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Development of Synthetic Pathways for Carbon Nanohoops

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Development of Synthetic Pathways for Carbon Nanohoops

Yiwei Huang

Thesis submitted to the
Eberly College of Arts and Sciences
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Chemistry

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Morgantown, West Virginia
2013

Keywords: Cycloparaphenylene, Carbon Nanotube, Carbon Nanohoop
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ABSTRACT

Development of Synthetic Pathways for Carbon Nanohoops

Yiwei Huang

A synthetic pathway was developed for the preparation of a precursor of a [6]cycloparaphenylene derivative, which represents the shortest repeating carbon nanohoop segment of an armchair (6,6) carbon nanotube. As a key intermediate of the synthetic sequence, trans,trans-1,4-di(4-bromophenyl)-1,3-butadiene was synthesized by using the Horner–Wadsworth–Emmons reaction between 4-bromocinnamaldehyde and diethyl 4-bromobenzylphosphonate reported in the literature. The use of BF₃·OEt₂ as a Lewis acid for the Lewis acid-catalyzed Diels–Alder reaction between trans,trans-1,4-di(4-bromophenyl)-1,3-butadiene and 1,4-benzoquinone was successful in producing cis-5,8-di(4-bromophenyl)-5,8-dihydro-1,4-naphthalenediol. The Diels–Alder reaction ensures that the two 4-bromophenyl substituents are cis to each other in the six-membered ring, which is of critical importance for the subsequent dimerization reaction. Methylation with dimethyl sulfate in the presence of potassium carbonate afforded the corresponding methylated hydroquinone. The nickel(0)-catalyzed homocoupling reactions produced the corresponding dimers as a mixture of diastereomers with the two 1,4-dimethoxyphenyl groups pointing either in the same direction or in the opposite directions. It is envisioned that aromatization of the dimers could then lead to the [6]cycloparaphenylene derivative.
Dedicated to

my parents
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Part I

Development of Synthetic Pathways for Carbon Nanohoops

1. Introduction

Carbon nanotubes (CNTs) are cylindrical nanostructures comprised of carbon atoms. They are allotropes of carbon. Carbon nanotubes were first discovered in 1952 by L. V. Radushkevich and V. M. Lukyanovich. Since the discovery, several methods for the synthesis of carbon nanotubes have been developed, including arc discharge, laser ablation, chemical vapor deposition, flame pyrolysis, and bottom-up organic synthesis approach.

Figure 1. Structures of single-walled armchair (6,6)-CNT, armchair (8,8)-CNT, zigzag (9,0)-CNT, and zigzag (12,0)-CNT.
There are three general types of single-walled carbon nanotubes: armchair, zigzag, and chiral. Typical examples of armchair and zigzag single-walled carbon nanotubes are given in Figure 1.

For armchair carbon nanotubes, \([n]\)cycloparaphenylenes represent the shortest segments of the repeating units. In the cases of zigzag carbon nanotubes, \([n]\)cyclacenes are the shortest repeating units. The structures of \([6]\)cycloparaphylene and \([12]\)cyclacene, representing the shortest segment of armchair (6,6)-CNT and zigzag (12,0)-CNT, respectively, are depicted in Figure 2. The structure of \([6]\)cycloparaphylene is constructed by \(para\) connections of six benzene rings whereas the structure of \([12]\)cyclacene is formed by side-by-side fusing of 12 benzene rings. Several representative \([n]\)cycloparaphenylenes have been synthesized. However, because of the reactive nature of the extended acene derivatives, \([n]\)cyclacenes have not yet been synthesized.

\[ \text{[6]cycloparaphylene} \quad \text{[12]cyclacene} \]

**Figure 2.** Structures of [6]cycloparaphylene and [12]cyclacene.

The first synthesis of cycloparaphenylenes was reported by Bertozzi, Jasti and co-workers in 2008 (Scheme 1).\(^3\) The first step of the synthetic sequence was monolithiation of 1,4-diiodobenzene with \(n\)-BuLi at \(-78^\circ\text{C}\), followed by addition of \(p\)-benzoquinone to generate a \(syn\)-diol. The diol was alkylated using methyl iodide to form diiodide 1.
Transformation of diiodide 1 to diboronate 2 followed by the Suzuki–Miyaura coupling reaction with diiodide 1 produced a mixture of macrocycles 3, 4 and 5. Each macrocycle was then treated with lithium napthalenide, leading to the corresponding [9]cycloparaphenylene 6, [12]cycloparaphenylene 7, and [18]cycloparaphenylene 8, respectively. Recently, this general synthetic strategy was extended to the synthesis of [6]cycloparaphenylene.


Yamago and co-workers reported a synthesis of [8]cycloparaphenylene from a square-shaped tetranuclear platinum complex in 2010 (Scheme 2). 4,4'-Bis(trimethylstannyl)biphenyl (9) was used as the starting material in this case. It was treated with one equivalent of PtCl2(COD) in THF under reflux for 35 hours, affording
the square-shaped platinum complex 10 in 57% yield. This platinum complex 10 was then treated with four equivalents of 1,1′-bis(diphenylphosphino)ferrocene in dichloromethane at room temperature for 20 hours, producing the square-shaped platinum complex 11 in 91% yield. Reductive elimination reaction was then carried out by treating platinum complex 11 with seven equivalents of bromine in toluene at 95 °C for 17 hours, producing [8]cycloparaphenylenic 12 in 49% yield. It was the smallest CPP at that time.


Itami and co-workers reported a selective synthesis of [12]cycloparaphenylenic in 2009 (Scheme 3). In this synthesis route, 1,4-diiodobenzene was first treated with n-BuLi at −78 °C for monolithiation to form 4-iodophenyllithium, followed by the addition of 1,4-cyclohexanedione. The cis-isomer 13 was produced as the major product (cis:trans = 81:19) in 48% yield. The cis-diol 13 has an L-shaped structure. The cis-diol 13 was
then converted to the methoxymethyl (MOM)-protected diiodide 14 in 98% yield and diboronate 15 in 81% yield. Suzuki–Miyaura coupling between diiodide 14 and diboronate 15 afforded the trimer 16 in 81% yield. Trimer diiodide 16 was then coupled with diboronate 15 again to form the cyclic tetramer 17. Microwave assisted aromatization reaction occurred when tetramer 17 was treated with p-toluenesulfonic acid in m-xylene at 150 °C for 30 minutes, producing [12]cycloparaphenylene 7 in 62% yield. Several other cycloparaphenylenes were likewise synthesized.

So far, synthesis of [6]-, [7]-, [8]-, [9]-, [10]-, [11]-, [12]-, [13]-, [14]-, [15]-, [16]-, and [18]cycloparaphenylene have been reported. Also, some cycloparaphenylene derivatives have been successfully synthesized.
2. Research Plan

Our research goal is to develop a new synthetic pathway to the [6]cycloparaphenylene ([6]CPP) derivative 20. To achieve this goal, we plan to use the synthetic sequence outlined in Scheme 4 for its preparation.

\[ \text{18a, } R = H \quad \text{18b, } R = \text{MeO} \]

**Scheme 4.** A proposed synthetic route for the [6]cycloparaphenylene derivative 20.

The precursor 18 is to be prepared by the Diels–Alder reaction between *trans*, *trans*-1,4-di(4-bromophenyl)-1,3-butadiene (21) and a suitable dienophile, such as benzyne or *p*-benzoquinone (Scheme 5).

\[ \text{21} \]

**Scheme 5.** A proposed synthetic route for dibromide 18.
3. Results and Discussion

Compound 18 is a key intermediate in the design for the synthesis of the [6]cycloparaphenylene derivative 20. In the structure of dibromide 18, the two hydrogen atoms on the six-membered ring are cis to each other. As a result, the two bromo-substituted phenyl rings are cis to each other as well. In addition, the two R groups on the benzene ring could also play a very significant role. With the presence of 1,3-allylic strains, the two bromo-substituted phenyl rings would be close to being parallel to each other, which would be very helpful in directing the following coupling reactions toward the formation of a dimer because of the reduced ring strain in the [6]cycloparaphenylene precursor 19.

The MM2-optimized structure of 18a (R = H) depicted in Figure 3 indicates that the two 4-bromophenyl substituents are oriented not parallel to each other. On the other hand, the MM2-optimized structure of 18b (R = MeO) showed that the two 4-bromophenyl substituents are close to being parallel to each other. The parallel orientation of the two 4-bromophenyl substituents in 18b minimizes the 1,3-allylic strain arising from the steric interactions between the methoxy group and its neighboring 4-bromophenyl group.

In most of the reported cycloparaphenylene syntheses, the greatest challenge is to overcome the enormous strain energy in the bent aromatic systems, which leads to very low yields of cycloparaphenylenes of small ring sizes, formation of a variety of large size cycloparaphenylenes, and a combination of these two problems. The parallel orientations of the two 4-bromophenyl substituents in 18b could greatly minimize the ring strains. As a result, the subsequent coupling reaction could favor the formation of the dimer 19,
leading to the [6]cycloparaphenylene derivative 20 containing only six benzene units in the cyclic system.

Figure 3. MM2-optimized structures of dibromides 18a and 18b.

As it was mentioned early, the two 4-bromophenyl substituents in 18b are cis to each other. This cis relationship could be achieved by the Diels–Alder reaction between dibromide 21 and p-benzoquinone as outlined in Scheme 5. Dibromide 21 was previously synthesized by the Horner–Wadsworth–Emmons reaction between 25 and 27 as outlined in Scheme 6. The synthetic sequence outlined in Scheme 6 was carried out, and several grams of trans,trans-1,4-di(4-bromophenyl)-1,3-butadiene(21) were obtained.
Scheme 6. Synthesis of trans,trans-1,4-di(4-bromophenyl)-1,3-butadiene (21).

In addition, two new synthetic methods for the preparation of dienes were explored in order to provide flexibility for introducing other functionalities on the diene. The first method was outlined in Scheme 7, and phenylacetylene was used in the model study. Dicyclohexylborane (28) was obtained from hydroboration of cyclohexene using one-half equivalent of borane-dimethyl sulfide complex,\(^{20}\) which then served as a hydroborating reagent for the second hydroboration reaction with phenylacetylene to produce \((E)\)-alkenyldicyclohexylborane \(29a.\)\(^{21}\) Borane \(29a\) was transferred into a suspension of \(\text{NaOCH}_3\) in THF at room temperature to form the ate complex \(30,\) which was then transferred into one-half equivalent of zinc chloride solution in THF\(^{22}\) or a suspension of one equivalent of copper(I) bromide-dimethyl sulfide complex in THF\(^{23}\), to form the trans,trans-1,4-diphenyl-1,3-butadiene \(31.\) However, the model study using
phenylacetylene as the starting material produced only low yields of diene 31 presumably because of small scales of the reaction.

Scheme 7. Synthesis of diene 21 by ZnCl$_2$- or CuBr-SMe$_2$-promoted reductive coupling reaction.

The second method which combined the hydroboration reaction and the Suzuki–Miyaura coupling reaction was shown in Scheme 8. The starting material 4-bromophenylacetylene 33 was obtained through the Sonogashira coupling reaction between 1-bromo-4-iodobenzene and (trimethylsilyl)acetylene, which produced (4-bromophenyl)ethynyltrimethylsilane 32, followed by desilylation with the treatment of aqueous sodium hydroxide solution in a mixture of diethyl ether and methanol. Hydroboration of phenylacetylene and 4-bromophenylacetylene 33 with catecholborane
at 70 °C produced the corresponding 2-(E-alkenyl)-1,3,2-benzodioxaboroles 34a and 34b, respectively. Hydrolysis of 34a and 34b at 70 °C afforded the corresponding alkenylboronic acids 35a and 35b, respectively. Treatment of boronic acids 35a and 35b with iodine in diethyl ether in the presence of sodium hydroxide afforded alkenyl iodides 36a and 36b, respectively.\(^{20,24}\) The following Suzuki–Miyaura coupling reaction between 36a and 34a produced diene 31. Similarly, diene 21 could be produced from coupling between 34b and 36b.\(^{25}\) However, in the case of 4-bromophenylacetylene 33, the overall yield of corresponding alkenyl iodide 36b was very low, so this method was not further used to synthesize diene 21 in this research project. Nevertheless a success of this method could be very useful for the synthesis of other dienes to further enhance the versatility of this research project in the future.

With 21 in hand, the Diels–Alder reaction between 21 and p-benzoquinone was investigated. Several conditions were used, including (a) heating at 75 °C in benzene, (b) heating at 95 °C in benzene, (c) heating at 138 °C in p-xylene, (d) heating at 55 °C in
glacial acetic acid, (e) room temperature in glacial acetic acid, (f) room temperature in a mixture of solvent of glacial acetic acid and ethanol in the presence of hydroquinone, and (g) heating at 65 °C in a mixture of solvent of glacial acetic acid and ethanol in the presence of hydroquinone. However, none of these conditions worked.

So we decided to investigate the Diels–Alder reaction of diene 21 with a more reactive dienophile, benzyne. The method of using a fluoride to induce the 1,2-elimination of TMS and OTf groups to generate benzyne for the Diels–Alder reaction with diene 21 was investigated, as shown in Scheme 9. Three triflates, 2-(trimethylsilyl)phenyl trifluoromethanesulfonate (37a), 3-methoxy-2-(trimethylsilyl)phenyl trifluoromethanesulfonate (37b) and 3,6-dimethoxy-2-(trimethylsilyl)phenyl trifluoromethanesulfonate (37c) were used. The Diels–Alder reaction between diene 21 and triflate 37a was carried out first. In the initial experiment, 3 equivalents of triflate 37a was added in one portion to a mixture of diene 21 and cesium fluoride (6 equiv) in acetonitrile, and the reaction mixture was stirred under a nitrogen atmosphere at room temperature for 18 hours. After 18 hours, all of the diene were consumed, and the desired DA adduct 18a was formed. The structure of 18a was elucidated by $^1$H NMR with the appearance of two distinct peaks from the benzylic protons at δ 4.69 and the alkenyl protons at δ 5.91. However, in addition to the desired DA adduct 18a, a substantial amount of byproducts was formed. In order to avoid the formation of byproducts, the amount of triflate 37a was decreased to 1.5 equivalents and 3 equivalents of cesium fluoride were used, with all the other conditions remained the same. However, this time a lot of diene 21 remained unreacted after 18 hours. After careful consideration of the potential source of the problem, we thought that this problem...
could come from the low solubility of diene 21. Since 21 was not very soluble, once the very reactive benzyne 38a was generated in situ, there would not have enough diene 21 to react with it, and the highly reactive benzyne 38a could then lead to some other reactions such as polymerization, which led to a lot of byproducts. In order to solve this problem, two modifications were made. The first one was using a mixed solvent of dichloromethane and acetonitrile to increase the solubility of diene, and the second one was adding the triflate dropwise over a period of 12 hours, which was achieved by utilizing a pressure equalizing funnel. In this way, the small amount of triflate which was dripped into the reaction mixture would react with the small amount of cesium fluoride that dissolved in acetonitrile to generate a small amount of benzyne, which would then immediately react with the diene that dissolved in the mixed solvent to form the desired DA adduct. And the experiment result proved that our hypothesis was correct, with much less byproducts formed. Also, by monitoring the reaction, it was found that all the diene was consumed after the addition of 2 equivalents of triflate. Unfortunately, when the same method was applied to 3-methoxybenzyne 38b and 3,6-dimethoxybenzyne 38c, which were generated from 3-methoxy-2-(trimethylsilyl)phenyl triflate (37b) and 3,6-dimethoxy-2-(trimethylsilyl)phenyl triflate (37c), respectively, the yields were extremely low with most of the diene remained unreacted. Even by increasing the amount of triflates 38b and 38c, the yields did not improve too much.
Scheme 9. Formation of benzyne for the Diels–Alder reactions with diene 21

Then the Diels–Alder reaction between diene 21 and p-benzoquinone was re-investigated in the presence of a Lewis acid. Boron trifluoride-diethyl etherate, aluminum chloride and titanium tetrachloride were used to investigate the Lewis-acid catalyzed Diels–Alder reaction. The experiment was not successful in the case of TiCl₄-catalyzed DA reaction, but the BF₃·OEt₂-catalyzed DA reaction was very successful, and three products 40, 41 and 42 were obtained after purification by flash column chromatography (Scheme 10). The X-ray crystal structures of 40 and 41 are shown in Figure 4. In a 1g-scale diene Diels–Alder reaction that was catalyzed by BF₃·OEt₂, 110 mg of the benzoquinone adduct 40 (9% yield), 62 mg of the desired DA adduct 41 (5% yield) and 940 mg of a mixture of 41 and the hydroquinone adduct 42 were isolated (73% yield total). The combined yield of 41 and 42 was 78%. We expected adduct 41 could be converted to 42 upon purification by silica gel column chromatography. However since it
was a relatively large scale reaction, the conversion from 41 to 42 was not complete. In order to convert 41 to 42, the mixture of 41 and 42 was treated with a 2 M hydrochloric acid in methanol at 60 °C for 1 hour. After purification by column chromatography, 720 mg of hydroquinone adduct 42 was obtained in 56% yield (calculation was based on 1g of diene 21). Interestingly, bis-DA adduct 43 was obtained from the AlCl₃-catalyzed DA reaction. The structure of 43 was established by X-ray structure analysis (Figure 5), and the X-ray crystal structure revealed that the four 4-bromophenyl groups are all cis to each other. This molecule is very interesting since it could allow us to synthesize a molecule bearing two cycloparaphenylene rings.

Scheme 10. BF₃·OEt₂ catalyzed Diels–Alder reaction.
Figure 4. (Left) Perspective view of the molecular structure of C\textsubscript{22}H\textsubscript{14}Br\textsubscript{2}O\textsubscript{2} (40) with the atom labeling scheme provided for the non-hydrogen atoms. The thermal ellipsoids are scaled to enclosed 30% probability. (Right) Perspective view of the molecular structure of C\textsubscript{22}H\textsubscript{16}Br\textsubscript{2}O\textsubscript{2} (41) with the atom labeling scheme provided for the non-hydrogen atoms. The thermal ellipsoids are scaled to enclosed 30% probability.
The methylation reaction of hydroquinone 42 was then carried out by treating 42 with a strong methylating reagent, dimethyl sulfate, in the presence of potassium carbonate in anhydrous acetone under reflux for 18 hours to afford dibromide 18b in 79% yield (Scheme 11).33, 34 After a literature review33, it is apparent that instead of converting 41 to 42 first, compound 41 could be used directly to conduct the methylation reaction using the same condition, so the conversion from 41 to 42 which was mentioned early

Figure 5. (Left) Structure of a bis-Diels–Alder adduct 43. (Right) Perspective view of the molecular structure of C_{38}H_{24}Br_4O_2 (43) with the atom labeling scheme provided for the non-hydrogen atoms. The thermal ellipsoids are scaled to enclosed 30% probability.
was probably not necessary. It could save a step of the synthetic sequence with one less silica gel column chromatography, which could further improve the overall yield of the synthetic scheme. The structure of 18b was established by X-ray structure analysis (Figure 6). In the crystal structure of dibromide 18b, the two 4-bromophenyl groups are not parallel to each other, which is different from our previous MM2-optimized structures. It is possible that the preferred conformation of the dibromide 18b in solution may be different from the one in crystal lattice.

Figure 6. Perspective view of the molecular structure of $\text{C}_{24}\text{H}_{20}\text{Br}_2\text{O}_2$ (18b) with the atom labeling scheme provided for the non-hydrogen atoms. The thermal ellipsoids are scaled to enclosed 30% probability.

The [6]CPP derivative precursor 19b was obtained by the nickel(0)-catalyzed homocoupling reaction (Scheme 11). Dibromide 18b, 2.5 equivalents of bis(1,5-cyclooctadiene)nickel(0) and 2.5 equivalents of 2,2'-bipyridyl were loaded in a glove box. Since the second step of the coupling reactions to form the dimer was an intramolecular reaction, a low concentration of monomer would increase the yield for the dimer. DMF was added to make the concentration of dibromide 18b at 5.56 mM. The crude $^1\text{H}$ NMR spectrum indicated the existence of a ratio of 3:2 of the two diastereomers of the dimer 19b (Scheme 11), one with the methoxy signal at 3.84 ppm (major), and the other at 3.86 ppm (minor). However, upon purification by flash column chromatography, only the
major diastereomer of the dimer was successfully isolated in 21% yield. The $^1$H and $^{13}$C NMR spectra are consistent with the structure of 19b. It is interesting to note that the signals from the aromatic hydrogens of the two biphenyl groups are shifted upfield significantly to $\delta$ 6.67 (doublet) and $\delta$ 6.60 (doublet). The upfield shifts of those proton signals can be attributed to the close proximity of the two biphenyl units, placing their aromatic hydrogens in the shielding regions of the aromatic ring current. In addition, the HRMS data further confirmed the formation of the dimer 19b. Furthermore, we believe that the more upfield methoxy signals (3.5–3.7 ppm) and more downfield aromatic proton signals (7.2–7.6 ppm) of the crude $^1$H NMR spectrum were from trimers, tetramers, and perhaps cyclic products of larger ring sizes.

4. Conclusion

A synthetic pathway has been successful developed for the concise synthesis of 19b, which could serve as the precursor of the [6]cycloparaphenylene derivative 20b. The Lewis acid-catalyzed Diels–Alder reaction and the Ni(0)-catalyzed homocoupling reaction are the two key steps of the synthetic sequence. It is envisioned that upon aromatization, compound 19b could be converted to the [6]cycloparaphenylene derivative 20b as a carbon nanohoop of an armchair (6,6) carbon nanotube.
Part II

Experimental Section

Glassware used for all reactions were dried in an oven (100 °C) for at least 12 hours. All reactions were conducted under a nitrogen atmosphere unless otherwise indicated. Tetrahydrofuran (≥ 99.9%, anhydrous, inhibitor-free), borane dimethyl sulfide complex, zinc chloride solution (0.5 M in THF), copper(I) iodide (98%), catecholborane (98%), benzene (99.8%, anhydrous), thionyl chloride (99.5%, low iron), sulfur trioxide pyridine complex (98%), diethyl ether (≥ 99.7%, anhydrous, contains 1 ppm BHT as inhibitor), boron trifluoride diethyl etherate, 2-(trimethylsilyl)phenyl trifluoromethanesulfonate (97%) (37a), dimethyl sulfate (≥ 99.8%), 2,2’-bipyridyl (≥ 99%) were purchased from Aldrich. Cyclohexene (99%), phenylacetylene (98%), sodium methoxide (anhydrous powder), triethylamine (99.7%), iodine (99.5%, resublimed), sodium ethoxide (21% in ethanol), methanol (99.8%, extra dry), diisobutylaluminium hydride (1M solution in hexane), toluene (99.8%, extra dry), dichloromethane (99.9%, extra dry, stabilized), dimethyl sulfoxide (99.7%, extra dry, over molecular sieve), triethyl phosphite (98%), potassium tert-butoxide (98+%), p-benzoquinone (99%), p-xylene (99%), hydroquinone (99.5%), cesium fluoride (99%), acetonitrile (99.9%, extra dry), aluminium chloride (98.5%, anhydrous, powder), titanium(IV) chloride (1 M solution in dichloromethane), acetone (99.8%, extra dry), N,N-dimethylformamide (99.8%, extra dry) were purchased from Acros. Copper(I) bromide-dimethyl sulfide complex was purchased from Alfa Aesar. 1-bromo-4-iodobenzene (99%), (trimethylsilyl)acetylene (99%), 4-bromocinnamic acid (98%), 4-bromobenzyl bromide (99%) were purchased from Oakwood. Trans-
dichlorobis(triphenylphosphi)ne)palladium(II) (99%), tetrakis(triphenylphosphine) palladium(0) (99%), bis(1,5-cyclooctadiene)nickel(0) (98+%) were purchased from Strem. 3-Methoxy-2-(trimethylsilyl)phenyl trifluoromethanesulfonate (>95.0%) (37b) was purchased from TCI. Absolute ethanol was purchased from AAPER Alcohol and Chemical CO. Sodium hydroxide (≥97.0%, pellets), potassium carbonate (anhydrous, ≥99.0%, granular powder), glacial acetic acid (≥99.7 w/w %) were purchased from Fisher Chemical. All chemicals were used as received. Silica gel for flash column chromatography was purchased from Dynamic Adsorbents Inc. $^1$H NMR (600 MHz), $^{13}$C NMR (150 MHz) and $^1$H NMR (400 MHz), $^{13}$C NMR (100 MHz) spectra were recorded in CDCl$_3$ using CHCl$_3$ ($^1$H δ 7.26) and CDCl$_3$ ($^{13}$C δ 77.0) as internal standards.

Compounds 21, 23, 24, 25, and 27 were prepared according to the reported procedure. $^{19}$ 3,6-Dimethoxy-2-(trimethylsilyl)phenyl trifluoromethanesulfonate (37c) was prepared according to the reported procedure. $^{35,36}$

**Compound 18a.** To a mixture of 100 mg of diene 21 (0.275 mmol) and 125 mg of cesium fluoride (99%, 0.815 mmol) in 20 mL of anhydrous acetonitrile and 10 mL of anhydrous dichloromethane was added dropwise a solution of 2-(trimethylsilyl)phenyl triflate (97%, 0.553 mmol) in 25 mL of anhydrous acetonitrile from a pressure equalizing funnel under a nitrogen atmosphere. The addition was finished in 12 hours. After an additional 6 hours of stirring, distilled water was added and the reaction mixture was extracted with dichloromethane. The combined organic layers were dried over sodium sulfate and concentrated. The residue was purified by flash column chromatography.
(silica gel, ethyl acetate:hexanes = 1:10) to produce 98 mg of 18a (0.223 mmol, 81\% yield) as a yellow solid (initially a viscous oil which under vacuum became a foam-like solid): $^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ 7.45 (4 H, d, $J = 8.4$ Hz), 7.09–7.12 (6 H, m), 6.99–7.01 (2 H, m), 5.91 (2 H, d, $J = 1.6$ Hz), 4.69 (2 H, d, $J = 1.2$ Hz); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 144.47, 136.06, 131.75, 130.38, 129.55, 127.86, 126.69, 120.42, 44.80. HRMS calcd for C$_{22}$H$_{16}$Br$_2$Na (M$^+$) 462.9491, found 462.9485.

**Compound 43.** A mixture of 36 mg of 1,4-benzoquinone (0.330 mmol) and 66 mg of aluminium chloride (0.488 mmol) in 30 mL of anhydrous dichloromethane was stirred under a nitrogen atmosphere at room temperature for 5 minutes. Then a solution of 100 mg of diene 21 (0.275 mmol) in 40 mL of anhydrous dichloromethane was added via cannula. The reaction mixture was stirred at room temperature for 45 hours. Distilled water was slowly added, and the reaction mixture was extracted with ethyl acetate. The combined organic layers were dried over sodium sulfate and concentrated. The residue was purified by flash column chromatography (silica gel, ethyl acetate:hexanes = 1:10 and then 1:5) to produce 18 mg of 43 (0.022 mmol, 16\% yield) as a yellow solid: $^1$H NMR (CDCl$_3$, 400 MHz) $\delta$ 7.26 (8 H, d, $J = 8.8$ Hz), 6.80 (8 H, d, $J = 8.8$ Hz), 5.84 (4 H, d, $J = 2.8$ Hz), 4.67 (4 H, d, $J = 2.4$ Hz); $^{13}$C NMR (CDCl$_3$, 100 MHz) $\delta$ 185.43, 141.31, 139.82, 131.77, 129.61, 126.28, 120.90, 39.29. Recrystallization of 43 from dichloromethane/hexanes produced a single crystal suitable for X-ray structure analysis.
Compounds 40, 41, and 42. To a mixture of 1.00 g of diene 21 (2.75 mmol) and 0.360 g of 1,4-benzoquinone (3.30 mmol) in 200 mL of anhydrous dichloromethane under a nitrogen atmosphere was added by using a syringe 0.61 mL of boron trifluoride-diethyl etherate (4.94 mmol). The reaction mixture was stirred at room temperature for 20 hours. Distilled water was slowly added and the reaction mixture was extracted with ethyl acetate. The combined organic layers were dried over sodium sulfate and concentrated. The residue was purified by flash column chromatography (silica gel, ethyl acetate:hexanes = 1:10 and then 1:5) to produce 110 mg of 40 (0.234 mmol, 9% yield) as a yellow solid, 62 mg of 41 (0.131 mmol, 5% yield) as a yellow solid and 940 mg of a mixture of 41 and 42 as a yellow solid. To the 940 mg mixture of 41 and 42 in methanol was added a 2 M hydrochloric acid and the reaction mixture was heated at 60 °C for 1 hour under a nitrogen atmosphere. Water was added and the reaction mixture was extracted with ethyl acetate. The combined organic layers were dried over sodium sulfate and concentrated. Purification by flash column chromatography (silica gel, ethyl acetate:hexanes = 1:5) produced 720 mg of 42 (1.52 mmol, 56% yield) as a white solid.

Compound 40: $^1$H NMR (CDCl₃, 600 MHz) $\delta$ 7.43 (4 H, d, $J = 9.0$ Hz), 7.15 (4 H, d, $J = 7.8$ Hz), 6.69 (2 H, s), 5.91 (2 H, d, $J = 2.4$ Hz), 4.72 (2 H, d, $J = 3.0$ Hz); $^{13}$C NMR (CDCl₃, 150 MHz) $\delta$ 185.97, 141.55, 140.17, 136.41, 131.78, 130.14, 126.51, 120.96, 39.95. Compound 41: $^1$H NMR (CDCl₃, 600 MHz) $\delta$ 7.39 (4 H, d, $J = 9.0$ Hz), 7.08 (4 H, d, $J = 8.4$ Hz), 6.20 (2 H, s), 5.99 (2 H, s), 3.84 (2 H, d, $J = 6.6$ Hz), 3.71 (2 H, d, $J = 6.6$ Hz); $^{13}$C NMR (CDCl₃, 150 MHz) $\delta$ 198.69, 139.98, 138.49, 131.18, 131.11, 128.63, 121.03, 51.49, 41.14. Compound 42: $^1$H NMR (CDCl₃, 600 MHz) $\delta$ 7.42 (4 H, d, $J = 8.4$ Hz), 7.14 (4 H, d, $J = 9.0$ Hz), 6.63 (2 H, s), 5.90 (2 H, d, $J = 2.4$ Hz), 4.78 (2 H, d, $J =
3.0 Hz), 4.29 (2 H, br); $^{13}$C NMR (CDCl$_3$, 150 MHz) $\delta$ 147.37, 142.35, 131.88, 129.72, 127.27, 124.78, 120.59, 115.07, 40.83. Recrystallization of 40 and 41 from dichloromethane/hexanes produced single crystals suitable for X-ray structure analyses.

**Compound 18b.** To a mixture of 0.693 g of 42 (1.48 mmol) and 2.840 g of potassium carbonate (20.5 mmol) in 100 mL of anhydrous acetone under a nitrogen atmosphere was added 1.4 mL of dimethyl sulfate (14.8 mmol) via a syringe, and the reaction mixture was then heated under reflux for 18 hours. Water was added and the reaction mixture was extracted with ethyl acetate and then dichloromethane. The combined organic layers were dried over sodium sulfate and concentrated. The crude solid residue was purified by flash column chromatography (silica gel, ethyl acetate:hexanes = 1:5) to produce 0.580 g of 18b (1.16 mmol, 79% yield) as a white solid: $^1$H NMR (CDCl$_3$, 600 MHz) $\delta$ 7.33 (4 H, d, $J = 8.4$ Hz), 7.05 (4 H, d, $J = 9.0$ Hz), 6.73 (2 H, s), 5.95 (2 H, d, $J = 3.0$ Hz), 4.83 (2 H, d, $J = 3.0$ Hz), 3.61 (6 H, s); $^{13}$C NMR (CDCl$_3$, 150 MHz) $\delta$ 151.23, 143.67, 131.04, 129.85, 127.74, 127.01, 119.52, 109.21, 55.64, 40.57. HRMS calcd for C$_{24}$H$_{21}$Br$_2$O$_2$ (MH$^+$) 498.9903, found 498.9910; calcd for C$_{24}$H$_{20}$Br$_2$O$_2$Na (MNa$^+$) 520.9722, 522.9702, 524.9681, found 520.9736, 522.9708, 524.9689, respectively. Recrystallization of 18b from chloroform/hexanes produced a single crystal suitable for X-ray structure analysis.

**Compound 19b.** In a glove box, a 250-mL flask was charged with 0.500 g of 18b (1.00 mmol), 0.702 g of bis(cyclooctadiene)nickel(0) (2.50 mmol) and 0.394 g of 2,2'-bipyridyl (2.50 mmol) and then fitted with a water condenser followed by the addition of
180 mL of \( N,N \)-dimethylformamide. The reaction mixture was heated at 85 °C for 44 hours under a nitrogen atmosphere. After the mixture was allowed to cool to room temperature, brine was added, and the reaction mixture was extracted with ethyl acetate and dichloromethane. The combined organic layers were dried over sodium sulfate and concentrated. The residue was purified by flash column chromatography (silica gel, ethyl acetate:hexanes = 1:20 then 1:10) to produce 72 mg of 19b (0.106 mmol, 21% yield) as a white solid: \(^1\)H NMR (CDCl\(_3\), 400 MHz) \( \delta \) 6.90 (4 H, s), 6.78–6.79 (4 H, m), 6.67 (8 H, d, \( J = 8.4 \) Hz), 6.60 (8 H, d, \( J = 8.0 \) Hz), 5.17–5.18 (4 H, m), 3.84 (12 H, s); \(^{13}\)C NMR (CDCl\(_3\), 100 MHz) \( \delta \) 150.93, 140.24, 138.35, 133.24, 131.41, 127.35, 125.90, 108.51, 55.91, 37.33. HRMS calcd for C\(_{48}\)H\(_{40}\)O\(_4\) (\( \text{M}^+ \)) 680.2921, found 680.2923; calcd for C\(_{48}\)H\(_{41}\)O\(_4\) (\( \text{MH}^+ \)) 681.2999, found 681.3009.
REFERENCES


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