SILICON-CONTAINING DERIVATIVES OF SYDNONES

E. S. Trankina, N. G. Frolova, I. A. Godovikov, and I. A. Cherepanov*

Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, ul. Vavilova 28, Moscow, 119991 Russia

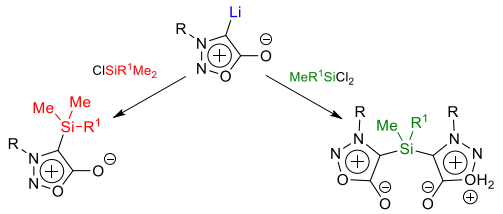
Cite this: *INEOS OPEN*, **2020**, *3* (*1*), 35–42
DOI: 10.32931/io2005a

Received 6 March 2020,
Accepted 18 April 2020

http://ineosopen.org

Abstract

Various sydnon-4-yl- and bis(4-sydnon-4-yl)silanes are prepared by reacting lithium derivatives of sydnones with chloro- and dichlorosilanes. For the first time, the complete ^{1}H, ^{13}C, ^{29}Si, and ^{15}N NMR studies of the silicon derivatives of sydnones are performed.



Key words: sydnones, 4-lithium derivatives, silicon derivatives, bis(sydnonyl)silanes.

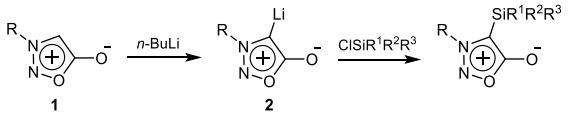
Introduction

Nowadays, silicon chemistry plays an indispensable role in the creation of new biologically active compounds [1–5]. The Si/C switch strategy (the displacement of carbon for silicon in biologically active molecules) [6–14] and the introduction of silyl substituents into the already known pharmaceuticals have demonstrated great potential [15–18]. The electronic features of a silicon atom (the lower electronegativity and the larger radius compared to the carbon atom, the longer carbon–silicon bonds compared to the carbon–carbon bonds, *etc.*) change the pharmacological properties of the carbon analogs. The introduction of additional substituents into organosilicon moieties or the displacement of the carbon atom for the silicon one can change the lipophilic properties of the resulting compounds that can adopt conformations and form metabolites differing from those of their carbon analogs. In some cases, the silicon-containing derivatives display improved penetration and selective binding with receptors in tissues [6–18]. This allows for lowering the drug doses and reducing the side effects. Hence, the introduction of silicon into a drug structure opens the way to modification of its pharmacodynamic and pharmacokinetic properties.

The synthesis of organosilicon derivatives of the nitrogen-containing heterocyclic compounds (pyrrole, imidazole, piperidine, pyrazole, *etc.*) is of particular interest since these structural motifs serve as bases for alkaloids, synthetic and natural antibiotics, and other pharmaceuticals [19–25].

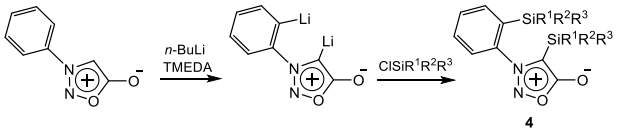
Sydnones refer to the unique class of mesoionic heterocyclic compounds [26–29]. Besides unusual structures, they exhibit a broad spectrum of biological activities [30–31]. Unfortunately, the silicon derivatives of sydnones are scarcely studied.

The main method for the introduction of silicon atoms into the molecules of sydnones **1** is the reaction of 4-lithium derivatives of sydnones **2** with the halogen-containing silicon compounds (Scheme 1) [32–39].

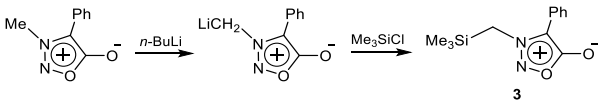


Scheme 1. Interaction of 4-lithium derivatives of sydnones with triorganochlorosilanes.

Sydnones **3** and **4** bearing silicon atoms in organic substituents at the third position were also obtained by the reaction of triorganochlorosilanes with the corresponding lithium derivatives (Schemes 2 [35–39] and 3 [40]).

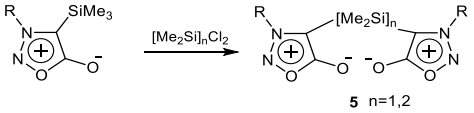


Scheme 2. Interaction of dilithium derivatives of sydnones with triorganochlorosilanes.



Scheme 3. Interaction of 3-methyllithium derivative of sydnone with trimethylchlorosilane.

Silanes **5** bearing two mesoionic moieties in their structures were obtained by the substitution of 4-trimethylsilyl moieties in the corresponding sydnones with dichlorodimethylsilane or dichlorotetramethyldisilane (Scheme 4) [32, 33].



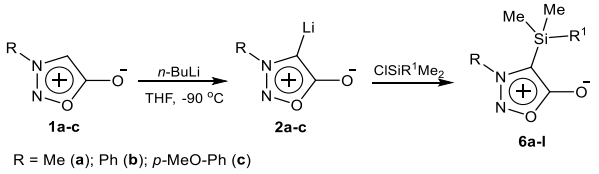
Scheme 4. Synthesis of bis(sydnonyl)silanes by transsilylation.

Dimethylsilyl derivatives of sydnones bearing hydride, vinyl, phenyl, and alkoxy substituents at the silicon atoms have not been described yet.

The goal of the present work was to study the interaction of 4-lithium derivatives of 3-methyl-, 3-phenyl- and 3-(*p*-methoxyphenyl)sydnones **2a**–**c** with different chlorosilanes and dichlorosilanes and to study the chemical shifts of ^{1}H, ^{13}C, ^{29}Si, and ^{15}N nuclei in the resulting compounds depending on the nature of substituents in the sydnone core by NMR spectroscopy.

Results and discussion

The interaction of 4-lithium derivatives of sydnones **1a**–**c** (compounds **2a**–**c**) with chlorosilanes afforded various 4-silicon-substituted derivatives **6a**–**l** (Scheme 5). The reactions proceeded smoothly in the case of trimethylchlorosilane and chlorodimethylsilane: silicon derivatives **6a**–**e** were obtained in 70–91% yields (Table 1). The chlorosilanes bearing vinyl or aryl substituent at the silicon atom reacted less actively, and the yields of target products **6f**–**i** composed 28–62%. This can be associated with both the steric and electronic effects of the additional substituents at the silicon atom.



Scheme 5. Interaction of 4-lithium derivatives of sydnones with chlorosilanes.

The yields of 4-silyl derivatives in the case of 3-methylsydnone were lower than those for 3-aryl-substituted sydnones, which can be explained by the lower stability of 4-lithium-3-methylsydnone **2a** at higher temperatures and its insufficient reactivity at lower temperatures. The low yields of dimethylethoxy derivatives **6j**–**l** are likely to be connected with their hydrolytic instability and losses during the chromatographic separation of the products. The other 4-silyl derivatives of sydnones did not display the propensity for hydrolysis.

Table 1. Interaction of 4-lithium derivatives of sydnones with chlorosilanes

6	R	R^1	Yield, %
a	*p*-$MeOC_6H_4$	Me	91
b	Ph	Me	76
c	Me	Me	70
d	Ph	H	84
e	Me	H	70
f	Ph	vinyl	62
g	Me	vinyl	28
h	Ph	Ph	53
i	Me	Ph	45
j	*p*-$MeOC_6H_4$	OEt	50
k	Ph	OEt	41
l	Me	OEt	68

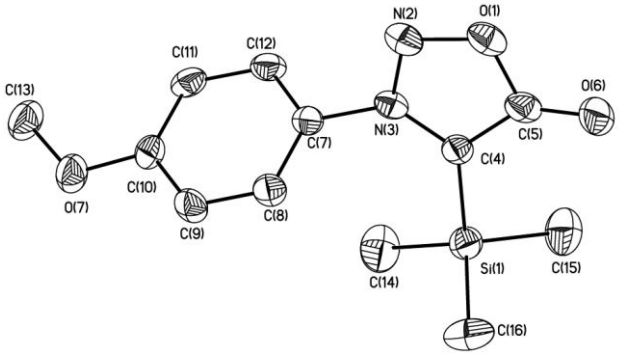
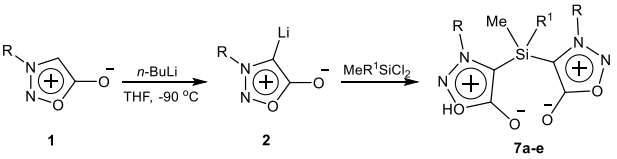


Figure 1. General view of **6a** in representation of atoms by thermal ellipsoids (p = 50%).

The molecular structure of **6a** was confirmed by X-ray diffraction (Fig. 1).

The presence of reactive hydride (**6d**,**e**), vinyl (**6f**,**g**), and alkoxy (**6j**–**l**) groups at the silicon atom enable the use of these silicon derivatives of sydnones in subsequent functionalization (polycondensation, hydrosilylation, and hydrothiolation), in particular, in the synthesis of polyorganosiloxanes bearing mesoionic (sydnonyl) heterocyclic moieties.

Bis(sydnonyl)-functionalized silicon derivatives **7** were obtained by the reactions of **2a**–**c** with dichlorodiorganylsilanes (Scheme 6). The yields of derivatives **7a**–**c** ranged within 65–80% and those of **7d**,**e** composed 20–26% in the reactions of **2** with dichlorodimethylsilane and dichloromethylvinylsilane, respectively (Table 2).



Scheme 6. Interaction of 4-lithium derivatives of sydnones with dichlorosilanes.

It should be noted that, during the reaction with dichloromethylphenylsilane, we did not detect bis(sydnonyl) derivatives. The low yield of methylvinyl derivatives **7d**,**e** and the lack of formation of the corresponding methylphenylsilyl derivatives bearing two sydnonyl substituents can be associated with both the steric and electronic effects of the substituents. Compounds **7** feature the lower hydrolytic stability than derivatives **6a**–**i**, especially in the presence of acid impurities. In a methanol solution, they completely decompose for 1–2 days.

The molecular structures of derivatives **7a** and **7c** were determined by X-ray diffraction and are presented in Figs. 2 and 3.

Table 2. Interaction of 4-lithium sydnones with dichlorosilanes

7	R	R^1	Yield, %
a	*p*-$MeOC_6H_4$	Me	74
b	Ph	Me	65
c	Me	Me	89
d	Ph	vinyl	20
e	Me	vinyl	26

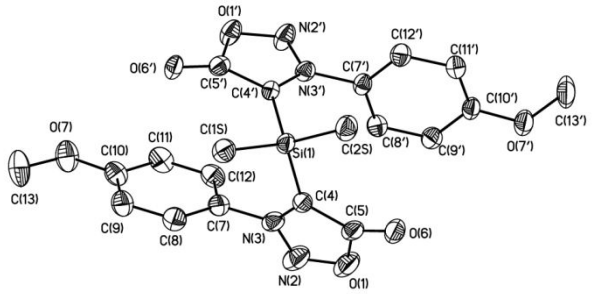


Figure 2. General view of **7a** in representation of atoms by thermal ellipsoids (p = 50%).

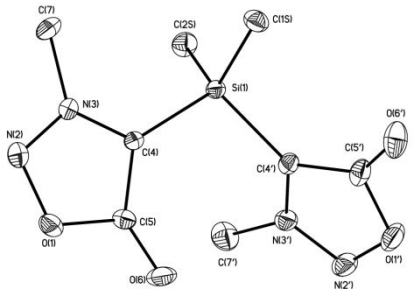


Figure 3. General view of **7c** in representation of atoms by thermal ellipsoids (p = 50%).

NMR studies

Up to date, only few NMR studies have been conducted to characterize the structures of sydnones. The ^{15}N and ^{29}Si spectra of silicon derivatives of these mesoionic heterocycles have not been described at all. Taking this into account, we carried out a detailed NMR study of compounds **6** and **7**. In addition, previously reported derivatives **8** [35], **9** [40], and **10** [41] were synthesized and explored as well (Fig. 4).

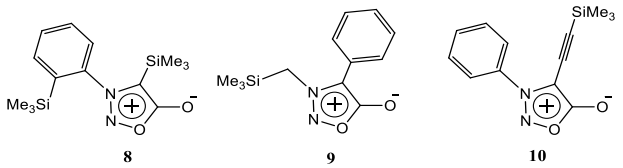


Figure 4. Structures of the previously reported silicon derivatives of sydnones.

The molecular structures of derivatives **9** and **10** were elucidated by X-ray diffraction (Figs. 5 and 6).

Some NMR spectroscopic features of the compounds explored are presented in Table 3. First of all, we analyzed the ^{13}C chemical shifts of C(4) and C(5) carbon nuclei depending on the substituents at N(3) and C(4) atoms of the oxadiazolium ring. As can be seen from Table 3, the chemical shifts of C(3) carbon nuclei fall into the narrow range of 172.7–173.9 ppm. The exceptions are compounds **9** and **10**, for which the signals of C(5) carbon nuclei were found to be shifted upfield (167.2–167.5 ppm). This is likely to be connected with the effect of ethynyl and aryl substituents at C(4) position, which are capable of participating in π–π conjugation with the aromatic system of the sydnone oxadiazole ring.

The chemical shifts of C(4) carbon nuclei lie in the wider range of 95.3–107.7 ppm. As it was expected, the C(4) carbon resonance is significantly affected by the substituent at this atom. It should also be noted that at the same substituent at C(4) position, the chemical shift of the carbon nucleus in the case of a methyl substituent at N(3) position of the oxadiazole ring is observed in the more upfield region.

Based on the ^{1}H^{15}N-HMBC correlation, the chemical shifts of N(3) nitrogen nuclei of the oxadiazole ring were determined (Table 3). In the case of 3-alkylsydnone derivatives, both of the nitrogen resonances were found. As it was expected, the ^{15}N(2) chemical shift featured the higher value (338.2–361.0 ppm) than that of ^{15}N(3) nitrogen nucleus (δ_N = 272.9–291.8 ppm). A downfield shift may stem from the proximity to O(1) electron-withdrawing moiety. As in the case of C(4) carbon nucleus, the presence of the donor methyl group at N(3) nitrogen atom leads to an upfield shift of its signal compared to that of the aryl analogs.

Another characteristic feature of the compounds under consideration is the presence of the second signal in the ^{1}H^{15}N-HMBC spectra of the sydnone derivatives bearing alkyl groups at the third position of the oxadiazolium ring. This may be rationalized by the following assumption: all the long-range constants of spin–spin interactions $^{2}J_{NH}$ and $^{3}J_{NH}$ between the protons at the α-position of the substituents and the nitrogen nuclei at N(3) and N(2) positions of the sydnone core are very close to the reference value used in the experiment (10 Hz). In the case when R^{1} substituent does not have a proton at the α-

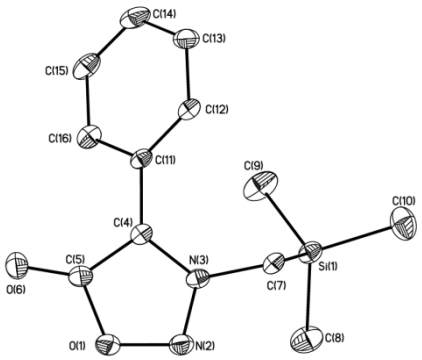


Figure 5. General view of **9** in representation of atoms by thermal ellipsoids (p = 50%).

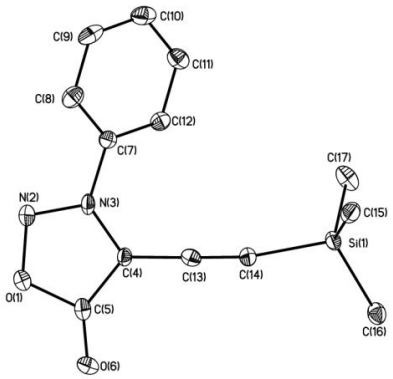
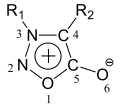


Figure 6. General view of **10** in representation of atoms by thermal ellipsoids (p = 50%).

Table 3. NMR characteristics of the organosilicon derivatives of sydnones



Sydnone	R^1	R^2	$\delta_{C(5)}$	$\delta_{C(4)}$	δ_{SiR^2}	δ_{SiR^1}	$\delta_{N(2)}$	$\delta_{N(3)}$
6a	*p*-$MeOC_6H_4$	$SiMe_3$	173.4	105.6	–8.1	–	–	288.5
6b	Ph	$SiMe_3$	173.3	105.6	–8.0	–	–	288.2
6c	Me	$SiMe_3$	173.7	103.0	–8.8	–	355.3	274.2
6d	Ph	$SiHMe_2$	173.5	102.8	–26.8	–	–	289.3
6e	Me	$SiHMe_2$	173.5	101.0	–28.7	–	357.0	272.9
6f	Ph	$SiMe_2CH{=}CH_2$	173.3	104.1	–16.8	–	–	288.7
6g	Me	$SiMe_2CH{=}CH_2$	173.7	101.4	–17.2	–	357.0	274.6
6h	Ph	$SiMe_2Ph$	173.5	104.3	–14.1	–	–	289.8
6i	Me	$SiMe_2Ph$	173.9	101.5	–14.5	–	356.6	275.4
6j	*p*-$MeOC_6H_4$	$SiMe_2OEt$	173.6	103.5	–1.3	–	–	289.6
6k	Ph	$SiMe_2OEt$	173.5	103.7	–1.2	–	–	282.1
6l	Me	$SiMe_2OEt$	173.7	101.7	1.0	–	358.3	273.2
7a	*p*-$MeOC_6H_4$	$SiMe_2Syd$	172.7	101.4	–20.9	–	–	–
7b	Ph	$SiMe_2Syd$	172.5	101.4	–20.8	–	–	290.6
7c	Me	$SiMe_2Syd$	173.5	99.2	–22.9	–	360.2	275.1
7d	Ph	$SiMe(CH{=}CH_2)Syd$	172.7	100.4	–30.8	–	–	289.1
7e	Me	$SiMe(CH{=}CH_2)Syd$	173.4	98.0	–32.3	–	361.0	274.2
8	*o*-$Me_3SiC_6H_4$	$SiMe_3$	173.3	106.3	–8.1	–2.3	–	291.8
9	Me_3SiCH_2	Ph	167.5	107.7	–	4.9	338.2	270.4
10	Ph	C≡C-$SiMe_3$	167.2	95.3	–15.6	–	–	279.4

position, the long-range constant $^4J_{NH}$ is too small compared to the reference value; therefore, it cannot be detected in the spectra. For these derivatives, the spectra show only one signal.

The use of ^{29}Si NMR spectroscopy appeared to be very productive for the characterization of the resulting compounds bearing organosilicon moieties. The chemical shifts of the Si nuclei ranged from –32.3 ppm (**7e**) to 1.0 ppm (**6j**). As it can be seen from Table 3, theses values strongly depend not only on the structure of a silicon-containing group but also on the structures of the other moieties, including R^1 and R^2 substituents.

In the case of the functionalized sydnones bearing more than one Si atoms in their structures (for example, compound **8**), we used 2D ^{29}Si^{1}H-HMBC NMR correlations to assign each of the Si nucleus signals in the spectra. It was shown that the presence of any ^{1}H nucleus next to the ^{29}Si nuclei enables unambiguous assignment of the ^{29}Si signals, even without recourse to the analysis of their chemical shifts discussed above.

Furthermore, we performed a comparative analysis of the results obtained with the literature data on the ^{29}Si chemical shifts for some silicon-containing compounds featuring close structures and bearing other moieties than sydnone (Table 4).

As is obvious from Table 4, the main peculiarity upon introduction of a sydnone moiety is an upfield shift of the silicon resonances in the ^{29}Si NMR spectra in all three groups of the homologous compounds. This suggests that sydnone moieties are characterized by a relative electron density excess and provide a shielding effect for the other structural units, thus, shifting the signals in the ^{29}Si NMR spectra to the upfield region. The value of this shift is defined by the nature of a silicon-containing moiety and by the second substituent at N(3) position as well.

Therefore, the NMR spectroscopic data obtained suggest that these sydnone-containing moieties should be considered as single structural blocks with conserved constants. It was shown that modern NMR techniques can serve as useful tools for identification of the structures of silicon-functionalized sydnones. Their chemical shifts in the ^{1}H, ^{13}C, ^{15}N, and ^{29}Si NMR spectra are highly characteristic and unique. To explain the observed effects for these compounds, a sydnone core and a substituent at the fourth position must be considered as a single system.

Experimental

General remarks

NMR spectra were recorded on Bruker Avance 400, Avance II 600, and Avance III HD 500 NMR spectrometers with basic frequencies of 400.13 MHz, 600.22 MHz, and 500.13 MHz for ^{1}H nuclei, 100.62 MHz and 125.76 MHz for ^{13}C nuclei, and 99 MHz and 79 MHz for ^{29}Si nuclei, respectively. All chemical shifts in the ^{1}H and ^{13}C spectra were referenced by TMS and residual deuterium solvent ($CDCl_3$) signals. ^{13}C and ^{29}Si NMR spectra were recorded with proton suppression. The data are reported as follows: chemical shifts (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad, hept = heptet, m = multiplet), coupling constants (J, Hz). In addition, two-dimensional NMR correlations (2D ^{1}H^{13}C-HSQC, 2D ^{1}H^{13}C-HMBC, 2D ^{1}H^{15}N-HMBC, 2D ^{1}H^{29}Si-SMBC) were used for the signal assignment. The elemental analyses were performed using a Carlo-Erba CE-1106 elemental analyzer. Melting points were determined with an Electrothermal 1001 MEL-TEMP® capillary melting point apparatus and were uncorrected. TLC was performed on Silufol UV-254 plates; the spots were visualized in an iodine chamber. Column liquid chromatography

Table 4. Chemical shifts in the ^{29}Si NMR spectra for some homolog compounds

Silicon compound	δ_{Si}, ppm
Ph**SiMe$_2$Ph** [42]	–7.5
6h (Syd**SiMe$_2$Ph**)	–14.1
6i (Syd**SiMe$_2$Ph**)	–14.5
7b (Syd**SiMe$_2$Syd**)	–20.8
7c (Syd**SiMe$_2$Syd**)	–22.9
Ph**SiMe$_3$** [42]	–6.0
8 (Syd**SiMe$_3$**)	–8.1
6c (Syd**SiMe$_3$**)	–8.8
6b (Syd**SiMe$_3$**)	–8.0
Ph**SiMe$_2$OEt** [43]	5.0
6j (Syd**SiMe$_2$OEt**)	–1.3
6k (Syd**SiMe$_2$OEt**)	–1.2
6l (Syd**SiMe$_2$OEt**)	1.0

was carried out using silica gel (particle size NMT 80 μm). Silica gel was dried at 140–150 °C at an ambient pressure until complete release of water (*ca.* 15 min) and stored in a hermetically sealed container.

All solvents were purified (dried and distilled) prior to use according to the published procedures [44]. All reactions were performed in an argon atmosphere in dried glassware. Unless otherwise stated, all reagents were used as supplied by commercial sources.

X-ray diffraction data for all the studied compounds were collected using a SMART APEX II area-detector diffractometer (graphite monochromator, ω-scan technique) at the temperature of 120(2) K, using $Mo_{K\alpha}$ radiation (0.71073 Å). The intensity data were integrated by the SAINT program and corrected for absorption and decay by the multi-scan method (semi-empirical from equivalents) implemented in SADABS. All structures were solved by direct methods using SHELXS and were refined against F^2 using SHELXL-2017 [45]. All non-hydrogen atoms were refined with anisotropic displacement parameters. Detailed crystallographic information is provided in Table 5 and can be obtained free of charge *via* http://www.ccdc.cam.ac.uk/conts/retrieving.html or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: 44-1223-336033 using the reference CCDC numbers (Table 5).

Syntheses

General procedure for the interaction of 4-lithium sydnones with chlorosilanes. A solution of *n*-BuLi (2.0 M, 1.72 mmol) was added dropwise at –78 °C to a stirred solution of the corresponding sydnone (1.56 mmol) in dry THF (20 mL). After stirring for 10 min at –78 °C, chlorotrialkylsilane or chlorodimetylsilane (1.87 mmol) was added. A cooling bath was removed, and the mixture was stirred at room temperature for 30 min. The solution was evaporated under vacuum. The resulting residue was dissolved in chloroform, filtered, and purified by column chromatography on silica gel (chloroform–ethyl acetate, v/v= 9:1) to give the target products as white (**6a**–**c**,**e**,**g**–**i**) or colorless (**6d**,**f**) crystalline solids after crystallization from toluene–petroleum ether (1:10).

3-(4-Methoxyphenyl)-4-trimethylsilylsydnone (6a). Yield: 91%. Mp: 115 °C. Anal. Calcd for $C_{12}H_{16}N_2O_3Si$: C, 54.52; H, 6.10; N, 10.60; Si, 10.62. Found: C, 54.47; H, 6.14; N, 10.54; Si, 10.53%. ^{1}H NMR: δ 7.39 and 7.06 (both d, J = 8.9 Hz, 2H + 2H,

Table 5. X-ray crystallographic data and refinement details for the studied molecules

	6a	**7a**	**7c**	**9**	**10**
CCDC	1987575	1987576	1987579	1987578	1987577
Formula	$C_{12}H_{16}N_2O_3Si$	$C_{23.50}H_{24}N_4O_6Si$	$C_8H_{12}N_4O_4Si$	$C_{12}H_{16}N_2O_2Si$	$C_{13}H_{14}N_2O_2Si$
M	264.36	486.56	256.31	248.36	258.35
T, K	120	120	120	120	120
Crystal system	Triclinic	Triclinic	Monoclinic	Orthorhombic	Monoclinic
Space groups	P-1	P-1	$P2_1/c$	$P2_12_12_1$	$P2_1/n$
$Z(Z')$	2(1)	2(1)	4(1)	4(1)	8(2)
a, Å	6.7423(10)	8.5417(17)	8.1645(2)	6.5602(10)	10.0527(11)
b, Å	10.2158(14)	12.080(2)	10.1675(2)	7.0973(10)	13.0619(12)
c, Å	10.652(2)	12.937(3)	14.1521(3)	28.269(4)	20.235(2)
α, °	68.628(3)	85.52(3)	90	90	90
β, °	83.287(5)	72.17(3)	95.6854(9)	90	95.650(2)
γ, °	89.741(3)	74.17(3)	90	90	90
V, Å^3	678.0(2)	1222.6(5)	1169.02(4)	1316.2(3)	2644.1(5)
d_{calc}, g·cm^{-3}	1.295	1.322	1.456	1.253	1.298
μ, cm^{-1}	1.75	1.42	2.11	1.71	1.73
F(000)	280	510	536	528	1088
$2\theta_{max}$, °	58	58	70	59	55
Reflections collected	8238	20241	88632	8180	9388
Reflections unique (R_{int})	3604	6486	5130	3603	5989
Reflections with $I > 2\sigma(I)$	2484	3951	4825	3290	3076
Parameters	167	336	158	155	325
$R1$	0.0473	0.0718	0.0295	0.0366	0.0579
$wR2$	0.1097	0.2058	0.0848	0.0864	0.1263
GOF	1.017	1.023	0.937	1.021	0.990
Largest difference in peak / hole (e/Å^3)	0.307/–0.251	0.764/–0.473	0.530/–0.311	0.361/–0.226	1.312/–0.395

C_6H_4), 3.91 (s, 3H, OMe), 0.11 (s, 9H, $SiMe_3$) ppm. ^{13}C NMR: δ 173.0, 162.1, 128.9, 126.5, 114.7, 105.6, 55.8, –1.4 ppm. ^{29}Si NMR: δ –8.1 ppm.

3-Phenyl-4-trimethylsilylsydnone (6b). Yield: 76%. Mp: 118 °C. Anal. Calcd for $C_{11}H_{14}N_2O_2Si$: C, 56.38; H, 6.02; N, 11.95; Si, 11.99. Found: C, 56.42; H, 5.96; N, 12.07; Si, 12.08%. ^1H NMR: δ 7.74–7.68 (m, 1H, Ph), 7.66–7.61 (m, 2H, Ph), 7.50 (m, 2H, Ph), 0.12 (s, 9H, $SiMe_3$) ppm. ^{13}C NMR: δ 173.3, 136.3, 132.2, 129.8, 125.3, 105.6, –1.4 ppm. ^{29}Si NMR: δ –8.0 ppm.

3-Methyl-4-trimethylsilylsydnone (6c). Yield: 70%. Mp: 115 °C. Anal. Calcd for $C_6H_{12}N_2O_2Si$: C, 41.84; H, 7.02; N, 16.26; Si, 16.30. Found: C, 41.87; H, 7.15; N, 16.15; Si, 16.21%. ^1H NMR: δ 4.01 (s, 3H, NMe), 0.39 (s, 9H, $SiMe_3$) ppm. ^{13}C NMR: δ 173.7, 103.0, 40.2, –1.4 ppm. ^{29}Si NMR: –8.8 ppm.

4-Dimethylsilyl-3-phenylsydnone (6d). Yield: 84%. Mp: 72–73 °C. Anal. Calcd for $C_{10}H_{12}N_2O_2Si$: C, 54.52; H, 5.49; N, 12.72; Si, 12.75. Found: C, 54.47; H, 5.41; N, 12.81; Si, 12.82%. ^1H NMR: δ 7.69 (m, 1H, Ph), 7.63 (m, 2H, Ph), 7.60–7.46 (m, 2H, Ph), 4.26 (hept, J = 3.8 Hz, 1H, SiH), 0.26 (d, J = 3.8 Hz, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.5, 135.9, 132.2, 129.9, 124.6, 102.8, 5.0 ppm. ^{29}Si NMR: δ –26.8 ppm.

4-Dimethylsilyl-3-methylsydnone (6e). Yield: 72%. Mp: 53–53.5 °C. Anal. Calcd for $C_5H_{10}N_2O_2Si$: C, 37.95; H, 6.37; N, 17.70; Si, 17.75. Found: C, 37.91; H, 6.28; N, 17.64; Si, 17.66%. ^1H NMR: δ 4.50 (hept, J = 3.8 Hz, 1H, SiH), 4.04 (s, 3H, NMe), 0.44 (d, J = 3.8 Hz, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.5, 101.0, 39.8, –5.2 ppm. ^{29}Si NMR: δ –28.7 ppm.

4-[Dimethyl(vinyl)silyl]-3-phenylsydnone (6f). Yield 62%. Mp: 56–57 °C. Anal. Calcd for $C_{12}H_{14}N_2O_2Si$: C, 58.51; H, 5.73; N, 11.37; Si, 11.40. Found: C, 58.49; H, 5.66; N, 11.45; Si, 11.51%. ^1H NMR: δ 7.70–7.66 (m, 1H, Ph), 7.59–7.57 (m, 2H, Ph), 7.49–7.44 (m, 2H, Ph), 5.98–5.87 (m, 2H, $CH=CH_2$), 5.64–5.59 (m, 1H, $CH=CH_2$), 0.20 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.3, 136.1, 134.8, 134.1, 132.2, 129.6, 125.3, 104.1, –3.6 ppm. ^{29}Si NMR: δ –16.8 ppm.

4-[Dimethyl(vinyl)silyl]-3-methylsydnone (6g). Yield: 28%. Mp: 66–67 °C. Anal. Calcd for $C_7H_{12}N_2O_2Si$: C, 45.63; H, 6.56; N, 15.20; Si, 15.24. Found: C, 45.70; H, 6.52; N, 15.27; Si, 15.17%. ^1H NMR: δ 6.25–6.14 (m, 2H, $CH=CH_2$), 6.00–5.80 (m, 1H, $CH=CH_2$), 3.97 (s, 3H, NMe), 0.46 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR ppm: δ 173.7, 135.5, 135.0, 101.4, 40.3, –3.6 ppm. ^{29}Si NMR: δ –17.2 ppm.

4-[Dimethyl(phenyl)silyl]-3-phenylsydnone (6h). Yield: 53%. Mp: 135–136 °C. Anal. Calcd for $C_{16}H_{16}N_2O_2Si$: C, 64.84; H, 5.44; N, 9.45; Si, 9.48. Found: C, 64.81; H, 5.51; N, 9.49; Si, 9.57%. ^1H NMR: δ 7.58–7.52 (m, 1H, Ph), 7.42–7.33 (m, 5H, Ph), 7.32–7.26 (m, 2H, Ph), 7.20–7.14 (m, 2H, Ph), 0.43 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.5, 135.9, 135.6, 133.7, 131.9, 130.1, 129.5, 128.1, 125.1, 104.3, 3.4 ppm. ^{29}Si NMR: δ –14.1 ppm.

4-[Dimethyl(phenyl)silyl]-3-methylsydnone (6i). Yield: 45%. Mp: 51–52 °C. Anal. Calcd for $C_{11}H_{14}N_2O_2Si$: C, 56.38; H, 6.02; N, 11.95; Si, 11.99. Found: C, 56.30; H, 5.94; N, 12.01; Si, 12.08%. ^1H NMR: δ 7.61–7.50 (m, 2H, Ph), 7.46–7.28 (m, 3H, Ph), 3.61 (s, 3H, NMe), 0.65 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.9, 134.8, 133.9, 130.4, 128.6, 101.5, 40.3, –3.3 ppm. ^{29}Si NMR: δ –14.5 ppm.

General procedure for the interaction of 4-lithium sydnones with chlorodimethylethoxysilane. A solution of *n*-BuLi (2.0 M, 1.94 mmol) was added dropwise at –78 °C to a stirred solution of the corresponding sydnone (1.85 mmol) in dry THF (20 mL). After stirring for 10 min at –78 °C, chlorodimethylethoxysilane (2.03 mmol) was added. A cooling bath was removed, and the mixture was stirred at room temperature for 30 min. The solution was evaporated under vacuum. The resulting residue was dissolved in chloroform, filtered, and purified by column chromatography on dried silica gel (chloroform–ethyl acetate, v/v = 9:1) to give the target products as white crystalline solids after crystallization from toluene–petroleum ether (1:10).

4-(Ethoxydimethylsilyl)-3-(4-methoxyphenyl)sydnone (6j). Yield: 50%. Mp: 49–50 °C. Anal. Calcd for $C_{13}H_{18}N_2O_4Si$: C, 53.04; H, 6.16; N, 9.52; Si, 9.54. Found: C, 53.09; H, 6.05; N, 9.59; Si, 9.41%. ^1H NMR: δ 7.54 (d, J = 9.0 Hz, 2H, C_6H_4), 7.06 (d, J = 9.0 Hz, 2H, C_6H_4), 3.90 (s, 3H, OMe), 3.65 (q, J = 7.0 Hz, 2H, $C\underline{H}_2CH_3$), 1.15 (t, J = 7.0 Hz, 3H, $CH_2C\underline{H}_3$), 0.21 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.6, 162.2, 129.0, 126.1, 114.7, 103.5, 59.0, 55.8, 18.2, –2.0 ppm. ^{29}Si NMR: δ –1.3 (s) ppm.

4-(Ethoxydimethylsilyl)-3-phenylsydnone (6k). Yield: 41%. Mp: 119–120 °C. Anal. Calcd for $C_{12}H_{16}N_2O_3Si$: C, 54.52; H, 6.10; N, 10.60; Si, 10.62. Found: C, 54.59; H, 5.99; N, 10.69; Si, 10.73%. ^1H NMR: δ 7.78–7.55 (m, 5H, Ph), 3.64 (q, J = 7.0 Hz, 2H, $C\underline{H}_2CH_3$), 1.13 (t, J = 7.0 Hz, 3H, $CH_2C\underline{H}_3$), 0.21 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.5, 136.2, 132.2, 129.7, 124.8, 103.7, 59.0, 18.1, –2.0 ppm. ^{29}Si NMR: δ –1.2 ppm.

4-(Ethoxydimethylsilyl)-3-metylsydnone (6l). Yield: 68%. Mp: 25–27 °C. Anal. Calcd for $C_7H_{14}N_2O_3Si$: C, 41.56; H, 6.98; N, 13.85; Si, 13.88. Found: C, 41.43; H, 6.95; N, 13.69; Si, 13.97%. ^1H NMR: δ 4.09 (s, 3H, NMe), 3.73 (q, J = 7.0 Hz, 2H, $C\underline{H}_2CH_3$), 1.22 (t, J = 7.0 Hz, 3H, $CH_2C\underline{H}_3$), 0.47 (s, 6H, $SiMe_2$) ppm. ^{13}C NMR: δ 173.7, 101.7, 59.0, 40.0, 18.3, –1.7 ppm. ^{29}Si NMR: δ 1.0 ppm.

General procedure for the interaction of 4-lithium sydnones with dichlorosilanes. A solution of *n*-BuLi (2.0 M, 3.30 mmol) was added dropwise at –78 °C to a stirred solution of the corresponding sydnone (3.00 mmol) in dry THF (20 mL). After stirring for 10 min at –78 °C, the reaction mixture was warmed to –10 °C. Then, a solution of dialkyldichlorosilane (1.8 mmol) in THF (5 mL) was added dropwise. A cooling bath was removed, and the mixture was stirred at room temperature for 30 min. After addition of triethylamine (6 mmol), the solution was evaporated under vacuum. The resulting residue was dissolved in chloroform, filtered through a layer of Al_2O_3, and washed with chloroform–ethyl acetate (v/v = 9:1). The solvent was removed under reduced pressure. The residue obtained was crystallized from toluene to give the target products as white solids. Compound **7a** was isolated as a solvate with toluene (2:1).

Bis[3-(4-methoxyphenyl)sydnon-4-yl]dimethylsilane (7a). Yield: 96%. Mp: 125–127 °C. Anal. Calcd for $C_{47}H_{48}N_8O_{12}Si_2$: C, 58.01; H, 4.97; N, 11.52; Si, 5.77. Found: C, 57.60; H, 4.88; N, 11.45; Si, 6.05%. ^1H NMR: δ 7.45 and 7.06 (both d, J = 8.4 Hz, 4H + 4H, $2C_6H_4$), 7.31–7.13 (m, 1H, PhMe), 7.29–7.20 (m, 1.5H, PhMe), 3.90 (s, 6H, 2OMe), 2.36 (s, 1.5H, PhMe), 0.14 (s, 6H, $2SiMe_2$) ppm. ^{13}C NMR: δ 172.7, 162.4, 137.9, 129.0, 128.3, 128.2, 126.3, 125.3, 115.0, 101.4, 55.9, 21.5, –3.27 ppm. ^{29}Si NMR: δ –20.9 ppm.

Bis(3-phenylsydnon-4-yl)dimethylsilane (7b). Yield: 65%. Mp: 195–197 °C. Anal. Calcd for $C_{18}H_{16}N_4O_4Si$: C, 56.83; H, 4.24; N, 14.73; Si, 7.38. Found: C, 56.94; H, 4.34; N, 14.65; Si, 7.44%. ^{1}H NMR: δ 7.73–7.65 (m, 2H, Ph), 7.65–7.57 (m, 4H, Ph), 7.55–7.49 (m, 4H, Ph), 0.09 (s, 6H, $2SiMe_2$) ppm. ^{13}C NMR: δ 172.5, 135.6, 132.5, 130.0, 125.0, 101.4, –3.4 ppm. ^{29}Si NMR: δ –20.8 ppm.

Bis(3-methylsydnon-4-yl)dimethylsilane (7c). Yield: 90%. Mp: 172–174 °C. Anal. Calcd for $C_8H_{12}N_4O_4Si$: C, 37.49; H, 4.72; N, 21.86; Si, 10.96. Found: C, 37.56; H, 4.83; N, 21.78; Si, 11.07%. ^{1}H NMR: δ 4.10 (s, 6H, 2NMe), 0.83 (s, 6H, $2SiMe_2$) ppm. ^{13}C NMR: δ 173.5, 99.2, 40.9, –3.5 ppm. ^{29}Si NMR: δ –22.9 ppm.

Dimethyl(3-phenylsydnon-4-yl)vinylsilane (7d). Yield: 20%. Mp: 151–152 °C. Anal. Calcd for $C_{19}H_{16}N_4O_4Si$: C, 58.15; H, 4.11; N, 14.28; Si, 7.16. Found: C, 58.03; H, 4.30; N, 14.23; Si, 7.03%. ^{1}H NMR: δ 7.70–7.65 (m, 2H, Ph), 7.65–7.50 (m, 4H, Ph), 7.56–7.50 (m, 4H, Ph), 5.86–5.80 (m, 1H, $CH=CH_2$), 5.76–5.55 (m, 1H, $CH=CH_2$), 5.62–5.68 (m, 1H, $CH=CH_2$), 0.17 (s, 3H, SiMe) ppm. ^{13}C NMR: δ 172.7, 136.7, 135.7, 132.5, 129.8, 129.1, 125.2, 100.4, –6.2 ppm. ^{29}Si NMR: δ –30.8 ppm.

Dimetyl(3-metylsydnon-4-yl)vinylsilane (7e). Yield: 26%. Mp: 103–105 °C. Anal. Calcd for $C_9H_{12}N_4O_4Si$: C, 40.29; H, 4.51; N, 20.88; Si, 10.47. Found: C, 40.21; H, 4.63; N, 20.81; Si, 10.56%. ^{1}H NMR: δ 6.72–7.62 (m, 1H, $CH=CH_2$), 6.42–6.38 (m, 1H, $CH=CH_2$), 6.10–6.05 (m, 1H, $CH=CH_2$), 4.09 (s, 6H, 2NMe), 0.90 (s, 3H, SiMe) ppm. ^{13}C NMR: δ 173.4, 139.0, 129.5, 98.0, 41.0, –5.6 ppm. ^{29}Si NMR: δ –32.3 ppm.

4-Trimethylsilyl-3-(2-trimethylsilylphenyl)sydnone (8) was obtained according to the previously published procedure [9a]. Yield: 93%. Mp: 72–74 °C (*cf.* 72–74 °C [9a]). ^{1}H NMR: δ 7.75–7.72 (m, 1H, Ph), 7.65–7.62 (m, 1H, Ph), 7.58–7.50 (m, 1H, Ph), 7.33–7.30 (m, 1H, Ph), 0.19 (s, 9H, Ph-$SiMe_3$), 0.07 (s, 9H, C(4)-$SiMe_3$) ppm. ^{13}C NMR: δ 173.3, 140.6, 137.5, 136.2, 131.2, 129.8, 126.0, 106.3, –0.8, –1.7 ppm. ^{29}Si NMR: δ –2.3 (Ph-Si), –8.1 (C(4)-Si) ppm.

4-Phenyl-3-[(trimethylsilyl)methyl]sydnone (9) was obtained according to the previously published procedure [10]. Yield: 50%. Mp: 80 °C (*cf.* 79–80 °C [10]). ^{1}H NMR: δ 7.67–7.20 (m, 5H, Ph), 3.95 (s, 2H, $SiCH_2$), 0.06 (s, 9H, $SiMe_3$) ppm. ^{13}C NMR: δ 167.5, 129.2, 129.1, 128.6, 124.9, 107.7, 43.3, 2.3 ppm. ^{29}Si NMR: δ 4.9 ppm.

3-Phenyl-4-[(trimethylsilyl)ethynyl]sydnone (10) was obtained according to the previously published procedure [11]. Yield: 55%. Mp: 75–76 °C (*cf.* 74.5–76.5 °C [11]). ^{1}H NMR: δ 7.85–7.80 (m, 2H, Ph), 7.71–7.68 (m, 1H, Ph), 7.65–7.61 (m, 2H, Ph), 0.18 (s, 9H, $SiMe_3$) ppm. ^{13}C NMR: δ 167.2, 134.3, 132.6, 129.7, 123.6, 111.2, 95.3, 87.6, –0.7 ppm. ^{29}Si NMR: δ –15.6 ppm.

Conclusions

Hence, the interaction of 4-lithium derivatives of 3-methyl-, 3-phenyl- and 3-*p*-methoxyphenylsydnones with chlorosilanes and dichlorosilanes was studied. A broad range of the silicon-containing derivatives of sydnones were synthesized, including those bearing reactive ethoxy, vinyl, and hydride groups at the silicon atoms. The compounds obtained were fully characterized by the ^{1}H, ^{13}C, ^{15}N, and ^{29}Si NMR spectra as well as X-ray diffraction.

Acknowledgements

This work was supported by the Russian Foundation for Basic Research, project no. 19-03-00333.

X-ray diffraction and NMR studies as well as elemental analyses were performed with the financial support from the Ministry of Science and Higher Education of the Russian Federation using the equipment of INEOS RAS.

The authors are grateful to Prof. Konstantin A. Lyssenko (Chemistry Department, Moscow State University) for X-ray studies.

Corresponding author

* E-mail: cherepanov@ineos.ac.ru (I. A. Cherepanov)

Electronic supplementary information

Electronic supplementary information (ESI) available online: NMR spectra of the compounds obtained. For ESI, see DOI: 10.32931/io2005a

References

1. R. Tacke, H. Linoh, in: *The Chemistry of Organic Silicon Compounds*, S. Patai, Z. Rappoport (Eds.), Wiley, New York, **1989**, vol. 1, ch. 18, 1143–1206. DOI: 10.1002/0470025107.ch18
2. R. Tacke, S. Dörrich, *Top. Med. Chem.*, **2016**, *17*, 29–60. DOI: 10.1007/7355_2014_55
3. J. S. Mills, G. A. Showell, *Expert Opin. Invest. Drugs*, **2004**, *13*, 1149–1157. DOI: 10.1517/13543784.13.9.1149
4. A. K. Franz, S. O. Wilson, *J. Med. Chem*., **2013**, *56*, 388–405. DOI: 10.1021/jm3010114
5. S. McN. Sieburth, C.-A. Chen, *Eur. J. Org. Chem*., **2006**, 311–322. DOI: 10.1002/ejoc.200500508
6. R. Tacke, V. I. Handmann, R. Bertermann, C. Burschka, M. Penka, C. Seyfried, *Organometallics*, **2003**, *22*, 916–924. DOI: 10.1021/om020354u
7. S. Gately, R. West, *Drug Dev. Res.*, **2007**, *68*, 156–163. DOI: 10.1002/ddr.20177
8. T. Heinrich, C. Burschka, M. Penka, B. Wagner, R. Tacke, *J. Organomet. Chem.*, **2005**, *690*, 33–47. DOI: 10.1016/j.jorganchem.2004.08.023
9. J. O. Daiss, M. Albrecht, K. Mohr, R. Tacke, *Organometallics*, **2004**, *23*, 6052–6057. DOI: 10.1021/om040088f
10. G. A. Showell, J. S. Mills, *Drug Discovery Today*, **2003**, *8*, 551–556. DOI: 10.1016/S1359-6446(03)02726-0
11. R. Ramesh, R. D. Shingare, V. Kumar, A. Anand, B. Swetha, S. Veeraraghavan, S. Viswanadha, R. Ummanni, R. Gokhale, D. S. Reddy, *Eur. J. Med. Chem*., **2016**, *122*, 723–730. DOI: 10.1016/j.ejmech.2016.07.009
12. M. Nakamura, D. Kajita, Y. Matsumoto, Y. Hashimoto, *Bioorg. Med. Chem*., **2013**, *21*, 7381–7391. DOI: 10.1016/j.bmc.2013.09.046
13. T. Heinrich, C. Burschka, J. Warneck, R. Tacke, *Organometallics*, **2004**, *23*, 361–366. DOI: 10.1021/om0305622
14. R. Tacke, B. Nguyen, C. Burschka, W. P. Lippert, A. Hamacher, C. Urban, M. U. Kassack, *Organometallics*, **2010**, *29*, 1652–1660. DOI: 10.1021/om901011t
15. V. V. Belakhov, Yu. D. Shenin, *Pharm. Chem. J*., **2008**, *42*, 322. DOI: 10.1007/s11094-008-0117-7
16. G. A. Bikzhanova, I. S. Toulokhonova, S. Gately, R. West, *Silicon Chem.*, **2007**, *3*, 209–217. DOI: 10.1007/s11201-006-9008-5

17. U. I. Zakai, G. Bikzhanova, D. Staveness, S. Gately, R. West, *Appl. Organomet. Chem.*, **2010**, *24*, 189–192. DOI: 10.1002/aoc.1572
18. T. Johansson, L. Weidolf, F. Popp, R. Tacke, U. Jurva, *Drug Metab. Dispos.*, **2010**, *38*, 73–83. DOI: 10.1124/dmd.109.028449
19. D. Kost, I. Kalikhman, in: *The Chemistry of Organic Silicon Compounds*, Z. Rappoport, Y. Apeloid, S. Patai (Eds.), Wiley, New York, **1998**, vol. 2, ch. 23, 1339–1446. DOI: 10.1002/0470857250
20. A. R. Katritzky, X. Lan, J. Z. Yang, O. V. Denisko, *Chem. Rev*., **1998**, *98*, 409–548. DOI: 10.1021/CR941170V
21. D. Troegel, F. Möller, R. Tacke, *J. Organomet. Chem*., **2009**, *695*, 310–313. DOI: 10.1016/j.jorganchem.2009.10.020
22. Y. Katsuda, *Top. Curr. Chem.*, **2012**, *314*, 1–30. DOI: 10.1007/128_2011_252
23. M. Fischer, R. Tacke, *Organometallics*, **2013**, *32*, 7181–7185. DOI: 10.1021/om400873w
24. B. A. Shainyan, S. V. Kirpichenko, E. Kleinpeter, *Tetrahedron*, **2012**, *68*, 7494–7501. DOI: 10.1016/j.tet.2012.05.106
25. D. Troegel, F. Möller, C. Burschka, R. Tacke, *Organometallics*, **2009**, *28*, 3218–3224. DOI: 10.1021/om900175m
26. W. Baker, W. D. Ollis, *Q. Rev.*, *Chem. Soc.*, **1957**, *11*, 15–29. DOI: 10.1039/qr9571100015
27. W. D. Ollis, C. A. Ramsden, *Adv. Heterocycl. Chem*., **1976**, *19*, 1–122. DOI: 10.1016/s0065-2725(08)60230-5
28. D. L. Browne, J. P. A. Harrity, *Tetrahedron*, **2010**, *66*, 553–568. DOI: 10.1016/j.tet.2009.10.085
29. I. A. Cherepanov, S. K. Moiseev, *Adv. Heterocycl. Chem*., **2020**, *131*, 49–164. DOI: 10.1016/bs.aihch.2019.11.003
30. S. K. Bhosale, S. R. Deshpande, R. D. Wagh, A. S. Dhake, *J. Chem. Pharm. Res.*, **2015**, *7 (5)*, 1247–1263.
31. M. Kawase, H. Sakagami, N. Motohashi, *Top. Heterocycl. Chem.*, **2007**, *16*, 135–152. DOI: 10.1007/7081_2007_096
32. H. Dickopp, *Tetrahedron Lett.*, **1971**, *12*, 4403–4404. DOI: 10.1016/s0040-4039(01)97453-2
33. H. Dickopp, *Chem. Ber.*, **1980**, *113*, 1830–1836. DOI: 10.1002/cber.19801130518
34. D. A. Grossie, K. Turnbull, D. M. Krein, *Acta Crystallogr.*, *Sect. E: Struct. Rep. Online*, **2001**, *57,* 985–987. DOI: 10.1107/s160053680101563x
35. K. Turnbull, D. M. Krein, *Tetrahedron Lett.*, **1997**, *38*, 1165–1168. DOI: 10.1016/s0040-4039(97)00015-4
36. S. T. Lin, H. S. Cheo, B. I. Chen, Z. Y. Own, *Heteroat. Chem.*, **1998**, *9*, 549–552. DOI: 10.1002/(SICI)1098-1071(1998)9:6<549::AID-HC4>3.0.CO;2-#
37. K. Turnbull, D. M. Krein, *Synth. Commun*., **2003**, *33*, 2061–2067. DOI: 10.1081/scc-120021032
38. K. Turnbull, I. F. Nashashibi, *Synth. Commun*., **2007**, *37*, 915–919. DOI: 10.1080/00397910601163562
39. K. Turnbull, D. M. Krein, *Synth. Commun*., **2009**, *39*, 2852–2858. DOI: 10.1080/00397910802664251
40. I. A. Cherepanov, S. N. Lebedev, V. N. Kalinin, *Synlett,* **1998**, *6*, 667–669. DOI: 10.1055/s-1998-1739
41. I. A. Cherepanov, D. D. Bronova, E. Yu. Balantseva, V. N. Kalinin, *Mendeleev Commun.*, **1997**, *7*, 93–94. DOI: 10.1070/mc1997v007n03abeh000695
42. E. A. Williams, J. D. Gargioli, *Annu. Rep. NMR Spectrosc*., **1979**, *9*, 221–318. DOI: 10.1016/S0066-4103(08)60162-3
43. K. Ebata, T. Inada, C. Kabuto, H. Sakurai, *J. Am. Chem. Soc.*, **1994**, *116*, 3595–3596. DOI: 10.1021/ja00087a054
44. W. L. F. Armarego, C. L. L. Chai, *Purification of Laboratory Chemicals*, *5th ed*., Butterworth-Heinemann, **2003**.
45. G. M. Sheldrick, *Acta Cryst.*, *Sect. A.: Found. Crystallogr.*, **2008**, *64*, 112–122. DOI: 10.1107/s0108767307043930