Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Molecular Catalysis A: Chemical 246 (2006) 237–241

JOURNAL OF MOLECULAR CATALYSIS A: CHEMICAL

www.elsevier.com/locate/molcata

Stable catalyst for intermolecular Pauson–Khand reaction

José Luis Arias [a,*], Armando Cabrera [b], Pankaj Sharma [b], Noe Rosas [b], Rafael Sampere [a]

[a] *Facultad de Estudios Superiores Cuautitlán, Universidad Nacional Autónoma de México, Cuautitlán Izcalli, C.P. 54700, Estado de México, México*
[b] *Instituto de Química, Universidad Nacional Autónoma de México, Ciudad Universitaria, Circuito Exterior, Coyoacán, 04510 México D.F., México*

Received 1 September 2005; received in revised form 2 September 2005; accepted 7 November 2005
Available online 13 December 2005

Abstract

The catalytic activity of previously formed $Co_2(CO)_6[P(Ph)_3]_2$ (**1**) was compared with $Co_2(CO)_8$ and the system formed by $Co_2(CO)_8$ plus PPh_3 in the intermolecular Pauson–Khand (PK) reaction between norbornadiene and phenylacetylene. The effects of pressure, catalyst concentration and temperature were also studied. Additionally, the catalytic activity of complex **1** was compared with $Co_2(CO)_6[P(OPh)_3]_2$ (**2**) in the intermolecular PK reaction between strained alkenes and terminal and non-terminal alkynes. Both catalysts are very stable, quite efficient and interestingly complex **2** leads to double PK reaction. The results indicate that these complexes are attractive alternatives to $Co_2(CO)_8$ as catalyst and in addition, complex **2** is an alternative catalyst for double cyclocarbonylation reaction.

Keywords: Pauson–Khand reaction; Homogeneous catalysis; Octacarbonyl dicobalt; Phosphine modified catalysts; Cyclocarbonylation

1. Introduction

The Pauson–Khand (PK) reaction is a powerful synthetic tool that involves 2 + 2 + 1 cycloaddition of an alkyne, an alkene and carbon monoxide to produce cyclopentenones.

The reaction was widely practiced using stoichiometric amounts of octacarbonyl dicobalt [1–3]. Recent advances in the development of catalysts have extended the application of the reaction, catalysts include complexes of Co, Rh [3,4], Ni [5], Ti [3,6], Mo [7], Fe [8] and Ru [3,9], but still cobalt carbonyls are of special interest [10–12]. For the success of the reaction using different cobalt systems, rigorous purification of $Co_2(CO)_8$ is essential which may be achieved through modifications, such as recrystallization of $Co_2(CO)_8$, opening a fresh commercial sample in glove box or prior base washing of the glassware and introduction of cyclohexylamine. Persistent problems associated with the stability and handling of $Co_2(CO)_8$ led to the development of stable alkyne cobalt complexes as catalyst precursors [13–15]. In continuation with this, very recently two reports have appeared where preformed stable phosphine and phosphite cobalt carbonyl complexes were used as catalysts for PK reaction under atmospheric pressures of CO [16,17]. These reports claimed $Co_2(CO)_7PPh_3$ in particular, being the most robust catalyst for the catalytic Pauson–Khand reaction (CPKR). Herein we wish to report the scope and limitations of preformed $Co_2(CO)_6[P(Ph)_3]_2$ and $Co_2(CO)_6[P(OPh)_3]_2$ catalysts for the intermolecular CPKR which provide an attractive alternative to the currently available catalysts.

2. Experimental

2.1. Hexacarbonyl-bis-(triphenylphosphine) dicobalt and hexacarbonyl-bis-(triphenoxyphosphine) dicobalt

Octacarbonyl dicobalt was purchased from Strem Chemical whereas triphenylphosphine and triphenoxyphosphine were obtained from Aldrich. Octacarbonyl dicobalt (1 g, 2.92 mM) was dissolved in anhydrous THF (40 mL), previously purified by distillation under argon from sodium benzophenone ketyl, in a dry Schlenk flask under nitrogen. Triphenylphosphine (1.53 g, 5.84 mM) was slowly added, ligand:carbonyl molar ratio 2:1, and the mixture was stirred at room temperature for 8 h. After this the solution was filtered and the red-brown solid was washed with hexane and CH_2Cl_2, in order to remove unreacted triphenylphosphine and octacarbonyl dicobalt. The product $Co_2(CO)_6[P(Ph)_3]_2$ **1** is a stable solid (2.16 g, 2.6 mM, yield 89.04%) which can be maintained at environmental conditions for a long time.

---

[*] Corresponding author. Tel.: +52 5 622 4515; fax: +52 616 2217.
E-mail address: jlartell@servidor.unam.mx (J.L. Arias).

1381-1169/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.molcata.2005.11.012

Similar procedure was used for the preparation of $Co_2(CO)_6[P(OPh)_3]_2$ **2**, in this case octacarbonyl dicobalt (1 g, 2.92 mM) was combined with triphenoxyphosphine (1.81 g, 5.84 mM). The stable complex was obtained after removing the reaction solvent under reduced pressure (1.89 g, 2.08 mM, yield 71.23%). Both synthesis were performed under inert conditions using Schlenk techniques [18].

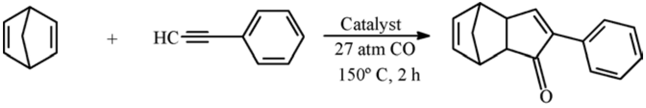
2.2. *Catalytic procedures*

(a) In a 45 mL Parr reactor model 4712, a solution of **1** (47 mg, 5.8×10^{-2} mM) in CH_2C1_2 (5 mL) was prepared, later norbornadiene (0.5 mL, 5 mM) and phenylacetylene (0.6 mL, 5 mM) were added to this solution. Then the reactor was closed, pressurized with 27 atm of CO and submerged in an oil bath warmed at 150 °C for 2 h. After 2 h, the reactor was cooled (final pressure at room temperature 24.5 atm), CO pressure was liberated and the reactor was opened, the solution obtained was flash chromatographied through a column packed with alumina and the resulting reddish solution was analyzed on a Hewlett Packard 5895B GC–MS equipment with a 25 m × 0.3 mm glass column packed with 5% phenyl silicone and quantified by GC on a Hewlett Packard 5890 analyzer with a 20 m × 0.2 mm glass column packed with carbowax 20 M.

(b) The last technique was performed when $Co_2(CO)_8$ (20 mg, 5.8×10^{-2} mM) or the system $Co_2(CO)_8$ (20 mg, 5.8×10^{-2} mM) plus PPh_3 (30.4 mg, 1.16×10^{-1} mM) were used as catalysts.

(c) *Double PK reaction*: The reaction mixture in the reactor was formed by phenylacetylene (0.6 mL, 5 mM), norbornadiene (0.5 mL, 5 mM) and complex **2** (49 mg, 5.8×10^{-2} mM) as catalyst in CH_2Cl_2 (5 mL). Then the reactor was closed, pressurized with 27 atm of CO and submerged in an oil bath warmed at 150 °C for 2 h. After 2 h, the reactor was cooled and was maintained for 24 h at room temperature under the remnant pressure. The reactor was depressurized and opened, crystalline product along with solution was obtained. The solution was filtered and the crystals were washed with acetone. These crystals correspond to the tetracycle compound (42.14% double PK reaction product). The filtrate was concentrated and the remaining solid was purified through flash chromatography using alumina as support and AcOEt as eluent affording 9.35% of simple PK reaction product. All these catalytic procedures, except those techniques in part (b), were carried out dispensing with an inert atmosphere. The ^1H and ^{13}C NMR spectra of the isolated compounds, were obtained in a Jeol spectrometer, using $(CH_3)_4Si$ as internal reference in $CDCl_3$ as solvent at 25 °C. IR spectra were obtained on a Nicolet 5 SX spectrometer employing pellets and solution techniques. X-ray structure of 4,10-diphenyl tetracyclo[5.5.1.$0^{2,6}$.$0^{8,12}$]4,10-tridecadien-3,9-dione was determined on a Bruker Smart APEX AXS CCD using graphite monochromated radiations. The structure was refined by full matrix least-squares calculations on F^2 with the aid of the program SHELX97 [19].

Table 1
Catalytic runs of the intermolecular Pauson–Khand reaction



Entry	Catalyst	Product (%)	Total conversion (%)[a]
1	$Co_2(CO)_8$	87.97	93.17
2	$Co_2(CO)_8/PPh_3$[b]	68.75	85.86
3	$Co_2(CO)_6[P(Ph)_3]_2$	90.82	90.83

[a] This value indicate product and by-products.

[b] Octacarbonyldicobalt and triphenylphosphine were added to the reaction mixture.

3. Results and discussion

3.1. *Catalytic species*

Complexes **1** and **2** are stable and can be maintained for long time at ambient conditions without decomposition. IR spectra of these complexes show the absence of CO bridging bands and exhibit only one strong band, located at 1946 and 1968 cm^{-1} for **1** and **2**, respectively, suggesting symmetrical structures in which both phosphine ligands are in the axial position. The catalytic activity of complex **1** was compared with the activity of $Co_2(CO)_8$ and $Co_2(CO)_8 + PPh_3$ system. Table 1 shows the yield of cyclopentenone derivatives produced when $Co_2(CO)_8$ was employed as catalyst (entry 1), when PPh_3 was added to the mixture reaction (entry 2) and when the preformed catalyst **1** was utilized (entry 3).

The results indicate that $Co_2(CO)_8$ is a good catalyst, with the highest transformation (93.17%), whereas PPh_3 addition to the catalyst $Co_2(CO)_8$, in the second system, generates a less active catalytic system which just produces 85.86% of total conversion with 68.75% of selectivity towards the cyclopentenone. Problems of these reactions are: they must be run under no ambient conditions and produce small amounts of by-products which were not studied. On the other hand, complex **1** previously formed affords clean reactions using CH_2Cl_2 as solvent giving high yield and excellent selectivity, no other compounds were detected by GC analysis. Moreover, this complex appears to have similar activity to $Co_2(CO)_8$ but experimental manipulation does not require Schlenk technique. IR spectra of final solutions from 2 and 3 entries exhibit absorption bands at 1950 and 1951 cm^{-1}, respectively showing that both reactions are catalyzed by the same catalytic species, and most likely complex **1** is the active specie. The lower yield observed in the system $Co_2(CO)_8$ plus PPh_3 is undoubtedly owing to an induction time that requires the catalytic species to be formed. Whereas the IR spectra from entry 1 shows characteristic bands of bridging and no bridging species of $Co_2(CO)_8$.

In order to compare the catalytic activities of **1** and **2** across a range of substrates including terminal and non-terminal alkynes, a standard set of experimental conditions was established by varying some reaction parameters.

Table 2
Influence of the $Co_2(CO)_6[P(Ph)_3]_2$ concentration on the CPKR

Entry	[Catalyst]	Product (%)	Ratio[a]
4	0.029	35.81	200
5	0.058	90.82	100
6	0.087	96.06	50
7	0.116	98.25	25

[a] Alkene/catalyst or alkyne/catalyst.

Table 3
Influence of the CO pressure on the PKR catalyzed by $Co_2(CO)_6[P(Ph)_3]_2$

Entry	CO pressure (atm)	Product (%)
8	–[a]	3.10
9	13.6	42.27
10	27.2	90.82
11	40.8	94.07
12	54.4	96.65

[a] Atmospheric pressure.

3.2. Effect of $Co_2(CO)_6[P(Ph)_3]_2$ concentration

To study the influence of catalyst amount on cyclopentenone yield, catalyst concentration was modified from 0.029 to 0.116 mM as shown in Table 2, and it was found that alkene/catalyst or alkyne/catalyst ratio equals to 100 give very good yields (entry 5). By using lower amounts of catalyst (entry 4), 35.81% of product was obtained and by increasing the catalyst concentration (until 0.116 mM), only a slight increment of product yield was observed (entry 7). These results show that the catalyst is reliable on a very modest CPKR scale 0.058 mM.

3.3. Effect of CO pressure

It was observed that at atmospheric pressure, the yield was insignificant and the product concentration increases with the increase of CO pressure, but after 27.2 atm (entry 10) the yield seems to be constant (Table 3).

3.4. Influence of temperature and time

When the reaction was carried out at 90, 120 and 150 °C, 35.83, 51.84 and 90.82% of product, respectively was obtained. In addition, the reaction was performed at different times, at 1 h 65.69% of cyclopentenone was obtained, whereas 2 h of reaction time gave 90.82% of product. Further increment of reaction time show very small increments in the product yield.

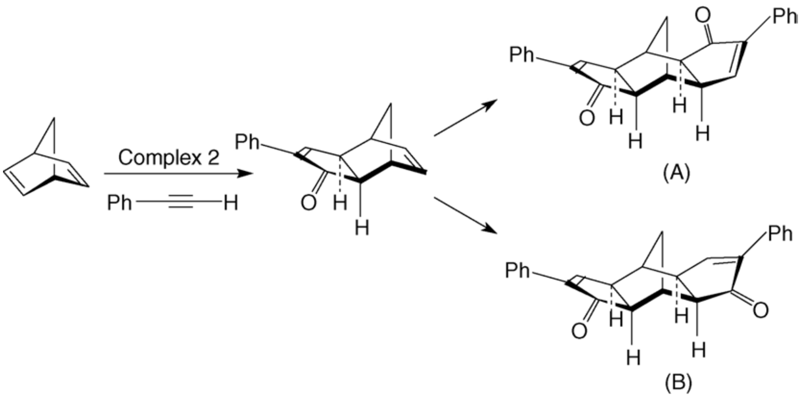
Table 4 shows the results of CPKR of norbornadiene or norbornene with different terminal/non-terminal alkynes catalyzed by cobalt modified complexes. It is very encouraging that the complexes **1** and **2** are much better catalysts even at 0.05 mM concentration (alkene, alkyne:catalysts 100:1) and give a very good product yield in 2 h. In comparison, a stable preformed $Co_2(CO)_7PPh_3$ catalyst [17], needs higher catalyst concentration (alkene, alkyne:catalyst 20:1) and the reaction is slow (4 h).

It shows that both alkenes/dienes react with terminal alkynes, the diene being more active and reacts almost quantitatively (entries 13a, 14a/14b) in contrast to the olefin (17a/17b and 18a/18b). The complex **2** is more active than complex **1**, and promotes a double PKR involving norbornadiene as substrate. Both complexes are ineffective to catalyze the reaction between alkenes and non-terminal alkynes, and in particular diphenylacetylene do not show any reaction. This may be due to steric hindrance introduced in the cobalt coordination sphere by the phosphine ligand and two phenyl substituents in the alkyne moiety.

As reported previously [23–25], in the CPKR ketones with *exo*-configuration are formed with specificity giving only two substituted ketones (Scheme 1).When complex **2** was used as catalyst, in addition to, monoketone which retain a norbornene system, reacts further with alkyne leads to the corresponding, *exo*-diketone in 42.14% yields with a 5:1 ratio of A and B products.

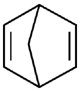
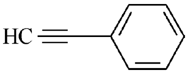
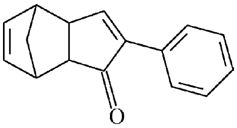
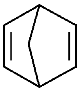
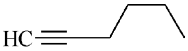
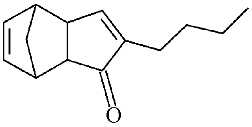
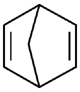
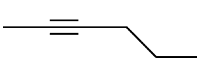
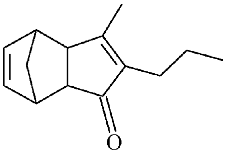
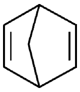
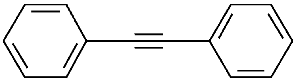
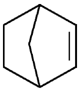
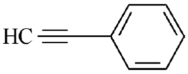
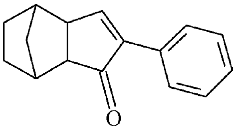
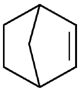
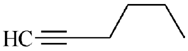
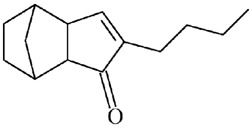
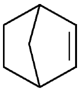
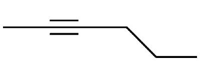
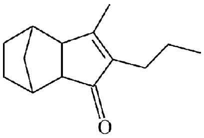
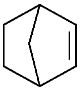
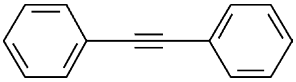
This complex in contrast to the complex **1** under this experimental condition allows a double CPKR. This product was previously detected when the reaction was carried out with an excess of alkyne, often two- or three-fold [26]. In this case, alkene/alkyne ratio is equal to 1 and the complex **2** favors the double PKR. The structure of tetracycle has been confirmed by X-ray [27] (Fig. 1), which has not been reported earlier and shows the regio and stereocontroled pathway involved in this reaction.

According to the known mechanism suggested for the PKR and on comparing with the experimental conditions used in this report, it is possible to suggest that these cobalt species



Scheme 1. Double Pauson–Khand favored by complex **2**.

Table 4
Intermolecular PKR catalyzed by $Co_2(CO)_6[P(Ph)_3]_2$ (a runs) or $Co_2(CO)_6[P(OPh)_3]_2$ (b runs)

Entries	Alkenes	Alkynes	Products[a]	Yield (%)
13a/13b				90.82/42.14[b]
14a/14b				94.89/96.38
15a/15b				5.13/5.82
16a/16b			–	–
17a/17b				58.66/74.86
18a/18b				62.85/73.51
19a/19b				1.03/2.34
20a/20b			–	–

Experimental conditions: alkyne (5 mM), alkene (5 mM), catalyst (0.05 mM), 27.2 atm CO, 150 °C, 2 h.

[a] Spectroscopic characterization of these compounds have been before reported [20–22].

[b] Yield of 13b correspond to a diketone and is based in diene.

can coordinate with both unsaturated substrates forming either alkyne–$Co(CO)_4L_2$ complex or alkene–$Co(CO)_4L_2$ complex and continue one or another to give the final cocyclization product. An experiment in the absence of alkyne under the established conditions was performed, after 2 h the reactor was depressurized and alkyne was added to the reaction mixture and was again pressurized with CO under the same conditions. The reaction did not offer significative yield of cyclopentenone and in consequence the alkene–$Co_2(CO)_4L_2$ complex can not be considered as a likely intermediate.

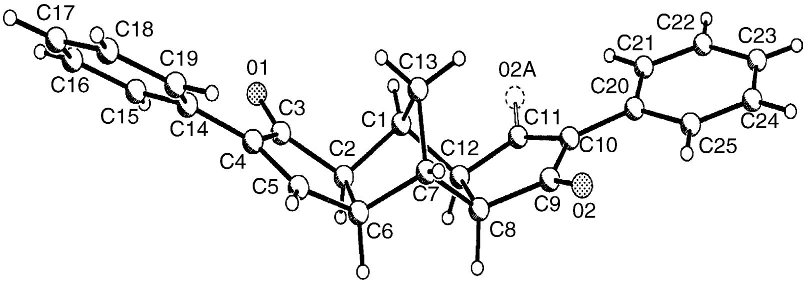


Fig. 1. Crystallographic structure of tetracycle compound.

4. Conclusion

In conclusion it is found that complexs **1** and **2** proved to be active catalyst as $Co_2(CO)_8$ for PK reaction under mild reaction conditions in a very short time with higher selectivity. In addition, complex **2** not only promotes this reaction, but remains active catalyst under the same experimental conditions for double PK reaction. These complexes could be considered very convenient substitutes of air sensitive $Co_2(CO)_8$ and much better than preformed $Co_2(CO)_7PPh_3$ [17] as a catalyst in respect to the catalyst concentration and reaction time probably because of following equilibria:

$$2Co_2(CO)_7PPh_3 \rightleftharpoons Co_2(CO)_6[P(Ph)_3]_2 + Co_2(CO)_8$$

Acknowledgement

We are grateful to DGAPA-UNAM (IN205302-3) for financial support of this research.

References

[1] D.L. Pauson, Tetrahedron 41 (1985) 5855.
[2] N.E. Schore, in: L.S. Hegedus (Ed.), Comprehensive Organometallic Chemistry II, vol. 12, 2nd ed., Pergamon, Oxford, 1995, p. 703.
[3] K.M. Brummond, J.L. Kent, Tetrahedron 56 (2000) 3263.
[4] T. Shibata, N. Toshida, K. Tagaki, Org. Lett. 4 (2002) 1619.
[5] K. Tamao, K. Kobayashi, Y. Ito, Synlett (1992) 539.
[6] S.C. Berk, R.B. Grosman, S.L. Buchwald, J. Am. Chem. Soc. 115 (1993) 4912.
[7] N. Jeong, S.L. Lee, B.Y. Lee, Y.K. Chung, Tetrahedron Lett. 34 (1993) 4027.
[8] A.J. Pearson, R.A. Dubbert, Organometallics 3 (1994) 1656.
[9] K. Villeneueve, N. Riddel, R.W. Jordan, G.C. Tsui, W. Tam, Org. Lett. 6 (2004) 4543.
[10] M.E. Krafft, L.V.R. Bonaga, Ch. Hirosawa, J. Org. Chem. 66 (2001) 3004.
[11] S.J. Son, Y.A. Yoon, D.S. Choi, J.K. Park, B.M. Kim, Y.K. Chung, Org. Lett. 3 (2001) 1065.
[12] M.R. Rivero, J.C. Carretero, J. Org. Chem. 68 (2003) 2975.
[13] B.L. Pagenkopt, T. Livinghouse, J. Am. Chem. Soc. 118 (1996) 2285.
[14] D.B. Belanger, J.R.O. O'Mahony, T. Livinghouse, Tetrahedron Lett. 39 (1998) 7637.
[15] D.B. Belanger, T. Livinghouse, Tetrahedron Lett. 39 (1998) 7641.
[16] A.C. Comely, S.E. Gibson, A. Stevenazzi, N.J. Hales, Tetrahedron Lett. 42 (2001) 1183.
[17] S.E. Gibson, C. Johnstone, A. Stevenazzi, Tetrahedron 58 (2002) 4937.
[18] D.F. Shriver, M.A. Dredzon, The Manipulation of Air Sensitive Compound, Wiley, Chichester, 1986.
[19] G.M. Sheldrick, SHELXTL-PC USER Manual Siemens Analytical X-Ray Instruments, Madison, WI, USA, 1990.
[20] M. Periasamy, M.R. Reddy, A. Devasagayaraj, Tetrahedron 50 (1994) 6955.
[21] J.W. Kim, Y.K. Chung, Synthesis (1998) 142.
[22] T. Sugihara, M. Yamaguchi, J. Am. Chem. Soc. 120 (1998) 10782.
[23] I.U. Khand, G.R. Knox, P.L. Pauson, W.E. Watts, M.I. Foreman, J. Chem. Soc. Perkin I (1973) 977.
[24] I.U. Khand, P.L. Pauson, J. Chem. Soc. Perkin I (1976) 30.
[25] S. MacWhorter, V. Sampath, M.M. Olmstead, N.E. Schore, J. Org. Chem. 53 (1988) 203.
[26] I.U. Khand, G.R. Knox, P.L. Pauson, W.E. Watts, J. Chem. Soc. Perkin I (1973) 975.
[27] Crystallographic data for the structure in this paper has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC263917. This data can be obtained free of charge via internet www.ccdc.cam.ac.uk/conts/retrieving.html or by sending an email to deposit@ccdc.cam.ac.uk.