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Electronic effects of icosahedral carboranes: kinetic evidence for interaction between boron atom and nucleophile in the solvolysis of (*o*-carboranyl)benzyl tosylates

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Abstract—Solvolysis of (*o*-, *m*- and *p*-carboranyl)benzyl toluene-*p*-sulfonates substituted at the second carbon atom with a phenyl group bearing a range of substituents at the *para* position has been performed. The rates of hydrolysis of *m*- and *p*-carboranyl derivatives measured linearly with increasing electron-releasing character of the substituent group ($\rho = -0.23$, $\rho = -0.35$), which indicates that these carboranes transmit electronic effects, and the substituents affect the stability of the neighboring carbocation. In contrast, the rate of hydrolysis of *o*-carboranyl derivatives showed a linear decrease with increasing electron-releasing character of the substituent ($\rho = +1.12$), which indicates that the interaction between the B(3) atom of the *o*-carborane cage and the nucleophile controls this particular reaction. © 2001 Elsevier Science Ltd. All rights reserved.

Icosahedral *closo* carboranes have been described as three-dimensional aromatic systems, and the implications for electronic interaction with substituents have been of particular interest since the first synthesis of these compounds.[1] Concerning the electronic effect of icosahedral carboranes on a substituent outside the cage, investigations of the pK_a values of carboranylbenzoic acids and carboranylanilinium ions,[2] and of the ^{19}F NMR chemical shifts of carboranylfluorobenzenes,[3] showed that the icosahedral carboranes behave as strongly electron-withdrawing groups in the sequence *ortho*≫*meta*>*para* towards carbon substituents. These investigations have also shown that the electron-withdrawing inductive effect of the carborane cage is similar to that of halogens, and that ground-state cage-ring-π interaction is not important. In our kinetic investigations, we have reported that the order of rates in the acetolysis of (*o*-, *m*- and *p*-carboranyl)benzyl tosylates (**1**, **2** and **3**) was consistent with the electron-withdrawing effect of the icosahedral carboranes.[4] However, we found that the hydrolysis of **1**, bearing what is thought to be the most electron-withdrawing group among the carboranes, was significantly accelerated compared with those of **2** and **3**.[4] Furthermore, in the hydrolysis of (+)-**1**, the reaction afforded the *retentive* product, with an enantiomeric purity of 71%, whereas the products formed from (+)-**2** and (+)-**3** were racemic.[4] Therefore, we suggested a mechanism involving interaction between the oxygen atom of the nucleophile and the 3-position boron atom in the *o*-carborane cage to explain the characteristic reaction of **1**. In this paper, we present the kinetic evidence for this new type of neighboring group effects by the cage-boron atom of *o*-carborane in nucleophilic solvolysis, as well as kinetic evidence for the transmission of electronic effects by *o*-, *m*- and *p*-carborane cages.

To evaluate the above electronic effects of icosahedral carboranes, we designed (*o*-, *m*- and *p*-carboranyl)benzyl tosylates substituted at the second carbon atom with a phenyl group bearing a range of electron-releasing or -withdrawing substituents at the *para* position (**4**, **5**, **6**), as shown in Fig. 1. The (*o*-carboranyl)benzyl tosylates (**4a**–**e**) were prepared from (4-substituted phenyl)-*o*-carboranes (**7a**–**e**), which were obtained by reaction of arylalkyne with *nido*-$B_{10}H_{14}$ (R = H, CH_3) or by coupling of the C-copper(I) derivative of 1,2-dicarba-*closo*-dodecaborane (*o*-carborane) with 4-substituted iodobenzene (R = CF_3, OCH_3, $N(CH_3)_2$).[5] The (*o*-carboranyl)benzyl tosylates (**4a**–**e**) were prepared by the reaction of lithiates of **7a**–**e** with benzaldehyde,[6] followed by reaction with toluene-*p*-sulfonyl chloride. The (*m*- and *p*-carboranyl)benzyl tosylates (**5a**–**e**, **6a**–**e**) were prepared from (4-substituted phenyl)-*m*- or *p*-carboranes by the same coupling procedure as that used for **4**.

Keywords: carboranes; electronic effects; kinetics; neighboring group effects.

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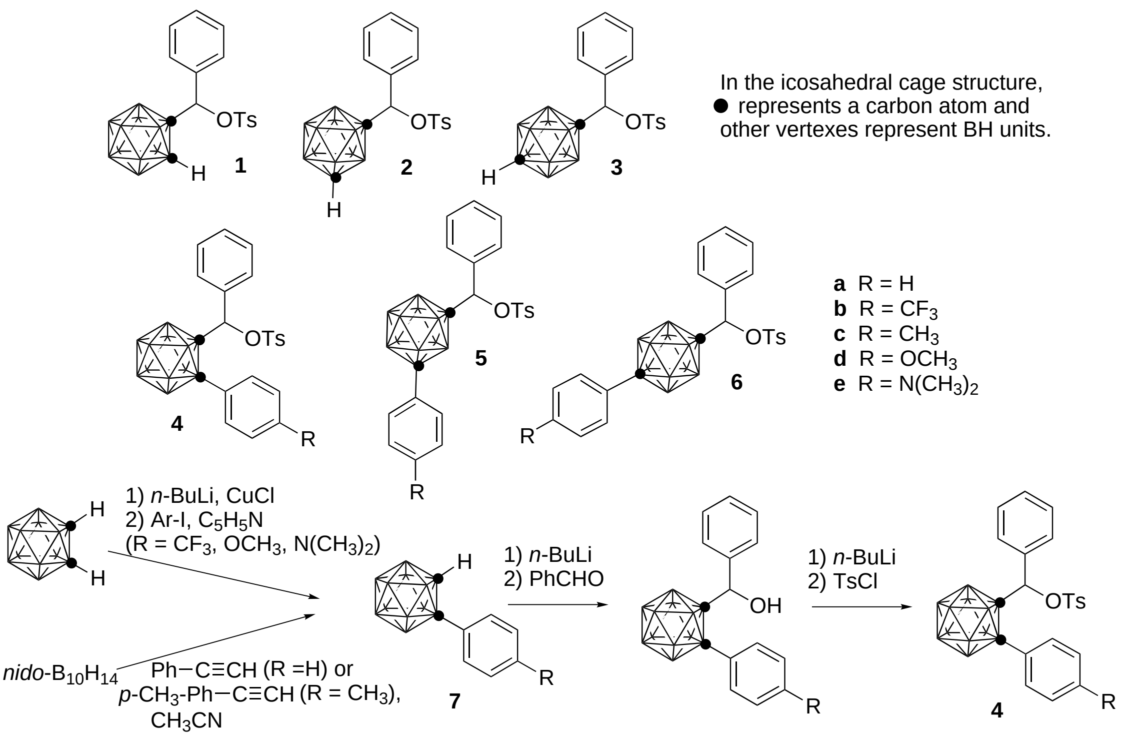

Figure 1.

The kinetic experiments on the acetolysis on the (carboranyl)benzyl tosylates (**4**–**6**) in CD_3COOD at 95.4°C were performed by NMR measurement of the decrease of starting materials.[7] The acetolysis of **4**–**6** gave the corresponding acetates quantitatively. The rate constants for the acetolysis are summarized in Table 1. In the case of (*o*-carboranyl)benzyl tosylates, introduction of the phenyl group at the 2-C position of the carborane cage resulted in a slight decrease of the acetolysis rate (**4a**: 7.39×10^{-6} s^{-1}) compared with the rate of **1** (1.32×10^{-5} s^{-1}), probably owing to steric hindrance. In the case of (*m*- and *p*-carboranyl)benzyl tosylates, introduction of the phenyl group did not appreciably affect the rate (**2**: 3.06×10^{-5} s^{-1} and **5a**: 2.96×10^{-5} s^{-1}). Fig. 2 shows a clear linear relation between the substituent electronic effect, represented by the Hammett σ_P value,[8] and the relative rate (k_X/k_H). The slopes of the lines correspond to the anticipated increase with increasing electron-releasing power of the substituent in each of the *o*-, *m*-, *p*-carboranyl series. The ρ values of **4**, **5** and **6** were −0.63, −0.25 and −0.36, respectively.

Kinetic experiments on the hydrolysis of the (carboranyl)benzyl tosylates (**4**–**6**) in 70% dioxane-d_8–D_2O at 86.0°C were also performed by NMR measurement of the decrease of the starting materials.[7] The hydrolysis of **4**–**6** gave the corresponding alcohol quantitatively. The rate constants for the hydrolysis are summarized in Table 2. Introduction of a phenyl group at the 2-C position of the carborane cage affected the rate constants similarly to those in the case of acetolysis. The hydrolysis rate of **4a** was decreased (1.20×10^{-4} s^{-1}) compared with the rate of **1** (1.09×10^{-3} s^{-1}, calculated from thermodynamic parameters), and the hydrolysis rate of **5a** (1.66×10^{-5} s^{-1}) was not appreciably different from that of **2** (1.86×10^{-5} s^{-1}). Fig. 3 shows a clear linear relation between the substituent electronic effect, represented by the Hammett σ_P value, and the relative rate (k_X/k_H). The slopes of the lines correspond to the anticipated increase with increasing electron-releasing power of the substituent in the cases of *m*- and *p*-carboranyl derivatives. The ρ values of **5** and **6** were −0.23 and −0.35, respectively. The results were consistent with those for the acetolysis of the carborane derivatives (**4**–**6**). However, the slope of the line shows the reverse effect in the case of *o*-carboranyl derivatives: the relative rate (k_X/k_H) decreased with increasing electron-releasing effect of the substituent. The ρ values of series of **4** was +1.12.[9]

Table 1. Pseudo-first-order rate constants (k_1 s^{-1}) for the acetolysis of **4**–**6** in CD_3COOD at 95.4°C

	R	k_1 (s^{-1})[a]	k_X/k_H
4b	CF_3	$3.65\pm0.24\times10^{-6}$	0.49
4a	H	$7.39\pm0.79\times10^{-6}$	1.00
4c	CH_3	$9.25\pm1.03\times10^{-6}$	1.25
4d	OCH_3	$1.22\pm0.08\times10^{-5}$	1.65
5b	CF_3	$2.21\pm0.09\times10^{-5}$	0.75
5a	H	$2.96\pm0.26\times10^{-5}$	1.00
5c	CH_3	$3.40\pm0.48\times10^{-5}$	1.15
5d	OCH_3	$3.46\pm0.39\times10^{-5}$	1.17
6b	CF_3	$2.81\pm0.09\times10^{-5}$	0.67
6a	H	$4.25\pm0.14\times10^{-5}$	1.00
6c	CH_3	$5.01\pm0.85\times10^{-5}$	1.17
6d	OCH_3	$5.39\pm0.57\times10^{-5}$	1.27

[a] The values are means for triplicate measurements.

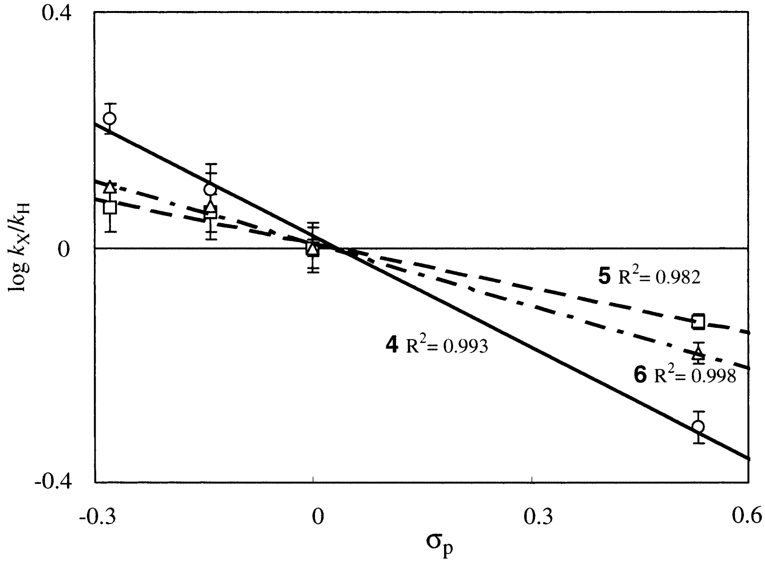

Figure 2. Hammett plot of kl_X/k_H against σ_p for the acetolysis of **4**–**6**. Results are shown as means ±S.D. for triplicate measurements.

Table 2. Pseudo-first-order rate constants (k_1 s^{-1}) for the hydrolysis of **4**–**6** in 70% dioxane-d_8–D_2O at 86.0°C

	R	k_1 (s^{-1})[a]	k_X/k_H
4b	CF_3	$4.86 \pm 0.06 \times 10^{-4}$	3.93
4a	H	$1.20 \pm 0.01 \times 10^{-4}$	1.00
4c	CH_3	$7.73 \pm 1.47 \times 10^{-5}$	0.65
4d	OCH_3	$6.04 \pm 1.14 \times 10^{-5}$	0.51
4e	$N(CH_3)_2$	$4.96 \pm 0.41 \times 10^{-5}$	0.42
5b	CF_3	$0.98 \pm 0.11 \times 10^{-5}$	0.59
5a	H	$1.66 \pm 0.16 \times 10^{-5}$	1.00
5c	CH_3	$1.74 \pm 0.17 \times 10^{-5}$	1.04
5d	OCH_3	$1.88 \pm 0.20 \times 10^{-5}$	1.12
5e	$N(CH_3)_2$	$1.92 \pm 0.19 \times 10^{-5}$	1.15
6b	CF_3	$1.33 \pm 0.18 \times 10^{-5}$	0.59
6a	H	$2.24 \pm 0.35 \times 10^{-5}$	1.00
6c	CH_3	$2.43 \pm 0.35 \times 10^{-5}$	1.09
6d	OCH_3	$2.72 \pm 0.13 \times 10^{-5}$	1.21
6e	$N(CH_3)_2$	$3.38 \pm 0.33 \times 10^{-5}$	1.50

[a] The values are means for triplicate measurements.

In the kinetic investigation and stereochemical analysis of the solvolysis of **1**–**3**, we have demonstrated that the acetolyses of **1**–**3**, and the hydrolyses of **2** and **3** proceed through typical S_N1 processes.[4] In the present experiments, the negative ρ values of the acetolyses of **4**–**6**, and the hydrolyses of **5** and **6** indicate that the substituents on the aromatic nuclei affect the stability of the neighboring carbocation, and the carborane cages transmit the electronic effects. Investigation of ^{13}C chemical shifts and the UV–vis spectra of aryl-p-carboranes afforded the spectroscopic evidence of the transmission of electronic effects by carboranes.[10] Several groups have synthesized rigid-rod molecules bearing carboranes.[11,12] These compounds have attracted interest, particularly in the field of materials such as liquid crystals.[13] The present results provide the first kinetic evidence that electronic effects are transmitted through carboranes.

On the other hand, the significant rate-acceleration in the hydrolysis of **1** and the results of stereochemical analysis

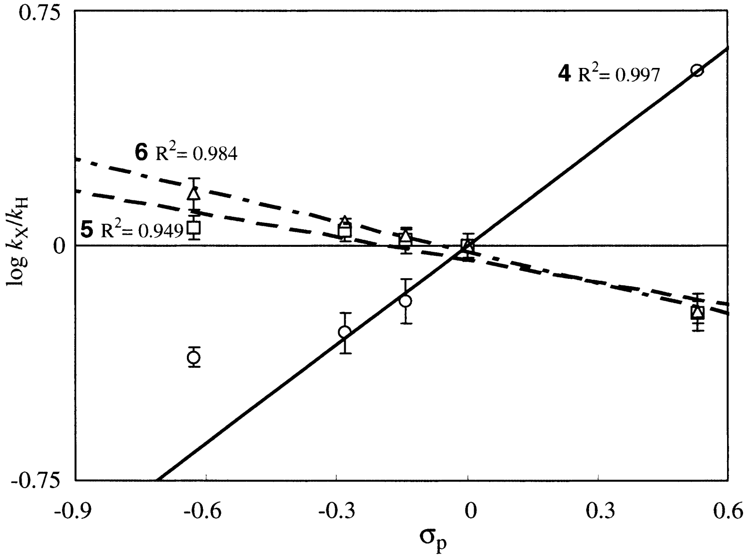

Figure 3. Hammett plot of k_X/k_H against σ_p for the hydrolysis of **4**–**6**. Results are shown as means ±S.D. for triplicate measurements.

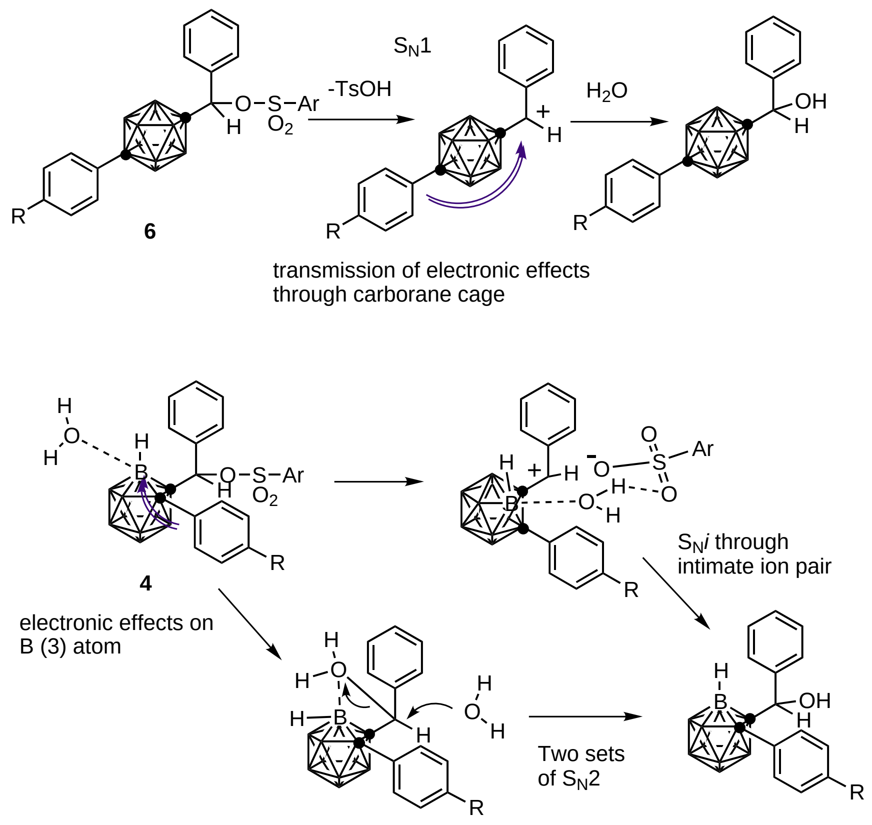

Figure 4.

lead us to conclude that the mechanism of the hydrolysis of **1** is distinct from those of **2** and **3**.[4] We hypothesize a mechanism initiated by interaction between the oxygen atom of the nucleophile and the most electron-deficient 3-position boron atom in the *o*-carborane cage for the characteristic reaction of **1**, because the interaction is expected to occur in the first step of deboronation of *o*-carborane to the *nido*-7,8-$C_2B_9H_{12}^-$ by strong nucleophiles such as alkoxides,[14] aliphatic amines[15] and fluoride ion.[16] The positive ρ value of the hydrolysis of **4** is not consistent with a stabilizing effect on the neighboring carbocation, but is consistent with alteration of the electron density of the 3-position boron atom by the aromatic substituents. The results indicated that the electron deficiency of the 3-position boron atom of the *o*-carborane cage and the character of the nucleophile determine the rate of this reaction. Fig. 4 shows an outline of our proposed two mechanisms and the electronic effects of the aromatic substituents in the hydrolyses of **4** and **6**. One of them is a six-membered cyclic structure (intermolecular S_Ni mechanism) as shown in the scheme. The first step of the reaction is interaction between the oxygen atom of nucleophile, which is hydrogen-bonded to sulfonate, and the 3-position boron atom in the carborane cage. This structure would afford the six-membered cyclic transition-state. Then elimination of sulfonic acid would give the retentive product. The other one is two sets of S_N2 processes in the scheme. The first step of the reaction is also interaction between the oxygen atom of nucleophile, which attack to carbon by intramolecular S_N2. This intermediate is attacked by the nucleophile, and elimination of the nucleophile to give the product. This mechanism seems to be unnatural, however, it is not excluded, because the mechanism of deboronation of *o*-carborane, especially the nature of the intermediate has not been established. We are currently examining the mechanism of this new type of neighboring group effect by the cage-boron atom of *o*-carborane in nucleophilic solvolysis, as well as the mechanism of deboronation of *o*-carborane to the *nido*-7,8-$C_2B_9H_{12}^-$, in more detail.

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into a JEOL JMN-A500 spectrometer (500 MHz), and warmed to the desired temperature. ^{1}H NMR spectra were recorded at intervals. Decrease of the starting materials obeyed good first-order kinetics ($R^2 = 0.99$). The temperature in the NMR probe were corrected by the measurement and calibration of the chemical shifts of ethylene glycol. (a) Van Geet, A. L. *Anal. Chem.* **1968**, *40*, 2227–2229; (b) Marino, D. F.; Wolff, F.; Ingle, Jr., J. D. *Anal. Chem.*, **1979**, *51*, 2050–2051.

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