Highly Active Trialkoxymolybdenum(VI) Alkylidyne Catalysts Synthesized by a Reductive Recycle Strategy

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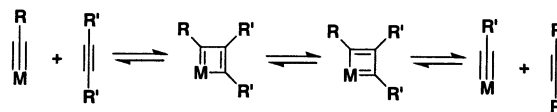
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Abstract: A systematic study of alkyne metathesis catalyzed by trialkoxymolybdenum(VI) alkylidyne complexes is reported, in which substrate functional groups, alkynyl substituents, and catalyst ligands are varied. Sterically hindered trisamidomolybdenum(VI) propylidyne complex **5** was prepared conveniently through a previously communicated reductive recycle strategy. Alcoholysis of **5** with various phenols/alcohols provides a set of active catalysts for alkyne metathesis at room temperature, among which the catalyst with *p*-nitrophenol as ligand shows the highest catalytic activity and is compatible with a variety of functional groups and solvents. A key finding that enabled the use of highly active molybdenum(VI) catalysts is replacement of the commonly used propynyl substituents on the starting alkyne substrates with butynyl groups. Under reduced pressure using 1,2,4-trichlorobenzene as an involatile solvent, the alkyne metathesis of butynyl substituted compounds proceeds well at 30 °C providing high yields (83%−97%) of dimers. Rationalization of the special role played by butynyl substrates is discussed.

Introduction

Despite the tremendous impact of alkene metathesis on organic synthesis and polymer chemistry over the past decade,[1] the analogous alkyne metathesis reaction is a less developed synthetic method. This appears to be changing, given the recent advances in alkyne metathesis catalysts.[2] For alkyne metathesis, two possible mechanistic pathways must be considered: the alkylidyne mechanism[3] and the metallacycle mechanism.[4] In the alkylidyne mechanism (Scheme 1), metallacyclobutadienes

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(1) For reviews, see: (a) Trnka, T. M.; Grubbs, R. H. *Acc. Chem. Res.* **2001**, *34*, 18−29. (b) Fürstner, A. *Angew. Chem., Int. Ed.* **2000**, *39*, 3012−3043. (c) Grubbs, R. H.; Chang, S. *Tetrahedron* **1998**, *54*, 4413−4450. (d) Schuster, M.; Blechert, S. *Angew. Chem., Int. Ed.* **1997**, *36*, 2037−2056. (e) Fürstner, A. *Top. Catal.* **1997**, *4*, 285−299. (f) Maier, M. E. *Angew. Chem., Int. Ed.* **2000**, *39*, 2073−2077. (g) Schrock, R. R. *Tetrahedron* **1999**, *55*, 8141−8153. (h) Schrock, R. R.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2003**, *42*, 4592−4633.

(2) For natural product synthesis, see: (a) Fürstner, A.; Guth, O.; Rumbo, A.; Seidel, G. *J. Am. Chem. Soc.* **1999**, *121*, 11108−11113. (b) Fürstner, A.; Rumbo, A. *J. Org. Chem.* **2000**, *65*, 2608−2611. (c) Fürstner, A.; Grela, K.; Mathes, C.; Lehmann, C. W. *J. Am. Chem. Soc.* **2000**, *122*, 11799−11805. (d) Fürstner, A.; Radkowski, J.; Writz, C.; Mynott, R. *J. Org. Chem.* **2000**, *65*, 8758−8762. (e) Fürstner, A.; Mathes, C.; Lehmann, C. W. *Chem.—Eur. J.* **2001**, *7*, 5299−5317. (f) Fürstner, A.; Castanet, A.-S.; Radkowski, K.; Lehmann, C. W. *J. Org. Chem.* **2003**, *68*, 1521−1528. (g) Fürstner, A.; Dierkes, T. *Org. Lett.* **2000**, *2*, 2463−2465. (h) Fürstner, A.; Mathes, C.; Grela, K. *Chem. Commun.* **2001**, *12*, 1057−1059. (i) Fürstner, A.; Stelzer, F.; Rumbo, A.; Krause, H. *Chem.—Eur. J.* **2002**, *8*, 1856−1871. For polymer synthesis, see: (j) Weiss, K.; Michel, A.; Auth, E.-M.; Bunz, U. H. F.; Mangel, T.; Mullen, L. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 506−509. (k) Kloppenburg, L.; Song, D.; Bunz, U. H. F. *J. Am. Chem. Soc.* **1998**, *120*, 7973−7974. (l) Bunz, U. H. F. *Acc. Chem. Res.* **2001**, *34*, 998−1010.

(3) The alkylidyne mechanism was proposed by Katz and experimentally established by Schrock; see: (a) Katz, T. J.; McGinnis, J. *J. Am. Chem. Soc.* **1975**, *97*, 1592−1594. (b) Wengrovius, J. H.; Sancho, J.; Schrock, R. R. *J. Am. Chem. Soc.* **1981**, *103*, 3932−3934. (c) Bencheick, A.; Petit, M.; Mortreux, A.; Petit, F. *J. Mol. Catal.* **1982**, *15*, 93−101.

(4) (a) Kerschner, J. L.; Fanwick, P. E.; Rothwell, I. P. *J. Am. Chem. Soc.* **1988**, *110*, 8235−8238. (b) Kaneta, N.; Hirai, T.; Mori, M. *Chem. Lett.* **1995**, 627−628.

Scheme 1. Alkylidyne Mechanism of Alkyne Metathesis

Scheme 2 Metallacycle Mechanism of Alkyne Metathesis
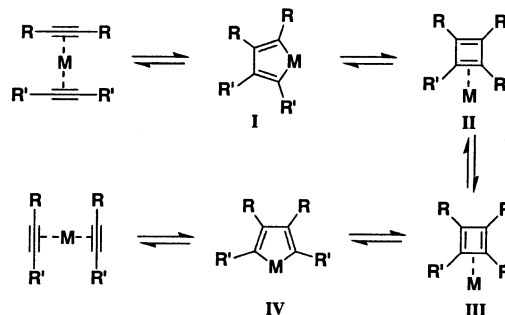
are initially formed from acetylenes and alkylidyne complexes in much the same way that metallacyclobutanes are formed from olefins and metal alkylidenes complexes.[1a] Following isomerization and ring opening steps, the metathesis product is formed. In the metallacycle mechanism (Scheme 2), metallacyclopentadienes are first formed through oxidative coupling. Reductive elimination then affords metal complex **II**, coordinated to cyclobutadiene. Isomerization of the cyclobutadiene complex to **III** followed by oxidative addition gives the metal complex **IV**, which is a regio isomer of metallacyclobutadiene **I**. From complex **IV**, metathesis products are formed upon cycloreversion.

The application of alkyne metathesis is impeded by the availability and performance of the alkyne metathesis catalysts, especially with regard to convenience of catalyst synthesis,

substrate compatibility, and temperature required for catalytic activity. The catalysts that have been most widely used for natural product synthesis and preparations of phenylene ethynylene polymers are based on molybdenum or tungsten complexes.[2] The most readily available of these catalysts is a poorly characterized species.[5] High temperature (≥ 130 °C) is required for metathesis activity, and limited functional group tolerance is exhibited. In a preliminary communication, we reported a reductive recycle strategy for the convenient synthesis of alkyne metathesis catalysts having activity at room temperature.[6] In this paper, systematic studies on the scope and limitations of these trialkoxymolybdenum(VI) alkylidyne complexes are reported. Most importantly, for internal alkynes unsymmetrically substituted with an alkyl and an aryl substituent, we have found that the metathesis activity depends significantly on the structure of the alkyl substituent. The origin of the reactivity difference of substrates with various alkynyl substituents is discussed.

Results

Recently Fürstner reported that the combination of readily available[7] Mo[N(*t*-Bu)Ar]$_3$ (Ar = 3,5-C$_6$H$_3$Me$_2$) with methylene chloride provides a mixture of ClMo[N(*t*-Bu)Ar]$_3$ (**2**) and HCMo[N(*t*-Bu)Ar]$_3$ (**3**) (eq 1).[8] Upon examing various reducing


(eq 1)
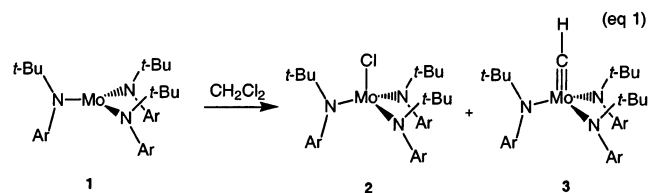
Reductive recycle appoach to Mo(VI) alkylidyne complexes.

(eq 2)
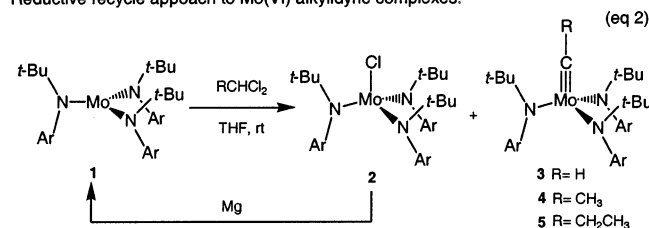
agents,[9] we found that magnesium is able to selectively react

with monochloride **2** returning it to starting complex **1**, while leaving complex **3** unaffected. In the presence of excess methylene chloride, the net result is a reductive recycle approach to selectively generate complex **3** in one pot (eq 2). Through this strategy, trisamidomolybdenum(VI) ethylidyne **4** and propylidyne **5** were prepared in high yield and purity by the treatment of triamide **1** with 1,1-dichloroethane (15 equiv) or 1,1-dichloropropane (2 equiv), respectively, in the presence of magnesium.[10] The X-ray crystal structure[6] of propylidyne **5** revealed a characteristic Mo−C triple bond distance of 1.735(2) Å,[11] in accordance with the observed ^{13}C NMR chemical shift of 302.6 ppm for the carbyne carbon. The X-ray analysis of **5** also showed the close packing of the amido ligands on one side of the molybdenum atom with the aryl rings adopting approximately C_3 symmetry. Alcoholysis of complex **5** with 3 equiv of phenol (e.g., α,α,α-trifluoro-*o*-cresol) or alcohol (e.g., perfluoro-*tert*-butyl alcohol) generated a catalytically active species, presumed to be trialkoxymolybdenum(VI) propylidyne, which was then directly applied to metathesis studies.[12]

Using amide **6** as the substrate (eq 3), the metathesis reaction with complex **5** and α,α,α-trifluoro-*o*-cresol was conducted in various solvents at room temperature in order to survey the dependence of catalytic activity on solvent. Com-

(eq 3)
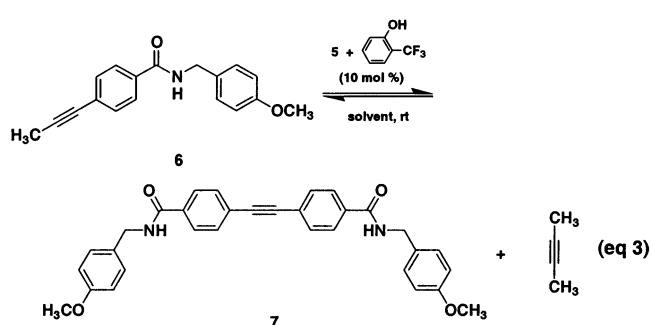
pound **6** was selected because it represented a moderately functionalized substrate. Reactions performed in chloroform and toluene produced nearly quantitative yields of dimer **7** in about 30 min. Precipitation of **7** drove the reaction to completion. Clearly the secondary amide functionality of **6** did not interfere with catalyst activity. In acetonitrile or tetrahydrofuran, the reaction was slower but still proceeded to 76% conversion within 8 h at room temperature. However, when the reaction was conducted in acetone, only 40% conversion was achieved, accompanied by catalyst decomposition as evidenced by the formation of a black precipitate. No dimer was formed in *N,N*-dimethylformamide or methanol. Metathesis of 3-propynyl

(5) (a) Mortreux, A.; Blanchard, M. *J. Chem. Soc., Chem. Commun.* **1974**, 786−787. (b) Kaneta, N.; Hirai, T.; Mori, M. *Chem. Lett.* **1995**, 1055−1056. (c) Vosloo, H. C. M.; du Plessis, J. A. K. *J. Mol. Catal. A: Chem.* **1998**, *133*, 205−211. (d) Recently, Grela reported the use of 2-fluorophenol as a cocatalyst with Mo(CO)$_6$ that is simple and of wider applicability. See: Grela, K.; Ignatowska, J. *Org. Lett.* **2002**, *4*, 3747−3749.
(6) Zhang, W.; Kraft, S.; Moore, J. S. *Chem. Commun.* **2003**, 832−833.
(7) Complex **1** is synthesized in four steps from commercially available MoCl$_5$. Cummins discovered and pioneered the synthesis and study of Mo[N(*t*-Bu)Ar]$_3$; see: (a) Laplaza, C. E.; Odom, A. L.; Davis, W. M.; Cummins, C. C.; Protasiewicz, J. D. *J. Am. Chem. Soc.* **1995**, *117*, 4999−5000. (b) Cummins, C. C. *Chem. Commun.* **1998**, 1777−1786. (c) Johnson, A. R.; Cummins, C. C.; Gambarotta, S. *Inorg. Synth.* **1998**, *32*, 123−132. (d) Tsai, Y.-C.; Stephens, F. H.; Meyer, K.; Mendiratta, A.; Gheorghiu, M. D.; Cummins, C. C. *Organometallics* **2003**, *22*, 2902−2913. Poli developed a convenient synthesis of MoCl$_3$(thf)$_3$; see: (e) Stoffelbach, F.; Saurenz, D.; Poli, R. *Eur. J. Inorg. Chem.* **2001**, 2699−2703.
(8) Fürstner, A.; Mathes, C.; Lehmann, C. W. *J. Am. Chem. Soc.* **1999**, *121*, 9453−9454.
(9) Several combinations of reducing agents and solvent were examined, but magnesium in THF is the most effective. A zinc−copper couple, manganese, and samarium slowly produced **3** at 50 °C, but unknown side products also formed. At 70 °C, monochloride **2** decomposed quickly which makes the reductive recycle strategy not applicable at high temperature. Also see ref 6.

(10) Triamide **1** was treated with 2 equiv of 1,1-dichloropropane instead of 15 equiv in order to minimize a side product which presumably arises from a Grignard reaction. Also see ref 6.
(11) (a) McCullough, L. G.; Schrock, R. R. *J. Am. Chem. Soc.* **1984**, *106*, 4067−4068. (b) McCullough, L. G.; Schrock, R. R.; Dewan, J. C.; Murdzek, J. C. *J. Am. Chem. Soc.* **1985**, *107*, 5987−5998. (c) Murdzek, J. S.; Schrock, R. R. *Carbyne Complexes*; VCH: New York, 1988. (d) Tsai, Y.-C.; Diaconescu, P. L.; Cummins, C. C. *Organometallics* **2000**, *19*, 5260−5262. (e) Blackwell, J. M.; Figueroa, J. S.; Stephens, F. H.; Cummins, C. C. *Organometallics* **2003**, *22*, 3351−3353.
(12) The isolation of pure trialkoxymolybdenum(VI) catalyst was unsuccessful, and the attempts to acquire MS and elemental analysis data for α,α,α-trifluoro-*p*-cresol Mo(VI) propylidyne and *p*-nitrophenol catalyst failed. α,α,α-Trifluoro-*p*-cresol Mo(VI) propylidyne was characterized by ^{1}H, ^{13}C, and ^{19}F NMR. See Supporting Information.

Table 1. Homodimerization of Monopropynyl Substrates

entry	Substrate	Product	Yield(%)[a] closed system	Yield(%)[b] with butyne removal
a	NC—⟨⟩—≡—CH₃	NC—⟨⟩—≡—⟨⟩—CN	15	37
b	F₃C—⟨⟩—≡—CH₃	F₃C—⟨⟩—≡—⟨⟩—CF₃	17	51
c	OHC—⟨⟩—≡—CH₃	OHC—⟨⟩—≡—⟨⟩—CHO	16	47
d	H₃CO—⟨⟩—≡—CH₃	H₃CO—⟨⟩—≡—⟨⟩—OCH₃	40	83
e	(H₃C)₂N—⟨⟩—≡—CH₃	(H₃C)₂N—⟨⟩—≡—⟨⟩—N(CH₃)₂	49	76
f	thienyl—≡—CH₃	thienyl—≡—thienyl	<5	<5
g	R'HNOC—⟨⟩—≡—CH₃[c]	R'HNOC—⟨⟩—≡—⟨⟩—CONHR'	>99	>99

[a] Closed system, d_8-toluene, 30 °C, yield based on NMR spectral analysis, ferrocene as internal standard, mass balance > 95%. [b] Dynamic vacuum (open driven conditions), solvent 1,2,4-trichlorobenzene, 30 °C, 22 h, 1 mm Hg, yield based on isolated purified product. [c] R' = $-CH_2CH_2OCH_3$.
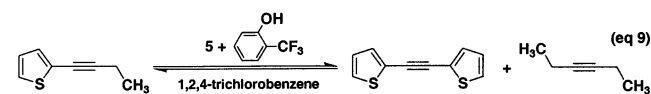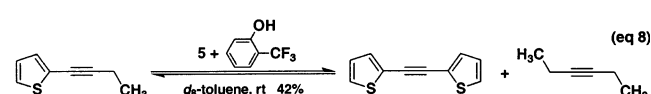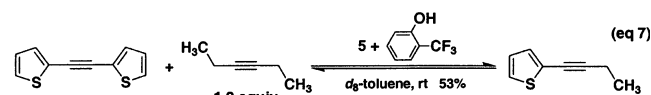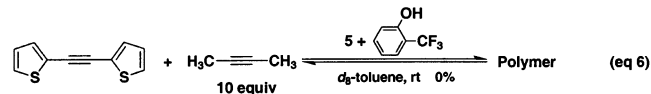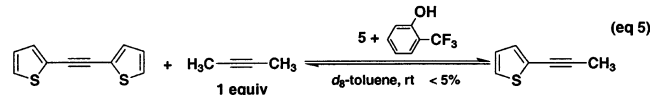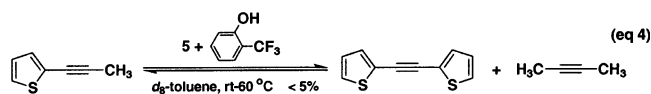
benzoate ester **8** in various solvents displayed similar reactivity trends.
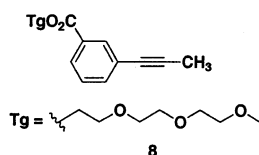
Next, we examined the substrate scope of this catalyst. Compounds **9a**−**g** were synthesized using either Negishi[13] or Sonogashira[14] cross-coupling reactions. Alkyne metathesis was performed either in a sealed NMR tube or in a round-bottomed flask under reduced pressure.[15] In a closed system, yields of soluble dimer products ranged from 15% to 49%, while, under reduced pressure, the metathesis reactions could be driven significantly further (37−83%) as shown in Table 1. The increased yields observed for **9a**−**e** when reduced pressure was applied presumably resulted from equilibrium shifting due to removing 2-butyne from the reaction mixture. We chose 1,2,4-trichlorobenzene as a high boiling point solvent for this purpose. It should be noted that, for the alkyne metathesis of amide containing substrate **9g**, a precipitate formed in 2 min after mixing the catalyst and the substrate. Nearly quantitative conversion was achieved within 30 min, due to the insolubility

(13) (a) King, A. O.; Okukado, N.; Negishi, E. *J. Chem. Soc., Chem. Commun.* **1977**, 683−684. (b) King, A. O.; Negishi, E.; Villani, F. J., Jr.; Silveira, A., Jr. *J. Org. Chem.* **1978**, *43*, 358−360. (c) Negishi, E. *Acc. Chem. Res.* **1982**, *15*, 340−348.
(14) (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467−4470. (b) Sonogashira, K.; Yatake, T.; Tohda, Y.; Takahashi, S.; Hagihara, N. *J. Chem. Soc., Chem. Commun.* **1977**, 291−292. (c) Sonogashira, K. In *Handbook of Organopalladium Chemistry for Organic Synthesis*; Negishi, E., Ed.; Wiley-Interscience: New York, 2002; pp 493−529.
(15) Vacuum conditions have been used for alkene/alkyne metathesis polymerization. See: Wagener, K. B.; Boncella, J. M.; Nell, J. G.; Duttweiler, R. P.; Hillmyer, M. A. *Makromol. Chem.* **1990**, *191*, 365−374 and ref 2j.

of the diamidophenyl acetylene product, which, as in the case of **6**, presented an alternative approach for shifting the metathesis equilibrium.

Our first attempt at synthesizing dimer **10f** (eq 4) from 2-propynylthiophene was unsuccessful (Table 1). This result is consistent with other reports[16] of failed metathesis dimerizations with thiophene derivatives. To rule out a thermodynamic bias for starting material **9f**, we also studied the metathesis reaction starting from the dimer and 2-butyne by ¹H NMR (eq 5). When

a mixture of dimer **10f** and 1 equiv of 2-butyne was treated with the molybdenum(VI) catalyst, only a trace amount of the

Table 2. Homodimerization of Monoalkynyl Substrates

entry	a	b	c	d
R	⌇—	⌇⁄	⌇⟨	⌇⟨
Yield(%)[a]	15	28	22	0

[a] Closed system, d_8-toluene, 20 °C, yield based on NMR spectral analysis.

cross alkyne metathesis product was observed. Even in the presence of 10-fold excess of 2-butyne, no further conversion was achieved. However, we suspected that butyne was polymerized under these conditions (presumably to a polybutyne) as the reaction mixture took on a gel-like consistency within 20 min upon addition of excess butyne. The gel-like material was an insoluble solid. The ^{1}H NMR spectrum of the supernatant liquid (d_8-toluene as the solvent) showed an incipient, broad peak at δ 1.6−2.0 ppm characteristic of vinyl methyl groups. At the same time, the signal for 2-butyne (δ 1.55 ppm) disappeared (eq 6), but all signals of 2-propynylthiophene remained unchanged. The hypothesis of butyne polymerization is also supported by the elemental analysis of the insoluble product obtained from treatment of 1 equiv of Mo(VI) catalyst with 35 equiv of 2-butyne.[17]

In great contrast, when 3-hexyne (1.2 equiv) was used in the cross metathesis reaction instead of 2-butyne, the reaction proceeded well with a 9:20 dimer-to-monomer ratio reached at room temperature (eq 7). Moreover, homodimerization of 2-butynylthiophene through metathesis was also accomplished (eq 8). The progress of the reaction was monitored in a sealed NMR tube. The metathesis of 2-butynylthiophene proceeded smoothly in the presence of α,α,α-trifluoro-*o*-cresol and **5**, reaching equilibrium in 1 h at room temperature with 42% conversion. Upon application of a dynamic vacuum, using 1,2,4-trichlorobenzene as the solvent, a conversion of 69% was achieved after 22 h at 30 °C (eq 9).

The difference between 2-butyne and 3-hexyne was made clear by the following experiments. When α,α,α-trifluoro-*o*-cresol and **5** were added to a solution of 2-butyne (10 equiv) in the absence of **10f** at 25 °C in d_8-toluene, a white, insoluble solid formed quickly. On the contrary, no polymerization was observed when α,α,α-trifluoro-*o*-cresol and **5** were added to a solution of 25 equiv of 3-hexyne, even after 24 h at 25 °C. Once the catalyst engages in polymerization, metathesis activity was significantly reduced. This was demonstrated by the following experiment. Complex **5** and α,α,α-trifluoro-*o*-cresol were allowed to polymerize 2-butyne and subsequently exposed to **9d**. Only 18% conversion of **9d** was achieved in 25 h in this case. On the contrary, without prior treatment of the catalytic species with 2-butyne, the metathesis reaction of **9d** proceeded to 40% conversion within 30 min. The metathesis catalyst appears to be "poisoned" after polymerizing butyne.

Given the findings that the alkyne's alkyl substituent can prevent undesirable polymerization and thus help maintain metathesis activity, we next screened alkyne metathesis reactions of various *p*-cyanosubstituted substrates **11**. The studies on metathesis activity were conducted in the closed system by using a 0.2 M solution of **11a−d** in d_8-toluene with a 10 mol % catalyst loading (Table 2). All the reactions were run in sealed NMR tubes and monitored by ^{1}H NMR until the ratio of product dimer-to-monomer stayed constant (ferrocene was used as an internal standard).[18] The highest conversion (28%) was achieved for butynyl substrate **11b**, while the *tert*-butyl terminated substrate **11d** was almost unreactive converting only 5% of the starting material to an unknown product, which was tentatively assigned to Mo(VI) *t*-pentylidyne complex with low reactivity for further metathesis possibly due to steric hindrance of the bulky *tert*-butyl groups.

To further demonstrate that the butynyl terminal group represents a generally useful alkynyl substituent, butynyl substituted compounds **12a−f** were then synthesized and subjected to alkyne metathesis conditions. Higher yields of dimers were consistently obtained for butynyl substrates compared to corresponding propynyl analogues **9a−f** in both closed and open driven systems (Table 3).[18]

In an effort to further improve the efficiency of the catalyst, we next tested a variety of phenols and alcohols as ligands, owing to the importance of electronic effects of the ligands on metathesis activity.[19] For the sake of comparing catalytic efficiency, butynyl substituted benzoate ester **13** was used as the substrate. Kinetic studies were performed at 20 °C by using a 0.2 M solution of **13** in d_8-toluene with a 10 mol % catalyst loading. All the reactions were run in sealed NMR tubes, and the approach to equilibrium was monitored by ^{1}H NMR.[20] Reaction conversion was calculated from the ratio of integrated intensities with ferrocene as an internal standard to check mass

(16) (a) Pschirer, N. G.; Bunz, U. H. F. *Tetrahedron Lett.* **1999**, *40*, 2481−2484. (b) Fürstner, A.; Mathes, C. *Org. Lett.* **2001**, *3*, 221−223 and ref 2e.
(17) Elemental analysis calcd (%) for polybutyne (n = 35) C$_{143}$H$_{215}$MoO(OH) (2063.60): C, 83.23; H, 10.55. Found: C, 83.99; H, 10.66.

(18) In closed systems, the ratio of product dimer-to-monomer reaching a constant value does not necessarily mean the reaction has reached equilibrium. We reasoned that metathesis of **9a−f** and **11d** did not reach the equilibrium due to catalyst poisoning by butyne polymerization and kinetically disfavored bulky intermediates. However, metathesis of butynyl substituted compounds **12a−f** proceeded further, and no side reactions or intermediates were detected. In these examples, equilibrium is likely reached. This notion was further supported by the results of the forward and backward metathesis of **9f** and **13**. In both systems, a pathway-independent ratio of product dimer-to-monomer was observed, indicating that equilibrium had been attained. Variation in equilibrium constants may also explain the different product-to-starting material ratios in metathesis reactions of propynyl or butynyl substituted analogues.
(19) Schrock, R. R. *Polyhedron* **1995**, *14*, 3177−3195.
(20) The equilibrium position was determined by conducting the metathesis reaction in both forward (starting from **13**) and backward (starting from **14** and 3-hexyne) directions. In both cases, the same ratio (2:3) of dimer to monomer was obtained.

Table 3. Homodimerization of Monopropynyl or Monobutynyl Substrates

entry	Substrate	Product	Yield(%)[a]		Yield(%)[b]	
			R' = Me	R' = Et	R' = Me	R' = Et
a	NC—⬡—≡—R'	NC—⬡—≡—⬡—CN	15	28	37	58
b	F₃C—⬡—≡—R'	F₃C—⬡—≡—⬡—CF₃	17	33	51	68
c	OHC—⬡—≡—R'	OHC—⬡—≡—⬡—CHO	16	35	47	70
d	H₃CO—⬡—≡—R'	H₃CO—⬡—≡—⬡—OCH₃	40	54	83	90
e	(H₃C)₂N—⬡—≡—R'	(H₃C)₂N—⬡—≡—⬡—N(CH₃)₂	49	55	76	87
f	(thienyl)—≡—R'	(thienyl)—≡—(thienyl)	<5	42	<5	69

[a] Closed system, d_8-toluene, 20 °C, yield based on NMR spectral analysis. [b] Dynamic vacuum (open driven conditions), solvent 1,2,4-trichlorobenzene, 30 °C, 22 h, 1 mm Hg, yield based on isolated product.

Table 4. $t_{1/2}$ for Alkyne Metathesis Reactions

Ligand	OH–⬡–CF₃ (ortho)	OH–⬡–CF₃ (para)	OH–⬡(3,5-(CF₃)₂)	F₃C,OH,CF₃–⬡–CF₃	F₃C–C(CF₃)–OH	F,OH,F–⬡–F,CF₃	OH–⬡–CN (ortho)	OH–⬡–CN (para)	OH–⬡–NO₂ (ortho)	OH–⬡–NO₂ (para)
$t_{1/2}$ (min)[a]	167	160	613[b]	20	12	< 8	86	12	38	< 8

[a] $t_{1/2}$ is the time required for the metathesis reaction to reach 50% of equilibrium conversion.[20] [b] Metathesis catalyzed by 3,5-bis(trifluoromethyl)phenol catalyst does not reach equilibrium within 2175 min.

balance. Based on the comparison of $t_{1/2}$ values, the catalysts with *p*-nitrophenol or 2,3,5,6-tetrafluoro-4-trifluoromethylphenol as ligands displayed the highest catalytic activity with a $t_{1/2}$ of less than 8 min (Table 4). This result shows significant improvement in reaction rate compared to the α,α,α-trifluoro-*o*-cresol catalyst. In addition to the fast reaction rates, the low price of *p*-nitrophenol prompted us to select this ligand for further studies.

The alkyne metathesis of substrates **12a–f** catalyzed by propylidyne **5** and *p*-nitrophenol was performed in both closed and open driven systems to verify the high catalytic activity of the complex. In the closed system, metathesis reactions were conducted in sealed NMR tubes with d_8-toluene as solvent. The reaction progress was monitored by ^{1}H NMR until the ratio of **10** to **12** stayed constant. All the metathesis reactions conducted in the presence of the *p*-nitrophenol catalyst reached limiting dimer-to-monomer ratios within 16 min. Under dynamic vacuum conditions, higher yields (83–97%) of dimer products were obtained with the *p*-nitrophenol complex compared with

metathesis reactions catalyzed by α,α,α-trifluoro-*o*-cresol Mo(VI) catalyst (58–90% yield) (Table 5). These results further demonstrated the importance of an appropriate alkyne substituent and the improved catalytic activity of the *p*-nitrophenol Mo(VI) propylidyne complex.

Discussion

The synthesis and demonstrated effectiveness of high oxidation state tungsten and molybdenum alkylidyne complexes for alkyne metathesis were reported by Schrock in the 1980s.[3b,11a–c] Recently, Cummins has reported a new route to synthesize analogous trialkoxymolybdenum(VI) alkylidyne complexes $(R^3O)_3MoCR^1$, which are active alkyne metathesis catalysts even at room temperature,[11d–e] but their scope has not been reported in detail. Although trialkoxy alkylidyne **16** can be conveniently obtained from alcoholysis of the metathesis inactive triamide **15** (eq 10),[21] the starting complex **15**[11,22,23] requires a tedious, multistep synthetic procedure and presents a practical limitation

Table 5. Homodimerization of Monobutynyl Substrates

entry	Substrate	Product	$t_{1/2}$ (min)[a]		Yield(%)[b]	
			ligand A[c]	ligand B[d]	ligand A	ligand B
a	NC—C6H4—C≡C—CH3	NC—C6H4—C≡C—C6H4—CN	17	<8.0	58	93
b	F3C—C6H4—C≡C—CH3	F3C—C6H4—C≡C—C6H4—CF3	10	<8.0	68	86
c	OHC—C6H4—C≡C—CH3	OHC—C6H4—C≡C—C6H4—CHO	8.5	<8.0	70	83
d	H3CO—C6H4—C≡C—CH3	H3CO—C6H4—C≡C—C6H4—OCH3	<8.0	<8.0	90	97
e	(H3C)2N—C6H4—C≡C—CH3	(H3C)2N—C6H4—C≡C—C6H4—N(CH3)2	<8.0	<8.0	87	94
f	thienyl—C≡C—CH3	thienyl—C≡C—thienyl	10.5	<8.0	69	91

[a] Closed system, d_8-toluene, 20 °C, $t_{1/2}$ is the time required for the reaction to reach 50% of final constant ratio of **10** to **12**. [b] Open driven condition, solvent 1,2,4-trichlorobenzene, 30 °C, 22 h, 1 mm Hg, yield based on isolated product. [c] Ligand A = α,α,α-trifluoro-*o*-cresol. [d] Ligand B = *p*-nitrophenol.

to this potentially useful catalyst. A related alkyne metathesis
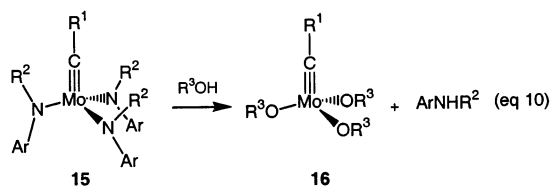
catalyst was developed by Fürstner who combined the readily available[7] Mo[N(*t*-Bu)Ar]3 (Ar = 3,5-C6H3Me2) with methylene chloride to produce a mixture of ClMo[N(*t*-Bu)Ar]3 (**2**) and HCMo[N(*t*-Bu)Ar]3 (**3**) (eq 1). This mixture exhibited alkyne metathesis activity at 80 °C with good functional group compatibility.[2e,8] The catalytically active species is derived from monochloride **2**, whereas methylidyne **3** exhibits poor metathesis activity.[24]

Given that Fürstner's method directly produces alkylidyne **3**, which is the precursor to Cummins' active trialkoxyalkylidyne **16**, we developed the reductive recycle strategy to accomplish

(21) Cummins has shown that well-defined alkyne metathesis catalysts can be prepared by alcoholysis of precursors R[1]CMo(NArR[2])3 (**15**) providing trialkoxymolybdenum alkylidyne complexes **16** with free aniline; see ref 11d and e.

(22) (a) Schrock, R. R.; Clark, D. N.; Sancho, J.; Wengrovius, J. H.; Rocklage, S. M.; Pedersen, S. F. *Organometallics* **1982**, *1*, 1645−1651. (b) Listemann, M. L.; Schrock, R. R. *Organometallics* **1985**, *4*, 74−83. (c) Schrock, R. R. *Acc. Chem. Res.* **1986**, *19*, 342−348. (d) Freudenberger, J. H.; Schrock, R. R.; Churchill, M. R.; Rheingold, A. L.; Ziller, J. W. *Organometallics* **1984**, *3*, 1563−1573.

(23) (a) Peters, J. C.; Odom, A. L.; Cummins, C. C. *Chem. Commun.* **1997**, 1995−1996. (b) Greco, J. B.; Peters, J. C.; Baker, T. A.; Davis, W. M.; Cummins, C. C.; Wu, G. *J. Am. Chem. Soc.* **2001**, *123*, 5003−5013. (c) Agapie, T.; Diaconescu, P. L.; Cummins, C. C. *J. Am. Chem. Soc.* **2002**, *124*, 2412−2413.

(24) Schrock reported that terminal alkynes are unsuitable in alkyne metathesis, which may be explained by the propensity of terminal alkylidynes to suffer ligand loss along the reaction pathway. See ref 19 and 22a−c. Recently it was reported by Fürstner that the terminal alkylidyne **3** exhibited poor metathesis activity. Using pure **3**, we have followed up on this observation using 10 mol % **3** in the metathesis of 2-butynylbenzene with 11% conversion achieved, and we conclude that **3** is *catalytically* inactive.

an expedient synthesis of complex **15**, which involves redirecting Fürstner's reaction in eq 1 to favor production of HCMo(N[*t*-Bu]Ar)3. In contrast to the reported incompatibilities of the tungsten alkylidyne complex (*t*-BuO)3WC(*t*-Bu) with amines or polyether chains,[2a,e,8] the trialkoxymolybdenum(VI) propylidyne catalyst prepared through the reductive recycle strategy displayed good compatibility with these and other functional groups as well as a wide variety of solvents.

In solvent studies (eq 3), the metathesis reactions conducted in toluene and chloroform proceeded fast with the highest conversions achieved, but in MeCN and THF, the reactions were less efficient. This likely reflects the fact that these trialkoxymolybdenum(VI) propylidynes are coordinatively unsaturated, $12e^-$ complexes and thus sensitive to coordinating solvents (e.g., MeCN and THF).[25] The noncoordinating solvents CHCl3 and toluene are preferable for metathesis reactions. The high oxidation state of molybdenum(VI) in these complexes gives the catalyst Lewis acid character, which makes the use of acetone as solvent unfavorable, possibly due to aldol condensation and the formation of water. Because Mo-phenoxide ligand is potentially displaced by water or methanol, protic solvents and adventitious water must be avoided.

Among the alkyne metathesis substrates, thiophene-containing compounds are especially attractive owing to potential applications of poly(2,5-thienyleneethynylene)s as conjugated polymers.[26] In the cross alkyne metathesis of 2,2′-dithienylethynylene (**10f**) with 10 equiv of 2-butyne, the polymerization of butyne

(25) Based on the same idea of a coordinating effect, 2-propynylthiophene substrate is problematic, which could partially be due to its high coordinative character. However, the fact that metathesis occurs in THF and MeCN and that 2-butynylthiophene undergoes metathesis indicates the coordination of these molecules is reversible and the affinity of the Mo center to alkynes is high.

(26) (a) Bunz, U. H. F. *Chem. Rev.* **2000**, *100*, 1605−1644. (b) Roncali, J. *Acc. Chem. Res.* **2000**, *33*, 147−156. (c) Garnier, F. *Acc. Chem. Res.* **1999**, *32*, 209−215. (d) Hayashi, H.; Yamamoto, T. *Macromolecules* **1997**, *30*, 330−332. (e) Rutherford, D. R.; Stille, J. K.; Elliott, C. M. *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)* **1990**, *31*, 643−644.

Scheme 3. Postulated Polymerization of 2-Butyne
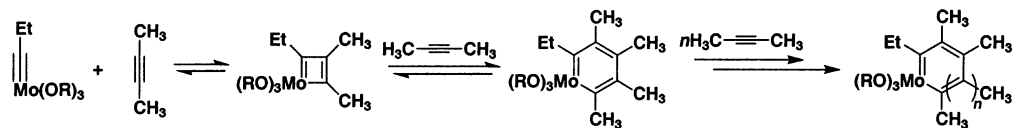
was observed. We also found that the butyne polymerization was faster in the presence of *p*-nitrophenol catalyst than the polymerization catalyzed by α,α,α-trifluoro-*o*-cresol and **5**. We suspect that a molybdenum(VI) alkylidyne complex initiated polymerization of 2-butyne by repeated insertion into the Mo−C bond (Scheme 3).[27] In this scenario, the resulting molybdenum-(VI) vinyl alkylidene species would be unavailable for alkyne metathesis. We reasoned that this undesirable pathway could be prevented if sterically more bulky alkynes were generated instead of 2-butyne in eq 4. This notion was supported by the successful cross metathesis of 2,2′-dithienylethynylene with 3-hexyne and homodimerization of 2-butynylthiophene. As far as we are aware, this represents the first successful homodimer-ization of thienyl compounds through alkyne metathesis, which could potentially be applied to the synthesis of poly(2,5-thienyleneethynylene)s.

This finding has important practical significance in that it demonstrates how the alkyl substituent on the substrates must be taken into consideration when optimizing these reactions.[28] 2-Butyne tends to polymerize by Mo(VI) catalysts, in which the alkylidyne is destroyed upon polymer formation through the "ring expansion" mechanism as shown in Scheme 3. Presumably because 3-hexyne is more sterically hindered than 2-butyne, alkyne polymerization was greatly retarded, which facilitated the catalyst to turn over giving the desired alkyne metathesis products. We speculate that butynyl group strikes the appropriate steric balance, hindering the polymerization side reaction while permitting the desired alkyne metathesis reactions. At the extreme, compound **11d** with a very bulky terminal group could not be converted to dimer. Apparently, the substrate's steric bulk in this case prevents both polymerization and the desired metathesis reactions. Therefore an optimal size of the terminal group is critical to successfully perform the alkyne metathesis reaction.

Studies on metathesis of substrates with various functional groups show electron donating groups enhance metathesis activity. Electron-rich alkynes are known to bind faster to the electrophilic metal center than the electron-poor ones.[29] Given that alkyne coordination influences the reaction rate, coordina-tion of the alkyne to the metal center is likely the rate-determining step (RDS) or happens prior to the RDS.[22d] This notion is also supported by the results of screening for highly active catalyst ligands (Tabel 4), in which the improved catalytic activity of trialkoxymolybdenum(VI) complexes was observed upon increasing the electron withdrawing character of the ligands, making the molybdenum metal center more electron deficient.

Under dynamic vacuum conditions, higher yields (83−97%) of dimer products were consistently obtained with *p*-nitrophenol complex compared with metathesis reactions catalyzed by α,α,α-trifluoro-*o*-cresol Mo(VI) catalyst (58−90% yield) (Table 5). This may result from the high catalytic activity of *p*-nitrophenol catalyst. Presumably, the *p*-nitrophenol catalyst was able to achieve a higher turnover number than the α,α,α-trifluoro-*o*-cresol catalyst before losing activity.

Conclusions

The size of the alkynyl substituent on the substrate is essential to successful alkyne metathesis. Butynyl substituted compounds were proven the most effective in metathesis reactions. The reductive recycle approach provides a convenient, large-scale preparation of trisamidomolybdenum(VI) alkylidyne complexes in pure form. Alcoholysis of molybdenum(VI) propylidyne **5** with various phenols/alcohols produced active catalysts for alkyne metathesis at room temperature. The *p*-nitrophenol Mo-(VI) catalyst showed the highest catalytic activity. This catalyst is compatible with a variety of functional groups and solvents. With the volatile byproduct constantly removed under dynamic vacuum, the alkyne metathesis proceeded smoothly, providing high product yields ranging from 83% to 97%. The catalytic activity of the *p*-nitrophenol Mo(VI) propylidyne has led us to envision synthesis of phenylene ethynylene foldamers[30] as well as other alkyne-bridged oligomers and polymers through alkyne metathesis.

Supporting Information Available: Characterization data for trialkoxymolybdenum(VI) propylidyne, **5**−**12**, and **14**, experi-mental details, and kinetic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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(27) Polymerization of alkynes by a tungsten carbyne catalyst was reported before. See: (a) Weiss, K.; Goller, R.; Lössel, G. *J. Mol. Catal.* **1988**, *46*, 267−275. (b) Bunz, U. H. F.; Kloppenburg, L. *Angew. Chem., Int. Ed.* **1999**, *38*, 478−481. (c) Katz, T. J.; Ho, T, H.; Shih, N. Y.; Ying, Y. C.; Stuart, V. I. W. *J. Am. Chem. Soc.* **1984**, *106*, 2659−2668 and ref 3b.

(28) Propynyl substituted compounds are the most commonly used substrates in alkyne metathesis in recent literature. See refs 2e,k, 4b, 8, 11d, and 16.

(29) The same trend of reactivity was observed before by Schrock using W/Mo carbyne catalysts. See ref 11b.

(30) For current synthesis and studies, see: (a) Nelson, J. C.; Saven, J. G.; Moore, J. S.; Wolynes, P. G. *Science* **1997**, *277*, 1793−1796. (b) Brunsveld, L.; Meijer, E. W.; Prince, R. B.; Moore, J. S. *J. Am. Chem. Soc.* **2001**, *123*, 7978−7984. (c) Prince, R. B.; Barnes, S. A.; Moore, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 2758−2762.