Pergamon

Tetrahedron Letters, Vol. 38, No. 22, pp. 3923-3926, 1997

0040-4039/97 $17.00 + 0.00

PII: S0040-4039(97)00780-6

Cyclotrimerization of Alkynes Using a Multicatalytic System, Pd(II) / Chlorohydroquinone / NPMoV, under Dioxygen

Takahiro Yokota, Yasunori Sakurai, Satoshi Sakaguchi, Yasutaka Ishii*

Department of Applied Chemistry, Faculty of Engineering & High Technology Research Center,
Kansai University, Suita Osaka 564, Japan

Abstract: Cyclotrimerization of internal and terminal alkynes was performed using a new triple catalytic system, Pd(II) / chlorohydroquinone / NPMoV, under atmospheric oxygen. Internal alkynes such as 3-hexyne and 4-octyne were converted into hexaethyl- and hexapropylbenzenes in quantitative yields. Terminal alkyne, *t*-butylacetylene, afforded 1,3,5-tri-*t*-butylbenzene without formation of unsymmetrical tri-*t*-butylbenzenes. The reaction did not take place in the absence of oxygen.

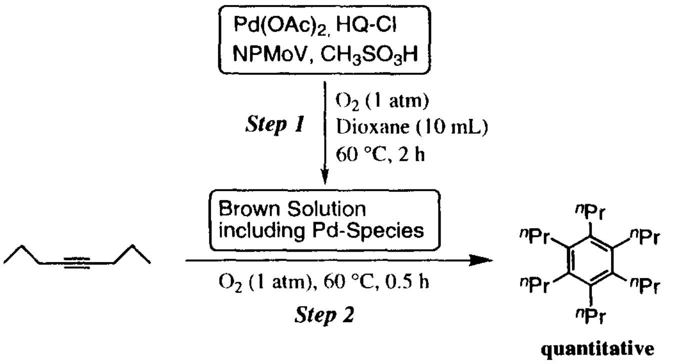
Alkynes are catalytically cyclotrimerized by a variety of transition-metals[1] such as Ti[2], Co[3], Zr[4], Rh[5], Pd[6], Nb[7], Ta[8] and Ir[9] *etc.*. In the palladium-catalyzed cyclotrimerization, both Pd(0) and Pd(II) were used as the catalysts.[10] To our knowledge, however, there is no paper on the Pd(II)-mediated cyclotrimerization reaction of alkynes under the influence of molecular oxygen.

In a previous paper, we reported that oxidative reactions like acetoxylation and acetalization of olefinic compounds are efficiently achieved by using the triple catalytic system consisted of Pd(II) / hydroquinone / molybdovanadophosphate (NPMoV) in the presence of molecular oxygen.[11] Thus, cyclohexene and acrylonitrile are readily converted into cyclohexenylacetate and cyanoacetaldehyde diethylacetal, respectively, in quantitative yields under mild conditions.

We report herein an oxidative cyclotrimerization of alkynes using $Pd(OAc)_2$ / chlorohydroquinone (HQ-Cl) / NPMoV system under oxygen atmosphere.

The reaction was carried out as follows. A solution of $Pd(OAc)_2$ (0.1 mmol), HQ-Cl (0.4 mmol), NPMoV (35 mg) and CH_3SO_3H (20 mg) in dioxane (10 mL) was placed in a three-necked flask equipped with a balloon filled with O_2, and stirred at 60 °C for 2 h (standard conditions) to give a brown solution involving an activated palladium complex (Eq. 1, Step 1). To the solution was added 4-octyne (**1**) (2 mmol) and then the mixture was stirred at 60 °C for 0.5 h (Eq. 1, Step 2). The reaction was quenched with wet ether and the products were extracted with *n*-hexane. Removal of the solvent under reduced pressure and then recrystallization from methanol gave hexa-*n*-propylbenzene (**2**) as white crystals in quantitative yield (Table 1, Run 1).

Table 1 shows the representative results for cyclotrimerization of **1** under various reaction conditions. The reaction of **1** using hydroquinone in place of HQ-Cl under these conditions gave a black solution, and



(Eq. 1)

most of **1** was recovered unchanged (Run 2). The reaction of **1** without preactivation of the palladium catalyst led to a trace amount of **2**, but low-yield trimerization of **1** was effected on prolonged heating (20 h) (Run 3). The preactivation of the catalyst under Ar atmosphere gave a black solution, and then the reaction of **1** under dioxygen for 1 h produced **2** in 73 % yield (Run 4), but no reaction took place in the absence of oxygen (Run 5). This shows that an active palladium complex is gradually generated by introducing dioxygen to the reaction system. After the activation of the palladium catalyst at 60 °C for 2 h, the reaction of **1** at room temperature for 4 h afforded **2** in 97 % yield (Run 6). However, the reaction of **1** by the palladium catalyst activated at room temperature for 2 h resulted in the recovery of the **1** (Run 7). This fact indicates

Table 1. Cyclotrimerization of 4-Octyne (1) to Hexapropylbenzene (2) under Various Reaction Conditions [a]

Run	Step 1			Step 2		Yield / %
	Time / h	Temp. / °C	Atmosphere	Time / h	Atmosphere	
1	2	60	O_2	0.5	O_2	quantitative
2[b]	2	60	O_2	1	O_2	6
3	0	60	O_2	1 (20)	O_2	< 1 (50)
4	2	60	Ar	1	O_2	73
5	2	60	Ar	1	Ar	< 1
6[c]	2	60	O_2	1 (4)	O_2	62 (97)
7	2	25	O_2	1	O_2	< 1
8[d]	2	60	O_2	1 (3)	Ar	11 (13)
9[d]	2	60	O_2	3	O_2	90
10[e]	2	60	O_2	5	O_2	no reaction

[a] After stirring a solution of $Pd(OAc)_2$ (0.1 mmol), HQ-Cl (0.4 mmol), NPMoV (35 mg) and CH_3SO_3H (20 mg) in dioxane (10 mL) under O_2 atmosphere at 60 °C for 2 h, 4-octyne (**1**) (2 mmol) was added and stirred at 60 °C for 0.5 – 20 h. [b] Hydroquinone was used instead of HQ-Cl. [c] Step 2 was performed at 25 °C. [d] 10 mmol of **1** was used. [e] In the absence of $Pd(OAc)_2$.

that generation of the active palladium catalyst was difficult at room temperature. Cyclotrimerization of **1** did not catalytically take place in the absence of O_2 even after the activation of the palladium catalyst under the standard conditions (Run 8). The reaction of **1** in preparative scale (10 mmol) under standard conditions formed **2** in 90 % yield (Run 9). Needless to say, no reaction took place in the absence of $Pd(OAc)_2$ (Run 10).

Table 2 shows the representative results for the cyclotrimerization of several alkynes catalyzed by the Pd(II) / HQ-Cl / NPMoV system under the influence of dioxygen. Like **1**, 3-hexyne (**3**), symmetrical alkyne, was cyclotrimerized to hexaethylbenzene (**4**) in quantitative yield. However, diphenylacetylene (**5**) was cyclotrimerized with some difficulty to give hexaphenylbenzene (**6**) in moderate yield (54 %). In the case of unsymmetrical alkyne such as 3-octyne (**7**), the reaction proceeded in high selectivity to give 1,2,4-tri-*n*-butyl-3,5,6-triethylbenzene (**8a**) and a small amount of its regioisomer 1,3,5-tri-*n*-butyl-2,4,6-triethylbenzene (**8b**) (**8a** / **8b** = 9 / 1) in 80 % yield. For 2-pentyne (**9**), however, 1,2,4-triethyl-3,5,6-trimethylbenzene (**10a**) and 1,3,5-triethyl-2,4,6-trimethylbenzene (**10b**) were formed in 50 % yield as an unseparated mixture. The cyclotrimerization of *t*-butylacetylene (**11**) gave exclusively 1,3,5-tri-*t*-butylbenzene (**12b**) without formation of its regioisomer, 1,2,4-tri-*t*-butylbenzene (**12a**), although trimerization of **11** by Me_3SiCl and Pd/C in refluxing THF is reported to give a 4:3 mixture of **12a** and **12b**.[7] 1-Octyne (**13**) polymerized under these conditions to form a complex mixture of products (Run 6).

Table 2. Cyclotrimerization of Various Alkynes by Pd(II) / HQ-Cl / NPMoV Under O_2 Atmosphere [a]

Run	Alkyne $R^1{-}{\equiv}{-}R^2$	Temp. / °C	Time / h	Product (Yield / %)	
1	**3**: $R^1 = R^2 = C_2H_5$	60	1	**4** (100)	
2	**5**: $R^1 = R^2 = C_6H_5$	60	5	**6** (54)	
3	**7**: $R^1 = n\text{-}C_4H_9$, $R^2 = C_2H_5$	60	1	**8a** (72)	**8b** (8)
4	**9**: $R^1 = C_2H_5$, $R^2 = CH_3$	60	2	**10a** + **10b** (50)	
5	**11**: $R^1 = t\text{-}C_4H_9$, $R^2 = H$	60	1	**12a** (0)	**12b** (63)
6	**13**: $R^1 = n\text{-}C_6H_{13}$, $R^2 = H$	60	1	complex mixture	

[a] Alkyne (2 mmol) was added to preactivated Pd(II) obtained by stirring a mixture of $Pd(OAc)_2$ (5 mol%), HQ-Cl (20 mol%), NPMoV (35 mg) and CH_3SO_3H (20 mg) in dioxane (10 mL) at 60 °C for 2 h and stirred at 60 °C for 1 ~ 5 h.

In the cyclotrimerization of alkynes by palladium catalysts, several modes of cyclization are reviewed by Maitlis and Hosokawa *et al.*[10] The processes involved in the reaction differ considerably according to the palladium species and the kind of alkynes used.

Owing to the complexity of the present multi-catalytic system employed and the difficulty of isolating any active intermediate from the catalytic solutions, it is difficult at this stage to make an accurate assessment of the palladium species involved in this reaction. However, we can make several proposals which seem to agree with the experimental results.

When a mixture of $Pd(OAc)_2$, HQ-Cl and CH_3SO_3H in dioxane was stirred at 60 °C for several minutes, a black precipitate, which appears to be the Pd(0) species, was generated. When the NPMoV was added to this solution under oxygen atmosphere, the precipitate was gradually dissolved to give a transparent brown solution. We assume that this color change reflects the slow oxidation of Pd(0) to Pd(II) with chlorobenzoquinone (BQ-Cl) derived from HQ-Cl and NPMoV under dioxygen atmosphere. In fact, the reaction lacking O_2 or NPMoV from the present catalytic system produced no cyclotrimerization product. Therefore, an active palladium(II) complex, $L_nPd(II)^*$, whose structure is not confirmed, is considered to be formed by treating $Pd(OAc)_2$ with HQ-Cl / CH_3SO_3H / NPMoV / O_2 in dioxane at around 60 °C, and it promotes the trimerization of alkynes.

In summary, it was found that a new catalytic cyclotrimerization of some internal and terminal alkynes to polyalkylbenzenes can be successfully achieved by using Pd(II) / HQ-Cl / NPMoV system under dioxygen atmosphere.

Attempts to reveal an active species and the reaction mechanism are now in progress.

Acknowledgment: This work was supported by Research for the Future program JSPS (JSPS-RFTF96P00301).

References and Notes

1. Recent works on the transition-metal catalyzed cyclotrimerization of alkynes are shown in references 2 to 8.
2. Hill, J. E.; Balaich, G.; Fanwick, P. E.; Rothwell, I. P. *Organometallics*, **1993**, *12*, 2911-2924.
3. Jerome, K. S.; Parsons, E. J. *Organometallics*, **1993**, *12*, 2991-2993.
4. Van der Linden, A. J.; Schaverien, C. J.; Meijboom, N.; Ganter, C.; Orpen, A. G. *J. Am. Chem. Soc.* **1995**, *117*, 3008-3021.
5. Taber, D. F.; Rahimizadeh, M. *Tetrahedron Lett.* **1994**, *35*, 9139-9140.
6. Jhingan, A. K.; Maier, W. F. *J. Org. Chem.* **1987**, *52*, 1161-1165.
7. Masuda, T.; Deng, Y.; Higashimura, T. *Bull. Chem. Soc. Jpn.*, **1983**, *56*, 2798-2801.
8. (a) Smith, D. P.; Stricker, J. R.; Gray, S. D.; Bruck, M. A.; Holmes, R. S.; Wigley, D. E. *Organometallics*, **1992**, *11*, 1275-1288.
   (b) Gambarotta, S.; Wielstra, Y.; Meetsma, A.; de Boer, J. L. *Organometallics*, **1989**, *8*, 2696-2702.
9. Bianchini, C.; Caulton, K. G.; Chardon, C.; Doublet, M.-L.; Eisenstein, O.; Jackson, S. A.; Johnson, T. J.; Meil, A.; Peruzzini, M.; Streib, W. E.; Vacca, A.; Vizza, F. *Organometallics*, **1994**, *13*, 2010-2023.
10. (a) Maitlis, P. M. *The Organic Chemistry of Palladium;* Academic Press New York, **1971**, Vol II, 47-58.
    (b) Maitlis, P. M. *Pure Appl. Chem.* **1973**, *33*, 489-512.
    (c) Hosokawa, T.; Calvo, C.; Lee, H. B.; Maitlis, P. M. *J. Am. Chem. Soc.* **1973**, *95*, 4914-4923.
11. Yokota, T.; Fujibayashi, S.; Nishiyama, Y.; Sakaguchi, S.; Ishii, Y. *J. Mol. Catal. A : Chemical*, **1996**, *114*, 113-122.

(*Received in Japan* 6 *March* 1997; *revised* 17 *April* 1997; *accepted* 21 *April* 1997)