

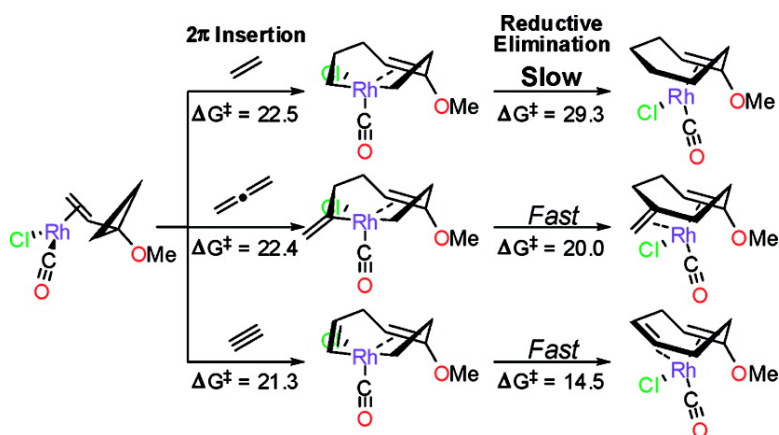
Communication

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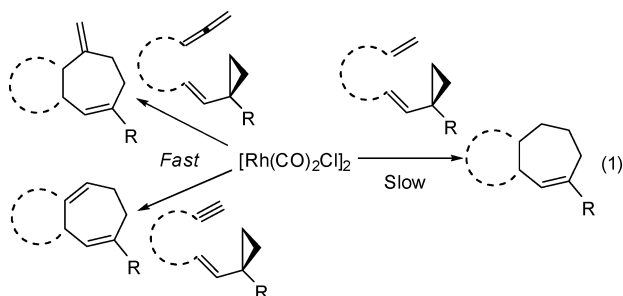
Origins of Differences in Reactivities of Alkenes, Alkynes, and Allenes in $[\text{Rh}(\text{CO})_2\text{Cl}]_2$ -Catalyzed (5 + 2) Cycloaddition Reactions with Vinylcyclopropanes

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The design or discovery of new transition metal-catalyzed cycloaddition reactions is of preeminent importance to the realization of practical, step economical, and green syntheses.^{1–5} The rhodium(I) dimer, $[\text{Rh}(\text{CO})_2\text{Cl}]_2$, is of particular interest as an efficient catalyst for the intra- and intermolecular (5 + 2) reactions of vinylcyclopropanes (VCP) with alkynes and allenes.^{4,5} However, this catalyst is relatively inactive toward alkenes, unlike the cationic Wilkinson's catalyst.⁶ We investigated the origins of this substrate selectivity computationally, and have discovered how substantial differences in reductive elimination barriers control the ease of reaction.



The computed free energy versus reaction progress profiles for the Rh dimer catalyzed (5 + 2) cycloaddition of VCP with acetylene, allene, and ethylene are shown in Figure 2.^{7,8} The catalytic cycle begins with the facile oxidative ring opening of the VCP by the active catalyst, $\text{Rh}(\text{CO})\text{Cl}$. Various isomers of the ring-opened intermediate can be found, and the most stable is **2**. The coordination of a 2π component (ethylene **3a**, allene **3b**, and acetylene **3c**), and its subsequent insertion into the Rh-allyl bond leads to the formation of intermediate metallacycles, **5a–c**. The final step of the reaction is the reductive elimination that forms the second C–C bond. The product complex liberates the product via transfer of catalyst to another VCP.

The computed barriers^{9a} for the 2π insertion steps are quite similar for all three species: 22.5 kcal/mol for ethylene (**TS-4a**), 22.4 kcal/mol for the allene (**TS-4b**), and 21.3 kcal/mol for the acetylene (**TS-4c**).^{9b} The main difference between the ethylene and allene or alkyne pathways is in the final reductive elimination step. This step is extremely fast for allene (**TS-6b**) and acetylene (**TS-6c**) with a free energy barrier of 20.0 kcal/mol and 14.5 kcal/mol, respectively, from the metallacycle intermediates (**5b** and **5c**). In contrast, the analogous barrier for ethylene (**TS-6a**) is quite high at 29.3 kcal/mol.

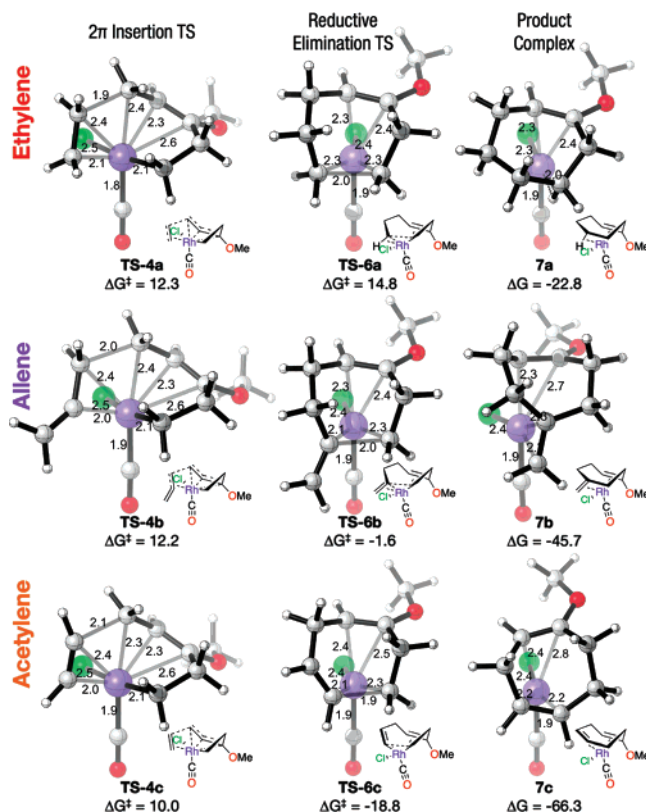


Figure 1. The computed 2π insertion, reductive elimination, and the product complex structures involving acetylene, allene, and ethylene.¹¹

The computed free energy spans¹⁰ for allene and acetylene^{9c} are small ($\Delta G^\ddagger = 22.4$ kcal/mol and 21.3 kcal/mol, respectively); these are identical to the 2π insertion barrier. In contrast, the free energy span is much higher for ethylene ($\Delta G^\ddagger = 29.3$ kcal/mol) and is identical to the barrier for reductive elimination. Thus, the difficulty of the reductive elimination is responsible for the failure of $[\text{Rh}(\text{CO})_2\text{Cl}]_2$ to catalyze the (5 + 2) reactions between VCP and alkenes.

The large difference in the reductive elimination barriers is attributed to the different ability of each substrate to facilitate the reductive elimination by the residual π -bond (Figure 1). In the allene (**TS-6b**) and acetylene (**TS-6c**) cases, the reductive elimination step is a migratory reductive elimination, involving the assistance of a traditional reductive elimination step by the developing ligand π -Rh coordination. The Rh–C σ -bond smoothly evolves into a Rh–C π -bond. However, in the case of ethylene, the reductive elimination

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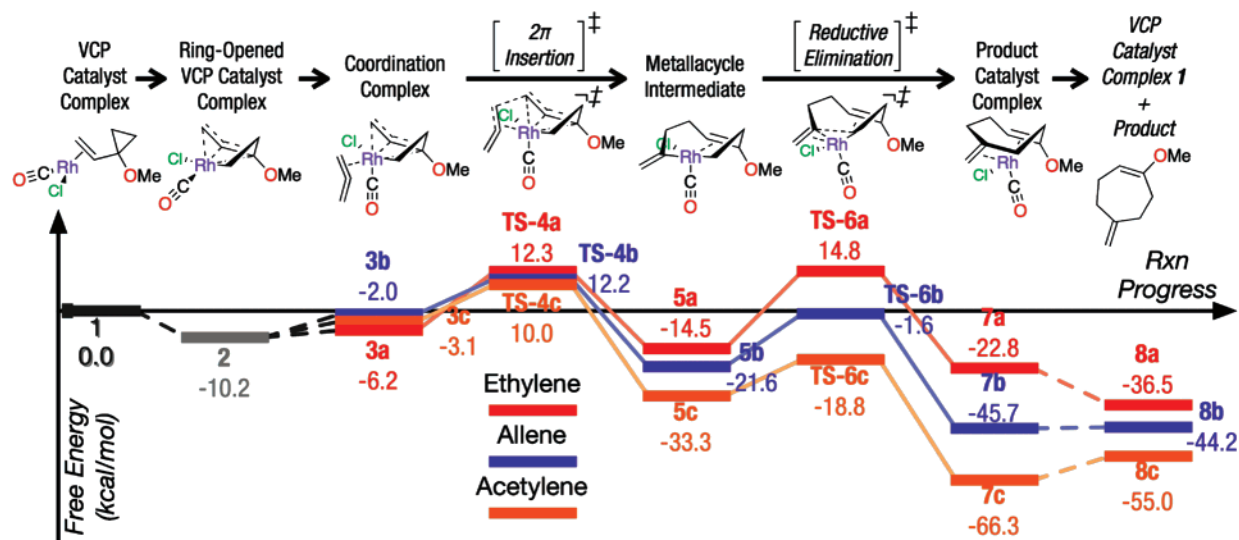
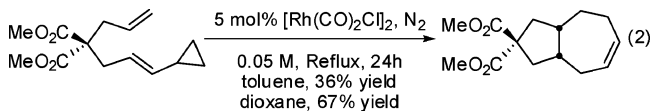


Figure 2. Free energy reaction progress profile for the Rh-dimer-catalyzed intermolecular (5 + 2) cycloadditions involving acetylene, ethylene, and allene.

is unassisted because of the lack of a π -system on the migrating ligand (TS-6a).¹²

The stability imbued by the π -coordination is most evident in the product Rh complexes. In structures **7b** and **7c**, the Rh is coordinated by two π -bonds, while in the ethylene case, **7a**, it is coordinated by a single π -bond and a weaker C–H agostic interaction. This difference renders the allene and acetylene reductive elimination more exergonic than that of ethylene by 8.3 and 33.0 kcal/mol, respectively.

Computed energetics reveal that the (5 + 2) cycloaddition of VCP and alkene should be difficult, but not impossible. Indeed, the intramolecular (5 + 2) cycloaddition involving an alkene has been found to occur under more forcing conditions (eq 2), as expected by these calculations.¹³



A comparison of the $[\text{Rh}(\text{CO})_2\text{Cl}]_2$ catalyzed (5 + 2) cycloadditions between vinylcyclopropane and acetylene, ethylene, and allene reveals that the reductive elimination step determines the substrate selectivities in these reactions. The reductive elimination involving alkenes is substantially more difficult than those involving alkynes or allenes.

Acknowledgment. We are grateful to the 985 Program for Excellent Research from Peking University, the Natural Science Foundation of China (9800445, 0240203, and 20672005), and United States National Science Foundation (Grants CHE-9800445, CHE-0240203, and CHE 0450638) for financial support. We are indebted to Mitchell P. Croatt and the entire Wender new reactions subgroup for helpful discussions.

Supporting Information Available: Complete ref 7b, cartesian coordinates, energies, thermal corrections, and enlarged Figure 1. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) (a) Wender, P. A.; Bi, F. C.; Gamber, G. G.; Williams, T. J. In *Modern Rhodium Catalyzed Organic Reactions*; Evans, P. A., Ed.; Wiley-VCH: Weinheim, Germany, 2005. (b) Yet, L. *Chem. Rev.* **2000**, *100*, 2963. (c) Lautens, M.; Klute, W.; Tam, W. *Chem. Rev.* **1996**, *96*, 49.
- (2) For a general review, see ref 1a and: Wender, P. A.; Bi, F. C.; Gamber, G. G.; Gosselin, F.; Hubbard, R. D.; Scanio, M. J. C.; Sun, R.; Williams, T. J.; Zhang, L. *Pure Appl. Chem.* **2002**, *74*, 25.
- (3) The (5 + 2) reactions can also be effected with other catalysts, see ref 1c: (a) Wang, B.; Cao, P.; Zhang, X. *Tetrahedron Lett.* **2000**, *41*, 8041. (b) Wender, P. A.; Love, J. A.; Williams, T. J. *Synlett.* **2003**, 1295. (c) Wender, P. A.; Williams, T. J. *Angew. Chem., Int. Ed.* **2002**, *41*, 4550. (d) Trost, B. M.; Shen, H. C.; Schultz, T.; Koradin, C.; Schirok, H. *Org. Lett.* **2003**, *5*, 4149 and references therein.
- (4) (a) Wender, P. A.; Correa, A. G.; Sato, Y.; Sun, R. *J. Am. Chem. Soc.* **2000**, *122*, 7815. (b) Wender, P. A.; Gamber, G. G.; Hubbard, R. D.; Zhang, L. *J. Am. Chem. Soc.* **2002**, *124*, 2876. (c) Wender, P. A.; Pedersen, T. M.; Scanio, M. J. C. *J. Am. Chem. Soc.* **2002**, *124*, 15154. (d) Wender, P. A.; Deschamps, N. M.; Gamber, G. G. *Angew. Chem., Int. Ed.* **2003**, *42*, 1853. (e) Wender, P. A.; Croatt, M. P.; Deschamps, N. M. *J. Am. Chem. Soc.* **2004**, *126*, 5948. (f) Wender, P. A.; Deschamps, N. M.; Williams, T. J. *Angew. Chem., Int. Ed.* **2004**, *43*, 3076. (g) Wender, P. A.; Gamber, G. G.; Hubbard, R. D.; Pham, S. M.; Zhang, L. *J. Am. Chem. Soc.* **2005**, *127*, 2836. (h) Wegner, H. A.; de Meijere, A.; Wender, P. A. *J. Am. Chem. Soc.* **2005**, *127*, 6530.
- (5) (a) Koga, Y.; Kobayashi, T.; Narasaka, K. *Chem. Lett.* **1998**, 249. (b) Kobayashi, T.; Koga, Y.; Narasaka, K. *J. Organomet. Chem.* **2001**, *624*, 73. (c) Jeong, N.; Lee, S.; Sung, B. K. *Organometallics* **1998**, *17*, 3642. (d) Jeong, N.; Sung, B. K.; Choi, Y. K. *J. Am. Chem. Soc.* **2000**, *122*, 6771. (e) Mukai, C.; Nomura, I.; Yamanishi, K.; Hanaoka, M. *Org. Lett.* **2002**, *4*, 1755. (f) Brummond, K. M.; Chen, H.; Fisher, K. D.; Kerekes, A. D.; Rickards, B.; Sill, P. C.; Geib, S. J. *Org. Lett.* **2002**, *4*, 1931. (g) Brummond, K. M.; Chen, H.; Sill, P.; You, L. *J. Am. Chem. Soc.* **2002**, *124*, 15186. (h) Brummond, K. M.; Chen, H.; Mitasev, B.; Casarez, A. D. *Org. Lett.* **2004**, *6*, 2161.
- (6) (a) See ref 3c. Both $(\text{Ph}_3\text{P})_3\text{RhCl}$ and $(\text{Naph})\text{Rh}(\text{COD})\text{SbF}_6$ catalyze the intramolecular (5 + 2) of alkenes and vinylcyclopropanes. $(\text{Naph})\text{Rh}(\text{COD})\text{SbF}_6$ was found to be an even better catalyst for the intramolecular (5 + 2) cycloaddition.
- (7) (a) The B3LYP hybrid functional with the 6-31G* (for H, C, O, and Cl) and LANL2DZ+ECP (for Rh) basis sets were used. (b) M. J. Frisch; et al. Gaussian, Inc.: Pittsburgh, PA, 2004.
- (8) For the mechanism for the Rh-catalyzed (5 + 2) cycloaddition of unsubstituted vinylcyclopropanes with acetylene, see: Yu, Z.-X.; Wender, P. A.; Houk, K. N. *J. Am. Chem. Soc.* **2004**, *126*, 9154.
- (9) (a) The activation barrier for a given transition state is the difference in energy between it and the lowest energy intermediate preceding it. (b) For the 2π insertion process, the most stable intermediates are **2** for ethylene and allene, and **8c** for acetylene. For the reductive elimination, these are the metallacycles, **5a–c**. (c) Product inhibition is apparent in the case of the acetylene, but not in the case of ethylene and allene.
- (10) (a) The free energy span is the activation free energy of a steady state catalytic system. It is computed as the free energy difference between the highest energy transition state and the catalyst resting state. (b) Kozuch, S.; Shaik, S. *J. Am. Chem. Soc.* **2006**, *128*, 3355. (c) Amatore, C.; Jutand, A. *J. Organomet. Chem.* **1999**, *576*, 254.
- (11) Figures made in the following: Legault, C. Y. *CYLVIEW*, version 1.0b; UCLA: Los Angeles, CA, 2007.
- (12) Similar effects were observed for the reductive elimination barriers of Pd catalyzed cross-coupling reactions. Some examples: (a) Calhorda, M. J.; Brown, J. M.; Cooley, N. A. *Organometallics* **1991**, *10*, 1431. (b) Ananikov, V. P.; Musaev, D. G.; Morokuma, K. *Organometallics* **2005**, *24*, 715. (c) Zuidema, E.; van Leeuwen, P. W. N.; Bo, C. *Organometallics* **2005**, *24*, 3703.
- (13) Wang, Y.; Wang, J.; Su, J.; Huang, F.; Jiao, L.; Liang, Y.; Yang, D.; Zhang, S.; Wender, P. A.; Yu, Z.-X. *J. Am. Chem. Soc.* **2007**, *129*, 10060. JA076444D