ORGANIC LETTERS

2013
Vol. 15, No. 10
2486–2489

Asymmetric Cross-Dimerization between Methyl Methacrylate and Substituted Alkene by Ru(0)–Bicyclononadiene Complex[†]

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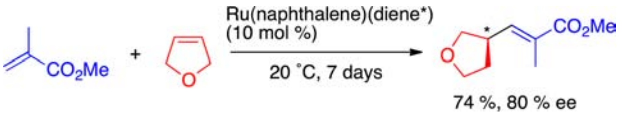
Received April 8, 2013

ABSTRACT



New Ru(0)–naphthalene complexes containing a bicyclononadiene ligand catalyze the linear cross-dimerization between methyl methacrylate and substituted alkenes by an oxidative coupling mechanism. The chiral (*S,S*)-2-methylbicyclo[3.3.1]nona-2,6-diene complex (*S,S*)-1b catalyzes asymmetric linear cross-dimerization between methyl methacrylate and 2,5-dihydrofuran to give the cross-dimer in 74% yield in 80% ee.

Catalytic dimerization of substituted alkenes is one of the most powerful and environmentally benign processes for the formation of C–C bonds, and it proceeds with complete atom efficiency.[1] However, cross-dimerization between substituted alkenes remains difficult, and the coupling partners are limited to norbornene/norbornadiene[2] and vinyl compounds.[3] One of the ultimate goals for this process is the asymmetric linear cross-dimerization of alkenes. However, few such reactions are known, although asymmetric [2 + 2 + 2] cyclotrimerization of alkynes is of topical interest.[4] The pioneering examples involve the cross-dimerizations between ethylene and styrenes[5] or between alkenes and alkynes.[6] However, the asymmetric linear cross-dimerization between substituted alkenes is unprecedented to the best of our knowledge.

We have studied stoichiometric and catalytic homo- and cross-dimerization by Ru(η^6-naphthalene)(η^4-1,5-COD) (**2**; COD = cyclooctadiene) and related compounds.[7] For example, the complex (η^4-1,5-COD)[*trans*-2,5-bis(methoxycarbonyl)ruthenacyclopentane] was isolated by the stoichiometric reaction of **2** with methyl acrylate, presumably formed by a prostereogenic face-selective

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[†] This paper is dedicated to Prof. Irina Petrovna Beletskaya at Moscow State University for her contribution to metal-catalyzed reactions.

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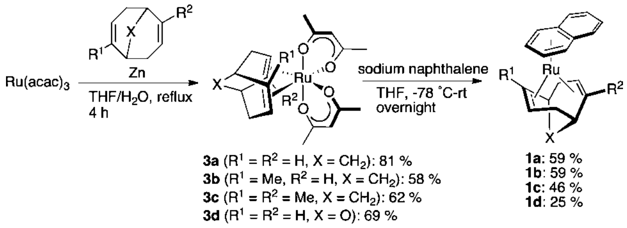
oxidative coupling reaction,[8] and this ruthenacyclopentane acts as an active catalyst for the tail-to-tail dimerization of methyl acrylate.[9] In these reactions, the 1,5-COD ligand remains attached on Ru throughout the reaction. Since these reactions are significantly suppressed by the addition of tertiary phosphine,[7e] employment of a cyclic diene ligand is the key to these catalyses. Thus, the presence of a chiral cyclic diene ligand in the Ru(0)−naphthalene complex could potentially provide an efficient catalyst for asymmetric linear cross-dimerization of substituted alkenes.

Just a decade ago, Hayashi et al. introduced a chiral cyclic diene ligand into transition-metal-mediated asymmetric catalysis.[10] Later, Carreira et al. developed very efficient synthetic method of a chiral diene from commercially available natural product.[11] All these systems currently constitute a powerful asymmetric induction method by the C−C bond forming reaction.[12] However, chiral cyclic dienes are dominantly employed for group 9 complexes, and have never been applied to Ru complexes. They also have never used as an ancillary ligand for the catalysts in the cross-dimerization of alkenes. Herein we report the synthesis of a series of Ru(0) complexes bearing a bicyclononadiene ligand,[13,14] their application to the linear cross-dimerization between substituted alkenes and their successful use for the first asymmetric reaction.

In order to study the catalytic activity of the bicyclononadiene complex, we have prepared racemic Ru(acac)$_2$-(cyclic diene) (**3**)[15] [cyclic diene = bicyclo[3.3.1]nona-2,6-diene (bnd) (**3a**), 2-methylbicyclo[3.3.1]nona-2,6-diene (Me-bnd) (**3b**),[16] 2,6-dimethylbicyclo[3.3.1]nona-2,6-diene (Me$_2$-bnd) (**3c**), and 9-oxabicyclo[3.3.1]nona-2,6-diene (oxa-bnd) (**3d**)] by a modification of the literature method. Ru(η^6-naphthalene)(cyclic diene)s (**1a**−**d**) were prepared from **3a**−**d** similarly to **2** in moderate yields (Scheme 1).[17]

Scheme 1. Synthesis of Ru(0)−Bicyclononadiene Complexes



Compounds **1a**−**d** were characterized by ^{1}H NMR, ^{1}H−^{1}H COSY, ^{13}C NMR, and ^{13}C−^{1}H HETCOR spectra, IR spectra, and elemental, analysis and **1a**−**c** were also characterized by the X-ray analysis.

The catalytic cross-dimerizations between MMA and substituted alkenes are listed in Table 1. Complex **1a** (1 mol %) showed quite high catalytic activity toward the cross-dimerization between MMA and 2,5-dihydrofuran, the product being formed in 85% yield (**4a**/**4b**/**4c** = 17/76/7) at 0 °C for 4 h under solvent-free conditions. In contrast, complex **2** gives almost exclusively compound **4c** (Table 1, entries 2 and 1).[7e] The Me−bnd complex **1b** was also displayed high product selectivity, although the catalytic activity is slightly lower (entry 3). The catalytic activity is further diminished for the Me$_2$−bnd complex **1c** (entry 4). In contrast to **1a**−**c**, the oxa−bnd analogue **1d** produced mainly **4c** (entry 5). We also found norbornene and trimethoxyvinylsilane to be good coupling partners with MMA. The cross-dimerization between MMA and norbornene catalyzed by **1a** or **1d** produced **5b** in high yield with *E* and exclusive *exo* selectivities (entries 7, 10). These cross-dimerizations using MMA are unprecedented, although there are a few reports of cross-dimerization between acrylates and substituted alkenes.[18] The cross-dimerization between MMA and trimethoxyvinylsilane dominantly produced the tail-to-tail cross-dimer **6a** by **1a** with high regio- and *E*-selectivities (entry 12). These results

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(15) Compounds **3a**, **3b**, and **3d** were observed as a mixture of diastereomers. Compound **3c** was observed as a single diastereomer *rac*-Δ-Ru(acac)$_2$((*S*,*S*)-Me$_2$-bnd).

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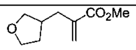
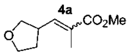
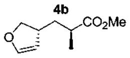
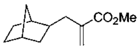
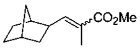
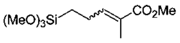
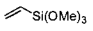
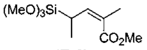
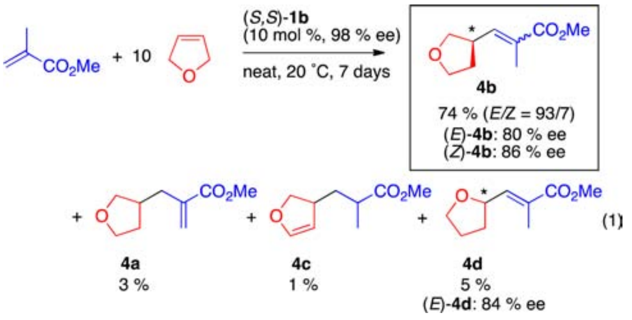
Table 1. Catalytic Cross-Dimerization of MMA with Substituted Alkenes[a],[b],[e]

entry	conditions				alkene	product		
	catalyst	mol %	temp °C	time h			yield[c] %	ratio[c]
								(**4a**/*E*-**4b**/*Z*-**4b**/**4c**)
1	**2**	5	0	24		**4a**	87	(6/ 2/ 0/92)
2	**1a**	1	0	4			85	(17/52/24/ 7)
3	**1b**	5	50	24		**4b**	37	(2/90/ 6/ 2)
4	**1c**	5	50	24			2	(0/100/ 0/ 0)
5	**1d**	1	0	24		*rac*-(2*S*,3′*R*)-**4c**	74	(18/ 2/ 1/79)
								(**5a**/*E*-**5b**/*Z*-**5b**)
6	**2**	5	30	2			83	(3/70/27)
7	**1a**	2	30	6		**5a**	95	(1/97/ 2)
8	**1b**	5	50	24			56	(6/89/ 5)
9	**1c**	5	50	24			3	(11/44/45)
10	**1d**	5	30	2		**5b**	90	(2/ 92/ 6)
								(*E*-**6a**/*Z*-**6a**/*Z*-**6b**)[d]
11	**2**	5	30	24			75	(15/37/48)
12	**1a**	5	30	4		**6a**	91	(87/ 5/ 8)
13	**1b**	5	50	24			15	(48/45/ 7)
14	**1c**	5	50	24			3	(70/21/ 9)
15	**1d**	5	30	8		(*Z*)-**6b**	70	(50/25/25)

[a] Typical conditions: MMA (2.54 mmol), 2,5-dihydrofuran (2−5 equiv vs MMA), cat. (1 or 5 mol % vs MMA), neat. (entries 1−5); MMA (1.04 mmol), alkene (1.2−5 equiv vs. MMA), cat. (2 or 5 mol %), THF, 2 mL (entries 6−10); MMA (0.52 mmol), alkene (2 equiv vs MMA), cat. (5 mol %), THF, 1 mL (entries 11−15). [b] Yields are estimated on the basis of MMA. [c] Determined by GLC. [d] A negligible amount of *E*-**6b** was observed. [e] In these reactions, small amounts of trimers (cross dimers between **4a** or **5a** and alkene) were observed.

point to the possibility of chiral induction if chiral bicyclononadienes are introduced into the catalyst. The ligands (*S*,*S*)-bnd and (*S*,*S*)-Me−bnd were obtained by the kinetic resolution of bicyclo[3.3.1]nonane-2,6-dione[13] and the corresponding chiral naphthalene complexes (*S*,*S*)-**1a** and (*S*,*S*)-**1b** were successfully prepared in 59% and 43% yields, respectively. The chiral catalyst (*S*,*S*)-**1b** (10 mol %) in the cross-dimerization between MMA and 2,5-dihydrofuran at 20 °C for 7 days under solvent-free conditions provided colorless oil consisting of cross-dimers in 83% total yield (eq 1).[19] Compound **4b** was dominantly obtained in 74% yield (E/Z = 93/7) and 80% ee for (*E*)-**4b**, which was determined by chiral HPLC.[20] This is the first asymmetric cross-dimerization between substituted alkenes. Note that **4b** was formed always as dominant product, suggesting direct formation of **4b** by the coupling reaction. In contrast, there was no asymmetric induction in the presence of (*S*,*S*)-**1a**. (*E*)-**4b** was isolated by silica gel column chromatography (hexane/ethyl acetate = 5/1 (v/v)) and its optical rotation was determined to be $[\alpha]^{20}_{D}$ = −13.7 (c = 0.59, 80% ee, $CHCl_3$); the absolute configuration can be determined to be (*R*).[21] The present results are consistent with the catalytic cycle shown in Scheme 2. After displacement of the 6e naphthalene ligand, MMA and 2,5-dihydrofuran coordinate as 4e and 2e donors, respectively. This is the origin of the chemoselectivity for this cross-dimerization. Then an oxidative coupling reaction followed by the β-hydride elimination and reductive elimination release the final coupling product. Note that a ruthenacyclopentane was isolated in the related example, suggesting an oxidative coupling mechanism for the present system.[9,22]



(1)

Since no asymmetric induction took place at all when (*S*,*S*)-**1a** was employed in this reaction, the Me group in

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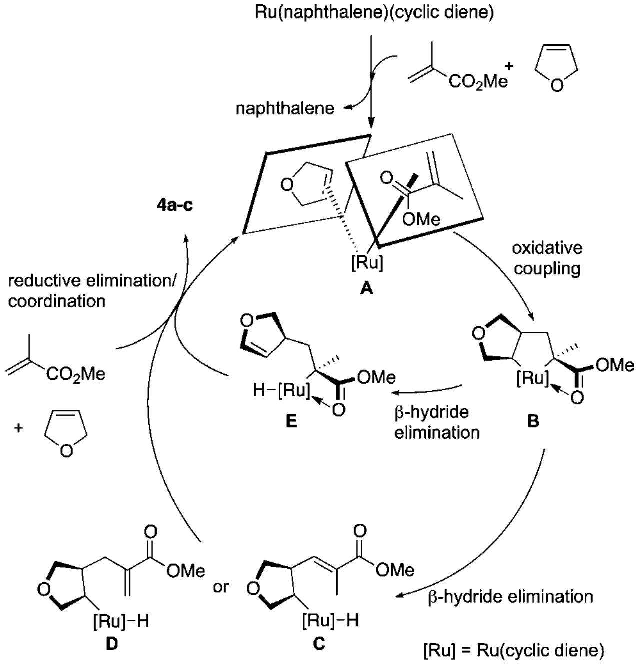
(19) The formation mechanism for **4d** is not clear to date. One of the possible pathways is prior isomerization of 2,5-dihydrofuran to 2,3-dihydrofuran followed by the coupling with MMA.

(20) The yield decreased to 48% ((S,S)-**1b**: 5 mol%, **4a**/*E*-**4b**/*Z*-**4b**/**4c** = 2/90/6/2) by the reaction at 50 °C: (*E*)-**4b** = 73% ee. No asymmetric induction was observed when norbornene was used as a coupling partner.

(21) (−)-(*E*)-**4b** was derivatized to the corresponding 2-naphthyl ester as a pure crystalline (*E*)-form, which was converted into the known optically active methyl tetrahydro-3-furanoate (**7**) ($[\alpha]^{18}_{D}$ = −20.3, c = 0.12, 84% ee, MeOH) by ozonolysis. By comparison of this data to the literature, we can determined the absolute configuration of (−)-(*E*)-**4b** to be (*R*): Horiuchi, T.; Ohta, T.; Shirakawa, E.; Nozaki, K.; Takaya, H. *J. Org. Chem.* **1997**, *62*, 4285.

(22) We believe alternative Alder−ene-type reaction starting from insertion of an alkene into a hydrido complex is ruled out because such a process gives a different product for the related reaction of ethyl acrylate with 2,5-dihydrofuran; see ref 7e.

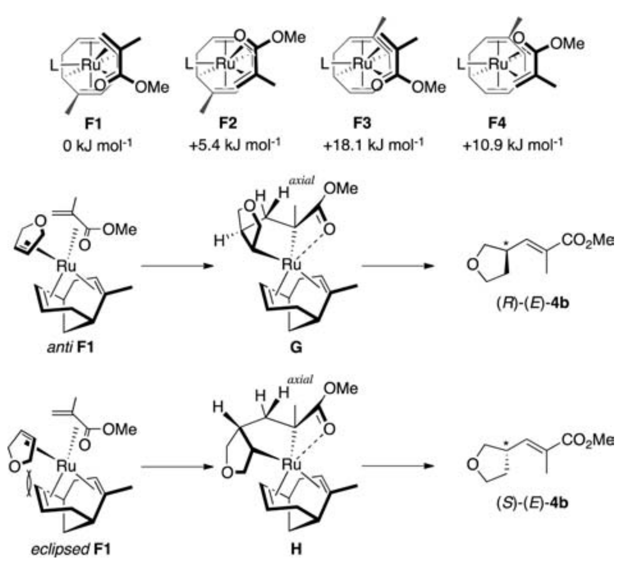
Scheme 2. Possible Catalytic Cycle



Me–bnd must play a key role in controlling the stereochemistry. The consistent mechanism for the asymmetric induction can be explained as follows. The DFT calculations show that a MMA molecule preferentially coordinates by the *si* face at the Ru(0) center to avoid repulsion between the methylene group in MMA and the Me group in Me–bnd ligand (Scheme 3, **F1**, L = MeCN). If 2,5-dihydrofuran coordinates to the Ru(0) as L in **F1**, the enantioselectivity is determined by the conformation of the coordinating 2,5-dihydrofuran.

Because there are no appropriate terms for such rotamers, we have tentatively defined the two rotamers of 2,5-dihydrofuran, whose C=C bond is assumed to be coplanar with that of MMA as *anti* and *eclipsed* **F1** with respect to the Me–bnd ligand. The *anti* rotamer, *anti* **F1** is 7.8 kJ mol^{-1} more stable than the *eclipsed* one according to DFT calculations. An oxidative coupling reaction takes place from *anti* **F1** to give a ruthenacyclopentane **G** followed by a sequence of axial β-hydride elimination from the methylene group in **G** and subsequent by reductive elimination, thus giving (*R*)-(*E*)-**4b** directly (Scheme 3).

Scheme 3. Relative Stability for the Coordinated MMA at Ru(0) by DFT Calculations and the Rotamers of 2,5-Dihydrofuran



In summary, we have reported a series of new Ru(η^6-naphthalene)(η^4-bicyclononadiene) complexes and used them to catalyze the linear cross-dimerization of substituted alkenes. Unsaturated compounds containing an asymmetric center are readily accessible from simple substituted alkenes through an efficient asymmetric oxidative coupling.

Acknowledgment. We are grateful to Prof. M. A. Bennett (ANU) for helpful discussions. We also thank Ms. S. Kiyota (TUAT) for elemental analysis and Prof. T. Takeda (TUAT) for ozonolysis of **4b**. We thank Daicel Co. for supporting the chiral HPLC measurements. We thank JST ACT-C and MEXT for financial support.

Supporting Information Available. Text, tables, and figures giving full experimental details involving the characterizations of **1a**–**d**, **3a**–**d**, **4b**, **5a**,**b**, and **6a**,**b**, X-ray data for **1a**–**c** and **3a**–**d**, and DFT calculations. This material is available free of charge via the Internet at http://pubs.acs.org.
