

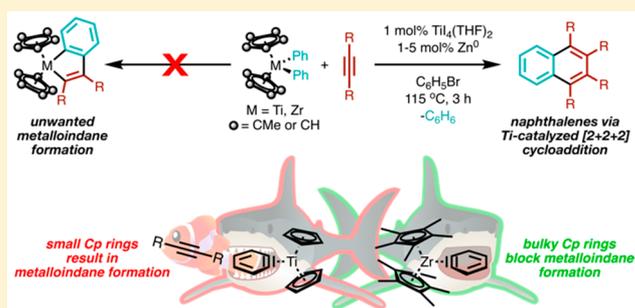
## Group 4 Diarylmetalloenes as Bespoke Aryne Precursors for Titanium-Catalyzed [2 + 2 + 2] Cycloaddition of Arynes and Alkynes

Benjamin R. Reiner and Ian A. Tonks\*<sup>1</sup>

Department of Chemistry, University of Minnesota—Twin Cities, 207 Pleasant Street SE, Minneapolis, Minnesota 55455, United States

### Supporting Information

**ABSTRACT:** Despite the ubiquity of reports describing titanium (Ti)-catalyzed [2 + 2 + 2] cyclotrimerization of alkynes, the incorporation of aryne into this potent manifold has never been reported. The in situ generation of aryne often requires fluoride, which instead will react with the highly fluorophilic Ti center, suppressing productive catalysis. Herein, we describe the use of group 4 diarylmetalloenes,  $\text{Cp}^{\text{R}}_2\text{MAr}_2$  ( $\text{Cp}^{\text{R}} = \text{C}_5\text{H}_5, \text{C}_5\text{Me}_5$ ;  $\text{M} = \text{Ti}, \text{Zr}$ ), as aryne precursors for the Ti-catalyzed synthesis of substituted naphthalenes via coupling with 2 equiv of an alkyne. Fair-to-good yields of the desired naphthalene products could be obtained with 1% catalyst loadings, which is roughly an order of magnitude lower than similar reactions catalyzed by palladium or nickel. Additionally, naphthalenes find broad applications in the electronics, photovoltaics, and pharmaceutical industries, urging the discovery of more economic syntheses. These results indicate that aryne transfer from a  $\text{Cp}^{\text{R}}_2\text{M}(\eta^2\text{-aryne})$  complex to another metal is a viable route for the introduction of aryne fragments into organometallic catalytic processes.



### INTRODUCTION

Titanium (Ti) is an attractive substitute to expensive noble metals owing to its natural abundance, low toxicity, and high activity in a number of synthetically relevant bond-forming reactions.<sup>1–3</sup> Our laboratory has an ongoing interest in leveraging the reactivity of multiple valence states of Ti toward the modular assembly of complex small molecules.<sup>4–13</sup> While  $\text{Ti}^{\text{II}}$  intermediates have been invoked in a multitude of catalytic and stoichiometric transformations, historically the chemistry of low-valent Ti species is weighted toward alkyne cycloaddition reactions such as alkyne cyclotrimerization.<sup>14</sup> Alkyne cyclotrimerization is a powerful synthetic tool that allows the rapid construction of aromatic hydrocarbons through the formation of three bonds in one pot.

Naphthalenes and phenanthrenes have important applications in pharmaceuticals,<sup>15</sup> photovoltaics,<sup>16</sup> and the design of functional electronic materials.<sup>17</sup> Moreover, substituted naphthalenes exhibit a myriad of biologically relevant activities including anticancer, antidepressant, antiinflammatory, antiviral, and antihypertensive activities.<sup>15</sup> For example, Naproxen, marketed as Aleve, is a nonsteroidal antiinflammatory drug (NSAID) that is very commonly prescribed for the treatment of arthritis (Figure 1).

The synthesis of naphthalenes via formal [2 + 2 + 2] cycloaddition requires the engagement of key metallacyclic intermediates with an in situ generated reactive aryne substrate. Fast generation and capture of a stoichiometric aryne reagent is essential for selective trimerization. Modern

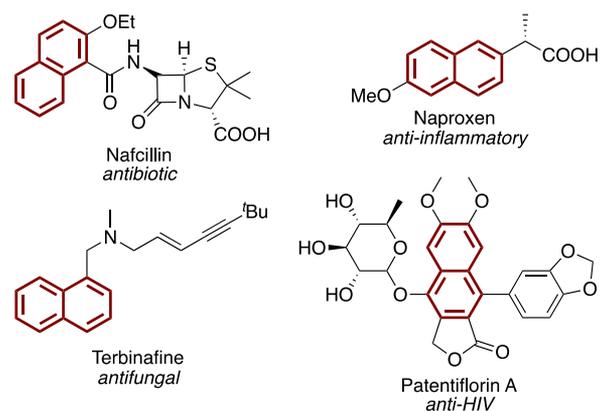


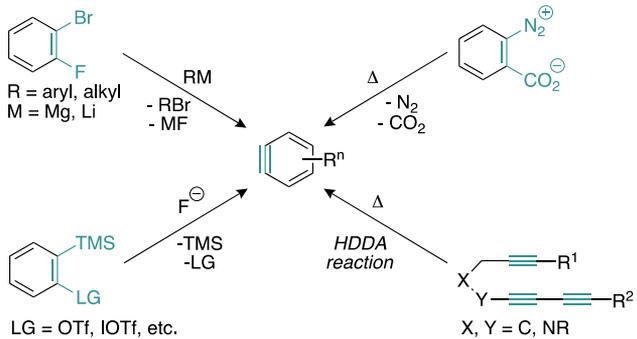
Figure 1. Examples of naphthalene cores in drug molecules.

techniques for the in situ generation of aryne have turned toward fluoride-based activators, which enjoy mild reaction conditions and easily accessible aryne precursors (Figure 2, top).<sup>18</sup> These methods avoid the use of strong reductants such as magnesium(0) or organolithiums, synthetically elaborate aryne precursors such as those employed in the hexadehydro

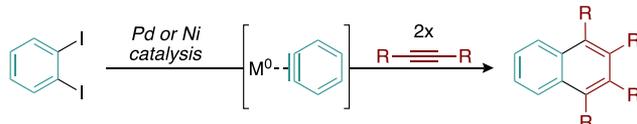
**Special Issue:** Celebrating the Year of the Periodic Table: Emerging Investigators in Inorganic Chemistry

**Received:** April 13, 2019

## Common Methods for In Situ Generation of Arynes



## Previous Work



## This Work

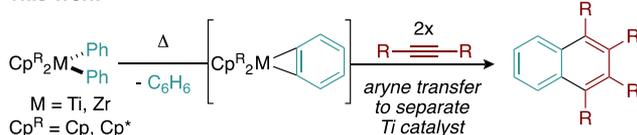


Figure 2. Modern methods of in situ aryne generation.

Diels–Alder (HDDA) reaction,<sup>19</sup> or thermally activated substrates such as diazonium salts, which can pose serious operational hazards.<sup>20</sup>

While catalytic synthesis of naphthalenes and phenanthrenes has been achieved using palladium (Pd),<sup>21–23</sup> nickel (Ni),<sup>24</sup> and rhodium<sup>25</sup> (Figure 2, middle), analogous reactivity with Ti has never been reported. The prohibitive fluorophilicity of Ti [Ti–F bond dissociation energy (BDE) = 138 kcal/mol],<sup>26,27</sup> which makes in situ aryne generation with fluoride incompatible with most potential Ti catalysts, likely contributes to this conspicuous absence. Considering the ubiquity of Ti-mediated trimerization reactions and the high catalytic activity reported therein, we were inspired to design aryne precursors that could be safely activated under conditions compatible with Ti.

The thermolysis and prolific ensuing insertion chemistry of group 4 diarylmetalocenes is well-established (Figure 3).<sup>28,29</sup> This chemistry is proposed to proceed via a putative aryne–metalocene adduct, which is formed via  $\beta$ -abstraction under relatively mild conditions ( $\sim 80^\circ\text{C}$ ). This aryne adduct can then be intercepted by a variety of unsaturated small molecules including alkynes, alkenes, nitriles,  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{N}_2$ .<sup>30–32</sup>

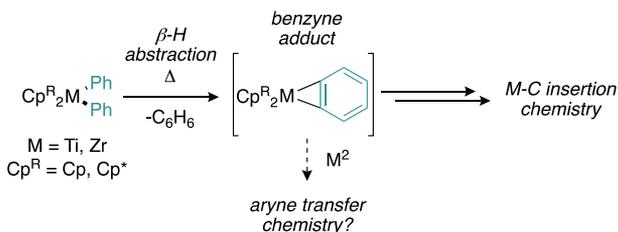


Figure 3. Group 4 diarylmetalocenes undergo  $\beta$ -hydrogen abstraction, leading to aryne adducts that can be intercepted via insertion.

The aryne intermediate can be stabilized via the addition of L-type ligands<sup>33</sup> or C–H activation of the cyclopentadienyl ligands.<sup>32,34</sup> Given this rich chemistry, we hypothesized that this putative benzyne adduct could serve as an aryne coupling partner via transfer from the metallocene fragment to a catalytic metal center. Unlike other aryne generation methods, we speculated that this simple and safe thermal generation of arynes would be compatible with Ti-mediated catalysis.

Herein, we report the investigation of group 4 diarylmetalocenes as aryne precursors for the catalytic synthesis of substituted naphthalenes (Figure 2, bottom). Good yields of naphthalene products could be obtained with catalyst loadings as low as 1%, which is an order of magnitude lower than similar reactions catalyzed by Pd<sup>21–23</sup> or Ni.<sup>24</sup> Overall, our experiments demonstrate that aryne transfer from a Cp<sup>R</sup><sub>2</sub>M( $\eta^2$ -aryne) complex to another metal is a viable route for the introduction of aryne fragments into organometallic catalytic processes.

## RESULTS AND DISCUSSION

**Model Reactions.** We began our investigation by choosing a suitable model reaction (Table 1). Diphenylacetylene was

Table 1. Screening of Reaction Conditions<sup>a</sup>

entry	Cp <sup>R</sup> <sub>2</sub> M <sup>b</sup>	catalyst	% yield 2 <sup>c</sup>	% yield 3 <sup>d</sup>
1	Cp <sub>2</sub> Ti	TiI <sub>4</sub> (THF) <sub>2</sub> <sup>e</sup>	>95	0
2	Cp <sub>2</sub> Ti	TiI <sub>4</sub> (THF) <sub>2</sub>	0	>95
3	Cp <sup>*</sup> <sub>2</sub> Ti	TiI <sub>4</sub> (THF) <sub>2</sub>	0	0
4	Cp <sup>*</sup> <sub>2</sub> Zr	TiI <sub>4</sub> (THF) <sub>2</sub>	71	0
5	Cp <sup>*</sup> <sub>2</sub> Zr	TiI <sub>4</sub> (THF) <sub>2</sub> <sup>f</sup>	55	0
6	Cp <sup>*</sup> <sub>2</sub> Zr	TiBr <sub>4</sub> (THF) <sub>2</sub>	trace	0
7	Cp <sup>*</sup> <sub>2</sub> Zr	TiCl <sub>4</sub> (THF) <sub>2</sub>	trace	0
8	Cp <sup>*</sup> <sub>2</sub> Zr	TiI <sub>4</sub> (THF) <sub>2</sub> <sup>g</sup>	0	0
9	Cp <sup>*</sup> <sub>2</sub> Zr	none	0	0

<sup>a</sup>Reaction conditions: metallocene (0.05 mmol), diphenylacetylene (0.05 mmol), catalyst (0.05–0.0005 mmol of Ti), Zn<sup>0</sup> (0.05–0.0005 mmol), 0.5 mL of C<sub>6</sub>H<sub>5</sub>Br, 115 °C, 3 h. <sup>b</sup>Cp = cyclopentadiene; Cp<sup>\*</sup> = pentamethylcyclopentadiene. <sup>c</sup>Determined by quantitative GC-FID with respect to an internal standard (1,3,5-trimethoxybenzene). <sup>d</sup>Determined by <sup>1</sup>H NMR with respect to an internal standard (1,3,5-trimethoxybenzene). <sup>e</sup>Reaction conducted with 100 mol % TiI<sub>4</sub>(THF)<sub>2</sub>. <sup>f</sup>Reaction conducted with 0.1 mmol of diphenylacetylene. <sup>g</sup>Reaction conducted in the absence of Zn<sup>0</sup>.

chosen as the alkyne coupling partner owing to the low proclivity toward self-cyclotrimerization and the high symmetry expected for the desired naphthalene products. Diphenyltitanocene was chosen as an initial benzyne precursor owing to its ease of synthesis. All reactions were carried out in the presence of stoichiometric or catalytic amounts of titanium tetrahalide catalyst precursors and zinc(0) (Zn<sup>0</sup>), along with equimolar amounts of diphenylacetylene and a metallocene benzyne precursor. Access to the active Ti<sup>III</sup> catalytic species is proposed to occur via the initial reduction of titanium tetrahalide to Ti<sup>III</sup> by Zn<sup>0</sup> followed by disproportionation to Ti<sup>II</sup> and Ti<sup>IV</sup>.<sup>35</sup> The product yields were determined by quantitative gas chromatography flame ionization detection

(GC-FID) with respect to an internal standard (trimethoxybenzene).

Under stoichiometric conditions, diphenyltitanocene served as a suitable benzyne precursor and generated 1,2,3,4-tetraphenylnaphthalene (**2**) in near-quantitative yields (Table 1, entry 1). However, under catalytic conditions, the quantitative formation of metalloindane species **3** was observed (Table 1, entry 2). This suggests that interception of the putative metallocene–benzyne adduct with diphenylacetylene is kinetically competitive to productive catalysis. Prolonged thermolysis of metalloindane **3** in the presence of additional diphenylacetylene does not afford naphthalene **2**, demonstrating that **3** is likely an off-cycle thermodynamic sink. We considered that increasing the steric bulk of the Cp rings (Cp = cyclopentadiene) on the titanocene might suppress the formation of parasitic metalloindane species such as **3**. However, the substitution of Cp<sub>2</sub>TiPh<sub>2</sub> for Cp\*<sub>2</sub>TiPh<sub>2</sub> (Cp\* = pentamethylcyclopentadiene) led to no product formation (Table 1, entry 3). Cp\*<sub>2</sub>TiPh<sub>2</sub> is known to favor Ti–C bond homolysis to form phenyl radical rather than  $\beta$ -abstraction to afford the desired benzyne adduct and benzene.<sup>36</sup>

Bearing in mind that the zirconium (Zr)–phenyl (Ph) bonds in Cp\*<sub>2</sub>ZrPh<sub>2</sub> (BDE ~ 75 kcal/mol) have a higher BDE than analogous Ti–Ph bonds (BDE ~ 67 kcal/mol),<sup>37</sup> we were prompted to consider Cp\*<sub>2</sub>ZrPh<sub>2</sub> as a benzyne precursor in the hopes of promoting  $\beta$ -abstraction over extrusion of the phenyl radical. Indeed, using Cp\*<sub>2</sub>ZrPh<sub>2</sub> as the benzyne precursor, **2** was delivered in 71% yield with no detectable amount of **3** (Table 1, entry 4). Reactions using a 1:2 stoichiometry of Cp\*<sub>2</sub>ZrPh<sub>2</sub> and diphenylacetylene afforded **2** in slightly lower yields, likely owing to decomposition of the incipient Zr–benzyne complex (entry 5). Control reactions conducted in the absence of catalytic Ti or Zn (Table 1, entries 8 and 9) showed no formation of **2**. Other TiX<sub>4</sub> precatalysts (Table 1, entries 6 and 7) only afforded trace amounts of **2**, demonstrating the importance of iodide ligands to catalysis. We have previously observed that TiI<sub>4</sub>-based precatalysts are significantly more productive for alkyne trimerization than TiCl<sub>4</sub>-based precatalysts,<sup>7</sup> likely due to the decreased donor ability of iodide (I<sup>-</sup>) compared to chloride (Cl<sup>-</sup>).<sup>38</sup> Reactions performed at lower temperatures (80 or 100 °C) afforded no naphthalene product; however, evolution of stoichiometric amounts of benzene signaled that  $\beta$ -hydrogen abstraction of Cp\*<sub>2</sub>ZrPh<sub>2</sub> did occur. Moreover, low-valent Ti is competent for trimerization under mild conditions.<sup>39</sup> Thus, the high reaction temperature may be more readily associated with the barrier for the generation of an active Ti<sup>II</sup> species. Notably, **2** is furnished in good yield at 1 mol % catalyst loading, while similar reactions employing Ni or Pd catalysts require 10 mol % catalyst loading to achieve comparable yields. This highlights the inherent advantage of utilizing Ti-based catalyst systems.

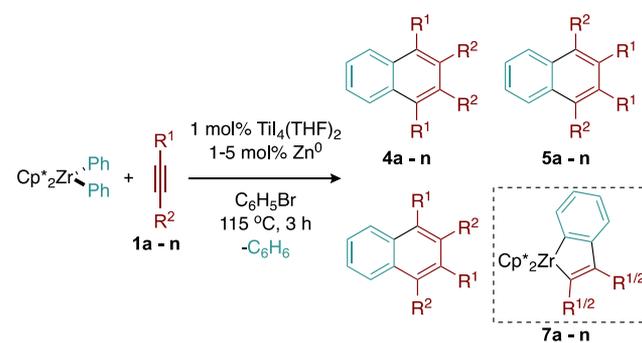
<sup>1</sup>H NMR spectra of catalytic reactions show decomposition of Cp\*<sub>2</sub>Zr<sup>II</sup> to multiple ill-defined species. In order to ascertain whether any of these species are catalytically competent, the cycloaddition of tetraphenylnaphthalene was attempted using catalytic amounts of Cp\*<sub>2</sub>ZrCl<sub>2</sub>/Zn. This system did not afford tractable amounts of naphthalene product. Similarly, attempts to catalyze the cyclotrimerization of 3-hexyne with Cp\*<sub>2</sub>ZrCl<sub>2</sub>/Zn were also unsuccessful. These observations suggest that Cp\*<sub>2</sub>Zr<sup>II</sup>-borne species are likely not involved in promoting cycloaddition catalysis.

**Alkyne Scope.** With optimized reaction conditions in hand, we set out to explore the scope of the alkyne coupling

partner. We hypothesized that only alkynes with sufficient steric bulk could engage in productive catalysis by avoiding the formation of parasitic metalloindane species. A simple structure–activity relationship was developed in order to qualitatively correlate the alkyne steric size to reactivity. While several models for substituent size have been developed,<sup>40–45</sup> *A* values proved sufficient. The *A* values for both alkyne substituents were summed to give a “composite *A* value” and plotted against the total yield of naphthalene products formed under catalytic conditions (Figure S20).

Alkynes with composite *A* values of below 4 delivered naphthalene products in zero or very poor yield (Table 2,

**Table 2.** Alkyne Partner Substrate Scope<sup>a</sup>



	R <sup>1</sup> , R <sup>2</sup>	% yield 4:5:6 <sup>b</sup>	% yield 7 <sup>c</sup>	% yield trimer <sup>d</sup>	<i>A</i> value <sup>e</sup>
<b>1a</b>	Et, Et	5	86	8	3.5
<b>1b</b>	<sup>i</sup> Pr, <sup>i</sup> Pr	4	88	9	3.6
<b>1c</b>	TMS, H	0	>95	0	2.5
<b>1d</b>	Ph, H	0	>95	0	3.0
<b>1e</b>	<sup>i</sup> Pr, Me	0	>95	0	3.9
<b>1f</b>	Ph, Me	0	>95	0	4.7
<b>1g</b>	Ph, <sup>n</sup> Bu	0:4:10	19	16	4.8
<b>1h</b>	Ph, Ph	71	0	24	6.0
<b>1i</b>	<i>p</i> -CF <sub>3</sub> Ph, <i>p</i> -CF <sub>3</sub> Ph	64	0	19	6.0
<b>1j</b>	<i>p</i> -OMe-Ph, <i>p</i> -OMe-Ph	78	0	15	6.0
<b>1k</b>	<i>p</i> <sup>-</sup> BuPh, <i>p</i> <sup>-</sup> BuPh	76	0	22	6.0
<b>1l</b>	Ph, TMS	8:14:26	0	0	5.5
<b>1m</b>	<sup>n</sup> Bu, TMS	0:34:31	0	0	4.3
<b>1n</b>	Me, <sup>t</sup> Bu	0	0	0	6.6

<sup>a</sup>Reaction conditions: metallocene (0.05 mmol), alkyne (0.05 mmol), catalyst (0.0005 mmol of Ti), Zn<sup>0</sup> (0.0005 mmol), 0.5 mL of C<sub>6</sub>H<sub>5</sub>Br, 115 °C, 3 h. Cp\* = pentamethylcyclopentadiene. <sup>b</sup>Determined by quantitative GC-FID with respect to an internal standard (1,3,5-trimethoxybenzene). <sup>c</sup>Determined by <sup>1</sup>H NMR with respect to an internal standard (1,3,5-trimethoxybenzene). <sup>d</sup>% yield of all alkyne cyclotrimer regioisomers; determined by <sup>1</sup>H NMR with respect to an internal standard (1,3,5-trimethoxybenzene). <sup>e</sup>Sum of both alkyne substituent *A* values.

alkynes **1a–1f**). These reactions were dominated by formation of the corresponding metalloindanes **7a–7f**. In the cases of 3-hexyne (Table 1, alkyne **1a**) and 4-octyne (Table 1, alkyne **2a**), alkylated benzenes formed via alkyne trimerization were observed in low yields (~10%).

Composite *A* values between 4 and 6 appear necessary but are not sufficient to furnish naphthalene products **4–6** in acceptable yields (Table 2, alkynes **1f–1m**). The product selectivity for asymmetric alkynes appears entirely substrate-biased in accordance with literature precedent.<sup>21–24</sup> Notably,

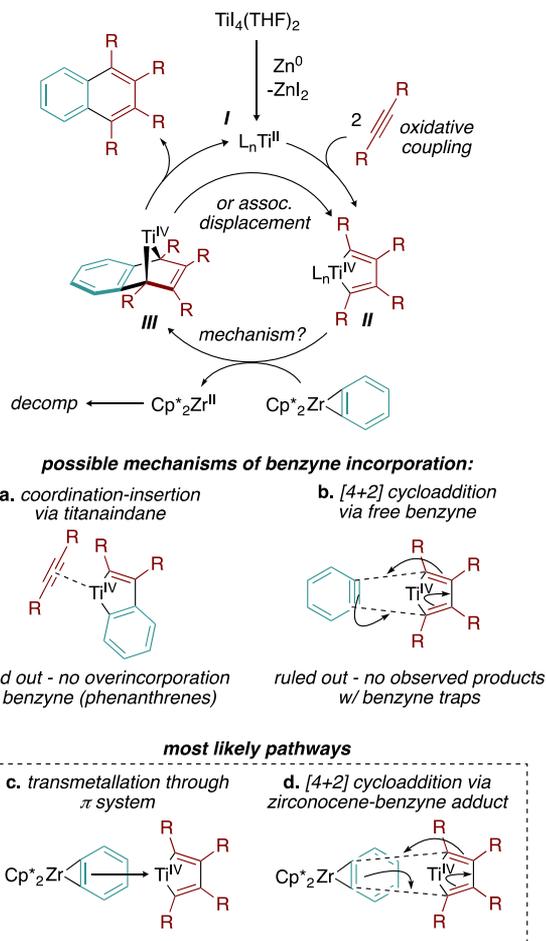
slight changes to the steric profile of the alkyne coupling partner can substantially affect the catalytic performance. While phenylpropyne affords the metalloindane complex **7f** as the exclusive product (Table 2, alkyne **1f**), phenylhexyne furnished the metalloindane complex **7g** in a substantially lower yield and produced both naphthalene and trimer products in comparable yields (~15%; Table 2, alkyne **1g**). The difference in the *A* values between Me and <sup>t</sup>Bu is only 0.1 kcal/mol, illustrating how even small steric perturbations can manifest in observable differences in the catalytic performance.

A substrate screen utilizing para-substituted diarylalkynes shows a slight yield dependence on the electronic character of the alkyne (Table 2, alkynes **1i–1k**). More electron-rich alkyne coupling partners deliver naphthalene products in higher yields. Alkynes with composite *A* values exceeding 6 did not convert under the reaction conditions (Table 2, alkyne **1n**) likely owing to the steric strain associated with the formation of metallacyclic intermediates. While limited in overall scope, the reactivity of the alkyne coupling partners appears to be more closely governed by the steric rather than electronic properties of the alkyne. Although the reaction yields delivered by productive alkynes are moderate, the relatively high turnover numbers are encouraging, and current work is directed toward developing more robust catalytic systems.

Only trace amounts of benzyne homocoupled products could be detected in the reactions with any alkynes. Thermolysis of Cp\*<sub>2</sub>ZrPh<sub>2</sub> in the absence of alkyne or catalyst also only affords trace yields of benzyne homocoupling products. This stands in contrast to other synthetically relevant metal–benzyne adducts of ruthenium,<sup>46</sup> Pd,<sup>21–23</sup> and Ni,<sup>24</sup> where benzyne coupling products such as biphenylene or triphenylene are furnished in more substantial yields. Additionally, Ti species generated during catalysis do not appear to promote the formation of metalloindane byproducts. The propensity of alkynes to form metalloindanes is identical in the presence or absence of catalytic Ti.

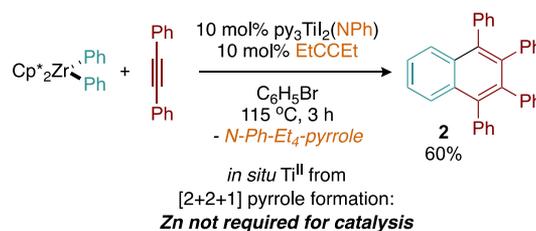
**Proposed Mechanism.** Synthetic success with a fairly unusual benzyne precursor prompted us to consider the mechanistic aspects of the ensuing catalytic reaction. The most likely pathway for naphthalene synthesis is as follows (Figure 4): after generation of an active Ti<sup>II</sup> species (I) by the Zn reductant, 2 equiv of alkyne undergo oxidative coupling to yield a titanacyclopentadiene (II). Next, the titanacyclopentadiene reacts with the in situ generated Zr–benzyne adduct, either via transmetalation of the benzyne to Ti or direct [4 + 2] cycloaddition of Zr–benzyne to the diene fragment. The resulting bound arene can either then dissociate to regenerate the reduced Ti<sup>II</sup> species I or undergo associative displacement by alkyne to generate II. We favor II over titanaindane (Figure 4a) formation owing to the observed product and byproduct selectivity: catalysis results in the formation of only naphthalenes and a small amount of hexasubstituted benzene as a consequence of alkyne cyclotrimerization. In principle, a titanaindane intermediate (or a Ti–benzyne adduct) could result in the formation of phenanthrene or triphenylene byproducts, neither of which are observed.

We were prompted to interrogate the role of Zn during catalysis because the ZnX<sub>2</sub> byproduct of Ti reduction could facilitate either transmetalation or act as a Lewis acid—in either case possibly impacting how naphthalenes are formed. We previously reported the generation of Ti<sup>II</sup> trimerization catalysts through the alkyne-triggered reduction of titanium imidos<sup>7</sup> instead of Zn reduction of titanium halides.



**Figure 4.** Plausible mechanism for the formation of naphthalene products from aryne/alkyne cyclization.

Conducting the coupling reaction with equimolar amounts of Cp\*<sub>2</sub>ZrPh<sub>2</sub> and PhCCPh in the presence of 10% py<sub>3</sub>TiI<sub>2</sub>(NPh) and 3-hexyne afforded naphthalene **2** in 60% yield (Figure 5).

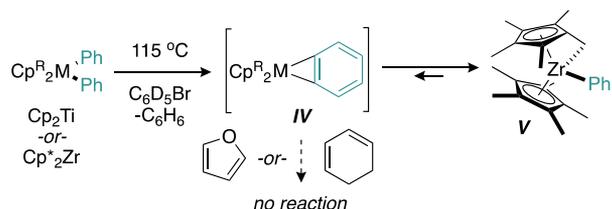


**Figure 5.** Zn-free reactions yield significant amounts of **2**, indicating that Zn is not critically important for catalysis.

3-Hexyne was chosen as a sacrificial alkyne owing to its high reactivity in the formation of the requisite pyrrole catalyst activation product. The formation of **2** in the absence of Zn demonstrates that Zn is “innocent”—not likely participating as a transmetalation agent or Lewis acid during the catalytic synthesis of naphthalenes.

Thus, benzyne incorporation into titanacyclopentadiene II likely occurs via direct engagement of the Zr–benzyne adduct with Ti, through either transmetalation (Figure 4c) or direct [4 + 2] cycloaddition with II (Figure 4d). Thermolysis of Cp\*<sub>2</sub>ZrPh<sub>2</sub> in the presence of furan and cyclohexadiene as benzyne traps yielded no products from free benzyne capture

(Figure 4c). Instead, only the tuck-in complex V (Figure 6) was observed. Identical benzyne trap experiments were



**Figure 6.** Free benzyne trap experiments led only to formation of the tuck-in complex V.

conducted with  $\text{Cp}_2\text{TiPh}_2$ , which cannot form a tuck-in complex, but still no products assignable to free benzyne capture were detected. Notably, the Zr tuck-in complex V does not exhibit evidence of interconversion to the benzyne adduct IV up to  $90\text{ }^\circ\text{C}$ ,<sup>32</sup> however, a small yet reactive population of the benzyne adduct may be responsible for direct transmetalation from Zr to Ti. How the bulky zirconocene fragment may hinder formation of the requisite transition state(s) needed for transmetalation remains a lingering question.

In order to determine whether the  $\text{Cp}^*_2\text{Zr}$  benzyne adduct IV is indeed a relevant species during catalysis, we examined substituted aryne coupling partner **8** as an isomerization probe to detect the intermediacy of an aryne complex (Figure 7). Metallocene aryne complexes that can be stabilized via C–H activation of the  $\text{Cp}^*$  ring (as in V) are expected to “proton walk” via the successive protonation of an incipient aryne intermediate (Figure 7).<sup>34</sup> By measurement of the product distribution, the aryne adduct isomer of  $\text{Cp}^*_2\text{Zr}(\text{C}_6\text{H}_3\text{Me})$  can be implicated as an on-cycle species in catalysis if isomerization occurs. Indeed, after complex **8** was subjected to the catalytic reaction conditions, a  $\sim 2:1$  mixture of 6-methyl-1,2,3,4-tetraphenyl-naphthalene (**9**) and 5-methyl-1,2,3,4-tetraphenyl-naphthalene (**10**) was afforded in 64% yield. The formation of naphthalene **10** can only arise following isomerization via an aryne adduct and thus implicates the intermediacy of a complex such as IV during catalysis (Figure 6). Notably, thermolysis of **8** shows almost immediate scrambling of the tolyl group to an equimolar mixture of ortho-, meta-, and para-

substituted analogues of V (Figure S21), demonstrating that isomerization is energetically facile and not dictated by  $\text{Cp}^*$  ring sterics. This isomerization behavior is consistent with the observed reactivity of the analogous  $\text{Cp}_2\text{Zr}(\text{tolyl})_2$  complex.<sup>47</sup>

Overall, the mechanistic data are most consistent with the direct engagement of a Zr–aryne adduct with a titanocyclopentadiene to afford the observed naphthalene products. Future work is focused on elucidating the fine details of this transmetalation event and how it may affect or effect product selectivity.

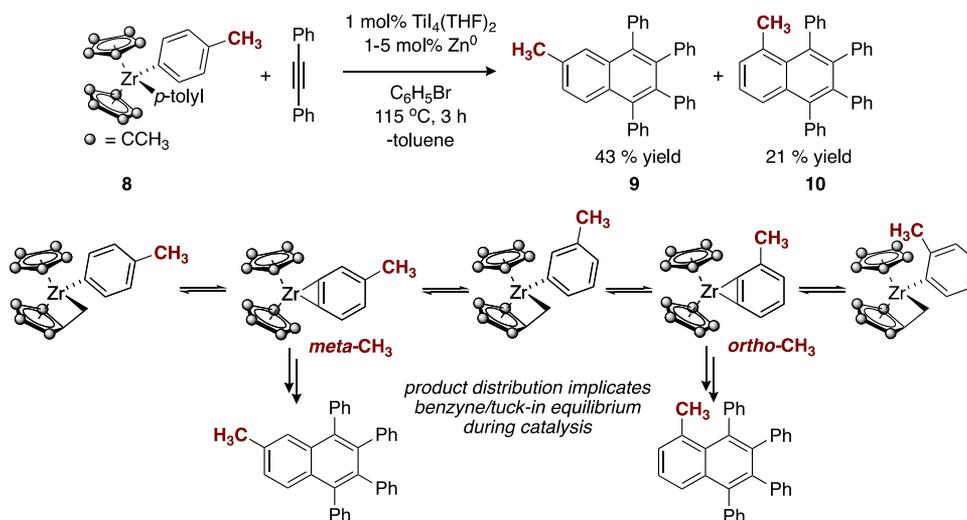
## CONCLUSIONS

$\text{Cp}^*_2\text{ZrPh}_2$  was employed as a benzyne precursor in a Ti-catalyzed formal  $[2 + 2 + 2]$  cycloaddition of arynes and alkynes to form highly substituted naphthalene products. Bulky  $\text{Cp}^*$  rings were required to suppress the formation of parasitic metalloindane byproducts. A screen of potential alkyne coupling partners showed that formation of the desired naphthalene products is best correlated to alkyne steric rather than electronic properties. The product selectivity toward naphthalenes over other potential coupling products including triphenylenes or phenanthrenes suggests a mechanism in which a titanacyclopentadiene is intercepted by a Zr–benzyne adduct. An isomerization probe substrate, **8**, was designed to interrogate this possibility. The product distribution arising from this substrate implicates isomerization through a Zr–aryne adduct during productive catalysis.

While the yields of naphthalene products are modest, the relatively low catalyst loading—nearly an order of magnitude lower than comparable systems with Ni or Pd—is encouraging. The high oxo- and fluorophilicity of Ti could be circumvented with an unusual aryne precursor, demonstrating a novel way to introduce aryne fragments into organometallic catalytic processes. Future work is directed toward expanding the scope of reactions that incorporate these metallocene-born arynes in the hopes of assembling more complex small molecules and understanding the mechanistic implications of aryne transmetalation in catalysis.

## EXPERIMENTAL SECTION

**General Considerations.** All air- and moisture-sensitive compounds were manipulated in a glovebox under a  $\text{N}_2$  atmosphere.



**Figure 7.** Formation of **10** implicating isomerization through a Zr–aryne adduct.

Benzene, pentane, diethyl ether (Et<sub>2</sub>O), tetrahydrofuran (THF), and toluene were sparged with ultrahigh-purity argon and dried via passage through drying columns using a solvent purification system from Pure Process Technologies. All solvents were stored over 4 Å molecular sieves. C<sub>6</sub>D<sub>3</sub>Br was dried over CaH<sub>2</sub> and distilled before use. All high-boiling liquid reagents were freeze–pump–thawed three times, brought into the glovebox, diluted in hexanes or Et<sub>2</sub>O, passed through activated basic alumina, pumped dry in vacuo, and checked by <sup>1</sup>H NMR in CDCl<sub>3</sub> to ensure the dryness. 1,2-Bis(4-*tert*-butylphenyl)ethyne,<sup>48</sup> bis(4-methoxyphenyl)ethyne,<sup>49</sup> bis(4-trifluoromethylphenyl)ethyne,<sup>50</sup> Cp<sub>2</sub>TiPh<sub>2</sub>,<sup>36</sup> Cp\*<sub>2</sub>TiPh<sub>2</sub>,<sup>36</sup> Cp\*<sub>2</sub>ZrPh<sub>2</sub>,<sup>32</sup> and *p*-tolyllithium<sup>51</sup> were prepared according to reported procedures. <sup>1</sup>H and <sup>13</sup>C NMR spectra were collected on a Bruker Avance III HD NanoBay 400 MHz spectrometer. Chemical shifts are reported with references of the residual protiosolvent impurity: <sup>1</sup>H (s, 7.26 ppm for CHCl<sub>3</sub>), <sup>13</sup>C (t, 77.16 ppm for CDCl<sub>3</sub>). GC-FID was performed using an Agilent 7890 series gas chromatograph system (HP-5 column, 30 m length, 0.32 mm inside diameter, 0.25 μm film thickness; temperature program = 50 °C for 1.5 min, 20 °C/min to 290 °C, and held for 6.5 min) equipped with a Polyarc reactor for quantitative C detection.

**General Procedure for Catalytic Reactions.** In an N<sub>2</sub>-filled glovebox, a vial was charged with Cp\*<sub>2</sub>ZrPh<sub>2</sub> (25.8 mg, 0.05 mmol, 1 equiv), alkyne (0.05 mmol, 1 equiv), Ti<sub>4</sub>(THF)<sub>2</sub> (0.350 mg, 0.0005 mmol, 0.01 equiv), C<sub>6</sub>D<sub>3</sub>Br (0.5 mL), and trimethoxybenzene (8.4 mg, 0.05 mmol, 1 equiv) as an internal standard. The reaction mixture was transferred into an NMR tube charged with Zn (0.1–0.3 mg, 0.0015–0.0030 mmol, 0.03–0.05 equiv). The reaction was heated at 115 °C for 3 h in a preheated oil bath outside the glovebox. After being cooled to ambient temperature, the reaction was concentrated in vacuo, and the resulting residue was dissolved in ethyl acetate (EtOAc) and passed over a plug of silica. Reactions using tetramethylsilane–alkynes that afforded naphthalene products were concentrated in vacuo and mixed with 10 mL of 2 M HCl in methanol. After the mixture was stirred for 2 h, it was diluted by 20 mL of deionized water and extracted by EtOAc (3 × 15 mL). The organic layer was washed with brine and dried by MgSO<sub>4</sub>. All reactions were analyzed by <sup>1</sup>H NMR in a CDCl<sub>3</sub> solvent, and spectra containing naphthalene products were compared to literature examples.<sup>24,52–58</sup> NMR samples were then diluted with dichloromethane (CH<sub>2</sub>Cl<sub>2</sub>) and analyzed by GC-FID. Product yields were determined by quantitative GC-FID.

**Synthesis of 8.** A solution of *p*-tolyllithium (68 mg, 0.69 mmol, 3 equiv) in THF (2 mL) was added dropwise to a stirring solution of Cp\*<sub>2</sub>ZrCl<sub>2</sub> (100 mg, 0.23 mmol, 1 equiv) in Et<sub>2</sub>O (5 mL) at –30 °C. The reaction was allowed to warm to room temperature and stirred for 6 h, affording a hazy orange solution. CH<sub>2</sub>Cl<sub>2</sub> (0.5 mL) was added dropwise to quench the remaining organolithium species. The reaction solvent was removed in vacuo, and the resulting residue was extracted into Et<sub>2</sub>O and filtered over Celite. The solution was concentrated to quarter volume and left to stand in the freezer overnight. The resulting white precipitate was collected and washed with hexanes (3 × 2 mL). **8** was isolated as a white microcrystalline powder (yield: 78 mg, 63%). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): δ 7.11 (d, 2H, t, <sup>3</sup>J<sub>H–H</sub> = 7.4 Hz, tolyl H), 6.97–6.91 (m, 6H), 2.26 (s, 6H, tolyl Me), 1.64 (s, 30H, Cp\*–Me). <sup>13</sup>C{<sup>1</sup>H} NMR (101 MHz, CDCl<sub>3</sub>): δ 189.1 (s, 2C, Zr C), 136.7 (s, 2C, tolyl Me), 134.11 (s, 2C, *o*-tolyl C), 133.0 (s, 2C, *o*-tolyl C), 126.9 (s, 1C, *m*-tolyl C), 126.6 (s, 1C, *m*-tolyl C), 120.3 (s, 2C, *m*-tolyl C), 21.3 (s, 2C, tolyl Me), 12.3 (s, 10C, Cp\* Me). Anal. Calcd for C<sub>34</sub>H<sub>44</sub>Zr: C, 75.08; H, 8.15. Found: C, 75.38; H, 8.21.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.inorgchem.9b01082.

Spectroscopic (NMR) and quantitative GC-FID data (PDF)

## ■ AUTHOR INFORMATION

### Corresponding Author

\*E-mail: itonks@umn.edu.

### ORCID

Ian A. Tonks: 0000-0001-8451-8875

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

Financial support was provided by the National Institutes of Health (Grant 1R35GM119457) and the Alfred P. Sloan Foundation (I.A.T. is a 2017 Sloan Fellow). Equipment for the Chemistry Department NMR facility was supported through a grant from the National Institutes of Health (Grant S10OD011952) with matching funds from the University of Minnesota.

## ■ REFERENCES

- (1) Kaim, W.; Schwederski, B. *Bioinorganic Chemistry: Inorganic Elements in the Chemistry of Life: An Introduction and Guide*; Wiley: Chichester, U.K., 1994.
- (2) Beaumier, E. P.; Pearce, A. J.; See, X. Y.; Tonks, I. A. Modern Applications of Low-Valent Early Transition Metals in Synthesis and Catalysis. *Nat. Rev. Chem.* **2019**, *3*, 15–34.
- (3) Egorova, K. S.; Ananikov, V. P. Toxicity of Metal Compounds: Knowledge and Myths. *Organometallics* **2017**, *36*, 4071–4090.
- (4) Davis-Gilbert, Z. W.; Tonks, I. A. Titanium Redox Catalysis: Insights and Applications of an Earth-Abundant Base Metal. *Dalt. Trans.* **2017**, *46*, 11522–11528.
- (5) Pearce, A. J.; See, X. Y.; Tonks, I. A. Oxidative Nitrene Transfer from Azides to Alkynes via Ti(II)/Ti(IV) Redox Catalysis: Formal [2 + 2 + 1] Synthesis of Pyrroles. *Chem. Commun.* **2018**, *54*, 6891–6894.
- (6) Gilbert, Z. W.; Hue, R. J.; Tonks, I. A. Catalytic Formal [2 + 2 + 1] Synthesis of Pyrroles from Alkynes and Diazenes via Ti(II)/Ti(IV) Redox Catalysis. *Nat. Chem.* **2016**, *8*, 63–68.
- (7) See, X. Y.; Beaumier, E. P.; Davis-Gilbert, Z. W.; Dunn, P. L.; Larsen, J. A.; Pearce, A. J.; Wheeler, T. A.; Tonks, I. A. Generation of Ti II Alkyne Trimerization Catalysts in the Absence of Strong Metal Reductants. *Organometallics* **2017**, *36*, 1383–1390.
- (8) Chiu, H.-C.; Tonks, I. A. Trimethylsilyl-Protected Alkynes as Selective Cross-Coupling Partners in Titanium-Catalyzed [2 + 2 + 1] Pyrrole Synthesis. *Angew. Chem., Int. Ed.* **2018**, *57*, 6090–6094.
- (9) Desnoyer, A. N.; See, X. Y.; Tonks, I. A. Diverse Reactivity of Diazatitanacyclohexenes: Coupling Reactions of 2 H<sup>-</sup>Azirines Mediated by Titanium(II). *Organometallics* **2018**, *37*, 4327–4331.
- (10) Davis-Gilbert, Z. W.; Yao, L. J.; Tonks, I. A. Ti-Catalyzed Multicomponent Oxidative Carboamination of Alkynes with Alkenes and Diazenes. *J. Am. Chem. Soc.* **2016**, *138*, 14570–14573.
- (11) Davis-Gilbert, Z. W.; Wen, X.; Goodpaster, J. D.; Tonks, I. A. Mechanism of Ti-Catalyzed Oxidative Nitrene Transfer in [2 + 2 + 1] Pyrrole Synthesis from Alkynes and Azobenzene. *J. Am. Chem. Soc.* **2018**, *140*, 7267–7281.
- (12) Davis-Gilbert, Z. W.; Kawakita, K.; Blechschmidt, D. R.; Tsurugi, H.; Mashima, K.; Tonks, I. A. In Situ Catalyst Generation and Benchtop-Compatible Entry Points for Ti(II)/Ti(IV) Redox Catalytic Reactions. *Organometallics* **2018**, *37*, 4439–4445.
- (13) Chiu, H.-C.; See, X. Y.; Tonks, I. A. Dative Directing Group Effects in Ti-Catalyzed [2 + 2 + 1] Pyrrole Synthesis: Chemo- and Regioselective Alkyne Heterocoupling. *ACS Catal.* **2019**, *9*, 216–223.
- (14) Yamamoto, K.; Nagae, H.; Tsurugi, H.; Mashima, K. Mechanistic Understanding of Alkyne Cyclotrimerization on Mononuclear and Dinuclear Scaffolds: [4 + 2] Cycloaddition of the Third Alkyne onto Metallocyclopentadienes and Dimetallocyclopentadienes. *Dalt. Trans.* **2016**, *45*, 17072–17081.

- (15) Makar, S.; Saha, T.; Singh, S. K. Naphthalene, a Versatile Platform in Medicinal Chemistry: Sky-High Perspective. *Eur. J. Med. Chem.* **2019**, *161*, 252–276.
- (16) Anthony, J. E. Functionalized Acenes and Heteroacenes for Organic Electronics. *Chem. Rev.* **2006**, *106*, 5028–5048.
- (17) Al Kobaisi, M.; Bhosale, S. V.; Latham, K.; Raynor, A. M.; Bhosale, S. V. Functional Naphthalene Diimides: Synthesis, Properties, and Applications. *Chem. Rev.* **2016**, *116*, 11685–11796.
- (18) Tadross, P. M.; Stoltz, B. M. A Comprehensive History of Arynes in Natural Product Total Synthesis. *Chem. Rev.* **2012**, *112*, 3550–3577.
- (19) Hoye, T. R.; Baire, B.; Niu, D.; Willoughby, P. H.; Woods, B. P. The Hexadehydro-Diels–Alder Reaction. *Nature* **2012**, *490*, 208–212.
- (20) Sullivan, J. M. Explosion during Preparation of Benzenediazonium-2-Carboxylate Hydrochloride. *J. Chem. Educ.* **1971**, *48*, 419.
- (21) Huang, W.; Zhou, X.; Kanno, K.; Takahashi, T. Pd-Catalyzed Reactions of *o*-Diiodoarenes with Alkynes for Aromatic Ring Extension. *Org. Lett.* **2004**, *6*, 2429–2431.
- (22) Yoshikawa, E.; Radhakrishnan, K. V.; Yamamoto, Y. Palladium-Catalyzed Controlled Carbopalladation of Benzynes. *J. Am. Chem. Soc.* **2000**, *122*, 7280–7286.
- (23) Peña, D.; Pérez, D.; Guitián, E.; Castedo, L. Palladium-Catalyzed Cocyclization of Arynes with Alkynes: Selective Synthesis of Phenanthrenes and Naphthalenes. *J. Am. Chem. Soc.* **1999**, *121*, 5827–5828.
- (24) Hsieh, J.-C.; Cheng, C.-H. O-Dihaloarenes as Aryne Precursors for Nickel-Catalyzed [2 + 2 + 2] Cycloaddition with Alkynes and Nitriles. *Chem. Commun.* **2008**, No. 26, 2992.
- (25) Fukutani, T.; Hirano, K.; Satoh, T.; Miura, M. Synthesis of Highly Substituted Naphthalene and Anthracene Derivatives by Rhodium-Catalyzed Oxidative Coupling of Arylboronic Acids with Alkynes. *Org. Lett.* **2009**, *11*, 5198–5201.
- (26) Kerr, J. A. Bond Dissociation Energies by Kinetic Methods. *Chem. Rev.* **1966**, *66*, 465–500.
- (27) Benson, S. W. III - Bond Energies. *J. Chem. Educ.* **1965**, *42*, 502.
- (28) Buchwald, S. L.; Nielsen, R. B. Group 4 Metal Complexes of Benzynes, Cycloalkynes, Acyclic Alkynes, and Alkenes. *Chem. Rev.* **1988**, *88*, 1047–1058.
- (29) Majoral, J.-P.; Meunier, P.; Igau, A.; Pirio, N.; Zablocka, M.; Skowronska, A.; Bredeau, S. Zirconocene [Cp<sub>2</sub>Zr] Synthons and Benzynezirconocene Complexes as Tools in Main Group Element Chemistry. *Coord. Chem. Rev.* **1998**, *178–180*, 145–167.
- (30) Berkovich, E. G.; Shur, V. B.; Vol'pin, M. E.; Lorenz, B.; Rummel, S.; Wahren, M. Die Reaktion von Stickstoff Mit Dehydrobenzol in Der Koordinationssphäre von Titan. *Chem. Ber.* **1980**, *113*, 70–78.
- (31) Vaughan, G. A.; Hillhouse, G. L.; Rheingold, A. L. Syntheses, Structures, and Reactivities of Unusual Four-Membered Metallacycles Formed in Insertion Reactions of N:N:O, N:N:NR, and N:N:CR<sub>2</sub> with (Eta.5-C5Me5)2Zr(C2Ph2). *J. Am. Chem. Soc.* **1990**, *112*, 7994–8001.
- (32) Schock, L. E.; Brock, C. P.; Marks, T. J. Intramolecular Thermolytic Carbon-Hydrogen Activation Processes. Solid-State Structural Characterization of a Mononuclear. Eta.6-Me4C5CH2 Zirconium Complex and a Mechanistic Study of Its Formation from (Me5C5)2Zr(C6H5)2. *Organometallics* **1987**, *6*, 232–241.
- (33) Campora, J.; Buchwald, S. L. Synthesis and Reactivity of a Titanocene-Benzyne Complex. *Organometallics* **1993**, *12*, 4182–4187.
- (34) Legrand, C.; Meunier, P.; Petersen, J. L.; Tavares, P.; Bodiguel, J.; Gautheron, B.; Dousse, G. Unexpected Synthesis of Ortho-Substituted Diselenophenylzirconocenes from the Para-Substituted Diphenylzirconocenes. Chemical and Structural Evidence of the Participation of a Cyclometalated Intermediate That Behaves as a Benzyne Zirconocene Equivalent. *Organometallics* **1995**, *14*, 162–169.
- (35) Kern, R. J. Tetrahydrofuran Complexes of Transition Metal Chlorides. *J. Inorg. Nucl. Chem.* **1962**, *24*, 1105–1109.
- (36) Tung, H.; Brubaker, C. H. Photochemical Decomposition of (Diphenyl)Bis(H<sub>5</sub>-Cyclopentadienyl) Titanium, (Diphenyl)Bis(H<sub>5</sub>-Pentamethylcyclopentadienyl) Titanium and the Zirconium Analogs. *Inorg. Chim. Acta* **1981**, *52*, 197–204.
- (37) Simoes, J. A. M.; Beauchamp, J. L. Transition Metal-Hydrogen and Metal-Carbon Bond Strengths: The Keys to Catalysis. *Chem. Rev.* **1990**, *90*, 629–688.
- (38) DiFranco, S. A.; Maciulis, N. A.; Staples, R. J.; Batrice, R. J.; Odum, A. L. Evaluation of Donor and Steric Properties of Anionic Ligands on High Valent Transition Metals. *Inorg. Chem.* **2012**, *51*, 1187–1200.
- (39) Okamoto, S.; Yamada, T.; Tanabe, Y.; Sakai, M. Alkyne [2 + 2] Cyclotrimerization Catalyzed by a Low-Valent Titanium Reagent Derived from CpTiX<sub>3</sub> (X = Cl, O-*i*-Pr), Me<sub>3</sub>SiCl, and Mg or Zn. *Organometallics* **2018**, *37*, 4431–4438.
- (40) Taft, R. W. Linear Free Energy Relationships from Rates of Esterification and Hydrolysis of Aliphatic and Ortho-Substituted Benzoate Esters. *J. Am. Chem. Soc.* **1952**, *74*, 2729–2732.
- (41) Taft, R. W. Polar and Steric Substituent Constants for Aliphatic and O-Benzoate Groups from Rates of Esterification and Hydrolysis of Esters I. *J. Am. Chem. Soc.* **1952**, *74*, 3120–3128.
- (42) Taft, R. W. Linear Steric Energy Relationships. *J. Am. Chem. Soc.* **1953**, *75*, 4538–4539.
- (43) Charton, M. Steric Effects. I. Esterification and Acid-Catalyzed Hydrolysis of Esters. *J. Am. Chem. Soc.* **1975**, *97*, 1552–1556.
- (44) Charton, M. The Nature of the Electrical Effect of Alkyl Groups. I. The Validity of the Sigma\* Constants. *J. Am. Chem. Soc.* **1977**, *99*, 5687–5688.
- (45) Clavier, H.; Nolan, S. P. Percent Buried Volume for Phosphine and N-Heterocyclic Carbene Ligands: Steric Properties in Organometallic Chemistry. *Chem. Commun.* **2010**, *46*, 841.
- (46) Hartwig, J. F.; Andersen, R. A.; Bergman, R. G. Synthesis of a Highly Reactive (Benzyne)Ruthenium Complex. Carbon-Carbon, Carbon-Hydrogen, Nitrogen-Hydrogen and Oxygen-Hydrogen Activation Reactions. *J. Am. Chem. Soc.* **1989**, *111*, 2717–2719.
- (47) Erker, G. The Reaction of Intermediate Zirconocene-Aryne Complexes with C-H Bonds in the Thermolysis of Diarylzirconocenes. *J. Organomet. Chem.* **1977**, *134*, 189–202.
- (48) Herwig, P. T.; Enkelmann, V.; Schmelz, O.; Müllen, K. Synthesis and Structural Characterization of Hexa-Tert-Butyl- Hexa-Peri-Hexabenzocoronene, Its Radical Cation Salt and Its Tricarbonylchromium Complex. *Chem. - Eur. J.* **2000**, *6*, 1834–1839.
- (49) Shintani, R.; Takagi, C.; Ito, T.; Naito, M.; Nozaki, K. Rhodium-Catalyzed Asymmetric Synthesis of Silicon-Stereogenic Dibenzosiloles by Enantioselective [2 + 2+2] Cycloaddition. *Angew. Chem., Int. Ed.* **2015**, *54*, 1616–1620.
- (50) Wang, C.; Morimoto, T.; Kanashiro, H.; Tanimoto, H.; Nishiyama, Y.; Kakiuchi, K.; Artok, L. Rhodium(I)-Catalyzed Carbonylative Arylation of Alkynes with Arylboronic Acids Using Formaldehyde as a Carbonyl Source. *Synlett* **2014**, *25*, 1155–1159.
- (51) Bodach, A.; Hebestreit, R.; Bolte, M.; Fink, L. Syntheses and Crystal Structures of Phenyl-Lithium Derivatives. *Inorg. Chem.* **2018**, *57*, 9079–9085.
- (52) Honjo, Y.; Shibata, Y.; Kudo, E.; Namba, T.; Masutomi, K.; Tanaka, K. Room Temperature Decarboxylative and Oxidative [2 + 2+2] Annulation of Benzoic Acids with Alkynes Catalyzed by an Electron-Deficient Rhodium(III) Complex. *Chem. - Eur. J.* **2018**, *24*, 317–321.
- (53) Kabalka, G. W.; Ju, Y.; Wu, Z. A New Titanium Tetrachloride Mediated Annulation of  $\alpha$ -Aryl-Substituted Carbonyl Compounds with Alkynes: A Simple and Highly Efficient Method for the Regioselective Synthesis of Polysubstituted Naphthalene Derivatives. *J. Org. Chem.* **2003**, *68*, 7915–7917.
- (54) Hu, F.; Lei, X. A Nickel Precatalyst for Efficient Cross-Coupling Reactions of Aryl Tosylates with Arylboronic Acids: Vital Role of Dppf. *Tetrahedron* **2014**, *70*, 3854–3858.
- (55) Kong, W.-J.; Finger, L. H.; Oliveira, J. C. A.; Ackermann, L. Rhodoelectrocatalysis for Annulative C-H Activation: Polycyclic Aromatic Hydrocarbons through Versatile Double Electrocatalysis. *Angew. Chem., Int. Ed.* **2019**, *58*, 6342–6346.

(56) Geng, K.; Fan, Z.; Zhang, A. Rhodium-Catalyzed Oxidative Coupling of N-Acyl Anilines with Alkynes Using an Acylamino Moiety as the Traceless Directing Group. *Org. Chem. Front.* **2016**, *3*, 349–353.

(57) Kitamura, T.; Yamane, M.; Inoue, K.; Todaka, M.; Fukatsu, N.; Meng, Z.; Fujiwara, Y. A New and Efficient Hypervalent Iodine-Benzyne Precursor, (Phenyl)[o-(Trimethylsilyl)Phenyl]Iodonium Triflate: Generation, Trapping Reaction, and Nature of Benzyne. *J. Am. Chem. Soc.* **1999**, *121*, 11674–11679.

(58) Fukutani, T.; Hirano, K.; Satoh, T.; Miura, M. Synthesis of Highly Substituted Acenes through Rhodium-Catalyzed Oxidative Coupling of Arylboron Reagents with Alkynes. *J. Org. Chem.* **2011**, *76*, 2867–2874.