

ORGANOMETALLICS

Volume 16, Number 18, September 2, 1997

© Copyright 1997
American Chemical Society

Communications

Reactivity of Ru(H)(H₂)Cl(PCy₃)₂ with Propargyl and Vinyl Chlorides: New Methodology To Give Metathesis-Active Ruthenium Carbenes

Thomas E. Wilhelm, Tomás R. Belderrain, Seth N. Brown, and Robert H. Grubbs*

The Arnold and Mabel Beckman Laboratory of Chemical Synthesis, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California 91101

Received June 23, 1997[®]

Summary: A procedure for generating the ruthenium hydride complex Ru(H)(H₂)Cl(PCy₃)₂ in 95% yield is presented. Following a novel insertion–elimination pathway, this hydride can react with propargyl or vinyl halides to make metathesis-active vinyl and alkyl carbene species with the general formulas (PCy₃)₂Cl₂Ru=CH–CH=CR₂ and (PCy₃)₂Cl₂Ru=CHR, respectively. Tertiary propargyl chlorides work best, giving Ru–vinyl carbenes in extremely high yield.

The use of olefin metathesis has expanded tremendously in recent years, with applications including the construction of macrocycles in peptides and other systems,^{1–4} tandem ring opening/ring closing and construction of fused ring systems,^{5–7} and ring-opening metathesis polymerization in aqueous media.⁸ Especially useful are metathesis catalysts based on ruthenium, which have demonstrated remarkable stability toward

oxygen, protic solvents, and many functional groups.^{8–10} While these compounds can be prepared in moderate to high yields, existing syntheses rely on relatively inaccessible or unstable organic compounds such as 3,3-diphenylcyclopropene¹⁰ or phenyl diazomethane.⁹ Here, we describe a simple, high-yield preparation of a ruthenium hydride system which can be condensed with a variety of propargyl or vinyl halides to give metathesis-active ruthenium carbenes via a novel insertion–elimination sequence.

The demonstration that osmium^{11–14} and ruthenium^{15–17} hydride systems could be used to generate

* Abstract published in *Advance ACS Abstracts*, August 1, 1997.

(1) Miller, S. J.; Blackwell, H. E.; Grubbs, R. H. *J. Am. Chem. Soc.* **1996**, *118*, 9606–9614.

(2) Furstner, A. *J. Org. Chem.* **1996**, *61*, 3942.

(3) Rutjes, F. P. J.; Schoemaker, H. E. *Tetrahedron Lett.* **1997**, *38*, 677.

(4) McKerrvey, M. A.; Pitarch, M. *Chem. Commun.* **1996**, 1689.

(5) Zuercher, W. J.; Hashimoto, M.; Grubbs, R. H. *J. Am. Chem. Soc.* **1996**, *118*, 6634–6640.

(6) Clark, J. S.; Kettle, J. G. *Tetrahedron Lett.* **1997**, *38*, 123.

(7) Barrett, A. G. M.; Gibson, V. C. *Chem. Commun.* **1997**, 155.

(8) Mohr, B.; Lynn, D. M.; Grubbs, R. H. *Organometallics* **1996**, *15*, 4317–4325.

(9) (a) Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, *118*, 100–110. (b) Schwab, P.; France, M. B.; Ziller, J. W.; Grubbs, R. H. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2039–2041.

(10) Nguyen, S. T.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1993**, *115*, 9858.

(11) Espuelas, J.; Esteruelas, M. A.; Lahoz, F. J.; Oro, L. A.; Ruiz, N. *J. Am. Chem. Soc.* **1993**, *115*, 4683–4689.

(12) Esteruelas, M. A.; Lahoz, F. J.; Onate, E.; Oro, L. A.; Zeier, B. *Organometallics* **1994**, *13*, 1662–1668.

(13) Hiraki, K.; Matsunaga, T.; Kawano, H. *Organometallics* **1994**, *13*, 1878–1885.

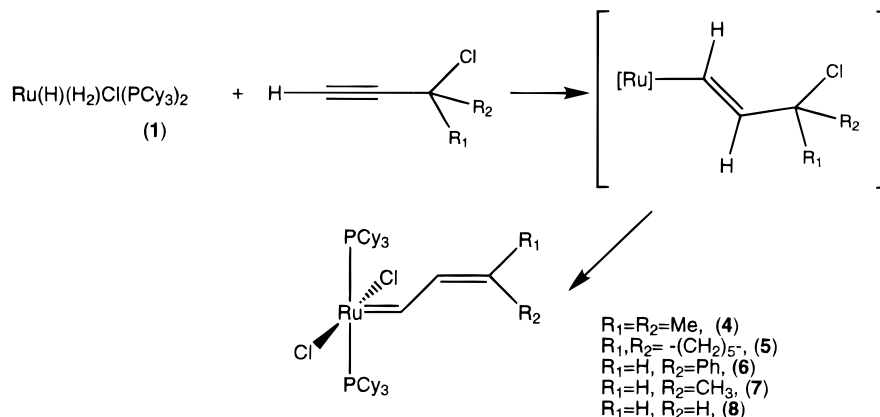
(14) Esteruelas, M. A.; Lahoz, F. J.; Onate, E.; Oro, L. A.; Valero, C.; Zeier, B. *J. Am. Chem. Soc.* **1995**, *117*, 7935–7942.

(15) Esteruelas, M. A.; Lahoz, F. J.; Onate, E.; Oro, L. A.; Zeier, B. *Organometallics* **1994**, *13*, 4258–4265.

(16) (a) Grunwald, C.; Gevert, O.; Wolf, J.; Gonzales-Herrero, P.; Werner, H. *Organometallics* **1996**, *15*, 1960–1962. (b) Burrow, T.; Saboetienne, S.; Chaudret, B. *Inorg. Chem.* **1995**, *34*, 2470–2472.

(17) Xia, H. P.; Jia, G. *Organometallics* **1997**, *16*, 1–4.

Scheme 1. Insertion-Elimination with Propargyl Chlorides



carbenes suggested to us that metal hydrides might be an efficient system for the generation of metathesis-active carbene complexes of general form $(\text{PCy}_3)_2\text{-Cl}_2\text{Ru}=\text{CHR}$. A suitable ruthenium hydride starting material is $\text{Ru(H)(H}_2\text{)Cl(PCy}_3\text{)}_2$ (**1**),^{18,19} which contains the appropriate number of phosphines and lacks tightly bound carbonyl ligands. Previous multistep syntheses of **1** focused on the transformation from $\text{Ru(1,3,5-cyclooctatriene)(1,5-cyclooctadiene)}$ either directly or through isolation of $\text{Ru(H)}_2\text{(H}_2\text{)}_2\text{(PCy}_3\text{)}_2$.¹⁸ Recently, in the preparation of $\text{Ru(H)}_2\text{(Cl)}_2\text{(PiPr}_3\text{)}_2$, the similar species $\text{Ru(H)(H}_2\text{)Cl(PiPr}_3\text{)}_2$ was proposed as an intermediate in a reaction with $[\text{RuCl}_2(\text{COD})]_x$ (**2**), PiPr_3 , and H_2 in *sec*-butyl alcohol.¹⁶ Further, it was demonstrated that a solution of this intermediate could be reacted with acetylenes to give ruthenium carbene species.¹⁶

Attempts to make **1** via **2** following the above method were promising, giving **1** in 40% yield along with a large amount of a Ru(IV) species presumed to be $\text{Ru(H)}_2\text{(Cl)}_2\text{(PCy}_3\text{)}_2$ (**3**) from ^1H and ^{31}P NMR data. Since the reaction between isolated **1** and HCl gives the same Ru(IV) species and since HCl is produced in the reaction that forms **1**, it was surmised that the addition of base to the reaction mixture would improve the yield of **1**. Reacting $[\text{RuCl}_2(\text{COD})]_x$, PCy_3 , H_2 , and NEt_3 in *sec*-butyl alcohol for 8 h at 80 °C gives the desired orange, air-sensitive hydride $\text{Ru(H)(H}_2\text{)Cl(PCy}_3\text{)}_2$ (**1**) in 94% yield.²⁰

The hydrido chloride complex $\text{Ru(H)(H}_2\text{)Cl(PCy}_3\text{)}_2$ (**1**) reacts rapidly with a variety of propargylic halides to yield ruthenium vinylcarbene complexes. For example, **1** reacts immediately with commercially available 3-chloro-3-methyl-1-butyne in methylene chloride to give the dimethylvinylcarbene complex $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH-CH=CMe}_2$ (**4**) in 95% isolated yield (Scheme 1, $\text{R}_1 = \text{R}_2 = \text{Me}$).²¹ Monitoring the reaction by ^1H NMR

indicates that it is complete in less than 10 min, even at -30 °C, and integration against an internal standard shows that the yield is ~99.5%.

Other propargylic halides react similarly. Alkynes with tertiary (1-ethynylchlorocyclohexane, to form $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH-CH=C(CH}_2\text{)}_5$ (**5**) or benzylic ($\text{HC}\equiv\text{CCH(Ph)Cl}$, to form $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH-CH=CHPh}$ (**6**)) chlorides react essentially quantitatively, although a trace of the ruthenium(IV) complex **3** is seen as a by-product. The amount of **3** formed increases as the steric bulk of the propargyl group decreases, with the mono-methyl-substituted $\text{HC}\equiv\text{CCH(CH}_3\text{)Cl}$ giving $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH-CH=CHMe}$ (**7**) and **3** in an 8:1 ratio and the parent propargyl chloride $\text{HC}\equiv\text{CCH}_2\text{Cl}$ giving $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH-CH=CH}_2$ (**8**) and **3** in a 0.8:1 ratio. Changing the halogen from chlorine to bromine also increases the amount of **3** formed: the dimethyl-substituted propargyl bromide, $\text{HC}\equiv\text{C(CH}_2\text{)}_2\text{Br}$, gives a 30:1 ratio of the expected mixed halogen carbene $(\text{PCy}_3)_2\text{ClBrRu}=\text{CH-CH=CMe}_2$ (**9**) to the mixed halogen Ru(IV) species $\text{Ru(H)}_2\text{ClBr(PCy}_3\text{)}_2$ (**10**), which is substantially different from the >200:1 ratio seen with the corresponding chloride. The ratios of carbene to **3** can be improved dramatically if the solvent is changed from dichloromethane to benzene or toluene: from 0.8:1 to 30:1 for **8**, from 8:1 to 37:1 for **7**, and to no detectable Ru(IV) in the generation of **6** and **9**.

The proposed mechanism for the formation of vinylcarbene complexes (Scheme 1) involves insertion of the alkyne into the Ru-H bond to form a γ -chloroalkenyl group, which rapidly undergoes rearrangement to give formal addition of chloride to ruthenium. It is less clear how the ruthenium(IV) product is formed, but the observed steric and solvent effects are consistent with a competing pathway involving direct oxidative addition of the carbon-halogen bond. Alkyne insertion is

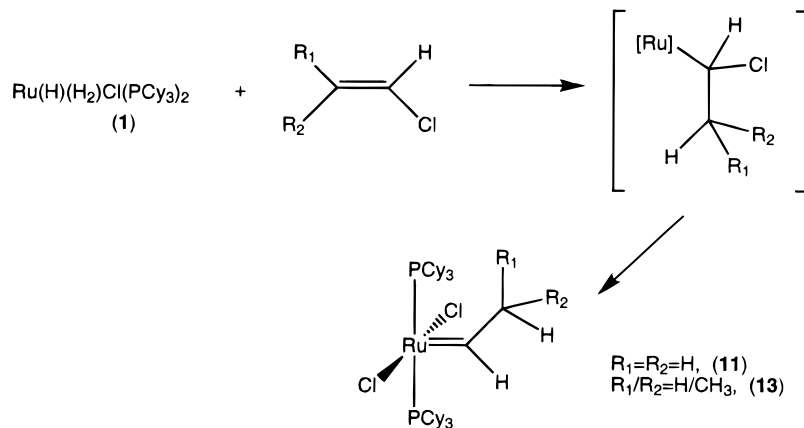
(18) Christ, M. L.; Sabo-Etienne, S.; Chaudret, B. *Organometallics* **1994**, *13*, 3800–3804.

(19) Beatty, R. P.; Paciello, R. A. U.S. Patent 5,554,778, 1996.

(20) **Ru(H)(H₂)Cl(PCy₃)₂ (1)**: $[\text{RuCl}_2(\text{COD})]_x$ (**3**) (4.00 g, 14.28 mmol) and tricyclohexylphosphine (Strem, 97% pure, 8.46 g, 29.26 mmol) were placed in a 500 mL high-pressure system equipped with a pressure gauge. To this system, 200 mL of degassed *sec*-butyl alcohol and triethylamine (1.99 mL, 14.28 mmol) were added. After purging with hydrogen, the system was pressurized with 1.5 atm of hydrogen and heated to 80 °C for a total of 20 h, repressurizing as needed. Generation of (**1**) can also be accomplished in a suitably-sized, thick-walled Teflon-valved Straus flask. The air-sensitive orange solid was isolated by cooling the system to room temperature, adding a volume (200 mL) of degassed methanol to ensure complete precipitation before filtering, washing with methanol (3 × 50 mL), and drying in vacuo to give 9.26 g, 94% of **1**.

(21) **(PCy₃)₂Cl₂Ru(=CH-CH=CMe₂) (2)**: $\text{Ru(H)(H}_2\text{)Cl(PCy}_3\text{)}_2$ (**1**) (1.00 g, 1.43 mmol) under an inert atmosphere is dissolved in 30 mL of dichloromethane cooled to -30 °C, and 3-chloro-3-methyl-1-butyne (170 μL , 1.5 mmol) is added. The solution instantly turns dark red-purple and is allowed to stir for 15 min before removing the flask from the cooling bath and concentrating to a viscous oil. Degassed methanol (20 mL) is added to precipitate the purple solid, which is then washed with methanol (3 × 10 mL) and dried to give 1.09 g, 95% of the carbene **2**. Selected NMR data (CD_2Cl_2): ^1H NMR δ 19.26 (d, RuCH , $J_{\text{HH}} = 11.7$ Hz), 7.81 (d, RuCHCH , $J_{\text{HH}} = 11.7$ Hz); ^{31}P NMR δ 36.4 (s, RuPCy_3); ^{13}C NMR δ 288.4 (t, RuCH , $J_{\text{CP}} = 9.6$ Hz), 146.9 (s), 133.5 (s). All other reactions with **1** were done in a similar fashion but on a 20 mg scale in 0.5 mL of CD_2Cl_2 . Noncommercially available alkynes were made following the procedures in Brandsma, L. *Preparative Acetylenic Chemistry*; Elsevier: Amsterdam, 1988.

Scheme 2. Formation of Carbenes by Insertion–Elimination with Vinyl Chlorides



well-precedented for closely related complexes such as $\text{MHCl(CO)(PiPr}_3\text{)}_2$ ($\text{M} = \text{Os, Ru}$).^{12,15,22} Ionization at the γ -carbon is also preceded, as in the formation of $[\text{trans-Cl(CO)(PiPr}_3\text{)}_2\text{Ru}=\text{CHCH}=\text{CR}_2]\text{BF}_4$ on protonation of the γ -hydroxyvinyl complex $\text{trans-Cl(CO)(PiPr}_3\text{)}_2\text{Ru}-\text{CH}=\text{CH}-\text{C(OH)R}_2$.¹⁵ Evidently the sequence of insertion–elimination made possible in this system by the presence of both an alkyne and a leaving group allows extremely efficient access to vinylcarbene species.

Another possible reaction type which could follow the same general insertion–elimination pathway is between metal hydrides and vinylic halides (Scheme 2). Again, insertion of olefins into $\text{Ru}-\text{H}$ bonds is well-known,^{13,23} and if the proper regiochemistry can be achieved, this opens the possibility of α -halide elimination to give carbenes (β -halogen elimination can yield only ruthenium halide and dehalogenated alkene).

Consistent with the insertion–elimination mechanism, the ruthenium hydride complex **1** does react with alkenyl halides to give carbene products, but the reactions are significantly less clean than those observed with propargyl halides. For example, **1** reacts with an excess of vinyl chloride to give the expected carbene $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH}-\text{CH}_3$ (**11**),⁹ the methylidene complex $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH}_2$ (**12**),⁹ (arising from cross-metathesis of **11** with vinylchloride to give **12** and 1-chloropropene), and the Ru(IV) species **3**. The ratio of total carbenes:**3** is a modest 2.1:1. Increasing the steric bulk at the β -carbon (to suppress β -addition) does not improve the yield of carbene, with **1** and a mixture of *cis*- and *trans*-

1-chloro-1-propene reacting to give the propylidene complex $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CHCH}_2\text{CH}_3$ (**13**)⁹ and **3** in a ratio of 0.8:1. This suggests that β -addition is not the dominant pathway in the generation of **3** from **1** and vinyl chlorides. The β -disubstituted olefin 1-chloro-2-methyl-1-propene produces no carbene and only gives **3** very slowly (several days vs <10 min for all other reactions).

In conclusion, we have presented a high-yield preparation for the ruthenium hydride starting material **1** and have shown that it can be used in conjunction with bulky propargyl chlorides to give ruthenium vinyl carbenes in excellent overall yields. In addition to its quantitative improvements, this process offers other advantages over previously available preparations: the need to waste 3 equiv of triphenylphosphine in the preparation of catalyst intermediates is eliminated and the organic fragment does not require a complex or dangerous synthetic methodology. The high yield and simple procedures involved appear to make this a nearly ideal preparation of 3,3-disubstituted vinylcarbene complexes $(\text{PCy}_3)_2\text{Cl}_2\text{Ru}=\text{CH}-\text{CH}=\text{CR}_2$ which are known to have significant activity in olefin metathesis.¹⁰ The reaction of **1** with alkenyl chlorides generates the more reactive alkyl carbenes,⁹ but with too many byproducts to be synthetically useful. Current investigations focus on expanding the scope of the insertion–elimination method for the generation of ruthenium carbenes, as well as on the mechanisms of the transformations involved.

OM9705259

(22) Werner, H.; Meyer, U.; Peters, K.; von Schnering, H. G. *Chem. Ber.* **1989**, *122*, 2097–2107.

(23) Hiraki, K.; Ochi, N.; Sasada, Y.; Hayashida, H.; Fuchita, Y.; Yamanaka, S. *J. Chem. Soc., Dalton Trans.* **1985**, 873–877.