the corresponding 2*H*-thiopyrans **7a**,**b** (90 and 95% yield) under the same conditions (Scheme 2).

In order to examine the mechanism of the studied thia-Diels–Alder reaction of hetaryl thioketones with non-

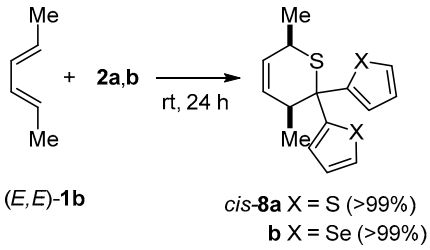
Scheme 2



activated 1,3-dienes, additional experiments involving (2*E*,4*E*)-hexa-2,4-diene ((*E*,*E*)-**1b**) were performed. The concerted (4+2) cycloaddition predicts stereospecific formation of a single product in each case. On the other hand, disruption of the concertedness would lead to mixtures of stereoisomeric products as a result of the appearance of intermediate zwitterionic or diradical species. The reaction of diene (*E*,*E*)-**1b** with thiobenzophenone (**6a**) has been reported to afford 3,6-dimethyl-2,2-diphenyl-3,6-dihydro-2*H*-thiopyran in 60% yield, but the configuration of the product has not been determined.[14b] In a more recent study, *cis* configuration of the stereospecifically formed analogous products from diaryl selenoketones was established on the basis of ^{1}H NMR data.[22] However, similar reactions performed with the less reactive (2*Z*,4*E*)-hexa-2,4-diene ((*Z*,*E*)-**1b**) and diaryl selenoketones or diaryl thioketones provided the *cis*-configured major products – 3,6-dihydro-2*H*-seleno- and 3,6-dihydro-2*H*-thiopyrans, respectively – together with small amounts of the corresponding *trans*-isomers. These results of a stereoconvergent reaction have been explained by a concerted cycloaddition in the case of diene (*E*,*E*)-**1b** and a two-step radical pathway *via* reversible formation of diradical intermediates in the case of the less reactive diene (*Z*,*E*)-**1b**.[22] In our recent publications, a nonconcerted mechanism involving diradical intermediates of formal (4+2) and (3+2) cycloadditions with hetaryl thioketones has been proposed and described.[18,23]

In continuation of this research, the reaction of hetaryl thioketones **2a**,**b** with excess of diene (*E*,*E*)-**1b** (2.2 equiv; as a mixture containing ca. 40% (*Z*,*E*)- and 5% (*Z*,*Z*)-**1b**) was performed without any solvent at room temperature for 24 h and in each case led to a single product, which was isolated in quantitative yield (Scheme 3). Based on the spectroscopic and elemental analysis data, the structures of the products were assigned to 2,2-dihetaryl-3,6-dimethyl-3,6-dihydro-2*H*-thiopyrans **8a**,**b**, respectively. Comparison of their ^{1}H NMR spectra with those of the corresponding 2,2-diaryl-2*H*-selenopyrans described in literature[22]

Scheme 3



allowed the *cis* configuration to be ascribed to products **8a**,**b**. Finally, the structure of *cis*-3,6-dimethyl-2,2-di-(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran (*cis*-**8a**) was confirmed by X-ray crystallography (Fig. 1).

The ratio of isomeric hexa-2,4-dienes **1b**, including diene (*E*,*E*)-**1b**, in the starting material was compared with the ratio determined in the sample after completion of the reaction with thioketones **2a**,**b**. Calculations performed for both reaction mixtures showed that, in the course of the studied (4+2) cycloadditions, the amount of (*E,E*)-isomer increased by ca. 12 mol %, whereas the amounts of (*Z*,*E*)- and (*Z,Z*)-isomers were reduced in total by ca. 12 mol %. These results strongly suggest that the amounts of the obtained products *cis*-**8a**,**b** are higher than expected for the consumed compound (*E,E*)-**1b**, based on the contents of the starting mixture.

Another experiment was performed using equimolar amounts of thioketone **2a** and hexa-2,4-diene **1b** as a mixture of (*E,E*)-, (*Z*,*E*)-, and (*Z,Z*)-isomers in a ratio of 22:70:8. The mixture of compounds **2a** and **1b** was heated in a closed reaction tube at 80°C for 18 h. After this time, the green color of the starting material **2a** completely disappeared, and the ^{1}H NMR analysis of the crude reaction mixture with a weighed internal standard (1,1,2,2-tetrachloroethane) revealed the formation of product *cis*-**8a** in 84% yield. Two characteristic doublets (1.31 and 1.04 ppm) of this previously described product were accompanied by another pair of low intensity doublets ($^2J_{HH}$ = 6.0 Hz) located at 1.31 and 1.16 ppm, respectively, which could be attributed to the isomeric product *trans*-**8a**. The location of these signals and the difference in chemical shifts were similar to the data reported for the *trans*-isomer of the analogous product, obtained from diene **1b** and thiobenzophenone (**6a**).[22] Based on the comparison of the intensities of these signals and the signal of CH_2 groups in the standard used for the quantitative analysis, the calculated yield of the postulated product *trans*-**8a** was ca. 6%. This result points out that, in the course of the studied reaction, a substantial amount of hexadiene (*Z,E*)-**1b**, present in the starting mixture, underwent isomerization in the course of the reaction and was subsequently consumed yielding an additional portion of product *cis*-**8a**.

A likely explanation of the observed results is a stepwise cycloaddition of the less reactive compounds (*Z*,*E*)- and (*Z,Z*)-**1b** and subsequent C–C bond rotation in the intermediate diradicals **9** leading to the formation of *cis*-configured thiopyrans **8a**,**b** (Scheme 4). On the other hand, the postulated reversible formation of intermediate diradicals leading to the increase of the most stable (and most reactive) compound (*E,E*)-**1b** in the reaction mixture is also acceptable.[22] Both interpretations, however, support the proposed stepwise diradical mechanism of the formal (4+2) cycloadditions of nonactivated, electron-rich 1,3-dienes and hetaryl thioketones.

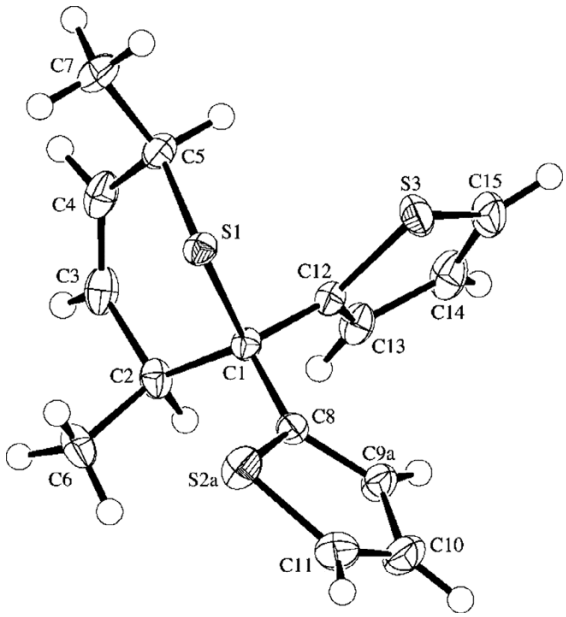
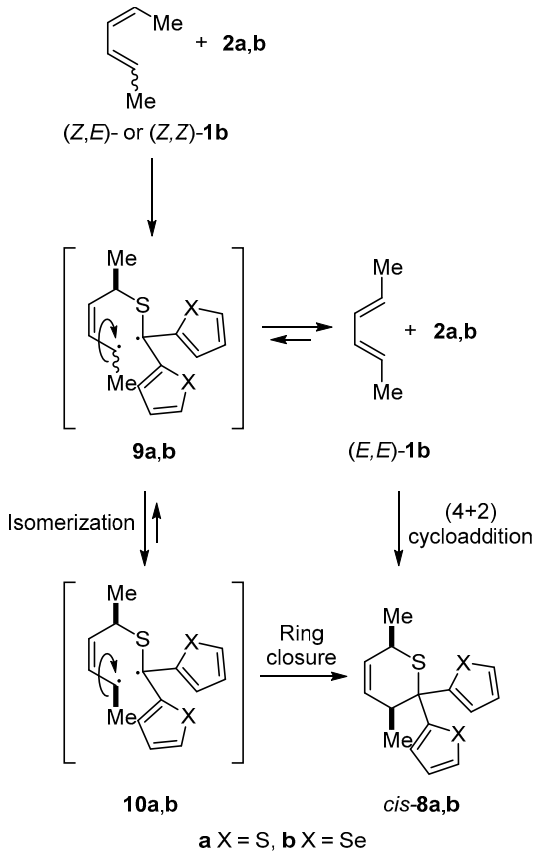


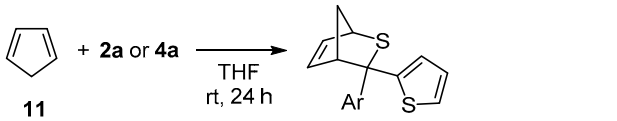
Figure 1. ORTEP representation[24] of the molecular structure of conformation A of 3,6-dihydro-2*H*-thiopyran *cis*-**8a** (with 50% probability ellipsoids; arbitrary numbering of atoms).

Scheme 4



As a third 1,3-diene, freshly prepared cyclopentadiene (**11**) was used in reactions with symmetric di(thiophen-2-yl)methanethione (**2a**) and nonsymmetric phenyl(thiophen-2-yl)methanethione (**4a**) to afford bicyclic products **12a**,**b** in reasonable yields (71 and 89%, respectively) (Scheme 5). In the second case, a mixture of two stereoisomeric products *exo*- and *endo*-**12b** in a 7:3 ratio (^{1}H NMR) was obtained after chromatographic purification. Similarly to the experiment with 2,3-dimethylbuta-1,3-diene (**1a**), the attempted (4+2) cycloaddition of cyclopentadiene (**11**) and di(*N*-methylpyrrol-2-yl) thioketone in THF solution at room temperature was unsuccessful and even after 24 h only the starting thioketone was recovered.

Scheme 5

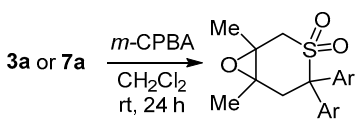


12a Ar = thiophen-2-yl (71%)
b Ar = Ph (89%, *exo*-, *endo*- (7:3))

The commercially available (1*E*,3*E*)-1,4-diphenylbuta-1,3-diene, which is known to display low reactivity toward nonactivated dienophiles,[25] was also tested in the reaction with thioketone **2a** in THF solution at room temperature. In that case, however, no formation of the expected (4+2) cycloadduct was observed even after 24 h. Instead, only gradual decomposition of the starting material **2a** was observed.

Finally, 2*H*-thiopyrans **3a** and **7a** were oxidized by treatment with excess of *m*-CPBA in CH_2Cl_2 at room temperature for 48 h (Scheme 6). In each case, a single product was isolated as a crystalline material in high yield (90 and 95%, respectively). The ^{1}H NMR spectra of both products revealed two AX systems attributed to two CH_2 groups. In addition, in the ^{13}C NMR spectra, five signals were observed between 40 and 70 ppm instead of expected three signals for the Csp^3 atoms of the heterocycle. Based on these data, structures of the bicyclic oxiranes **13a**,**b** were postulated and subsequently confirmed by elemental analysis. These structures indicate that oxidation of the S atom in compounds **3a** and **7a** to the sulfone group occurs along with the formation of the corresponding oxiranes. Similar course of oxidation of variously substituted 3,6-dihydro-2*H*-thiopyrans with Oxone®,[26] as well as *m*-CPBA[27,28] has been reported.

Scheme 6



13a Ar = thiophen-2-yl (90%)
b Ar = Ph (95%)

In conclusion, the presented study shows that, similarly to aryl thioketones, hetaryl analogs are superior hetero-dienophiles in thia-Diels–Alder reactions with nonactivated 1,3-dienes. The (4+2) cycloadditions can be performed under mild conditions in the absence of any catalyst. The results obtained for the reactions with (2*E*,4*E*)-hexa-2,4-diene that give *cis*-configured 3,6-dimethyl-3,6-dihydro-2*H*-thiopyrans suggest a concerted (4+2) cycloaddition. However, the enhanced amounts of the isolated *cis*-products in reactions with mixtures of isomeric hexa-2,4-dienes indicate that some isomerization processes might occur during the course of the reactions. The postulated diradical intermediates, formed in the initial step of the reaction, may either isomerize to the most stable precursors of the *cis*-configured (4+2) cycloadducts or, in a reversible process, may be converted into more reactive (2*E*,4*E*)-hexa-2,4-diene. The latter may subsequently react with the starting thioketone in a concerted, stereospecific manner. In contrast to dihetaryl thioketones bearing thiophen-2-yl, selenophen-2-yl, or furan-2-yl rings, the analogous di(*N*-methylpyrrol-2-yl) thioketone does not display reactivity of a "superdienophilic" reagent and the expected 2*H*-thiopyran derivative does not form in the reaction with 2,3-dimethylbuta-1,3-diene. Treatment of 3,6-dihydro-2*H*-thiopyrans with an excess of *m*-CPBA at room temperature leads to the oxidation of the S atom as well as the C=C bond to produce bicyclic oxiranes containing a sulfonyl group.

Experimental

IR spectra were recorded on a Thermo Nicolet NEXUS 470 FT IR spectrometer in KBr pellets. ^{1}H and ^{13}C NMR spectra were obtained on a Bruker Avance III instrument (600 and 150 MHz, respectively) in $CDCl_3$. Chemical shifts were referenced to the residual non-deuterated solvent signals (7.26 and 77.0 ppm, respectively). The multiplicity of ^{13}C signals was deduced from DEPT experiments supported by HMQC spectra. Mass spectra were recorded on a Varian 500-MS IT mass spectrometer (ESI, 50 eV). Elemental analyses were performed in the Microanalytical Laboratory of the Chemistry Faculty in Łódź using a VARIO ELIII apparatus (Elementar Analysensysteme GmbH). Melting points were determined in a capillary using a Sigma-Aldrich MEL-TEMP apparatus and are uncorrected. Microwave-supported syntheses of thioketones **2a**–**c**, **4a**–**c**, and **6a**,**b** were performed in a Discover SP microwave reactor.

Applied dienes such as (1*E*,3*E)*-1,4-diphenylbuta-1,3-diene, 2,3-dimethylbuta-1,3-diene (**1a**), and hexa-2,4-diene **1b** (mixture of (*E*,*E)*-, *(Z*,*E)*-, and (*Z*,*Z)*-isomers in a ratio of 55:40:5), inorganic reagents, and solvents are commercially available (Sigma-Aldrich) and were used as received. The (*Z*,*E*)-**1b** enriched mixture of (*E*,*E*)-, (*Z*,*E*)-, and (*Z*,*Z*)-isomers in a ratio of 22:70:8, was prepared from the commercial sample based on a reported protocol.[29] The ratio of isomeric hexa-2,4-dienes **1b** was established based on the ^{1}H NMR spectrum registered in $CDCl_3$ solution. Cyclopentadiene (**11**) was freshly prepared by distillation of the commercially available dimer according to a known protocol.[30]

Synthesis of thioketones 2a–c, 4a–c, and 6a,b (General method).[20] A solution of the corresponding ketone (1 mmol) and Lawesson's reagent (LR) (1 mmol) in dry $PhCH_3$ (2 ml) was placed in a microwave reaction tube. All

reactions were performed at 150 W for 2 min. After cooling the reaction mixture to room temperature, the solvent was evaporated *in vacuo*. The residue was purified by column chromatography (silica gel) using a mixture of petroleum ether and $CHCl_3$ (7:3) as the eluent.

Synthesis of 2*H*-thiopyrans 3a–c, 5a–c, and 7a,b (General method). A solution of the corresponding thioketone **2**, **4**, or **6** (1 mmol) and 2,3-dimethylbuta-1,3-diene (**1a**) (0.2 ml, 2 mmol) in dry THF (1 ml) was stirred at room temperature for 24 h. After this time, the solvent was evaporated *in vacuo*. The residue was purified by column chromatography (silica gel) using CH_2Cl_2 as the eluent.

4,5-Dimethyl-2,2-di(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran (3a). Yield 239 mg (82%), green solid, mp 80–81°C. IR spectrum, ν, cm^{-1}: 3084 (w), 2864 (m), 1425 (m), 1231 (s), 708 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.66 (3H, s, CH_3); 1.75 (3H, s, CH_3); 3.06 (2H, s, CH_2); 3.10 (2H, s, CH_2); 6.90–6.91 (2H, m, H Ar); 6.98 (2H, dd, *J* = 3.6, *J* = 1.2, H Ar); 7.22 (2H, dd, *J* = 5.4, *J* = 1.2, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.3, 20.5 ($2CH_3$); 33.2, 47.9, 48.4 ($3Csp^3$); 122.8, 125.8 ($2Csp^2$); 125.0, 125.4, 126.5 (6CH Ar); 151.1 (2C Ar). Found, %: C 61.61; H 5.45; S 32.97. $C_{15}H_{16}S_3$. Calculated, %: C 61.59; H 5.52; S 32.88.

4,5-Dimethyl-2,2-di(selenophen-2-yl)-3,6-dihydro-2*H*-thiopyran (3b). Yield 343 mg (89%), dark-red solid, mp 68–69°C. IR spectrum, ν, cm^{-1}: 3051 (w), 2863 (m), 1445 (s), 1227 (s), 705 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.67 (3H, s, CH_3); 1.74 (3H, s, CH_3); 3.07 (2H, s, CH_2); 3.12 (2H, s, CH_2); 7.12–7.14 (4H, m, H Ar); 7.92 (2H, dd, *J* = 5.4, *J* = 1.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.3, 20.6 ($2CH_3$); 33.6, 49.7, 51.7 ($3Csp^3$); 122.8, 125.8 ($2Csp^2$); 127.4, 129.0, 130.7 (6CH Ar); 159.2 (2C Ar). Found, %: C 46.83; H 4.41; S 8.66. $C_{15}H_{16}SSe_2$. Calculated, %: C 46.64; H 4.18; S 8.30.

2,2'-(4,5-Dimethyl-3,6-dihydro-2*H*-thiopyran-2,2-diyl)difuran (3c). Yield 211 mg (85%), orange solid, mp 53–54°C. IR spectrum, ν, cm^{-1}: 3118 (w), 2911 (m), 1498 (s), 1146 (s), 1014 (s), 737 (s). ^{1}H NMR spectrum, δ, ppm: 1.67 (3H, s, CH_3); 1.74 (3H, s, CH_3); 2.95 (2H, s, CH_2); 2.99 (2H, s, CH_2); 6.20–6.21 (2H, m, H Ar); 6.30–6.31 (2H, m, H Ar); 7.35 (2H, br. s, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.4, 20.4 ($2CH_3$); 31.5, 41.0, 44.8 ($3Csp^3$); 122.6, 125.4 ($2Csp^2$); 107.4, 110.3, 142.1 (6CH Ar); 154.9 (2C Ar). Found, %: C 69.28; H 6.14; S 12.28. $C_{15}H_{16}O_2S$. Calculated, %: C 69.20; H 6.19; S 12.32.

4,5-Dimethyl-2-phenyl-2-(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran (5a). Yield 213 mg (84%), green solid, mp 74–75°C. IR spectrum, ν, cm^{-1}: 3053 (w), 2894 (m), 1442 (s), 1256 (m), 720 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.69 (3H, s, CH_3); 1.80 (3H, s, CH_3); 2.91 (1H, d, *J* = 15.6) and 3.01–3.11 (3H, m, $2CH_2$); 6.92–6.94 (2H, m, H Ar); 7.23–7.29 (2H, m, H Ar); 7.32–7.35 (2H, m, H Ar); 7.48–7.49 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.3, 20.4 ($2CH_3$); 32.4, 47.2, 50.8 ($3Csp^3$); 123.3, 126.2 ($2Csp^2$); 125.0, 125.7, 126.2, 127.1, 127.2, 128.2 (8CH Ar); 145.6, 151.5 (2C Ar). Found, %: C 71.28; H 6.29; S 22.20. $C_{17}H_{18}S_2$. Calculated, %: C 71.33; H 6.29; S 22.38.

4,5-Dimethyl-2-phenyl-2-(selenophen-2-yl)-3,6-dihydro-2*H*-thiopyran (5b). Yield 280 mg (84%), dark-red solid, mp 74–75°C. IR spectrum, ν, cm^{-1}: 3058 (w), 2896 (m), 1490 (m), 1443 (s), 1221 (m), 700 (s). ^{1}H NMR spectrum, δ, ppm: 1.67 (3H, s, CH_3); 1.77 (3H, s, CH_3); 2.88–3.07 (4H, m, $2CH_2$); 6.99–7.00 (1H, m, H Ar); 7.11–7.13 (1H, m, H Ar); 7.23–7.25 (1H, m, H Ar); 7.29–7.32 (2H, m, H Ar); 7.49–7.51 (2H, m, H Ar); 7.90–7.91 (1H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.2, 20.4 ($2CH_3$); 32.5, 47.6, 52.6 ($3Csp^3$); 123.3, 126.1 ($2Csp^2$); 127.1, 127.2, 127.6, 128.1, 128.8, 130.5 (8CH Ar); 145.7, 159.6 (2C Ar). Found, %: C 61.07; H 5.33; S 9.90. $C_{17}H_{18}SSe$. Calculated, %: C 61.26; H 5.40; S 9.61.

2-(4,5-Dimethyl-2-phenyl-3,6-dihydro-2*H*-thiopyran-2-yl)furan (5c). Yield 238 mg (88%), orange solid, mp 62–63°C. IR spectrum, ν, cm^{-1}: 3021 (w), 2888 (m), 1491 (s), 1445 (s), 1154 (s), 1013 (s), 747 (s), 705 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.68 (3H, s, CH_3); 1.76 (3H, s, CH_3); 2.83 (1H, d, *J* = 16.8) and 2.90–2.98 (3H, m, $2CH_2$); 6.24 (1H, d, *J* = 3.0, H Ar); 6.32 (1H, dd, *J* = 3.6, *J* = 1.8, H Ar); 7.22–7.25 (1H, m, H Ar); 7.29–7.31 (2H, m, H Ar); 7.35–7.36 (3H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.3, 20.3 ($2CH_3$); 31.8, 44.1, 49.2 ($3Csp^3$); 123.0, 126.1 ($2Csp^2$); 108.0, 110.1, 127.0, 127.2, 128.3, 142.0 (8CH Ar); 144.0, 156.5 (2C Ar). Found, %: C 75.29; H 6.63; S 12.09. $C_{17}H_{18}OS$. Calculated, %: C 75.55; H 6.66; S 11.85.

4,5-Dimethyl-2,2-diphenyl-3,6-dihydro-2*H*-thiopyran (7a).[14b,31] Yield 252 mg (90%), white solid, mp 50–51°C (mp 52–53°C (hexane)[31]). ^{1}H NMR spectrum, δ, ppm: 1.70 (3H, s, CH_3); 1.83 (3H, s, CH_3); 2.78 (2H, s, CH_2); 2.94 (2H, s, CH_2); 7.23–7.25 (2H, m, H Ar); 7.29–7.32 (4H, m, H Ar); 7.37–7.39 (4H, m, H Ar).

3',6',10,11-Tetrahydro-4',5'-dimethylspiro[dibenzo-[*a*,*d*][7]annulene-5,2'-thiopyran] (7b). Yield 291 mg (95%), colorless crystals, mp 89–90°C (MeOH). IR spectrum, ν, cm^{-1}: 3056 (w), 2871 (m), 1484 (s), 1446 (s), 729 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.64 (3H, s, CH_3); 1.96 (3H, s, CH_3); 2.76 (2H, s, CH_2); 3.01–3.08 (2H, m, $C\underline{H}_2CH_2$); 3.35 (2H, s, CH_2); 4.20–4.27 (2H, m, $CH_2C\underline{H}_2$); 7.05–7.08 (2H, m, H Ar); 7.10–7.14 (4H, m, H Ar); 7.19 (2H, d, *J* = 7.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.0, 20.7 ($2CH_3$); 32.7, 33.1, 44.3, 50.3 ($5Csp^3$); 124.1, 126.5 ($2Csp^2$); 125.6, 126.1, 127.5, 132.0 (8CH Ar); 140.0, 141.4 (4C Ar). Found, %: C 82.20; H 7.12; S 10.71. $C_{21}H_{22}S$. Calculated, %: C 82.29; H 7.25; S 10.46.

Synthesis of 2*H*-thiopyrans *cis*-8a,b (General method). A solution of the corresponding thioketone **2** (1.0 mmol) in hexa-2,4-diene **1b** (0.25 ml, 2.2 mmol) as a mixture of (*E*,*E*)-, (*Z*,*E*)-, and (*Z*,*Z*)-isomers in a ratio of 55:40:5 was stirred at room temperature for 24 h. Diene **1b** was evaporated *in vacuo*, and the residue was recrystallized from MeOH.

***cis*-3,6-Dimethyl-2,2-di(thiophen-2-yl)-3,6-dihydro-2*H*-thiopyran (*cis*-8a)**. Yield 292 mg (>99%), colorless crystals, mp 76.0–76.5°C (MeOH). IR spectrum, ν, cm^{-1}: 3101 (w), 2961 (w), 2857 (w), 1445 (m), 1429 (m), 1239 (s), 1223 (s), 1093 (m), 761 (m), 707 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.04 (3H, d, *J* = 6.6, CH_3); 1.31 (3H, d, *J* = 7.2, CH_3); 3.08–3.12 (1H, m, $C\underline{H}CH_3$); 3.29–3.34 (1H, m, $C\underline{H}CH_3$); 5.52 (1H, dt, *J* = 10.8, *J* = 1.8, $C\underline{H}$=CH); 5.84–5.87 (1H, m, CH=C$\underline{H}$); 6.88 (1H, dd,

J = 4.8, *J* = 3.6, H Ar); 6.90 (1H, dd, *J* = 4.8, *J* = 3.6, H Ar); 6.97 (1H, dd, *J* = 3.6, *J* = 1.2, H Ar); 7.13 (1H, dd, *J* = 3.6, *J* = 1.2, H Ar); 7.19 (1H, dd, *J* = 5.4, *J* = 1.2, H Ar); 7.21 (1H, dd, *J* = 4.8, *J* = 1.2, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.1, 19.7 ($2CH_3$); 35.5, 40.4, 54.1 ($3Csp^3$); 124.1, 124.9, 125.1, 125.3, 125.7, 126.3, 129.1, 132.6 ($2Csp^2$, 6CH Ar); 150.9, 153.4 (2C Ar). Found, *m/z*: 315.0307 $[M+Na]^+$. $C_{15}H_{16}NaS_3$. Calculated, *m/z*: 315.0306. Found, %: C 61.72; H 5.55; S 32.89. $C_{15}H_{16}S_3$. Calculated, %: C 61.60; H 5.51; S 32.89.

***cis*-3,6-Dimethyl-2,2-di(selenophen-2-yl)-3,6-dihydro-2*H*-thiopyran (*cis*-8b)**. Yield 386 mg (>99%), colorless crystals, mp 97.8–98.3°C (MeOH). IR spectrum, ν, cm^{-1}: 3006 (w), 2968 (w), 1445 (m), 1239 (s), 1226 (m), 1084 (w), 758 (m), 688 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.09 (3H, d, *J* = 6.6, CH_3); 1.32 (3H, d, *J* = 7.2, CH_3); 3.02–3.06 (1H, m, C<u>H</u>CH_3); 3.41–3.45 (1H, m, C<u>H</u>CH_3); 5.53 (1H, dt, *J* = 10.8, *J* = 1.8, C<u>H</u>=CH); 5.85–5.88 (1H, m, CH=C<u>H</u>); 7.10 (1H, dd, *J* = 5.4, *J* = 3.6, H Ar); 7.13–7.16 (2H, m, H Ar); 7.23–7.24 (1H, m, H Ar); 7.89–7.91 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 19.5, 19.7 ($2CH_3$); 36.0, 40.8, 57.6 ($3Csp^3$); 125.7, 126.7, 128.3, 128.9, 129.1, 130.6, 130.8, 132.6 ($2Csp^2$, 6CH Ar); 159.0, 162.7 (2C Ar). Found, %: C 46.69; H 4.11; S 8.35. $C_{15}H_{16}SSe_2$. Calculated, %: C 46.64; H 4.18; S 8.30.

Test experiment with equimolar amounts of thioketone 2a and a mixture of hexa-2,4-dienes (*Z*,*E*)-, (*E*,*E*)-, and (*Z*,*Z*)-1b. A solution of thioketone **2a** (210 mg, 1 mmol) in a freshly prepared[29] mixture of hexa-2,4-dienes (*Z*,*E*)-, (*E*,*E*)-, and (*Z*,*Z*)-**1b** (70:22:8; 0.1 ml, 1 mmol) was placed into a closed reaction tube. The solution was heated in an oil bath at 80°C for 18 h. After this time, the mixture was cooled to room temperature, and 1,1,2,2-tetrachloroethane (58 mg, 0.34 mmol) was added as a standard. The ^{1}H NMR spectrum of this mixture was obtained in $CDCl_3$ solution.

Synthesis of 2-thiabicyclo[2.2.1]hept-5-enes 12a,b (General method). Freshly distilled cyclopentadiene (**11**) (0.2 ml, 2 mmol) was added at 0°C to a solution of thioketone **2a** (210 mg, 1 mmol) or **4a** (204 mg, 1 mmol) in dry THF (1 ml). The mixture was stirred at 0°C for 2 h, then at room temperature for 24 h. The solvent was evaporated *in vacuo*, and the residue was purified by column chromatography (NEt_3-treated silica gel) using a mixture of petroleum ether and Et_2O (1:1) (for compound **12a**) or CH_2Cl_2 (for compound **12b**) as the eluent.

3,3-Di(thiophen-2-yl)-2-thiabicyclo[2.2.1]hept-5-ene (12a). Yield 196 mg (71%), orange solid, mp 66−69°C (decomp., green coloration). IR spectrum, ν, cm^{-1}: 3101 (m), 2970 (m), 2924 (s), 2854 (m), 1802 (m), 1572 (w), 1519 (w), 1434 (s), 1328 (s), 1331 (m), 1229 (s), 807 (s), 694 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.92 (1H, dt, *J* = 9.6, *J* = 2.4, CH_A); 2.15–2.17 (1H, m, CH_B); 3.92–3.93 (1H, m, CH); 4.28–4.29 (1H, m, CH); 5.80–5.81 (1H, m, C<u>H</u>=CH); 6.48–6.50 (1H, m, CH=C<u>H</u>); 6.83 (1H, dd, *J* = 4.8, *J* = 3.6, H Ar); 6.85 (1H, dd, *J* = 3.6, *J* = 1.8, H Ar); 6.94 (1H, dd, *J* = 4.8, *J* = 3.6, H Ar); 7.08 (1H, dd, *J* = 5.4, *J* = 1.2, H Ar); 7.14 (1H, dd, *J* = 3.6, *J* = 1.2, H Ar); 7.18 (1H, dd, *J* = 5.4, *J* = 1.2, H Ar). ^{13}C NMR spectrum, δ, ppm: 51.4; 54.8; 59.4; 64.4; 124.5; 124.6; 124.7; 126.1; 126.5; 126.6; 133.1; 138.5; 151.6; 154.1. Found, %: C 61.06; H 4.38; S 34.84. $C_{14}H_{12}S_3$. Calculated, %: C 60.83; H 4.37; S 34.80.

3-Phenyl-3-(thiophen-2-yl)-2-thiabicyclo[2.2.1]hept-5-ene (12b). Yield 240 mg (89%), orange solid, mp 79–81°C. The compound consisted of a mixture of two stereoisomers (*endo*- and *exo*-**12b**) in a ratio 7:3. IR spectrum, ν, cm^{-1}: 3047 (w), 2939 (w), 1594 (w), 2896 (m), 1489 (m), 1442 (s), 1331 (m), 1223 (m), 717 (s), 698 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz) (values for the minor isomer in italics): 1.99–2.00 (2H, m, *major*,*minor*-CH_A); 2.10 (1H, d, *J* = 9.0, *major*-CH_B); *2.35* (1H, d, *J* = 9.0, *minor*-CH_B); *4.11* (1H, br. s, *minor*-CH); 4.14 (1H, br. s, *major*-CH); 4.30 (2H, br. s, *major*,*minor*-CH); 5.79–5.83 (2H, m, *major*,*minor*-C<u>H</u>=CH); *6.41* (1H, dd, *J* = 5.4, *J* = 3.0, *minor*-CH=C<u>H</u>); 6.59 (1H, dd, *J* = 5.4, *J* = 2.4, *major*-CH=C<u>H</u>); 6.79–6.80 (1H, m, H Ar); 6.86–6.87 (1H, m, H Ar); *6.92–6.94* (1H, m, H Ar); 7.03–7.05 (1H, m, H Ar); 7.12 (2H, d, *J* = 4.8, H Ar); *7.18* (1H, d, *J* = 5.4, H Ar); 7.21–7.37 (5H, m, H Ar); 7.50 (2H, d, *J* = 7.2, H Ar); 7.59 (2H, d, *J* = 7.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 50.7; 51.5; 53.5; 55.0; 55.5; 57.6; 67.8; 69.2; 124.4; 124.5; 126.2; 126.5; 126.6 (2C); 126.7; 127.9; 128.3; 128.7; 133.2; 133.3; 137.8; 139.1; 145.7; 148.0; 152.8; 155.5. Found, %: C 71.06; H 5.43; S 23.56. $C_{16}H_{14}S_2$. Calculated, %: C 71.06; H 5.23; S 23.71.

Oxidation of 2*H*-thiopyrans 3a and 7a with *m*-CPBA (General method). A solution of 2*H*-thiopyran **3a** (292 mg, 1 mmol) or **7a** (280 mg, 1 mmol) and *m*-CPBA (70% purity; 740 mg, 3 mmol) in CH_2Cl_2 (3 ml) was stirred at room temperature for 48 h. The reaction mixture was extracted with saturated aqueous $NaHCO_3$ solution (3 × 10 ml) and distilled water (1 × 10 ml). The organic phase was dried over anhydrous Na_2SO_4 and concentrated *in vacuo*. Products **13a**,**b** were purified by recrystallization from petroleum ether.

1,6-Dimethyl-4,4-di(thiophen-2-yl)-7-oxa-3-thiabicyclo-[4.1.0]heptane 3,3-dioxide (13a). Yield 306 mg (90%), white crystals, mp 171–172°C (petroleum ether). IR spectrum, ν, cm^{-1}: 3083 (w), 2925 (s), 1459 (m), 1432 (m), 1308 (s), 1120 (s), 851 (m), 700 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.33 (3H, s, CH_3); 1.53 (3H, s, CH_3); 3.27 and 3.62 (2H, AX, *J* = 18.0, 5-CH_2); 3.28 and 3.48 (2H, AX, *J* = 18.0, 2-CH_2); 7.02 (1H, dd, *J* = 5.4, *J* = 4.2, H Ar); 7.06 (1H, dd, *J* = 5.4, *J* = 4.2, H Ar); 7.35–7.40 (3H, m, H Ar); 7.41–7.42 (1H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 20.8, 21.4 ($2CH_3$); 46.0, 53.0, 60.2, 61.1, 65.2 ($5Csp^3$); 127.1, 127.2, 127.5, 127.6, 128.9, 130.0 (6CH Ar); 139.2, 139.5 (2C Ar). Mass spectrum, *m*/*z* (I_{rel}, %): 363 $[M+Na]^+$ (100), 364 $[M+H+Na]^+$ (10). Found, %: C 52.96; H 4.72; S 28.35. $C_{15}H_{16}O_3S_3$. Calculated, %: C 52.91; H 4.75; S 28.25.

1,6-Dimethyl-4,4-diphenyl-7-oxa-3-thiabicyclo[4.1.0]-heptane 3,3-dioxide (13b). Yield 312 mg (95%), white solid, mp 191–192°C (petroleum ether). IR spectrum, ν, cm^{-1}: 3060 (w), 2926 (m), 1497 (m), 1446 (m), 1308 (s), 1124 (s), 893 (m), 697 (s). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.33 (3H, s, CH_3); 1.49 (3H, s, CH_3); 3.13 and 3.52 (2H, AX, *J* = 18.0, 5-CH_2); 3.25 and 3.51 (2H, AX, *J* = 18.0,

2-CH_2); 7.30–7.37 (6H, m, H Ar); 7.52–7.54 (2H, m, H Ar); 7.59–7.61 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 21.0, 21.5 (2CH_3); 43.4, 54.5, 60.5, 60.9, 70.1 (5Csp^3); 128.2, 128.4, 128.5, 128.7, 129.2, 129.5 (10CH Ar); 137.5, 137.9 (2C Ar). Mass spectrum, *m*/*z* (I_{rel}, %): 246 (25), 351 $[M+Na]^+$ (100), 352 $[M+H+Na]^+$ (20). Found, %: C 69.33; H 5.99; S 9.67. $C_{19}H_{20}O_3S$. Calculated, %: C 69.47; H 6.15; S 9.76.

X-ray crystal structure determination of compound *cis*-8a. Suitable single crystals of compound ***cis*-8a** were obtained by slow evaporation of a solution of the compound in MeOH. All measurements were performed on a Rigaku Oxford Diffraction SuperNova area-detector diffractometer[32] using Mo*K*α radiation (λ 0.71073 Å) from a micro-focus X-ray source and an Oxford Instruments Cryojet XL cooler. Data reduction was performed with CrysAlisPro.[32] Intensities were corrected for Lorentz and polarization effects, and an empirical absorption correction using spherical harmonics[32] was applied. Equivalent reflections, other than Friedel pairs, were merged. The structure was solved by dual space methods using SHELXT-2014,[33] which revealed the positions of all non-hydrogen atoms. One of the thiophene rings is disordered through a rotation of approximately 180° about the ring pivot axis, thus interchanging the positions of the S atom and a C atom. Two positions were defined for these atoms, and the site occupation factor of the major conformation refined to 0.847(3). Similarity restraints were applied to the chemically equivalent bond lengths involving the disordered atoms, while neighboring atoms from the two conformations of the disordered ring were restrained to have similar atomic displacement parameters. The non-hydrogen atoms were refined anisotropically. All of the H atoms were placed in geometrically calculated positions and refined by using a riding model where each H atom was assigned a fixed isotropic displacement parameter with a value equal to $1.2U_{eq}$ of its parent C atom ($1.5U_{eq}$ for the methyl groups). The refinement of the structure was carried out on F^2 by using full-matrix least-squares procedures, which minimized the function $\Sigma w(F_o^2–F_c^2)^2$. A correction for secondary extinction was not applied. Refinement of the absolute structure parameter[34] yielded a value of 0.03(2), which confidently confirms that the refined model represents the true absolute structure. Neutral atom scattering factors for non-hydrogen atoms were taken from ref.[35], and the scattering factors for H atoms were taken from ref.[36] Anomalous dispersion effects were included in F_c;[37] the values for *f*′ and *f*″ were those of ref.[38] The values of the mass attenuation coefficients are those of ref.[39] The SHELXL-2016 program[40] was used for all calculations.

Crystal data for compound ***cis*-8a**: $C_{15}H_{16}S_3$, *M* 292.46, crystallized from methanol, colorless, prism, crystal dimensions 0.16 × 0.18 × 0.25 mm, monoclinic, space group *Ia*, *Z* 4, reflections for unit cell determination 7331, 2θ range for unit cell determination 7–61°, *a* 15.2401(4), *b* 8.36686(16), *c* 12.1476(3) Å, β 111.886(3)°, *V* 1437.33(6) Å^3, *T* 160(1) K, D_X 1.352 g×cm^{-3}, μ(Mo*K*α) 0.495 mm^{-1}, scan type ω, $2\theta_{max}$ 60.8°, transmission factors (min; max) 0.923; 1.000, total reflections measured 9233, symmetry independent reflections 3712, reflections with $I > 2\sigma(I)$ 3660, reflections used in refinement 3712, parameters refined 184, restraints 26, $R(F)$ ($I > 2\sigma(I)$ reflections) 0.0214, $wR(F^2)$ (all data) 0.0561 ($w = (\sigma^2(F_o^2) + (0.0340P)^2 + 0.2427P)^{-1}$, where $P = (F_o^2 + 2F_c^2)/3$), goodness of fit 1.041, final Δ_{max}/σ 0.001, Δρ (max; min) 0.22; –0.25 e·Å^{-3}.

The crystallographic data and refinement parameters of compound *cis*-**8a** have been deposited at the Cambridge Crystallographic Data Center (deposit CCDC-1523861). These data can be obtained free of charge *via* www.ccdc.cam.ac.uk/getstructures

The authors thank the National Science Center (Cracow, PL) for financial support within the project Maestro (Grant Number: Dec-2012/06/A/ST5/00219). This work is a part of the planned PhD thesis of Paulina Grzelak, University of Łódź.

References

1. Blond, G.; Gulea, M.; Mamane, V. *Curr. Org. Chem*. **2016**, *20*, 2161.
2. (a) Block, E. In *Science of Synthesis*, Molander, G. A., Ed.; G. Thieme Verlag: Stuttgart, 2007, vol. 33, ch. 33, p. 235. (b) Tavakolinia, F.; Baghipour, T.; Hossaini, Z.; Zareyee, D.; Mohammad, A.; Khalilzadeh, M. A.; Rajabi, M. *Nucleic Acid Ther.* **2012**, *22*, 265.
3. (a) Bogdanowicz-Szwed, K.; Budzowski, A. *Wiad. Chem.* **2003**, *57*, 435 (PL-ISSN 0043-5104). (b) Mlostoń, G.; Grzelak, P.; Heimgartner, H. *J. Sulfur Chem*. **2017**, *38*, 1.
4. Timoshenko, V. M.; Siry, S. A.; Rozhenko, A. B.; Shermolovich, Y. G. *J. Fluorine Chem*. **2010**, *131*, 172.
5. Dentel, H.; Chataigner, I.; Lohier, J.-F.; Gulea, M. *Tetrahedron* **2012**, *68*, 2326.
6. (a) Kanishchev, O. S.; Sanselme, M.; Bouillon, J.-P. *Tetrahedron* **2013**, *69*, 1322. (b) Mikhailichenko, S. S.; Bouillon, J.-P.; Besson, T.; Shermolovich, Y. G. *Tetrahedron Lett*. **2010**, *51*, 990.
7. Larsen, C.; Harpp, D. N. *J. Org. Chem*. **1980**, *45*, 3713.
8. (a) Schönberg, A.; König, B. *Chem. Ber.* **1968**, *101*, 725. (b) König, B.; Martens, J.; Praefcke, K.; Schönberg, A.; Schwarz, H.; Zeisberg, R. *Chem. Ber.* **1974**, *107*, 2931. (c) Praefcke, K.; Weichsel, C. *Liebigs Ann. Chem.* **1979**, 784. (d) Weinreb, S. M.; Staib, R. R. *Tetrahedron* **1982**, *38*, 3087. (e) Metzner, P. *Synthesis* **1992**, 1185. (f) Itoh, T.; Fujikawa, K.; Kubo, M. *J. Org. Chem.* **1996**, *61*, 8329. (g) Mlostoń, G.; Grzelak, P.; Hamera-Fałdyga, R.; Jasiński, M.; Pipiak, P.; Urbaniak, K.; Albrecht, Ł.; Hejmanowska, J.; Heimgartner, H. *Phosphorus, Sulfur Silicon Relat. Elem.* **2017**, *192*, 204.
9. (a) Baumann, K.; Fromm, E. *Ber. Dtsch. Chem. Ges.* **1889**, *22*, 2593. (b) Gaumont, A. C.; Wazneh, L.; Denis, J. M. *Tetrahedron* **1991**, *47*, 4927.
10. (a) Middleton, W. J. *J. Org. Chem*. **1965**, *30*, 1390. (b) Schuler, B.; Sundermeyer, W. *Chem. Ber.* **1990**, *123*, 177.
11. (a) Larsen, S. D.; Fisher, P. V.; Libby, B. E.; Jensen, R. M.; Mizsak, S. A.; Watt, W. *J. Org. Chem.* **1996**, *61*, 4725. (b) Huang, N.-Z.; Lakshmikantham, M. V.; Cava, M. P. *J. Org. Chem.* **1987**, *52*, 169.
12. (a) Sasaki, T.; Eguchi, S.; Katada, T. *Heterocycles* **1984**, *21*, 682. (b) Katada, T.; Eguchi, S.; Sasaki, T. *J. Org. Chem.* **1986**, *51*, 314.
13. (a) Bonini, B. F.; Mazzanti, G.; Zani, P.; Maccagnani, G. *J. Chem. Soc., Perkin Trans. 1* **1989**, 2083. (b) Bonini, B. F.; Lenzi, A.; Maccagnani, G.; Barbaro, G.; Giorgianni, P.; Macciantelli, D. *J. Chem. Soc., Perkin Trans. 1* **1987**, 2643.

14. (a) Ito, S.; Okujima, T.; Kikuchi, S.; Shoji, T.; Morita, N.; Asao, T.; Ikoma, T.; Tero-Kubota, S.; Kawakami, J.; Tajiri, A. *J. Org. Chem*. **2008**, *73*, 2256. (b) Breu, J.; Höcht, P.; Rohr, U.; Schatz, J.; Sauer, J. *Eur. J. Org. Chem*. **1998**, 2861.
15. (a) Schatz, J.; Sauer, J. *Tetrahedron Lett.* **1994**, *35*, 4767. (b) Rohr, U.; Schatz, J.; Sauer, J. *Eur. J. Org. Chem*. **1998**, 2875.
16. Kiselev, V. D.; Kashaeva, E. A.; Potapova, L. N.; Iskhakova, G. G.; Konovalov, A. I. *Russ. Chem. Bull.*, *Int. Ed.* **2005**, *54*, 2034. [*Izv. Akad. Nauk*, *Ser. Khim.* **2005**, 1973.]
17. Jiang, H.; Cruz Cruz, D.; Li, Y.; Lauridsen, V. H.; Jørgensen, K. A. *J. Am. Chem. Soc*. **2013**, *135*, 5200.
18. Hejmanowska, J.; Jasiński, M.; Mlostoń, G.; Albrecht, Ł. *Eur. J. Org. Chem.* **2017**, 950.
19. Mlostoń, G.; Urbaniak, K.; Gębicki, K.; Grzelak, P.; Heimgartner, H. *Heteroat. Chem*. **2014**, *25*, 548.
20. Hamera-Fałdyga, R.; Grzelak, P.; Pipiak, P.; Mlostoń, G. *Phosphorus*, *Sulfur Silicon Relat. Elem.* **2017**, *192*, 197.
21. Varma, R. S.; Kumar, D. *Org. Lett*. **1999**, *1*, 697.
22. Wilker, S.; Erker, G. *J. Am. Chem. Soc.* **1995**, *117*, 10922.
23. (a) Mlostoń, G.; Urbaniak, K.; Linden, A.; Heimgartner, H. *Helv. Chim. Acta* **2015**, *98*, 453. (b) Mlostoń, G.; Pipiak, P.; Linden, A.; Heimgartner, H. *Helv. Chim. Acta* **2015**, *98*, 462. (c) Mlostoń, G.; Pipiak, P.; Heimgartner, H. *Beilstein J. Org. Chem.* **2016**, *12*, 716. (d) Mlostoń, G.; Hamera-Fałdyga, R.; Linden, A.; Heimgartner, H. *Beilstein J. Org. Chem*. **2016**, *12*, 1421.
24. Johnson, C. K. *ORTEPII*, *Report ORNL-5138*: Oak Ridge National Laboratory: Oak Ridge, Tennessee, 1976.
25. Praefcke, K.; Weichsel, C. *Liebigs Ann. Chem.* **1980**, 1604.
26. Li, H.; Silver, J. E.; Watson, W. H.; Kashyap, R. P.; Le Noble, W. J. *J. Org. Chem.* **1991**, *56*, 5932.
27. (a) Petrov, V. A.; Lustig, S.; Marshall, W. *J. Fluorine Chem*. **2007**, *128*, 1227. (b) Schwab, M.; Sundermeyer, W. *Chem. Ber.* **1986**, *119*, 2458.
28. Block, E.; Wall, A. *Tetrahedron Lett.* **1985**, *26*, 1425.
29. Alder, K.; Vogt, W. *Liebigs Ann. Chem.* **1951**, *571*, 137.
30. Magnusson, G. *J. Org. Chem.* **1985**, *50*, 1998.
31. Biellmann, J. F.; Ducep, J. B.; Vicens, J. J. *Tetrahedron* **1976**, *32*, 1801.
32. *CrysAlisPro*, *Version 1.171.38.43c*; Rigaku Oxford Diffraction: Abingdon, 2015.
33. Sheldrick, G. M. *Acta Crystallogr. Sect. A* **2015**, *71*, 3.
34. Parsons, S.; Flack, H. D.; Wagner, T. *Acta Crystallogr. Sect. B* **2013**, *69*, 249.
35. Maslen, E. N.; Fox, A. G.; O'Keefe, M. A. In *International Tables for Crystallography*, Wilson, A. J. C., Ed.; Kluwer Academic Publishers: Dordrecht, 1992, vol. C, Table 6.1.1.1, p. 477.
36. Stewart, R. F.; Davidson, E. R.; Simpson, W. T. *J. Chem. Phys.* **1965**, *42*, 3175.
37. Ibers, J. A.; Hamilton, W. C. *Acta Crystallogr.* **1964**, *17*, 781.
38. Creagh, D. C.; McAuley, W. J. In *International Tables for Crystallography*; Wilson, A. J. C., Ed.; Kluwer Academic Publishers: Dordrecht, 1992, vol. C, Table 4.2.6.8, p. 219.
39. Creagh, D. C.; Hubbell, J. H. In *International Tables for Crystallography*; Wilson, A. J. C., Ed.; Kluwer Academic Publishers: Dordrecht, 1992, vol. C, Table 4.2.4.3, p. 200.
40. Sheldrick, G. M. *Acta Crystallogr*., *Sect. C: Struct. Chem.* **2015**, *C71*, 3.