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Examination of the Mechanism of Rh_2(II)-Catalyzed Carbazole Formation Using Intramolecular Competition Experiments

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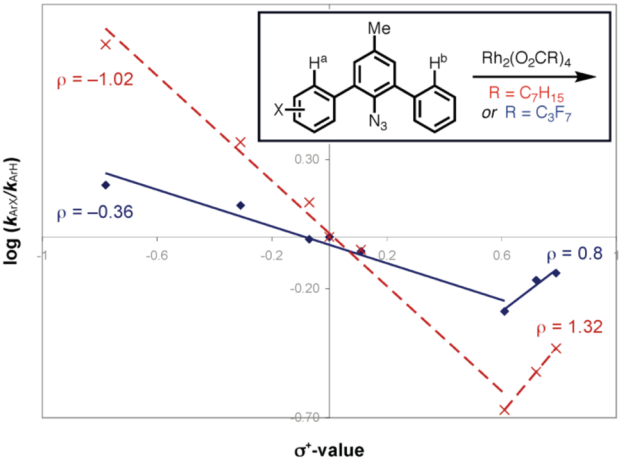

The use of a rhodium(II) carboxylate catalyst enables the mild and stereoselective formation of carbazoles from biaryl azides. Intramolecular competition experiments of triaryl azides suggested the source of the selectivity. A primary intramolecular kinetic isotope effect was not observed, and correlation of the product ratios with Hammett σ^+ values produced a plot with two intersecting lines with opposite ρ values. These data suggest that electronic donation by the biaryl π-system accelerates the formation of rhodium nitrenoid and that C−N bond formation occurs through a 4π-electron-5-atom electrocyclization.

Introduction

The development of efficient methods for the selective transformation of carbon−hydrogen bonds into carbon−heteroatom bonds remains a goal of synthetic chemistry.[1] The direct incorporation of functionality into carbon−hydrogen bonds improves synthetic efficiency[2] by minimizing functional group manipulation.[1f,3] Dirhodium(II) complexes have proven to be efficient C−H bond amination catalysts by stabilizing the nitrene intermediate.[1e,4−9] Our group has used these complexes to catalyze the intramolecular formation of C−N bonds from vinyl or aryl azides to form indoles, pyrroles, and carbazoles.[10] Use of the rhodium catalyst provides a mild and stereoselective alternative to the thermal- or photochemical reaction (Scheme 1).[11] In this paper, we report mechanistic studies aimed at determining

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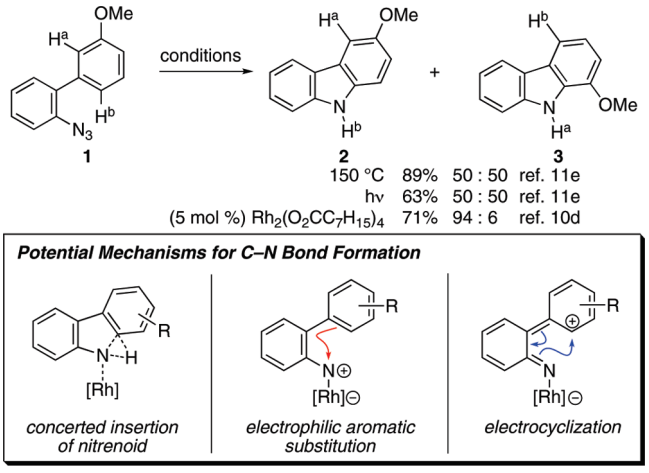
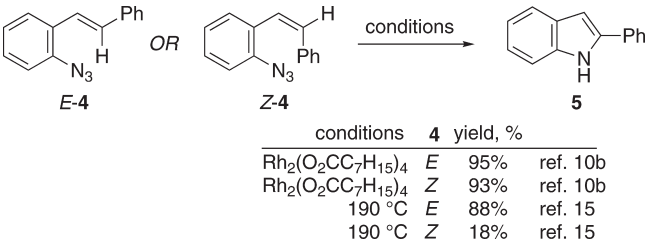
SCHEME 1. Comparison of Regioselectivity of Carbazole Formation from Biaryl Azide 1: Potential Mechanisms for C−N Bond Formation



SCHEME 2. Comparison of the Reactivity of *E*- and *Z*-Isomers of Styryl Azide 4



conditions	4	yield, %	
$Rh_2(O_2CC_7H_{15})_4$	*E*	95%	ref. 10b
$Rh_2(O_2CC_7H_{15})_4$	*Z*	93%	ref. 10b
190 °C	*E*	88%	ref. 15
190 °C	*Z*	18%	ref. 15

the role of the catalyst in promoting and controlling this regioselective transformation. Our results enable distinction between a concerted aryl C−H bond insertion, electrophilic aromatic substitution, and electrocyclization of the rhodium nitrenoid as the mechanism for C−N bond formation.

In contrast to the thorough studies on the mechanism of thermal or photolytic nitrene formation from *o*-biaryl azides,[11e,12,13] mechanistic studies on metal nitrenoids generated from aryl azides are less common.[14] The improved regioselectivity observed when biaryl azide **1** was treated with rhodium(II) octanoate (as compared to thermolysis) reveals that the rhodium catalyst is involved in the C−N bond-forming step of the mechanism. The analogous reactivity of the *E*- or *Z*-stilbene isomer of **4** toward rhodium(II) octanoate indicated that the functionalization of the C−H bond occurs by a stepwise mechanism (Scheme 2).[10b] This behavior contrasts with the metal-free pyrolysis of **4**, where the yield of 2-phenylindole **5** depended on the stereochemistry of the styryl azide (88% from *E*-**4**; 18% from *Z*-**4**).[15] These results illustrate the differences between a rhodium nitrenoid and an arylnitrene and suggest that arylnitrenes might not be the best models for rhodium arylnitrenoids.

Instead, we anticipated that the rhodium arylnitrenoid might be more similar to an arylnitrenium ion.[16,17] The

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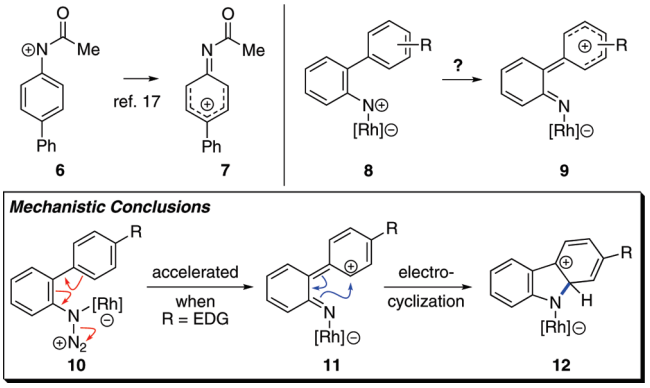
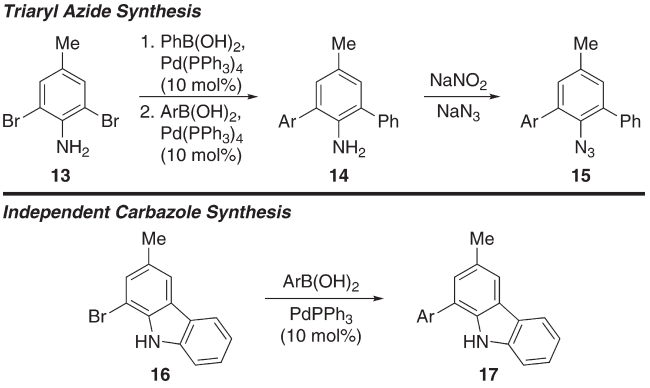
SCHEME 3. Arylnitrenium Ions as Potential Models for Rhodium(II) Arylnitrenoids: Mechanistic Conclusions



SCHEME 4. Synthesis of Triaryl Azides To Study the Mechanism of Carbazole Formation



singlet ground state of an arylnitrenium ion contains extensive delocalization of the positive charge into the adjacent π-system (Scheme 3).[17d,18,19] If rhodium nitrenoid **8** behaved similarly to **7**, the electronic nature of the aryl substituents would influence the mechanism of *N*-heterocycle formation through stabilization of the quinoid resonance structure **9**. Herein, we report the results of our mechanistic studies, which support this assertion. Our data suggest that electronic donation by the biaryl π-system accelerates rhodium nitrenoid formation from **10** and that C−N bond formation occurs through a 4π-electron-5-atom electrocyclization of **11**.

Results and Discussion

Triaryl azides **15** were chosen to study the rhodium-catalyzed *N*-heterocycle formation. These substrates allowed the investigation of an intramolecular competition reaction between the reactive intermediate and the C−H bond on either the phenyl or aryl substituent. This was necessary because the rate-determining step of the mechanism was unknown,[20,21] and the intramolecular reaction would allow the ratio of carbazole products obtained from **15** to offer insight into the mechanism of the C−N bond-forming event even if it occurred after the turnover-limiting step. The triaryl azides that were used for the intramolecular competition experiments were synthesized from dibromoaniline **13** by two consecutive Suzuki cross-coupling reactions (Scheme 4).[22] Carbazoles **17** were also independently synthesized from carbazole **16** through a Suzuki cross-coupling reaction to verify the product ratio. Triaryl azides **15** would be used first to determine if C−H bond cleavage and C−N bond formation occurred simultaneously and then to investigate the electronic effect of substituents on the *o*-aryl group.

Triaryl azide **15a**-d_5 was used to determine if the reaction between the rhodium nitrenoid and the *o*-aryl C−H bond was concerted (Scheme 5).[23,24] If C−N bond formation and C−H bond cleavage occurred simultaneously (via **20**),[24] a primary kinetic isotope effect would result from preferential reaction of the reactive intermediate with the unlabeled phenyl substituent.[25,26] Exposure of **15a**-d_5 to rhodium(II) perfluorobutyrate at 70 °C, however, gave a kinetic isotope effect of 1.01. A similar isotope effect was observed in **21**-d_1.[10a] These experiments show that C−H bond cleavage occurs after the product-determining step of the reaction.[27,28] Together with the equal reactivity of *Z*- and *E*-**4**, these results confirm that a concerted insertion of the

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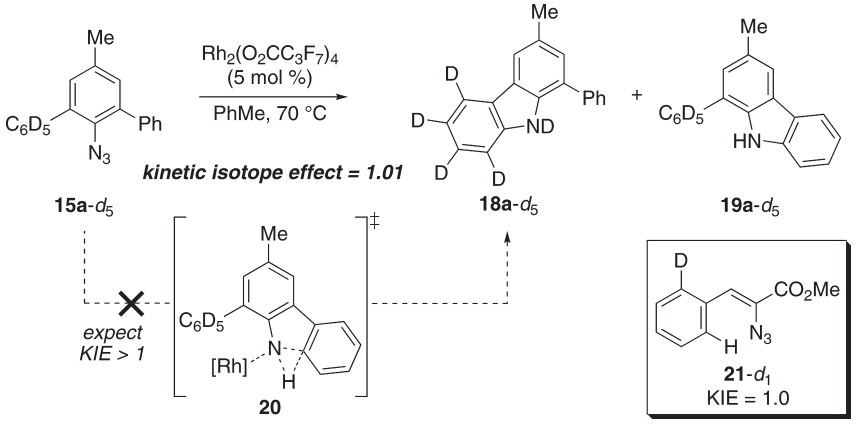
(27) A similar kinetic isotope effect (1.13) was observed in the thermolysis of **15a**-d_5. This secondary kinetic isotope effect indicates that C−N bond formation and C−H bond cleavage are not concerted in the thermal reaction as well.

(28) A modest kinetic isotope effect (KIE = 1.9; cyclohexane solvent) was observed in the photolysis of 2-azidobiphenyl by Sundberg and coworkers (ref 13d). They imply that this result suggests that the singlet nitrene does not insert directly into the ortho-C−H bond but rather adds to the carbon.

SCHEME 5. Secondary Kinetic Isotope Effect Obtained from Intramolecular Competition Experiments



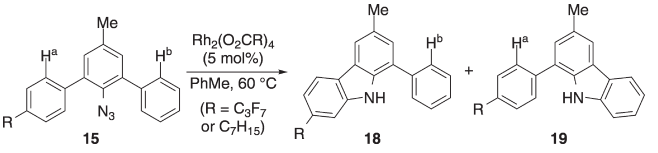
nitrenoid into the *o*-aryl C−H bond is not occurring to form either carbazole or indole products.

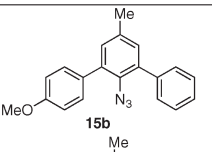
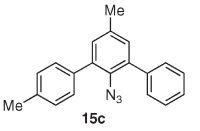
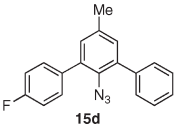
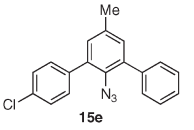
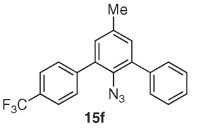
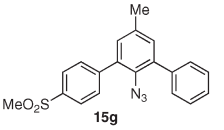
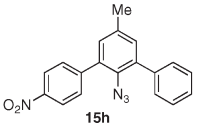
A series of triaryl azides with electron-donating or electron-withdrawing aryl substituents were screened as substrates to determine the electronic dependence of the C−H bond functionalization (Table 1). 4-Substituted aryl groups were chosen to simplify product analysis by providing only one regioisomer. The results of these experiments are given in Table 1 and show that C−N bond formation occurs preferentially with the more electron-rich aryl group.

The product ratios from the reaction of **15** were analyzed using the Hammett equation to determine if an electrophilic aromatic substitution produced the C−N bond (Scheme 6).[29] In this mechanism, nucleophilic attack of the pendant aryl or phenyl group onto the electrophilic rhodium nitrenoid **22** would form arenium ion **23** or **24**. If this mechanism occurs, a linear correlation of the product ratios from triaryl azides **15** with Hammett σ_m values should be observed because the C−N bond is forming *meta* to the R group.[30,31] Figure 1 clearly shows that the relationship between σ_m values and the product ratios from **15** is *not* linear. We interpret this result to mean that C−N bond formation does not occur by electrophilic aromatic substitution.[32] This conclusion is supported by the reactivity patterns of aryl- and vinyl azides (**40**, **42**, and **43**), which will be discussed below (eq 2 and Scheme 9).

Alternatively, the aryl substituents could affect the formation of rhodium nitrenoid by controlling the amount of electron density in the π-system (Scheme 7). Overlap of the π-system with σ^*_{N-N2} best occurs when the N_2-leaving group is oriented orthogonal to the triaryl group (**31**). If all three arenes are planar, a destabilizing steric interaction occurs between the rhodium catalyst and an *o*-aryl hydrogen (**32**). As a result, the more electron-deficient aryl group

TABLE 1. Rhodium-Catalyzed Intramolecular Competition Reactions of Triaryl Azides



entry	triaryl azide **15**	$Rh_2(O_2CC_3F_7)_4$ (**18** : **19**)[a]	$Rh_2(O_2CC_7H_{15})_4$ (**18** : **19**)[a]
1	 **15b**	61:39	85:15
2	 **15c**	57:43	70:30
3	 **15d**	50:50	58:42
4	 **15e**	47:53	47:53
5	 **15f**	34:66	17:83
6	 **15g**	40:60	23:77
7	 **15h**	42:58	27:73

[a] As determined using ^{1}H NMR spectroscopy.

(29) For leading discussions of the correlation of the rate of the electrophilic aromatic substitution reaction with the Hammett equation, see: (a) Jaffé, H. H. *Chem. Rev.* **1953**, *53*, 191. (b) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1957**, *79*, 1913. (c) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979. (d) Stock, L. M.; Brown, H. C. *Adv. Phys. Org. Chem.* **1963**, *1*, 35. (d) Charton, M. *J. Org. Chem.* **1969**, *34*, 278. (e) Gawley, R. E. *J. Org. Chem.* **1981**, *46*, 4595.

(30) Hansch, C.; Leo, A.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165.

(31) For other Hammett correlation diagrams, see the Supporting Information.

(32) Caution should be exercised in drawing firm conclusions from the nonlinearity of the Hammett correlation using σ values for electrophilic reactions. Refer to ref 29 for a detailed discussion.

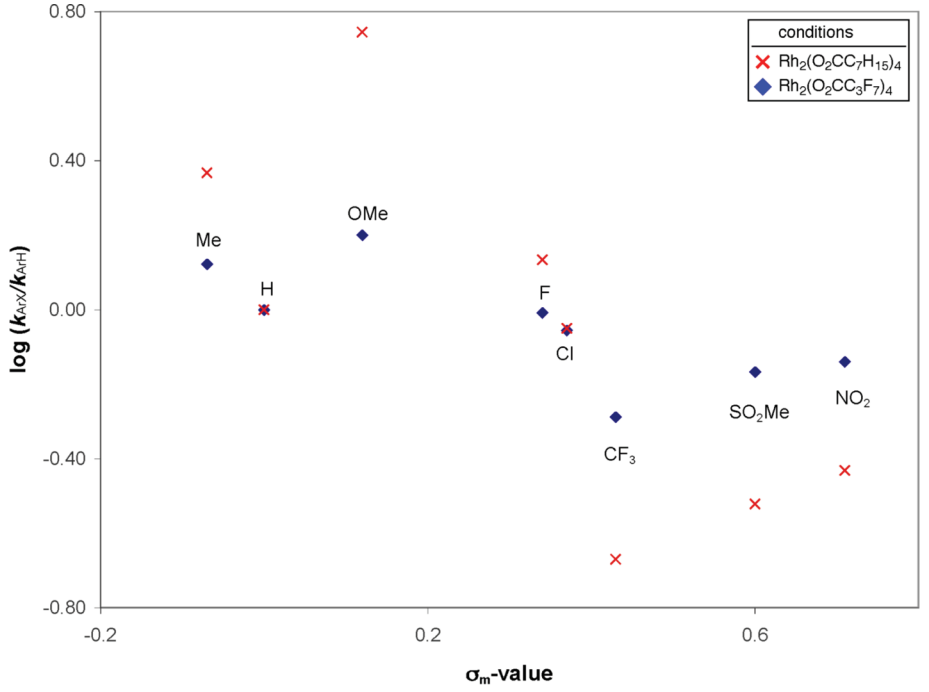
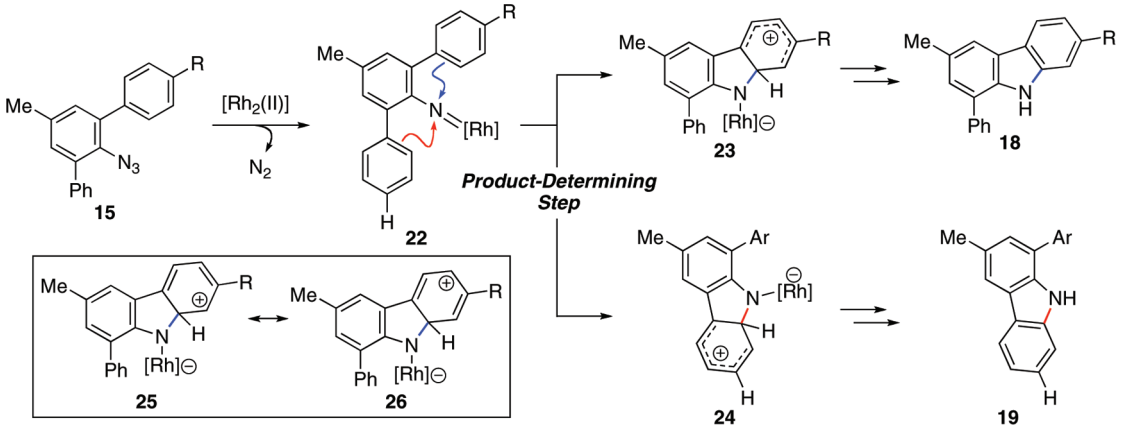


FIGURE 1. Correlation of log (k_{rel}) of the Rhodium-Catalyzed Decomposition of Triaryl Azides **15** with σ_m Values in the Hammett Equation.

SCHEME 6. Nucleophilic Attack of the Aryl Group as the C−N Bond-Forming Step



would rotate out of the plane to form **27** or **28**. Expulsion of N_2 then occurs to form *N*-rhodiumimine **29** or **30**.[33,34] If the electronic nature of the R group affects the rate of nitrenoid formation, linear correlation of the product ratios from **15** with Hammett σ^+ values (or σ_p values) would be expected because the reaction is occurring *para* to the R substituent. Because electron density is flowing away from the arene, a ρ value less than zero should be observed.

The product ratios from **15** were plotted against Hammett σ^+ values[29c,35] to test this mechanistic hypothesis (Figure 2).[36] Both rhodium perfluorobutyrate and rhodium octanoate gave plots that contained two intersecting lines (Figure 2). As predicted by our hypothesis, a negative ρ value was obtained from triaryl azides **15b−f**. Triaryl azides with stronger electron-withdrawing groups (**15f−h**), however, diverged from this trend to provide a line with a positive ρ value. The V-shaped Hammett plot suggests a change in mechanism (or rate-determining step) because the two lines exhibit opposite ρ values.[37] We did not observe this V-shape

(33) Cf. (a) Erker, G.; Frömberg, W.; Atwood, J. L.; Hunter, W. E. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 68. (b) Review: Cainelli, G.; Panuzio, M.; Andreoli, P.; Martelli, G.; Spunta, G.; Giacomini, D.; Bandini, E. *Pure Appl. Chem.* **1990**, *62*, 605. (c) Gilbertson, R. D.; Haley, M. M.; Weakley, T. J. R.; Weiss, H.-C.; Boese, R. *Organometallics* **1998**, *17*, 3105. (d) Hevia, E.; Pérez, J.; Riera, V.; Miguel, D. *Angew. Chem., Int. Ed.* **2002**, *41*, 3858.

(34) While **29** and **30** could interconvert, *N*-metalloimine isomerization would be slow in comparison to the subsequent C−N bond-forming step. *Z*/*E* thermal isomerization of imines was measured to be approximately 15−25 kcal/mol. See: (a) Roberts, J. D.; Hall, G. E.; Middleton, W. J. *J. Am. Chem. Soc.* **1971**, *93*, 4778. (b) Boyd, D. R.; Jennings, W. B.; Waring, L. C. *J. Org. Chem.* **1986**, *51*, 992. (c) Asano, T.; Furuta, H.; Hofmann, H. J.; Cimiraglia, R.; Tsuno, Y.; Fujio, M. *J. Org. Chem.* **1993**, *58*, 4418. (d) Yamataka, H.; Ammal, S. C.; Asano, T.; Ohga, Y. *Bull. Chem. Soc. Jpn.* **2005**, *78*, 1851.

(35) For a general discussion of the uses of σ^+ values in the Hammett reaction, see: (a) Lowry, T. H.; Richardson, K. S. *Mechanism and Theory in Organic Chemistry*; Harper-Collins: New York, 1987; pp 149−151. (b) Carpenter, B. K. *Determination of Organic Reaction Mechanisms*; Wiley-Interscience: New York, 1984; pp 144−148.

(36) While a better linear correlation was obtained using σ_p values, the lines did not pass through the origin. See the Supporting Information or additional Hammett correlation plots.

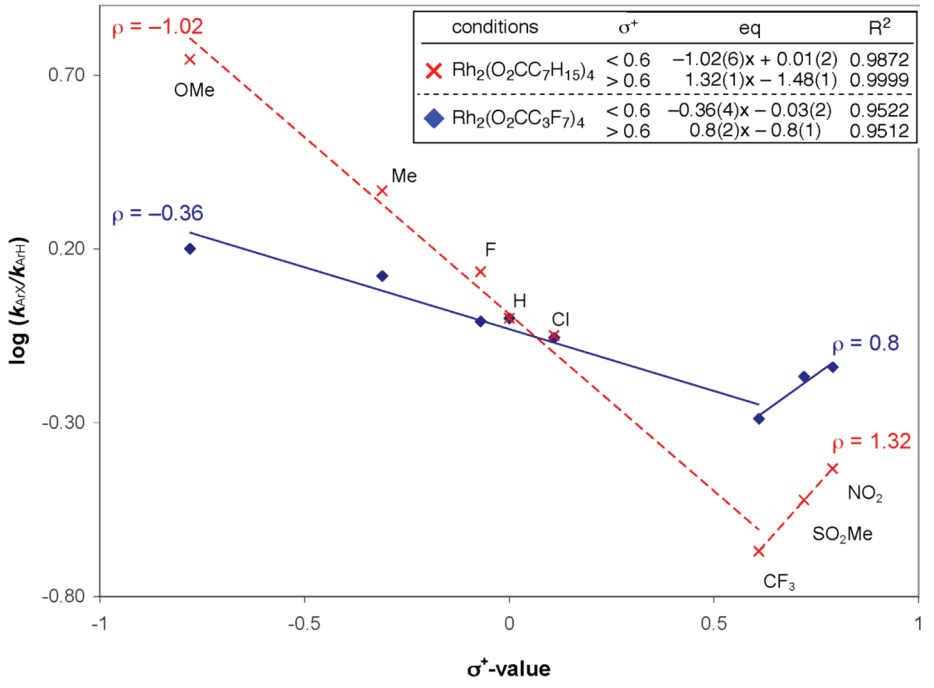
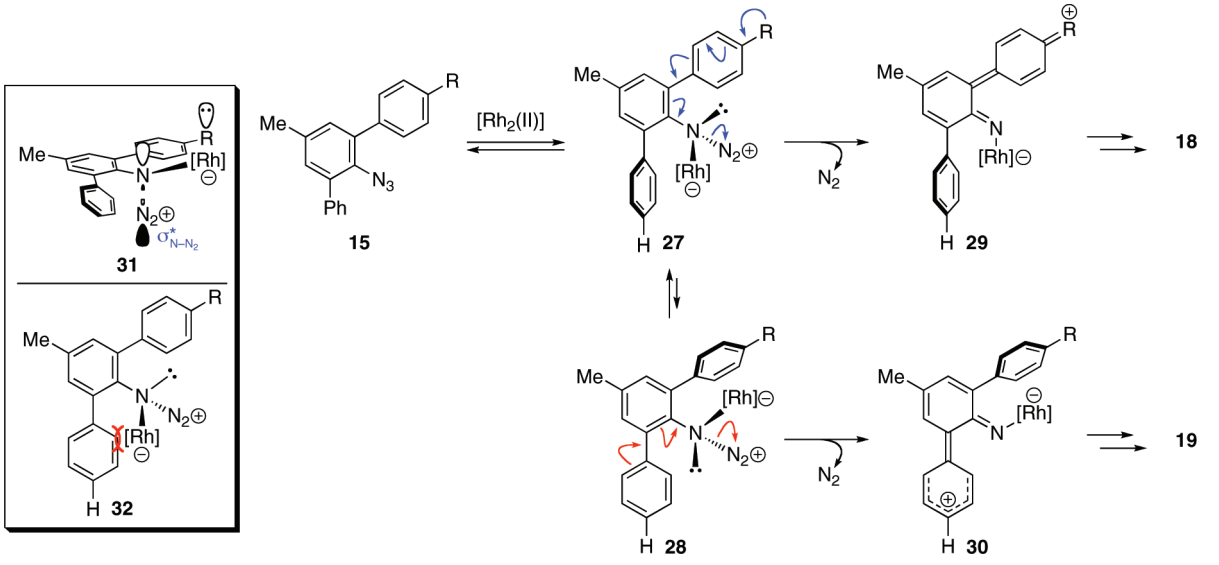


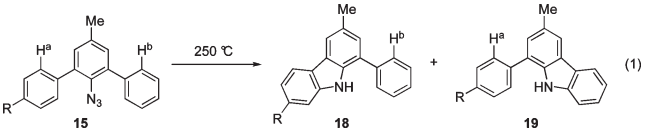
FIGURE 2. Hammett correlation of log (k_{rel}) with σ^+ values for the rhodium-catalyzed decomposition of triaryl azides **15**.

SCHEME 7. Influence of the Electronic Nature of the R Group on the Formation of the Rhodium Nitrenoid



for the metal-free thermolysis of triaryl azides **15**, which gave a single line with a negative ρ value (−0.66; Figure 3).[31,38,39]

The V-shape of the Hammett plot suggests that at least two mechanisms are occurring in the rhodium-catalyzed formation of carbazoles.[37] The negative ρ value observed for triaryl azides **15b−g** reveals that electron density is leaving the aryl π-system in the product-determining step.



This result is best accommodated by a mechanism where the

(37) U- or V-shaped Hammett plots have been interpreted as evidence for dual reaction mechanisms. For leading reports, see: (a) Fuchs, R.; Carlton, D. M. *J. Am. Chem. Soc.* **1963**, *85*, 104. (b) Buckley, N.; Oppenheimer, N. J. *J. Org. Chem.* **1996**, *61*, 7360. (c) Tanner, D. D.; Koppula, S.; Kandanarachchi, P. *J. Org. Chem.* **1997**, *62*, 4210. (d) Huang, R.; Espenson, J. H. *J. Org. Chem.* **1999**, *64*, 6374. (e) Swansburg, S.; Buncel, E.; Lemieux, R. P. *J. Am. Chem. Soc.* **2000**, *122*, 6594. (f) Ohshiro, H.; Mitsui, K.; Ando, N.; Ohsawa, Y.; Koinuma, W.; Takahashi, H.; Kondo, S. i.; Nabeshima, T.; Yano, Y. *J. Am. Chem. Soc.* **2001**, *123*, 2478. (g) Moss, R. A.; Ma, Y.; Sauers, R. R. *J. Am. Chem. Soc.* **2002**, *124*, 13968. (h) Zdilla, M. J.; Dexheimer, J. L.; Abu-Omar, M. M. *J. Am. Chem. Soc.* **2007**, *129*, 11505.

(38) Smith and co-workers did not observe any linear correlation with Hammett substituent constants in the decomposition of 2-azidobiaryls. The reaction rate depended only on the arene bearing the azide group. See ref 11c.

(39) The error in slope and intercept was determined using least-squares analysis.

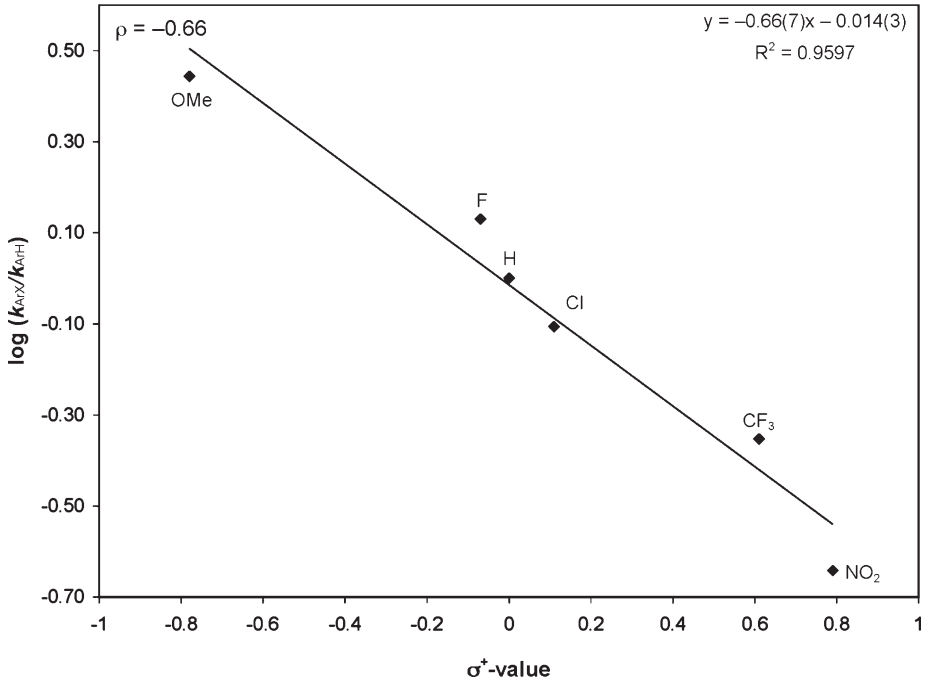
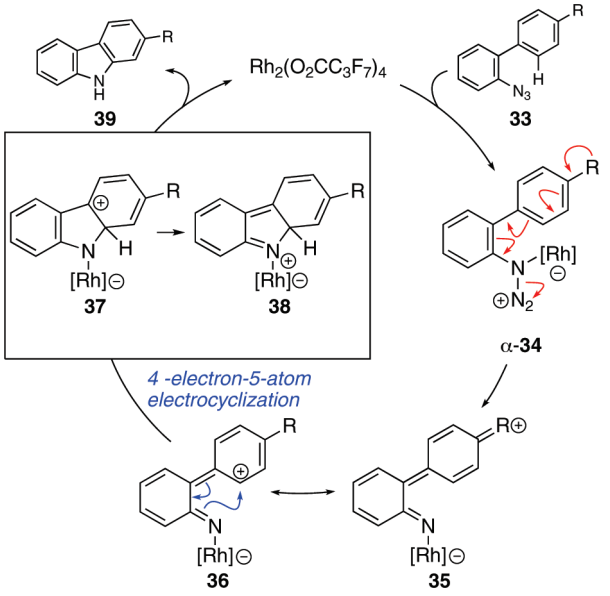


FIGURE 3. Hammett correlation of log (k_{rel}) with σ^+ values for the thermolysis of triaryl azides **15**.

SCHEME 8. Possible 4π-Electron-5-Atom Electrocyclization Step to Account for C−N Bond Formation



R substituent assists in the extrusion of N_2 from the initial metal−azide complex to form quinoid **35** (Scheme 8). In support of the potential quinoidal structure of **35**, time-resolved infared spectroscopy of related *N*-aryl-*N*-methylnitrenium ions revealed that the frequency of the C=C bond stretch increased in proportion to the electron-donating ability of the aryl substituent.[40] Falvey and co-workers interpreted these results as evidence that arylnitrenium ions can be described as 4-iminocyclohexa-2,5-dienyl cations.[40]

Electronic donation by the biaryl π-system to form the rhodium nitrenoid influences the mechanism of C−N bond formation (Scheme 8). The planar nature of quinoid **35** enables a 4π-electron-5-atom electrocyclization to form the C−N bond.[28,41,42] This pericyclic reaction can be visualized easier by examining **36**, the resonance form of **35**, which clearly contains a contiguous, planar array of π-orbitals.[43] Upon formation of **38**, a 1,5-hydride shift then provides carbazole **39**.[44−46]

(40) When *N*-aryl-*N*-methylnitrenium ions were substituted with electron-donating groups, higher frequency aromatic C=C bond stretches were observed using time-resolved infared spectroscopy. Falvey and co-workers attributed the longer bond stretch to represent substantial charge delocalization in the aromatic system to favor a quinoid structure. See ref 17d.

(41) For recent reviews of 4π-electron-5-atom-electrocyclizations, see: (a) Harmata, M. *Chemtracts* **2005**, *17*, 416. (b) Tius, M. A. *Eur. J. Org. Chem.* **2005**, 2193. (c) Pellissier, H. *Tetrahedron* **2005**, *61*, 6479. (d) Frontier, A. J.; Collison, C. *Tetrahedron* **2005**, *61*, 7577.

(42) Electrocyclization mechanisms have been suggested for the pyrolyses of 2-azidobenzophenones and 2-nitroazidobenzenes. For mechanistic studies, including Hammett correlations, see: (a) Dyall, L. K. In *The Chemistry of Functional Groups. Supplement D: The Chemistry of Halides, Pseudo-Halides, and Azides*; Patai, S., Rappoport, Z., Eds.; Wiley: New York, 1968; Chapter 7. (b) Dyall, L. K. *Aust. J. Chem.* **1986**, *39*, 89. (c) Dyall, L. K.; Karpa, G. J. *Aust. J. Chem.* **1988**, *41*, 1231.

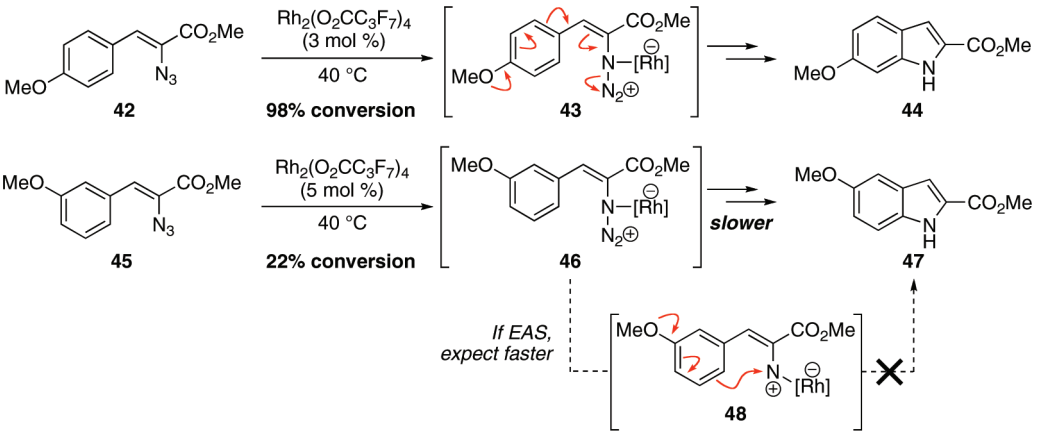
(43) A 6π-electron-5-atom electrocyclization was posited as a potential mechanism in the related deoxygenation of nitroaromatics; see: (a) Davies, I. W.; Guner, V. A.; Houk, K. N. *Org. Lett.* **2004**, *6*, 743. (b) Davies, I. W.; Smitrovich, J. H.; Sidler, R.; Qu, C.; Gresham, V.; Bazaral, C. *Tetrahedron* **2005**, *61*, 6425. (c) Leach, A. G.; Houk, K. N.; Davies, I. W. *Synthesis* **2005**, 3463.

(44) In the related thermal nitrene C−H amination reaction, C−N bond formation is believed to precede N−H bond formation. See: (a) Reference . (b) Smith, P. A. S. Aryl and heteroaryl azides and nitrenes. In *Azides and Nitrenes, Reactivity and Utility*; Scriven, E. F. V., Ed.; Academic Press: London, 1984; p 95 (mechanistic discussion pp 175−182).

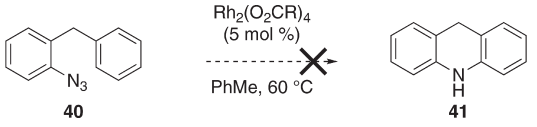
(45) A related diradical mechanism was proposed for the isomerization of aryl-substituted azirines to indoles; see: Taber, D. F.; Tian, W. *J. Am. Chem. Soc.* **2006**, *128*, 1058.

(46) In triaryl substrates, planarization of the more electron-rich ring should increase the rate of N_2-extrusion. We expect that the resulting nitrenoid to react faster with this ring than with the more electron-deficient ring, which is not necessarily in the plane.

SCHEME 9. Potential Explanation for Reactivity Differences of Methoxy-Substituted Azidoacrylates



Aryl azide **40**, which contains a methylene spacer in between the two arenes, was examined to test the requirement for a contiguous array of π-orbitals (eq 2). Exposure of **40** to reaction conditions did not produce dihydroacridine **41**. Instead, >95% of azide **40** was recovered. The lack of reactivity of **40** agrees with our proposed electrocyclization mechanism and is inconsistent with an electrophilic aromatic substitution mechanism, which would not require a contiguous π-system.

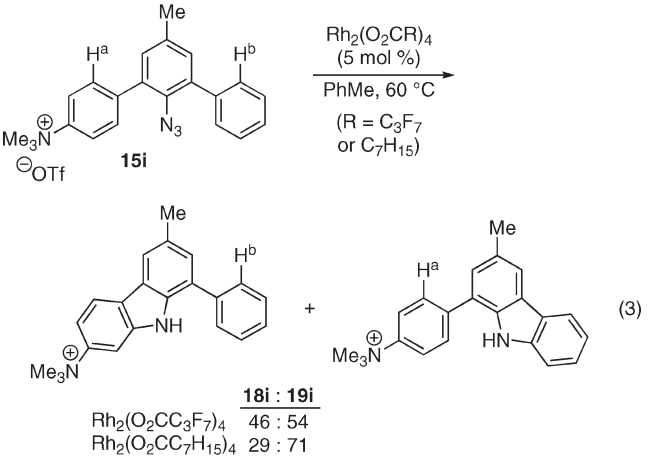


(2)

The electrocyclization mechanism also offers an explanation for the unusual reactivity trends that we observed with methoxy-substituted azidoacrylates (Scheme 9). In azide **42**, the *p*-methoxy-substituent is positioned to donate electron density to accelerate the formation of the nitrenoid species to result in the efficient formation of indole **44**. In contrast, placing the methoxy group at the 3-position of vinyl azide causes it to act as an inductive electron-withdrawing group and slow nitrenoid formation from **45**: only 22% of azide **45** was converted into indole **47** with 5 mol % of catalyst. The remainder of the mixture was unreacted vinyl azide **45**. If an electrophilic aromatic substitution mechanism occurred to form indole, azide **45** would be expected to react faster because the methoxy group is positioned to donate electron density to attack the electron-deficient rhodium nitrenoid (**48**).

The V-shape of the Hammett plot indicates that a change in mechanism occurs for substrates bearing strongly electron-withdrawing groups ($\sigma^+ \geq 0.6$). The positive ρ value for this portion of the plot reveals that the aryl group accepts electron density in the product-determining step. Changing the identity of the product-determining step to the electrocyclization or hydride shift appears unlikely, however, because it would require a nucleophilic rhodium(II) nitrenoid species[47−49] and a reversible N_2-extrusion step.[21] Alternatively, a different mechanism could be operating for these substrates. Coordination of the rhodium carboxylate complex to the nitro or sulfone group might cause the catalytic system to deviate from the thermal behavior of these substrates (Scheme 10).[50]

Triaryl azide **15i** (X = NMe_3) was used to investigate if the rhodium carboxylate were functioning as a Lewis acid through σ-coordination to the X substituent (eq 3).[50,51]



(3)

If this phenomenon was occurring, the product ratio from **15i** would not correlate linearly with substrates **15f−h** because coordination to the trimethylammonium substituent

(47) For discussions on the electronic nature of rhodium(II) nitrenoids, see: refs 5e, 14c, and: Espino, C. G.; Du Bois, J. In *Modern Rhodium-Catalyzed Organic Reactions*; Evans, P. A., Ed.; Wiley: New York, 2005; p 379 (discussion on pp 402−405).

(48) Some nucleophilic group 8 metal nitrenoid complexes have been reported. For leading examples, see: (a) Ir: Glueck, D. S.; Hollander, F. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 2719. (b) Rh: Ge, Y. W.; Sharp, P. R. *J. Am. Chem. Soc.* **1990**, *112*, 3667. (c) Ir: Glueck, D. S.; Wu, J.; Hollander, F. J.; Bergman, R. G. *J. Am. Chem. Soc.* **1991**, *113*, 2041. (d) Co: Jenkins, D. M.; Betley, T. A.; Peters, J. C. *J. Am. Chem. Soc.* **2002**, *124*, 11238.

(49) While nitrenes and nitrenoids are generally assumed to be electrophilic (see ref 5e for a discussion of ρ values), the pK_b of singlet phenyl nitrene was measured to be −2 . See: (a) ref 18. (b) Wang, J.; Burdzinski, G.; Platz, M. S. *Org. Lett.* **2007**, *9*, 5211.

(50) For the use of dirhodium(II) complexes as Lewis acids, see: (a) Doyle, M. P.; Phillips, I. M.; Hu, W. *J. Am. Chem. Soc.* **2001**, *123*, 5366. (b) Anada, M.; Washio, T.; Shimada, N.; Kitagaki, S.; Nakajima, M.; Shiro, M.; Hashimoto, S. *Angew. Chem., Int. Ed.* **2004**, *43*, 2665. (c) Doyle, M. P.; Valenzuela, M.; Huang, P. *Proc. Nat. Acad. Sci. U.S.A.* **2004**, *101*, 5391. (d) Wang, Y.; Wolf, J.; Zavalij, P.; Doyle, M. P. *Angew. Chem., Int. Ed.* **2008**, *47*, 1439.

(51) For leading reports of rhodium(II) η^2−π complexes, see: (a) Doyle, M. P.; Colsman, M. R.; Chinn, M. S. *Inorg. Chem.* **1984**, *23*, 3684. (b) Cotton, F. A.; Falvello, L. R.; Gerards, M.; Snatzke, G. *J. Am. Chem. Soc.* **1990**, *112*, 8979. (c) Cotton, F. A.; Dikarev, E. V.; Stiriba, S. E. *Organometallics* **1999**, *18*, 2724. (d) Cotton, F. A.; Dikarev, E. V.; Petrukhina, M. A. *J. Am. Chem. Soc.* **2001**, *123*, 11655.

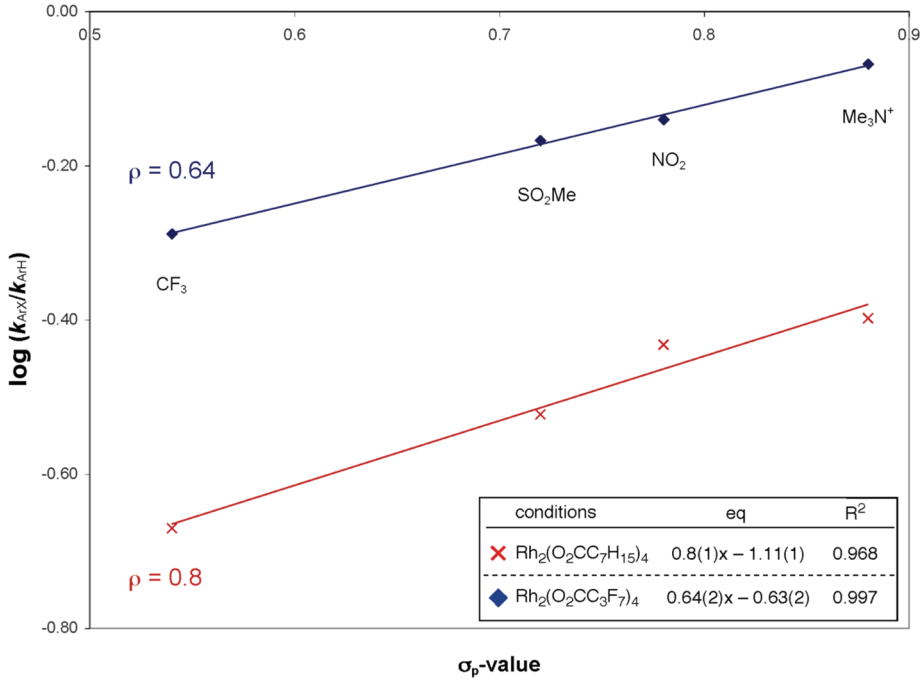
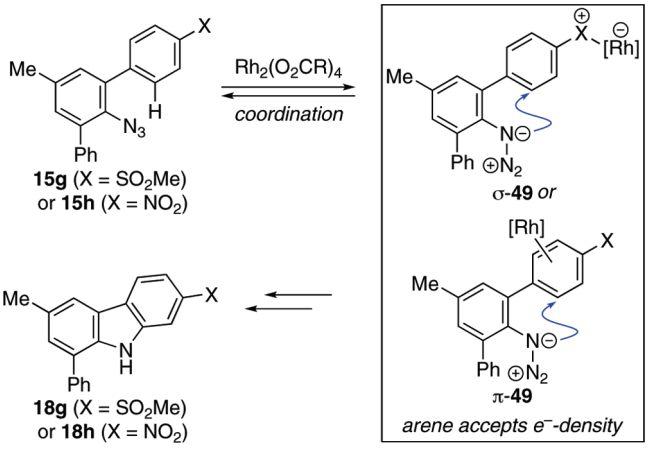


FIGURE 4. Hammett correlation of log (k_{rel}) with σ_p values for the rhodium-catalyzed decomposition of triaryl azides **15f**−**i**.

SCHEME 10. Possible Mechanism Involving Coordination of Rhodium to Arene



is not possible. The product ratio from **15i**, however, does correlate linearly with the azides **15f**−**h** using Hammett σ_p values. This relationship reveals that σ-coordination of the R substituent to the rhodium(II) carboxylate is not occurring in the mechanism for substrates bearing strongly electron-withdrawing groups (Figure 4).

Conclusions

The mechanism of *N*-heterocycle formation from aryl and vinyl azides was examined through intramolecular competition experiments. The lack of a primary intramolecular kinetic isotope effect suggests that the C−H(D) bond cleavage does not occur in the product-determining step. Correlation of the product ratios obtained from a series of substituted triaryl azides with the Hammett equation generated plots with two intersecting lines. The best linear correlation was obtained when the methoxy substituent was considered to be an electron-donating group. We interpreted these results as evidence for two different mechanisms. Electron-rich substrates appear to react through a mechanism in which electronic donation by an aryl R substituent assists in the formation of a planar arylnitrenoid that undergoes a 4π-electron-5-atom electrocyclization to form the new C−N bond. In agreement with our mechanistic hypothesis, substrates that lack a contiguous π-system are unreactive. While our experimental results prevent definitive conclusions for the mechanism operating in electron-deficient substrates, our data does suggest that the rhodium carboxylate does not σ-coordinate to the R group. We believe that these studies provide new models for azide reactivity toward rhodium carboxylates, and that the mechanistic insight gained herein will guide future methodology development that builds on our understanding of the interactions of metal complexes and azides.

Experimental Section

2-Bromo-4-methyl-6-phenylaniline. In a dry 500 mL round-bottom flask, phenylboronic acid (5.00 g, 43.0 mmol, 1.3 equiv), K_2CO_3 (21.50 g, 156 mmol, 4.0 equiv), and $Pd(PPh_3)_4$ (2.00 g, 1.73 mmol, 0.1 equiv) were dissolved in 150 mL of toluene, 100 mL of H_2O, and 50 mL of EtOH. 2,6-Dibromo-4-methylaniline (10.48 g, 39.8 mmol, 1.0 equiv) was added, and the resulting mixture was heated to 95 °C for 16 h. After cooling, the biphasic solution was diluted with 100 mL of saturated aqueous NH_4Cl and 100 mL of CH_2Cl_2 and separated. The aqueous phase was extracted with an additional 2 × 100 mL of CH_2Cl_2, and the combined organic phases were washed 1 × 100 mL of water and 1 × 100 mL of saturated aqueous $NaHCO_3$. The organic phase was dried over Na_2SO_4 and filtered. The filtrate was concentrated in vacuo to afford a brown oil. Purification by MPLC (15:85 benzene/hexanes) afforded 2-bromo-4-methyl-6-phenylaniline as a white powder (4.90 g, 47%): mp 58 °C; R_f = 0.31 (15:85 benzene/hexanes, visualized by 254 nm UV light); ^{1}H NMR ($CDCl_3$, 500 MHz) δ

7.50−7.45 (m, 4H), 7.42−7.38 (m, 1H), 7.31 (s, 1H), 6.93 (s, 1H), 4.04 (s, 2H), 2.30 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) 139.3 (C), 139.0 (C), 132.1 (CH), 130.4 (CH), 129.1 (CH), 128.9 (CH), 128.7 (C), 128.5 (C), 127.7 (CH), 109.9 (C), 20.2 (CH_3); IR (thin film) 3477, 3385, 3045, 3028, 2924, 1619, 1593, 1473, 1441, 1302, 1234, 1073, 1058, 861, 638, 575 cm^{-1}; HRMS (EI) m/z calcd for $C_{13}H_{12}NBr$ (M^+) 261.0153, found 261.0154.

2-(4-Chlorophenyl)-4-methyl-6-phenylaniline. To a dry 100 mL round-bottom flask equipped with a stir bar were added 2-bromo-4-methyl-6-phenylaniline (0.500 g, 1.90 mmol, 1.0 equiv), 4-chlorophenylboronic acid (0.343 g, 2.09 mmol, 1.3 equiv), K_2CO_3 (1.050 g, 7.63 mmol, 4.0 equiv), and $Pd(PPh_3)_4$ (0.110 g, 0.950 mmol, 0.1 equiv). Toluene (30 mL), 20 mL of H_2O, and 10 mL of EtOH were added, and the resulting mixture was heated to 95 °C for 16 h. After cooling, the biphasic solution was diluted with 100 mL of saturated aqueous NH_4Cl and 100 mL of CH_2Cl_2 and separated. The organic phase was washed 1 × 100 mL of water and 1 × 100 mL of saturated aqueous $NaHCO_3$. The organic phase was dried over Na_2SO_4 and filtered. The filtrate was concentrated in vacuo to afford a brown oil. Purification by MPLC (0:10:90−10:10:80 EtOAc/benzene/hexanes) afforded 2-(4-chlorophenyl)-4-methyl-6-phenylaniline as a white powder (0.463 g, 83%): mp 101 °C; R_f = 0.56 (10:10:80 benzene/EtOAc/hexanes, visualized by 254 or 365 nm UV light); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.55−7.45 (m, 8H), 7.42−7.39 (m, 1H), 7.03 (d, J = 1.6 Hz, 1H), 6.98 (d, J = 1.6 Hz, 1H), 3.67 (br s, 2H), 2.36 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 139.7 (C), 138.4 (C), 138.2 (C), 133.2 (C), 130.8 (CH), 130.7 (CH), 130.3 (CH), 129.4 (CH), 129.0 (CH), 128.9 (CH), 128.4 (C), 127.6 (C), 127.4 (CH), 126.9 (C), 20.5 (CH_3); IR (thin film) 3455, 3386, 3053, 2985, 2923, 2859, 2305, 1615, 1599, 1492, 1466, 1438, 1392, 1265, 1092, 1015, 896, 872, 837, 749, 704 cm^{-1}; HRMS (EI) m/z calcd for $C_{19}H_{16}NCl$ (M^+) 293.0971, found 293.0973.

Azide 15b. In a 20 mL scintillation vial, 2-(4-methoxyphenyl)-4-methyl-6-phenylaniline (0.076 g, 0.253 mmol, 1.0 equiv) was dissolved in 3 mL of HOAc and chilled in an ice bath. $NaNO_2$ (0.026 g, 0.367 mmol, 1.45 equiv) was added slowly, and the resulting mixture was stirred at 0 °C for 1 h. NaN_3 (0.393 g, 0.393 mmol, 1.55 equiv) was then added slowly, and the resulting mixture was warmed to ambient temperature and stirred for 30 min. The solution was diluted with 20 mL of water and 20 mL of CH_2Cl_2 and basified by the slow addition of K_2CO_3 until bubbling ceased. The phases were separated, and the aqueous phase was extracted with an additional 2 × 20 mL of CH_2Cl_2. The combined organic phases were washed 1 × 20 mL of water and 1 × 20 mL of brine. The resulting organic phase and dried over Na_2SO_4 and filtered. The filtrate was concentrated in vacuo to afford an oil. Purification by MPLC (100% hexanes) afforded azide **15b** as a faint yellow oil (0.080 g, 97%): R_f = 0.55 (10:10:80 benzene/EtOAc/hexanes, visualized by 254 nm UV light); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.53−7.52 (m, 2H), 7.49−7.45 (m, 4H), 7.42−7.39 (m, 1H), 7.13 (m, 2H), 7.03−7.00 (m, 2H), 3.88 (s, 3H), 2.42 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 159.2 (C), 138.7 (C), 136.4 (C), 136.1 (C), 135.2 (C), 132.1 (C), 131.1 (CH), 131.0 (C), 130.8 (CH), 130.5 (CH), 129.4 (CH), 128.4 (CH), 127.6 (CH), 113.9 (CH), 55.4 (CH_3), 20.9 (CH_3); IR (thin film) 2122, 2093, 1513, 1455, 1422, 1290, 1265, 1179, 1033, 896 cm^{-1}; HRMS (EI) m/z calcd for $C_{20}H_{17}ON_3$ (M^+) 315.13717, found 315.13679.

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Supporting Information Available: Complete experimental procedures and spectroscopic and analytical data for the products. This material is available free of charge via the Internet at http://pubs.acs.org.