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gem-Bromochlorospiropentane reactivity toward methyllithium: an unusual carbenoid rearrangement

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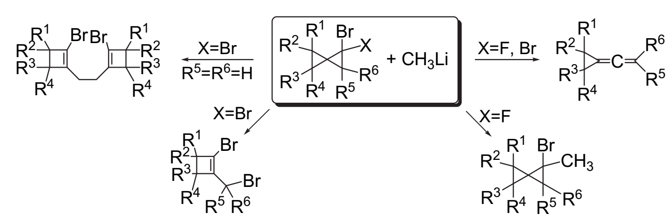
ABSTRACT

A skeletal carbenoid rearrangement of the *gem*-bromochlorospiropentanes in the presence of methyllithium has been studied. The synthetic and mechanistic aspects of this rearrangement as well as the influence of the halogen atom nature on the reaction pathway are discussed.

1. Introduction

The reaction of *gem*-dihalogenocyclopropanes with alkyllithium reagents is a traditional method for the synthesis of substituted allenes (the Doering–LaFlamme reaction).[1] However, *gem*-dihalogeno substituted spiropentanes—the substrates containing unique strained framework—were found to react with alkyllithium reagents in quite a different way.[2] Recently we have described our investigations of *gem*-dibromospiropentanes and *gem*-bromofluorospiropentanes reactivity toward methyllithium.[3,4] When treated with methyllithium at low temperature (−55 °C), dibromospiropentanes underwent carbocationic skeletal rearrangement leading to monomeric or dimeric bromocyclobutenes.[2,3] On the other hand, the preferable pathway of *gem*-bromofluorospiropentane reaction with methyllithium was the formal substitution of the fluorine atom for a methyl group with the retention of the spiropentane framework (Scheme 1).[4]

After we had established such a dramatic influence of the halogen atom on the reaction pathway, we decided to study a series of mixed *gem*-bromochlorospiropentanes in the reaction with methyllithium. Taking the previous results into consideration, we could expect the formation of rearranged products in addition to the substitution of one of the halogen atoms for a methyl group with the *gem*-bromochlorospiropentanes. It is of interest to determine if the change in the nature of the halogen atom (Br, Cl, F) results in a change of reactivity.



Scheme 1. Reaction of *gem*-dihalogenospiropentanes with methyllithium.

2. Results and discussion

A series of previously unknown *gem*-bromochlorospiropentanes **1–8** were obtained via bromochlorocarbene cycloaddition to the corresponding alkylidenecyclopropanes under PTC conditions (Table 1). According to literature data, the possible formation of dibromospiropentanes as byproducts could be prevented by using dibenzo-18-crown-6 as phase-transfer catalyst.[5] Indeed, the target bromochlorospiropentanes **1–8** were the sole products obtained under these conditions.

gem-Bromochlorospiropentanes **1–8** were treated with methyllithium at low temperature. We have previously shown −55 °C to be the most favorable temperature for *gem*-dibromospiropentane skeletal rearrangement. However, *gem*-bromochlorospiropentanes

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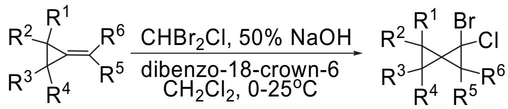
Table 1
Synthesis of *gem*-bromochlorospiropentanes



1-8

No	*gem*-Bromochlorospiropentanes	Yield[a] (%)
1	R^1=R^2=R^3=R^4=R^5=R^6=H	54
2	R^1=Ph, R^2=R^3=R^4=R^5=R^6=H	72
3	R^1–R^2=$(CH_2)_3$, R^3=R^4=R^5=R^6=H	62
4	R^1–R^2=$(CH_2)_5$, R^3=R^4=R^5=R^6=H	62
5	R^1–R^2=$(CH_2)_3$, R^3–R^4=$(CH_2)_3$, R^5=R^6=H	55
6	R^1–R^3=$(CH_2)_4$, R^2=R^4=R^5=R^6=H	70
7	R^1–R^3=$(CH_2)_6$, R^2=R^4=R^5=R^6=H	77
8	R^1–R^2=$(CH_2)_2$, R^3–R^4=H, R^5=R^6=$(CH_2)_2$	56

[a] Isolated yields.

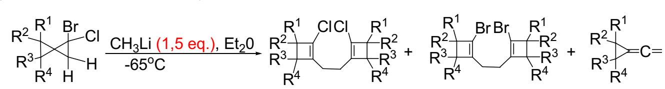
yielded a large amount (up to 50%) of allenes under these conditions and the best yields of the rearranged products were achieved while carrying out the reaction at −65 °C. The results are presented in Table 2.

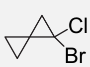
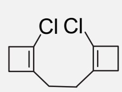
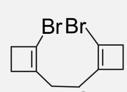
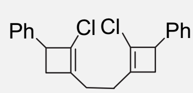
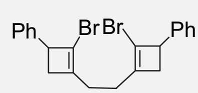
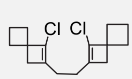
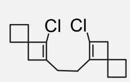
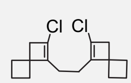
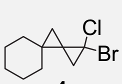
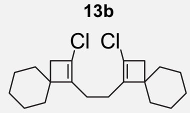
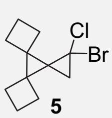
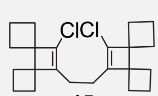
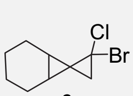
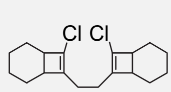
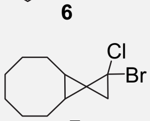
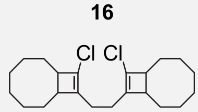
Reaction of unsubstituted *gem*-bromochlorospiropentane **1** with methyllithium led to dimeric chlorocyclobutene **9** and bromocyclobutene **10** in a ratio of 4:1 (Table 2). This ratio did not change while lowering the temperature to −78 °C. While using butyllithium or *tert*-butyllithium instead of methyllithium we observed only traces of the halogenocyclobutenes in the reaction mixture, besides the products of polymerization or decomposition.

Basing on the earlier obtained data for *gem*-dihalogenospiropentane carbenoid rearrangement,[3] we can suppose the following method for cyclobutene formation (Scheme 2). In the first step, the halogenophilic substitution of the bromine atom occurs leading to chlorolithium carbenoid **I**. In the next step nucleophilic attack of the C–C bond at the carbenoid center takes place giving the fused species **II**, which isomerizes quickly into four-membered ring **III**. Then lithium migration in the allylic system leads to alkyllithium intermediate **Va**. Another halogenophilic reaction of **Va** with **1** results in alkylhalogenide **VIa**, whose interaction with alkyllithium intermediate **Va** affords chlorocyclobutene **9**.

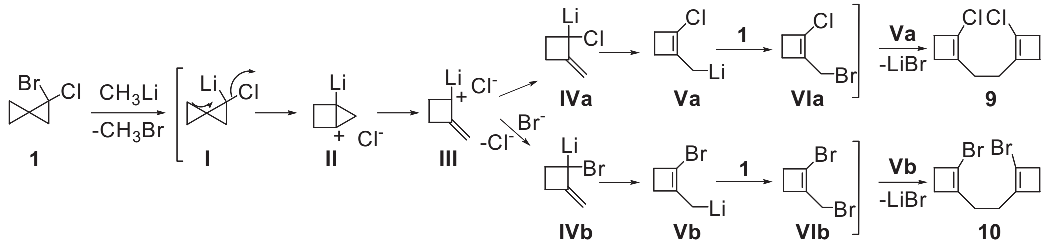
Formation of bromocyclobutene **10** can result from the partial substitution of the chlorine for bromine in ionic pair **III**. Chlorine substitution at the first stage of reaction leading to bromolithium carbenoid is unlikely, as the C–Cl bond is more stable and less

Table 2
Reaction of terminal *gem*-bromochlorospiropentanes **1**–**7** with methyllithium



Bromochlorospiropentanes	Halogenocyclobutenes	Yield[a] (%)	Allenes yield[b] (%)
 **1**	 **9**  **10**[2a]	61[c] (4:1)	—
 **2**	 **11**  **12**[3e]	42[c] (3:1)	21
 **3**	 **13a**  **13b**  **13c**	40	19
 **4**	 **14**	74	18
 **5**	 **15**	42	10
 **6**	 **16**	29	36
 **7**	 **17**	33	24

[a] Isolated yields.
[b] Allenes were not isolated, the yields refer to NMR data of reaction mixture.
[c] The yields refer to the mixture of bromo- and chlorocyclobutenes.

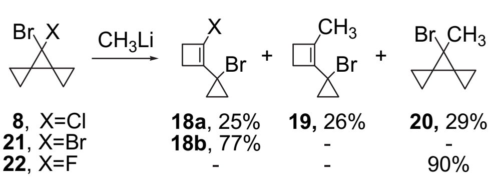


Scheme 2. Reaction of *gem*-bromochlorospiropentane **1** with methyllithium.

reactive toward methyllithium cf. the C–Br bond.[6] Additional experiments showed that *gem*-dichlorospiropentanes of similar structure did not react with methyllithium under similar conditions.

Moving ahead, we studied how the substituents in cyclopropane moiety influence the reaction pathway and the products (Table 2). Phenyl substituted bromochlorospiropentane **2** was found to react with methyllithium giving a mixture of chloro- and bromo-substituted products of rearrangement **11** and **12**, chlorocyclobutene **11** being the major one. At the same time, spirocycloalkyl substituted spiropentanes **3**–**5** and compounds **6** and **7**, which contain 1,2-fused rings afforded chlorocyclobutenes **14**–**17** without the presence of bromocyclobutenes. This seems to result from sterical hindrance, which prevents the exchange of halogen atoms in the intermediate **III** (Scheme 2). In the reactions of compound **6** and **7** the yield of allenes is higher and the yield of chlorocyclobutenes is lower because in these cases C–C-bond migration might be hindered by a fixed polycyclic structure.

An unexpected result was obtained for *gem*-bromochlorodispiroheptane **8**, which contains the internal *gem*-bromochlorocyclopropane fragment. In the reaction of this substrate with methyllithium we observed both possible reaction pathways, i.e., skeletal rearrangement, leading to cyclobutenes **18a** and **19**, and methylation with the retention of spiropentane moiety (product **20**, Scheme 3).



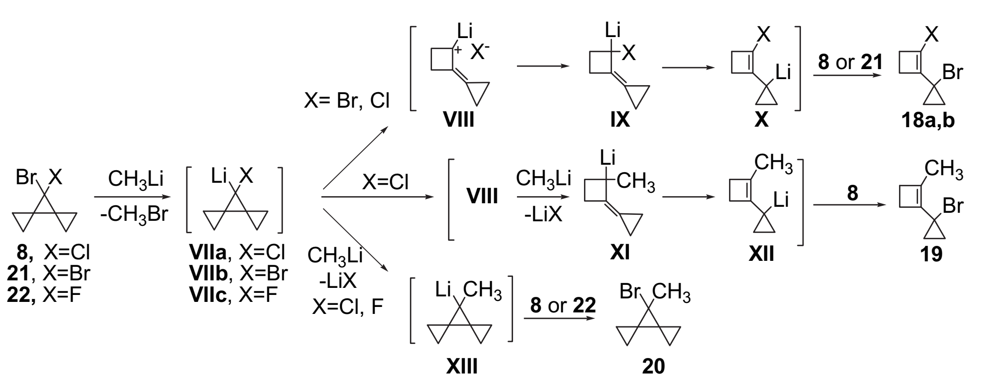
Scheme 3. Reaction of *gem*-dihalogenodispiroheptanes with methyllithium.

It is interesting to compare the results for the bromochloride **8** with the other *gem*-bromohalogenodispiroheptanes. The reactions of dihalogenospiropentanes **21** and **22** with methyllithium were studied in our previous works (Scheme 3).[2a,3c,d,4]

These results illustrate the differences in the stability of halogenolithium carbenoids **VII** (Scheme 4). Fluorolithium carbenoid **VIIc** is stable enough toward nucleophilic attack of the C–C bond that makes fluorine substitution by an external nucleophile (such as methyllithium molecule) possible and leads to product **20** via halogenophilic reaction of intermediate **XIII** with starting spiropentane **22**. Bromolithium carbenoid **VIIb** isomerizes faster than any possible bimolecular reaction with methyllithium could occur and bromocyclobutene **18b** (X=Br) is the sole product of the reaction. For the chlorine containing carbenoid **VIIa**, that has intermediate stability, we observed the competition of both processes and the formation of rearranged products **18a** and **19** as well as dispiro compound **20**.

It is notable, that the formation of dimeric cyclobutenes is never observed for dihalogenides containing internal dihalogenocyclopropane moiety. Halogenophilic reaction of allyllithium intermediate **X** or **XII** with a source of bromine, such as the starting *gem*-dihalogenospiropentane or reaction with methyl bromide results in the corresponding product **18** or **19**. In contrast with intermediates **VIa** and **VIb** (Scheme 2) compounds **18** and **19** do not interact with allyllithium particles **X** and **XII**, probably, due to sterical hindrance.

The investigation of the carbenoid rearrangement of a new series of mixed *gem*-bromochlorospiropentanes together with recently studied *gem*-dibromo- and *gem*-bromofluorospiropentanes gives new insight into the halogenolithium spiropentyl carbenoids reactivity toward nucleophiles. The mechanism of the reaction can be viewed as a carbocationic stepwise rearrangement, which suggests the nucleophilic attack of C–C bond of the neighboring spiro three-membered cycle on the carbenoid center.[3] This process leads to the formation of a series of carbocationic intermediates, which ultimately yield cyclobutene products. The obtained results demonstrate the substantial influence of the nature of the halogen atom in lithium carbenoids on its transformation pathway. The reactivity of *gem*-bromochlorospiropentanes is mainly similar to the reactivity of *gem*-dibromospiropentanes (and not bromofluorospiropentanes), and the difference in the stabilities of C–Br and C–Cl bonds results in the formation of chloro substituted cyclobutenes as the major or the sole products of the reaction.



Scheme 4. Proposed mechanism of the reaction of *gem*-dihalogenodispiroheptanes with methyllithium.

3. Experimental

3.1. General

NMR spectra were recorded on a Bruker DPX-400 spectrometer (400.13 and 100.62 MHz for ^{1}H and ^{13}C, respectively) at room temperature; chemical shifts δ were measured with reference to the solvent (^{1}H: $CDCl_3$, δ=7.24 ppm; ^{13}C: $CDCl_3$, δ=77.13 ppm). Mass spectra were taken on a Finnigan MAT 95 XL spectrometer (70 eV) using electron impact ionization (EI) and GC–MS coupling. Accurate mass measurements (HRMS) were carried out using a Bruker micro TOF-Q™ ESI-TOF mass spectrometer. Microanalyses were performed on a Carlo Erba 1106 instrument at the Microanalytic Laboratory, Department of Chemistry, Moscow State University. Infrared spectra were recorded on a Thermo Nicolet FT IR-200 spectrometer. Analytical thin layer chromatography (TLC) was carried out with Silufol silica gel plates (supported on aluminum); the detection was done by UV lamp (254 and 365 nm) and chemical staining (iodine vapor). Column chromatography was performed using silica gel 60 (230–400 mesh, Merck). GLC analyses and separation were performed using silicone E-301 (15% on Inerton AW). Petroleum ether used refers to the fraction boiling at 60–70 °C. All reagents except commercial products of satisfactory quality were purified by literature procedures prior to use. Starting compounds: methylenecyclopropane,[7] (2-methylenecyclopropyl) benzene,[8] 1-methylenespiro[2.3]hexane,[9] 1-methylenespiro[2.5] octane,[10] 9-methylenedispiro[3.0.3.1]nonane,[11] 7-methylenebicyclo [4.1.0]heptane,[12] 9-methylenebicyclo[6.1.0]nonane,[12] 1-*tert*-butoxy-2-methylenecyclopropane,[13] bicyclopropylidene[14] were synthesized by known procedures.

3.2. General procedure 1: addition of bromochlorocarbene to alkenes

A 50% (w/w) aqueous solution of NaOH (22 mL) was added to 11.0 mmol of the corresponding alkene, $CHBr_2Cl$ (2.74 g, 13.1 mmol) and dibenzo-18-crown-6 (0.1 g, 0.3 mmol) in dichloromethane (22 mL) at 0 °C over 0.5 h. The reaction mixture was warmed up to room temperature and stirred for 24 h. Then it was treated with ice (20 g). The organic phase was separated and the water phase extracted with dichloromethane (3×10 mL). The combined organic fractions were washed with water (50 mL) and dried over $MgSO_4$. The solvent was evaporated; the residue was distilled or purified by preparative column chromatography.

*3.2.1. 1-Bromo-1-chlorospiro[2.2]pentane (**1**).* Yield 1.08 g (54%), colorless liquid, bp 80 °C/140 Torr. IR (film): ν 3078, 3003, 2927, 1556, 1498, 1423, 1396, 1149, 1089, 1039, 1016, 899, 849, 719, 660, 640 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.17–1.27 (m, 3H, CH_2), 1.31–1.37 (m, 1H, CH_2), 1.91–1.94 (m, 2H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 10.1 (CH_2), 11.3 (CH_2), 27.2 (C_{spiro}), 28.1 (CH_2), 47.7 (CBrCl). MS (EI, 70 eV) m/z: 147 (6), 145 (6) [M−Cl^{+}], 103 (7), 101 (23) [M−Br^{+}], 66 (43), 65 (100), 63 (3), 51 (4), 40 (46), 39 (44), 38 (16). HRMS (EI): [M−Br]$^{+}$ calcd for $C_5H_6{}^{35}Cl$ 101.0158, found 101.0166.

*3.2.2. 1-Bromo-1-chloro-4-phenylspiro[2.2]pentane (**2**).* Yield 2.04 g (72%), colorless oil, R_f 0.5 (petroleum ether). Two diastereomers, A:B 1:1. IR (film): ν 3078, 3062, 3030, 2993, 2925, 2852, 1604, 1493, 1452, 1348, 1207, 1099, 1072, 1053, 1030, 945, 926, 899, 866, 769, 751, 719, 698, 588, 550 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.57 (dd, 1H, $^{2}J_{HH}$ 5.4, $^{3}J_{CH}$ 5.6, CH_2), 1.63 (dd, 1H, $^{2}J_{HH}$ 5.4, $^{3}J_{CH}$ 5.6, CH_2), 1.85–1.91 (m, 1H+2H, CH_2), 1.96–2.03 (m, 1H, CH_2), 2.03–2.07 (m, 2H, CH_2), 2.69 (dd, 1H, $^{3}J_{HH}$=5.6, $^{3}J_{HH}$=8.7, CH), 2.81 (dd, 1H, $^{3}J_{HH}$=5.6, $^{3}J_{CH}$=8.7, CH), 7.14–7.19 (m, 4H, 4CH, Ph), 7.21–7.33 (m, 2H, 2CH, Ph), 7.34–7.40 (m, 4H, 4CH, Ph). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 18.7 (CH_2), 20.0 (CH_2), 26.2 (CH), 26.9 (CH_2CBrCl, A+CH_2CBrCl, B), 27.4 (CH), 35.0 (C_{spiro}, A+C_{spiro}, B), 47.1 (CBrCl), 47.2 (CBrCl), 126.5 (2CH, Ph, A+2CH, Ph, B), 126.6 (CH, Ph, A+CH, Ph, B), 128.6 (2CH, Ph, A+2CH, Ph, B), 139.4 (C, Ph), 139.64 (C, Ph). Anal. Calcd for $C_{11}H_{10}BrCl$: C 51.30, H 3.91%. Found: C 51.18, H 4.07%.

*3.2.3. 1-Bromo-1-chlorodispiro[2.0.3.1]octane (**3**).* Yield 1.51 g (62%), colorless liquid, R_f 0.8 (petroleum ether). Two diastereomers, A:B 1.25:1. IR (film): ν 3053, 2981, 2951, 2929, 2850, 1514, 1460, 1429, 1400, 1259, 1117, 1080, 1043, 1012, 987, 897, 860, 717 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.05 (d, 1H, $^{2}J_{HH}$ 5.5, CH_2, cy−Pr, B), 1.07 (d, 1H, $^{2}J_{HH}$ 5.4, CH_2, cy−Pr, A), 1.17 (d, 1H, $^{2}J_{HH}$ 5.4, CH_2, cy−Pr, A), 1.27 (d, 1H, $^{2}J_{HH}$ 5.5, CH_2, cy−Pr, B), 1.75 (d, 1H, $^{2}J_{HH}$ 6.1, CH_2, cy−Pr, B), 1.77 (d, 1H, $^{2}J_{HH}$ 6.1, CH_2, cy−Pr, A), 1.88 (d, 1H, $^{2}J_{HH}$ 6.1, CH_2, cy−Pr, A), 1.92 (d, 1H, $^{2}J_{HH}$ 6.1, CH_2, cy−Pr, B), 1.93–2.04 (m, 1H, CH_2, cy−Bu, A+1H, CH_2, cy−Bu, B), 2.04–2.15 (m, 2H, CH_2, cy−Bu, A+2H, CH_2, cy−Bu, B), 2.16–2.30 (m, 2H, CH_2, cy−Bu, A+2H, CH_2, cy−Bu, B), 2.68–2.83 (m, 1H, CH_2, cy−Bu, A+1H, CH_2, cy−Bu, B). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 17.0 ($^{1}J_{CH}$ 139, CH_2, cy−Bu, B), 17.1 ($^{1}J_{CH}$ 139, CH_2, cy−Bu, A), 19.8 ($^{1}J_{CH}$ 161, CH_2, cy−Pr, B), 21.6 ($^{1}J_{CH}$ 162, CH_2, cy−Pr, A), 25.8 ($^{1}J_{CH}$ 137, CH_2, cy−Bu, B), 26.3 ($^{1}J_{CH}$ 138, CH_2, cy−Bu, A), 27.1 ($^{1}J_{CH}$ 165, CH_2CBrCl, cy−Pr, A), 27.5 ($^{1}J_{CH}$ 166, CH_2CBrCl, cy−Pr, B), 28.9 ($^{1}J_{CH}$ 138, CH_2, cy−Bu, B), 29.3 ($^{1}J_{CH}$ 137, CH_2, cy−Bu, A), 32.3 (C_{spiro}), 32.6 (C_{spiro}), 32.6 (C_{spiro}), 33.0 (C_{spiro}), 48.5 (CBrCl, B), 49.2 (CBrCl, A). Anal. Calcd for $C_8H_{10}BrCl$: C 43.38, H 4.55%. Found: C 43.50, H 4.61%.

*3.2.4. 1-Bromo-1-chlorodispiro[2.0.5.1]decane (**4**).* Yield 1.71 g (62%), colorless liquid, R_f 0.8 (petroleum ether). Two diastereomers, A:B 1.7:1. IR (film): ν 3062, 2992, 2941, 2862, 1518, 1448, 1405, 1356, 1171, 1087, 1030, 952, 890, 860, 726, 720, 680, 500 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 0.84 (d, 1H, $^{2}J_{HH}$ 4.5, CH_2, cy−Pr, B), 0.86 (d, 1H, $^{2}J_{HH}$ 4.4, CH_2, cy−Pr, A), 0.97 (d, 1H, $^{2}J_{HH}$ 4.4, CH_2, cy−Pr, A), 1.06 (d, 1H, $^{2}J_{HH}$ 4.5, CH_2, cy−Pr, B), 1.22–1.34 (m, 1H, CH_2, cy−Pr, A+1H, CH_2, cy−Pr, B), 1.34–1.44 (m, 1H, CH_2, cy−Pr, A+1H, CH_2, cy−Pr, B), 1.47–1.69 (m, 6H, CH_2, cy−Hex, A+6H, CH_2, cy−Hex, B), 1.71–1.91 (m, 4H, CH_2, cy−Hex, A+4H, CH_2, cy−Hex, B). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 20.8 (CH_2, cy−Pr, B), 22.7 (CH_2, cy−Pr, A), 25.3 (CH_2, A+CH_2, B), 25.7 (CH_2, B), 25.9 (CH_2, A), 26.0 (CH_2, A), 26.1 (CH_2, B), 26.7 (CH_2, A), 26.9 (CH_2, B), 32.3 (CH_2, B), 32.4 (C_{spiro}, B), 32.5 (C_{spiro}, A), 32.6 (CH_2, A), 33.7 (CH_2, B), 34.0 (CH_2, A), 35.6 (C_{spiro}, B), 36.0 (C_{spiro}, A), 47.4 (CBrCl, B), 48.6 (CBrCl, A). Anal. Calcd for $C_{10}H_{14}BrCl$: C 48.12, H 5.65%. Found: C 47.99, H 5.51%.

*3.2.5. 1-Bromo-1-chlorotrispiro[2.0.3^{4}.0.3^{8}.0^{3}]undecane (**5**).* Yield 1.59 g (55%), colorless liquid, R_f 0.8 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.66 (d, 1H, $^{2}J_{HH}$ 5.8, CH_2, cy−Pr), 1.68 (d, 1H, $^{2}J_{HH}$ 5.8, CH_2, cy−Pr), 1.80–1.89 (m, 2H, CH_2, cy−Bu), 1.93–2.19 (m, 8H, CH_2, cy−Bu), 2.44–2.59 (m, 2H, CH_2, cy−Bu). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 16.0 ($^{1}J_{CH}$ 139, CH_2, cy−Bu), 16.1 ($^{1}J_{CH}$ 139, CH_2, cy−Bu), 21.7 ($^{1}J_{CH}$ 137, CH_2, cy−Bu), 22.3 ($^{1}J_{CH}$ 136, CH_2, cy−Bu), 24.8 ($^{1}J_{CH}$ 136, CH_2, cy−Bu), 25.0 ($^{1}J_{CH}$ 137, CH_2, cy−Bu), 25.9 ($^{1}J_{CH}$ 165, CH_2, cy−Pr), 34.7 (C_{spiro}), 35.6 (C_{spiro}), 36.2 (C_{spiro}), 49.7 (CBrCl). Anal. Calcd for $C_{11}H_{14}BrCl$: C 50.51, H 5.39%. Found: C 50.65, H 5.73%.

*3.2.6. 2′-Bromo-2′-chlorospiro[bicyclo[4.1.0]heptane-7,1′-cyclopropane] (**6**).* Yield 1.81 g (70%), colorless liquid, R_f 0.5 (petroleum ether). IR (film): ν 3020, 2938, 2867, 1463, 1381, 1150, 1060, 1049, 961, 847, 764, 727, 660, 568 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.15–1.25 (m, 2H, CH_2), 1.26–1.35 (m, 2H, CH_2), 1.42–1.52 (m, 2H, CH_2), 1.59 (ddd, 1H, $^{3}J_{HH}$ 1.6, 6.9, 8.7, CH), 1.73 (ddd, 1H, $^{3}J_{HH}$ 1.6, 6.9, 8.7, CH), 1.75 (br s, 2H, CH_2, cy−Pr), 1.84–1.96 (m, 2H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 18.9 ($^{1}J_{CH}$ 165, CH), 20.1 ($^{1}J_{CH}$ 165, CH), 21.1 ($^{1}J_{CH}$ 127, CH_2, cy−Hex), 21.2 ($^{1}J_{CH}$ 127, CH_2, cy−Hex), 21.2 ($^{1}J_{CH}$ 127,

CH_2, cy–Hex), 21.5 ($^1J_{CH}$ 127, CH_2, cy–Hex), 25.1 ($^1J_{CH}$ 165, CH_2, cy–Pr), 34.8 (C_{spiro}), 48.9 (CBrCl). Anal. Calcd for $C_9H_{12}BrCl$: C 45.89, H 5.13%. Found: C 45.74, H 5.07%.

*3.2.7. 2′-Bromo-2′-chlorospiro[bicyclo[6.1.0]nonane-9,1′-cyclopropane] (**7**).* Yield 2.24 g (77%), colorless solid, R_f 0.7 (petroleum ether), mp 35–36 °C. IR (film): ν 3060, 2992, 2938, 2860, 1527, 1470, 1418, 1380, 1360, 1196, 1147, 1120, 1073, 1024, 972, 949, 823, 760, 745, 653, 583, 552 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.02–1.15 (m, 2H, CH_2), 1.36–1.54 (m, 6H, CH_2), 1.57–1.65 (m, 2H, CH_2), 1.66 (s, 2H, CH_2, cy–Pr), 1.68–1.76 (m, 2H, CH_2), 1.77–1.84 (m, 2H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 24.4 ($^1J_{CH}$ 165, CH_2, cy–Pr), 24.4 ($^1J_{CH}$ 125, CH_2, cy–Oct), 24.7 ($^1J_{CH}$ 125, CH_2, cy–Oct), 24.8 ($^1J_{CH}$ 158, CH), 26.1 ($^1J_{CH}$ 160, CH), 26.5 ($^1J_{CH}$ 126, 2CH_2, cy–Oct), 29.0 ($^1J_{CH}$ 127, 2CH_2, cy–Oct), 35.2 (C_{spiro}), 48.1 (CBrCl). Anal. Calcd for $C_{11}H_{16}BrCl$: C 50.12, H 6.12%. Found: C 50.23, H 6.27%.

*3.2.8. 7-Bromo-7-chlorodispiro[2.0.2.1]heptane (**8**).* Yield 1.28 g (56%), colorless solid, R_f 0.1 (petroleum ether), mp 48–50 °C. IR (film): ν 3085, 3009, 2969, 2937, 2862, 1566, 1465, 1382, 1321, 1158, 1123, 1058, 1038, 1023, 916, 897, 798, 670 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.02–1.10 (m, 4H, CH_2), 1.21–1.25 (m, 2H, CH_2), 1.33–1.38 (m, 2H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 9.5 (2CH_2), 10.6 (2CH_2), 30.9 (2C_{spiro}), 55.7 (CBrCl). Anal. Calcd for C_7H_8BrCl: C 40.52, H 3.89%. Found: C 40.61, H 3.78%.

3.3. General procedure 2: reaction of *gem*-bromochlorospiropentanes with methyllithium

A solution of 1.5 M methyllithium (4.0 mL, 6.0 mmol) in ether was added dropwise to solution of 4.0 mmol bromochlorospiropentane in absolute ether (10 mL) at −65 °C in argon. The reaction mixture was stirred for 10 h. Then it was warmed up to 0 °C and quenched with an equal amount of cold water. The organic phase was separated, the water phase extracted with ether (3×3 mL). The combined organic fractions were washed with water (5 mL) and dried over $MgSO_4$. The solvent was evaporated; the products were isolated by preparative column chromatography or GLC (column 3000×5 mm, silicone E-301, 15% on Inerton AW).

*3.3.1. 1,1′-Ethane-1,2-diylbis(2-chlorocyclobutene) (**9**).* Yield 0.20 g (40%), colorless liquid, R_f 0.6 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 2.26 (br s, 4H, 2CH_2), 2.33–2.38 (m, 4H, 2CH_2, cy–Bu), 2.60–2.65 (m, 4H, 2CH_2, cy–Bu). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 24.7 ($^1J_{CH}$ 129, 2CH_2), 27.6 ($^1J_{CH}$ 141, 2CH_2, cy–Bu), 33.8 ($^1J_{CH}$ 142, 2CH_2, cy–Bu), 119.9 (2C═), 142.7 (2CCl═). MS (EI, 70 eV) *m*/*z*: 206 (1), 204 (6), 202 (9) [M$^+$], 167 (22), 169 (8) [M–Cl$^+$], 103 (26), 102 (12), 101 (71), 91 (8), 80 (6), 77 (8), 66 (9), 65 (100), 51 (9), 39 (16). Anal. Calcd for $C_{10}H_{12}Cl_2$: C 59.13, H 5.96%. Found: C 58.83, H 6.09%.

*3.3.2. 1,1′-[Ethane-1,2-diylbis(2-chlorocyclobut-2-ene-3,1-diyl)]dibenzene (**11**).* Yield 0.22 g (25%), colorless oil, R_f 0.2 (petroleum ether). Two diastereomers, A:B 1.1:1. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 2.29–2.37 (m, 2H, CH_2, A+2H, CH_2, B), 2.46–2.54 (m, 4H, CH_2, A+4H, CH_2, B), 2.91–2.99 (m, 2H, CH_2, A+2H, CH_2, B), 4.05–4.09 (m, 2H, CH, A+2H, CH, B), 7.26–7.41 (m, 10H, CH, Ph, A+10H, CH, Ph, B). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 24.6 ($^1J_{CH}$ 130, 2CH_2, B), 24.7 ($^1J_{CH}$ 130, 2CH_2, A), 38.2 ($^1J_{CH}$ 141, 2CH_2, cy–Bu, A), 38.2 ($^1J_{CH}$ 141, 2CH_2, cy–Bu, B), 50.2 ($^1J_{CH}$ 142, 2CH, cy–Bu, A), 50.2 ($^1J_{CH}$ 142, 2CH, cy–Bu, B), 123.6 (C═, A+C═, B), 126.9 ($^1J_{CH}$ 160, 4CH, Ph, A+4CH, Ph, B), 126.9 ($^1J_{CH}$ 160, 2CH, Ph, A+2CH, Ph, B), 128.6 ($^1J_{CH}$ 160, 4CH, Ph, A+4CH, Ph, B), 139.8 (2C, Ph, A), 139.9 (2C, Ph, B), 142.9 (2CCl, A), 143.0 (2CCl, B). MS (EI, 70 eV) *m*/*z*: 356 (0.5), 354 (1) [M$^+$], 321 (1), 319 (3) [M–Cl$^+$], 318 (3), 283 (8), 252 (16), 250 (21), 231 (9), 229 (31), 227 (16), 215 (20), 193 (16), 180 (20), 179 (31), 178 (26), 165 (23), 155 (37), 142 (23), 141 (100), 129 (32), 128 (50), 127 (34), 115 (56), 102 (16), 91 (42), 77 (19), 51 (10). HRMS (TOF ESI$^-$): [M]$^+$ calcd for $C_{22}H_{20}{}^{35}Cl_2$ 354.0942, found 354.0931.

*3.3.3. 2,2′-Ethane-1,2-diylbis(1-chlorospiro[3.3]hept-1-ene) (**13a**), 2-chloro-1-[2-(1-chlorospiro[3.3]hept-1-en-2-yl)ethyl]spiro[3.3]hept-1-ene (**13b**), 1,1′-ethane-1,2-diylbis(2-chlorospiro[3.3]hept-1-ene) (**13c**).*[†] Yield 0.23 g (40%), colorless oil, R_f 0.7 (petroleum ether). Three isomers, A:B:C 5:2.5:1. IR (film): ν 3080, 2970, 2960, 2880, 1661, 1469, 1440, 1385, 1302, 1229, 1193, 1088, 902, 760, 700 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.73–1.84 (m, 6H), 1.85–1.98 (m, 6H), 2.03–2.16 (m, 12H), 2.17–2.33 (m, 12H), 2.25 (s, 4H, B), 2.37 (s, 4H, C), 2.42 (s, 4H, B), 2.65 (s, 4H, C), 2.66 (s, 4H, B), 2.68 (s, 4H, A). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 15.8 (2CH_2, cy–Bu, B), 16.3 (2CH_2, cy–Bu, A), 17.0 (2CH_2, cy–Bu, C), 22.7 (2CH_2), 22.8 (2CH_2), 24.2 (2CH_2), 28.7 (2CH_2), 28.8 (2CH_2), 28.8 (4CH_2), 29.7 (4CH_2), 30.3 (4CH_2), 42.4 (2C_{spiro},) 42.7 (2C_{spiro}+2C_{spiro}), 48.8 (2CH_2), 49.2 (4CH_2), 126.4 (C), 126.6 (C), 143.4 (C), 146.6 (C). HRMS (TOF ESI$^-$): [M]$^+$ calcd for $C_{16}H_{20}{}^{35}Cl_2$ 282.0942, found 282.0947.

*3.3.4. 1,1′-Ethane-1,2-diylbis(2-chlorospiro[3.5]non-1-ene) (**14**).* Yield 0.50 g (74%), colorless oil, R_f 0.8 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.10–1.23 (m, 2H, CH_2), 1.25–1.40 (m, 8H, CH_2), 1.43–1.79 (m, 14H, CH_2), 2.26 (s, 2H, CH_2), 2.36 (s, 2H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 22.7 ($^1J_{CH}$ 127, 2CH_2), 24.4 ($^1J_{CH}$ 124, 4CH_2), 25.5 ($^1J_{CH}$ 124, 2CH_2), 34.3 ($^1J_{CH}$ 125, 4CH_2), 46.5 ($^1J_{CH}$ 140, 2CH_2, cy–Bu), 47.3 (2C_{spiro}), 120.5 (2C═), 150.5 (2CCl). MS (EI, 70 eV) *m*/*z*: 342 (1), 340 (5), 338 (8) [M$^+$], 305 (4), 303 (11) [M–Cl–H$^+$], 272 (4), 270 (7), 267 (8), 257 (7), 255 (10), 223 (8), 221 (20), 207 (5), 195 (9), 189 (12), 187 (16), 185 (9), 133 (63), 127 (29), 105 (53), 91 (100), 81 (22), 79 (32), 77 (26), 67 (35), 55 (24), 41 (24). HRMS (TOF APCI$^+$): [M–Cl]$^+$ calcd for $C_{20}H_{28}{}^{35}Cl$ 303.1880, found 303.1885.

*3.3.5. 9,9′-Ethane-1,2-diylbis(10-chlorodispiro[3.0.3.2]dec-9-ene) (**15**).* Yield 0.30 g (42%), colorless oil, R_f 0.8 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.71–1.91 (m, 8H, CH_2, cy–Bu), 2.07–2.15 (m, 16H, CH_2, cy–Bu), 2.43 (s, 4H, CH_2). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 15.2 (2CH_2, cy–Bu), 15.8 (2CH_2, cy–Bu), 22.8 (2CH_2), 26.6 (4CH_2, cy–Bu), 27.9 (4CH_2, cy–Bu), 54.2 (2C_{spiro}), 58.8 (2C_{spiro}), 127.3 (2C═), 144.6 (2CCl). MS (EI, 70 eV) *m*/*z*: 364 (1), 362 (2) [M$^+$], 310 (2), 308 (21), 306 (32), 280 (60), 279 (16), 278 (97), 271 (15), 252 (23), 250 (37), 245 (23), 243 (63), 235 (19), 229 (9), 217 (30), 216 (17), 215 (75), 206 (23), 207 (49), 193 (16), 180 (32), 179 (55), 178 (27), 165 (35), 153 (20), 141 (16), 130 (16), 129 (23), 128 (26), 127 (31), 125 (66), 117 (72), 115 (87), 105 (21), 103 (36), 99 (19), 91 (96), 89 (100), 77 (50). Anal. Calcd for $C_{22}H_{28}{}^{35}Cl_2$: C 72.72, H 7.77%. Found: C 72.77, H 8.04%.

*3.3.6. 7,7′-Ethane-1,2-diylbis(8-chlorobicyclo[4.2.0]oct-7-ene) (**16**).* Two isomers, A:B 1:1. Yield 0.18 g (29%), colorless liquid, R_f 0.7 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.36–1.48 (m, 12H, CH_2, cy–Hex), 1.48–1.62 (m, 12H, CH_2, cy–Hex), 1.62–1.73 (m, 8H, CH_2, cy–Hex), 2.14–2.25 (m, 4H, CH_2, 2CH_2, A+B), 2.29–2.40 (m, 4H, 2CH_2, A+B), 2.75–2.80 (m, 4H, 4CH, A+B), 2.89–2.95 (m, 4H, 4CH, A+B). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 17.9 ($^1J_{CH}$ 127, 4CH_2), 18.2 ($^1J_{CH}$ 127, 2CH_2), 18.3 ($^1J_{CH}$ 127, 2CH_2), 22.1 ($^1J_{CH}$ 127, 4CH_2), 23.0 ($^1J_{CH}$ 126, 2CH_2), 23.0 ($^1J_{CH}$ 127, 2CH_2), 23.5 ($^1J_{CH}$ 130, 2CH_2), 23.6 ($^1J_{CH}$ 128, 2CH_2), 38.5 ($^1J_{CH}$ 143, 2CH), 38.7 ($^1J_{CH}$ 143,

† The weak ^{13}C signals of C═C fragment were not found for minor isomer C.

2CH), 44.3 ($^1J_{CH}$ 143, 4CH), 123.6 (2C=), 123.7 (2C=), 144.9 (2CCl), 145.1 (2CCl). HRMS (TOF ESI$^+$): $[M{-}Cl]^+$ calcd for $C_{18}H_{24}{}^{35}Cl$ 275.1567, found 275.1544.

Two isomers, A:B 1:1. Yield 0.24 g (33%), colorless oil, R_f 0.7 (petroleum ether). IR (film): ν 2994, 2945, 2867, 1670, 1530, 1471, 1452, 1360, 1119, 1028, 960, 719, 622 cm^{-1}. ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.25–1.87 (m, 24H, A+24H, B), 2.10–2.19 (m, 2H, A+2H, B), 2.23–2.35 (m, 2H, A+2H, B), 2.58–2.64 (m, 2H, A+2H, B), 2.73–2.78 (m, 2H, A+2H, B). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 22.5 ($^1J_{CH}$ 124, 4CH_2), 22.7 ($^1J_{CH}$ 125, 4CH_2), 25.0 ($^1J_{CH}$ 124, 4CH_2), 25.9 ($^1J_{CH}$ 124, 4CH_2), 26.3 ($^1J_{CH}$ 126, 4CH_2), 29.7 ($^1J_{CH}$ 124, 4CH_2), 30.0 ($^1J_{CH}$ 123, 4CH_2), 45.4 ($^1J_{CH}$ 139, 2CH), 45.7 ($^1J_{CH}$ 139, 2CH), 51.0 ($^1J_{CH}$ 137, 4CH), 123.8 (2C=), 123.9 (2C=), 143.5 (2CCl), 143.7 (2CCl). MS (EI, 70 eV) m/z: 370 (1), 368 (3), 366 (5) [M$^+$], 334 (2), 332 (6) [M−Cl$^+$], 333 (7), 331 (21) [M−Cl−H$^+$], 295 (10), 235 (8), 199 (9), 185 (9), 181 (9), 161 (8), 147 (26), 145 (14), 131 (15), 129 (14), 127 (13), 119 (29), 117 (19), 115 (17), 105 (51), 93 (28), 91 (100), 81 (26), 67 (45), 65 (21), 55 (24). HRMS (TOF APCI$^+$): $[M]^+$ calcd for $C_{22}H_{32}{}^{35}Cl_2$ 366.1881. Found 366.1860.

*3.3.7. 1-(1-Bromocyclopropyl)-2-chlorocyclobutene (**18a**).* Yield 0.18 g (25%), colorless liquid, R_f 0.6 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.25–1.29 (m, 2H, CH_2, cy−Pr), 1.31–1.35 (m, 2H, CH_2, cy−Pr), 2.43–2.46 (m, 2H, CH_2, cy−Bu), 2.54–2.57 (m, 2H, CH_2, cy−Bu). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 16.5 ($^1J_{CH}$ 166, 2CH_2, cy−Pr), 25.1 (CBr), 27.9 ($^1J_{CH}$ 142, CH_2, cy−Bu), 32.5 ($^1J_{CH}$ 143, CH_2, cy−Bu), 120.1 (C=), 142.0 (CCl=). MS (EI, 70 eV) m/z: 210 (2), 208 (11), 206 (10) [M$^+$], 129 (14), 127 (51) [M−Br$^+$], 92 (24), 91 (100), 65 (23), 63 (9), 51 (12), 49 (10). HRMS (TOF ESI$^-$): $[M]^+$ calcd for $C_7H_8Br^{35}Cl$ 205.9498, found 205.9502.

*3.3.8. 1-(1-Bromocyclopropyl)-2-methylcyclobutene (**19**).* Yield 0.19 g (26%), colorless liquid, R_f 0.7 (petroleum ether). ^{1}H NMR (400.1 MHz, $CDCl_3$) δ: 1.07–1.10 (m, 2H, CH_2, cy−Pr), 1.21–1.25 (m, 2H, CH_2, cy−Pr), 1.79 (s, 3H, CH_3), 2.19–2.22 (m, 2H, CH_2, cy−Bu), 2.29–2.33 (m, 2H, CH_2, cy−Bu). ^{13}C NMR (100.6 MHz, $CDCl_3$) δ: 14.6 ($^1J_{CH}$ 126, CH_3), 16.1 ($^1J_{CH}$ 165, 2CH_2, cy−Pr), 27.0 ($^1J_{CH}$ 138, CH_2, cy−Bu), 27.9 (CBr), 28.6 ($^1J_{CH}$ 138, CH_2, cy−Bu), 139.1 (C=), 139.8 (C=). Anal. Calcd for $C_8H_{11}Br$: C 51.36, H 5.93%. Found: C 51.18, H 6.08%.

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