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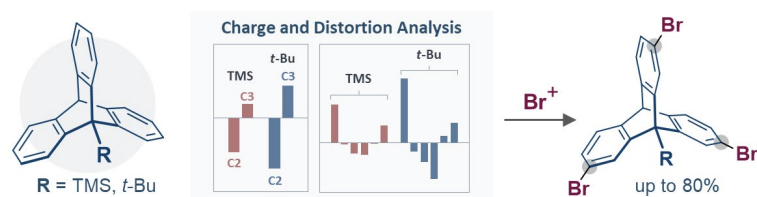
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Electrophilic Substitution of Asymmetrically Distorted Benzenes within Triptycene Derivatives

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Supporting Information Placeholder



ABSTRACT: Herein we disclose a unique directing effect of 9-substituted triptycenes in electrophilic substitution to achieve the regioselective functionalization of the triptycene core. The Hirshfeld population analysis was adopted to predict the selectivity in electrophilic substitution. TMS and *t*-Bu groups were found to considerably accelerate the reaction at C2 positions to produce C₃-symmetric isomers. Correlation between distortion and charge distribution within benzene rings was systematically examined.

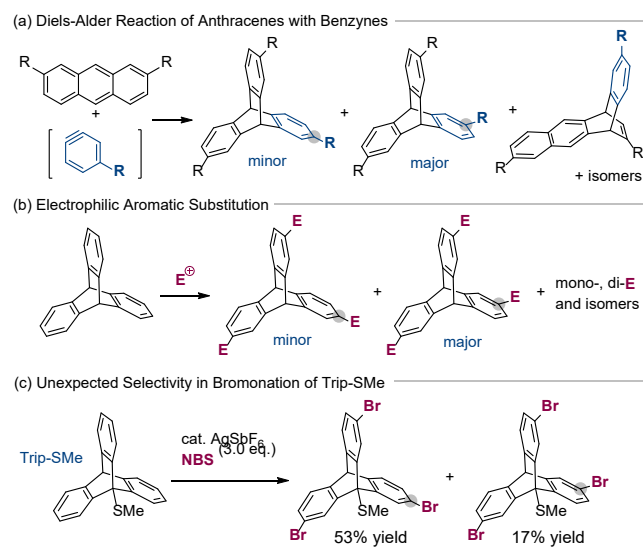
Triptycene is a paddle-wheel shaped aromatic hydrocarbon in which three benzene rings are fused within a barrelene core.¹ Functionalized triptycene derivatives have been of privileged structures in many research areas involving material science, supramolecular chemistry, molecular machine, etc.^{2,3} owing to the unique three-dimensional rigid architecture. Accordingly, a significant interest has focused on the development of efficient and controllable synthetic methods to manufacture functionalized triptycenes.

A conventional synthetic method is the Diels-Alder reaction of anthracenes with benzyne (Scheme 1a). This strategy is not suitable for synthesizing functionalized triptycenes because it is hardly possible to control the regioselectivity of the cycloaddition event.^{4,5} Moreover, cumbersome multi-step synthesis would be inevitable for the preparation of substituted reactants. Alternatively, electrophilic substitution has been a practical tool to directly introduce functionalities onto the periphery of triptycene core.⁶ The transannular π - π interaction between the remote benzene rings has been well-established,⁷ but this interaction exerts negligible effects on the site-selectivity. Therefore, the three benzene rings independently react with electrophiles to form all possible isomers whose distribution is statistically governed (Scheme 1b). Iridium-catalyzed C-H borylation has also been utilized to directly install functionalities to the triptycene core.⁸ The selectivity in this method can be treated similarly to the electrophilic substitution and give the same result. Obviously, it is highly challenging to break the D_{3h} symmetry of this molecule and systematically construct C₃-symmetric aromatic scaffolds, and a new synthetic approach should be required to overcome the statistical limitation.⁹

Meanwhile, we recently introduced a triptycene-based Lewis base catalyst Trip-SMe (Trip = 9-triptyceny) for electrophilic

halogenation of unactivated aromatics using *N*-halosuccinimides.¹⁰ This catalyst forms a corresponding halo-sulfonium complex in situ, and its enhanced charge-separated ion character contributes the high catalytic activity, and AgSbF₆ was employed as a source of weakly coordinating anion. During the study, we found that the bromination of Trip-SMe proceeded with considerable regioselectivity to give the C₃-symmetric isomer as a major product (Scheme 1c).

Scheme 1. Synthetic Methods for Functionalized Triptycene Derivatives



This result indicates that the substituent at the bridgehead position can modulate the positional selectivity in functionalizing the aromatic moiety, leading to an efficient synthetic method

for Janus-type triptycene derivatives. Herein, we evaluated the unprecedented directing effect for a series of 9-substituted triptycenes. The Hirshfeld population analysis was adopted to predict the selectivity in aromatic electrophilic reactions. Additionally, a unique trend between the distortion within a benzene ring and the charge distribution was theoretically examined.

At the outset, we conducted a computational study to evaluate the unexpected C2-selectivity observed in the bromination of Trip-SMe (**1b**). In 2019, Galabov established a quantitative correspondence between the σ^0 substituent constants of benzene derivatives and the Hirshfeld charge on ring carbon atoms.¹¹ This method was adopted to estimate the reactivity and regioselectivity of **1b** as well as several triptycene derivatives (**1c–1f**). Geometry optimizations and frequency calculations were carried out at the M06X-2/6-311+G(d,p) level of theory with IEF-PCM (DCE) solvation. The Hirshfeld population analysis was conducted at the B3LYP/6-311+G(3df,2pd) level. The charge differences according to a reference triptycene (**1a**: R = H, $\Delta q = 0$) were summarized in Figure 1. Note that the lower Δq values correspond to the higher nucleophilicity of carbon atoms.

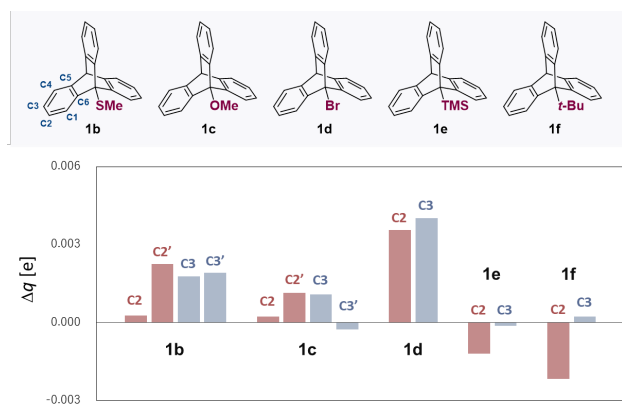


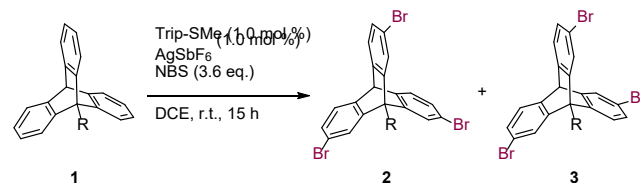
Figure 1. Summary of the difference in Hirshfeld charges calculated at the B3LYP/6-311+G(3df,2pd) level.

All the triptycene derivatives have staggered conformations as the energy minima. Accordingly, inequivalent benzene rings were considered for Trip-SMe (**1b**) and Trip-OMe (**1c**): two rings close to the methyl group (C2 and C3) and the other one opposite to the methyl group (C2' and C3').¹² The calculated charges for Trip-SMe (**1b**) indicated that the C2 position is more nucleophilic than the other three carbon atoms. This is consistent with the selectivity observed in the halogenation (Scheme 2b). On the other hand, the C3' atom was somewhat activated for Trip-OMe (**1c**). Trip-Br (**1d**) exhibited positive charges both on C2 and C3 atoms, suggesting its low reactivity toward electrophiles. Intriguingly, installation of TMS (**1e**) or *t*-Bu (**1f**) group at the bridgehead carbon established considerable negative charges on C2 atoms, whereas C3 atoms were almost neutral as compared to that of triptycene (**1a**). These results prompted a speculation that the electrophilic substitution of Trip-TMS (**1e**) and Trip-*t*-Bu (**1f**) proceeds with better regioselectivity.

With this picture in mind, we evaluated the regioselectivity in bromination adopting a Trip-SMe/AgSbF₆ catalyst system. A series of triptycene derivatives were treated with NBS under the standard conditions (Table 1). The reaction of triptycene (**1a**) ended up in 60% mono-bromination probably because of its poor solubility in DCE (entry 2). Trip-OMe (**1c**) afforded a

complex mixture of isomers, and the yield of **2c** and **3c** could not be determined (entry 3). Trip-Br (**1d**) reacted rather sluggishly to give the target products only in low yield (up to 10% in total, entry 4). To our delight, the C2 position was preferentially brominated for Trip-TMS (**1e**) (C2/C3 = 85/15), and the corresponding C₃-symmetric molecule **2e** was obtained in 64% yield along with 22% of a minor isomer **3e** (entry 5). Further improvement in selectivity was observed for the reaction of Trip-*t*-Bu (**1f**) to produce **2f** in 80% yield (entry 6), and the formation of other isomers was considerably reduced. The structures of **2e** and **2f** were unambiguously determined by 2D NMR and X-ray crystallographic analyses (CCDC 2067724 and 2067725). These outcomes correspond well to the charge analysis (Figure 1).

Table 1. Optimization Study ^a



entry	R	yield of 2 and 3 ^b	note ^b
1 ^c	SMe (1b)	2b (53%), 3b (17%)	--
2	H (1a)	not detected	1a 44%, mono 60%
3	OMe (1c)	not determined	complex mixture
4	Br (1d)	<10% in total	mono 27%, di 59%
5	TMS (1e)	2e 64% (61%), 3e 22%	<20% other isomers
6	<i>t</i> -Bu (1f)	2f 80% (51%)	<20% other isomers

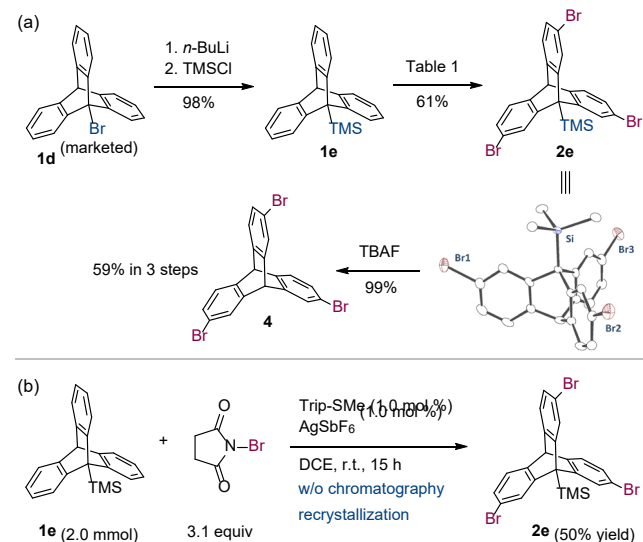
^a Reaction conditions: **1** (0.2 mmol), NBS (0.72 mmol), Trip-SMe (1.0 mol %), and AgSbF₆ (1.0 mol %) in DCE solvent (2.0 mL). ^b Estimated by NMR and GC-MS analyses. Isolated yield is in parentheses. ^c Data from the ref 10.

In particular, the directing effect of TMS group is synthetically valuable to obtain a statistically minor isomer. Trip-TMS (**1e**) was readily prepared from commercially available Trip-Br (**1d**) in one step (Scheme 2). The bromination product **2e** was isolated by regular silica-gel column chromatography, and the directing group was quantitatively removed upon treatment with TBAF (tetrabutylammonium fluoride), affording 2,7,14-tribromotriptycene (**4**) in 59% yield over 3 steps. A conventional method for this compound has required cumbersome multistep processes via nitration by conc. HNO₃, Raney Ni reduction of the minor isomer, and Sandmeyer halogenation (total 13% yield).¹³ Notably, the bromination of **1e** could be conducted in 2.0 mmol scale, and the desired product was isolable in 50% yield by recrystallization from the crude material without chromatographic purification. Although Trip-*t*-Bu (**1f**) exhibited better selectivity in the bromination (Table 1, entry 6), its preparation suffers from low efficiency (total 15% yield over three steps).¹⁴ Moreover, purification of **2f** from the crude reaction mixture is not easy (51% isolated yield, Table 1 entry 6), and it is hardly possible to remove the *t*-Bu directing group afterward.

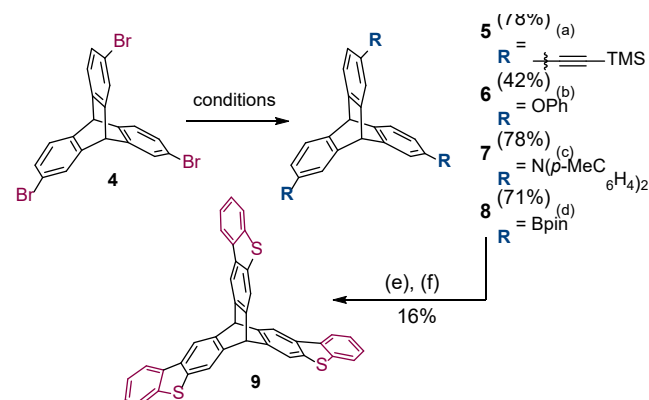
Next, we examined some derivatizations of **4** to highlight the synthetic utility (Scheme 3). Under the standard Sonogashira conditions, three alkyne units were efficiently introduced to the triptycene core (**5**, 78% yield). The corresponding aryl ether **6** and amine **7** were synthesized by Buchwald-Hartwig coupling reactions in 42% and 78% yield, respectively.¹⁵ It is noteworthy

that a thiophene-fused three-dimensional π architecture (**9**) was readily constructed via the sequential borylation (**8**, 71% yield), cross-coupling reaction, and acid-mediated intramolecular cyclization. Synthesis of these isomerically uniform molecules have been scarce probably due to the limited availability of suitable building blocks such as **4** and **8**.

Scheme 2. (a) Installation and Removal of the TMS Directing Group (b) Scale-Up Reaction



Scheme 3. Derivatization of **4**



Reaction Conditions: (a) TMS-acetylene (7.5 eq.), Pd(PPh₃)₄ (15 mol %), CuI (10 mol %), and *i*-Pr₂NH (7.5 eq.) in toluene at 85 °C for 18 h; (b) phenol (3.3 eq.), Pd(OAc)₂ (15 mol %), *t*-BuXPhos (20 mol %), and K₂CO₃ (6.0 eq.) in toluene at 100 °C for 24 h; (c) di(*p*-tolyl)amine (3.3 eq.), Pd(OAc)₂ (15 mol %), dppf (45 mol %), and *t*-BuONa (9.0 eq.) in toluene at 100 °C for 18 h; (d) B₂pin₂ (3.3 eq.), PdCl₂(PPh₃)₂ (10 mol %), and KOAc (3.3 eq.) in 1,4-dioxane at 120 °C for 18 h; (e) (2-bromophenyl)methyl sulfoxide (3.9 eq.), Pd(PPh₃)₄ (10 mol %), TBAB (10 mol %), and K₂CO₃ aq. in THF at 70 °C for 24 h; (f) TfOH in DCE at r.t. for 24 h, then pyridine and H₂O, reflux for 4 h.

The directing effect of TMS group was also examined for other electrophiles (Scheme 4). The C2/C3 selectivity was 72/28 for trifluoromethylthiolation using SCF₃-saccharin¹⁶ to produce **10** in 35% yield. On the other hand, lower selectivity was observed for nitration (C2/C3 = 57/43),¹⁷ giving the target product **11** in 11% yield. These results indicated that the regioselectivity considerably depends on the electrophile as well as

the reaction conditions employed (for details, see the Supporting Information).¹⁸

Triptycene (**1a**) is a molecule with a typical Mills-Nixon effect,¹⁹ exhibiting a considerable bond alternation within the benzene rings: C1–C2, C3–C4, and C5–C6 bonds have single bond character. As a result, the enhanced positional selectivity in the electrophilic substitution was observed at β carbons (C2 and C3) rather than α carbons (C1 and C4). Additionally, substituents at the bridgehead position of triptycene derivatives **1b**–**1f** would asymmetrically distort the ring (for details, see the Supporting Information). In order to elucidate correlation between such a strain and the charge distribution, we calculated Hirshfeld atomic charges for “distorted *o*-xylenes” quarried from the optimized geometries of **1b**–**1f** (Figure 2).

Scheme 4. Reaction of **1e** with Other Electrophiles

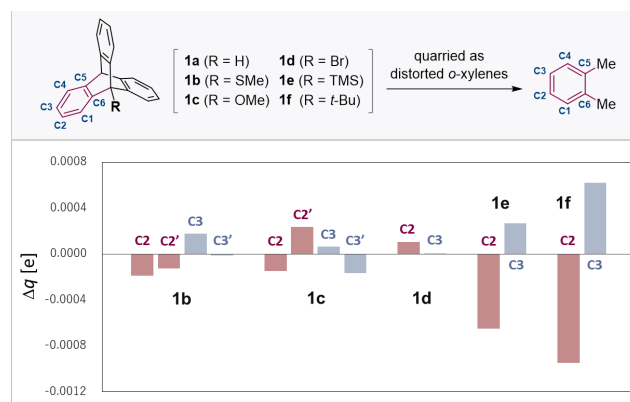
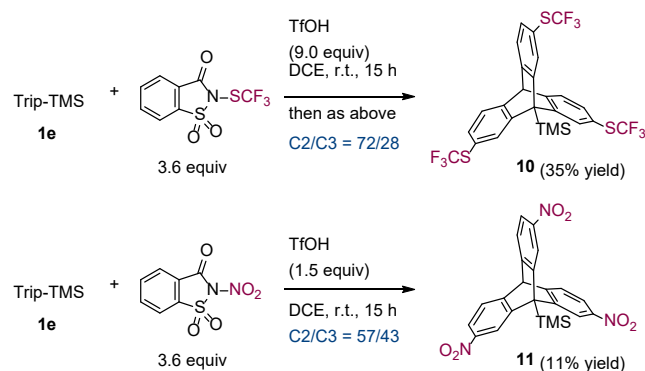


Figure 2. Summary of the difference in Hirshfeld charges calculated at the B3LYP/6-311+G(3df,2pd) level.

Trip-SMe (**1b**), Trip-OMe (**1c**), and Trip-Br (**1d**) showed no clear trend. In sharp contrast, each C2 atom of Trip-TMS (**1e**) and Trip-*t*-Bu (**1f**) carried significant negative charges, whereas C3 atoms were positively charged. Because TMS and *t*-Bu groups exert minimal inductive effects to the triptycene core, the high C2 selectivity observed for Trip-TMS (**1e**) and Trip-*t*-Bu (**1f**) can be mainly attributed to the structural distortion by the steric effect.²⁰ As compared to the benchmark triptycene (**1a**), these two molecules have elongated bonds close to the R group (C5–C6 and C6–C1) and shortened bonds distant from it (C2–C3 and C3–C4). This might lead to the increased diene character over C2–C5 atoms within benzene rings, thereby the terminal C2 carbon atom preferentially reacted with electrophiles. We would like to emphasize that such a selectivity induced by asymmetrical distortion has not been investigated, and the triptycene scaffold would be a suitable model for the study.

Conventionally, the site selectivity in aromatic substitution reactions has been discussed based on the stability of corresponding sigma complexes.²¹ We acquired relative energies for C2- and C3-protonated species of Trip-TMS (**1e**) as well as Trip-*t*-Bu (**1f**) at the M06X-2/6-311+G(d,p) level. In both cases, the C2 adduct had lower energy than the C3 adduct by 2.25 kcal/mol for **1e** and 1.63 kcal/mol for **1f**, respectively. The positive charge within each complex considerably localized at the para position to the sp³ carbon. This is also consistent with the observed regioselectivity.

In conclusion, we disclosed a unique directing effect of 9-substituted triptycene derivatives for the electrophilic substitution. The Hirshfeld population analysis was utilized to predict the selectivity in bromination reactions, and Trip-TMS (**1e**) and Trip-*t*-Bu (**1f**) were found to produce C₃-symmetric isomers as major products. In addition to the Mills-Nixon effect, structural distortion of benzene rings was found to be a key factor to enhance the positional selectivity.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

- Experimental procedures, computational method, product identification data, and copy of NMR spectra (PDF)
- Atomic coordinates of all calculated molecules (XYZ)
- Crystallographic data for **2e** (CIF)
- Crystallographic data for **2f** (CIF)

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Notes

The authors declare no competing financial interest.

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