

same is true for interaction (77-7). Thus, as in 2', π -donation dominates over π -back-donation.

Electron Counting in 1 and 2 Revisited. The experimentally determined molecular structures of 1 and 2 lead to the descriptions of 64-electron spiked triangular and 62-electron butterfly clusters, respectively.^{30,31} For 1, we may consider the $\text{Ru}_4(\text{CO})_{12}$ skeleton as providing 56, the boron atom 3, two endo-hydrogen atoms 1 each, and the CPhCHPh unit 1 σ - and 2 π -electrons, making a total of 64 electrons. From 1 to 2, the observed increase in dihedral angle, α , and height, h , of the boron atom above the wing tip-wing tip vector led us in the discussion of the molecular structure of 2 to conclude that the boron atom was no longer interstitial. Thus an appropriate electron count would be 57 from the $\text{CpWRu}_3(\text{CO})_{11}$ skeleton, 1 from the cluster hydride ligand, 2 from the olefinic π -interaction, and 2 from the exo-BR ($\text{R} = \text{CPhCHPh}$) unit, making a total of 62 electrons. While these electron distributions clearly "work" in terms of the effective atomic number rule,^{30,31} the results of the Fenske-Hall calculations imply that in both compounds there is a degree of ambiguity concerning any simple (e.g. exo versus interstitial character for the boron atom and Dewar-Chart-Duncanson model for the ruthenium-alkene bonding) bonding scheme which may be used to describe the two molecules.

Conclusions. The reaction of $\text{HRu}_4(\text{CO})_{12}\text{BH}_4$ with $\text{PhC}\equiv\text{CPh}$ leads to an unprecedented cluster by virtue of concomitant B-C bond formation, transfer of a cluster-bound hydrogen atom to the alkyne, and insertion of the

organic unit into the Ru_4 butterfly to yield a spiked triangular framework retaining a μ_4 -boron atom. In contrast, the reaction of $\text{PhC}\equiv\text{CPh}$ with $\text{H}(\text{CpW})\text{Ru}_3(\text{CO})_{11}\text{BH}$ proceeds with retention of the butterfly skeleton although, as in the first reaction, cluster-to-alkyne hydrogen atom transfer occurs along with B-C bond formation. Both reactions involve the formation of an alkene-ruthenium π -bond.

The reason(s) for the differences in reaction pathways are not as yet clear to us. One possibility is that the presence of the additional B-H-Ru hydrogen atom in 1 inhibits the boron atom from moving out of the butterfly framework as is required in the formation of 2. However, other work in progress in our laboratory indicates that in some cases a small unsaturated molecule may be incorporated into $\text{HRu}_4(\text{CO})_{12}\text{BH}_2$ without cluster opening.³²

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Supplementary Material Available: Tables of positional and thermal parameters and bond distances and angles (15 pages). Ordering information is given on any current masthead page.

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Determination of the Free Activation Energies for the Interconversion of Isomers of 2,4-Pentadienyldipropylborane via Consecutive 1,3-Boron Shifts

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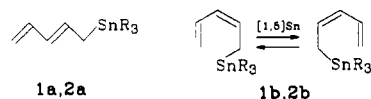
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The fluxional behavior of the *E* (4a) and *Z* (4b) isomers of 2,4-pentadienyldipropylborane has been studied by dynamic ^1H and ^{13}C NMR spectroscopy. Activation barriers have been determined for degenerate metallotropic rearrangements of 4a and 4b and for 4a \rightleftharpoons 4b interconversion by complete line shape analysis of ^{13}C DNMR spectra. The data obtained suggest that only 1,3 shifts of BPr_2 groups take place in both isomers rather than 1,5 sigmatropic shifts.

Introduction

The chemistry of the 2,4-pentadienyl organometallic compounds has been extensively investigated.¹ Pentadienyl derivatives of alkali metals (Na, K, Rb, Cs) are ionic and fluxional in solution due to the rapid equilibration of S-, W-, and U-conformers of the pentadienyl anion.²⁻⁴

Scheme I



1b $\text{R} = \text{Ph}$, ΔG^\ddagger 81 kJ/mol [9]
2b $\text{R} = \text{Cl}$, $\Delta G^\ddagger < 30$ kJ/mol [10]

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Pentadienyl compounds of lithium,⁵ magnesium,⁶ beryllium,⁷ and zinc⁷ demonstrate more complex fluxionality

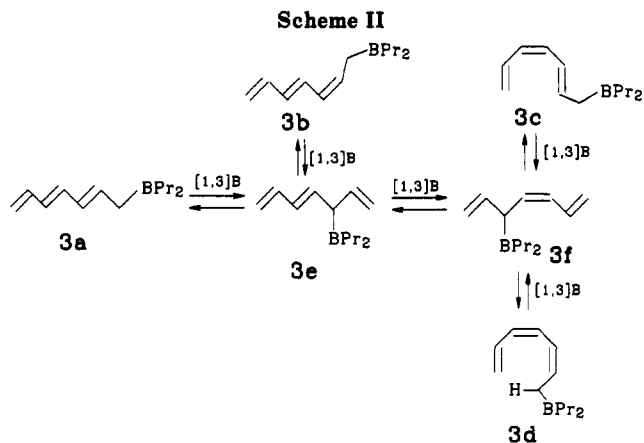


Table I. NMR Data for (E)- and (Z)-2,4-Pentadienyldipropylboranes 4a and 4b

compound	atom number	atom number				
		1	2	3	4	5
4a	$\delta(^1\text{H})$	2.02	5.66	5.82	6.16	4.72 (H^{5c}), 4.85 (H^{5t})
	$^3J(\text{HH})$	7.2	15.0	9.8	9.9	17.0
	$\delta(^{13}\text{C})$	33.3	131.0	132.4	137.6	113.1
4b	$\delta(^1\text{H})$	2.12	5.48	5.84	6.44	4.88 (H^{5c}), 4.98 (H^{5t})
	$^3J(\text{HH})$	8.4	9.9	10.1	10.1	16.9
	$\delta(^{13}\text{C})$	33.4	128.3	129.5	132.4	116.0

which includes equilibria between ionic and σ -bonded structures as well as the anion conformational interconversions.

The metallotropic rearrangements of covalent σ -bonded pentadienyl derivatives have received little study. Pentadienyltrimethylsilane is nonfluxional.⁸ Pentadienyltriphenyltin (1b)⁹ and 2,4-pentadienyl(trichloro)tin (2b)¹⁰ were found to consist of a mixture of *E*- and *Z*-isomers. Only the latter proved to be fluxional via 1,5-Sn sigma-tropic shifts.^{8,11} The activation barriers of these processes differ greatly—the estimated value of ΔG^\ddagger in 1b is 81 kJ/mol and for 2b ΔG^\ddagger is lower than 30 kJ/mol.

2,4-Pentadienyldiphenylborane¹¹ as well as some pentadienyldimethoxyboranes⁵ have been described previously, but their dynamic properties have not been studied. Fast 1,3 migration of the BR_2 group in allylboranes (per-

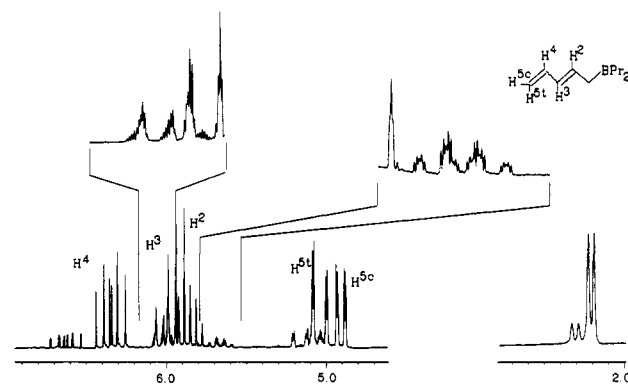


Figure 1. Section plot of the ^1H NMR spectrum (200 MHz, CDCl_3) of 2,4-pentadienyldipropylborane (4) (olefin region).

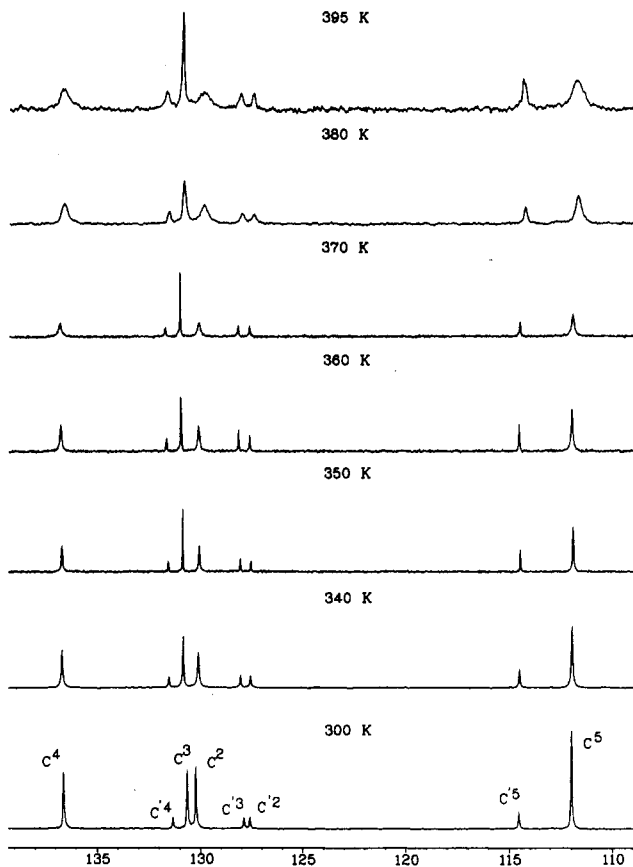


Figure 2. Temperature dependence of the line shape of the ^{13}C NMR spectrum (50 MHz, neat liquid) of 4 (low-field region).

manent allylic rearrangement, PAR) had been found by Mikhailov et al. earlier.¹² Recently, we have started the more detailed study of PAR using complete line shape analysis of ^{13}C DNMR spectra. More accurate activation parameters were determined for PAR of some simple allylboranes.¹³ In the case of 2,4,6-heptatrienyldipropylborane (3) we have found that four geometric isomers 3a–d interconvert reversibly via 1,3 shifts of BPr_2 . A 1,7 sigmatropic hydrogen shift was found for *Z,Z*-isomer 3d but no 1,7-boron migration.¹⁴

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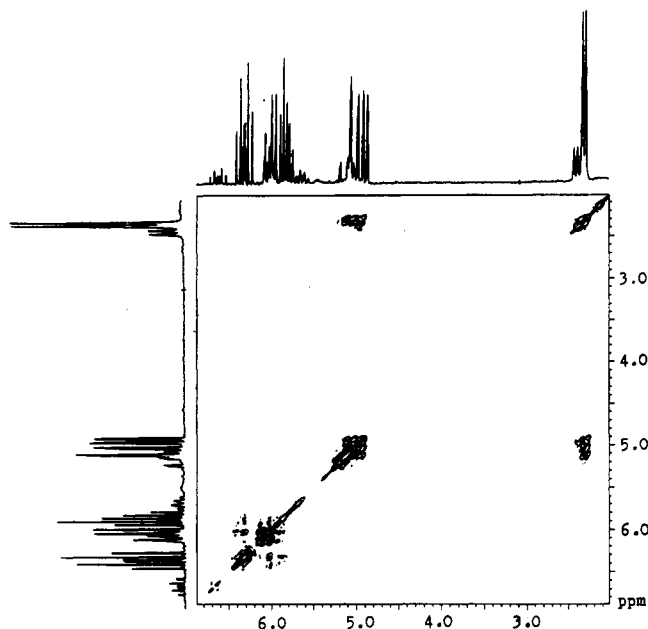


Figure 3. Contour plot of the chemical exchange 2D ^1H NMR spectrum of **4** (200 MHz, neat liquid); $T = 350\text{ K}$, $\tau = 0.5\text{ s}$.

Therefore a study of 2,4-pentadienyl derivatives of boron seemed to be of great interest with regard to the possible competition between 1,3-B, 1,5-B, and 1,5-H sigmatropic shifts.

Results and Discussion

2,4-Pentadienyldipropylborane (**4**) was obtained by reaction of pentadienyllithium with chlorodipropylborane in hexane-THF at $-30\text{ }^\circ\text{C}$.

NMR Spectral Assignment and Spectral Dynamics. The ^1H NMR spectrum of **4** at room temperature, shown in Figure 1, indicates the presence of *E*- and *Z*-isomers **4a** and **4b** in a 4:1 ratio. Values of chemical shifts and coupling constants are given in Table I. The values $^3J(\text{H}^2, \text{H}^3)$ 15.09 for **4a** and 9.41 Hz for **4b** point out the predominance of an *E*-isomer in the mixture.

The $^{13}\text{C}\{-^1\text{H}\}$ NMR spectrum of **4a** is shown in Figure 2a. Signal assignment was performed by the standard 2D procedure XHCORR. The values of ^{13}C chemical shifts are given in the Table I.

In the temperature range 300–395 K a characteristic reversible temperature dependence of the ^1H and ^{13}C NMR spectra of **4** is observed. The signals of the carbon atoms C^2 , C^4 , and C^5 of *E*-isomer **4a** broaden with increasing temperature (Figure 2). For the same signals of the *Z*-isomer **4b** dynamic broadening is less distinct. The character of the temperature dependence of ^{13}C NMR spectrum indicates an intramolecular migration of the BPr_2 group in **4a** and **4b**. At temperatures higher than 370 K the broadening of the C^3 signals of both isomers is distinct, pointing out that the interconversion of *E*- and *Z*-isomers **4a** and **4b** also becomes fast on the NMR time scale.

The occurrence of the intramolecular migration of the BPr_2 group in **4a** also is proved by a two-dimensional NMR ^1H NOESY experiment which was carried out at 350 K, mixing time $\tau = 0.5\text{ s}$ (Figure 3). Intensive exchange cross peaks are observed for the signals of H^1 and H^5 and of H^2 and H^4 of the *E*-isomer **4a**, while similar cross peaks for the *Z*-isomer **4b** are absent. Exchange cross peaks are observed only for the signals C^2 and C^4 of the *E*-isomer in 2D ^{13}C NOESY experiment at 296 K (mixing time $\tau = 0.5\text{ s}$). Therefore the rate of rearrangement is greater in the *E*-isomer than in the *Z*-isomer.

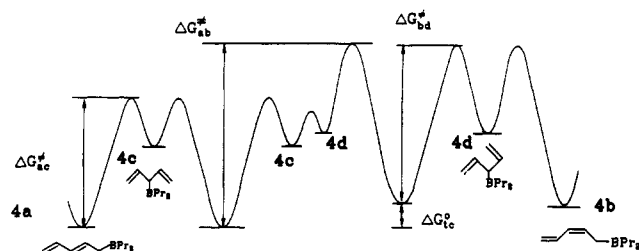
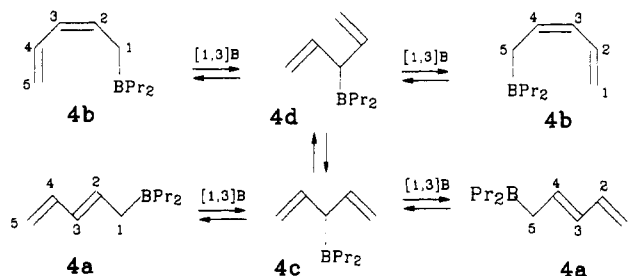


Figure 4. Potential energy profile for the permanent allylic rearrangement in 2,4-pentadienyldipropylborane (**4**).

Scheme III



Taking into account the literature data on the dynamic properties of allylic and 2,4-dimethylpentadienyl organometallic compounds (see Introduction), two kinetic schemes of rearrangement in **4** could be proposed: (1) direct 1,5-B sigmatropic shift of the BPr_2 group; (2) two consequent 1,3-B shifts of the BPr_2 group.

Having in mind the above discussed experimental data, the former mechanism can be excluded because the exchange is slower in the *Z*-isomer **4b**, which is geometrically favored for the 1,5-B shift, and because in the *E*-isomer **4a**, in which the rate of exchange is faster, a 1,5-B shift is spatially impossible.

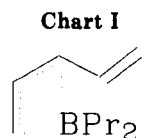
Migration of the BPr_2 group from C^1 to C^5 proceeds via two consecutive 1,3-B shifts with intermediate formation of isomer **4c** which is not detected in the spectra. Similar processes were observed earlier for the reversible interconversion of the *Z*- and *E*-isomers of tricrytylborane where intermediate formation of the α -methylallyl form was not detected under any conditions.¹⁵ The same picture is also observed for the interconversion of the four isomers of 2,4,6-heptatrienyldipropylborane (**3**)—the intermediate compounds with internal disposition of the boron atom are not detectable in the spectra.¹⁴

Therefore, the complete scheme of the dynamic processes in 2,4-pentadienyldipropylborane (**4**) can be presented as shown in Scheme III.

The corresponding profile of the potential energy is given in Figure 4.

Determination of the Activation Parameters of Rearrangement. Degenerate migration of boron in the *E*-isomer **4a** proceeds via intermediate **4c** and can be described with a barrier ΔG^{\ddagger}_{ac} and difference of free energies ΔG°_{ac} . Similarly, degenerate rearrangement in the *Z*-isomer **4b** proceeds via intermediate formation of **4d** (ΔG^{\ddagger}_{bd} , ΔG°_{bd}). In turn, the conversion of **4a** into **4b** requires intermediate formation of **4c**, its transformation into **4d** by the rotation around the $\text{C}^2\text{-C}^3$ bond (ΔG^{\ddagger}_{cd} , ΔG°_{cd}), followed by a 1,3-boron shift in **4d**. Since intermediates **4c** and **4d** are not observed in the spectra, analysis of the temperature dependence of the NMR spectra makes it possible to obtain only effective activation barriers indicative of the highest energy transition states. The values

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of ΔH^\ddagger and ΔS^\ddagger which could be obtained in the calculations cannot be correlated with the individual steps. Therefore, we have only determined the values of the effective barriers ΔG^\ddagger_{ac} , ΔG^\ddagger_{bd} , and ΔG^\ddagger_{ab} and the difference of free energies ΔG^\ddagger_{ab} . To obtain these values properly, line shape analysis of several spectra at different temperatures was essential because all the three processes affect the line shape simultaneously.

Complete line shape analysis of the ^{13}C NMR spectra of **4**, shown in the Figure 2, was performed using the DISPARD program.¹³ All the three values of the free activation energies as well as the thermodynamic free energy were treated as variable parameters during the final iteration circle. The values obtained after the iterations are

$$\Delta G^\circ_{ab}(366) = 3.5 \pm 0.2 \text{ kJ/mol}$$

$$\Delta G^\ddagger_{ac}(366) = 82.3 \pm 0.9 \text{ kJ/mol}$$

$$\Delta G^\ddagger_{bd}(366) = 91.5 \pm 0.9 \text{ kJ/mol}$$

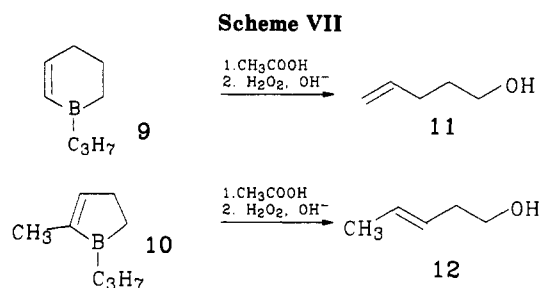
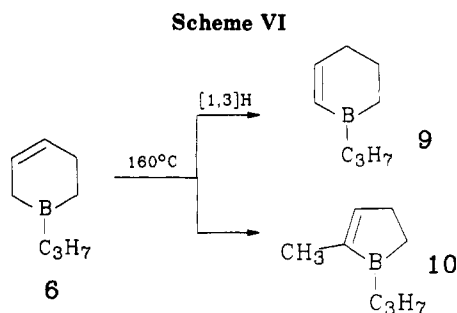
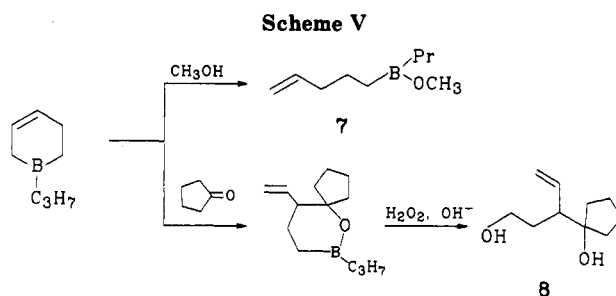
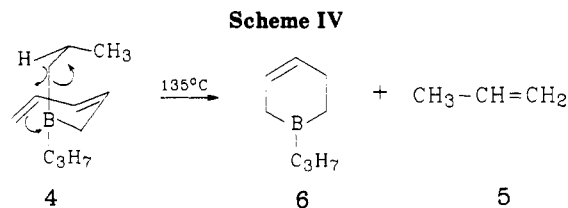
$$\Delta G^\ddagger_{ab}(366) = 85.5 \pm 0.9 \text{ kJ/mol}$$

It should be noted that the complete line shape analysis makes possible the search of the activation parameters for several simultaneous processes with rather close values of activation energies. An earlier similar problem could be solved only when the difference between activation barriers of simultaneous processes was great, for example, 65 and 103 kJ/mol.¹⁶

Thus, in 2,4-pentadienyldiborane (**4**) the 1,3-B shift predominates over the 1,5-B shift. This result demonstrates clearly the unique feature of organoboron compounds—the facile intramolecular 1,3-B sigmatropic shift. Such rearrangements are prohibited by orbital symmetry¹⁷ and were never observed for other allylic-type organometallic compounds with covalent C–M bonds. However, the presence of the vacant 2p AO of the boron atom makes normally very high-lying transition state for the suprafacial 1,3 shift easily accessible¹⁸ and the permanent allylic rearrangement (1,3 shift of boron)^{12,14,15} is observed in most allylic triorganoboranes.

The permanent allylic rearrangement in 2,4-pentadienyldipropylborane is slower than the same reactions for the other organoboranes of the allylic type. This fact can be explained by the influence of the second double bond in the molecule of **4**. Apparently, the higher the electron density of the π -orbital of C^3 carbon atom of the allylborane, the greater the rate of PAR. In the case of pentadienyldipropylborane (**4**) the electron density at the C^3 atom is decreased due to the conjugation with the second double bond; therefore the rate of PAR is also decreased.

The lower rate of PAR in the *Z*-isomer **4b** apparently is due to the considerable steric hindrance to the transition-state formation in the latter case (Chart I).



Thermal Cyclization of 2,4-Pentadienyldipropylborane. Reversible changes in the NMR spectra of **4** are observed at temperatures lower than 130 °C. If **4** is heated to 135–150 °C, vigorous propylene (**5**) evolution is observed.

In contrast to the initial ^1H NMR spectrum of **4**, the olefin part of the ^1H NMR spectrum of the thermolysis product contained only one unresolved multiplet corresponding to the two olefin protons (see Figure 5). In the high-field area the signals due to three CH_2 groups ($\delta = 1.80, 2.22, \text{ and } 2.39$ ppm) were detectable. These spectral data pointed out a cyclization reaction occurring in **4** during thermolysis.

Unfortunately, the yield of 3-borinene **6** is rather low (25–30%) due to the side process—symmetrization of **4** giving tripropylborane and bis(2,4-pentadienyl)propylborane. The latter polymerizes readily.

Reactions of the thermolysis product **6** with methanol and cyclopentanone, which gave compounds **7** and **8**, correspondingly enabled us to elucidate the structure of the thermolysis product as 1-propyl-3-borinene (**6**).

Thermal Isomerization of 1-Propyl-3-borinene (6) to Vinylic Type Boracyclenes 9 and 10. We have found that compound **6** undergoes further transformation yielding two compounds **9** and **10** in a ratio of 1:1 when heated to 160–180 °C.

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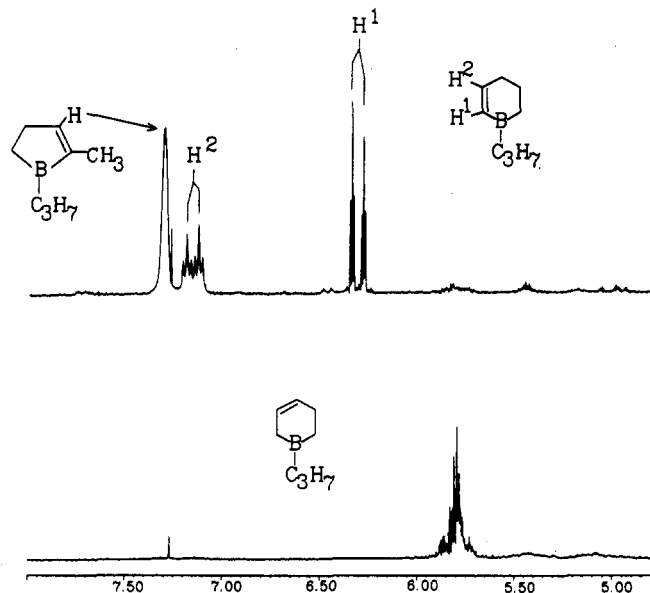


Figure 5. ^1H NMR spectra (200 MHz, CDCl_3) of the products of thermolysis of 2,4-pentadienyldipropylborane (4): (a) spectrum of 1-propyl-3-borinene (6). (b) spectrum of the same sample after heating 1 h at 160°C .

In the IR spectrum a strong absorption at 1580 cm^{-1} was observed which is characteristic for a vinylic ($\text{B}=\text{C}=\text{C}$) bond instead of the weak band at 1650 cm^{-1} of compound 6. Two broad signals in the low-field area of ^{13}C NMR spectra (133.95 and 149.88 ppm) also indicated the presence of B-vinylic fragments in compounds 9 and 10. The signals of the C^2 carbon atoms for compounds 9 and 10 had chemical shifts of 166.8 and 158.3 ppm. Similarly, unusually high values of chemical shifts were reported earlier for related systems.^{19,20} The reaction of compounds 9 and 10 with acetic acid followed by oxidation gave the corresponding alcohols 11 and 12, which provides additional evidence for their structures. Formation of 1-propyl-2-borinene 10 from 9 can be described as the consequence of dehydroboration-hydroboration reactions.

Conclusion

The investigation of the dynamic behavior of 2,4-pentadienyldipropylborane 4 showed that both *E*- and *Z*-isomers 4a and 4b can interconvert reversibly or undergo intramolecular degenerate rearrangement via two consecutive 1,3-B shifts, with the thermodynamically unstable isomer 4c as an intermediate. The most facile is the degenerate rearrangement of the *E*-isomer 4a. Such dynamic properties of borane 4 are completely different from those of pentadienyl derivatives of Sn, Zn, and Be; unusual properties of boron compounds are due to the unoccupied 2p atomic orbital of the boron atom.

Experimental Section

NMR spectra were recorded on the Bruker AC-200P spectrometer. IR spectra were obtained with the UR-20 spectrophotometer. All operations with organoboron compounds were performed in the atmosphere of dry argon.

2,4-Pentadienyldipropylborane 4. To a solution of pentadienyllithium obtained from 26.8 g (0.39 mol) of 1,4-pentadiene and an equimolar amount of 1.8 N butyllithium in hexane-THF²¹

was slowly added at -50°C 52.3 g (0.39 mol) of dipropylchloroborane. Then the mixture was heated to room temperature and stirred for 2 h. The precipitate was filtrated and the solvent removed. The residue was distilled in vacuo to give 4 (ratio 4a:4b is 4:1). Yield: 53.6 g (83%), bp $35\text{--}38^\circ\text{C}$ (2 mmHg), $n_D^{20} = 1.4652$. IR (cm^{-1}): ν 895, 1608, 1650, 3091. Anal. Calcd for $\text{C}_{11}\text{H}_{21}\text{B}$: C, 80.40; H, 12.89; B, 6.71. Found: C, 80.11; H, 12.50; B, 6.94.

Thermolysis of 2,4-Pentadienyldipropylborane 4. Compound 4 was heated at 135°C for 5 h. Propylene (0.55 equiv) was evolved. The residue was distilled in vacuo, and the fraction with bp $35\text{--}45^\circ\text{C}$ (15 mmHg) was collected. According to the spectral data it contained 3-borinene 6 and tripropylborane in a 4:5 ratio. Spectral data for 6: ^1H NMR (CDCl_3 , 200 MHz) δ 1.05 (t, $J = 8.4$ Hz, 3 H, CH), 1.25 (m, 2 H, CH), 1.46 (m, 2 H, CH_2), 1.82 (d, $J = 6.5$ Hz, 2 H, CH_2), 2.22 (m, 2 H, CH_2), 2.39 (m, 2 H, CH_2), 5.78 (m, 2 H, 2 CH); $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3 , 50 MHz) δ 17.15 (CH_2), 17.92 (CH_3), 21.89 (CH_2), 25.80 (br, CH_2B), 30.69 (br, CH_2B), 39.45 (br, CH_2B), 124.38 ($\text{CH}=\text{C}$), 128.50 ($\text{CH}=\text{C}$); ^{11}B (CDCl_3 , 64 MHz) δ 86.6 ppm (rel to $\text{Et}_2\text{O}\cdot\text{BF}_3$).

Reaction of 3-Borinene 6 with Methanol. An excess of methanol was added at room temperature to the mixture of tripropylborane and compound 6 (5:4) obtained by thermolysis of 4. A small amount of ethereal HCl was added for the completion of the reaction. According to the ^{11}B NMR spectrum after 1 h, the mixture consisted of tripropylborane (50%) and 4-pentenylpropylmethoxyborane 7 (50%), bp $48\text{--}50^\circ\text{C}$ (15 mmHg). ^1H NMR (CDCl_3 , 200 MHz): δ 0.87 (t, $J = 7.2$ Hz, 3 H, CH_3), 1.0–1.6 (m, 8 H, 4 CH_2), 2.04 (dt, $J = 7.5, 8.0$ Hz, 2 H, CH_2), 3.52 (s, 3 H, OCH_3), 4.87 (dm, $J = 9.2$ Hz, 1 H, $\text{CH}_2=\text{C}$), 4.98 (dm, $J = 15.2$ Hz, 1 H, $\text{CH}_2=\text{C}$), 5.77 (m, 1 H, $\text{CH}=\text{C}$); ^{13}C NMR (CDCl_3 , 50 MHz), δ 17.35 (CH_2), 17.80 (CH_3), 23.36 (CH_2), 30.95 (br, 2 CH_2B), 36.75 (CH_2), 114.41 ($\text{CH}_2=\text{C}$), 139.17 ($\text{CH}=\text{C}$); ^{11}B NMR (CDCl_3 , 64 MHz) δ 53.2.

Reaction of 3-Borinene 6 with Cyclopentanone. The mixture (1.19 g) of tripropylborane and compound 6 (4:5, see above) was treated with an excess of cyclopentanone (20 mL) at room temperature without solvent. After 1 day, the standard oxidation was performed ($\text{H}_2\text{O}_2 + \text{NaOH}$); the reaction mixture was extracted with ether; the solvent was evaporated, and the product was purified by column chromatography (silica gel, eluent ether-hexane) to give 0.56 g of 3-(1-hydroxycyclopentyl)-4-pentenol (8), mp $83\text{--}84^\circ\text{C}$ (from ether). ^1H NMR (CDCl_3 , 200 MHz): δ 1.5–1.9 (m, 10 H, 5 CH_2), 2.23 (td, $J = 9.7, 3.7$ Hz, 1 H, CH), 3.62 (m, 2 H, CH_2OH), 5.10 (m, 2 H, $\text{CH}_2=\text{C}$), 5.76 (ddd, $J = 9.7, 10.6, 16.8$ Hz, 1 H); ^{13}C NMR (CDCl_3 , 50 MHz) 23.76, 23.81, 37.95, 38.34 (CH_2 of cyclopentane), 32.77 (CH_2), 50.87 (CH), 60.80 (CH_2OH), 83.75 (COH), 117.23 ($\text{CH}_2=\text{C}$), 138.94 ($\text{CH}=\text{C}$). Anal. Calcd for $\text{C}_{10}\text{H}_{18}\text{O}_2$: C, 70.55; H, 10.66. Found: C, 70.31; H, 10.50.

Thermolysis of 3-Borinene 6. Compound 6 in a mixture with tripropylborane (4:5, see above) was heated in a sealed tube at 160°C during 2 h. According to NMR spectra this resulted in quantitative conversion of 6 into an equimolar mixture of 1-propyl-2-borinene (9) and 1-propyl-2-methyl-2-borinene (10).

9: ^1H NMR (CDCl_3 , 200 MHz) δ 0.92 (t, $J = 7.8$ Hz, 3 H, CH_3), 1.19 (m, 2 H, CH_2), 1.45 (m, 4 H, 2 CH_2B), 1.58 (m, 2 H, CH_2), 2.23 (m, 2 H, CH_2), 6.32 (dt, $J = 11.5, 1.8$ Hz, 1 H, H^1), 7.15 (dt, $J = 11.5, 3.7$ Hz, 1 H, H^2); ^{13}C NMR (CDCl_3 , 50 MHz) δ 17.59, 18.03, 30.91 (C_3H_7), 19.24 (C^5), 23.95 (br, C^6), 33.49 (C^4), 133.95 (br, C^2), 167.65 (C^3); ^{11}B NMR (CDCl_3 , 64 MHz) δ 73.8.

10: ^1H NMR (CDCl_3 , 200 MHz) δ 1.19 (t, $J = 7.8$ Hz, 3 H, CH_3), 1.19 (m, 2 H, CH_2), 1.33 (m, 4 H, 2 CH_2B), 1.91 (dt, $J = 2.0, 2.2$ Hz, 3 H, CH_3), 2.42 (m, 2 H, CH_2), 7.33 (br s, 1 H, $\text{CH}=\text{C}$); ^{13}C NMR (CDCl_3 , 50 MHz) δ 15.46 (CH_3), 17.59, 18.03, 30.91 (C_3H_7), 25.94 (br, C^5), 30.30 (C^4), 149.88 (br, C^2), 157.50 (C^3); ^{11}B NMR (CDCl_3 , 64 MHz): δ 82.9.

Reaction of Compounds 9 and 10 with Acetic Acid. An equimolar amount of acetic acid was slowly added to the mixture of 9 and 10 at room temperature. After 2 h of stirring, the standard oxidation ($\text{H}_2\text{O}_2 + \text{NaOH}$) was carried out. The product was extracted with ether and then distilled in vacuo to give an equimolar mixture of 11 and 12, yield 78%, bp $113\text{--}115^\circ\text{C}$ (740 mmHg).

4-Pentenol (11). ^1H NMR (CDCl_3 , 200 MHz): δ 1.5 (m, 2 H,

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CH₂), 2.12 (dt, $J_1 = J_2 = 6.2$ Hz, 2 H, CH₂), 3.61 (t, $J = 6.2$ Hz, 2 H, CH₂), 4.99 (dm, $J = 9.3$ Hz, 1 H), 5.06 (dm, $J = 17.8$ Hz, 1 H), 5.85 (m, 1 H, CH=).

3-Pentenol (12). ¹H NMR (CDCl₃, 200 MHz): δ 1.68 (dm, $J = 7.1$ Hz, 1 H), 2.24 (dt, $J_1 = J_2 = 6.2$ Hz, 2 H, CH₂), 3.68 (t, $J = 6.2$ Hz, 2 H, CH₂OH), 5.45 (m, 1 H, CH=), 5.57 (dt, $J = 15.3$, 6.1 Hz, 1 H, CH=).

Registry No. **4a**, 143775-62-6; **4b**, 143775-67-1; **6**, 143775-63-7; **7**, 143775-64-8; **8**, 143775-65-9; **9**, 143775-66-0; **10**, 143790-34-5; **11**, 821-09-0; **12**, 39161-19-8; CH₃OH, 67-56-1; 1,4-pentadiene, 591-93-5; dipropylchloroborane, 22086-53-9; cyclopentanone, 120-92-3.

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Molecular Recognition Using Bioorganometallic Probes: NMR, X-ray Crystallographic, and Molecular Modeling Study of the Conformations of Cr(CO)₃ Derivatives of Hexestrol and Their Relevance to Estradiol-Receptor Binding

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The structures of the *meso*-hexestrol derivatives R¹OC₆H₄CH₂CH₂EtC₆H₄OR², where R¹ = R² = H, **1**; R¹ = R² = CH₂Ph, **6**; R¹ = HO(CH₂)₃, R² = H, **7**, have been investigated both by molecular modeling techniques and by ¹H NMR spectroscopy at 500 MHz; the centrosymmetric antiperiplanar conformation **10** is favored. The tricarbonylchromium complexes of **6** and **7**, viz. **9** and **8**, respectively, as well as the DES derivative PhCH₂OC₆H₄CET=CETC₆H₄[Cr(CO)₃]OCH₂Ph, **13**, have also been prepared. Crystals of **8** are monoclinic, of space group *Cc* with $a = 15.449$ (6)  , $b = 21.077$ (5)  , $c = 7.623$ (3)  , $\beta = 113.41$ (3) , and $V = 2278$ (1)  ³ for $Z = 4$. For **13**, $a = 14.905$ (7)  , $b = 8.558$ (2)  , $c = 26.084$ (13)  , $\beta = 115.58$ (3) , and $V = 3001$ (2)  ³ for $Z = 4$ in the monoclinic space group *P2₁/n*. In **8** the phenyl rings are not parallel; the twist angle is 25 . In **13**, the phenyl rings are within 11  of being parallel (as is the case for DES itself) but are almost orthogonal to the plane containing the central double bond. The relative binding affinity of **7** is 15% of the RBA for the natural hormone, 17 -estradiol, and this diminishes slightly upon incorporation of the Cr(CO)₃ group, as in **8**. The RBA's for the series of hexestrol derivatives have been measured and are discussed in terms of the favored molecular conformers. IR spectroscopy in the ν_{∞} region is used to demonstrate not only that the Cr(CO)₃ tripod remains attached but also that the organometallic derivative of hexestrol is still well recognized by the estradiol receptor.

Introduction

The interactions of organometallic moieties with systems of significance to molecular biology have become a new and important area of study. In this burgeoning area, one of the concepts which is of increasing current importance involves the utilization of metal fragments as cold (i.e. nonradioactive) markers.¹ Typically, cobalt and molybdenum carbonyl cluster derivatives of the mycotoxin zearalenone have high binding affinities for specific antibodies and provide the basis of new immunoassay techniques.² The pivotal factor in such studies is the recognition of the particular protein receptor site by a biological molecule *even when modified by the incorporation of the organometallic fragment*. It is thus apparent that the influence of the organometallic bioprobe on the molecular geometry of these systems needs to be understood at a rather fundamental level so that some measure of steric control may be achieved. We here describe how a combination of molecular modeling techniques and high-field NMR spectroscopy, together with X-ray crystallographic structural determinations for some key molecules, allows

the rationalization of the relative binding affinities (RBA's) of a series of nonsteroidal hormones.

Results and Discussion

Nonsteroidal hormones such as hexestrol, **1**, and diethylstilbestrol (DES), **2**, occupy an important place in studies of the hormone \rightleftharpoons estradiol receptor system.³ This topic has gained in significance with the recognition that the mechanism of the development of certain types of breast cancer is hormone dependent. Moreover, this knowledge has been exploited not only in terms of early diagnosis of such cancers but also in hormonal treatment therapy.

The nonsteroidal hormones possess two important characteristics. First of all they have in general a very good

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