Organometallics **2007,** *26,* 20−21

Aliphatic Carbon−Carbon Bond Activation of Nitriles by Rhodium(II) Porphyrin

Kin Shing Chan,* Xin Zhu Li, Chun Wah Fung, and Lirong Zhang

Department of Chemistry, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong, People's Republic of China

Received September 10, 2006

Summary: The aliphatic C(α)−C(β) bonds of a series of nitriles were activated by Rh(tmp) using Ph_3P as the promoting ligand from 100 to 130 °C. Kinetic studies at 130 °C revealed the rate law, rate $= k'K_1[\mathrm{Rh(tmp)}][\mathrm{Ph_3P}]^n + k_3K_2(K_1[\mathrm{Ph_3P}])/(1 + K_1[\mathrm{Ph_3P}])[\mathrm{Rh(tmp)}][{}^t\mathrm{BuCN}]$ *and suggested the carbon−carbon bond activation occurred at the coordinated ^{t}BuCN with Rh(tmp) in a 1:1 ratio in the transition state.*

Carbon−carbon bond activation (CCA) by a transition-metal complex is an active and challenging research area.[1] Selective aliphatic CCA is difficult and is often associated with competitive carbon−hydrogen bond activation (CHA).[1] The activation of the C(α)−CN bond in alkyl or aryl nitriles is of great interest, because the alkyl or aryl metal cyanides formed have been proposed as intermediates in a number of important catalytic processes such as cyanation of aryl halides,[2] utilization of aryl cyanides for cross-coupling,[3] arylcyanation of alkynes,[4] and methylation using acetonitrile.[5] Most reports of CCA of nitriles by transition-metal complexes show that it occurs at the C(α)−CN bonds[6] rather than at the aliphatic C(α)−C(β) bonds. The more facile C(α)−CN activation may likely be steric in origin, since the bond energies of C(α)−CN (103−125 kcal mol^{-1}) are higher than those of C(α)−C(β) bonds (60−83 kcal mol^{-1}).[7] The formation of a strong metal cyanide may also contribute to the driving force of the activation.

We have reported that rhodium(II) *meso*-tetramesitylporphyrin (**1**; Rh(tmp)[8]) activates the aliphatic carbon−carbon bonds in nitroxides[9] and ketones.[10] In expanding the scope of the aliphatic CCA, we have investigated the reactions of Rh(tmp) with alkyl nitriles. Herein, we report the discovery of the selective and ligand-enhanced aliphatic CCA at the C(α)−C(β) positions of nitriles as well as results of mechanistic studies.

Table 1. Optimization of CCA Conditions

entry	amt of PPh_3 (equiv)	temp (°C)	reaction time (h)	product (yield[a] (%))
1	0	130	120	Rh(tmp)Me (trace)
2	1	110	60	Rh(tmp)Me (20)
3	1	130	60	Rh(tmp)Me (52)
4	1	150	48	Rh(tmp)Me (30) Rh(tmp)Et (16)

[a] Average yield of at least two runs.

When the prototypical substrate of *tert*-butyl cyanide was reacted with Rh(tmp) in benzene at 70 °C for 2 days, no reaction was observed. When the reaction temperature was increased to 130 °C, a trace of Rh(tmp)Me was detected (Table 1, entry 1 and eq 1). Further optimization of CCA was achieved by the

$$\underset{\mathbf{1}}{\mathrm{Rh(tmp)}} + \underset{\text{5 equiv}}{{}^t\mathrm{BuCN}} \xrightarrow{C_6H_6,\ N_2} \underset{\mathbf{2}\ \text{(trace to 52\%)}}{\mathrm{Rh(tmp)Me}} \qquad (1)$$

addition of Ph_3P to form a more electron-rich and reactive Rh(tmp)Ph_3P.[10,11] At 110 °C, when 1 equiv of Ph_3P was used, 20% of Rh(tmp)Me was obtained in 120 h. At 130 °C, a higher yield (52%) of Rh(tmp)Me was isolated in 60 h. However, at 150 °C, the reaction gave a mixture of Rh(tmp)Me (30%) and Rh(tmp)Et (16%). The formation of Rh(tmp)Et was rationalized from the reaction of Rh(tmp)Me with Rh(tmp) to give Rh(tmp)-CH_2, which further reacted with Rh(tmp)Me to give Rh(tmp)-Et. Indeed, Rh(tmp) reacted with Rh(tmp)Me at 150 °C in 60 h to give 26% Rh(tmp)Et and recovered Rh(tmp)Me in 43%. Therefore, the CCA of *tert*-butyl cyanide appears to have a narrow temperature range from about 110 to 130 °C.

The optimized reaction conditions were then applied to a series of nitriles (eq 2), and Table 2 gives the results. Except in

$$\mathrm{Rh(tmp)} + \underset{\text{5 equiv}}{\mathrm{R{-}CN}} \xrightarrow[130\ ^\circ\mathrm{C},\ 24-60\ \mathrm{h}]{PPh_3,\ C_6H_6,\ N_2} \mathrm{Rh(tmp)Me} \qquad (2)$$

CH_3CN, which underwent C(α)−CN activation to give a low yield of Rh(tmp)Me (Table 2, entry 1), all of the other nitriles showed selective aliphatic C(α)−C(β) CCA. The yields and rates of reactions increased with decreasing C(α)−C(β-Me)

---

* To whom correspondence should be addressed. E-mail: ksc@cuhk.edu.hk.

[1] Crabtree, R. H. *Chem. Rev.* **1985**, *85*, 245−269. (b) Murakami, M.; Ito, Y. In *Topics in Organometallic Chemistry*; Murai, S., Ed.; Springer: Berlin, 1999; Vol. 3, pp 97−129. (c) Rybtchinski, B.; Milstein, D. *Angew. Chem., Int. Ed.* **1999**, *38*, 870−883. (d) Jun, C.-H. *Chem. Soc. Rev.* **2004**, *33*, 610−618.

[2] For a recent review: Sundermeier, M.; Zapf, A.; Beller, M. *Eur. J. Inorg. Chem*. **2003**, 3513−3526.

[3] (a) Miller, J. A. *Tetrahedron Lett.* **2001**, *42*, 6991−6993. (b) Miller, J. A.; Dankwardt, J. W. *Tetrahedron Lett.* **2003**, *44*, 1907−1910. (c) Miller, J. A.; Dankwardt, J. W.; Penney, J. M. *Synthesis* **2003**, 1643−1648. (d) Penney, J. M.; Miller, J. A. *Tetrahedron Lett.* **2004**, *45*, 4989−4992.

[4] Nakao, Y.; Oda, S.; Hiyama, T. *J. Am. Chem. Soc.* **2004**, *126*, 13904−13905.

[5] Nakazawa, H.; Kamdata, K.; Itazaki, M. *Chem. Commun*. **2005**, 4004−4006.

[6] (a) Brunkan, N. M.; Brestensky, D. M.; Jones, W. D. *J. Am. Chem. Soc.* **2004**, *126*, 3627−3641. (b) García, J. J.; Arévalo, A.; Brunkan, N. M.; Jones, W. D. *Organometallics* **2004**, *23*, 3997−4002. (c) Taw, F. L.; Mueller, A. H.; Bergman, R. G.; Brookhart, M. *J. Am. Chem. Soc.* **2003**, *125*, 9808−9813. (d) Lu, T.; Zhuang, X.; Li, Y.; Chen, S. *J. Am. Chem. Soc.* **2004**, *126*, 4760−4761.

[7] (a) McMillen, D. F.; Golden, D. M. *Annu. Rev. Phys. Chem.* **1982**, *33*, 493−532. (b) Luo, Y. R. *Handbook of Bond Dissociation Energies in Organic Compounds*, 1st ed.; CRC Press: Boca Raton, FL, 2003.

[8] (a) Wayland, B. B.; Ba, S.; Sherry, A. E. *J. Am. Chem. Soc.* **1991**, *113*, 5305−5311. (b) Tse, M. K.; Chan, K. S. *Dalton Trans*. **2001**, 510−511.

[9] Zhang, L.; Chan, K. S. *J. Organomet. Chem.* **2006**, *691*, 3782−3787.

[10] Mak, K. W.; Yeung, S. K.; Chan, K. S. *Organometallics* **2002**, *21*, 2362−2364.

[11] Formation of a 1:1 Rh(tmp)−ligand complex has been reported: (a) Wayland, B. B.; Sherry, A. E. Bunn, A. G. *J. Am. Chem. Soc.* **1993**, *115*, 7675−7684. (b) Collman, J. P.; Boulvtov, R. *J. Am. Chem. Soc*. **2000**, *122*, 11812−11821.

10.1021/om060828f CCC: $37.00

Table 2. CCA of Nitriles with Rh(tmp)

entry	nitriles	C(α)−C(β) BDE[7] (kcal mol^{-1})	time (h)	yield[a] (%)
1	MeCN		60	10
2	EtCN	83.2	48	38
3	Me_2CHCN	79.5	48	41
4	Me_3CCN	74.7	24	52
5	$Me_2C(CN)_2$	76	48	47
6	PhMeCHCN	63	36	48
7	$PhMe_2CCN$	59.9	24	61
8	Ph_2MeCCN		36	38
9	$4\text{-}MeC_6H_4CMe_2CN$		24	57
10	$4\text{-}CF_3C_6H_4CMe_2CN$		24	65

[a] Average isolated yield of at least two runs.

bond dissociation energy (BDE).[7] The absence of Rh(tmp)Ph suggests that the reaction goes through a radical[12] rather than a concerted oxidative addition process via an elusive Rh(IV).[13,14] The slight decrease in reactivity in Ph_2MeCCN as compared to that in $PhMe_2CCN$ (Table 2, entry 8 vs 7) can be accounted for by an increase in large steric hindrance caused by the phenyl group. The electron-withdrawing CF_3 appeared to increase the yield of Rh(tmp)Me slightly to 65% in comparison to the more electron rich Me-substituted species (Table 2, entries 9 and 10 vs 7).

Competitive carbon−hydrogen bond activation at the benzylic or aliphatic hydrogens did not likely occur to give Rh(tmp)H.[15] If there were any Rh(tmp)H formed, $PhMe_2CCH{=}NH[Rh(tmp)]$ would have been observed, as Rh(tmp)H was found to react with $PhMe_2CCN$ to give $PhMe_2CCH{=}NH[Rh(tmp)]$ in 27% yield at 130 °C in 24 h. The absence of other tertiary Rh alkyls is likely due to the instability of the tertiary rhodium macrocycle caused by steric hindrance.[16]

Kinetic studies were carried out to gain further mechanistic insight into the CCA. First, the stoichiometry and binding constants of Ph_3P with Rh(tmp) were measured spectrally at 522 nm from 20 to 50 °C (Table S1 and Figure S1, Supporting Information) and analyses of the data confirmed the formation of 1:1 complex and yielded $K_{1,130\ °C}$(extrapolated) $= 10.7\ M^{-1}$ ($=k_1/k_{-1}$), $\Delta H_1 = -12 \pm 1$ kcal mol^{-1}, and $\Delta S_1 = -26 \pm 2$ cal mol^{-1} K^{-1} (Figure S2, Supporting Information).

Kinetic measurements of the reaction of Rh(tmp) and ^tBuCN with excess Ph_3P carried out spectrally at 522 nm under the conditions 130 °C and initial concentrations $(5.55-16.65) \times 10^{-5}$ M Rh(tmp), $(2.97-8.90) \times 10^{-3}$ M ^tBuCN, and 1.10×10^{-3} M Ph_3P for at least 4 half-lives yielded the rate law shown in eq 3.

$$-d[Rh(tmp)]/dt = k'K_1[Rh(tmp)]_0[Ph_3P]^n + k_3K_2(K_1[Ph_3P])/(1 + K_1[Ph_3P])[Rh(tmp)]_0[^tBuCN] \quad (3)$$

The rate is composed of two parallel processes, with the first process being ^tBuCN independent and the second one ^tBuCN dependent (Figures S3−5 and Table S2, Supporting Information). Since Rh(tmp) was stable in benzene at 130 °C for 2 days (Figure S6, Supporting Information), the ^tBuCN-independent reaction was found to be dependent on Ph_3P, as evidenced by the spectral change of $Ph_3Rh(tmp)$ at 130 °C (Figure S7, Supporting Information). We rationalized that $Ph_3PRh(tmp)$ undergoes disproportionation (k') to $Rh^I(tmp)^-$ and $(Ph_3P)_2Rh^{III}(tmp)^+$ at high temperature.[11,17,18] For the ^tBuCN-dependent process relevant to aliphatic CCA, the rate was found to be first order in both Rh(tmp) and ^tBuCN and exhibited saturation kinetics in excess Ph_3P.[14]

A proposed mechanism for CCA conforming to the kinetic evidence is depicted in Scheme 1. Initially, facile coordination of Ph_3P with Rh(tmp) occurs to give $Ph_3PRh(tmp)$ (k_1), which is then complexed by ^tBuCN to give $Ph_3PRh(tmp)^tBuCN$ (k_2). The mode of nitrile coordination is likely N-bound rather than side-bound, to minimize steric hindrance. Subsequently, Rh abstracts the methyl group of loosely bound ^tBuCN to yield $Ph_3PRh(tmp)Me$ in the transition state in the rate-determining step (k_3), which is in contrast with the termolecular transition state in the activation of methane by Rh(tmp).[8,15] The fate of the nitrile-containing fragment, presumably a carbon-centered radical, remains unclear. We were not able to detect any coupling product of $(NCMe_2C)_2$ in the reaction mixture of Rh(tmp) with ^tBuCN by GC-MS. Presumably, $NCMe_2C$ readily abstracts a hydrogen atom rather than coupling with either itself or Rh(tmp).[19,20]

Scheme 1

$$Rh(tmp) + Ph_3P \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} Ph_3PRh(tmp) \quad (4)$$

$$Ph_3PRh(tmp) + Me_3CCN \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} Ph_3PRh(tmp)NCCMe_3 \quad (5)$$

$$Ph_3PRh(tmp)NCCMe_3 \xrightarrow[\text{rds}]{k_3} Ph_3PRh(tmp)Me + Me_2CCN \quad (6)$$

$$Ph_3PRh(tmp)Me \xrightarrow[\text{fast}]{} Rh(tmp)Me + Ph_3P \quad (7)$$

In summary, the selective aliphatic C(α)−C(β) bonds of a series of nitriles have been activated by Rh(tmp) using PPh_3 as the promoting ligand. The CCA was affected by bond energy, steric hindrance, and the small electronic effect of aryl acetonitriles. No C(aryl)−C(α) bond nor CH activation was observed. Further studies of bond activation are ongoing.

Acknowledgment. We thank the Research Grants Council of Hong Kong of the SAR of China for financial support (No. 400203).

Supporting Information Available: Text, tables, and figures giving experimental details and kinetic data. This material is available free of charge via the Internet at http://pubs.acs.org.

OM060828F

---

(12) (a) Ingold, K. U.; Roberts, B. P. *Free Radical Substitution Reactions*; Wiley: New York, 1971. (b) Davis, A. G.; Roberts, B. P. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 2, pp 547−589.

(13) Pestovsky, O.; Bakac, A. *Inorg. Chem.* **2002**, *15*, 3975−3982.

(14) Chan, K. S.; Zhang, L.; Fung, C. W. *Organometallics* **2004**, *23*, 6097−6098.

(15) (a) Cui, W.; Zhang, X. P.; Wayland, B. B. *J. Am. Chem. Soc.* **2003**, *125*, 4994−4995. (b) Cui, W.; Wayland, B. B. *J. Am. Chem. Soc.* **2004**, *126*, 8266−8274.

(16) Giese, B.; Hartung, J.; Kesselheim, C.; Lindner, H. J.; Svoboda, I. *Chem. Ber.* **1993**, *12*6, 1193−1200.

(17) Wayland, B. B.; Balkus, K. J., Jr.; Franos, M. D. *Organometallics* **1989**, *8*, 950−955.

(18) The kinetic order of Rh(tmp) was preliminarily estimated from the first-order fit of the absorbance change. We did not investigate the kinetic order of Ph_3P: i.e., *n* in eq 3.

(19) No $^tBuRh(tmp)$ was observed in the reaction of ^tBuNC with Rh(tmp).[11a] The formation of $Rh(tmp)CMe_2CN$ is likely sterically hindered.

(20) Reaction of $BrCMe_2CN$ with Rh(tmp) gave Rh(tmp)Br but no $Rh(tmp)CMe_2CN$. However, the sterically less hindered $BrCH_2CN$ reacted with Rh(tmp) at room temperature in 1 h to give Rh(tmp)Br and $Rh(tmp)CH_2CN$ in 38 and 47%, yields, respectively. These reactions demonstrated the importance of steric effects in coupling.