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Highly *Z*-Selective Metathesis Homocoupling of Terminal Olefins

Annie J. Jiang,[†] Yu Zhao,[†] Richard R. Schrock,*[,†] and Amir H. Hoveyda[‡]

Department of Chemistry 6-331, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, and Department of Chemistry, Merkert Chemistry Center, Boston College, Chestnut Hill, Massachusetts 02467

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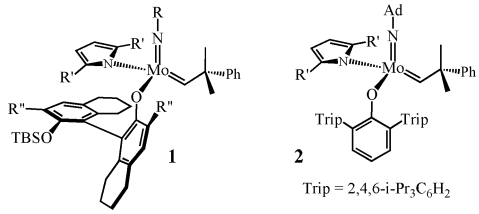
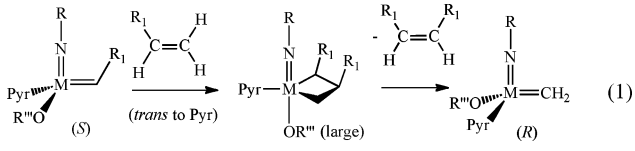
Highly reactive monoaryloxide-pyrrolide (MAP) olefin metathesis catalysts of Mo[1] (**1**) have been prepared from bispyrrolide precursors[2] in situ and employed for enantioselective olefin metathesis reactions, such as a total synthesis of quebrachamine (when R = 2,6-*i*-$Pr_2C_6H_3$, R′ = Me, R″ = Br).[3] Cross-metatheses with **1** (when R = 1-adamantyl) were found to be *Z*-selective, as well as enantioselective, as a consequence, we proposed, of restrictions imposed on substituents within the metallacyclobutane in the TBP intermediate by a "large" axial aryloxide in combination with a "small" imido group.[4] The above principle guided the synthesis of related complexes **2** (R′ = H (**2H**) or Me (**2Me**)), which have been shown to catalyze the *Z*-selective metathesis of selected internal *Z*-olefins and to polymerize substituted norbornadienes to yield >99% cis and >99% syndiotactic polymers.[5] We report here that the principles of *Z*-selectivity by MAP catalysts can be extended to homocoupling of terminal olefins.

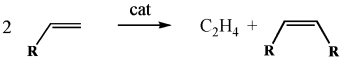


The principles of *Z*-selective homocoupling of $R_1CH{=}CH_2$ by a *syn*,*rac*-MAP complex are shown in eq 1. (Only *syn* isomers[1] have been observed to date in NMR or X-ray studies.) The terminal olefin enters the coordination sphere *trans* to the pyrrolide (Pyr)[5,6] to generate an intermediate metallacyclobutane with adjacent R_1 substituents pointing away from the axial OR‴ group; this scenario holds *if* OR‴ is sufficiently large to prevent formation of any metallacycle in which R_1 is oriented toward OR‴. Loss of *Z*-$R_1CH{=}CHR_1$ yields a methylene complex with an inverted configuration at the metal center (*S*→*R* in eq 1). A productive metathesis reaction between the methylene species and $R_1CH{=}CH_2$ then yields ethylene and reforms (*S*)-M(NR)(CHR_1)(Pyr)(OR‴). Inversion of configuration at the metal center is a consequence of each forward metathesis step.[5,6] Inversion itself should not be an important feature of a homocoupling reaction, but if OR‴ is enantiomerically pure, then both diastereomers must be *Z*-selective.



(1)

Initially, we concentrated on small-scale experiments involving 1-hexene (S_1) or 1-octene (S_2; Table 1; eq 2) with 4 mol % catalyst in a closed system (NMR tube or vial). On the basis of extensive screening (see Supporting Information) we conclude that (i) a relatively small imido group is not necessary for highly *Z*-selective couplings of a *terminal* olefin and (ii) W-based complexes deliver higher %*Z* than Mo complexes. Examples of higher selectivity furnished by W include $\mathbf{3_W}$ versus $\mathbf{3_{Mo}}$ and $\mathbf{5_W}$ versus $\mathbf{5_{Mo}}$.[7] Compound $\mathbf{4_W}$[6a] is as effective as $\mathbf{3_W}$, and 95% *Z*-product is obtained at low conversion. The *Z*-product isomerizes to *E* with time and conversion (e.g., see $\mathbf{5_W}$). The results for the homocoupling of 1-hexene are similar to those shown in Table 1 in all cases; for example, catalyst $\mathbf{4_W}$ gave 95% *Z*-5-decene at 33% conversion after three days.



(2)

R = n-butyl (S_1), n-hexyl (S_2), CH_2Ph (S_3), CH_2SiMe_3 (S_4), $(CH_2)_8CO_2Me$ (S_5), $(CH_2)_7CO_2Me$ (S_6), CH_2–B(O,O) (S_7), $CH_2OBenzyl$ (S_8), $CH_2NHTosyl$ (S_9), CH_2NHPh(S_{10})

Table 1. Homocoupling of 1-Octene (S_2)[a]

	Catalyst	time	% Conv	%*Z*
$\mathbf{2_{Me}}$	Mo(NAd)(Me_2Pyr)(CHR_2)(OHIPT)[b]	3 h	43	68
$\mathbf{3_{Mo}}$	Mo(NAr)(Pyr)(CHR_2)(OHIPT)[b]	20 m	80	40
$\mathbf{3_W}$	W(NAr)(Pyr)(CHR_2)(OHIPT)[b]	26 h	88	88
$\mathbf{4_W}$	W(NAr)(Pyr)(C_3H_6)(OHIPT)	3 h	33	95
$\mathbf{5_{Mo}}$	Mo(NAr)(Pyr)(CHR_2)(Mes_2Bitet)*[b]	15 m	58	70
$\mathbf{5_W}$	W(NAr)(Pyr)(CHR_2)(Mes_2Bitet)*[b]	30 m	38	93
		2 h	72	88

[a] 4 mol % cat in C_6D_6 at 22 °C; R_2 = CMe_2Ph; Ad = 1-adamantyl; Ar = 2,6-*i*-$Pr_2C_6H_3$; OHIPT is the aryloxide shown in structure **2**; Mes_2Bitet is the ligand in structure **1** with R″ = mesityl. [b] Prepared *in situ*; see Supporting Information.

Table 2. Screening of Substrates S_3–S_9[a]

S_n		Catalyst	*t* (h)	% Conv	%*Z*
S_3	$\mathbf{3_W}$	W(NAr)(Pyr)(CHR_2)(OHIPT)[b]	3	40	91
S_3	$\mathbf{4_W}$	W(NAr)(Pyr)(C_3H_6)(OHIPT) (2%)	14	52	94
S_3	$\mathbf{6_W}$	W(NAr^{Cl})(Pyr)(CHR_2)(Mes_2Bitet)*[b]	3	62	93
S_4	$\mathbf{7_{Mo}}$	Mo(NAd)(Me_2Pyr)(CHR_2)(Br_2Bitet)*[b]	3	33	98
S_5	$\mathbf{8_W}$	W(NAr′)(Pyr)(CHR_2)(Mes_2BitetOMe)*[b]	1.5	69	92
S_6	$\mathbf{9_W}$	W(NAr′)(Pyr)(CHR_2)(OHIPT)*[b]	3	33	90
S_7	$\mathbf{3_W}$	W(NAr)(Pyr)(CHR_2)(OHIPT)[b]	3	30	94
S_7	$\mathbf{10_W}$	W(NAr^{Cl})(Pyr)(CHR_3)(OHIPT)*	1.5	70	96
S_7	$\mathbf{7_{Mo}}$	Mo(NAd)(Me_2Pyr)(CHR_2)(Br_2Bitet)[b]	3	33	98
S_8	$\mathbf{11_W}$	W(NAr^{Cl})(Pyr)(CHR_3)(Mes_2Bitet)*[b]	1.5	24	98
S_9	$\mathbf{11_W}$	W(NAr^{Cl})(Pyr)(CHR_2)(Mes_2Bitet)*[b]	3	52	98

[a] 4 mol % cat in C_6D_6 at 22 °C in NMR tube; R_2 = CMe_2Ph; Ar^{Cl} = 2,6-$Cl_2C_6H_3$; Ar′ = 2,6-$Me_2C_6H_3$; Br_2Bitet is the ligand in structure **1** with R″ = Br; Mes_2BitetOMe is the methyl-protected analogue of the ligand in structure **1** with R″ = Mesityl; R_3 = *t*-Bu. [b] Prepared *in situ*.

A selection of some of our findings in connection with initial screening of substrates S_3–S_9 is shown in Table 2.[7] Note that $\mathbf{7_{Mo}}$ and $\mathbf{3_W}$ both give high %*Z* for S_7, although a direct comparison of Mo and W is not possible since 1-adamantyl imido species of W are not known. It should be noted also that moderate conversion is satisfactory since the product can be separated easily from the unreacted substrate, which can be recycled.

To test the degree to which ethylene might be deleterious to *Z*-selectivity, we explored reactions involving several of the higher boiling substrates under a 0.5 or 10 mmHg vacuum with 1 or 2 mol % catalyst

[†] Massachusetts Institute of Technology.
[‡] Boston College.

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on larger scales and compared the findings with those obtained at 1 atm of nitrogen (Table 3). The results suggest that the effects of carrying out reactions at reduced pressure are not significant. Only the coupling of S_5 carried out with $\mathbf{8_W}$ over 15 h suggests that reduced pressure *may* be required to maintain high %*Z* for long periods. Some loss of monomer at ~0.5 mm naturally is observed over extended times (~14% measured in the case of $\mathbf{8_W}$ after 15 h).

Table 3. Effect of Reduced Pressure on *Z*-Content (1 mol % cat.)[a]

Substrate	Catalyst	*P* (mmHg)	*t* (h)	% Conv	%*Z*
S_5	$\mathbf{8_W}$	~0.5	0.2 (15)	25 (>98)	>98 (>98[b])
S_5	$\mathbf{8_W}$ (2%)	~760	1.5 (15)	84 (86)	97 (88)
S_5	$\mathbf{12_{Mo}}$[c]	~0.5	0.6 (16)	36 (34)	61 (61)
S_5	$\mathbf{12_{Mo}}$[c]	~760	0.6 (16)	24 (24)	61 (59)
S_5	$\mathbf{4_W}$	~0.5	5 (21)	7 (22)	>98 (>98)
S_5	$\mathbf{4_W}$	~760	5 (21)	10 (27)	>98 (>98)
S_5	$\mathbf{3_{Mo}}$	10	19	62	88
		~760	19	42	90
S_7	$\mathbf{3_{Mo}}$	~0.5	2	64	94
		~760	2	52	96
S_{10}	$\mathbf{12_{Mo}}$(2%)	~0.5	14	70	95

[a] Reaction scale ~200 mg, neat substrate, catalyst added as a solid. [b] 86% yield after 15 h. [c] $\mathbf{12_{Mo}}$ = Mo(NAr)(Pyr)(CHR_2)(Mes_2BitetOMe).

The results of reactions performed at 80−120 °C (bath temp), larger scales, and lower catalyst loadings are shown in Table 4. In several cases, the remaining monomer was removed *in vacuo* and the *Z*-product yields were established. A number of reactions proceed with >90% *Z*-selectivity and in good yield.

Table 4. Reactions Carried out at Elevated Temperatures[a]

Substrate	Catalyst	%	*t* (h)	°C (Bath)	%Conv.	%*Z*	%Yield
S_1	$\mathbf{4_W}$	0.4	48	80	72	95	58
S_2	$\mathbf{4_W}$	0.4	24	120	94	86	78
	$\mathbf{10_W}$	0.2	3	120	>98	77	77
S_3	$\mathbf{4_W}$	0.2	4	120	63	93	56
	$\mathbf{10_W}$	0.2	24	100	94	88	65
S_4	$\mathbf{13_W}$[b]	0.2	18	90	28	86	26
S_5	$\mathbf{13_W}$[b]	2	23	100	>97	95	
S_6	$\mathbf{13_W}$[b]	1	16	100	97	87	80
S_7	$\mathbf{4_W}$	0.2	1	100	46	91	
	$\mathbf{10_W}$	0.2	18	100	74	94	
S_8	$\mathbf{5_W}$	4	24	100	46	>98	42
S_9	$\mathbf{4_W}$	4	18	100	95	91	90
	$\mathbf{10_W}$	4	24	90	50	94	36

[a] Reaction scale ~0.5 g to ~4 g; catalyst was dissolved in ~1 mL of benzene, and substrate was added in one portion. The mixture was refluxed under N_2. [b] W(NAr′)(Pyr)(C_3H_6)(OHIPT).

We propose that the efficiency of the mechanism of formation of *Z*-product shown in eq 1 depends upon a ligand combination that allows only a *syn*,*syn*-α,R_1/*β*,R_1 metallacyclobutane to form from a *syn* alkylidene. Therefore, a large OR‴ ligand is required to form *Z*-product with high selectivity, as we proposed previously. A "small" imido group is not required, most likely because the steric demands of a *syn*,*syn*-α,R_1/*β*,R_1 metallacyclobutane are less severe than the steric demands of an all *syn*, *trisubstituted* metallacycle.[5]

A critical question relates to the mechanism of formation of *E*-product. Three possible direct ways of forming *E*-product are (i) approach of monomer to the *syn* alkylidene to yield a metallacycle with R_1 pointed toward OR‴; (ii) reaction of monomer with a highly reactive (unobservable) *anti* alkylidene (in equilibrium with a *syn* alkylidene) to give a *trans* disubstituted metallacyclobutane intermediate; and (iii) approach of the monomer in a manner different from that shown in eq 1 to generate a different type of metallacyclobutane. On the basis of what we know at present we propose that a significant amount of *E*-product is not formed through a direct method if OR‴ is sufficiently large (eq 1); formation of *Z*-product in the primary step obviously is required for a *Z*-selective reaction.

One possible indirect mode of forming *E*-product is for the *Z*-product to be isomerized through reaction with a M = CHR_1 species to afford a trisubstituted metallacycle that contains two adjacent *trans* substituents. Such a process is likely to be relatively slow in many circumstances for steric reasons[5] because two R_1 groups must be oriented toward the large OR‴ in the metallacyclobutane, if that metallacyclobutane is the only type that forms. A second possible indirect mode is for the reverse of eq 1 to be fast (ethenolysis[8]), but only if the monomer is reformed and recoupled many times in the presence of ethylene, and if a "mistake" that results in formation of *E*-product in any single step (eq 1 and immediately above) is thereby magnified. On the basis of the results summarized in Table 3, rapid and repeated ethenolysis is probably not the main pathway giving rise to *E*-products with the catalysts and substrates explored here. Therefore, at this stage we propose that *E*-product forms primarily through isomerization of the initial *Z*-product.

Formation of high %*Z* homocoupled acyclic products, as described herein, has, to the best of our knowledge, never been observed. The experiments detailed here have evolved as a consequence of our discovery and investigation of MAP catalysts.[1−6,8] We expect that the results will continue to depend sensitively upon a combination of steric factors within each catalyst and substrate, and upon experimental conditions.

It should be noted that intermediate metallacyclobutanes in ruthenium-based metathesis catalysts that contain two chlorides[9] are proposed to be 14 electron TBP species with the chlorides in axial positions.[10] Axial chlorides would not be able to control the substitution pattern in the ruthenacyclobutane in the manner that we have achieved with the MAP complexes described here. No comparable *Z*-selectivities in homocoupling reactions have been reported for ruthenium-based catalysts.

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Supporting Information Available: Experimental details for the synthesis of all compounds and metathesis reactions. This material is available free of charge via the Internet at http://pubs.acs.org.

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