10998 *J. Am. Chem. Soc.* **1993,** *115,* 10998–10999

Highly Selective Cross-Metathesis of Terminal Olefins

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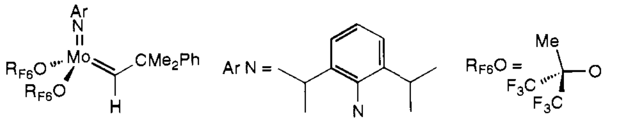
Received August 12, 1993

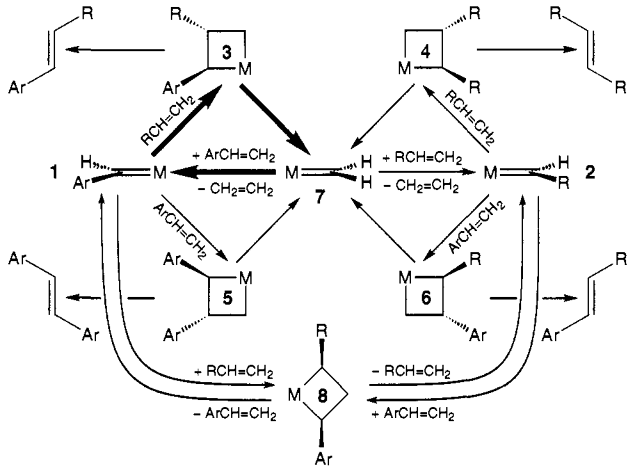
Olefin metathesis catalysts mediate the exchange of alkylidene units between olefins to produce a mixture of olefin products. For reactions involving a single olefin (self-metathesis), selectivity can be achieved by providing a driving force for the reaction such as strain energy relief or removal of a volatile olefin byproduct. In such cases, catalytic olefin metathesis can be a powerful carbon–carbon bond-forming reaction, as exemplified by its wide application to polymer synthesis[1,2] and a few recent applications to organic synthesis.[3,4] The cross-metathesis of a pair of olefins requires not only a driving force but also the suppression of competing self-metathesis pathways. To date there are no general, selective methods for the cross-metathesis of unlike olefins. This restricts the type of polymers that can be prepared by olefin metathesis and severely limits the application of olefin metathesis to organic synthesis. Herein we report the selective cross-metathesis of aryl- and alkyl-substituted terminal olefins using the molybdenum catalyst $Mo(OR_{F6})_2(NAr)(CHCMe_2Ph)(R_{F6} = C(CF_3)_2Me$, Ar = 2,6-$i$-$Pr_2C_6H_3$) developed by Schrock and co-workers.[5,6]



When molybdenum catalyst $Mo(OR_{F6})_2(NAr)(CHCMe_2Ph)$ is treated with either styrene or 1-decane at room temperature, self-metathesis products (stilbene or 9-octadecene) form very slowly.[7] When both olefins are added to the catalyst, together or sequentially in either order, 1-phenyl-1-decene is formed rapidly and selectively. We found that styrene and substituted styrenes can be cross-metathesized with a variety of functionalized terminal olefins to give unsymmetrical olefin products with >95% trans selectivity. In most cases, high yields of cross-metathesis products were obtained using 1 mol% catalyst and excess styrene (2 equiv).[8] Results are summarized in Table I.

The cross-metathesis reaction shows the expected selectivity for monosubstituted versus disubstituted olefins (entries 2, 3) and good tolerance of heteroatom functionality (entries 4–12).

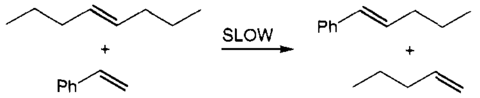
Scheme I



Note that although ketones are not good participants in the cross-metathesis reaction, silyl enol ethers obtained from ketones are somewhat better (entries 7, 8). In these cases, greater catalyst loading (5 mol %) was required in order to obtain useful product yields.

Cross-metathesis/self-metathesis product ratios are substrate dependent, ranging from 1.2:1 to >40:1. Selectivity is lowered by the inductive effect of electron-withdrawing substituents on the alkyl-substituted olefin (note the effect of bromine position in entries 4–6 and remote carbon oxidation state in entries 9–10).[9]

Since the molybdenum catalyst used here is known to metathesize internal olefins, it is possible that cross-metathesis selectivity may be affected by such secondary reactions. To examine this possibility, we treated various mixtures of dialkyl-,diaryl- and alkyl-,aryl-substituted olefins with the catalyst and found no significant change in component ratio over the course of several hours. We also looked at the reaction of *trans*-stilbene with 1-pentene and *trans*-4-octene with styrene and found that the former pair did not react, but the latter pair reacted selectively to produce the cross-metathesis product *trans*-β-propylstyrene (equiv 1). The latter reaction consumes an undesired self-metathesis product but not rapidly enough to influence product ratios.



(1)

Even in the absence of secondary reactions, two terminal olefins treated with an olefin metathesis catalyst can give six possible (three pairs cis/trans isomers) by eight competing reaction pathways. Key intermediates for the four pathways leading to trans olefin products are shown in Scheme I, with the proposed favored pathway indicated by bold arrows.[10] We propose that alkylidenes **1** and **2** interconvert via unsymmetrical α,α'-disubstituted metallocycle **8** at a rate much faster than formation of α,β-disubstituted metallocycles **3–6**. Productive metathesis

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(1) (a) Gilliom, L. R.; Grubbs, R. H. *J. Am. Chem. Soc.* **1986**, *108*, 733–742. (b) Wallace, K. C.; Schrock, R. R. *Macromolecules* **1987**, *20*, 448. (c) Schrock, R. R.; Feldman, J.; Grubbs, R. H.; Cannizzo, L. *Macromolecules* **1987**, *20*, 1169. (d) Chan, Y. N. C.; Schrock, R. R. *Chem. Mater.* **1993**, *5*, 566–570. (e) Komiya, Z.; Schrock, R. R. *Macromolecules* **1993**, *26*, 1387–1392. (f) Albagli, D.; Bazan, G.; Wrighton, M. S.; Schrock, R. R. *J. Am. Chem. Soc.* **1992**, *114*, 4150–4158. (g) Ng Cheong, Chan, Y.; Schrock, R. R.; Cohen, R. E. *J. Am. Chem. Soc.* **1992**, *114*, 7295–7296. (h) Conticello, V. P.; Gin, D. L.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, *114*, 9708–9710. (i) Nguyen, S. T.; Johnson, L. K.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1992**, *114*, 3974–3975. (j) Risse, W.; Grubbs, R. H. *J. Mol. Catal.* **1991**, *65*, 211–217.

(2) (a) Patton, J. T.; Boncella, J. M.; Wagener, K. B. *Macromolecules* **1992**, *25*, 3862–3867. (b) Wagener, K. B.; Boncella, J. M.; Nel, J. G. *Macromolecules* **1991**, *24*, 2649–2657. (c) Wagener, K. B.; Nel, J. G.; Konzelman, J.; Boncella, J. M. *Macromolecules* **1990**, *23*, 5155–5157.

(3) Fu, G. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, *114*, 7324–7325.

(4) Fu, G. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, *114*, 5426–5427.

(5) Murdzek, J. S.; Schrock, R. R. *Organometallics* **1987**, *6*, 1373.

(6) Schrock, R. R.; Murdzek, J. S.; Bazan, G. C.; Robbins, J.; DiMare, M.; O'Regan, M. *J. Am. Chem. Soc.* **1990**, *112*, 3875–3886.

(7) Schrock reported that $Mo(OR_{F6})_2(NAr)(CHCMe_2Ph)$ metathesizes 20 equiv of styrene to equilibrium in 1.5–2 h at 25 °C: Schrock, R. R.; Murdzek, J. S.; Bazan, G. C.; Robbins, J.; DiMare, M.; O'Regan, M. *J. Am. Chem. Soc.* **1990**, *112*, 3875–3886.

(8) A representative procedure: to a mixture containing 208 mg (2 mmol) of styrene and 112 mg (1 mmol) of 1-octene in 2 mL of methylene chloride was added 7.7 mg (1 mol %) of catalyst. The resulting mixture was stirred at room temperature for 1 h and then passed through a pad of silica gel and rinsed with methylene chloride. The solvent was removed under pressure, and the crude residue was chromatographed on silica gel to give 166 mg (89%) of 1-phenyl-1-octene as a colorless oil. A similar reaction run with 9.29 g (89.2 mmol) of styrene, 5 g (44.6 mmol) of 1-octene, and 342 mg (1 mol %) of catalyst afforded 7.9 g (94%) 1-phenyl-1-octene.

(9) There is a good empirical correlation between cross-metathesis selectivity and the chemical shift of the substrate protons. High selectivity is observed for δ <2.2; low selectivity is observed for δ >2.3.

0002-7863/93/1515-10998$04.00/0

Table I. Cross-Metathesis Reactions[a]

entry	Ar	R	ArCH=CHR (%)[b]	RCH=CHR (%)
1	Ph	*n*-hexyl	89	2
2	Ph	$CH_2CH_2C(=CH_2)CH_3$	86	2
3	Ph	cyclohex-4-enyl	60	15
4	Ph	$CH_2CH_2CH_2Br$	90	4
5	Ph	$CH_2CH_2CH(Br)CH_3$	84	8
6	Ph	CH_2CH_2Br	50	42
7	Ph	$CH_2CH_2COCH_3$	0 (11)[c]	*e*
8	Ph	$CH_2CH_2C(=CH_2)OTMS$	22 (66)[c,d]	*e*
9	Ph	$CH_2CH_2CO_2CH_2Ph$	67	20
10	Ph	$CH_2CH_2CH_2OCH_2Ph$	85	2
11	*p*-$MeOC_6H_4$	*n*-hexyl	88	2
12	*m*-$O_2NC_6H_4$	*n*-hexyl	48	39

[a] Reactions were run with 2 equiv of styrene and 1 mol % catalyst. The amount of stilbene formed in most cases is less than 4%. [b] Only the trans isomer was detected by ^{1}H NMR. [c] The yield in parentheses is for a reaction using 5 mol % catalyst. [d] Isolated as the ketone. [e] Yield was not determined.

then occurs selectively through the lowest energy transition state available (Curtin–Hammett principle).

Formation of the α,β-disubstituted metallacycle **3** should be favored by the smaller size and greater basicity of incoming alkyl-substituted olefin and by conjugation of the α-aryl substituent with the polarizable, electron-rich metal–carbon bond.[11,12] Thus alkyl substituents are selectively incorporated into the β position and aryl substituents into the α position of metallacyclobutane intermediates.[13] The dependence of selectivity on substrate electron-withdrawing substituents is consistent with this model. Electron-deficient alkyl substituents lower cross-metathesis selectivity by stabilizing competing metallacycle **4**.

The high trans selectivity observed in cross-metathesis reactions is consistent with selective formation of *trans*-α,β-disubstituted metallacyclobtane intermediates. High trans selectivity is also observed in the acyclic diene metathesis (ADMET) polymerization of α,ω-dienes.[2]

In conclusion, we have found that styrenes are ideal participants in cross-metathesis reactions since they inhibit the self-metathesis of terminal alkyl olefins and only slowly self-metathesize to stilbenes. An important advantage of cross-metathesis over other methods of olefin synthesis is its operational simplicity and atom economy;[14] the only byproduct formed in the reaction is ethylene. The scope of the cross-metathesis reaction is enhanced by the remarkable functionality tolerance exhibited by Schrock's molybdenum imido alkylidene catalysts. Recent advances in the syntheses of these versatile catalysts have made them very accessible.[6,15] Since the reactivity of Schrock's imido alkylidene catalysts is very sensitive to subtle steric and electronic changes in either the metal ligands or the olefin substrate, it should be possible to identify a number of catalyst/olefin combinations that lead to selective cross-metathesis reactions. Efforts to do this are currently in progress.[16]

Acknowledgment. Support of this work by the Emory University Research Fund is gratefully acknowledged.

Supplementary Material Available: Experimental procedures and spectral data for all compounds (6 pages). Ordering information is given on any current masthead page.

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(10) (a) One of several subtle features of the imido alkylidene catalyst systems not depicted in this simplified scheme is the possibility of *syn* and *anti* rotamers. Such rotamers have been structurally characterized[10b] and have been shown to have relative reactivities which can very over several orders of magnitude, with the *anti* rotamer being more reactive.[10c] (b) Schrock, R. R.; Crowe, W. E.; Bazan, G. C.; DiMare, M.; O'Regan, M. B.; Schofield, M. H. *Organometallics* **1991**, *10*, 1832–1843. (c) Oskam, J. H.; Schrock, R. R. *J. Am. Chem. Soc.* **1992**, *114*, 7588–7590.

(11) Similar explanations have been proposed for the regioselectivity of metallacyclobutane formation: (a) Gassman, P. G.; Johnson, T. H. *J. Am. Chem. Soc.* **1977**, *99*, 622–623. (b) Schrock, R. R.; Rocklage, S. M.; Wengrovius, J.; Rupprecht, G.; Fellmann, J. *J. Mol. Catal.* **1980**, *8*, 73. (c) McLain, S. J.; Wood, C. D.; Schrock, R. R. *J. Am. Chem. Soc.* **1977**, *99*, 3519.

(12) Such regioselectivity is not always observed: Rocklage, S. M.; Fellmann, J. D.; Rupprecht, G. A.; Messerle, L. W.; Schrock, R. R. *J. Am. Chem. Soc.* **1981**, *103*, 1440.

(13) Analogous selectivity is observed when tungsten neopentylidene complex $W(OR_{F6})_2(NAr)(CH\text{-}t\text{-}Bu)$ reacts with excess *cis*-β-methylstyrene. $W(NAr(OR_{F6})_2(CHPh)$ is formed by selective incorporation of methyl into the β position and phenyl into the α position of the metallacyclobutane intermediate leading to product: Schrock, R. R.; DePue, R. T.; Feldman, J.; Schaverien, C. J.; Dewan, J. C.; Liu, A. H. *J. Am. Chem. Soc.* **1988**, *110*, 1423–1435.

(14) Trost, B. M. *Science* **1991**, *254*, 1471–1477.

(15) Fox, H. H.; Yap, K. B.; Robbins, J.; Cai, S.; Schrock, R. R. *Inorg. Chem.* **1992**, *31*, 2287–2289.

(16) Preliminary studies indicate that acrylonitrile can be selectively cross-metathesized with alkyl-substituted olefins: Crowe, W. E.; Goldberg, D. R., to be published.