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5 precursor

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Abstract

Dithiolated derivatives of 1,2-dicarba-*closo*-dodecaboranes are common ligands to be used for self-assembling monolayers, nanoparticles or transition metal complexes due to their robust molecular structure. The 9,12-Dimercapto-1,2-dicarba-*closo*-dodecaborane, a derivative with two SH-groups in neighbored positions is an interesting unit for the preparation of in positions 1 and 2 functionalized derivatives. In this contribution, we report a convenient synthesis of 1,2-disubstituted 9,12-dimercapto-1,2-dicarba-*closo*-dodecaboranes via a with the methoxy-methyl group (MOM) S-protected precursor in good yields. All compounds are well characterized via HiRes-mass spectroscopy, proton, carbon and boron nmr-spectroscopy and infrared spectroscopy. The precursor 9,12-Bis(methoxy-methylthio)-1,2-dicarba-*closo*-dodecaborane was proved via a X-Ray-crystal structure.

Keywords: Carborane, Dicarba-*closo*-dodecaborane, Dimercapto-carborane, Surfactant, protecting group, Dithiolcarborane

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15 Introduction

16 1,2-Dicarba-*closo*-dodecaboranes ($C_2B_{10}H_{12}$)—often abbreviated as *ortho*-
17 or *o*-carboranes—are due to their wide applicability an intensively investigated
18 research field of boron chemistry[1, 2, 3, 4]. Mono- or multithiolated *o*-carborane
19 derivatives are often used as ligands in transition metal complex chemistry or
20 in self assembling monolayers (SAMs)[5, 6, 7]. Their ball like shape leads to
21 the formation of two dimensional highly packed quasi crystalline monolayers on
22 metal surfaces like gold, silver or copper. The most often investigated thiolated
23 *o*-carborane derivative is the 1,2-dimercapto-*o*-carborane ($1,2-(HS)_2C_2B_{10}H_{10}$).
24 The less common isomer 9,12-dimercapto-*o*-carborane **2** ($9,12-(HS)_2C_2B_{10}H_{10}$)
25 is differing not only in the position of the SH-groups but also in several properties
26 such as dipol moment or pk-Values[5, 8]. One interesting aspect of the 9,12-
27 isomer is, that the dipol moment in protonated ($(HS)_2C_2B_{10}H_{10}$) state points
28 in the same direction as in deprotonated ($(C_2B_{10}H_{10}S_2)^{2-}$) state. In case of the
29 1,2-isomer the dipole moment turns to the opposite direction after deprotonation
30 of the SH-groups.

31 As up to now research has been done only on unmodified 9,12-dimercapto-*o*-
32 carborane **2**, we were interested in the influence of substituents on the properties
33 on 1,2-disubstituted 9,12-dimercapto-*o*-carboranes. The positions one and two
34 of the *o*-carborane cluster are the most reactive and are the positive charge
35 extrema of the dipol. A substitution at these positions is easiest to perform and
36 will have the strongest influence on the dipole and hence to the properties of
37 the carborane cluster¹.

38 *o*-Carborane is synthesized by reaction of acetylene with decaborane. The
39 same approach can be used to obtain 1,2-disubstituted *o*-carboranes just by
40 using correspondingly substituted acetylene derivatives[9, 10, 11]. Introduction
41 of mercapto groups in positions nine and twelve of *o*-carborane to synthesize
42 9,12-dimercapto-*o*-carborane is performed under harsh conditions with elemen-
43 tal sulfur in a aluminium chloride melt at 160–180°C and affords the product in
44 good yields[12]. In case of 1-mono- or 1,2-disubstituted *o*-carboranes the same

¹Substitution of positions 9 and 12 as the most negative part of cause too, but they are already substituted by the SH-groups.

45 conditions will lead to monothiolation of the *o*-carborane cluster in position
46 nine or twelve only[13]. Furthermore these conditions will lead to degradation
47 of structural more complex substituents and hence impedes a broader applica-
48 bility.

49 Another method for introducing substituents into unsubstituted *o*-carboranes
50 at the carbon positions is to deprotonate the cluster at these positions with
51 strong bases such as sodium amide or butyl lithium followed by reaction with
52 electrophilic agents f.e. alkylants like alkyl bromides or iodides[14, 15], ether
53 groups[16], carbonyl compounds like aldehydes[17, 18], ketones[19, 20], chloroformates[14]
54 or carbon dioxide[21, 22, 23], michael acceptors[24], silanes[14, 25], amino groups
55 [23] or elements sulfur[26, 7], selenium and tellurium[7]. This method of sub-
56 stituent introduction was never used for 9,12-dimercapto-*o*-carborane and its
57 derivatives. In this contribution we describe a convenient way for the synthe-
58 sis of 1,2-disubstituted 9,12-dimercapto-*o*-carboranes by introduction of an easy
59 obtainable 9,12-dithiolated *o*-carborane precursor. Recently a similar approach
60 has been described independently by HEY-HAWKINS and coworkers. This study
61 provides us with a basis for comparison of both synthetic routes.[27]

62 [Figure 1 about here.]

63 [Table 1 about here.]

64 Figure 1 shows a general approach. The key molecule in this approach is
65 the precursor for the introduction of the 9,12-dithiolated *o*-carborane unit. To
66 avoid undesired attack of the sulfur atoms, a protection group for the sulfur
67 atoms is necessary which is stable against strong basic conditions and cleav-
68 able under mild conditions without degrading the carborane cluster or attached
69 structures. The methoxy-methyl-group seems to be ideal for this purpose. Its
70 easy introducability, broad stability against various conditions especially from
71 strong basic and acidic conditions, non-oxidative character and easy cleavability
72 from thiols with mercury(II)-salts makes it the protecting group of choice for
73 mercapto functionalities[28].

74 In a first experiment, we checked whether a quantitative lithiation at posi-
75 tions one and two of the 9,12-bis(methoxy-methylthio)-*o*-carborane precursor **2**
76 is possible. This can be done via a deuteration (R=D in figure 1) through deu-

terium oxide of the dilithiated species. Additionally, we followed the mercuration of the icosahedral carbons as an unwanted side reaction of the deprotection of the mercapto groups by mercury(II)-salts.

The second step is the introduction of the substituents in positions one and two, analogously to the synthesis of 1,2-disubstituted *o*-carboranes starting from plain *o*-carborane. The precursor 9,12-bis(methoxy-methylthio)-*o*-carborane is lithiated in positions one and two quantitatively by *n*-butyl lithium followed by addition of the alkyl halogenide.

Synthesis

Analytical equipment. NMR-spectra were acquired on Varian MercuryPlus or Bruker Avance400 spectrometer with 400 MHz in proton, 100 MHz in carbon and 128 MHz in boron-11 channel at room temperature. Infrared spectra were measured with a Nicolet Nexus 670- FT-Infrared Spectrometer as film or KBr tablet in a range of 4000–400 1/cm. Mass analysis was made with a Thermo-Finnigan LQC-Fleet Ion Trap spectrometer in negative mode using electro spray ionisation (ESI). Concentration $\approx 100 \text{ ng}\cdot\text{mL}^{-1}$. injection volume $5 \text{ }\mu\text{L}\cdot\text{min}^{-1}$, source voltage 5.48 kV, tube lens voltage -124.67 V , capillary voltage -11.05 V . HiRes mass spectroscopy was measured using a TQ Orbitrap Velos (Thermo Scientific) spectrometer in negative mode with a mass accuracy better than 3 ppm. Solvent: acetonitrile, vaporizer temperature 350°C , capillary temperature 300°C .

Chemicals. Deuterium oxide, *n*-butyl lithium, *n*-heptylbromide, ethylbromide and bromomethyl methylether were purchased from Sigma Aldrich chemicals and used as received. 9,12-Dimercapto-*o*-carborane was obtained from Katchem and recrystallized prior use. Solvents like THF and Ether were dried over sodium metal/benzophenone and distilled before use.

Synthesis of 9,12-Bis(methoxy-methylthio)-o-carborane 2. 9,12-Dimercapto-*o*-carborane (500 mg, 2.4 mmol, 1 eq.) is dissolved in dry and degassed THF under inert atmosphere at rt. potassium *tert*-butanolate (592.4 mg, 5.3 mmol, 2.2 eq) is added and a cream white solid precipitates immediately. The suspension is stirred for further 1 h at rt followed by the addition of bromomethyl methylether

107 (719.7 mg, 5.76 mmol, 2.4 eq). The color switches from cream white to lime white
108 directly (formation of KBr). The suspension is stirred for 3 h.

109 A saturated aqueous NaCl-solution (20 mL) is added and the two-phase sys-
110 tem stirred vigorously for 30 min. The organic phase is separated, dried over
111 Na₂SO₄, filtered and the solvent removed under reduced pressure. The residue
112 is dissolved in ether (20 mL) and washed 2× with water (20 mL). The phases are
113 separated, the organic phase is dried over Na₂SO₄ and the solution evaporated
114 to dryness.

115 The remaining solid is purified via column chromatography on silica gel.
116 First with chloroform as eluent to remove remaining *tert*-butanol, then switching
117 to chloroform/acetonitrile (4:1; v/v, R_f=0.62) to eluate the product.

118 Smaller amounts (<= 500 mg) can be recrystallized from cyclohexane or
119 cyclohexane/toluene (9:1 v/v).

120 9,12-Bis(methoxy-methylthio)-*o*-carborane is obtained in 61% yield (434 mg).

121 ¹H-NMR (CDCl₃): δ = 4.68 (s, 4H, SCH₂O), 3.61 (s, 2H, Borane-CH), 3.33
122 (s, 6H, OCH₃), 3.2–1.04 (m, 8H, BH).

123 ¹³C-NMR (CDCl₃): δ = 75.1 (SCH₂O), 55.7 (OCH₃), 48.1 (icosahedral-CH).

124 ¹¹B-NMR (CDCl₃): δ = 14.65, −0.87, −6.65, −8.9.

125 HiRes-MS: m/z = 296.190 (100%, M⁺), 299.182 (8%, cut-off-peak).

126 *Synthesis of 9,12-bis(methoxy-methylthio)-1,2-dideutero-o-carborane 3a.* 9,12-
127 bis(methoxy-methylthio)-*o*-carborane (201.9 mg, 0.681 mmol, 1 eq) is dissolved
128 in abs. diethylether (10 mL) under argon atmosphere. The solution is cooled to
129 0°C (ice bath). A solution of 2.5 M *n*-Buli in hexane (0.85 mL, 0.135 mmol, 2 eq.)
130 is added dropwise with a syringe and a white precipitate is formed immediately.
131 The suspension is stirred for further 15 min at this temperature, followed by
132 the addition of deuteriumoxide (5 mL, 250 mmol, 370 eq.) and stirred for 1 h
133 at rt. The phases are separated and the aqueous phase is extracted 2× with
134 diethylether (10 mL). The combined organic phases are dried over Na₂SO₄ and
135 the solvent is evaporated. The resulting oil is allowed to crystallize and the solid
136 recrystallized from cyclohexane/toluene (9:1).

137 Yield 100%.

138 ¹H-NMR (CDCl₃): δ = 4.68 (s, 4H, SCH₂O), 3.34 (s, 6H, OCH₃), 3.2–1.04
139 (m, 8H, BH).

¹³C-NMR (CDCl₃): δ = 75.1 (SCH₂O), 55.7 (OCH₃), 47.8 (triplet, borane-CH).

¹¹B-NMR (CDCl₃): δ = 7.02, -8.42, -14.27, -16.53.

HiRes-MS: m/z = 298.202 (100%, M⁻), 301.194 (7%, cut-off-peak).

9,12-dimercapto-1,2-dideutero-o-carborane 4a. 9,12-Bis(methoxy-methylthio)-1,2-dideutero-*o*-carbaborane (150 mg, 0.5 mmol, 1 eq.) is dissolved in 10 mL acetonitrile/water (4:1) and a solution of mercury(II)-chloride (220.2 mg, 1 mmol, 2 eq.) in acetonitrile/water (4:1, 5 mL) is added. The mercury-carborane complex precipitates as a white solid after a few seconds. For completion of the reaction, the mixture is allowed to stir for additional 2 h. The mercury complex is collected and washed 2× with acetonitrile/water (4:1, 5 mL), suspended in ethanol (10 mL) and H₂S is bubbled through the suspension for 4 h. The carborane dissolves and a black precipitate is formed. The black mercury sulfide removed by filtration and the solvent is evaporated. The synthesis affords 26.2 mg (98%) of 9,12-dithio-1,2-dideutero-*o*-carborane.

¹H-NMR (CDCl₃): δ = 3.23–1.33 (m, 8H, BH), 0.59 (s, 2H, SH).

¹³C-NMR (CDCl₃): δ = 47.0 (t, CD).

¹¹B-NMR (CDCl₃): δ = 5.38, -6.40, -13.80, -16.30.

HiRes-MS: m/z = 210.150 (100%, M⁻), 213.142 (9%, cut-off-peak).

Synthesis of 9,12-dimercapto-1,2-diethyl-o-carborane 4c. 9,12-Bis(methoxy-methylthio)-*o*-carborane (110.1 mg, 0.37 mmol, 1 eq.) is dissolved in abs. THF (2.5 mL) and cooled to 0°C (ice bath) under nitrogen atmosphere. *n*-BuLi (0.47 mL, 1.6 M in hexane, 0.75 mmol, 2.03 eq.) is added dropwise with a syringe. The solution is stirred for 30 minutes at 0°C. After this period, ethylbromide (88.7 mg, 0.81 mmol, 2.2 eq.) is added and the ice bath is removed. The solution is allowed to stir overnight. The solvent is removed, the residue dissolved in methylenchloride (5 mL) and washed 2× with water (5 mL). After drying over Na₂SO₄, the solvent is evaporated.

The resulting solid is dissolved in acetonitrile/water (4:1, 10 mL). Mercury(II)-chloride (201 mg, 0.74 mmol) in acetonitrile/water (4:1, 1 mL) is added and the formed white suspension is stirred for further two hours. The solid is collected and washed 2× with of acetonitrile/water (4:1, 5 mL). The solid is suspended

172 in ethanol and H₂S is bubbled through. The white precipitate dissolves and
173 black mercurysulfide is formed. After two hours, the solid is removed by filtra-
174 tion and the solution evaporated to dryness. The resulting solid is sublimed at
175 140°C (oil bath temperature) at 2*10⁻² mbar. 85 mg of 9,12-dithio-1,2-diethyl-
176 1,2-carborane were obtained (87%).

177 ¹H-NMR (CDCl₃): δ = 3.25–1.59 (m, 8H, BH), 2.23 (q, 4H, CH₂, ³J=7.50 Hz),
178 1.17 (t, 6H, CH₃, ³J=7.50 Hz).

179 ¹³C-NMR (CDCl₃): δ = 73.9 (Borane-C), 27.6 (CH₂), 14.2 (CH₃).

180 ¹¹B-NMR (CDCl₃): δ = 3.34 (B-S), -5.00–-11.19 (m).

181 GC-MS (EI): m/z = 263 (M+1, 100%), 236, 209, 183, 156, 131, 114.

182 *Synthesis of 9,12-bis(methoxy-methylthio)-1,2-diheptyl-o-carborane 3b.* A solu-
183 tion of 9,12-Bis(methoxy-methylthio)-o-carborane (274 mg, 0.92 mmol, 1 eq.)
184 in absolute THF (100 mL) is cooled to 0°C under inert atmosphere. *n*-BuLi
185 (0.74 mL, 1.86 mmol, 2.5M in hexane, 2.02 eq.) are added with a syringe. The
186 solution is stirred for further 15 minutes at 0°C. After that period, 1-bromo-
187 *n*-heptane (362.5 mg, 2.024 mmol, 2.2 eq) is added dropwise and the mixture is
188 stirred at 0°C for 30 minutes and at room temperature overnight.

189 The solvent is removed, the residue dissolved in 10 mL ether and washed 2×
190 with water (10 mL). After separation of the organic layer, drying over sodium
191 sulfate, the mixture is passed through a pad of silica gel with ether as eluent.
192 After removal of the ether, the product 364 mg 9,12-bis(methoxy-methylthio)-
193 1,2-diheptyl-*o*-carborane is obtained (80%).

194 ¹H-NMR (CDCl₃): δ = 4.68 (s, 4H, S–CH₂–O), 3.35 (s, 6H, CH₃O), 3.14–
195 1.63 (m, 8H, BH), 2.13 (t, 4H, B–C–CH₂, ³J=8.7 Hz), 1.53 (m, 4H, B–C–CH₂–CH₂),
196 1.28 (m, 16H, (CH₂)₄–CH₃), 0.86 (t, 6H, CH₃, ³J=7.25 Hz).

197 ¹³C-NMR (CDCl₃): δ = 75.1 (S–CH₂–O), 75.54 (icosahedral-C), 55.60
198 (CH₃O), 34.10 (icosahedral-C–CH₂), 31.47 ((CH₂)₄–CH₃), 29.78 (icosahedral-
199 C–CH₂–CH₂), 29.10 ((CH₂)₄–CH₃), 28.7 ((CH₂)₄–CH₃), 22.43 ((CH₂)₄–CH₃),
200 13.93 (CH₃).

201 ¹¹B-NMR ((CDCl₃)): δ = 12.51 (B-S), 4.82–-13.16 (BH).

202 HiRes-MS: m/z = 492.408 (100%, M⁻), 495.401 (10%, cut-off-peak).

203 *Synthesis of 9,12-dimercapto-1,2-diheptyl-o-carborane 4b.* To a solution of 9,12-
204 bis(methoxy-methylthio)-1,2-diheptyl-*o*-carborane (589 mg, 1.2 mmol, 1 eq.) in
205 10 mL acetonitrile are added a solution of mercury(II)-chloride (651.6 mg, 2.4 mmol,
206 2 eq.) in acetonitrile (2 mL). After a few seconds, a white precipitate is formed,
207 separated via centrifugation and the solid washed 2× with acetonitrile (5 mL).

208 The residue is dissolved in chloroform and H₂S is bubbled through and after
209 a while, a black precipitate of mercurysulfide is formed. For completion of the
210 reaction H₂S is passed though for further two hours. The black suspension is
211 filtered and the clear colorless solution is evaporated to dryness.

212 The 9,12-dimercapto-1,2-diheptyl-*o*-carborane is obtained in 69% yield (335 mg)

213

214 ¹H-NMR (CDCl₃): δ = 3.24–1.66 (m, 8H, BH), 2.20–2.05 (t, 4H, B–C–CH₂,
215 ³J=8.54 Hz), 1.53 (m, 4H, B–C–CH₂–CH₂), 1.28 (m, 16H, (CH₂)₄–CH₃),
216 0.88 (t, 6H, CH₃, ³J=6.63 Hz).

217

218 ¹³C-NMR (CDCl₃): δ = 73.11 (icosahedral-C), 34.04 (B–C–CH₂), 31.54
219 ((CH₂)₄–CH₃), 29.89 (B–C–CH₂–CH₂), 29.14 ((CH₂)₄–CH₃), 28.77 ((CH₂)₄–CH₃),
220 22.53 ((CH₂)₄–CH₃), 14.04 (CH₃).

221

222 ¹¹B-NMR: (CDCl₃): δ = 11.10 (B–S), –0.07 (BH), –3.48 (BH).

223 HiRes-MS: m/z = 404.356 (100%, M[–]), 407.358 (8%, cut-off-peak).

224 Results and Discussion

225 Precursor 9,12-bis(methoxy-methylthio)-*o*-carborane 2

226 The synthesis of the key precursor 9,12-bis(methoxy-methylthio)-*o*-carborane
227 **2** starts from commercially available 9,12-dimercapto-*o*-carborane **1**. The methoxy-
228 methyl-protecting group is introduced by deprotonation of the SH-groups by
229 potassium *tert*-butanolate and addition of bromomethyl-methyl ether to the
230 formed suspension. Attempts to replace *tert*-butanulates by potassium car-
231 bonate or butyl lithium led to much lower yields. To avoid oxidative degra-
232 dation the reaction must be performed under Schlenk conditions, the use of
233 balloon techniques is insufficient. Purification is done by column chromatogra-
234 phy. Impurities and remaining *tert*-butanol are first washed off with chloroform

235 and the product eluted with chloroform/acetonitrile afterwards. Alternatively,
236 the product can also be recrystallized from a cyclohexane/toluene 9:1. The
237 9,12-bis(methoxy-methylthio)-*o*-carborane **2** does not easily crystallize from the
238 mother liquor, it rather separates as an insoluble oil layer which subsequently
239 solidifies. This happens mainly when the compound is dissolved f. e. in toluene,
240 THF or chloroform, and cyclohexane or hexane is added for precipitation. Re-
241 crystallization is not recommended for amounts >500 mg as the precursor suffers
242 from thermal degradation when molten. This decreases the yield in the extent
243 as more substance is to be recrystallized. For purification of amounts greater
244 than 500 mg of precursor, column chromatography is more appropriate.

245 [Figure 2 about here.]

246 [Figure 3 about here.]

247 In the proton nmr spectrum (figure 2) of the compound two singlets at 4.68
248 (methylene) and 3.33 ppm (methoxy) can be seen and furthermore the absence
249 of the SH-signal at 0.59 ppm. The signals at 3.61 ppm (CH) and from 3.2 to
250 1.04 ppm (BH) belong to the carborane icosahedron. In the ¹³C-NMR (figure
251 3) the three expected signals occur at 75.1 ppm for the methylene groups, at
252 55.7 ppm for the methoxy groups and at 48.1 ppm for the icosahedral carbons.
253 The proton decoupled B-11 nmr spectrum signals shows the typical *o*-carborane
254 pattern with signals at 14.65, -0.87, -6.65 and -8.9 ppm.

255 [Figure 4 about here.]

256 A comparison of the single crystal X-ray-structures of 9,12-Bis(methoxy-
257 methylthio)-*o*-carborane **2** (figure 4) and 9,12-Dimercapto-*o*-carborane[5] shows
258 by 0.005 Å shorter boron-boron distances in **2**. On icosahedral carbon-boron
259 bonds this is a more distinct effect than on the other (boron-boron) cluster
260 bonds. This bond length enlargement corresponds with the electron density in
261 the carborane cluster. An explanations of this effect is the assumption, that in **2**
262 the electron density of the etherified sulfur is lower compared to the SH-groups
263 of the 9,12-dimercapto-*o*-carborane and thus a decreased electron density inside
264 the carborane cluster. The shortening of the distance of the etherified sulfur
265 atoms of about 0.25 Å supports this estimation whereas the increased dihedral

angle of about 1 degree can be explained by the higher sterical demand of the MOM-group.

[Figure 5 about here.]

The infrared spectrum of compound **2** (figure 5) shows an intense valence C-H vibration band in the range 3080–2750 cm⁻¹. The intense band at 2600 cm⁻¹ belongs to the borane BH-vibrations. The shoulder at 2812 cm⁻¹ is a typical band of the methoxy group and is visible only in the S-MOM-protected *o*-carborane species.

Despite the strong Raman activity of the mercapto group, the attachment and detachment of the MOM-groups onto the mercapto functionality of the carborane cluster can not be followed by Raman spectroscopy. The thiol band at about 2600 cm⁻¹ is overlapping with the bands of the boron cluster. Chemical modification of the mercapto functionality results only in a slight intensity change.

9,12-Bis(methoxy-methylthio)-1,2-dideutero-o-carborane 3a and 9,12-dimercapto-1,2-dideutero-o-carborane 4a

A lithiation/deuteration of 9,12-bis(methoxy-methylthio)-*o*-carborane **2** at the icosahedral carbon atoms proved, that substitution of CH protons proceeds analogously to unmodified *o*-carborane.[23, 26] The synthesis was performed according to typical procedures by dissolving the carborane derivative in dry ether and using *n*-butyl lithium for deprotonation of the carbon atoms. In contrast to the lithiation of unfunctionalized *o*-carborane, where only the dilithiated *o*-carborane species precipitates, monolithiated **2** precipitates directly. This may be caused by complexation of the lithium by the SMOM-groups. The free carborane anion formed is then insoluble in ether. After the addition of two equivalents of butyl lithium the obtained dilithiated carborane species is quenched with deuterium oxide. After work up the product was obtained in quantitative yield.

The 100% conversion is proved by proton and carbon NMR. The signal at 3.61 ppm in the proton spectrum disappears (figure 2) and the signal at 48.1 ppm in the carbon spectrum turns into a triplet (figure 3). In the HiRes-mass spectrum the signals are by two units shifted to higher mass from 296.19 to

298 298.20 $\frac{m}{z}$. This and the complete absence of any proton related signals reveals
299 a quantitative deuteration of both carbon anions.

300 Cleavage of the MOM-group is achieved under mild conditions with mercury(II)-
301 chloride in acetonitrile/water mixture as solvent. The 9,12-dimercapto-1,2-
302 dideutero-*o*-carborane mercury complex precipitates immediately after addition
303 of the HgCl₂ solution as a white solid. After a couple of minutes, the precipitate
304 is isolated and suspended in ethanol. **4a** is released from mercury by bubbling
305 H₂S through the suspension of the mercury complex and can be obtained in
306 75% yield.

307 In the proton nmr the resonance of the thiol proton occurs at 0.39 ppm. In
308 the carbon nmr, the C-D triplet undergoes a slight shift to lower frequencies of
309 about 2 ppm. No evidence for a reprotonation of icosahedral carbon through
310 mercury reagents used can be found under the given reaction conditions, neither
311 in the proton spectra nor in the carbon spectra (see below).

312 The infrared spectra of **4a** and **3a** are identical to their protonated coun-
313 terparts except the expected shift of the icosahedral hydrocarbon bands from
314 3043 cm⁻¹ (3014 cm⁻¹) to 2272 cm⁻¹ (2260 cm⁻¹) after deuteration (figure 5).

315 The immediate separation of the mercury complex of **3a** from excess mercury(II)-
316 chloride is necessary to avoid metallization of the icosahedral carbon atoms,
317 which has been described in the literature[29, 30, 31]. A reaction time of 10 h
318 with mercury(II) chloride leads together with the release by H₂S to a repro-
319 tonation of the icosahedral carbon atoms. This reprotonation is shown by a
320 comparison of the proton spectra of 9,12-dimercapto-1,2-dideutero-*o*-carborane
321 **4a** and its reactant 9,12-bis(methoxy-methylthio)-1,2-dideutero-*o*-carborane **3a**
322 (figure 6). It shows an increased C-H signal at 3.6 ppm which indicates a repro-
323 tonation of about 18% of the deuterated carbon atoms.

324 [Figure 6 about here.]

325 *Alkylation of 9,12-bis(methoxy-methylthio)-o-carborane 2 and release of the thi-*
326 *ols*

327 After the evidence of a quantitative lithiation of both icosahedral carbons
328 of **2** was achieved by complete deuteration as described above, the feasibility of
329 the thereby formed dianion for a nucleophilic substitution with alkyl halogenides
330 was investigated.

331 To attach alkylchains—ethyl and heptyl for the herein described derivatives—
332 onto the carbon positions, **2** was lithiated analogously to the deuteration reac-
333 tion described above, using THF as solvent instead of ether for better support
334 of Sn-reactions. The dianion is then allowed to react with two equivalents of
335 the corresponding alkylhalogenide.

336 For the heptyl derivative **3b** the solvent was removed and yellowish im-
337 purities were easily removed via filtration over silica gel with diethyl ether as
338 eluent. The MOM groups were cleaved with mercury(II) chloride whereby he
339 mercapto-carborane mercury complex separated as a waxy solid. Product **4b**
340 was obtained after passing H₂S through a solution of the mercury complex and
341 removal of precipitating mercury sulfide. The 9,12-dimercapto-1,2-diheptyl-*o*-
342 carborane **4b** incurs as a colorless oil.

343 The ethyl substituted compound was worked up differently. It was roughly
344 separated from reactants and solvent and the raw product **3c** was used without
345 further purification for the synthesis of **4c** by cleaving the protecting groups
346 with mercury(II) chloride. The final product was released by passing H₂S gas
347 into a ethanolic suspension of the mercury-product complex and purified by
348 sublimation.

349 In the proton spectra of **3b** and **4b** the resonance of the icosahedral C-H
350 at 3.61 ppm is missing. The signals of the alkyl chains occur at typical ranges
351 from 2.12 to 0.86 ppm (heptyl).

352 The icosahedral carbon interestingly undergoes a strong shift to higher frequencies—
353 even when alkylated with simple alkyl groups—of about 30 ppm. The successful
354 attachment of the alkyl substituents is proved by a HMBC correlation spectrum
355 of **3b** (figure 7). It shows a cross peak between the resonances at 73 ppm (icosa-
356 hedral carbon) and 2.12 ppm (first CH₂ side chain).

357 [Figure 7 about here.]

358 In a decoupled boron NMR-spectrum of **3b**, alkylation of the icosahedral
359 carbons results in a shift of the hydrogen bound from three distinct signals
360 to one overlapping peak with two maxima at -2.02 and -3.62 ppm. The SH-
361 bound borons undergo a slight shift from 14.62 ppm before to 12.43 ppm after
362 alkylation.

363 The spectra—proton and carbon—of **4b** show the expected amount of res-
364 onances with almost same chemical shifts as **3b**. In both carbon and proton
365 NMR spectra, the signals of the MOM-group are missing and the typical SH-
366 proton resonance at 0.39 ppm occurs in the proton spectra. In contrast, the
367 boron spectrum of **4b** shows a more complex pattern compared to **3b** with dis-
368 tinct signals for B-S (11.06 ppm) and borons in positions 8 and 10. All other
369 borons are summarized below one broad peak at -3.51 ppm.

370 In the infrared spectrum, both derivatives **3b** and **4b** show next to the typical
371 boron-vibrations at 2600 cm⁻¹ strong C-H valence and deformation bands at
372 3080–2750 cm⁻¹ and 1460 cm⁻¹ respectively. The MOM-protected derivative has
373 the typical methoxy band, which occurs at 2812 cm⁻¹. The strong resonances
374 at 3043 cm⁻¹ which belongs to the icosahedral CH-vibrations, are missing.

375 The proton spectrum of 9,12-dimercapto-1,2-diethyl-*o*-carborane **4c** shows
376 the expected ethyl pattern at 1.17 (CH₃) and 2.23 ppm (CH₂) next to the boron
377 and mercapto proton resonances (figure 8). The carbon spectrum shows three
378 signals. The resonance of the icosahedral carbon encounters with 74 ppm in the
379 same shift after alkylation as in case of **4b**.

380 [Figure 8 about here.]

381 Conclusion

382 We described a new synthetic pathway to 1,2-dialkylated 9,12-dimercapto-*o*-
383 carboranes through a 9,12-methoxy-methylthio (MOM) substituted *o*-carborane
384 precursor. This 9,12-bis(methoxy-methylthio)-*o*-carborane was prepared using
385 potassium *tert*-butanolate and bromomethyl-methyl ether with a reasonable
386 yield of about 60–65% and purity.

387 Deuteration experiments of the 9,12-bis(methoxy-methylthio)-*o*-carborane
388 precursor showed a 100% proton-deuteron exchange in the positions one and
389 two and hence revealed a quantitative lithiation at these positions

390 The corresponding alkylated derivatives were synthesized by lithiation with
391 *n*-BuLi followed by reaction with alkyl halides and were obtained in good yields
392 of about 60–65%.

393 Prior to alkylation experiments, deuteration experiments revealed a 100%
394 proton-lithiation exchange at positions 1 and 2 of the S-protected mercapto-

395 *o*-carborane icosahedron. Cleavage of the MOM-groups was achieved using
396 mercury(II)-chloride followed by release of the mercapto-compound by H₂S in
397 almost quantitative yields. In case of the 1,2-dideuterated compound, longer
398 reaction times with HgCl₂ led to a metallization of the *o*-carborane cluster and
399 thereby to a reprotonation at the carbon positions during release with H₂S.

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404 Supplementary data

405 Crystallographic data for compound **2** can be obtained . . . Complete spectral
406 data can be found in a separate supplementary data file.

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Figure 1: General scheme of substitution of 9,12-bis(methoxy-methylthio)-*o*-carborane **2**. Conditions a) *K*-*o*-tert-butanol in abs. THF, then MOM-bromide b) *n*-buli, then D₂O or R-X c) HgCl₂ then H₂S. For description of R see table 1.

Figure 2: ^1H -NMR spectra of the 9,12-dimercapto-*o*-carborane derivatives: a) **1**, b) **2**, c) **3a**, d) **4a**. Signal 1a and 1b: MOM-group, signal 2: icosahedral CH, 3 BH, 4: SH.

Figure 3: ^{13}C -NMR spectra of the 9,12-Bis(methoxy-methylthio)-*o*-carborane precursor and of the products of the deuteration reaction sequence. a) **1**, b) **2**, c) **3**, d) **4**.

Figure 4: ORTEP model of the 9,12-bis(methoxy-methylthio)-*o*-carborane **2**. The ellipsoids are displayed with a probability of 50% at a temperature of 293 K.

Figure 5: Infrared spectra of **1**, **2**, **3a** and **4a**. Assigned resonances: a) CH (icosaeder), b) CH (MOM, stretch), c) BH, d) CD, e) C-C (stretch, icosaeder), f) CH (MOM, deformation).

Figure 6: Details of the NMR spectra of 9,12-dimercapto-1,2-dideutero-*o*-carborane and 9,12-bis(methoxy-methylthio)-1,2-dideutero-*o*-carborane. The reprotoation at the carbon atoms is displayed by the increase of the signal at 3.55/3.6 ppm.

Figure 7: HMBC-correlation spectrum of 9,12-bis(methoxy-methyl-thio)-1,2-diheptyl-*o*-carborane. The displayed correlations reveals the successful substitution of the icosahedral carbons.

Figure 8: Proton spectrum of **4c**.

Number	R=
3a/4a	Deuterium
3b/4b	Heptyl
3c/4c	Ethyl

Table 1: List of derivatives of compound **3**.