JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
Cite This: J. Am. Chem. Soc. 2018, 140, 2450−2454
pubs.acs.org/JACS

Titanocene-Mediated Dinitrile Coupling: A Divergent Route to Nitrogen-Containing Polycyclic Aromatic Hydrocarbons

Gavin R. Kiel, Adrian E. Samkian, Amélie Nicolay, Ryan J. Witzke, and T. Don Tilley*

Department of Chemistry, University of California, Berkeley, Berkeley, California 94720, United States

Supporting Information

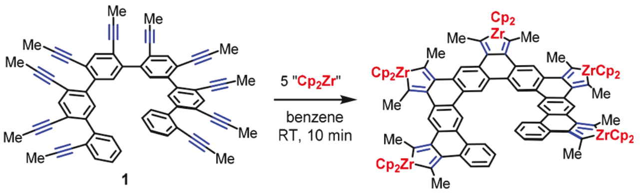
ABSTRACT: A general synthetic strategy for the construction of large, nitrogen-containing polycyclic aromatic hydrocarbons (PAHs) is reported. The strategy involves two key steps: (1) a titanocene-mediated reductive cyclization of an oligo(dinitrile) precursor to form a PAH appended with di(aza)titanacyclopentadiene functionality; (2) a divergent titanocene transfer reaction, which allows final-step installation of one or more *o*-quinone, diazole, or pyrazine units into the PAH framework. The new methodology enables rational, late-stage control of HOMO and LUMO energy levels and thus photophysical and electrochemical properties, as revealed by UV/vis and fluorescence spectroscopy, cyclic voltammetry, and DFT calculations. More generally, this contribution presents the first productive use of di(aza)metallacyclopentadiene intermediates in organic synthesis, including the first formal [2 + 2 + 2] reaction to form a pyrazine ring.

Heterocyclic rings have a profound impact on the electronic, photophysical, and supramolecular properties of polycyclic aromatic hydrocarbons (PAHs) and related carbon nanostructures.[1,2] In particular, nitrogen-containing PAHs have attracted tremendous interest in organic electronics, as they often are good electron acceptors and have increased stability.[2] Such compounds are also models or building blocks for nitrogen-doped graphene, which is currently under intense investigation for its applications in electronics and catalysis.[3] The general, directed incorporation of nitrogen and other heteroatoms into PAHs is a significant challenge. Many synthetic methods have emerged, but few are *divergent*, which provide access to libraries of analogous compounds and facilitate the identification of structure−property relationships.[4] Indeed, the future success of PAHs as components in functional materials will critically depend on the availability of reliable synthetic methods that can be used to rationally tune properties in this way.

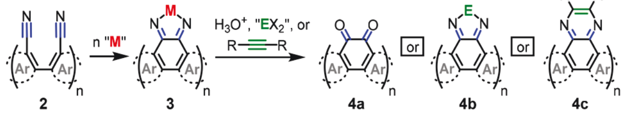
As part of an effort to expand the utility of [2 + 2 + *n*] cycloadditions in PAH synthesis, we recently developed a general strategy for the synthesis of large PAHs, exemplified by the quantitative cyclization of oligo(diyne) compounds such as **1** (Scheme 1a) with a zirconocene reagent or Ir catalyst.[5] The extension of this approach to include analogous precursors of general structure **2** (Scheme 1b), containing one or more tethered dinitrile units, would provide access to nitrogen-containing or other electron-deficient analogues. Notably, in contrast to diyne coupling,[6] there is little precedent for the reductive coupling of two nitrile units to form a 2,5-di(aza)metallacyclopentadiene ring. Rosenthal and co-workers recently reported a breakthrough in this regard, demonstrating the competence of $Cp^*_2M(Me_3SiC{\equiv}CSiMe_3)$ (M = Ti or Zr) for the formation of several 2,5-di(aza)metallacyclopentadienes (the first unambiguous examples with any transition metal).[7]

Scheme 1

(a) Previously-reported oligo(diyne) coupling



(b) This report: extension of strategy to analogous oligo(dinitrile)s



M = low-valent transition metal fragment
E = main group fragment

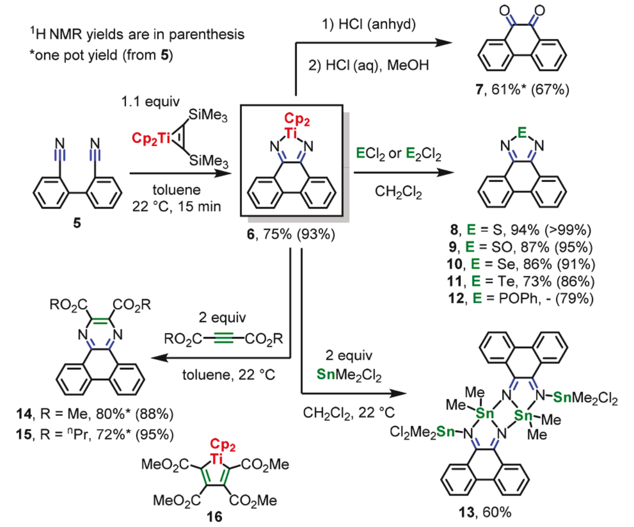
This report describes a cheaper and more accessible coupling reagent, $Cp_2Ti(Me_3SiC{\equiv}CSiMe_3)$,[8] that efficiently cyclizes tethered dinitrile compounds of general structure **2**. Furthermore, treatment of the resulting π-extended di(aza)-titanacycles **3** with an aqueous acid, main-group dihalides, or acetylene dicarboxylates provides a divergent route to π-extended *o*-quinones (**4a**), diazoles (**4b**), or pyrazines (**4c**), respectively. These transformations represent the first development of metallacycle transfer chemistry[6c,d] for di(aza)metallacyclopentadienes (to prepare **4b**) and the first examples of formal [2 + 2 + 2] reactions to form pyrazine rings. This chemistry was initially developed in the model system of Scheme 2 and then applied to *divergently* tune the HOMO−LUMO gap in two different PAH systems via installation of a range of substituents and heterocyclic rings.

The model system of Scheme 2 formed the basis of our investigations. Based on our favorable experience with biaryl-tethered diynes (e.g., **1**),[5] we hypothesized that the required *intra*molecular coupling of tethered dinitrile **5** might proceed with readily accessible $Cp_2Ti(Me_3SiC{\equiv}CSiMe_3)$, despite the failure of this reagent in an analogous *inter*molecular coupling.[7a]

Received: December 31, 2017
Published: January 31, 2018

DOI: 10.1021/jacs.7b13823
J. Am. Chem. Soc. 2018, 140, 2450−2454

Scheme 2. Investigations of a Model System



Furthermore, it seemed that the relatively small Cp ligands would provide a reactive titanacycle better poised for further transformations. Indeed, treatment of **5** with 1.1 equiv of $Cp_2Ti(Me_3SiC{\equiv}CSiMe_3)$ gave the phenanthrene-annulated di(aza)titanacyclopentadiene **6** in 75% isolated yield. The structure of this compound was verified by X-ray crystallography (see Supporting Information (SI), Figure S82), and its isolation allowed streamlined reactivity studies (*vide infra*).

The first transformation employed **6** *in situ* as a synthetic intermediate. A one-pot procedure involving coupling of **5**, protodemetalation of **6**, and hydrolysis of the resulting bis-imine gave 9,10-phenanthrenequinone **7** in 61% isolated yield. This represents a new way to access *π*-extended *o*-quinones, which are most commonly obtained by functionalization of one of the few commercially available *o*-quinones, or via oxidation of the parent PAH. These compounds are attractive for their electronic properties (most notably, their ability to reversibly accept electrons),[9] as ligands for transition metal complexes,[10] and as synthetic precursors.[2e,11]

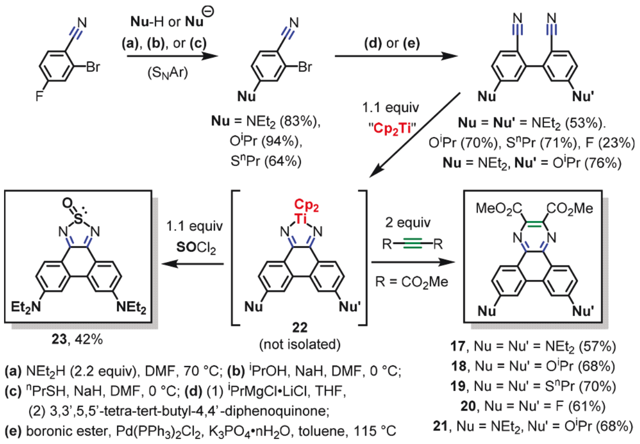
In analogy to Fagan and Nugent's versatile and well-established zirconacyclopentadiene transfer chemistry,[6c,d] the "Cp$_2$Ti" fragment in **6** can be exchanged for a range of heteroatoms. For example, this compound provided divergent access to chalcogenadiazoles **8**−**11**. Phenanthrene-annulated thiadiazole **8** and thiadiazole-oxide **9** were isolated in good yields by treatment of **6** with S_2Cl_2 and $SOCl_2$, respectively.[12] The reaction of **6** with SO_2Cl_2 failed to yield the corresponding thiadiazole-dioxide, resulting primarily in decyclization to reform **5**. The heavier chalcogen analogues **10** and **11** were similarly synthesized by treatment of **6** with the isolable, base-stabilized chalcogen dihalides $SeCl_2$(bipy)[13] and $TeCl_2$(bipy),[13,14] respectively. Benzannulated chalcogenadiazole heterocycles are heavily used as electron acceptors in conducting polymers, and their unique self-assembly properties are well-documented.[15] These two features make them attractive for incorporation into PAHs;[15d−f,16] however, this typically requires *o*-quinone or *o*-diamine functionality, which can be difficult to install.

The chemistry was extended to other main group diazole heterocycles, such as the *π*-extended phosphadiazole **12**,[17] which was produced in 79% yield (by ^{1}H NMR spectroscopy) upon treatment of titanacycle **6** with $POCl_2Ph$. Unfortunately, compound **12** could not be isolated due to the difficulty in separating the Cp_2TiCl_2 byproduct, which was complicated by the hydrolytic lability of the P−N bond in this compound. Treatment of a CH_2Cl_2 solution of **6** with 2 equiv of $SnMe_2Cl_2$ resulted in precipitation of dimeric **13**, as revealed by single crystal X-ray crystallography (Figure S83). It is well-known that diazole heterocycles (e.g., **10** and **11**) associate noncovalently by formation of cyclic E−N−E−N linkages viewed as Lewis acid−base adducts,[15] but the short bonds in the central Sn−N−Sn−N ring of **13** suggest that this dimeric compound is associated through normal covalent bonding.

The formal [2 + 2 + 2] products **14** and **15** were produced in good yields by treatment of **6**, generated *in situ* from **5**, with excess di(alkyl)acetylene dicarboxylate. An interesting feature of this transformation is its occurrence in the absence of additives, as it formally requires the extrusion of thermally unstable "Cp$_2$Ti".[18] It is possible that the excess alkyne plays a role in this extrusion, as metallacyclopentadiene **16**[19] is observed (by ^{1}H NMR spectroscopy) as a byproduct in the synthesis of **14**. Furthermore, the yield drops to 63% when 1.1 equiv of acetylene is used. No reaction occurred with 3-hexyne and diphenylacetylene, even at elevated temperature, suggesting that an electron-deficient alkyne is required. Surprisingly, this appears to be the first example of a [2 + 2 + 2] reaction to form a pyrazine ring, despite the extensive literature on [2 + 2 + 2] reactions involving nitriles.[20]

An appealing feature of the dinitrile precursors is the ease with which functionalized derivatives can be accessed. For example, the cyano group is a good activating group in nucleophilic aromatic substitution (S_NAr) reactions.[21] By subjection of commercially available 2-bromo-4-fluorobenzonitrile to the simple three-step sequence of S_NAr, aryl−aryl coupling, and the [2 + 2 + 2] conditions described above, a range of 7,10-substituted dibenzo[*f*,*h*]quinoxalines **17**−**21** were produced (Scheme 3). The 57−70% yields for the [2 + 2 + 2] reactions are for the two-step, one-pot procedure. The S_NAr reactions are notable for their scalability and simplicity. For example, introduction of the amino substituent requires simple heating of a concentrated mixture of secondary amine (2.2 equiv) and 2-bromo-4-fluorobenzonitrile in DMF.

Scheme 3. Functionalized Derivatives *via* an S_NAr/Aryl−Aryl Coupling/[2 + 2 + *n*] Sequence

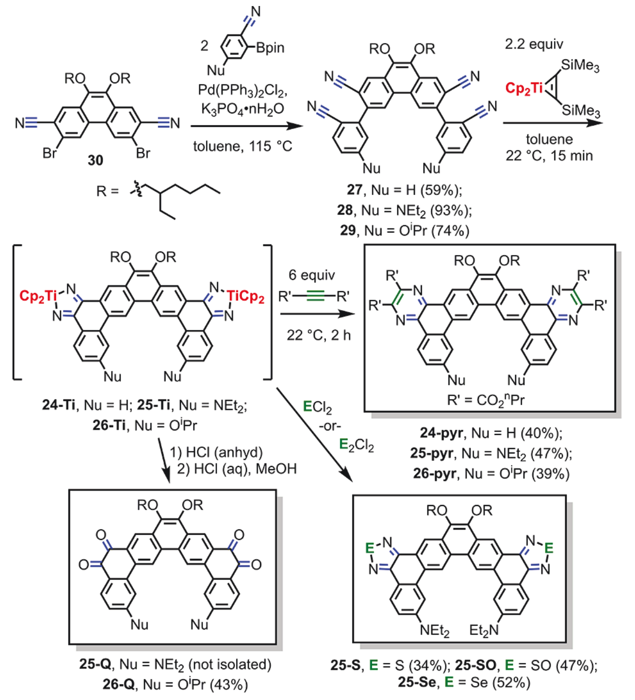


(**a**) NEt_2H (2.2 equiv), DMF, 70 °C; (**b**) ^{i}PrOH, NaH, DMF, 0 °C; (**c**) ^{n}PrSH, NaH, DMF, 0 °C; (**d**) (1) ^{i}PrMgCl•LiCl, THF, (2) 3,3',5,5'-tetra-tert-butyl-4,4'-diphenoquinone; (**e**) boronic ester, $Pd(PPh_3)_2Cl_2$, $K_3PO_4{\bullet}nH_2O$, toluene, 115 °C

A critical feature of the new synthetic strategy is that the intermediate di(aza)titanacyclopentadienes (**22**) can be subjected to any of the reactions described in Scheme 2. This is shown in the synthesis of thiadiazole-oxide **23**, which was targeted for its expected small HOMO−LUMO gap due to its donor−acceptor (D−A) structure.

The advantages of this strategy are more apparent in the construction of larger PAHs, such as those resulting from multifold coupling reactions and containing two or more quinones, pyrazines, or diazoles. The focus here is on the series of large, angular PAHs **24**−**26** (Scheme 4), which were targeted in the context of our general interest in expanded helicenes.[5b] These compounds possess an alternation of donor and acceptor units, which might give rise to ambipolar charge transport and/or novel self-assembly. The bis(dinitrile) precursors **27**−**29** were obtained via Suzuki cross-coupling[22] of compound **30** with the appropriate boronic ester. The former was easily prepared on a gram scale using a Pd-catalyzed cyanation reaction,[23] and the latter were produced via another exploitation of S$_N$Ar chemistry (see SI).

Scheme 4. Large, Angular PAHs *via* Twofold Coupling



The first targets were the pyrazine-annulated **24**−**26-pyr**, which differ only in the electron-donating ability of the "Nu" substituent, by employment of the [2 + 2 + 2] conditions described above. These compounds were isolated in 39−47% yields for the two-step, one-pot reaction, which are consistent with the yields expected based on the onefold couplings described above. The side products were easily separated by column chromatography. Monitoring of the reactions by ^{1}H NMR spectroscopy revealed formation of the intermediate bis(di(aza)titanacyclopentadiene)s **24**−**26-Ti** in 58%, 76%, and 67% yields, respectively. The NEt$_2$-substituted bis(dinitrile) **28** was next subjected to the titanocene-coupling/chalcogen transfer reactions described above, which produced bis(chalcogenadiazoles) **25-S**, **25-SO**, and **25-Se** in 34%, 47%, and 52% yields, respectively. Compound **25-SO** is an inseparable mixture of two diastereomers, resulting from the chiral S═O centers. It is important to note that, in contrast to the model system (Scheme 2), these compounds were produced in a one-pot reaction from bis(dinitrile) **28**. An attempt to produce the bis(*o*-quinone) **25-Q** using the conditions presented for **7** gave a complex mixture, probably due to the basicity of the NEt$_2$ group; however, synthesis of bis(*o*-quinone) **26-Q** using these conditions proceeded without difficulty.

A high level of control over HOMO and LUMO energy levels, and thus photophysical and electronic properties, can be achieved using the chemistry developed above. In the series of pyrazine-annulated PAHs **14** and **17**−**21**, a bathochromic shift in the absorption onset (λ_{onset}) value of 129 nm results on going from F-substituted **20** to NEt$_2$-substituted **17** (Figure 1a), with intermediate shifts for less-donating substituents. This results from an increase in the HOMO energy level, as supported by cyclic voltammetry (CV) and DFT calculations (see Figures S80 and S84 and Table S2). Emission λ_{max} values span a range of 158 nm in this series of compounds (Figure 1b). The LUMO energy level can be manipulated by modification of the heterocyclic ring,[16a] as shown for thiadiazole-oxide-annulated PAH **23**. Compared to pyrazine-annulated **17**, this compound exhibits a further bathochromic shift in absorption (λ_{onset}) of 84 nm and in emission (λ_{max}) of 91 nm. The total shifts in absorption and emission (from **20** to **23**) are 213 and 249 nm, respectively. Thus, a large decrease in the optical HOMO−LUMO gaps, from 3.20 eV for **20** to 2.06 eV for **23**, can be achieved from rational and independent perturbations of HOMO and LUMO energy levels in this PAH system.

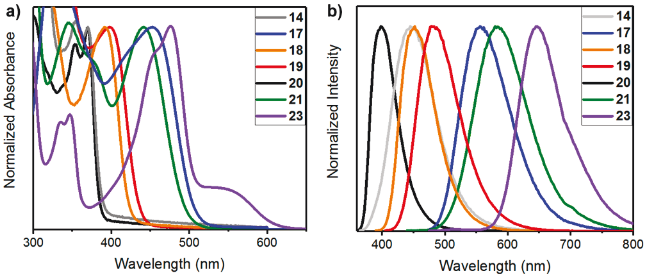


Figure 1. Normalized (a) absorption and (b) emission spectra (CH_2Cl_2) for PAHs **14**, **17**−**21**, and **23**.

The expected red shift in absorption and emission is again seen on going from unsubstituted **24-pyr** to NEt$_2$-substituted **25-pyr** (Figure 2a and 2b); however, the effect of the substituent is attenuated since the HOMO is partially distributed onto the central phenanthrene unit, which also contains electron-donating groups. Introduction of the thia- and selenadiazole rings in compounds **25-S** and **25-Se** results in

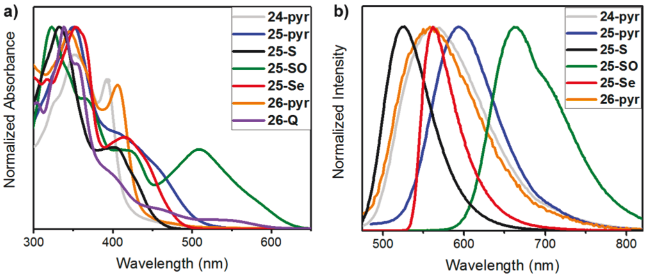


Figure 2. Normalized (a) absorption and (b) emission spectra (CH_2Cl_2) for **24**−**26**.

blue-shifted absorption and emission maxima (λ_{max}) compared to compound **25-Pyr**; however, the absorption and emission (λ_{max}) of bis(thiadiazole-oxide) **25-SO** exhibit large red shifts and a concomitant decrease in optical HOMO−LUMO gap of 0.35 eV (from 2.31 to 1.96 eV) compared to **25-pyr**. Bis(quinone) **26-Q** exhibits a weak, red-shifted absorption band, and this compound is nonfluorescent.

Given the facility with which *o*-quinones accept electrons, the rare bis(*o*-quinone) **26-Q** was analyzed by CV in THF with 0.1 M $N^{n}Bu_4PF_6$ as the supporting electrolyte (Figure S81). This compound exhibits four reduction events (three reversible and one irreversible) with $E_{1/2}$ values of −1.16, −1.32, −1.91, and −3.01 V vs Fc/Fc$^+$. No oxidation events could be observed within the solvent window.

In conclusion, a general, divergent synthetic strategy to rationally control the electronic and optical properties of nitrogen-substituted PAHs has been disclosed. The initial focus is on application of this strategy to PAHs and graphene nanostructures; however, this chemistry should find applications in other fields where *o*-quinone, diazole, or pyrazine functionalities are desirable. Metallacyclopentadiene intermediates have long been employed to access highly substituted benzenes and metallole heterocycles (e.g., thiophenes, phospholes, and stannoles).[6] This strategy has now been extended to seven di(aza)-analogues. Current efforts involve application of the method to synthesis of more complex electron-deficient PAHs (e.g., expanded helicenes), especially those containing multiple redox centers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b13823.

Crystallographic information file for **6** (CIF)
Crystallographic information file for **13** (CIF)
Experimental procedures and characterization data for all new compounds (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*tdtilley@berkeley.edu

ORCID

Gavin R. Kiel: 0000-0001-6449-8547
T. Don Tilley: 0000-0002-6671-9099

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was funded by the National Science Foundation under Grant No. CHE-1708210. Crystallographic analysis of compound **6** was performed at The Advanced Light Source, which is supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Crystallographic analysis of compound **13** was performed at the ChexRay X-ray crystallographic facility (UC Berkeley), which is funded by the National Institutes of Health under Grant No. S10-RR027172. DFT calculations were performed at the Molecular Computation and Graphics Facility at UC Berkeley, which is funded by the National Institutes of Health under Grant No. S10OD023532.

■ REFERENCES

(1) (a) Jiang, W.; Li, Y.; Wang, Z. *Chem. Soc. Rev.* **2013**, *42*, 6113. (b) Stępień, M.; Gońka, E.; Żyła, M.; Sprutta, N. *Chem. Rev.* **2017**, *117*, 3479. (c) Anthony, J. E. *Chem. Rev.* **2006**, *106*, 5028. (d) Vostrowsky, O.; Hirsch, A. *Chem. Rev.* **2006**, *106*, 5191. (e) *Polycyclic Arenes and Heteroarenes*; Miao, Q., Ed.; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2015. (f) Narita, A.; Wang, X.-Y.; Feng, X.; Müllen, K. *Chem. Soc. Rev.* **2015**, *44*, 6616.

(2) (a) Bunz, U. H. F.; Engelhart, J. U.; Lindner, B. D.; Schaffroth, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 3810. (b) Bunz, U. H. F. *Acc. Chem. Res.* **2015**, *48*, 1676. (c) Miao, Q. *Adv. Mater.* **2014**, *26*, 5541. (d) Li, J.; Zhang, Q. *ACS Appl. Mater. Interfaces* **2015**, *7*, 28049. (e) Mateo-Alonso, A. *Chem. Soc. Rev.* **2014**, *43*, 6311.

(3) (a) Wang, H.; Maiyalagan, T.; Wang, X. *ACS Catal.* **2012**, *2*, 781. (b) Kong, X.-K.; Chen, C.-L.; Chen, Q.-W. *Chem. Soc. Rev.* **2014**, *43*, 2841.

(4) Many of the methods employed to date are summarized in refs 1 and 2. Notable examples of divergent approaches: (a) Jiang, W.; Qian, H.; Li, Y.; Wang, Z. *J. Org. Chem.* **2008**, *73*, 7369. (b) He, B.; Dai, J.; Zherebetskyy, D.; Chen, T. L.; Zhang, B. A.; Teat, S. J.; Zhang, Q.; Wang, L.; Liu, Y. *Chem. Sci.* **2015**, *6*, 3180.

(5) (a) Kiel, G. R.; Ziegler, M. S.; Tilley, T. D. *Angew. Chem., Int. Ed.* **2017**, *56*, 4839. (b) Kiel, G. R.; Patel, S. C.; Smith, P. W.; Levine, D. S.; Tilley, T. D. *J. Am. Chem. Soc.* **2017**, *139*, 18456.

(6) (a) Müller, E. *Synthesis* **1974**, *1974*, 761. (b) Vollhardt, K. P. C. *Acc. Chem. Res.* **1977**, *10*, 1. (c) Fagan, P. J.; Nugent, W. A. *J. Am. Chem. Soc.* **1988**, *110*, 2310. (d) Yan, X.; Xi, C. *Acc. Chem. Res.* **2015**, *48*, 935. (e) Agenet, N.; Buisine, O.; Slowinski, F.; Gandon, V.; Aubert, C.; Malacria, M. In *Organic Reactions*; Overman, L. E., Ed.; John Wiley & Sons: Hoboken, NJ, 2007, Vol. *68*, pp 1−302. (f) *Transition-Metal-Mediated Aromatic Ring Construction*; Tanaka, K., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, 2013.

(7) Initial report: (a) Becker, L.; Arndt, P.; Jiao, H.; Spannenberg, A.; Rosenthal, U. *Angew. Chem., Int. Ed.* **2013**, *52*, 11396. Follow-up reports: (b) Becker, L.; Arndt, P.; Spannenberg, A.; Jiao, H.; Rosenthal, U. *Angew. Chem., Int. Ed.* **2015**, *54*, 5523. (c) Becker, L.; Reiß, F.; Altenburger, K.; Spannenberg, A.; Arndt, P.; Jiao, H.; Rosenthal, U. *Chem. - Eur. J.* **2016**, *22*, 10826.

(8) (a) Review: Rosenthal, U.; Burlakov, V. V.; Arndt, P.; Baumann, W.; Spannenberg, A. *Organometallics* **2003**, *22*, 884. (b) This reagent has also been used to construct hexaazatriphenylenes *via* an intermolecular, dehydrogenative C−C bond forming reaction: Piglosiewicz, I. M.; Beckhaus, R.; Saak, W.; Haase, D. *J. Am. Chem. Soc.* **2005**, *127*, 14190.

(9) (a) Schweinfurth, D.; Zalibera, M.; Kathan, M.; Shen, C.; Mazzolini, M.; Trapp, N.; Crassous, J.; Gescheidt, G.; Diederich, F. *J. Am. Chem. Soc.* **2014**, *136*, 13045. (b) Urakawa, K.; Sumimoto, M.; Arisawa, M.; Matsuda, M.; Ishikawa, H. *Angew. Chem.* **2016**, *128*, 7558.

(10) Pierpont, C. G.; Buchanan, R. M. *Coord. Chem. Rev.* **1981**, *38*, 45.

(11) Wasserfallen, D.; Kastler, M.; Pisula, W.; Hofer, W. A.; Fogel, Y.; Wang, Z.; Müllen, K. *J. Am. Chem. Soc.* **2006**, *128*, 1334.

(12) One thiadiazole-oxide has been synthesized by treatment of a di(aza)titanacyclopentadiene with $SOCl_2$, but the yield was low (ref 7c). To the best of our knowledge, this is the only previous example of metallacycle transfer chemistry with a di(aza)metallacyclopentadiene.

(13) Dutton, J. L.; Farrar, G. J.; Sgro, M. J.; Battista, T. L.; Ragogna, P. J. *Chem. - Eur. J.* **2009**, *15*, 10263.

(14) He, G.; Kang, L.; Torres Delgado, W.; Shynkaruk, O.; Ferguson, M. J.; McDonald, R.; Rivard, E. *J. Am. Chem. Soc.* **2013**, *135*, 5360.

(15) (a) Cozzolino, A. F.; Vargas-Baca, I.; Mansour, S.; Mahmoudkhani, A. H. *J. Am. Chem. Soc.* **2005**, *127*, 3184. (b) Ono, K.; Tanaka, S.; Yamashita, Y. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1977. (c) Langis-Barsetti, S.; Maris, T.; Wuest, J. D. *J. Org. Chem.* **2017**, *82*, 5034. (d) Neidlein, R.; Knecht, D.; Endres, H. *Z. Naturforsch., B: J. Chem. Sci.* **1987**, *42*, 84. (e) Appleton, A. L.; Miao, S.; Brombosz, S. M.; Berger, N. J.; Barlow, S.; Marder, S. R.; Lawrence, B. M.; Hardcastle, K. I.; Bunz, U. H. F. *Org. Lett.* **2009**, *11*, 5222. (f) Xia, D.; Wang, X.-Y.; Guo, X.; Baumgarten, M.; Li, M.;

Müllen, K. *Cryst. Growth Des.* **2016**, *16*, 7124. (g) Wang, Y.; Michinobu, T. *J. Mater. Chem. C* **2016**, *4*, 6200.

(16) (a) Linder, T.; Badiola, E.; Baumgartner, T.; Sutherland, T. C. *Org. Lett.* **2010**, *12*, 4520. (b) Xie, Y.; Shuku, Y.; Matsushita, M. M.; Awaga, K. *Chem. Commun.* **2014**, *50*, 4178. (c) Xiao, J.; Xiao, X.; Zhao, Y.; Wu, B.; Liu, Z.; Zhang, X.; Wang, S.; Zhao, X.; Liu, L.; Jiang, L. *Nanoscale* **2013**, *5*, 5420.

(17) Linder, T.; Sutherland, T. C.; Baumgartner, T. *Chem. - Eur. J.* **2010**, *16*, 7101.

(18) In contrast, the reaction between a zirconacyclopentadiene and a di(alkyl)acetylene dicarboxylate requires an initial transmetallation to Cu: Takahashi, T.; Xi, Z.; Yamazaki, A.; Liu, Y.; Nakajima, K.; Kotora, M. *J. Am. Chem. Soc.* **1998**, *120*, 1672.

(19) Demerseman, B.; Dixneuf, P. H. *J. Chem. Soc., Chem. Commun.* **1981**, 665.

(20) A closely related transformation is a 1,2,4-triazine synthesis *via* a [2 + 2 + 2] reaction between a dinitrile and a nitrile: Gesing, E. R. F.; Groth, U.; Vollhardt, K. P. C. *Synthesis* **1984**, *1984*, 351. For a review of [2 + 2 + 2] reactions involving nitriles, see: Varela, J. A.; Saá, C. *Chem. Rev.* **2003**, *103*, 3787.

(21) Bunnett, J. F.; Zahler, R. E. *Chem. Rev.* **1951**, *49*, 273.

(22) Urawa, Y.; Naka, H.; Miyazawa, M.; Souda, S.; Ogura, K. *J. Organomet. Chem.* **2002**, *653*, 269.

(23) Tschaen, D. M.; Desmond, R.; King, A. O.; Fortin, M. C.; Pipik, B.; King, S.; Verhoeven, T. R. *Synth. Commun.* **1994**, *24*, 887.

DOI: 10.1021/jacs.7b13823
J. Am. Chem. Soc. 2018, 140, 2450−2454