

Radical Isomerization and Cycloisomerization Initiated by H• Transfer

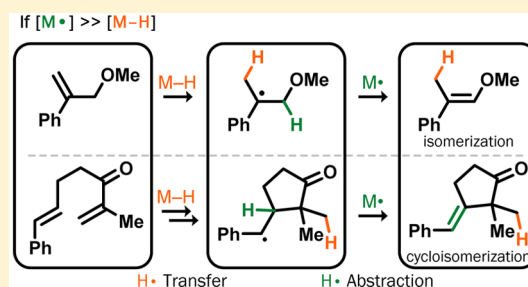
Gang Li,^{†,§} Jonathan L. Kuo,^{†,§} Arthur Han,[†] Janine M. Abuyuan,[‡] Lily C. Young,[†] Jack R. Norton,^{*,†} and Joshua H. Palmer[†]

[†]Department of Chemistry, Columbia University, 3000 Broadway, New York, New York 10027, United States

[‡]Department of Chemistry, Barnard College, 3009 Broadway, New York, New York 10027, United States

S Supporting Information

ABSTRACT: Under H₂ pressure, Co^{II}(dmgBF₂)₂L₂ (L = H₂O, THF) generates a low concentration of an H• donor. Transfer of the H• onto an olefin gives a radical that can either (1) transfer an H• back to the metal, generating an isomerized olefin, or (2) add intramolecularly to a double bond, generating a cyclized radical. Transfer of an H• back to the metal from the cyclized radical results in a cycloisomerization. Both outcomes are favored by the low concentration of the cobalt H• donor, whereas hydrogenation and cyclohydrogenation are more likely with other catalysts (when the concentration of the H• donor is high).



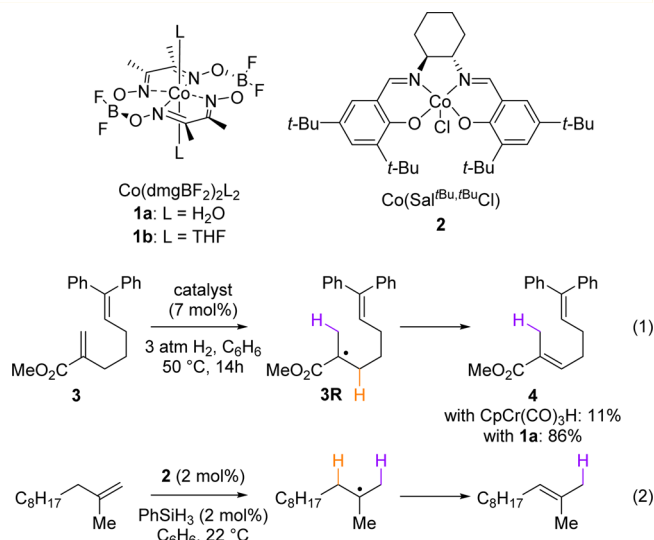
INTRODUCTION

The use of transition-metal hydrides to isomerize olefins has been known for many years. The best-known early example, with HRh(CO)₃(PPh₃)₃, was published by Wilkinson in 1970.¹ Generally, these reactions are thought to occur by (1) insertion of the olefin into the M–H bond and (2) β-hydrogen elimination in the opposite direction along the carbon chain. Many of the hydride-catalyzed olefin isomerizations discussed in a recent review² occur by this mechanism.^{3,4}

A plausible alternative mechanism for isomerization begins with hydrogen atom transfer, or HAT.⁵ The rates of H• transfer to alkenes⁶ and alkynes⁷ from CpCr(CO)₃H have been reported, giving the relative rates shown in Scheme 1, and enabling us to predict which radicals will be formed. Abstraction of an H• from a different carbon would result in isomerization.

We have reported the isomerization of **3** to **4** (via **3R**) can be catalyzed in low yield by CpCr(CO)₃H under H₂ (eq 1),⁸ and in much higher yield by a cobaloxime **1a** under H₂.⁹ The Shenvi group has reported that the cobalt salen complex **2**, when treated with PhSiH₃, can effect isomerizations (e.g., eq 2),¹⁰ also apparently via HAT from a cobalt-based H• donor. In both cases the isomerization goes from a 1-substituted or 1,1-disubstituted double bond to only the first internal position, and does not proceed to the most stable alkene.^{10,11}

With appropriate diene substrates (like **5**), the radical formed by HAT can cyclize (e.g., to **6R**).^{6b,7,8,10} With traditional H• donors (such as SnBu₃H) the result is a reductive cyclization, or cyclohydrogenation (e.g., generating **6**). Alternatively, the removal of a hydrogen atom from the cyclized radical will give a cycloisomerization.¹² We first became aware of this possibility when we observed that some cyclization substrates—those with sterically accessible methyl groups—lost an H• with a catalyst that normally effected cyclohydrogenation (CpCr(CO)₃H in eq 3¹³ or HV(CO)₄dpppe in eq 4^{8b}). The Shenvi group has reported additional examples with the cobalt-containing **2** (eq 5),



as well as the retrocycloisomerization of substrates that contain strained rings.¹⁰

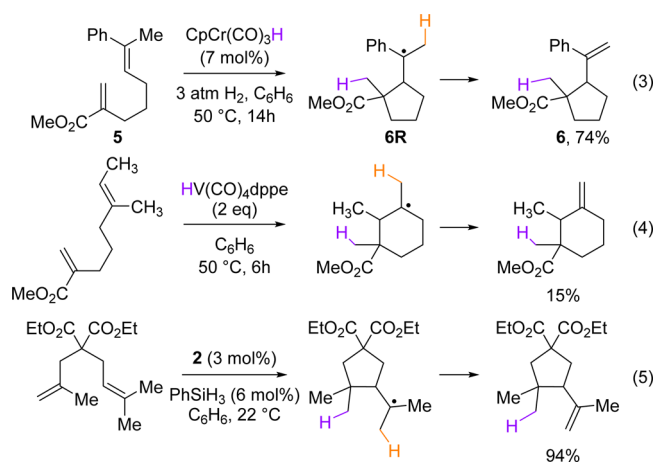
We also observed a cycloisomerization in one cobaloxime-catalyzed case (eq 9, below),⁹ and became interested in the factors determining the outcome of such reactions. We now offer a detailed account of the catalysis of the isomerization of olefins, and of the cycloisomerization of dienes, by Co(dmgBF₂)₂(THF)₂ (**1b**) under H₂.¹⁴

EXPERIMENTAL SECTION

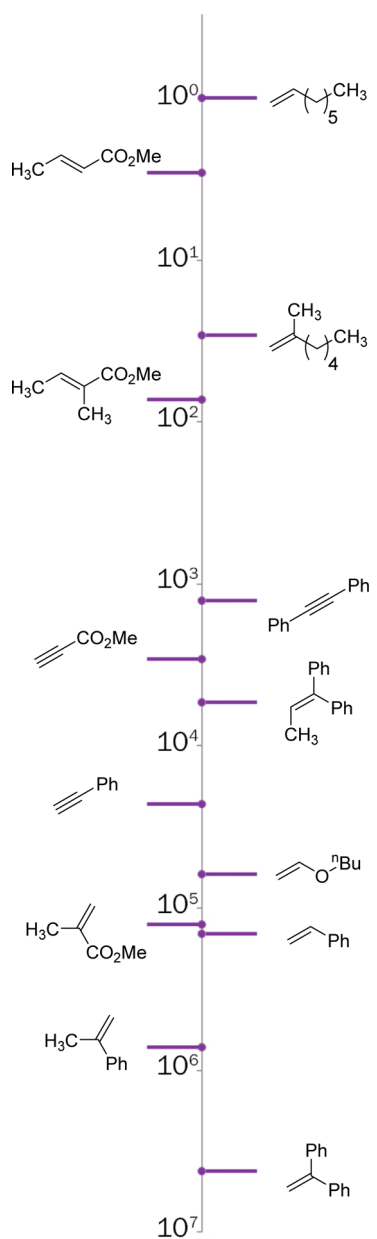
All manipulations were performed under an argon atmosphere using standard Schlenk or inert atmosphere box techniques. NMR spectra were taken on either a Bruker 300, 400, or 500 MHz spectrometer. IR

Received: April 5, 2016

Published: May 11, 2016



Scheme 1. Relative Rate of H• Transfer to Various Olefins from CpCr(CO)₃H



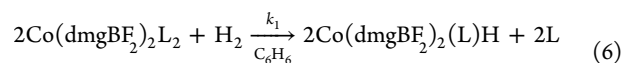
spectra were taken with a Perkin-Elmer Spectrum 2000 FT-IR spectrometer. Crystal data, data collection and refinement parameters are

summarized in the [Supporting Information](#), Table S1. The structures were solved using direct methods and standard difference map techniques, and were refined by full matrix least-squares procedures on F^2 with SHELXTL (Version 6.1).¹⁵ Benzene and THF were distilled from Na or K/benzophenone ketyl. Benzene- d_6 (Cambridge Isotope Laboratories) was dried by distillation from K/benzophenone ketyl and then deoxygenated by three freeze–pump–thaw cycles, then stored over 3 Å molecular sieves. All liquids were dried by distillation from CaH₂ and then deoxygenated by three freeze–pump–thaw cycles and stored under an argon atmosphere.

Procedure for Isomerization or Cycloisomerization Reactions. Caution! All reactions under gas pressure should be properly shielded! A solution of cobaloxime (**1**) (7 mol %) and benzene were prepared in a Fischer–Porter reactor, and the substrate was added. The vessel was sealed and then pressurized to 6 atm, and then placed in an oil bath at 50 °C. After stirring for the amount of time indicated in the reaction conditions, the reaction was allowed to return to room temperature, and the H₂ pressure was vented. The crude reaction mixture was run through a plug of silica, concentrated in-vacuo, then subjected to column chromatography to afford the reaction products. Spectral details of all the reaction products can be found in the [Supporting Information](#).

RESULTS AND DISCUSSION

Isomerization Reactions. Kinetic analysis of the rate at which various Co(dmgBF₂)₂L₂ activate H₂ in benzene has shown that k_1 (eq 6) increases by an order of magnitude between L = H₂O (**1a**) and L = THF (**1b**).¹⁶ The THF complex **1b** should thus be more effective than **1a** at catalyzing isomerizations under H₂, so **1b** has been used in examining the scope of the isomerization reaction. Even with **1b**, however, these reactions require a day or more under 6 atm of H₂ at 50 °C. (Because the resting state of the catalyst is Co(II),⁹ the concentration of the H• donor¹⁷ is low.¹⁴)



From the results in [Scheme 1](#), we expected that a terminal or 1,1-disubstituted olefin—with radical-stabilizing substituents—would accept H• effectively. Transfer to the methylene carbon in **7**, for example, resulted in its isomerization to the enol ether **8** (entry 1 in [Table 1](#)). Such isomerizations¹⁸ have previously been achieved with strong bases (e.g., *n*-BuLi),¹⁹ or with Lewis acidic transition-metal catalysts (e.g., (Ph₃P)₃RhCl²⁰ or Ir(PCy₃)₃⁺²¹), but a radical-based methodology should offer greater scope and functional group tolerance.

Similarly, a phenyl-substituted allylic alcohol **9** is isomerized to an aldehyde **10** (entry 2), presumably via an enol intermediate.^{14,22} We expected a similar result with the carbomethoxy-substituted allyl alcohol **11** (entry 3), but were surprised to isolate a dienol ether **12** instead (which was identified by X-ray crystallography, details in the [Supporting Information](#)). Presumably, **11** first results in the generation of **13**, which is in equilibrium with its aldehyde tautomer **14** (see [eq 7](#)). We prepared and isolated, by a reported method,²³ an equilibrium mixture of **13** and **14**, and subjected the mixture to the conditions

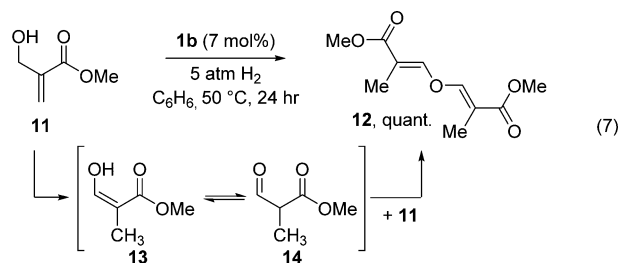


Table 1. Cobalt-Catalyzed Isomerization Reactions

entry	substrate	product	yield ^a
1			75%
2			78%
3			>95%
4			>95%
5			74%
6			>95%
7			52% 86:14 E:Z
8			83% 75:25 E:Z
9			87% 77:23 E:Z
10			65%

^aReaction conditions: **1b** (7 mol%), 6 atm H₂, C₆H₆ at 50 °C for 1.5 d.

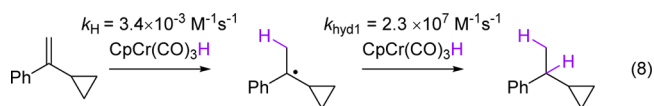
in Table 1. However, we did not observe the formation of **12**, suggesting that the latter is formed from the reaction of **13** or **14** with **12** under the influence of the cobalt catalyst **1b**. A general method for the synthesis of dienol ethers such as **12** has been reported,²⁴ and several groups have reported dienol ethers as byproducts, though they are probably formed by a different mechanism.²⁵

With unconjugated dienes (entries 4 and 7) we observed the selectivity predicted by the data in Scheme 1:^{6a} the 1,1-disubstituted double bond, with a phenyl substituent, is isomerized in preference to the terminal double bond. In entry 4 the result is a skipped diene in greater than 95% yield, while entry 7 gives an enol carbonate. These entries illustrate the mildness of our reaction conditions, as both of the functionalities that result are quite reactive. Our results complement the recent HAT isomerizations by Shenvi and co-workers: at room temperature their Co(salen) system isomerizes 1-decene (a model for the terminal double bonds in entries 4 and 7),¹⁰ implying that the H• donor in their system is more reactive.

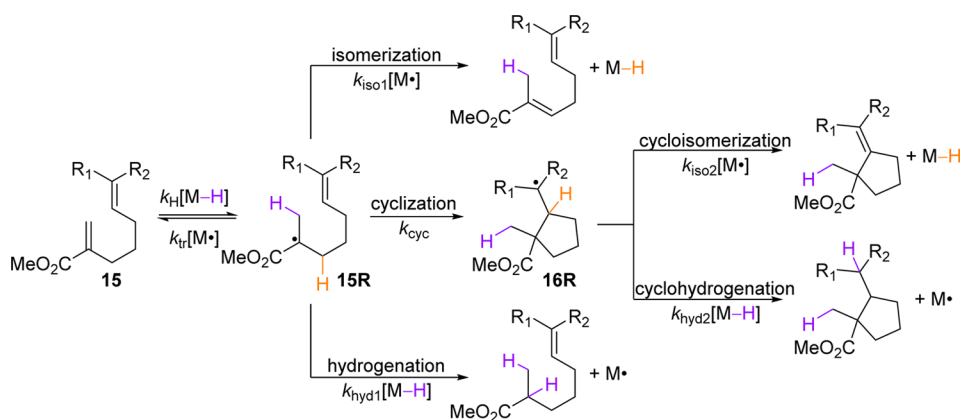
Donor substrates often inhibit metal-catalyzed isomerizations by preventing olefin coordination.²⁶ However, the cobaloxime/H₂ system tolerates free alcohols (entries 2, 3, 10), ketones (entries 8, 9), carbonates (entry 7), and heterocycles (entries 5, 10); this tolerance of Lewis bases is consistent with the fact that the HAT reaction does not require coordination of the olefin.²⁷ A pyridine can also replace a phenyl (entry 5) as the radical-stabilizing substituent on the olefin substrate. The isomerization reaction tolerates an aryl chloride (entry 6), indicating that a chlorine atom is not easily abstracted by Co^{II}(dmgBF₂)₂L.

Scheme 2 shows the alternatives available to a radical **15R** after it has been formed by H• transfer to a substrate **15**. For the substrates in Table 1 the alternatives to isomerization ($k_{\text{iso}}[\text{M}\cdot]$) are in principle hydrogenation ($k_{\text{hyd}}[\text{M}-\text{H}]$) and back transfer ($k_{\text{tr}}[\text{M}\cdot]$). However, we have not observed hydrogenation byproducts in any of the cases in Table 1, implying that $k_{\text{hyd}}[\text{M}-\text{H}]$ does not compete effectively with $k_{\text{iso}}[\text{M}\cdot]$ when **1b** is used as a catalyst.

With a stable hydride as an H• donor^{5b-e,6b,7,28} the second transfer is faster than the first. With CpCr(CO)₃H and α -cyclopropylstyrene, for example, Bullock has measured the rate constant k_{H} as $3.4 \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$ and has estimated the rate constant k_{hyd1} as $2.3 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ (both at 22 °C, eq 8).²⁷ In the



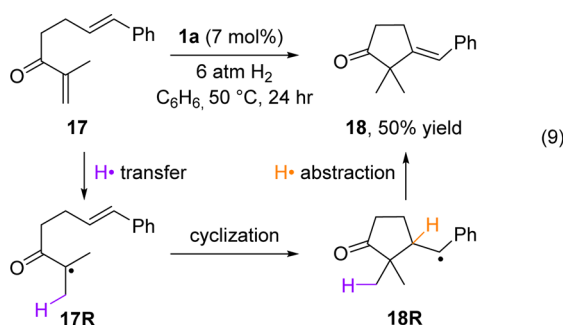
Scheme 2. Alternatives Available to a Radical Formed by H• Transfer to an Olefin



cases in Table 1, however, the concentration of the cobalt H• donor is so low that the rate of the second transfer is negligible.

5-Exo Cyclizations and the Resulting Cycloisomerizations. If the radical generated by H• transfer has an appropriate internal double bond like 15R, it can cyclize to a radical like 16R. That radical, like 15R, can accept another H• ($k_{\text{hyd2}}[M-H]$, cyclohydrogenation) or have an H• abstracted ($k_{\text{iso2}}[M\bullet]$, cycloisomerization). Our earlier work, with CpCr(CO)₃H and HV(CO)₄dppe, largely gave cyclohydrogenation, although eqs 3 and 4 show exceptions. Such cycloisomerization reactions, which neither add nor subtract atoms but merely rearrange those in the starting material, offer excellent atom economy.²⁹

Earlier we had also (in view of the ability of acyl substituents to stabilize radicals)³⁰ replaced the acrylate in eq 3 with an enone.^{13,31} With CpCr(CO)₃H, 17R accepted a second H• before it cyclized; however, with 1a we obtained 50% cycloisomerization. We concluded that the cobalt catalyst not only limited the hydrogenation of 17R, but abstracted an H• from the cyclized radical 18R (eq 9).



Given the effectiveness of 1b at activating H₂ (see above), the reaction in eq 9 should be faster with 1b as catalyst rather than 1a. Indeed, catalyst 1b gives not only an increase in rate but an improvement in yield (entry 1 in Table 2). Similar results are obtained without a methyl substituent on the α carbon (entry 2), though the double bond now moves to a position within the ring. Acrylate esters give even better yields (entries 3–8), slightly higher when the substituents on C5 and C6 are trans (entry 3, 4) (a pattern we observed earlier with CpCr(CO)₃H).¹³ Moderate yields are obtained with the indole derivative in entry 9 and the substituted benzene in entry 10, in both cases presumably because the planarity of the aromatic system makes cyclization more challenging.^{8b}

As in the isomerization reactions in Table 1, our cobalt cycloisomerization catalyst 1b tolerates an unprotected hydroxyl substituent (entry 8), or an oxygen in the backbone (entry 7). The latter is known to increase the rate of cyclization reactions,³² although 1b does not require this increase to produce good yields. In contrast, the PhSiH₃/Co(salen) system seems to require heteroatom acceleration or the Thorpe–Ingold effect.¹⁰ We expect the broad functional group tolerance demonstrated in Table 1 to translate into functional group tolerance for cycloisomerization—if the corresponding cyclizations are fast enough.

After any of these substrates cyclizes to a five-membered ring, the radical center moves to C6. A hydrogen atom can be abstracted not only from any suitable substituent on C6 (entries 5, 6, and 11)

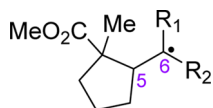


Table 2. Cycloisomerization Reactions

entry	substrate	product	yield ^a
1			61%
2			57%
3			>95%
4			92%
5			88%
6			95%
7			>95%
8			90%
9			67%
10			80%
11			>95%

^aReaction conditions: 1b (7 mol%), 6 atm H₂, C₆H₆ at 50 °C for 1.5 d.

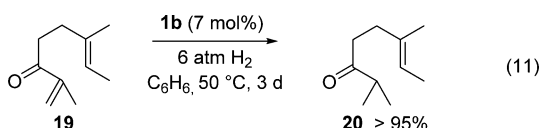
but also (when there is no suitable substituent on C6) from C5 (entries 1, 3, 4, 7, 10), as the C–H bonds on that carbon have been weakened by the adjoining radical center.³³ Cycloisomerizations of the former type have been reported by Shenvi and co-workers (see eq 4 above),¹⁰ but cycloisomerizations of the latter type have not been reported for the PhSiH₃/Co(salen) system.

Slower Cyclizations. As Scheme 2 and the resulting eq 10 show, isomerization and hydrogenation can compete with

$$\frac{\text{cyclized products}}{\text{uncyclized products}} = \frac{k_{\text{cyc}}}{k_{\text{hyd}}[M-H] + k_{\text{iso}}[M\bullet]} \quad (10)$$

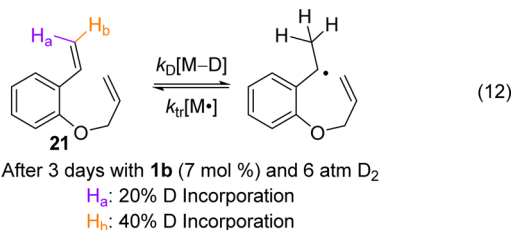
cyclization and decrease the yield of cyclized product. 5-Exo cyclizations are straightforward, because their k_{cyc} is large.³⁴ Any change that decreases k_{cyc} will permit the radical to react in other ways. For example, 6-endo and 7-endo cyclizations are generally slower than 5-exo cyclizations.³⁵ (The 5-exo cyclization³⁶ of the 5-hexenyl radical is about 50 times faster than the 6-endo one.^{35a,37})

We have attempted the cyclization of **19**, in part because its structure eliminates the possibility of isomerization. Even with the Co catalyst **1b**, however, hydrogenation to **20** is quantitative after 4 days.



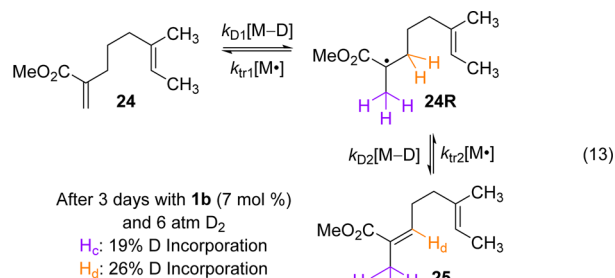
In other cases we can avoid both isomerization and hydrogenation. As with **19**, the structure of **21** makes isomerization impossible, and no hydrogenation is observed after several days. However, instead of the cyclized **22**, we isolate a good yield of the dimer **23** (Scheme 3).^{35b,38} Presumably the initial radical **22R** adds to another equivalent of **21** more rapidly than it cyclizes, and abstraction of H• from **23R** produces **23**. Diluting the reaction 10-fold suppresses the formation of **23**, but we recover only starting material. Apparently k_{cyc} for a 7-endo cyclization is simply too slow.^{37,39}

Transfer of H• Back to the Catalyst. It is apparent from Scheme 2 that transfer of H• back to M• ($k_{tr}[M•]$) can compete with isomerization, cyclization, and hydrogenation. The direct measurement of k_{tr} is not practical, given the poor solubility of **1b** and the reactivity of the organic radical. Some information is available if we carry out the reaction under D₂. For example, deuterium is incorporated into both the **a** and the **b** positions of **21** when the reaction in Scheme 3 is run at high dilution under D₂; H• transfer must be occurring, but reversibly (eq 12).

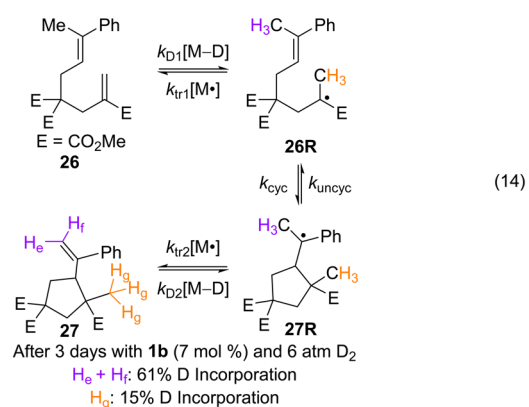


In eq 13, there is a net (and quantitative) isomerization of **24** to **25**. Under D₂ there is H/D exchange at the expected position **c**, demonstrating reversible H• transfer to the methylene of the

acrylate **24**. There is also some H/D exchange at the more congested position **d**, which implies that after its initial formation, **25** can reversibly accept D• (regenerating **24R**).



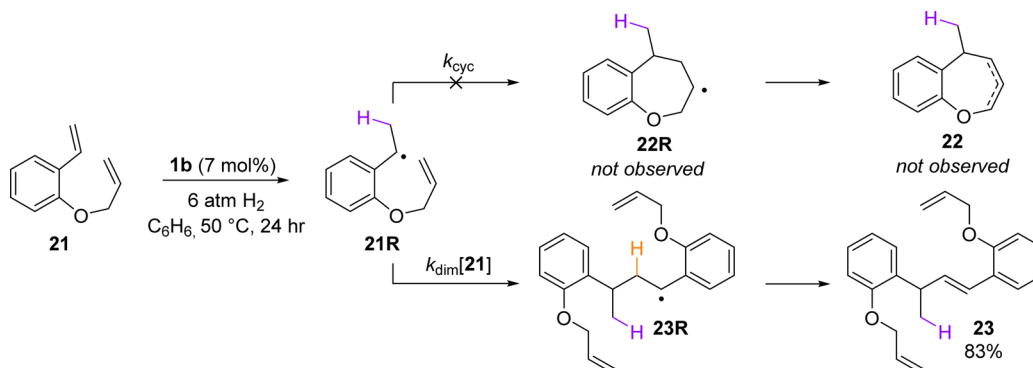
Equation 14 achieves a cycloisomerization in good yield. Under D₂ there is again H/D exchange at the **g** position (the acrylate double bond), but more H/D exchange occurs at positions **e** and **f** of the terminal methylene in the product **27**. These results imply that the abstraction of H• from **27R** is fast and reversible.

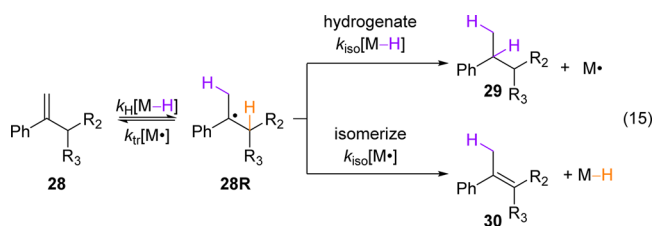


CONCLUSION

Both CpCr(CO)₃H and Co(dmgBF₂)₂(THF)₂ are effective H• donor systems under H₂; i.e., both can promote the formation of **28R** from **28**. However, they take **28R** in different directions. With CpCr(CO)₃H, [M-H] is relatively high and the formation of **29** will prevail. With Co(dmgBF₂)₂L₂ (**1**), [M•] dominates and the formation of **30** is favored. Thus, we can select the fate of radicals such as **28R** by the selection of catalyst.

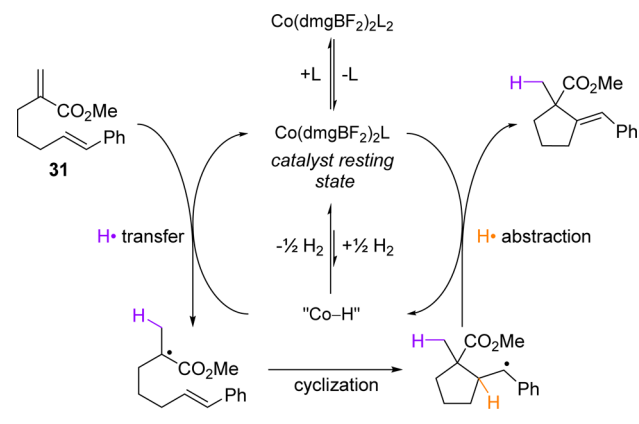
Scheme 3. Potential Reaction Pathways for **21**





The choice between the Cr and the Co catalysts also determines the mode of termination after cyclization of the initial radical. With the substrate **31**, for example, CpCr(CO)₃H maintains a relatively high [M–H] and cyclohydrogenation will prevail. With Co(dmgBF₂)₂L₂ (**1**), on the other hand, [M•] dominates and cycloisomerization will result (Scheme 4).

Scheme 4. Catalytic Cycle for Cycloisomerizations with **1**



■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.6b03509.

X-ray crystallographic data for **14** (CIF)

Starting material preparation; experimental procedures for cyclizations; characterization data, including ¹H and ¹³C NMR spectra; and X-ray data collection (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*jrn11@columbia.edu

Author Contributions

[§]G.L. and J.L.K. contributed equally.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This material was supported by the National Science Foundation under Grant No. CHE-1401049 (IUPAC Novel Molecular and Supramolecular Theory and Synthesis Approaches for Sustainable Catalysis). J.L.K. acknowledges the National Science Foundation Graduate Research Fellowship Program (DGE-11-44155). J.M.A. acknowledges the Con Edison Summer Internship in Science through Barnard College for financial support. The National Science Foundation (CHE-0619638) is thanked for the acquisition of an x-ray diffractometer. The authors are grateful to Scott A. Snyder, Andreas Gansäuer, and John Hartung for helpful discussions.

■ REFERENCES

- (a) Evans, D.; Osborn, J. A.; Wilkinson, G. *J. Chem. Soc. A* **1968**, 3133. (b) Yagupsky, M.; Wilkinson, G. *J. Chem. Soc. A* **1970**, 941.
- Larionov, E.; Li, H. H.; Mazet, C. *Chem. Commun.* **2014**, 50, 9816.
- An alternative, also discussed in ref 2, involves the formation of an η³-allyl hydride intermediate by the oxidative addition of an allylic C–H bond (to a metal that need not bear a hydride ligand at the beginning of the cycle). The hydride is subsequently transferred to the carbon at the other end of the allyl ligand. The isomerization of allylic alcohols to enols (ref 4) proceeds by this mechanism.
- Bergens, S. H.; Bosnich, B. *J. Am. Chem. Soc.* **1991**, 113, 958.
- (a) Sweany, R. L.; Comberrel, D. S.; Dombourian, M. F.; Peters, N. A. *J. Organomet. Chem.* **1981**, 216, 37. (b) Sweany, R. L.; Halpern, J. *J. Am. Chem. Soc.* **1977**, 99, 8335. (c) King, S. M.; Ma, X.; Herzon, S. B. *J. Am. Chem. Soc.* **2014**, 136, 6884. (d) Iwasaki, K.; Wan, K. K.; Oppedisano, A.; Crossley, S. W. M.; Shenvi, R. A. *J. Am. Chem. Soc.* **2014**, 136, 1300. (e) Ma, X.; Herzon, S. B. *Chem. Sci.* **2015**, 6, 6250.
- (a) Choi, J.; Tang, L.; Norton, J. R. *J. Am. Chem. Soc.* **2007**, 129, 234. (b) Kuo, J. L.; Hartung, J.; Han, A.; Norton, J. R. *J. Am. Chem. Soc.* **2015**, 137, 1036.
- Estes, D. P.; Norton, J. R.; Jockusch, S.; Sattler, W. *J. Am. Chem. Soc.* **2012**, 134, 15512.
- (a) Smith, D. M.; Pulling, M. E.; Norton, J. R. *J. Am. Chem. Soc.* **2007**, 129, 770. (b) Hartung, J.; Pulling, M. E.; Smith, D. M.; Yang, D. X.; Norton, J. R. *Tetrahedron* **2008**, 64, 11822. (c) Hartung, J.; Norton, J. R., *Catalysis Involving the H• Transfer Reactions of First-Row Transition Metals*. In *Catalysis without Precious Metals*; Bullock, R. M., Ed.; Wiley-VCH: Weinheim, 2010; p 1.
- Li, G.; Han, A.; Pulling, M. E.; Estes, D. P.; Norton, J. R. *J. Am. Chem. Soc.* **2012**, 134, 14662.
- Crossley, S. W.; Barabé, F.; Shenvi, R. A. *J. Am. Chem. Soc.* **2014**, 136, 16788.
- With 1-decene as substrate, the Shenvi group obtained six minor isomers from further isomerization, in a total yield of 14% (ref 10).
- (a) Widenhoefer, R. A. *Acc. Chem. Res.* **2002**, 35, 905. (b) Trost, B. M. *Acc. Chem. Res.* **1990**, 23, 34. (c) Yamamoto, Y. *Chem. Rev.* **2012**, 112, 4736.
- Han, A.; Spataru, T.; Hartung, J.; Li, G.; Norton, J. R. *J. Org. Chem.* **2014**, 79, 1938.
- Estes, D. P.; Grills, D. C.; Norton, J. R. *J. Am. Chem. Soc.* **2014**, 136, 17362.
- (a) Sheldrick, G. M. *SHELXTL*, An Integrated System for Solving, Refining, and Displaying Crystal Structures from Diffraction Data; University of Gottingen: Gottingen, Germany, 1981. (b) Sheldrick, G. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **2008**, 64, 112.
- Li, G.; Estes, D. P.; Norton, J. R.; Ruccolo, S.; Sattler, A.; Sattler, W. *Inorg. Chem.* **2014**, 53, 10743.
- It is not certain that the H• donor is a cobalt hydride (ref 16).
- For a recent review on the isomerization of allyl ethers to enol ethers, see: Kuznik, N.; Krompiec, S. *Coord. Chem. Rev.* **2007**, 251, 222.
- (a) Lunazzi, L.; Ingold, K. U. *J. Am. Chem. Soc.* **1974**, 96, 5558. (b) Evans, D. A.; Andrews, G. C.; Buckwalter, B. *J. Am. Chem. Soc.* **1974**, 96, 5560.
- Aloui, M.; Chambers, D. J.; Cumpstey, I.; Fairbanks, A. J.; Redgrave, A. J.; Seward, C. M. P. *Chem. - Eur. J.* **2002**, 8, 2608.
- Nelson, S. G.; Wang, K. *J. Am. Chem. Soc.* **2006**, 128, 4232.
- The H• donor that is formed from **1b** and H₂ has a pK_a of about 13.4 in acetonitrile,¹⁴ so it may play a role in the tautomerization.
- Noy, R. S.; Gindin, V. A.; Ershov, B. A.; Kol'tsov, A. I.; Zubkov, V. A. *Org. Magn. Reson.* **1975**, 7, 109.
- Kulkarni, M. G.; Doke, A. K.; Davawala, S. I.; Doke, A. V. *Tetrahedron Lett.* **2003**, 44, 4913.
- (a) McCulloch, A. W.; McInnes, A. G. *Can. J. Chem.* **1974**, 52, 3569. (b) Carless, H. A. J.; Haywood, D. J. *J. Chem. Soc., Chem. Commun.* **1980**, 980. (c) Davis, M.; Fisher, J. A. *Aust. J. Chem.* **1970**, 23, 205. (d) Volkonskii, A. Y.; Kagrananov, E. M.; Mysov, E. I.; Mysova, N. E. *Russ. Chem. Bull.* **2004**, 53, 2774. (e) Volkonskii, A. Y.; Kagrananov, E. M.; Mysov, E. I.; Kagrananov, N. D. *Russ. Chem. Bull.* **2010**, 59, 569.

(26) (a) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987. (b) Hartwig, J. F. *Organotransition Metal Chemistry: From Bonding to Catalysis*. University Science Books: Sausalito, CA, 2010.

(27) Bullock, R. M.; Samsel, E. G. *J. Am. Chem. Soc.* **1990**, *112*, 6886.

(28) (a) Sweany, R. L.; Butler, S. C.; Halpern, J. J. *Organomet. Chem.* **1981**, *213*, 487 and references therein. (b) Feder, H. M.; Halpern, J. J. *Am. Chem. Soc.* **1975**, *97*, 7186. (c) Smith, D. M.; Pulling, M. E.; Norton, J. R. *J. Am. Chem. Soc.* **2007**, *129*, 770. (d) Obradors, C.; Martinez, R. M.; Shenvi, R. A. *J. Am. Chem. Soc.* **2016**, *138*, 4962.

(29) (a) Trost, B. M. *Acc. Chem. Res.* **2002**, *35*, 695. (b) Trost, B. M. *Science* **1991**, *254*, 1471. (c) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259.

(30) (a) Zipse, H. *Top. Curr. Chem.* **2006**, *263*, 163. (b) Such an enone is an attractive substrate because radicals are stabilized by acyl substituents: Brocks, J. J.; Beckhaus, H. D.; Beckwith, A. L. J.; Rüchardt, C. *J. Org. Chem.* **1998**, *63*, 1935.

(31) 1-Carbomethoxy-1-methyl-5-hexenyl radicals cyclize more readily with only one phenyl substituent on C6; two phenyl substituents, or a phenyl and a methyl substituent, result in slower cyclizations (see ref 13).

(32) Beckwith, A. L. J.; Glover, S. A. *Aust. J. Chem.* **1987**, *40*, 157.

(33) Blanksby, S. J.; Ellison, G. B. *Acc. Chem. Res.* **2003**, *36*, 255.

(34) (a) Beckwith, A. L. J.; Easton, C. J.; Lawrence, T.; Serelis, A. K. *Aust. J. Chem.* **1983**, *36*, 545. (b) Chatgililoglu, C.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 7739.

(35) (a) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron* **1985**, *41*, 3925. (b) Lo, J. C.; Gui, J.; Yabe, Y.; Pan, C. M.; Baran, P. S. *Nature* **2014**, *516*, 343.

(36) Beckwith, A. L. J.; Schiesser, C. H. *Tetrahedron Lett.* **1985**, *26*, 373.

(37) Beckwith, A. L. J.; Moad, G. *J. Chem. Soc., Chem. Commun.* **1974**, 472.

(38) Lo, J. C.; Yabe, Y.; Baran, P. S. *J. Am. Chem. Soc.* **2014**, *136*, 1304.

(39) Walton, J. Unusual Radical Cyclisations. In *Radicals in Synthesis II*; Gansäuer, A., Ed.; Springer: Berlin/Heidelberg, 2006; Vol. 264, p 163.