1-Methyl-1-azacyclohexa-2,3-diene(*N*−*B*)borane − Generation and Interception of an Unsymmetrical Isodihydropyridine[‡]

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Dedicated to Professor Siegfried Hünig on the occasion of his 80th birthday

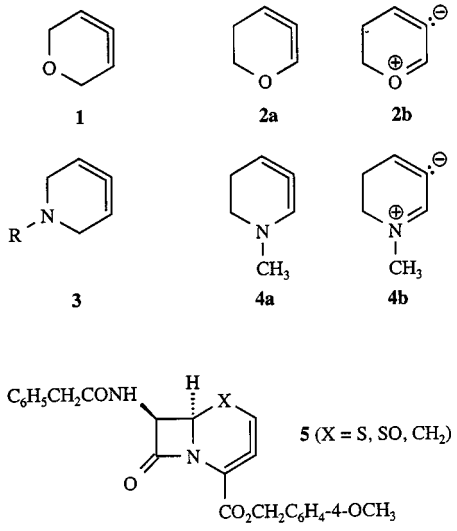
Keywords: Allenes / Amines / Boranes / Cycloadditions / Eliminations / Strained molecules

3-Bromo-1-methyl-1,2,5,6-tetrahydropyridine(*N*–*B*)borane (**7**) was prepared from 3-bromopyridine by conversion to 3-bromo-1-methylpyridinium iodide, hydrogenation of the latter with sodium tetrahydroborate and treatment of the resulting 3-bromo-1-methyl-1,2,5,6-tetrahydropyridine (**6**) with borane–dimethyl sulfide. Whereas no trapping product of the possible intermediate 1-methyl-1-azacyclohexa-2,3-diene (**4**) could be observed on treatment of **6** with potassium *tert*-butoxide in the presence of furan, the subjection of **7** to the same conditions produced the hexahydroepoxyquinoline derivatives **8a**–**c**. Treatment of **7**, dissolved in styrene, with sodium bis(trimethylsilyl)amide furnished the hexahydrocyclobutapyridine derivatives **9a**–**c**. The six-membered cycloallene 1-methyl-1-azacyclohexa-2,3-diene(*N*–*B*)borane (**10**) must be regarded as the key intermediate en route to **8** and **9**.

Introduction

Cyclohexa-1,2-diene and a number of its derivatives are extremely short-lived intermediates.[1−3] Stable compounds result only if several atoms of a second-row element of the Periodic Table, such as silicon[4] or phosphorous,[5] are members of the tether connecting the allene termini. Our contributions to the field of six-membered cycloallenes have the principal goal of trapping species with a fleeting existence with activated olefins, thus giving cycloadducts; their main results have been summarized in two reviews.[1,2] In two more recent studies, we have investigated reactions undergone by cyclohexa-1,2,4-triene[6] and 3δ²-1*H*-naphthalene[7] in addition to cycloadditions with activated olefins.[8]

The symmetrical (**1**)[9] and the unsymmetrical isopyran (**2**)[10−12] (Scheme 1) have been generated and characterised by trapping products. Derivatives **3** (R = aryl, alkyl) of the symmetrical isodihydropyridine are accessible from 6,6-dibromo-3-azabicyclo[3.1.0]hexanes and amenable to interception by styrene, buta-1,3-diene, furan, cyclopenta-1,3-diene, and cyclohexa-1,3-diene.[13] The first unsymmetrical isodihydropyridines were discovered accidentally in studies designed for the preparation of new cephalosporins. The unexpected products obtained suggested the intermediacy of **5** (X = S) (Scheme 1), while the cycloallenes **5** (X = SO, CH_2) were subsequently also generated and trapped.[14] The ease of the liberation of the species **5** and the high efficiency of their interception even by nonactivated olefins and acetylenes are astonishing and extremely useful for preparative purposes. However, the aminoallene subunits of **5** are subject to strong electronic effects arising from the acyl group at the nitrogen atom and the carboxylate functionality at the adjacent allene carbon atom. We therefore performed a study to test for the existence of 1-methyl-1-azacyclohexa-2,3-diene (**4**) (Scheme 1), in which the lone pair of the nitrogen atom can fully interact with the electrons of the allene group. Thus, the zwitterionic structure **4b** has to be considered as well as the allene structure **4a**. In the case of the



Scheme 1

[‡] Cycloallenes, 16. − Part 15: Ref.[7]

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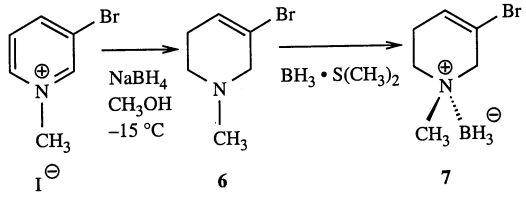
unsymmetrical isopyran, a contribution of the polar structure **2b** to the most probable ground state **2a** has been invoked to explain the site of attack of nucleophiles.[15]

Results

Both the Doering–Moore–Skattebøl method[11] and the β-elimination route[10,12] are suitable for the generation of the unsymmetrical isopyran (**2**). To access **4**, we chose the latter technique, because the necessary precursor – 3-bromo-1-methyl-1,2,5,6-tetrahydropyridine (**6**) – could readily be synthesised (Scheme 2). In analogy to the preparation of 1-methyl-1,2,5,6-tetrahydropyridine,[16] we hydrogenated 3-bromo-1-methylpyridinium iodide with sodium tetrahydroborate in anhydrous methanol and obtained **6** in 70% yield.

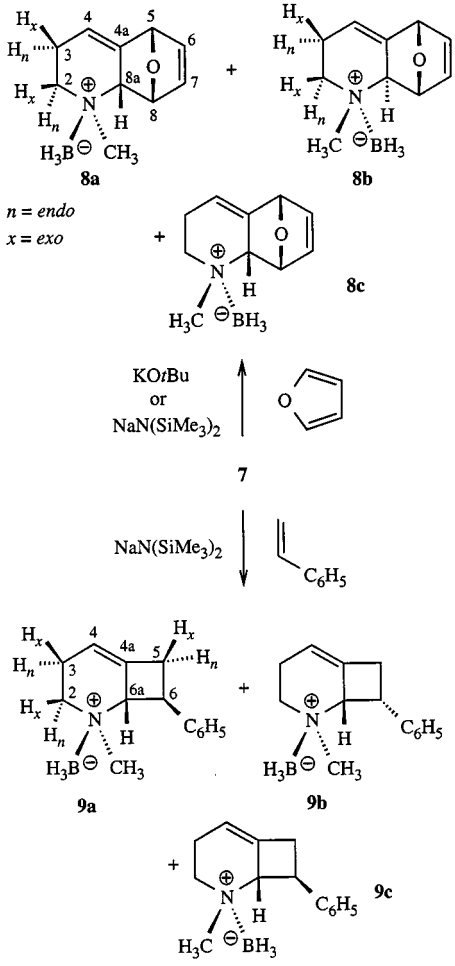


Scheme 2

Treatment of **6** with potassium *tert*-butoxide (KO*t*Bu) in the presence of furan or styrene was of no avail, however. On one hand, the base alone did not react with **6** and, on the other, when [18]crown-6 was added to the mixtures to enhance the reactivity of KO*t*Bu, **6** was indeed consumed completely, but no product attributable to the intermediacy of the target **4** could be detected.

A remarkable coincidence made us persevere in our efforts. The first experiments for the preparation of **6** provided mixtures of the desired product with a second one, which exhibited a ^{13}C NMR spectrum closely related to that of **6**, but the ^{1}H NMR spectrum of which indicated diastereotopic methylene protons. When such a mixture, dissolved in furan, was exposed to KO*t*Bu, a compound apparently resulting from the cycloaddition of **4** to furan was isolated (and eventually identified as **8a**). Our proposal that, in addition to **6**, its borane adduct **7** might have been formed in the reaction between the bromopyridinium salt and sodium tetrahydroborate was corroborated by treatment of **6** with borane–dimethyl sulfide, giving rise to **7** in 94% yield (Scheme 2).

Indeed, compound **7** reacted rather readily with KO*t*Bu in the presence of furan, providing the hexahydroepoxyquinolines **8a–c** (Scheme 3), although the yield turned out to be only 13%. On replacement of KO*t*Bu by sodium bis(trimethylsilyl)amide [$NaN(SiMe_3)_2$], the yield increased to 20%, with the ratio of **8a/8b/8c** being about 3:2:1. When styrene was used instead of furan, with $NaN(SiMe_3)_2$ as base, the hexahydrocyclobutapyridines **9a–c** (Scheme 3) were obtained in 30% yield in a ratio of ca. 6:2:1. The higher yield with styrene was to have been anticipated on the basis of results of Bottini et al.,[17] who, in competition experiments, found styrene to be 14 times as reactive as furan towards cyclohexa-1,2-diene.



Scheme 3

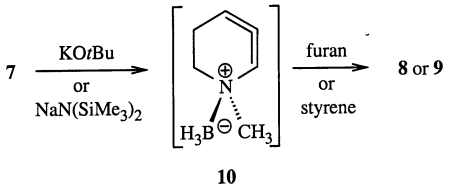
The structures of the products were established by X-ray diffraction of the major components of the mixtures (**8a**[18] and **9a**[19]). As to the configuration of the ring junction in the compounds **8** and the arrangement of the phenyl group in the compounds **9**, it was possible to apply ^{1}H NMR spectral criteria that had been advanced in previous papers of this series. Thus, the tetrahydropyridine moiety had to be annulated *endo* in the least abundant furan adduct (**8c**), as in **8a**, because of the similarity of the coupling constants $J_{8,8a}$ = 3.6 and 4.0 Hz, respectively, whereas in the third product (**8b**) the *exo* annulation was indicated by $J_{8,8a}$ = 0.9 Hz. The orientations of the methyl and the borane groups in **8b** were determined by an NOESY experiment. Because of the coupling constant $J_{5n,6}$ = 8.8 Hz, the least abundant styrene adduct (**9c**) had to bear the phenyl group in the same position (*exo*-6) as in **9a** ($J_{5n,6}$ = 9.0 Hz). In consequence, the only difference between these diastereomers had to reside in the locations of the methyl and the borane group. In the third product (**9b**), the phenyl group occupies the *endo*-6 position, as attested by the coupling constant $J_{5n,6}$ = 3.0 Hz. That the methyl singlet of this product appears at an unusually high field position of δ =

1.69, in comparison with the corresponding values in **9a** and **9c** (δ = 2.52, 2.47), is evidence for the *endo* orientation of this group and its subjection to the anisotropic effect of the phenyl group.

Employing a number of different reagents, we tried to remove the borane moiety from the compounds **8** and **9**, but obtained only multicomponent mixtures, which did not encourage attempts to isolate a pure compound. In search of precursors of cycloadducts related to **8** that might be more efficient than the amine−borane compound **7**, we have prepared complexes of tetrahydropyridine **6** with boron trifluoride, tris(pentafluorophenyl)borane and sulfur trioxide. None of these compounds, however, gave a product like **8** on treatment with KO*t*Bu in the presence of furan.

Discussion

The isolation of the amine−borane compounds **8** and **9** testifies that the key intermediate is not the desired cycloallene **4** but its borane complex **10** (Scheme 4). The resistance of the N−B bond to cleavage under the rather drastic reaction conditions came as a surprise to us. Further evidence for the strength of this bond is to be found in our unsuccessful attempts to remove the borane group from **8** and **9** to obtain the free tertiary amines, which would be formal cycloadducts of **4**.

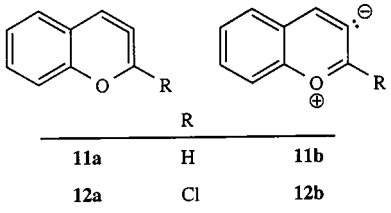


Scheme 4

Whereas **7** underwent β-elimination of hydrogen bromide with KO*t*Bu in the absence of [18]crown-6, **6** was unreactive under these conditions. Thus, complexation by BH_3 enhances the acidity of the 2-CH_2 group of the 3-bromo-1,2,5,6-tetrahydropyridine system. This finding, discovered by chance, is in agreement with the recently described[20] activation of tertiary amines towards deprotonation by complexation with Lewis acids such as BH_3 and BF_3, developed into a useful tool for electrophilic α-substitution.[21]

As to the intermediate **4**, the key question is why we did not observe one of its cycloadducts on treatment of **6** with KO*t*Bu in the presence of [18]crown-6 and furan. The activation of KO*t*Bu by [18]crown-6 has already been utilised for the generation of cycloallenes, such as **2**,[10] cyclohexa-1,2,4-triene[6] and 3δ^2-1*H*-naphthalene.[7] In two[7,10] out of the of three cases, cycloadducts of the intermediates with activated olefins were isolated, which inclines us to assume that we would have detected furan adducts of **4** had they been formed. The lack of such products most probably has its origin in the nature of **4**, which may well be better characterised as the dipole **4b** rather than as the allene structure **4a**. At any rate, even if it is only the transition state of the enantiomerisation of **4a**, **4b** should be very close in energy to **4a**. In consequence, **4** might be trapped by KO*t*Bu more rapidly than by furan, and this would occur preferentially in positions 2 and/or 4, with the formation of an N,O-acetal and a vinylogous N,O-acetal, respectively. These products may have decomposed or may have been lost during the workup.

These speculations regarding **4** are based on the known behaviour of six-membered cycloallenes towards nucleophiles. Nonpolar ones such as cyclohexa-1,2-diene,[1] 3δ^2-1*H*-naphthalene[7] and its 1,1-dimethyl derivative,[1] together with **1**[9] and **3**,[13a] are attacked by nucleophiles exclusively at the central allene carbon atom. In contrast, the unsymmetrical isopyran (**2**) is known to react with nucleophiles in positions 2, 3, and 4,[10b,12] although it affords good yields of cycloadducts with activated olefins even in the presence of nucleophiles.[10,11] The interactions with nucleophiles in positions 2 and 4 have been interpreted as a manifestation of polar character in **2**, corresponding to the electron distribution of **2b**.[15] 3δ^2-Chromene (**11**) should even be more polar, since the dipole **11b** can take advantage of the aromatic stabilisation of the benzopyrylium ion (Scheme 5). The high yield (79%) of the acetal formed in the reaction between KO*t*Bu and **11**, in which position 2 is attacked exclusively, is in line with this assumption. However, if furan or styrene is present, **11** preferentially undergoes a cycloaddition.[15] An experimental and theoretical study of 2-chloro-3δ^2-chromene (**12**) (Scheme 5) has recently been published.[3] This species was observed directly in a matrix at 35 K and gave the 2-chlorobenzopyrylium ion on reaction with hydrogen chloride, which is in agreement with the properties of the dipole **12b**. Quantum chemical calculations gave an energy difference of 2.5 kcal/mol between **12a** and **12b**, with **12b** being the transition state for the enantiomerisation of **12a** in the gas phase.

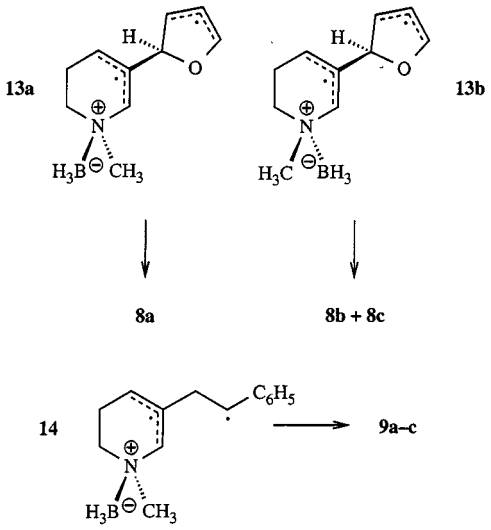


Scheme 5

Since a nitrogen atom is a better electron donor than an oxygen atom, the polar character of **4** as represented by **4b** should be greater than that of **2** as **2b**. It is thus to be expected that **4** should display higher reactivity than **2** toward nucleophiles, with the possible consequence that **4** might not undergo cycloadditions with activated olefins in the presence of strong nucleophiles.

With no lone pair on the nitrogen atom, the borane complex **10** of **4** cannot be polarised in a zwitterionic structure fashion. Compound **10** should therefore be considered as a real allene, like cyclohexa-1,2-diene.[1] It has recently been suggested that even [4+2] cycloadditions of the latter pro-

ceed stepwise through diradical intermediates, on the basis of a convincing theoretical investigation.[22] Analogously, the possible presence of diradicals **13** and **14**, respectively, should be taken into account en route to **8** and **9** (Scheme 6).



Scheme 6

The astounding feature of **13** and **14** appears to be their highly regioselective ring closure to furnish **8** and **9**. However, we refrain from an interpretation in view of the rather low yields of the products, since at present we cannot exclude the possibility that regioisomers of **8** and **9** are labile compounds, which would not have survived the workup.

In conclusion, we have presented evidence for the existence of the 1-azacyclohexa-2,3-diene derivative **10**. On the other hand, the nitrogen atom of **10** does not possess a lone pair, due to the presence of the borane group. Therefore, unambiguous proof of an electronically genuine 1-azacyclohexa-2,3-diene, in which complete interaction between the lone pair of the nitrogen atom and the allene subunit is operative, as in **4**, must await further investigations.

Experimental Section

Instrumentation: ^{1}H and ^{13}C NMR: Bruker AC 200, AC 250, Avance 400, DMX 600. − ^{11}B NMR: Bruker Avance 400. − IR: Perkin−Elmer 1605 FT-IR spectrometer. − MS: Finnigan MAT 8200, MAT 90. − Elemental analyses: LECO CHNS 932 Elemental Analyzer. − Melting points: Kofler hot stage from C. Reichert, Optische Werke A.G., Wien, Austria.

3-Bromo-1-methylpyridinium Iodide: Methyl iodide (67.4 g, 475 mmol) was added to a solution of 3-bromopyridine (25.0 g, 158 mmol) in anhydrous acetone (50 mL). The flask was sealed and the mixture was stirred at room temperature for 6 d. The precipitate was then collected by filtration, washed with light petroleum ether (b.p. 30−50 °C) and dried to give the product (46.6 g, 98%) as a cream-coloured powder, m.p. 155 °C (159.1−159.9 °C[23]), which was used without further purification. − ^{1}H NMR [200 MHz, $(CD_3)_2SO$]: δ = 4.37 (s, 3 H, CH_3), 8.13 (dd, $J_{4,5}$ = 8.6, $J_{5,6}$ = 6.1 Hz, 1 H, 5-H), 8.85 (br. d, $J_{4,5}$ = 8.6 Hz, 1 H, 4-H), 9.06 (d, $J_{5,6}$ = 6.1 Hz, 1 H, 6-H), 9.46 (br. s, 1 H, 2-H). − ^{13}C NMR [63 MHz, $(CD_3)_2SO$]: δ = 48.1, 121.5, 128.5, 144.0, 146.1, 147.5.

3-Bromo-1-methyl-1,2,5,6-tetrahydropyridine (6): Solid sodium tetrahydroborate (1.30 g, 34.4 mmol) was added in small portions to a stirred suspension of 3-bromo-1-methylpyridinium iodide (10.0 g, 33.3 mmol) in anhydrous methanol (50 mL), kept under nitrogen and cooled to −15 °C, in such a way that the temperature did not exceed −10 °C. After continued stirring at −15 °C for 30 min, the mixture was allowed to warm to 0 °C, and then treated with ice/water (50 mL) and extracted with diethyl ether (3 × 100 mL). The combined organic layers were dried with $MgSO_4$ and concentrated in vacuo. From the residue, analytically pure **6** (2.60 g, 44%) was obtained as a colourless liquid by distillation at 58 °C/6 mbar. Alternatively, crude **6** was purified by filtration through basic Al_2O_3 (activity IV) with diethyl ether to give 4.10 g (70%) of **6** of purity sufficient for the next step. − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.24 (pseudo tdt, line distances 5.4, 4.0, and 2.8 Hz, 2 H, 5-H), 2.36 (s, 3 H, CH_3), 2.55 (pseudo t, line distance 5.4 Hz, 2 H, 6-H), 3.14 (pseudo td, line distances 2.8 and 1.8 Hz, 2 H, 2-H), 6.06 (tt, $J_{4,5}$ = 4.0, $J_{2,4}$ = 1.8 Hz, 1 H, 4-H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 27.5 (t, C-5), 44.8 (q, CH_3), 50.3 (t, C-6), 60.9 (t, C-2), 118.1 (s, C-3), 126.2 (d, C-4). − IR (film): $\tilde{\nu}$ = 2970 cm^{-1}, 2940, 2842, 2786, 2738, 2704, 1657, 1459, 1376, 1336, 1285, 1254, 1198, 1186, 1141, 1127, 1070, 1043, 997, 972, 950, 893, 798, 763. − MS (EI, 70 eV): *m/z* (%) = 177 (13) and 175 (13) [M^+], 96 (61), 94 (24), 81 (13), 53 (44), 51 (16), 50 (12), 44 (22), 43 (79), 42 (100), 41 (19), 40 (11), 39 (24), 38 (13). − $C_6H_{10}BrN$ (176.1): calcd. C 40.93, H 5.73, N 7.96; found C 40.72, H 5.75, N 7.96.

3-Bromo-1-methyl-1,2,5,6-tetrahydropyridine(*N*−*B*)borane (7): Borane−dimethyl sulfide (18.0 mmol, 1.8 mL, 10 M in dimethyl sulfide) was added under nitrogen to a stirred solution of **6** (2.84 g, 16.1 mmol), over 20 min at room temperature. Stirring was continued at that temperature for 2 h, after which the mixture was treated with 2 mL of saturated aqueous $NaHCO_3$ and stirred until gas formation could no longer be observed (ca. 30 min). The layers were then separated and the aqueous one was extracted with diethyl ether (3 × 5 mL). After the combined organic layers had been dried with $MgSO_4$, they were concentrated in vacuo to give **7** (2.86 g, 94%) as a cloudy, colourless oil. − ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.65 (very br. q, $J_{H,B} \approx$ 100 Hz, BH_3), 2.34 (m, 2 H, 5-H), 2.62 (s, 3 H, CH_3), 2.95−3.04 (m, 2 H, 6-H), 3.33 (br. d, $J_{2,2}$ = 17.4 Hz, 1 H, 2-H), 3.78 (dq, $J_{2,2}$ = 17.4 Hz, average of $J_{2,4}$ and $J_{2,5}$ = 2.8 Hz, 1 H, 2-H), 6.19 (tdd, $J_{4,5}$ = 4.0, $J_{2,4}$ = 2.4 and 1.2 Hz, 4-H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 23.8 (t, C-5), 47.4 (q, CH_3), 54.5 (t, C-6), 63.7 (t, C-2), 114.7 (s, C-3), 125.3 (d, C-4). − IR (film): $\tilde{\nu}$ = 2954 cm^{-1}, 2369, 2310, 2270, 1656, 1465, 1450, 1430, 1415, 1340, 1179, 1164, 1108, 1099, 1018, 1006, 846, 826, 759. − MS (EI, 70 eV): *m/z* (%) = 190 (39) and 188 (50) [$M^+ - H$], 177 (24) and 175 (27) [$M^+ - BH_3$], 162 (21), 161 (24), 160 (30), 159 (23), 136 (77), 134 (83), 110 (20), 108 (38), 96 (42), 94 (22), 82 (50), 80 (46), 69 (22), 67 (21), 56 (100), 55 (36), 54 (24), 53 (41), 43 (31), 42 (42), 41 (37), 40 (27), 39 (38). − $C_6H_{13}BBrN$ (189.9): calcd. C 37.95, H 6.90, N 7.37; found C 37.77, H 6.78, N 7.51.

(1α,5β,8β,8aβ)-, (1α,5α,8α,8aβ)-, and (1α,5α,8α,8aα)-1-Methyl-1,2,3,5,8,8a-hexahydro-5,8-epoxyquinoline(*N*−*B*)borane (8a, 8b, and 8c)

a) Treatment of 7 with KO*t*Bu in the Presence of Furan: KO*t*Bu (1.33 g, 11.9 mmol) was added under nitrogen to a solution of **7** (667 mg, 3.51 mmol) in furan (10 mL). The mixture was stirred at 25 °C for 24 h and then cautiously treated with water (4 mL). After separation of the layers and extraction of the aqueous layer with

diethyl ether (3 × 40 mL), the combined organic layers were dried with $MgSO_4$ and concentrated in vacuo. The residue was purified by flash chromatography [SiO_2, light petroleum ether (b.p. 30−50 °C)/diethyl ether, 2:1] to give, in order of elution, **8b** (16 mg, 3%) as a yellowish oil and **8a** (60 mg, 10%) as yellowish crystals with m.p. 95−98 °C. In one experiment, **8a** was contaminated with ca. 3% of **8c**.

8a: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.72 (very br. q, $J_{B,H}$ = 96 Hz, 3 H, BH_3), 2.03 (s, 3 H, CH_3), 2.08 (dddt, $J_{3,3}$ = 18.6, $J_{2x,3n}$ = 12.0, $J_{2n,3n}$ = 6.8, average of $J_{3n,4}$ and $J_{3n,8a}$ = 3.0 Hz, 1 H, 3-H_n), 2.21 (ddt, $J_{3,3}$ = 18.6, $J_{2x,3x}$ = 6.1, average of $J_{3x,4}$ and $J_{3x,8a}$ = 2.9 Hz, 1 H, 3-H_x), 2.95 (dd, $J_{2,2}$ = 13.8, $J_{2n,3n}$ = 6.8 Hz, 1 H, 2-H_n), 3.08 (ddd, $J_{2,2}$ = 13.8, $J_{2x,3n}$ = 12.0, $J_{2x,3x}$ = 6.1, 1 H, 2-H_x), 3.92 (dq, $J_{8a,8}$ = 4.0, average of $J_{3n,8a}$, $J_{3x,8a}$ and $J_{4,8a}$ = 2.5 Hz, 1 H, 8a-H), 5.14 (br. s, 1 H, 5-H), 5.33 (br. d, $J_{8,8a}$ = 4.0 Hz, 1 H, 8-H), 5.65 (br. q, average of $J_{3n,4}$ and $J_{3x,4}$ and $J_{4,8a}$ = 3.0 Hz, 1 H, 4-H), 6.18 (dd, $J_{6,7}$ = 5.7, $J_{7,8}$ = 1.6 Hz, 1 H, 7-H), 6.42 (dd, $J_{6,7}$ = 5.7, $J_{5,6}$ = 2.0, 1 H, 6-H); the assignment is supported by an NOESY experiment [interactions inter alia between the following signal pairs: 1.72 (BH_3)−3.92 (8a-H), 1.72 (BH_3)−5.33 (8-H), 2.03 (CH_3)−6.18 (7-H), 2.03 (CH_3)− 6.42 (6-H), 3.08 (2-H_x)−3.92 (8a-H), 5.14 (5-H)−6.42 (6-H), 5.33 (8-H)−6.18 (7-H)]. − ^{13}C NMR (63 MHz, $CDCl_3$): δ = 21.6 (C-3), 39.7 (CH_3), 59.2 (C-2), 66.1 (C-8a), 78.7 (C-8), 80.6 (C-5), 114.2 (C-4), 130.2 (C-7), 132.8 (C-4a), 135.3 (C-6); the assignment is based on a C,H COSY spectrum. − ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −9.3 (q, $J_{B,H}$ ≈ 96 Hz). − IR (KBr): $\tilde{\nu}$ = 2957 cm^{-1}, 2928, 2364, 2313, 2269, 1468, 1460, 1452, 1424, 1378, 1305, 1261, 1170, 1158, 1124, 1105, 1080, 1042, 1019, 1007, 883, 835, 816, 735. − MS (EI, 70 eV): *m*/*z* (%) = 177 (5) [M^+], 176 (31), 146 (21), 134 (100), 105 (31), 94 (25), 93 (22), 91 (50), 82 (23), 81 (23), 79 (27), 77 (39), 72 (21), 65 (25), 56 (61), 55 (23), 51 (26), 44 (34), 42 (66), 41 (29), 39 (45). − $C_{10}H_{16}BNO$ (177.1): calcd. C 67.84, H 9.11, N 7.91; found C 67.58, H 8.99, N 7.54.

8b: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.70 (very br. q, $J_{B,H}$ ≈ 96 Hz, 3 H, BH_3), 2.245 (“ddtd”, $J_{3,3}$ = 18.9, $J_{2n,3n}$ = 6.6, $J_{3n,4}$ and $J_{3n,8a}$ = 3.2 and 2.1, $J_{2x,3n}$ = 0.9 Hz, 1 H, 3-H_n), 2.275 (“ddddd”, $J_{3,3}$ = 18.9, $J_{2n,3x}$ = 11.0, $J_{2x,3x}$ = 7.1, $J_{3x,4}$ and $J_{3x,8a}$ = 3.8, 2.0 Hz, 1 H, 3-H_x), 2.36 (s, 3 H, CH_3), 3.068 (“ddd”, $J_{2,2}$ = 14.3, $J_{2n,3x}$ = 11.0, $J_{2n,3n}$ = 6.6 Hz, 1 H, 2-H_n), 3.093 (“ddd”, $J_{2,2}$ = 14.3, $J_{2x,3x}$ = 7.1, $J_{2x,3n}$ = 0.9 Hz, 1 H, 2-H_x), 3.24 (br. q, average of $J_{3n,8a}$, $J_{3x,8a}$ and $J_{4,8a}$ = 2.0 Hz, 1 H, 8a-H), 5.08 (br. s, 1 H, 5-H), 5.35 (dt, $J_{7,8}$ = 1.9, $J_{5,8}$ = $J_{8,8a}$ = 0.9 Hz, 1 H, 8-H), 5.92 (br. q, average of $J_{3n,4}$, $J_{3x,4}$ and $J_{4,8a}$ = 2.9 Hz, 1 H, 4-H), 6.43 (dd, $J_{6,7}$ = 5.8, $J_{5,6}$ = 1.6 Hz, 1 H, 6-H), 6.57 (dd, $J_{6,7}$ = 5.8, $J_{7,8}$ = 1.9 Hz, 1 H, 7-H); the assignment is supported by an NOESY experiment [interactions inter alia between the following signal pairs: 1.70 (BH_3)−3.24 (8a-H), 3.24 (8a-H)−5.35 (8-H), 3.24 (8a-H)−6.57 (7-H), 5.08 (5-H)−6.43 (6-H), 5.35 (8-H)−6.57 (7-H)]; the parameters of 2-H_n, 2-H_x, 3-H_n, and 3-H_x, which give a higher order spectrum, were obtained by simulation. − ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.6 (C-3), 39.6 (CH_3), 57.8 (C-2), 67.4 (C-8a), 78.5 (C-8), 80.5 (C-5), 117.3 (C-4), 130.1 (C-4a), 134.6 (C-6), 136.5 (C-7); the assignment is based on a C,H COSY spectrum. − ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −9.9 (q, $J_{B,H}$ ≈ 96 Hz). − MS (EI, 70 eV): *m*/*z* (%) = 177 (7) [M^+], 176 (43), 146 (29), 134 (100), 105 (25), 104 (28), 91 (36), 77 (27), 73 (21), 57 (30), 56 (51), 42 (34), 41 (21), 39 (22). − HRMS ([M^+ − H] $C_{10}H_{15}BNO$): calcd. 176.1247; found 176.1246.

8c: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.54 (dddt, $J_{3,3}$ = 18.0, $J_{2x,3n}$ = 11.6, $J_{2n,3n}$ = 6.0, average of $J_{3n,4}$ and $J_{3n,8a}$ = 3.0 Hz, 1 H, 3-H_n), 2.67 (td, $J_{2,2}$ = $J_{2x,3n}$ = 11.6, $J_{2x,3x}$ = 4.8 Hz, 1 H, 2-H_x), 2.78 (s, 3 H, CH_3), 3.48 (br. quint, average of $J_{3n,8a}$, $J_{3x,8a}$, $J_{4,8a}$ and $J_{8,8a}$ = 2.8 Hz, 1 H, 8a-H), 5.08 (br. d, $J_{8,8a}$ = 3.6 Hz, 1 H, 8-H), 5.13 (br. s, 1 H, 5-H), 5.61 (br. q, average of $J_{3n,4}$, $J_{3x,4}$ and $J_{4,8a}$ = 2.8 Hz, 1 H, 4-H), 6.32 (dd, $J_{6,7}$ = 5.6, J = 1.8 Hz, 1 H) and 6.39 (dd, $J_{6,7}$ = 5.6, J = 1.3 Hz, 1 H) (6-H, 7-H); the signals of 2-H_n, 3-H_x, and the BH_3 group are superimposed by signals of **8a**. − ^{13}C NMR (63 MHz, $CDCl_3$): δ = 24.0 (C-3), 55.0 (CH_3), 61.3 (C-2), 68.3 (C-8a), 78.6 and 80.9 (C-5, C-8), 114.5 (C-4), 131.2 and 133.1 (C-6, C-7); being of too low intensity or superimposed by a signal of **8a**, the line of C-4a was not observed. − ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −15.7 (q, $J_{B,H}$ ≈ 96 Hz).

b) Treatment of 7 with $NaN(SiMe_3)_2$ in the Presence of Furan: $NaN(SiMe_3)_2$ (2.00 g, 10.9 mmol) was added in several portions, under nitrogen, to a stirred solution of **7** (500 mg, 2.63 mmol) in furan (30 mL) at room temperature, over a period of 3 d. Stirring was continued for 4 d and the workup was then conducted as in procedure a) to give **8b** (34 mg, 7%) as a yellowish oil and a 3:1 mixture of **8a** and **8c** (60 mg, 13%) as a highly viscous yellowish oil. Dissolved in $CDCl_3$ (NMR sample), **8c** decomposed over several weeks at room temperature, whereas **8a** was unchanged.

1α,6β,6aβ-, 1α,6α,6aβ-, and 1α,6α,6aα-1-Methyl-6-phenyl-1,2,3,5,6,6a-hexahydrocyclobuta[*b*]pyridine(*N*−*B*)borane (9a, 9b, and 9c): $NaN(SiMe_3)_2$ (5.78 g, 31.5 mmol) was added under nitrogen to a stirred solution of **7** (1.50 mg, 7.90 mmol) in styrene (25 mL) at room temperature. The mixture was stirred for 3 d and then cautiously treated with water (5 mL). After separation of the layers and extraction of the aqueous one with diethyl ether (3 × 40 mL), the combined organic fractions were dried with $MgSO_4$ and concentrated in vacuo. The residue was purified by flash chromatography [SiO_2, light petroleum ether (b.p. 30−50 °C)/diethyl ether, 5:1] to give, in order of elution, **9c** (10 mg, 1%) as a colourless solid with m.p. 73−75 °C, followed by a 4:1 mixture of **9c** and **9b** (51 mg, 3%), a 1:3 mixture of **9c** and **9b** (101 mg, 6%), a 1:2 mixture of **9b** and **9a** (103 mg, 6%), and **9a** (230 mg, 14%), each as a yellowish oil. On treatment with dichloromethane/cyclohexane, the last fraction gave **9a** as beige needles with m.p. 104 °C.

9a: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.65 (very broad, BH_3), 2.18 (dm, $J_{3,3}$ = 18.5 Hz, 1 H, 3-H_x), 2.28 (dm, $J_{3,3}$ = 18.5 Hz, 1 H, 3-H_n), 2.52 (s, 3 H, CH_3), 2.71 (m, 1 H, 5-H_x), 3.02 (dddq, $J_{5,5}$ = 14.0, $J_{5n,6}$ = 9.0, $J_{4,5n}$ = 2.3, average of $J_{3n,5n}$, $J_{3x,5n}$, and $J_{5n,6a}$ = 1.6 Hz, 1 H, 5-H_n), 3.06 (br. dd, $J_{2,2}$ = 13.8, $J_{2n,3n}$ = 6.3 Hz, 1 H, 2-H_n), 3.11 (ddd, $J_{2,2}$ = 13.8, $J_{2x,3n}$ = 11.6, $J_{2x,3x}$ = 5.3 Hz, 1 H, 2-H_x), 3.57 (q, average of $J_{5n,6}$, $J_{5x,6}$, and $J_{6,6a}$ = 8.7 Hz, 1 H, 6-H), 4.35 (m, 1 H, 6a-H), 5.54 (br. quint, $J_{average}$ = 2.7 Hz, 1 H, 4-H), 7.24 (tt, 1 H, *p*-H), 7.34 (m, 2 H, *m*-H), 7.45 (m, 2 H, *o*-H); the assignment is supported by an NOESY experiment [interactions inter alia between the following signal pairs: 2.28 (3-H_n)−2.52 (CH_3), 2.52 (CH_3)−3.57 (6-H), 2.71 (5-H_x)−7.45 (*o*-H), 3.11 (2-H_x)−4.35 (6a-H), 4.35 (6a-H)−7.45 (*o*-H)]. − ^{13}C NMR (151 MHz, $CDCl_3$): δ = 21.8 (C-3), 35.6 (C-5), 40.3 (CH_3), 42.0 (C-6), 57.8 (C-2), 72.3 (C-6a), 112.5 (C-4), 126.8 (*p*-C), 127.2 (*o*-C), 128.4 (*m*-C), 132.1 (C-4a), 141.1 (*i*-C); the assignment is based on a C,H COSY spectrum. − ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −9.9 (q, $J_{B,H}$ = 95 Hz). − MS (EI, 70 eV): *m*/*z* (%) = 213 (7%) [M^+], 212 (20), 199 (80), 198 (50), 141 (22), 134 (21), 129 (38), 128 (33), 120 (28), 117 (27), 115 (28), 110 (29), 109 (32), 108 (39), 107 (36), 106 (29), 104 (21), 94 (49), 92 (20), 91 (54), 82 (35), 81 (29), 80 (21), 77 (21), 56 (100), 55 (23), 42 (22). − HRMS ([M^+ − H] $C_{14}H_{19}BN$): calcd. 212.1611; found 212.1609.

9b: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.60 (very broad, BH_3), 1.69 (s, 3 H, CH_3), 2.12 (dm, $J_{3,3}$ = 18.0, 1 H, 3-H_x), 2.22 (m, 1 H, 3-H_n), 2.78 (br. dd, $J_{2,2}$ = 13.7, $J_{2n,3n}$ = 5.6 Hz, 1 H, 2-H_n), 2.93 (dm, $J_{5,5}$ = 14.3 Hz, 1 H, 5-H_n), 2.99 (ddd, $J_{2,2}$ = 13.7, $J_{2x,3n}$ = 12.0, $J_{2x,3x}$ = 5.2 Hz, 1 H, 2-H_x), 3.04 (m, 1 H, 5-H_x), 4.20 (td, $J_{5x,6}$ = $J_{6,6a}$ = 9.3, $J_{5n,6}$ = 3.3 Hz, 1 H, 6-H), 4.42 (dm, $J_{6,6a}$ = 9.3 Hz, 1 H, 6a-H), 5.57 (br. quint, $J_{average}$ = 3.0 Hz, 1 H, 4-H), 7.24 (tt, 1 H, *p*-H), 7.30 (m, 2 H, *m*-H), 7.41 (m, 2 H, *o*-H). – ^{13}C NMR (151 MHz, $CDCl_3$): δ = 21.8 (C-3), 31.7 (C-5), 41.4 (CH_3), 44.3 (C-6), 59.6 (C-2), 68.2 (C-6a), 111.8 (C-4), 127.3 (*p*-C), 128.4 (*m*-C), 129.1 (very broad, *o*-C), 135.6 and 137.7 (C-4a, *i*-C); the assignment is based on a C,H COSY spectrum. – ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −10.5 (q, $J_{B,H}$ = 97 Hz).

9c: ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.52 (very broad, BH_3), 2.13 (dm, $J_{3,3}$ = 17.5 Hz, 1 H, 3-H_x), 2.47 (s, 3 H, CH_3), 2.60 (td, $J_{2,2}$ = $J_{2x,3n}$ =11.5, $J_{2x,3x}$ = 4.5 Hz, 1 H, 2-H_x), 2.73 (m, 1 H, 3-H_n), 2.79 (m, 1 H, 5-H_x), 2.95 (dddq, $J_{5,5}$ =13.6, $J_{5n,6}$ = 8.8, $J_{4,5n}$ = 2.8, average of $J_{3n,5n}$, $J_{3x,5n}$ and $J_{5n,6a}$ = 1.4 Hz, 1 H, 5-H_n), 2.99 (br. dd, $J_{2,2}$ = 11.5, $J_{2n,3n}$ = 5.5 Hz, 1 H, 2-H_n), 3.62 (m, 1 H, 6a-H), 4.21 (q, average of $J_{5n,6}$, $J_{5x,6}$ and $J_{6,6a}$ = 8.7 Hz, 6-H), 5.50 (quint, $J_{average}$ = 2.9 Hz, 1 H, 4-H), 7.24 (tt, 1 H, *p*-H), 7.34 (m, 2 H, *m*-H), 7.39 (m, 2 H, *o*-H); the assignment is supported by an NOESY experiment [interactions inter alia between the following signal pairs: 1.52 (BH_3)−4.21 (6-H), 2.60 (2-H_x)−3.62 (6a-H), 2.79 (5-H_x)−3.62 (6a-H), 2.79 (5-H_x)−7.39 (*o*-H), 3.62 (6a-H)−7.39 (*o*-H)]. – ^{13}C NMR (151 MHz, $CDCl_3$): δ = 24.2 (C-3), 34.1 (C-5), 41.9 (C-6), 53.5 (CH_3), 59.6 (C-2), 75.2 (C-6a), 113.3 (C-4), 126.9 (*p*-C), 127.0 (*o*-C), 128.6 (*m*-C), 130.8 (C-4a), 141.8 (*i*-C); the assignment is based on a C,H COSY spectrum. – ^{11}B NMR [128 MHz, $CDCl_3$, $(C_2H_5)_2O{\cdot}BF_3$ as external reference]: δ = −15.8 (q, $J_{B,H}$ = 94 Hz). – MS (EI, 70 eV): *m/z* (%) = 213 (2) [M^+], 212 (12), 210 (19), 199 (100), 198 (56), 155 (20), 141 (20), 129 (61), 128 (30), 117 (20), 115 (23), 109 (43), 108 (53), 104 (47), 94 (46), 91 (40), 82 (23), 81 (21), 56 (58). – HRMS ([M^+ − H] $C_{14}H_{19}BN$): calcd. 212.1611; found 212.1613.

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[1] R. P. Johnson, *Chem. Rev.* **1989**, *89*, 1111−1124.
[2] M. Balci, Y. Taskesenligil, *Adv. Strained Interesting Org. Mol.* **2000**, *8*, 43−81.
[3] T. Khasanova, R. S. Sheridan, *J. Am. Chem. Soc.* **2000**, *122*, 8585−8586.
[4] Y. Pang, S. A. Petrich, V. G. Young, Jr., M. S. Gordon, T. J. Barton, *J. Am. Chem. Soc.* **1993**, *115*, 2534−2536; T. Shimizu, F. Hojo, W. Ando, *J. Am. Chem. Soc.* **1993**, *115*, 3111−3115.
[5] M. A. Hofmann, U. Bergsträßer, G. J. Reiß, L. Nyulászi, M. Regitz, *Angew. Chem.* **2000**, *112*, 1318−1320; *Angew. Chem. Int. Ed.* **2000**, *39*, 1261−1263.
[6] M. Christl, S. Groetsch, *Eur. J. Org. Chem.* **2000**, 1871−1874.
[7] S. Groetsch, J. Spuziak, M. Christl, *Tetrahedron* **2000**, *56*, 4163−4171.
[8] M. Christl, M. Braun, G. Müller, *Angew. Chem.* **1992**, *104*, 471−473; *Angew. Chem. Int. Ed. Engl.* **1992**, *31*, 473−476.
[9] M. Schreck, M. Christl, *Angew. Chem.* **1987**, *99*, 720−721; *Angew. Chem. Int. Ed. Engl.* **1987**, *26*, 690−692.
[10] [10a] M. Schlosser, *Yuki Gosei Kagaku Kyokaishi* **1988**, *46*, 528−539. – [10b] R. Ruzziconi, Y. Naruse, M. Schlosser, *Tetrahedron* **1991**, *47*, 4603−4610.
[11] M. Christl, M. Braun, *Chem. Ber.* **1989**, *122*, 1939−1946.
[12] B. Jamart-Grégoire, V. Grand, S. Ianelli, M. Nardelli, P. Caubère, *Tetrahedron Lett.* **1990**, *31*, 7603−7606; B. Jamart-Grégoire, S. Mercier-Girardot, S. Ianelli, M. Nardelli, P. Caubère, *Tetrahedron* **1995**, *51*, 1973−1984.
[13] [13a] M. Christl, M. Braun, E. Wolz, W. Wagner, *Chem. Ber.* **1994**, *127*, 1137−1142. – [13b] W. Wagner, Dissertation, Universität Würzburg, **1994**.
[14] R. L. Elliott, A. K. Takle, J. W. Tyler, J. White, *J. Org. Chem.* **1993**, *58*, 6954−6955; R. L. Elliott, N. H. Nicholson, F. E. Peaker, A. K. Takle, J. W. Tyler, J. White, *J. Org. Chem.* **1994**, *59*, 1606−1607; R. L. Elliott, N. H. Nicholson, F. E. Peaker, A. K. Takle, C. M. Richardson, J. W. Tyler, J. White, M. J. Pearson, D. S. Eggleston, R. C. Haltiwanger, *J. Org. Chem.* **1997**, *62*, 4998−5016.
[15] M. Christl, S. Drinkuth, *Eur. J. Org. Chem.* **1998**, 237−241.
[16] M. Ferles, *Collect. Czech. Chem. Commun.* **1958**, *23*, 479−484.
[17] A. T. Bottini, L. L. Hilton, J. Plott, *Tetrahedron* **1975**, *31*, 1997−2001.
[18] K. Peters, E.-M. Peters, S. Drinkuth, S. Groetsch, M. Christl, *Z. Kristallogr. NCS* **2000**, *215*, 600.
[19] E.-M. Peters, K. Peters, S. Groetsch, M. Christl, *Z. Kristallogr. NCS* **2001**, *216*, 121−122.
[20] S. V. Kessar, P. Singh, R. Vohra, N. P. Kaur, K. N. Singh, *J. Chem. Soc., Chem. Commun.* **1991**, 568−570.
[21] V. Ferey, T. Le Gall, C. Mioskowski, *J. Chem. Soc., Chem. Commun.* **1995**, 487−489; M. R. Ebden, N. S. Simpkins, D. N. A. Fox, *Tetrahedron Lett.* **1995**, *36*, 8697−8700; E. Vedejs, J. T. Kendall, *J. Am. Chem. Soc.* **1997**, *119*, 6941−6942; A. J. Blake, M. R. Ebden, D. N. A. Fox, W.-S. Li, N. S. Simpkins, *Synlett* **1998**, 189−191.
[22] M. Nendel, L. M. Tolbert, L. E. Herring, Md. N. Islam, K. N. Houk, *J. Org. Chem.* **1999**, *64*, 976−983.
[23] H. L. Bradlow, C. A. Vanderwerf, *J. Org. Chem.* **1951**, *16*, 1143−1152.

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