

Conjugation between σ - and π -Aromaticity in 1-C-Arylated Monocarba-*closo*-dodecaborate Anions

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Supporting Information

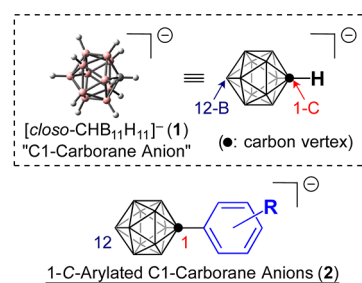
ABSTRACT: Conjugation between σ - and π -aromatic moieties in 1-C-arylated monocarba-*closo*-dodecaborate anion derivatives **2** has been identified by means of kinetic experimental studies combined with theoretical calculations. We found that the reaction rate of iodination at the 12-B vertex of the carborane anion cage was affected by distal substituents on the benzene ring connected at the antipodal carbon vertex. Hammett and Yukawa–Tsuno plots indicated that substantial resonance effects are involved. Density functional theory calculations enabled detailed interpretation of the electronic interaction.

Monocarba-*closo*-dodecaborate [*closo*-CHB₁₁H₁₁][−] (**1**; denoted here as C1-carborane anion)¹ is an icosahedral cluster molecule that consists of 1 carbon and 11 boron atoms. It has long been regarded as a three-dimensional aromatic system,² by analogy with two-dimensional π -aromaticity, in terms of its chemical properties such as bond equivalence, thermal stability, charge delocalization, and reaction characteristics.³ However, this similarity is essentially superficial, because C1-carborane anion is structurally and electronically quite different from π -aromatic compounds, as can be appreciated from the fact that it is constructed with only σ -bonds (so-called “ σ -aromaticity”).⁴ Thus, the question of electronic interaction between σ - and π -aromaticity is of great interest. In this Communication, we report the first example of kinetic investigation of an electrophilic substitution reaction of a series of 1-C-arylated C1-carborane anion derivatives **2**, leading to the discovery of a unique σ – π conjugation.

Extended electron delocalization, namely conjugation, is a key feature of many functional molecules. In this connection, several attempts have been made to study electronic transmission between antipodal substituents (i.e., at the 1-C and 12-B vertices) through the cage of **1**.⁵ Static analyses (acidity measurement of carboxylic acid derivatives^{5a} and an NMR study of alkynyl derivatives^{5b,c}) have suggested the existence of partial resonance effects between the antipodal substituents. To obtain detailed insight into the electronic interaction between σ - and π -aromatic compounds, we focused on kinetic investigation of an electrophilic iodination reaction at the 12-B vertex of 1-C-arylated C1-carborane anions **2**. A series of **2** was prepared by means of our previously developed cross-coupling reaction of C1-carborane anion at the 1-C vertex,

using the copper complex of **1** in the presence of a palladium catalyst (Chart 1).⁶

Chart 1. Structures of [*closo*-CHB₁₁H₁₁][−] (1**, “C1-Carborane Anion”) and 1-C-Arylated C1-Carborane Anions **2****



1-C-Arylated C1-Carborane Anions (**2**)
2a: R = H, **2b:** R = Me, **2c:** R = *p*-OMe, **2d:** R = *m*-OMe,
2e: R = *p*-CO₂Me, **2f:** R = *m*-CO₂Me, **2g:** R = *p*-CF₃, **2h:** R = *m*-CF₃
2i: R = *p*-CN, **2j:** R = *m*-CN, **2k:** R = *p*-F, **2l:** R = *p*-Cl, **2m:** R = *p*-Br

The kinetic experiments were performed using a series of [NMe₄]**2** derivatives with an excess of I₂ in AcOH/THF at 70 °C. The reaction rates were measured by using ¹¹B{¹H} NMR analysis to follow the decrease of the starting materials.⁷ Electrophilic iodination reaction of **2** selectively proceeds at the 12-B vertex of the spherical cage, not on the aryl group.^{2,8} We found that the reaction rate was dependent on the π -aromatic substituents, and therefore we examined the iodination reactions of **2** having various substituents on the π -aromatic ring. Initially, given that the reaction occurred on the C1-carborane anion cage, which consists of only σ -bonds and is well away from the benzene ring, we used σ° values that were developed for systems with predominantly “inductive effects” (resonance-free parameters) for the preparation of a Hammett plot, as shown in Figure 1a.⁹ But a poor correlation was observed between σ° values and the logarithm of the ratio of reaction rate constants (k_X/k_H), and in particular, we noted that *para*-substituents having electron-donating resonance effects, such as *p*-OMe and *p*-F, deviate upward from the *meta*-line. Thus, the observed substituent effects seemed not to be governed only by inductive effects. Instead, we found that the use of Brown and Okamoto’s σ^+ parameters¹⁰ provided a much better correlation (Figure 1b), suggesting that not only inductive effects, but also “resonance effects”, which are

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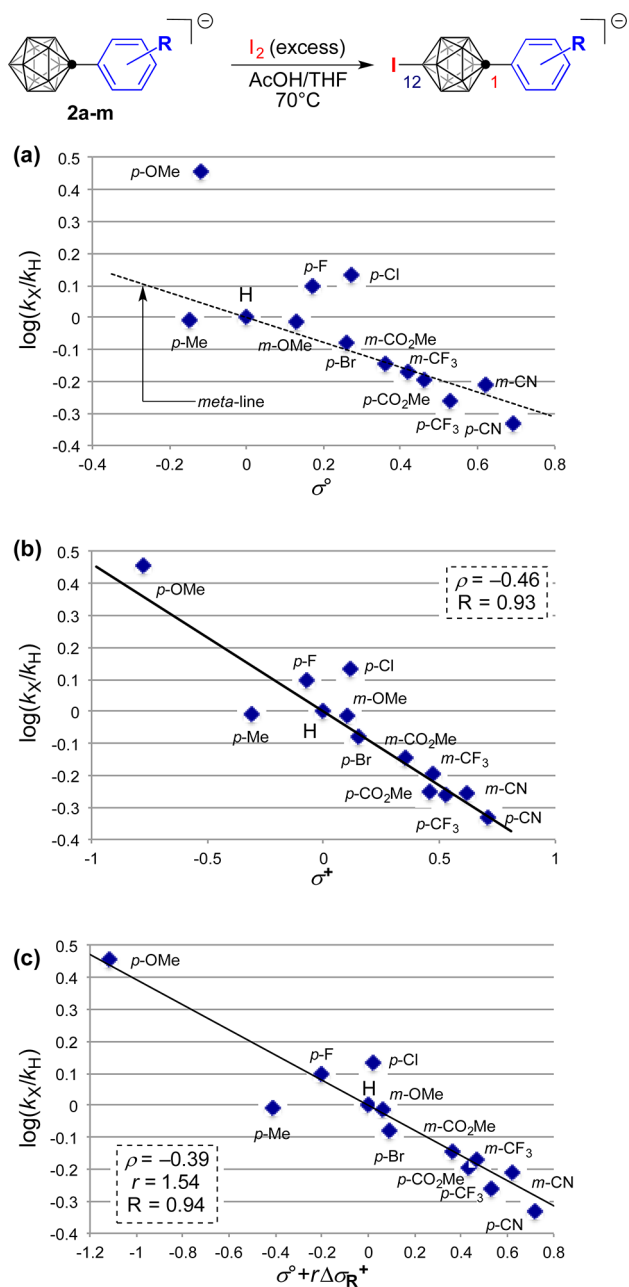


Figure 1. Electrophilic iodination reaction of 1-C-arylated C1-carborane anion derivatives: (a) Hammett plot for σ values (the *meta*-line is shown), (b) Hammett plot for σ^+ parameters, and (c) Yukawa-Tsuno plot.

transmitted from substituent R of the benzene ring to the opposite side of the C1-carborane anion cage in **2**, should be involved in the iodination.¹¹ Further detailed analysis was performed using the Yukawa-Tsuno equation,¹² $\log(k_X/k_H) = \rho(\sigma + r\Delta\sigma_R^+)$, where r is the resonance reaction constant, which treats the resonance and inductive effects separately: $\Delta\sigma_R^+ \equiv \sigma^+ - \sigma$. The Yukawa-Tsuno plot (Figure 1c) gave a good correlation and a rather large r value ($r = 1.54$), indicating that resonance(-type) effects play a substantial role in the iodination of the C1-carborane anion framework of **2**.

To obtain further insight into the reaction mechanism and resonance-type effects on the iodination reaction, DFT calculations were performed. First, the reaction course of iodination was investigated with Li-**2** as a model system (Figure

2).¹³ Introduction of an iodine atom at the 12-B vertex of Li-**2a** was found to proceed in an electrophilic manner with a

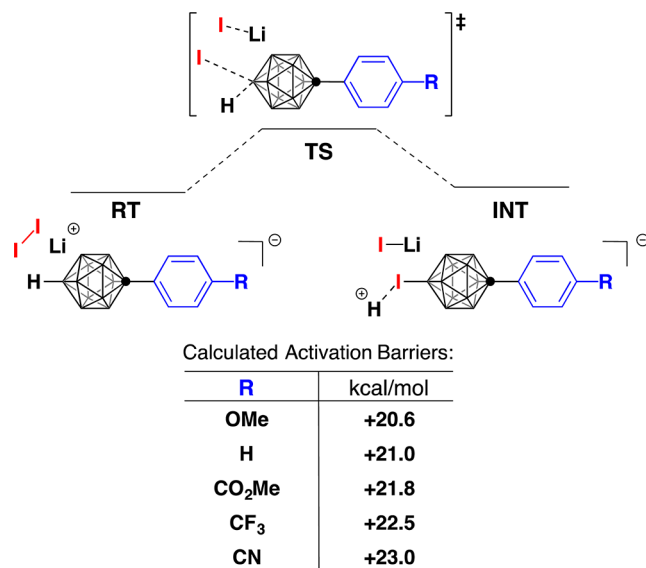


Figure 2. Computed reaction pathway of the iodination of Li-**2** and calculated activation barriers. Energy changes at the B3LYP/6-31+G* and SDD (for I) level of theory are shown.

reasonable activation barrier (21.0 kcal/mol), and the transition-state structure was related to the cationic Wheland intermediate in electrophilic aromatic substitution (S_EAr). Changing to a substrate having an electron-donating *p*-OMe substituent (Li-**2b**) lowers the activation barrier, while electron-withdrawing groups (CO₂Me, CF₃, and CN) on **2** result in higher activation energies for the iodination.

Given that the iodination of **2** proceeds in an electrophilic manner, we next investigated the occupied frontier orbitals of 1-C-arylated C1-carborane anion derivatives. Michl and co-workers have presented a detailed interpretation of the frontier MOs of **1**.⁴ The results of our DFT calculations at the B3LYP/6-31+G* level¹⁴ are consistent with their analysis (Figure 3, left); the doubly degenerate HOMO of **1** does not have any coefficient on the 1-C and 12-B vertices, and the next degenerate orbital pair (HOMO-1) has coefficients on the antipodal vertices. A schematic diagram of the frontier orbitals of **2a** is shown in Figure 3. Rather strong orbital interaction was observed between one of the degenerate HOMO-1s of **1** and one of the HOMOs of the benzene ring (shown with red lines). Out-of-phase interaction at the carbon vertex forms the HOMO of **2a**,¹⁵ which appears to show π -conjugation-like interaction over the whole molecule, and the in-phase interaction provides the more stable HOMO-5. Much weaker orbital interaction between one of the HOMO-1s of **1** and the other HOMO of benzene was found to generate a small split of HOMO-1 and HOMO-4 of **2a** (shown with blue lines). Side views of these orbitals show similar symmetry properties. The other HOMO-1s and the HOMO-1s of **1** (black line) were not involved in the interaction between the two moieties, because of mismatch of symmetry (i.e., the vertical π -symmetric contributions). Changing the model substrate to other derivatives of **2** having electron-donating or electron-withdrawing substituents (such as *p*-OMe and *p*-CO₂Me) provided very similar conjugation behavior.⁷ Thus, similar HOMO-

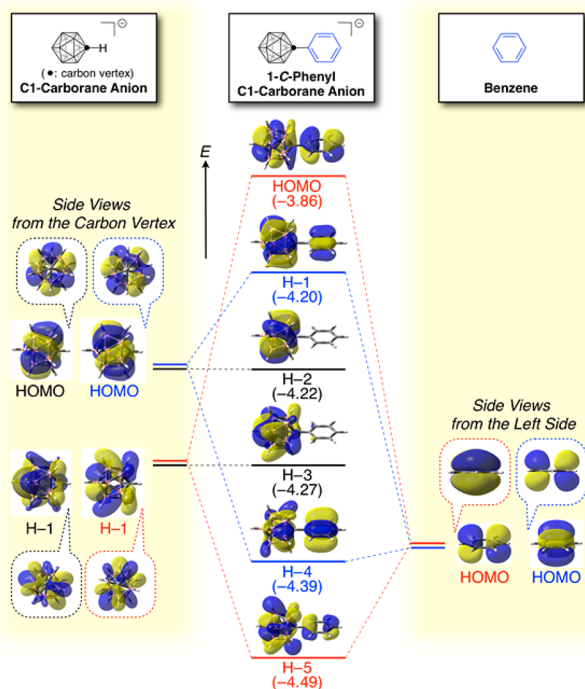


Figure 3. Orbital correlation diagram for **2a**. Calculations were performed at the B3LYP/6-31+G* level. The calculated energies (eV) are shown in parentheses.

controlled reaction appears to occur throughout the series of **2**, with efficient delocalization along the whole molecule.¹⁶

It was confirmed that the delocalized HOMO plays a key role and participates in the transition state of the electrophilic iodination of **2a** (Figure 4a). Given that such conjugation results from effective orbital interaction between two aromatic moieties, the electronic properties of the substituted π -aromatic

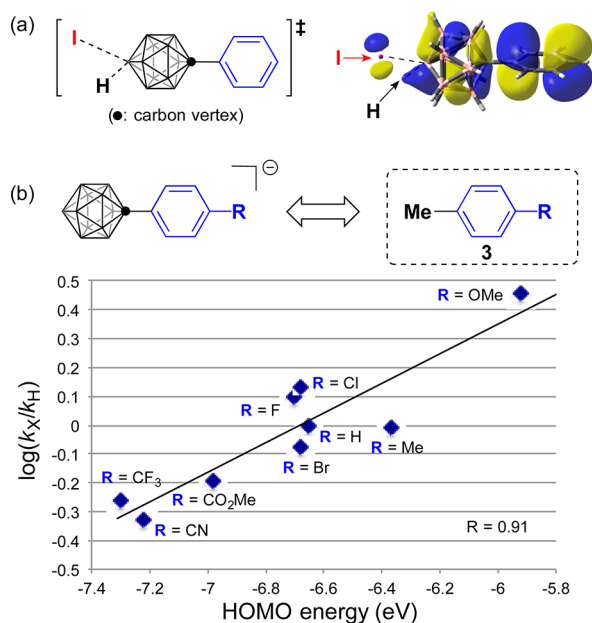


Figure 4. (a) Kohn–Sham HOMO of TS structure in the iodination of **2a** [**2a**...I⁺]. (b) Relation between the calculated HOMO energies of **3** and reaction rates of the iodination. Calculations were performed at the B3LYP/6-31+G* and SDD (for Br, I) level.

moiety should directly affect the kinetic behavior, namely the reaction rate. Thus, we plotted the calculated HOMO energy levels of a variety of *p*-substituted toluene derivatives **3**, which represent models of the *p*-substituted aryl moiety in **2**, against the logarithm of the relative rate constants (k_x/k_H), as shown in Figure 4b. A good correlation was observed with a variety of *p*-substituents of **3**, corroborating the existence of resonance effects from the π -aromatic benzene unit to the C1-carborane cage (see Figure 1).^{17,18} These substituent effects intuitively match the expected behavior for π -conjugation. Thus, the effects of conjugation between the σ - and π -aromatic moieties on the kinetic behavior in the electrophilic reaction are both experimentally and theoretically supported.

In summary, we have identified extensive electronic interaction along the whole molecule of 1-C arylated C1-carborane anion derivatives, and evaluated its effects on the kinetic behavior, namely reactivity, in electrophilic iodination. Substituents on the benzene ring significantly affect the reaction rate, and kinetic analysis suggested that resonance-type effects play a key role. The existence of efficient conjugation was confirmed by DFT calculations. In contrast with electrically neutral C2-carborane [*closo*-C₂B₁₀H₁₂],¹⁶ C1-carborane anion can construct conjugation with π -aromatic groups, by virtue of the appropriately high energy level of its frontier occupied orbitals due to the intrinsic character of the anion molecule. Here, the molecular design and the choice of reaction as a probe enabled us to highlight the unprecedented, rather strong resonance effects between the C1-carborane anion framework and the benzene ring. Further investigations of conjugation between σ - and π -aromaticity and the utilization/application of compounds showing this effect as “conjugated materials” are the subjects of ongoing research.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b10321.

Experimental procedures, spectral data, and computational details (PDF)

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Notes

The authors declare no competing financial interest.

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- (13) The reaction mechanism of electrophilic halogenation is not known in detail; see ref 1. It should be pointed out that the electrophile-induced nucleophilic substitution mechanism is not completely excluded, though such pathways have not been determined in our calculations.
- (14) Calculations at the HF/STO-3G level also gave consistent results with simplified pictures of the orbitals. See [Supporting Information](#), Figures S4 and S5.
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- (16) Related electrically neutral C2-carborane ($[closo-C_2B_{10}H_{12}]$) derivatives having a π -aromatic ring show only inductive effects without effective orbital interaction, due to the much lower HOMO level of the C2-carborane moiety. For a reported example, see: Morisaki, Y.; Tominaga, M.; Chujo, Y. *Chem. - Eur. J.* **2012**, *18*, 11251. For the results of our calculations, see [Supporting Information](#), Figure S7.
- (17) There was also a good correlation between the HOMO energy levels of a series of **2** and $\log(k_X/k_H)$ for the iodination reaction. For details, see [Supporting Information](#), Figure S8.
- (18) The relation between the HOMO energy levels of *m*-substituted toluenes was not simple, probably due to the (partial) involvement of HOMO-1 orbitals in *m*-substituted derivatives of **2**. For details, see [Supporting Information](#), Figures S10–S12.