Molybdenum-Catalyzed Ring-Closing Metathesis of Allenynes

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ABSTRACT

A ring-closing metathesis reaction of allenynes occurred at room temperature in the presence of a molybdenum alkylidene complex to give ring-closed vinylallenes. The vinylallene skeletons were constructed by a metathesis-type reaction between the alkyne moiety and the proximal carbon–carbon double bond of the allene moiety.

Ring-closing metathesis (RCM) reactions have rapidly become one of the most versatile and efficient methods for constructing carbo- and heterocyclic compounds.^{1,2} They have been widely employed as a key step in a number of natural product syntheses to install cyclic structure. The molybdenum imido alkylidene complex **1** (Schrock catalyst)³ and the ruthenium benzylidene complex **2** (second-generation Grubbs catalyst)⁴ are the most commonly used catalysts beacuse of their high catalytic activities and their tolerance of a range of functional groups (Figure 1).



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While a variety of cross-metathesis reactions between alkenes and alkynes (enyne metathesis) have been reported,^{1,5} there has been only one example of metathesis that involves allenes; 1,3-disubstituted allenes are formed by a ruthenium-catalyzed metathesis of monosubstituted allenes.⁶ Herein, we report a molybdenum-catalyzed RCM reaction of allenynes⁷ producing allenyl-substituted cyclic alkenes.

Allenyne 3a was treated with complex 1 (15 mol %) in

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toluene⁸ at room temperature for 3 h. Metathesis between the alkyne and the proximal carbon–carbon double bond of the allene moiety took place to afford five-membered ring product **4a** with an allene side chain in 71% yield (eq 1).⁹ Surprisingly, only the Schrock catalyst **1** successfully mediated the reaction of **3**. Grubbs catalyst **2**, which has been most often employed in enyne metathesis reactions,⁵ gave a complex mixture of products.¹⁰



When allenyne **3a**-*d* with the alkyne terminus deuterated (>90% D) was used, the deuterium was labeled at the 1-position of the produced allene (>82% D) (eq 2).



Next, a crossover reaction using a mixture of 3b (1.00 equiv) and 3c (1.00 equiv) was carried out in the presence of complex 1 (0.20 equiv) (Scheme 1). Crossover products



4a (0.23 equiv) and **4d** (0.22 equiv) were obtained together with products **4b** (0.48 equiv) and **4c** (0.72 equiv).

There are two mechanisms, A and B, conceivable for the formation of **4** from **3**. In mechanism A (Scheme 2), molyb-



denum vinylidene species $D^{11,12}$ is initially generated from the alkylidene complex 1 and allenyne 3; a molybdacyclobutene A is formed by [2 + 2] cycloaddition of 1 with the alkyne moiety of 3.¹³ Electrocyclic ring-opening affords vinylcarbene species B, which undergoes intramolecular [2 + 2] cycloaddition with the proximal allenic carbon–carbon double bond. A resulting methylenemolybdacyclobutane C splits into the molybdenum vinylidene species D and a 1,3diene E by retro [2 + 2] cycloaddition. The species D thus formed turns over the catalytic cycle by following a sequence analogous to that through A, B, and C, i.e., via [2 + 2] cycloaddition forming F, electrocyclic ring-opening giving G, intramolecular [2 + 2] cycloaddition forming H, and finally retro [2 + 2] cycloaddition affording the product 4 and D.

Alternatively, mechanism B, which does not involve molybdenum vinylidene species **D**, also explains the forma-

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⁽⁸⁾ Unsatisfactory results were obtained with other solvents such as 1,2dimethoxyethane (no reaction) and CH_2Cl_2 (12% yield).

⁽⁹⁾ Intermolecular cross-metathesis of terminal alkynes with allenes has so far failed with the catalysis of **1**; the alkynes were completely consumed, whereas the allenes remained unchanged.

⁽¹⁰⁾ No RCM occurred at room temperature when other Ru complexes such as $(PCy_3)_2Cl_2Ru=CHPh$ and $(PCy_3)_2Cl_2Ru=CHPh$ were used as the catalyst.

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⁽¹³⁾ For a theoretical study on [2 + 2] cycloaddition of Mo alkylidene with alkyne and ring-opening of molybdacyclobutene, see: Sheng, Y.; Wu, Y.-D.; Leszczynski, J. *Organometallics* **2004**, *23*, 3189.



tion of 4 (Scheme 3). The initial [2 + 2] cycloaddition of the molybdenum alkylidene complex 1 with the proximal allenic carbon-carbon double bond of 3 forms molybdenum alkylidene species J and an allene K. Then, intramolecular [2 + 2] cycloaddition with the alkyne moiety and ringopening follow to give a new Mo alkylidene species M, which reacts with another allenyne 3 to afford 4.

We carried out a stoichiometric reaction of **3** with **1** in order to get further mechanistic insights. Diene **5** was isolated (9%) in addition to **4a** (69%) (eq 3). The formation of the diene **5**, albeit the yield is low, is explained by assuming mechanism A rather than mechanism B. These product yields of **5** and **4a** suggest that the reaction of vinylidene complex **D** with **3** occurs much faster than the reaction of alkylidene complex **1** with **3**. A considerable amount of the catalyst precursor **1** remained unchanged.¹⁴ Thus, we at this stage with these results favor mechanism A although further experimental studies are desired for discussion in more detail.

Other examples of the allenyne RCM are listed in Table 1. Allenynes 3a,b,e-h having tosylamine in a tether were successfully transformed into the corresponding vinylallenes in a range of 68-84% yields (entries 1-6). *N*-Benzyl derivative **3i** also afforded the product **4i** in 73% yield (entry 7). Malonate derivatives **3c** and **3j** were excellent substrates for this reaction and led to nearly quantitative yield (entries 8 and 9). The product **4c** was isolated in 88% yield even with a lower catalyst loading (7.5 mol %), although it required a longer reaction time. Allenyne **3k** with the allenic terminus monosubstituted also participated in the RCM but with less efficiency, giving a mixture of vinylallene **4k** (26%) and diene **5** (13%) (entry 10).

The reactions using substrates listed in Figure 2 were unsuccessful under the conditions described here, showing the limitations of the metathesis reaction. No reaction occurred with allenyne **31** with the allenic terminus unsubstituted. Allenyne **3m** bearing an ether linkage failed to





		allenyne					product	
entry	3	Z	\mathbb{R}^1	\mathbb{R}^2	\mathbb{R}^3	4	% yield ^b	
1	3a	TsN	Н	Me	Me	4a	71^c	
2	3b	TsN	Η	Me	\mathbf{Et}	4b	84	
3	3e	TsN	Η	-(CI)	$(H_2)_5 -$	4e	81	
4	3f	TsN	н	i-Pr	i-Pr	4f	76	
5	3g	TsN	Me	Me	Me	4g	68	
6	3h	TsN	Η	Me	\mathbf{Ph}	4h	84	
7	3i	BnN	Η	Me	Me	4i	73	
8	3c	$(MeO_2C)_2C$	\mathbf{H}	Me	Me	4c	$96(88^d)$	
9	3j	$(EtO_2C)_2C$	Η	Me	Me	4j	95	
10	3k	TsN	Η	\mathbf{Me}	н	4k	26^e	

^{*a*} Allenyne **3** was stirred in toluene (0.02 M) in the presence of **1** (15 mol %) at room temperature for 3 h unless otherwise noted. ^{*b*} Isolated yield by preparative TLC. ^{*c*} Result with 20 mol % of **1** for 20 min. ^{*d*} Result with 7.5 mol % of **1** for 9 h. ^{*e*} Obtained as a mixture of **4k** (26%) and **5** (13%).

undergo the RCM, presumably because of coordination of the ether oxygen to the Mo center. Methyl-substituted allenyne 3n gave a complex mixture that included the desired product in low yield (<40%), and the phenyl-substituted 3o was unreactive. Attempts to form a six-membered ring by RCM of 3p and 3q were also unsuccessful.



Vinylallenes thus obtained can be used as a 1,3-diene in the Diels–Alder reaction.¹⁵ The reaction of vinylallene **4c** with maleic anhydride in toluene at room temperature furnished cycloadduct **6** as a single diastereomer in 70% yield presumably via an *endo* transition state (eq 4).¹⁶



In conclusion, we have achieved the first RCM of allenynes producing vinylallenes by the use of molybdenum imido alkylidene complex **1**.

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Supporting Information Available: Experimental details and spectral data for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org. OL0514348

⁽¹⁴⁾ Such a phenomenon is often observed in Ru-catalyzed metathesis reaction. For a recent example, see ref 5b.

⁽¹⁵⁾ Murakami, M.; Matsuda, T. In *Modern Allene Chemistry*; Krause, N., Hashmi, A. S. K., Eds.; Wiley-VCH: Weinheim, 2004; Vol. 2, p 727.

⁽¹⁶⁾ The stereochemistry was assigned by analogy to a similar reaction. Regás, D.; Afonso, M. M.; Rodríguez, M. L.; Palenzuela, J. A. J. Org. Chem. 2003, 68, 7845.