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The production of low molecular weight oxygenates from carbon monoxide and ethene

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Contents

Abstract

Transition metal catalysed reactions of CO and ethene can lead to a variety of products ranging from small molecules to perfectly alternating long chain polyketones. In this review, we discuss the formation of small molecules with chain lengths up to 12 C atoms. Palladium based complexes of monodentate tertiary phosphines tend to give methyl propanoate under most conditions, but the selectivity can be varied by altering the electron donating power of the ligand or the nature of added acid co-catalysts. In addition to methyl propanoate, the major products can be co-oligomers, 3-pentanone or propanal. Using rhodium catalysts, the same products can be obtained, but the different selectivities depend upon the electron donating power of the ligand and the potential for chelate binding. In some cases, the extra H atoms required for the formation of 3-pentanone or oligoketones can be abstracted from the solvent, whereas in others they come from hydrogen formed by the water–gas shift reaction. The different reaction selectivities are discussed in terms of the reaction mechanisms operating. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Ethene; Carbon monoxide; Methyl propanoate; 3-Pentanone; Co-oligomerisation; Palladium; Rhodium

1. Introduction

Over the last few decades, the production of perfectly alternating polyketones using transition metal catalysts has attracted much interest with many eminent contributions to the field by Drent [1,2], Sen [3–6] and Keim [7]. These polymeric materials are synthesised using the readily available and inexpensive monomers, ethene and carbon monoxide. The properties of these highly crystalline perfectly alternating ethene–CO (E–CO) copolymers are more desired than those of the random copolymers which resulted from the free radical initiated [8] or γ-radiation induced methods [9] previously used. Some of these qualities include good solvent resistance and barrier properties as well as high stiffness, strength and melting point, which make the polymers suitable for a wide range of applications [10]. Reports of perfectly alternating ethene–CO copolymers are now ubiquitous in the literature and their production by Shell to give the Carilon material is now a commercial reality [10].

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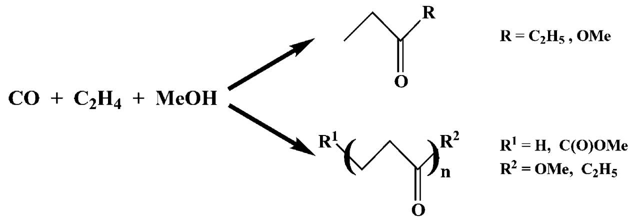
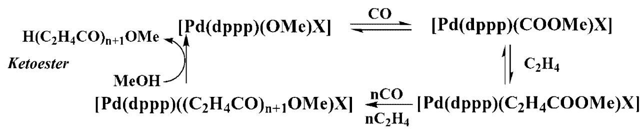


Scheme 1. Possible reaction products of ethene and carbon monoxide in methanol using transition metal catalysts.

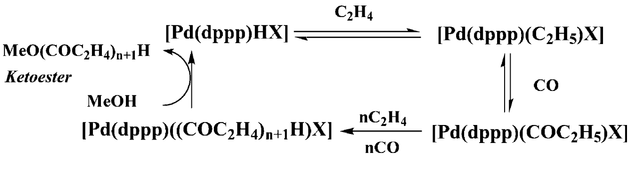
Scheme 2. Formation of active palladium precursor for the copolymerisation of ethene and carbon monoxide (X is a weakly coordinating anion).

$$[\mathrm{Pd(dppp)X_2}] + \mathrm{MeOH} \longrightarrow [\mathrm{Pd(dppp)(OMe)X}] + \mathrm{HX}$$

Scheme 3. Formation of active methoxide complex.



Scheme 4. Palladium catalysed ketoester formation via the carbomethoxy cycle.



Scheme 6. Palladium catalysed ketoester formation via hydride cycle.

However, the production of short chain E–CO co-oligomers is less well covered [11–13]. These materials belong to a class of compounds called oxygenates, which can be employed as solvents for a variety of purposes. Many oxygenates that are readily available from simple processes are volatile and hence potentially polluting. There is a demand for the production of less volatile oxygenates for use as environmentally friendly solvents and their production from cheap starting materials would be especially appealing. E–CO co-oligomers with up to 11 or more atoms in their backbone such as 3,6-octanedione or 3,6,9-undecanetrione are low volatility compounds with high solvating ability and so meet these current demands. In this review, we examine catalytic systems which show selectivity to the co-oligomers or to the first members of the series, 3-pentanone or alkyl propanoates ($n = 1$) (Scheme 1). We do not cover the production of perfectly alternating copolymers in detail, nor of the hydroformylation of ethene, which are both commercial processes.

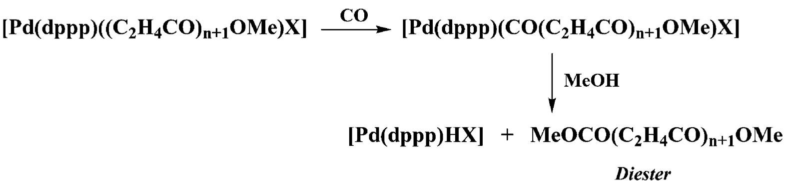
Gough at ICI disclosed the first example of palladium catalysed alternating copolymerisation of ethene and CO in 1967 [14]. However, the process suffered from severe reaction conditions (250 °C and 2000 bar) and relatively low rates. In the early 1980s, a breakthrough occurred in this field at Shell Research in Amsterdam with the report by Drent et al. of a dicationic palladium–diphosphine system that produced perfectly alternating ethene–CO copolymer with high rates and essentially 100% selectivity [1] (Scheme 2).

The most efficient catalyst system was formed from an equimolar amount of 1,3-bis(diphenylphosphino)propane (DPPPr) and $[\mathrm{Pd(OAc)_2}]$ upon the addition of 2 equivalents of a Bronsted acid such as HBF_4 or HO_3STol. The resulting complex, $[\mathrm{Pd(DPPPr)X_2}]$ ($X = BF_4$, O_3STol) formed by displacement of the acetate anions, contains weakly coordinating anions which can be readily displaced by nucleophiles such as monomers or solvent molecules.

The reaction with methanol forms a methoxide complex, (Scheme 3) which initiates the so-called carbomethoxy cycle (Scheme 4). Termination of the alkyl intermediates after multiple monomer insertions generates polymeric ketoesters and reforms the methoxide complex.

Alternatively, methanolysis of the acyl intermediates leads to diesters and formation of an active Pd hydride species (Scheme 5). Generation of this hydride species allows crossover from the carbomethoxy to the hydride cycle, from which ketoesters and diketones result (Scheme 6). Crossover from the hydride cycle to the carbomethoxy cycle occurs by protonation of the alkyl intermediate to give the diketone products (Scheme 7).

The high activity displayed by the $[\mathrm{Pd(DPPPr)X_2}]$ system was attributed to optimal stabilisation by this ligand (containing three bridging methylenes) of both the square planar ground state and the trigonal bipyra-



Scheme 5. Diester formation via methanolysis of acyl intermediate (carbomethoxy cycle).

midal transition state which is believed to result during substitution and nucleophilic attack. Efficient catalysis resulted due to the low energy barrier between these two states. The cationic nature of these catalysts prevents strong binding of ethene and CO, which facilitates rapid alternate insertion steps. Typical reaction rates of the order of 10^4 mol of converted ethene (mol Pd)$^{-1}$ h^{-1} were achieved, producing polymers with an average molecular weight of 20 000.

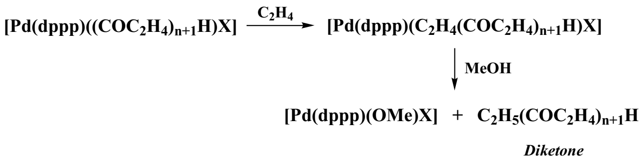
The unexpected breakthrough, which led to the development of these efficient catalysts for copolymerisation, came from a study of the alkoxycarbonylation of ethene to methyl propanoate in methanol. The catalyst system prepared from [Pd(OAc)$_2$], an excess of triphenylphosphine and a Bronsted acid of a weakly or non-coordinating anion (e.g. *p*-tosylate (OTs$^-$)) produced methyl propanoate in contrast to polyketones [1,2].

The dramatic difference in chemoselectivities displayed by the monodentate and bidentate systems was rationalised by the potential of the former system only for geometric isomerisation. Catalytic intermediates containing *cis*-chelated diphosphine ligands, such as DPPPr, cannot isomerise and thereby impose *cis* orientation of the vacant coordination site and the growing chain. This favours multiple insertion steps and therefore the production of polyketones (Scheme 8).

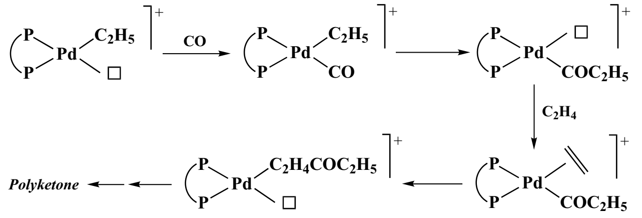
On the other hand, *cis*/*trans* isomerisation is possible for intermediates containing monodentate ligands such as PPh$_3$. In fact, both the alkyl and acyl palladium intermediates prefer the phosphine ligands to be in a *trans* orientation to one another as this avoids the unfavourable occurrence of a Pd–P bond *trans* to a Pd–C bond. Hence, as soon as the acyl complex is formed, isomerisation of the *cis* PPh$_3$ ligands to a *trans* arrangement occurs. The presence of excess PPh$_3$ allows this *cis*/*trans* isomerisation to be rapid. Further chain growth is therefore unfavourable, as the vacant coordination site is *trans* to the acyl chain. The acyl intermediate can therefore be terminated by methanolysis to yield methyl propanoate (Scheme 9).

However, *cis*/*trans* isomerisation in these monodentate PPh$_3$ intermediates can be suppressed using low reaction temperatures in the absence of excess ligand. As a result, the likelihood of co-oligomer or copolymer formation under these conditions is higher. Indeed, Sen et al. reported the production of E–CO copolymers at 25 °C from the series of cationic monodentate ligand systems, $[\mathrm{Pd(PPh_3)}_n(\mathrm{CH_3CN})_{4-n}](\mathrm{BF_4})_2$ ($n = 1$–3), in aprotic solvents such as chloroform [3,4]. However, the reaction rates were found to be low under the moderate pressure and low temperature conditions employed, as were the molecular weights of the polymers. An increase in the number of equivalents of PPh$_3$ ($n = 4$–6) led to inactivity in copolymer formation. The active Pd–H species, which initiated the reaction, most probably formed from the interaction of the Pd(II) compounds with protic impurities in the reaction mixture. Internal coordination of the growing polymer chain to the Pd centre through the carbonyl oxygen donor was proposed by Drent to aid copolymerisation in these monodentate ligand systems by enforcing the necessary *cis* geometry for successful propagation [2] (Fig. 1).

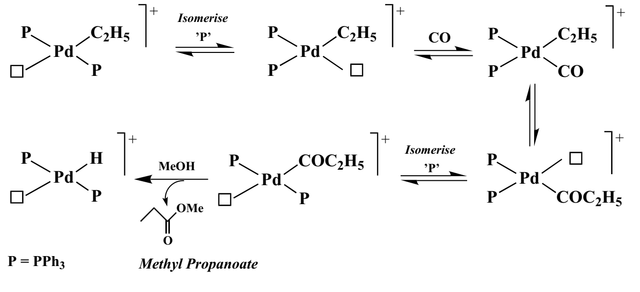
The growing chain effectively assists its own stereoregular formation through formation of these oxametallocycle rings. The competition between CO and ethene to effect displacement of the oxygen donor prevents the double insertion of ethene and unfa-



Scheme 7. Diketone formation via protonation of alkyl intermediate (hydride cycle).



Scheme 8. Production of polyketones via chain propagation (due to enforced *cis* geometry by chelating diphosphine). □ represents a vacant site or weakly coordinated anion or solvent.



Scheme 9. *Cis*/*trans* isomerisation in monodentate ligand system (PPh$_3$) leading to methyl propanoate). □ represents a vacant site or weakly coordinated anion or solvent.

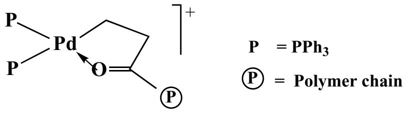


Fig. 1. Internal coordination of polymer chain aids chain growth in monodentate systems (low temperature conditions required and absence of excess PPh$_3$).

vourable thermodynamics prevents the double insertion of CO. Strictly alternating E–CO copolymers, therefore, result (Scheme 10).

The catalytic formation of E–CO co-oligomers would appear to involve finding the middle ground between the two extremes of methyl propanoate and polyketone formation. This review will focus on reports of ethene–CO co-oligomerisation as well as on the selective synthesis of 3-pentanone and methyl propanoate, which are the first members of the saturated family of oligoketones and oligoketoesters, respectively.

2. Co-oligomerisation of ethene and carbon monoxide

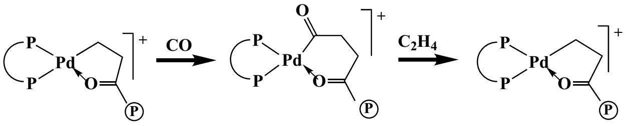
Typically, cationic palladium complexes are used to catalyse the copolymerisation of ethene and carbon monoxide in a variety of solvents such as methylene chloride or alcohols [1–4]. However, palladium systems that are efficient in effecting copolymerisation when contacted with a 1:1 ratio of ethene to CO can be directed towards production of unsaturated alternating co-oligomers when higher ratios of 10:1 are used [11]. The allyl palladium complexes containing functionalised phosphine ligands shown in Fig. 2, were found to be active in the production of these unsaturated co-oligomers. Complexes **1**–**6** showed optimal stability and activity at 50–65 °C with near complete conversion of CO achievable.

The low concentration of carbon monoxide permits chain termination by β-H elimination to compete with propagation producing lower molecular weight products. The co-oligomers produced are outlined in Scheme 11. Comparable results were found for the phosphine–ester and phosphine–thiophene complexes.

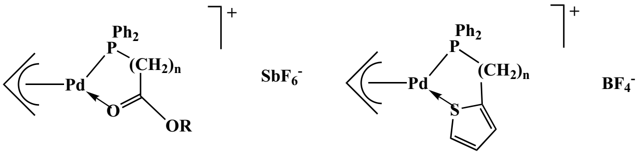
The coordination behaviour of the ligands was also investigated. The lack of impact of the nature of the donor atom or varying the number of atoms in the ligand backbone on the system activity or selectivity suggested that these ligands were monodentate in the catalytic intermediates and served only to stabilise the precursor complex through chelation. On the other hand, complexes which have been shown through model experiments to retain the chelating ligand such as those shown in Fig. 3 produced only insoluble copolymers even under high ethene–CO ratios.

This result can again be explained by the enforcement of a *cis* orientation of the vacant fourth coordination site and the growing chain, which favours multiple propagation steps in these bidentate ligated systems.

Initiation of activity in the hemilabile ligand systems is believed to occur via substitution of the labile arm by ethene followed by insertion into the allyl moiety (Scheme 12). Several insertions of CO and ethene may then result prior to β-H abstraction and generation of a Pd/H species, which is the active species in the hydride cycle from which the major products result.



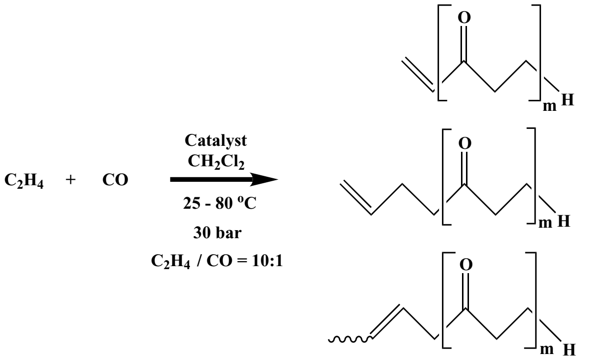
Scheme 10. Preferred reaction steps of five- and six-membered oxametallocycles.



1 : n=1, R = Me
2 : n=2, R = Et
3 : n=3, R = Et

4 : n=1
5 : n=2
6 : n=3

Fig. 2. Cationic palladium allyl complexes with hemilabile ligands used as catalyst precursors.



m = 1 : 3-pentenone
6-hepten-3-one
cis & *trans* 5-hepten-3-one

m = 2 : 1-octen-3,6-dione
9-decen-3,6-dione
cis & *trans* 8-decen-3,6-dione

Scheme 11. Unsaturated products resulting from co-oligomerisation of ethene and carbon monoxide using cationic allyl Pd complexes.

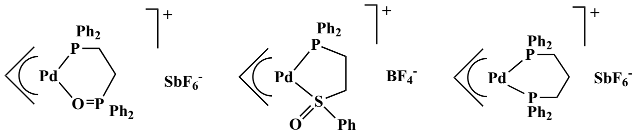
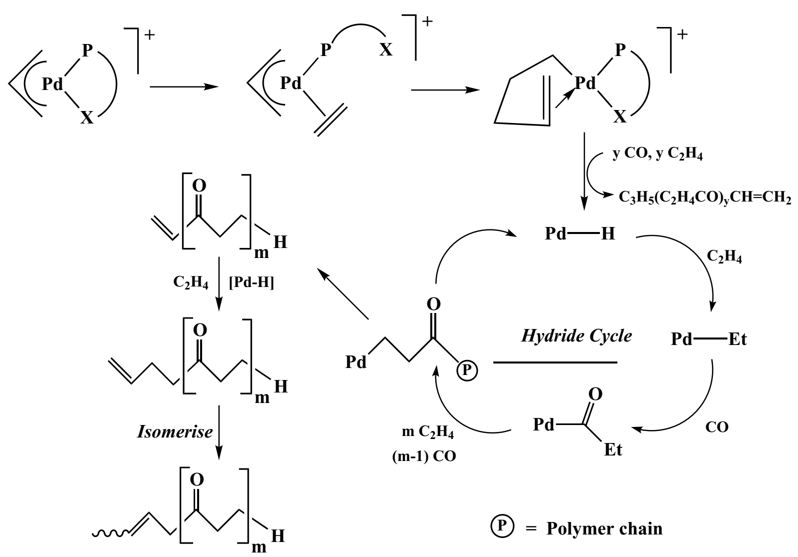


Fig. 3. Bidentate complexes of Pd which produce only polymeric products.

The unsaturated co-oligomers form by several alternate insertions of ethene and CO into the Pd–H bond followed by β-H abstraction. The early termination step prevents copolymerisation and reforms the hydride complex for initiation of another cycle. The co-oligomers with butenyl end groups were proposed to form by codimerisation of vinyl ketones and ethene rather than by the double insertion of ethene into a



Scheme 12. Mechanism of ethene/CO co-oligomerisation employing cationic allyl palladium complexes with hemilabile functionalised phosphine ligands as precursors.

Pd–acyl bond. The selectivities to the internal or terminal isomers were found to vary according to the reaction conditions and to the catalytic precursor employed.

Alternatively, saturated E–CO oligomers have also been reported [1,4,12,13]. Oligoketoesters of the general formula $MeO(COCH_2CH_2)_nH$ where $n = 1–5$ were identified and separated from the longer chain polyketoesters ($n > 5$) which were also produced when $[Pd(PPh_3)_n(CH_3CN)_{4-n}][BF_4]_2$ ($n = 1–3$) was treated with $CO–C_2H_4$ in the presence of methanol as the only solvent [4]. However, these oligoketoesters were not formed exclusively and were isolated simply to gain understanding of the mode of stepwise chain growth. The rate of termination relative to the rate of propagation was found to be crucially dependent on the concentration, steric nature of the alcohol and also on the nucleophilicity of the alcohol. The termination rate was 1.74 times slower in ethanol than in methanol due to the increase in steric size. Only the higher polyketoesters ($n > 5$) were formed when the reaction was carried out in CF_3CH_2OH, which is less nucleophilic than CH_3CH_2OH due to the presence of electron withdrawing fluorine substituents.

Drent et al. reported [1] the dramatic shift in chemoselectivity from methyl propanoate to polyketones by using the bidentate ligand, 1,3-bis(diphenylphosphino)propane, instead of PPh_3 in the presence of cationic palladium catalysts. However, when studying the more subtle variation of changing the number of methylene bridges between the diphenylphosphine ends within the series of bidentate chelating ligands, $Ph_2P(CH_2)_mPPh_2$, a significant effect on the reaction rate and molecular weight distribution was observed. The rates were negligible with DPPMe and DPPHe but rapidly increased and decreased between these values, reaching a maximum with DPPPr (Table 1).

A similar variation was noted for the product distribution. The molecular weight of the copolymer decreased in the order, DPPPr > DPPEt > DPPBu > DPPPe (Table 1). Short chain co-oligomers were selectively made from the DPPMe, DPPHe and DPPPe systems although only the last system gave appreciable rates. The methanol soluble oligomer fractions ($n = 1–5$) produced from the $[Pd(MeCN)_2(O_3STol)_2]$/DPPBu system at 85 °C, were clearly identified in the GC trace and end group analysis of these co-oligomers provided evidence for diketones, ketoesters and diesters. (Fig. 4; The same end groups were proposed for the high molecular weight copolymers. Distinguishing the end groups by NMR through direct observation of the copolymers was difficult as n was large).

Table 1
The effect of varying m in $Ph_2P(CH_2)_mPPh_2$ on the palladium catalysed reaction of ethene and carbon monoxide [a] (taken from Ref. [1])

Ligand	Abbreviation	n of $H(C_2H_4CO)_nOCH_3$	Reaction rate (g/g Pd/h)
$Ph_2P(CH_2)PPh_2$	DPPMe	2	1
$Ph_2P(CH_2)_2PPh_2$	DPPEt	100	1000
$Ph_2P(CH_2)_3PPh_2$	DPPPr	180	6000
$Ph_2P(CH_2)_4PPh_2$	DPPBu	45	2300
$Ph_2P(CH_2)_5PPh_2$	DPPPe	6	1800
$Ph_2P(CH_2)_6PPh_2$	DPPHe	2	5

[a] Reaction carried out in 150 cm^3 MeOH with $[Pd(MeCN)_2(O_3STol)_2]$ (0.1 mmol) and $Ph_2P(CH_2)_mPPh_2$ (0.1 mmol): $C_2H_4/CO = 1$, 45 MPa, $T = 84$ °C.

$C_2H_5(COC_2H_4)_nCOOMe$	(I)	***Ketoester***
$MeO(COC_2H_4)_nCOOMe$	(II)	***Diester***
$C_2H_5(COC_2H_4)_nCOC_2H_5$	(III)	***Diketone***

Fig. 4. Ketoester, diester and diketone end groups from end group analysis of oligomer fraction ($n = 0–5$).

Mainly oligoketoesters were synthesised at 85 °C with selectivities greater than 95%. However, higher temperatures, e.g. 125 °C, substantially increased the production of the diesters and diketones, for which a combined selectivity of 50% was noted. The GC trace of the reaction products formed at 125 °C also showed that higher temperatures favoured the formation of the lower molecular weight co-oligomers. The intensity of the peaks for 3-pentanone and methyl propanoate were the largest, with a gradual decrease in size of the subsequent sets of signals. (Each set contained three peaks corresponding to the diester, ketoester and diketone in that order.) At 80 °C, a rise and fall in intensity of the signals was observed, with maximum intensity occurring for the ketoester with three repeating units, $C_2H_5(COC_2H_4)_3COOMe$.

The application of rhodium(I) catalysts in the alternating co-oligomerisation of alkenes and carbon monoxide has also received attention [12]. Sen et al. tested the hypothesis that typical hydroformylation catalysts could, in principle, produce co-oligomers of alkenes and CO in preference to aldehydes under low H_2 and high alkene concentrations. Under these conditions, further successive insertions of the alkene and CO into the metal–acyl intermediates were possible before termination. Indeed, oligoketones and oligoketoesters were formed upon contacting the catalysts, $[RhH(PPh_3)_4]$, $[RhH(CO)(PPh_3)_3]$ and $[RhCl(CO)(PPh_3)_2]$, with a 1:1 mixture of ethene and CO in a variety of solvent systems at elevated temperature (Scheme 13).

The reaction was found to proceed smoothly for all three rhodium complexes mentioned above. These complexes were catalyst precursors and their structural similarities most probably caused the formation of the same active catalytic species. The only subtle difference noted was in the ratio of 3,6-octanedione to 3-pentanone, which decreased as the phosphine to metal ratio increased.

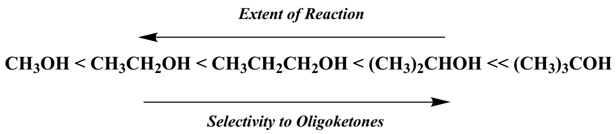


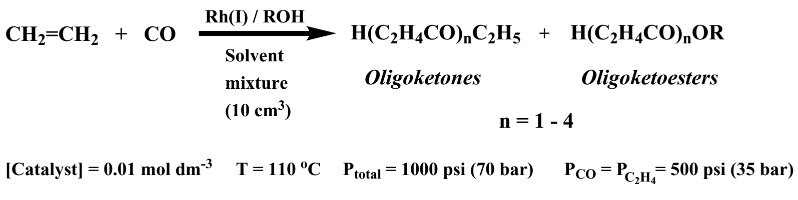
Fig. 5. Effect of alcohol on extent of reaction and ketone to ester ratio.

The solvent system was found to have a large impact on the nature and weight distribution of the products. Reactions carried out in a 1:1 (v/v) mixture of acetic acid and alcohol produced both oligoketones and oligoketoesters. The extent of the reaction and the ketone to ester ratio was found to depend on the steric bulk of the alcohol employed (Fig. 5). The bulkier the alcohol, the more limited the reaction (as evidenced by a smaller drop in pressure) and the higher the selectivity to the oligoketones. In fact, almost exclusive formation of oligoketones was noted from the reaction carried out in acetic acid and ^{t}BuOH.

Reactions performed in a 5:1 methanol–water solvent mixture were much more selective than those in acetic acid–alcohol, producing oligoketones with only trace quantities of the ester products. Surprisingly, no reaction was observed when pure water or pure methanol was used. Likewise, no products were generated in pure acetone or acetic acid, but upon addition of water as a cosolvent, the co-oligomerisation proceeded smoothly once again. The acetic acid–water system yielded the oligoketone products predominantly but contamination by a substantial quantity of propanoic acid was also noted. In contrast, the acetone–water system produced oligoketones without propanoic acid contamination.

Several experiments were designed in order to probe the origins of the hydrogen atoms required for mass balance in the formation of the ketonic products. Possible sources of hydrogen atoms in the system were from water, dehydrogenation of the alcohol, or the water–gas shift reaction (WGSR) (Scheme 14).

The absence of cyclopentanone in the system carried out in cyclopentanol–water made it unlikely that alcohol dehydrogenation was the source. Extensive deuterium scrambling into 3-pentanone produced in $CH_3OD–D_2O$ proved problematic. However, the origin of the hydrogen atoms from the WGSR was finally confirmed through the observation of $^{13}CO_2$ by ^{13}C-



Scheme 13. Rh(I) catalysed co-oligomerisation of ethene and carbon monoxide.

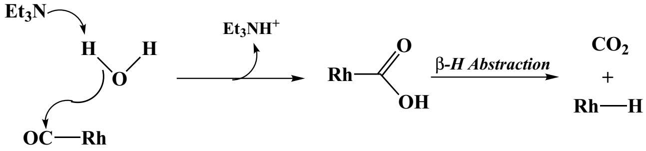
$$R_2CHOH \longrightarrow R_2C{=}O + 2[H]$$

$$CO + H_2O \rightleftharpoons CO_2 + 2[H]$$

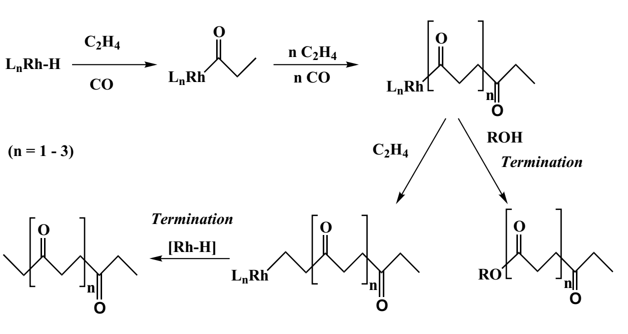
Scheme 14. Possible sources of hydrogen atoms for mass balance in the formation of ketonic products.

NMR spectroscopy in the system using ^{13}CO in place of CO. In addition, the occurrence of the WGSR in these systems explains the method of initiation by formation of a Rh–H active species. The insertion of ethene into this hydride complex followed by subsequent alternate insertions of CO and ethene provides a rational mechanism for the co-oligomerisation process. (Although water was not added in the acetic acid–alcohol systems, activity was observed due to the formation of water as a byproduct from esterification of the solvents.)

Formation of the oligoketoesters from an initiating metal alkoxide species (carbomethoxy cycle) was ruled out for three reasons. Firstly, if the esters were indeed formed from a metal alkoxide species, oligoketoester formation should have resulted and, indeed, been enhanced from the reaction carried out in dry alcoholic solvents. However, no reaction was observed in pure alcohols at all. Secondly, the absence of diester formation makes the carbomethoxy cycle unlikely as termination of an acyl intermediate during this cycle should have led to these products. Finally, the dependence of the termination rate on the steric bulk of the alcohol suggests that methanolysis of intermediate acyl species is the operative route to the esters. Formation of the ester from the carbomethoxy cycle would involve termination by protonation, a step that should be almost independent of the steric bulk of the alcohol.



Scheme 15. Promotion of the WGSR using NEt_3 and generation of the chain terminating Rh–H species.



Scheme 16. Hydride cycle for the production of ketone and ester products in Rh(I) triphenylphosphine catalysed systems.

Hence, both the oligoketones and oligoketoesters result from a common metal hydride species and the product that forms after several monomer insertions is dependent on the method of termination. Alcoholysis of the rhodium acyl intermediates yields the esters. The mode of termination generating the oligoketones was proposed to encompass a bimolecular reductive elimination of the Rh–H and Rh–alkyl species. Reactions of this type are well documented [15,16]. The evidence favouring this mechanism over protonolysis was the observation of high yields of 3-pentanone under basic conditions. The addition of triethylamine increased formation of this co-oligomer over longer chain ketones through promotion of the WGSR, which generates more of the chain terminating Rh–H species for the bimolecular reductive elimination step (Scheme 15).

Protonolysis of the Rh–alkyl is unlikely as the weight distribution of the ketone products, which is governed by the termination rate, was largely unaffected by changes in the concentration of the proton sources (such as water, alcohol or acetic acid). In addition, if protonolysis was the method of termination, the ratio of the ketone to ester products should be higher under acidic conditions than neutral conditions. In fact, just the opposite was observed. Selectivity to the ketones was much higher in neutral solvent systems such as methanol–water than under acidic solvent conditions (e.g. methanol–acetic acid). Scheme 16 describes the hydride cycle in operation and the methods of termination that lead to the ester and ketone products.

The addition of an excess of PPh_3 was found to cause drastic suppression of the formation of higher weight products in $MeOH–H_2O$ solvent. The selectivity to 3-pentanone was improved, with small amounts of methyl propanoate and 3,6-octanedione also formed. The use of pyridine as an additive tended to favour production of the ketoesters and at high concentrations of this base, the monomeric methyl propanoate was produced in yields exceeding 90%. On the other hand, the addition of triethylamine favoured production of 3-pentanone over methyl propanoate. The different result using the two bases as additives was interpreted as arising from differing electronic influences during coordination to the rhodium centre. Pyridine can coordinate to rhodium and remove electron density through back donation from the metal into the vacant π-orbitals. This would cause the acyl intermediates to become more electropositive and therefore more susceptible to nucleophilic attack by the alcohol, increasing the selectivity to the ketoesters. The higher the concentration of pyridine, the more the vacant coordination sites for monomers are blocked, reducing the chain growth in favour of the monomeric methyl propanoate. Due to its steric bulk, triethylamine most probably has difficulty in coordinating to rhodium. There is no potential for

Table 2
Main products from ethene–CO co-oligomerisation using [Rh_2O_3] (50 mg) in a variety of solvent systems at 130 °C for 24 h, CO:$C_2H_4 = 6$:1, (taken from Ref. [13])

Solvents	Main products	Yield (%)
CH_3OH (50 cm^3)	3,6-Octanedione	14
	3,6,9-Undecanetrione	2
	Methyl 4-oxohexanoate	25
CH_3OH (25 cm^3), CH_3CO_2H (25 cm^3)	3,6-Octanedione	26
	3,6,9-Undecanetrione	6
	3,6,9,12-Tetradecanetetraone	1
	Methyl 4-oxohexanoate	15
CH_3OH (50 cm^3), pyridine (0.1 mol)	Methyl propanoate	58
CH_3OH (50 cm^3), NEt_3 (0.1 mol)	3-Pentanone	27
	Methyl propanoate	4
CH_3OH (50 cm^3), H_2O (0.2 mol), NEt_3 (0.1 mol)	3-Pentanone	71
	Methyl propanoate	4

back donation from the metal so the acyl carbon is not activated towards nucleophilic attack. Instead, reaction with ethene ensues. The main effect of NEt_3 on the reaction is its promotion of the WGSR, which produces more of the chain terminating Rh–H species (Scheme 15). Hence, the bimolecular reductive elimination of Rh–H with the alkyl intermediates was found to occur early on in the reaction sequence, resulting in the production of mainly short chain ketones.

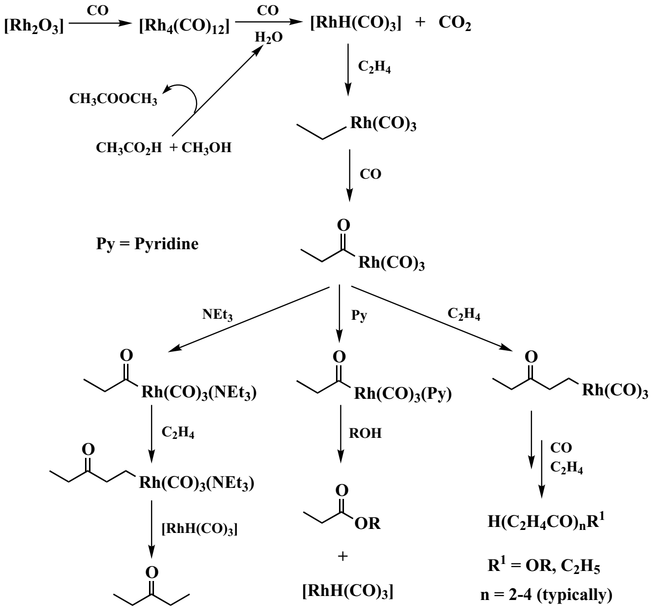
The absence of unsaturated products, in all the systems tested, suggested that the metal–alkyl intermediates were short lived, as the rate of β-H abstraction forming these products must have been slow in comparison to the rapid insertion of CO or intermolecular hydride transfer. Therefore, the rate-determining step in the mechanism was proposed to be the insertion of ethene into the Rh–acyl bond. These catalytic systems proved unsuccessful in the synthesis of higher alkene–CO co-oligomers. Low activity, side reactions and the inability to form higher co-oligomers were all problematic.

Prior to this work, Iwashita et al. described the alternating co-oligomerisation of ethene and CO catalysed by rhodium carbonyl, [$Rh_4(CO)_{12}$] [13]. The oligoketones of general formula, $H(C_2H_4CO)_nR$ ($R = C_2H_5$, OCH_3 and OC_2H_5), were produced with high conversion rates when a suspension of rhodium oxide in a 1:1 mixture of acetic acid–alcohol was exposed to a 1:6 molar ratio of ethene and carbon monoxide and heated to 130 °C for 24 h. The remarkable feature of this work is the production of co-oligomers from a catalyst system without phosphine modification and at high CO to ethene ratios. Previously, high ethene to CO ratios had been required to improve selectivity to the co-oligomers over the copolymers in palladium phosphine systems [11]. Nonetheless, in a typical experiment (Table 2) in 1:1 acetic acid–methanol, 3,6-octanedione (26%), 3,6,9-undecanetione (6%), 3,6,9,12-tetradecanetetraone (1%) and methyl 4-oxohexanoate (15%) were produced alongside smaller amounts of higher members ($n = 7$, 9). These compounds were characterised by infrared and showed carbonyl stretching frequencies at 1700 cm^{-1} as well as by NMR spectroscopy. The degree of oligomerisation was determined for the pure substances by comparison of the NMR integration of the terminal methyl protons and the methylene protons.

Carbon dioxide (85.2%) was identified on analysis of the gas phase at the end of the reaction, in addition to remaining ethene (1.3%) and carbon monoxide (3.6%). This provided evidence for the operation of the WGSR. The water required for this process originated from the formation of methyl acetate (from acetic acid and methanol) and generation of the initiating active hydride species, [$RhH(CO)_3$], was proposed to occur via the [$Rh_4(CO)_{12}$] catalysed WGSR. [$Rh_4(CO)_{12}$] was formed from reaction of the rhodium source (rhodium oxide) with excess CO.

Scheme 17 describes the reaction sequence for the production of the co-oligomers and the effect of added bases. As observed by Sen in the rhodium triphenylphosphine catalysed reaction of CO and ethene, the addition of pyridine altered the reaction selectivity to methyl propanoate [12]. The reaction carried out in pure methanol with added pyridine (0.1 mol) produced 58% yield of this product alone. Similarly, the addition of triethylamine (0.1 mol) to the reaction in methanol–water produced 3-pentanone as the main product in 71% yield with only 4% yield of methyl propanoate. The explanation, based on the electronic nature of the bases coordinated to rhodium, was suggested as being the same as that discussed above for the Rh–PPh_3 system.

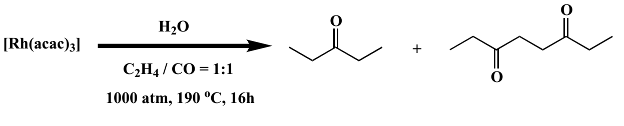
The observation of products from the [$Rh_4(CO)_{12}$] system in pure alcohols, in addition to the acetic acid–alcohol solvent mixtures, may seem surprising based on the reliance of the system on the WGSR for the generation of the active species. The absence of water in the system would surely make generation of the hydride species impossible. For this reason, no reaction was



Scheme 17. Co-oligomerisation of ethene and carbon monoxide catalysed by $[Rh_4(CO)_{12}]$ in acetic acid–alcohol solvent and the effect of added base.

observed from the rhodium triphenylphosphine system in pure alcohols [12]. However, the formation of water was proposed to arise in the former system from methanol via the formation of dimethyl ether, although detection of the ether product was not reported [17].

Examples of transition metal catalysed co-oligomerisation of ethene and CO can also be found in the patent literature [18,19]. Anderson et al. patented a method in 1962 for the production of oxygenated organic compounds from carbon monoxide and alkenes in the presence of a chelate complex of a Group VIII noble metal in alcohols or water [18]. The method was successful using a wide range of alkenes such as ethene, propene, butadiene and methyl acrylate in a variety of aliphatic alcohols. Typically, solutions of rhodium(III) acetylacetonate or ruthenium(III) acetylacetonate in water or methanol were used as catalysts. The oligoketones, 3-pentanone and 3,6-octanedione, were generated upon contacting a solution of $[Rh(acac)_3]$ or $[Ru(acac)_3]$ in water with a 1:1 molar ratio of ethene and CO at 190 °C and 1000 atmospheres for 16 h (Scheme 18). Harsh conditions were therefore necessary using this early method.



Scheme 18. Production of 3-pentanone and 3,6-octanedione from $[Rh(acac)_3]$ catalysed co-oligomerisation of ethene and carbon monoxide in water.

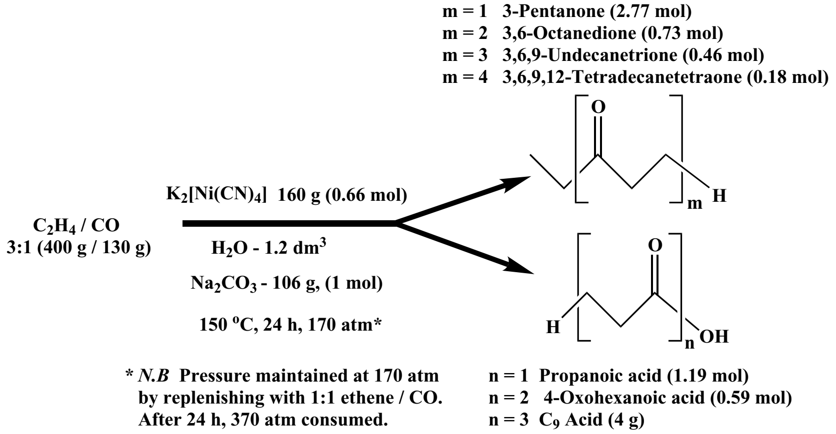
However, Reppe and Magin patented the very first example of metal catalysed co-oligomerisation of ethene and carbon monoxide in 1951. Using alkali metal or alkaline earth metal salts of nickel cyanide complexes such as $K_2[Ni(CN)_4]$, alkene–carbon monoxide co-oligomers were produced under a variety of conditions in water or water–cosolvent mixtures. Many aliphatic and cyclic alkenes were found to be suitable starting materials as well as functionalised alkenes such as allyl alcohol or allyl chloride. The observation of carbon dioxide at the end of the process confirmed operation of the WGSR. With ethene–CO gas mixtures, growth of the alternating E–CO chain was either interrupted by reaction with water, forming oligoketo acids or by addition of hydrogen from the WGSR, producing oligoketones.

In general, temperatures between 100 and 250 °C were used. Longer chain co-oligomers were preferentially formed using temperatures at the lower end of the scale (110 °C) whilst, under identical conditions at 200 °C, the reaction products consisted of ca. 50% 3-pentanone and a mixture of the longer co-oligomers. This effect was attributed to the promotion of the WGSR at elevated temperatures, which produced higher concentrations of hydrogen for chain termination. Typically, pressures in the range of 50–200 atmospheres were employed in the batch autoclave or continuous process method with a variety of CO and ethene molar ratios. Using an excess of ethene increased the selectivity to the ketone products, whereas the keto acids were preferably formed using excess carbon monoxide. Diluting the water with a cosolvent such as ethers, ketones or saturated hydrocarbons was found to aid formation of the higher co-oligomers. The pH of the reaction was also a parameter that could be changed to influence the weight distribution. Alkaline pH, achieved by the addition of amines or sodium carbonate for example, favoured the lower co-oligomers compared with the neutral reaction systems. Scheme 19 describes a typical experiment, showing the conditions used and the products.

3. Selective synthesis of methyl propanoate from ethene, carbon monoxide and methanol

The synthesis of esters such as methyl propanoate from hydroesterification processes has been described extensively (Scheme 20). [1,2,20–23] Methyl propanoate is a key intermediate in the production of methyl methacrylate, which is an important monomer in the plastics industry and is produced annually on a multi-million tonne scale [24].

Standard carbonylation catalysts such as $[Co_2(CO)_8]$ and $[Ni(CO)_4]$ have been largely superseded by Pd, Pt, Rh and Ru catalysts due to improved performance

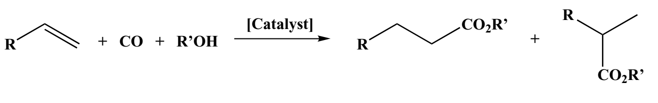


Scheme 19. Production of oligoketones and oligoketo acids from potassium tetracyanonickelate catalysed co-oligomerisation of ethene and carbon monoxide in water.

under milder reaction conditions. For instance, palladium catalysts were found to operate successfully at temperatures in the range of 70–120 °C and pressures between 1 and 200 bar whereas higher temperatures and pressures (150–200 °C and 150–200 bar) were required for cobalt catalysed systems.

As with the formation of polyketones (see Section 1), two possible mechanisms for the hydroesterification reaction are typically described [25]. The hydride mechanism involves formation of a metal hydride bond presumably via reaction with adventitious hydrogen, a proton source or the alcohol solvent. Alkene insertion into this bond followed by alkyl migration onto coordinated CO then forms a labile acyl intermediate, which readily undergoes alcoholysis, yielding the ester. The carbomethoxy mechanism stems from formation of a metal alkoxide by reaction with the alcohol. Insertion of CO and migration of the carbomethoxy ligand so formed onto a bound alkene molecule occurs before cleavage of the ester by a proton source.

With alkenes other than ethene, regioselectivity of the catalyst becomes an important factor. Selectivity to the branched and linear esters was found to be influenced by the temperature, pressure, presence of additives or co-catalysts and by varying the phosphine ligand used [26–30].



Scheme 20. Hydroesterification of alkenes to esters.

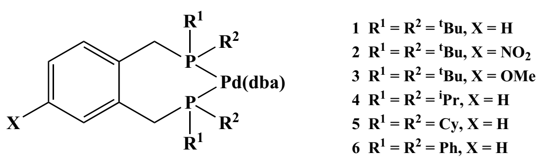


Fig. 6. Structure of various catalyst precursors tested for selectivity in formation of methyl propanoate.

As previously discussed in Section 1, the use of palladium(II) bidentate phosphine complexes as catalysts for the transformation of ethene–carbon monoxide mixtures in methanol generally affords high selectivity to polyketones, whereas the use of monodentate phosphines, such as PPh_3, produces methyl propanoate [1,2]. Detailed studies of the P containing by-products of the reaction using Pd–PPh_3 complexes by HPLC and mass spectrometry showed increasing levels of phosphonium salts, $[RPPh_3]^+$ (R = Me, Et, and 3-oxopentyl) throughout the reaction from metal catalysed reactions confirming that a hydride mechanism is operative in this case [31].

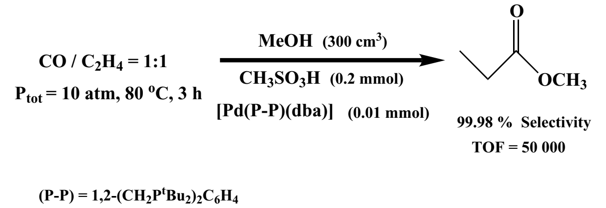
Examples of complexes containing bidentate phosphine ligands, which promote the Pd catalysed formation of methyl propanoate rather than co-oligomerisation are rare [32–34]. Nonetheless, Tooze et al. reported the discovery of a catalytic system containing 1,2-bis(di-*tert*-butylphosphino)benzene, which was capable of producing methyl propanoate with up to 99.98% selectivity [35,36]. The catalyst precursor, **1**, shown in Fig. 6 was formed upon addition of the bidentate ligand to $[Pd_2(dba)_3]$ (dba = *trans,trans*-dibenzylideneacetone) in methanol.

A study of the complexes shown in Fig. 6 revealed the expected η^2-binding of one of the alkene groups of the dba ligand in addition to the chelate ring structure formed by the bidentate ligand. The geometry around the palladium centre was found to be trigonal planar and the diphosphine ligand bite angle of 104° was consistent across the range (**1**–**6**) [35].

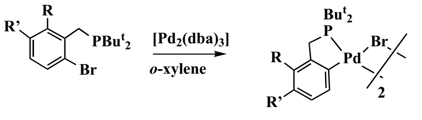
The addition of a sulphonic acid, e.g. methanesulphonic acid, initiated the reaction by generation of the active species in situ. The process was carried out under very mild temperature and pressure conditions (80 °C and 10 atm, respectively). The system containing 1,2-

bis(di-*tert*-butylphosphinomethyl)benzene was capable of converting ethene, CO and methanol to methyl propanoate at a rate of 50 000 mol of product (mol Pd)$^{-1}$ h^{-1} with 99.98% selectivity (Scheme 21). Under steady state conditions, the catalyst was found to be stable and gave total turnover numbers on palladium in excess of 100 000. In contrast, PPh_3 based systems have only shown modest stability in methyl propanoate synthesis under continuous operation [37].

The presence of electron releasing and withdrawing groups such as OMe and NO_2 on the aryl bridge (compounds **2** and **3** in Fig. 6) did not cause any substantial effect on the catalyst performance, presumably due to the remote location of these functional groups from the palladium centre. Using a ligand similar to **2** (Fig. 6), but containing a Br atom also on the ring, the major species isolated from the reaction with $[Pd_2(dba)_3]$ was a dimer containing the ligand bound through only 1 P atom and an *ortho*-metallated C atom (**1** in Scheme 22) [38]. This complex itself was an active catalyst, but related complexes such as **2** and **3** in Scheme 22, which do not contain the pendant P^tBu_2 functionality are not active. This suggests that the active complex must contain the ligand bound in a bidentate manner through both P atoms. Presumably this is formed by protonation of the *o*-metallated complex. When bidentate (through 2 P atoms) coordination is impossible, the complex formed by protonation is presumably too unstable to survive for any length of time since it only contains one phosphine ligand.

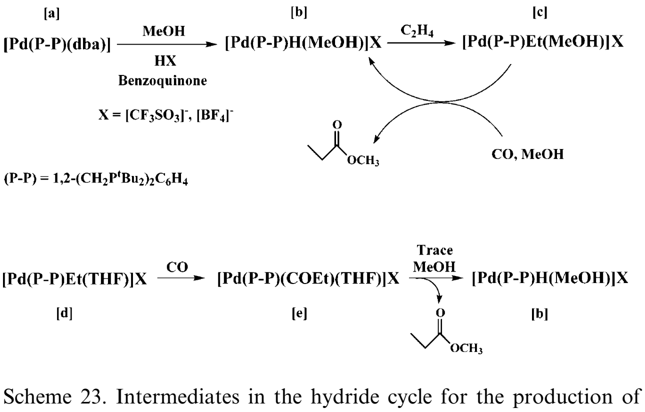


Scheme 21. Highly selective formation of methyl propanoate using a palladium complex of 1,2-bis(di-*tert*-butylphosphinomethyl)benzene under mild conditions.



1 R = $CH_2PBu^t_2$, R' = OMe
2 R = H, R' = OMe
3 R = H, R' = H

Scheme 22. Metallation of ligands containing Br *ortho* to a $CH_2P^tBu_2$ group.



Scheme 23. Intermediates in the hydride cycle for the production of methyl propanoate catalysed by a palladium complex of 1,2-bis(di-*tert*-butylphosphino)benzene.

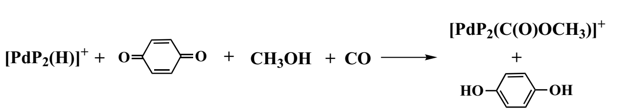
A more dramatic effect than that observed when substituents were present on the ring of ligand **1** in Fig. 6 occurred if the substituents on the phosphorus atoms were changed. The isopropyl analogue was less active by a factor of 60. Not only was the activity reduced by replacement of the *tert*-butyl groups with other substituents, but the selectivity to methyl propanoate also decreased. For example, the phenyl analogue produced a mixture of oligomers and polymers with only 20% selectivity to methyl propanoate. This effect was thought to be related to the steric environment created by the substituents on phosphorus, which control the possibility of single or multiple monomer insertions prior to termination [32,33]. Subsequently, a detailed spectroscopic investigation of all the possible intermediates in this system was carried out and the results unambiguously confirmed the sole operation of the hydride cycle in the formation of methyl propanoate [39].

Scheme 23 shows all the reaction intermediates identified by ^{31}P-, ^{1}H- and ^{13}C-NMR spectroscopy at various stages during the model studies. The addition of HBF_4 or CF_3SO_3H to the catalyst precursor [**a**], in the presence of oxygen or benzoquinone, was found to produce a solvento-cation species, [**b**], containing a Pd–H bond. The anion was present only as a non-coordinating counter ion. Bubbling of ethene gas through the methanolic solution of [**b**] produced the ethyl complex [**c**] by insertion of ethene into the Pd–H bond. Passing carbon monoxide through the resulting solution immediately produced methyl propanoate and regenerated [**b**] without the observation of the expected acyl intermediate from the insertion of CO. However, the acyl intermediate was confirmed by repeating the process in THF instead of methanol. Production of methyl propanoate and regeneration of [**b**] once again ensued upon addition of trace amounts of methanol to a solution of [**e**].

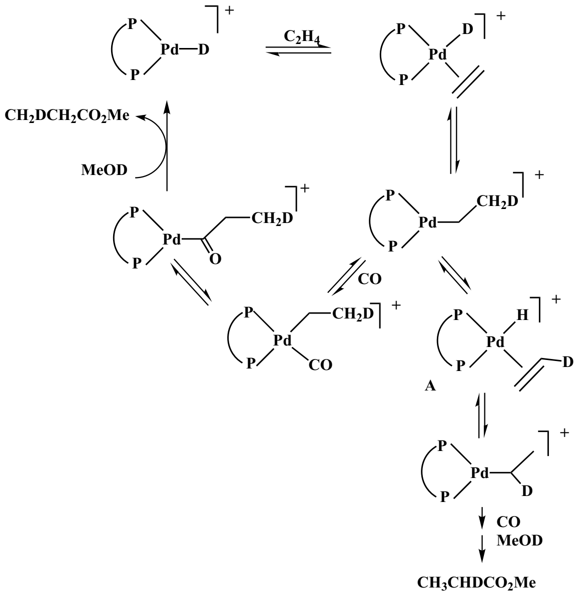
Drent, who described the production of polyketones from similar bidentate phosphine systems, provided evidence for the operation of the carbomethoxy cycle (through the observation of diesters) and even suggested that this cycle was dominant over the hydride cycle in the presence of oxidants [2,40]. An increase in selectivity to the diester products, which can only be generated from the carbomethoxy cycle, in the presence of benzoquinone suggested that oxidation of the palladium hydride into a palladium carbomethoxy species had occurred [1,41] (Scheme 24). An increase in rate was also noted and possibly indicated a faster rate of the carbomethoxy cycle over the hydride cycle.

However, complex [**b**] (Scheme 23) was stable in the presence of excess benzoquinone and upon bubbling of oxygen for 30 min at 80 °C [39]. No evidence for the formation of a methoxy species was found. As a result, the catalytic mechanism for the production of methyl propanoate from these systems was proposed to arise from the hydride cycle only.

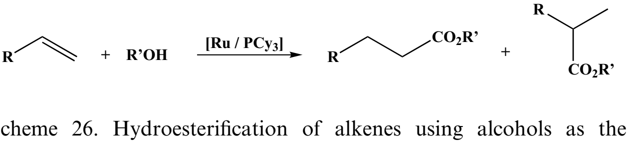
Final confirmation that the hydride mechanism is operating in these reactions comes from the labelling pattern of the products obtained from reactions carried out in CH_3OD using palladium complexes of ligand **1** in Fig. 6. This depended upon the rate of mixing during the reaction [42]. Under fast stirring conditions (not mass transport limited) only two products, $CH_2DCH_2CO_2Me$ and CH_3CHDCO_2Me, were detected. These show that the hydride mechanism is operating and that the migration of H/D onto the coordinated ethene molecule is fast and reversible. Exchange of free and bound ethene does not occur to any extent and migration of the ethyl group onto CO is rate determining (Scheme 25). Under conditions of poor mixing, much more extensive scrambling occurs and a significant proportion of the ethyl groups do not contain D. This is interpreted as meaning that CO mass transport is rate limiting and that exchange of free and bound ethene becomes significant. Analysis of the unreacted ethene during the reaction shows incorporation of up to 3 D atoms [42]. There is no way that the carbomethoxy mechanism can account for the production of the undeuteriated methyl propanoate, since termination must proceed via protonolysis with CH_3OD and there is little or no exchange of D for H in the solvent.



Scheme 24. Oxidation of $[PdP_2(H)]^+$ to $[PdP_2(C(O)OCH_3)]^+$ in the presence of benzoquinone, methanol and carbon monoxide.



Scheme 25. Formation of monodeuterio products from ethene and CO in CH_3OD under efficient gas transport conditions.



Scheme 26. Hydroesterification of alkenes using alcohols as the $CO–H_2$ source.

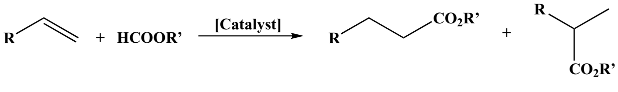
The palladium complex derived from *exo*,*endo*-2,3-bis(diphenylphosphinomethyl)-2,2,1-bicycloheptene also shows high selectivity to the formation of methyl propanoate, whilst the similar ligand, *cis*-1,2-bis-(diphenylphosphinomethyl)cyclohexane, is active for CO–ethene colpolymerisation. The *trans* isomer shows lower activity for either reaction [34].

Keim et al. carried out an investigation into the hydroesterification of alkenes to esters using alcohols as the source of CO as well as hydrogen [43] (Scheme 26). This research followed on from a 1971 patent by McClure and Slaugh [44]. Ruthenium complexes of basic phosphine ligands such as $[Ru(CO)_3(PCy_3)_2]$ proved most effective in this alternative route to esters.

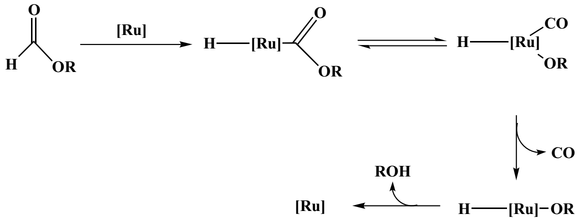
When ethene was used, methyl propanoate was obtained with 100% selectivity in a yield of 81%. Longer alkenes afforded both linear and branched esters in ca. 60:40 ratio. An experiment carried out in $^{13}CH_3OH$ with propene confirmed the origins of CO from the alcohol through observation of $C_3H_7^{13}C(O)O^{13}CH_3$ and $(CH_3)_2CH^{13}C(O)O^{13}CH_3$. The hydride cycle was proposed with the initial formation of a Ru–H from dehydrogenation of methanol. Carbon monoxide for incorporation into the ester backbone was generated by decarbonylation of the resulting formaldehyde. Although high temperature (240 °C) and pressure conditions (400 bar) were required, the application of the alcohol as the source of CO and H_2 simplifies gas transport and handling. Another benefit of the process is its ability to form esters from internal alkenes via initial isomerisation to a terminal double bond.

Subsequently, decarbonylation of formates [45] appeared more attractive than alcohol decarbonylation due to the simultaneous release of CO and ROH, which could afford esters directly on reaction with alkenes [46,47] (Scheme 27).

Jenner proposed the mechanism of formate decomposition to involve activation of the formate C–H bond



Scheme 27. Esterification of alkenes with alkyl formates.



Scheme 28. Decarbonylation of formates to alcohols and carbon monoxide.

followed by formation of a hydridocarbonyl ruthenium alkoxide species [45]. Loss of CO from this intermediate generated a complex capable of losing ROH (Scheme 28).

Interception of this intermediate before loss of ROH (or reformation from reaction of the Ru-complex with ROH) by the insertion of an alkene into the Ru–H bond would lead to an alkyl ruthenium alkoxide complex. Coordination and insertion of the CO previously released would generate an acyl ruthenium alkoxide, which could eliminate the ester product [47]. Indeed, contacting a variety of catalytic systems with ethene allowed production of methyl propanoate in high yields with excellent selectivities [48–50]. However, alternative mechanisms via metal formyl intermediates [48,50] or carbomethoxy alkyl intermediates [46] were also proposed.

Comparison of methyl propanoate production using either HCO_2Me or MeOH–CO as methoxycarbonylation reagents of ethene showed that the formate process was far superior giving a yield of 93% compared to 30% [48]. Identical conditions of pressure (90 bar N_2 or 90 bar CO) and temperature (230 °C) were employed for fair comparison in the $Ru_3(CO)_{12}$ catalysed processes.

Jenner et al. extended the study of the application of methyl formate as an in situ source of CO by applying aqueous methyl formate as a source of synthesis gas [51] in the hydroformylation of alkenes [52,53]. The water and the CO generated in situ from the decarbonylation of the formate allowed the formation of H_2 via the WGSR.

4. Selective synthesis of 3-pentanone

In methanol, in the presence of a variety of complexes of Pd(II), CO and ethene react to give either perfectly alternating copolymers or methyl propanoate, which is formed being dependent upon the other ligands present in the complex [2]. 3-Pentanone is sometimes observed as a side product, but high selectivities to this product, which is a useful solvent of relatively low volatility, are often only obtained if water or hydrogen gas is a component of the mixture [54–57]. Various ethene hydrocarbonylation systems selective to 3-pentanone are now described.

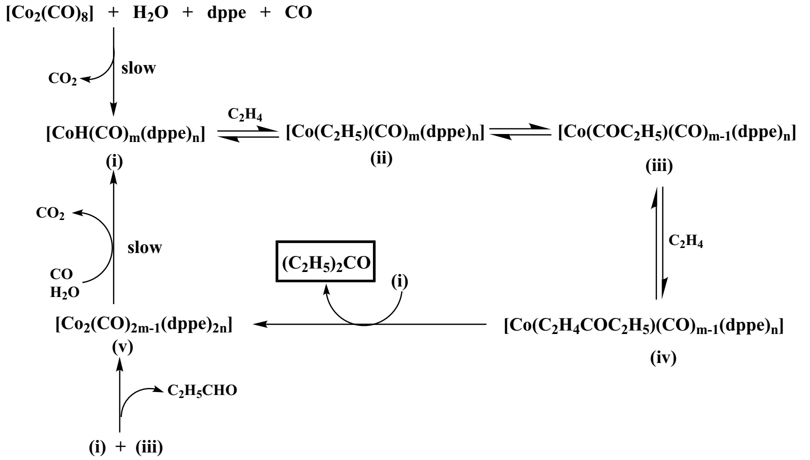
Early investigations into ethene hydrocarbonylation by Murata and Matsuda found that 3-pentanone could be selectively formed from C_2H_4–CO and H_2O in dioxane solvent using a relatively high ratio of ethene and a phosphine modified $[Co_2(CO)_8]$ catalyst [54]. Selectivities of the order of $99 \pm 1\%$ were noted and the only by-product of the reaction was propanal, $(1 \pm 1\%)$. The high ethene to carbon monoxide ratio (75:1) allowed direction of the system towards production of the ketone over the aldehyde (from hydroformylation). The same effect had been previously noted with propene as the substrate. High concentrations of C_3H_6 resulted in formation of dipropyl ketones as the primary products whilst lower concentrations produced predominantly C_4 aldehydes [58,59].

The effect of various reaction parameters upon the $[Co_2(CO)_8]$ system using 1,2-bis(diphenylphosphino)-ethane (dppe) was studied, but the selectivity to 3-pentanone remained fairly high under a variety of conditions tested. The main detrimental effects on the selectivity were the use of excess phosphine or an equimolar amount of hydrogen instead of water. Only slight variations in selectivity were noted in changing the nature of the bidentate phenyl phosphine ligand and triphenylphosphine performed equally well.

In the absence of alkenes, the system was found to catalyse the WGSR. From this reaction, the origins of the active species, $[CoH(CO)_m(dppe)_n]$, were proposed. However, direct spectroscopic evidence for this complex was not obtained under the reaction conditions at 165 °C, presumably due to rapid consumption of the active species.

Generation of 3-pentanone occurs via the hydride mechanism as described by Scheme 29. $[CoH(CO)_m(dppe)_n]$ is trapped by ethene and thereby prevented from releasing hydrogen gas. 3-Pentanone is liberated by the bimolecular reductive elimination of the 3-oxopentyl complex, (**iv**), with the hydride species, forming $[Co_2(CO)_{2m-1}(dppe)_{2n}]$ (**v**), which is then converted back to the active hydride by the WGSR pathway.

The steps are fast from the insertion of ethene right up to the formation of the dimer. The initial formation of the hydride from $[Co_2(CO)_8]/H_2O/dppe/CO$ is slow and accounts for the induction period of 1 h. Regeneration of the hydride from the dimer is also slow and proceeds only at relatively high temperature, (120 °C or above). The small amount of propanal observed was produced from the bimolecular reductive elimination of



Scheme 29. Mechanism for the synthesis of 3-pentanone from ethene, CO and H_2O using conditions of high $[C_2H_4]$ in the presence of $[Co_2(CO)_8]$ and dppe.

the acyl complex, (**iii**), with the hydride complex, (**i**), but this step occurs rarely and can be virtually disregarded. In summary, this cobalt system was very selective and typical rates, using dppe as the phosphine ligand, were 22.9 mmol DEK h^{-1}.

Zudin et al. also noted the production of small quantities of dialkyl ketones during the hydroformylation of alkenes, and set about finding the reaction conditions that favoured this process over formation of aldehydes [55]. In the absence of hydrogen gas, contacting the Pd(II)/PPh_3 catalyst solution in 80% aqueous trifluoroacetic acid with a mixture of ethene and CO resulted in formation of 3-pentanone at a rate of 2 mol (g-atom Pd)$^{-1}$ h^{-1} under very mild conditions. In the absence of ethene, the homogeneous catalyst system was capable of effecting the WGSR, a process that undoubtedly led to the origins of the necessary Pd–H bond for the formation of the ketone. The liberation of H_2 from this Pd–H complex was inhibited in favour of the hydrocarbonylation of the ethene with CO–H_2O giving 3-pentanone. Indeed, the rate of CO_2 formation was equal to the rate of 3-pentanone formation (Scheme 30).

A substantial increase in the rate was obtained when hydrogen gas was introduced into the gas mixture along with ethene and CO. When a 2:1:1 mixture of ethene–CO–H_2 was used, the system produced rates up to 35 mol (g-atom Pd)$^{-1}$ h^{-1} with high selectivities to 3-pentanone of 95–99% (Scheme 31). Only traces of ethane and carbon dioxide were detected.

The same active Pd–H complex, $[PdH(PPh_3)_3]X$, was formed in both systems, however, the origins of this complex differed. In the former system, the WGSR was operative and formed the Pd–H bond during reduction of the Pd(II) complex by CO in the presence of excess PPh_3 (Scheme 32).

However the WGSR was obviously suppressed in the latter system due to the presence of added H_2, as only traces of CO_2 were produced. Instead, $[PdH(PPh_3)_3]X$ was probably formed by heterolytic rupture of H_2 by the initial Pd(II) complex, $[Pd(PPh_3)_2X_2]$ (Scheme 33).

The hydride mechanism generates 3-pentanone from consecutive insertions of ethene and CO into Pd–H. The reaction was sensitive to the water concentration, as levels of propanoic acid resulting from hydrolysis of the acyl intermediate became significant with increasing levels of water. Kinetic investigations into the mechanism revealed the slow and potentially rate-determining steps to be the formation of the hydride complex and the insertion of ethene into the acyl intermediate [56].

$$2\,C_2H_4 + 2\,CO + H_2O \xrightarrow[\substack{30-70\,^{\circ}C\,/\,1\,atm \\ CF_3CO_2H\,/\,H_2O}]{Pd(II) : PPh_3} (C_2H_5)_2CO + CO_2$$

Scheme 30. Production of 3-pentanone from ethene, CO and water using an aqueous trifluoroacetic acid solution of $Pd(OAc)_2/PPh_3$ under mild conditions.

$$2\,C_2H_4 + CO + H_2 \xrightarrow[\substack{30-70\,^{\circ}C\,/\,1\,atm \\ CF_3CO_2H\,/\,H_2O}]{Pd(II) : PPh_3} (C_2H_5)_2CO$$

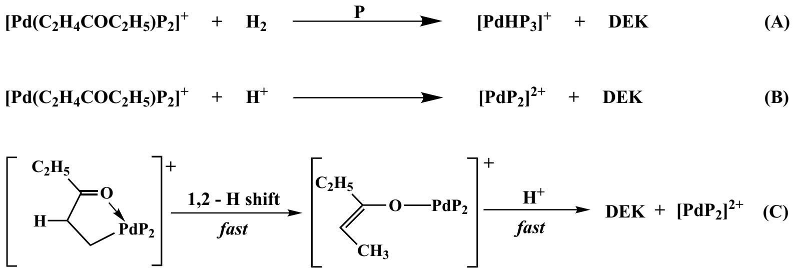
Scheme 31. Production of 3-pentanone from ethene, CO and H_2 using an aqueous trifluoroacetic acid solution of $Pd(OAc)_2/PPh_3$ under mild conditions.

$$[Pd(PPh_3)_2X_2] + CO + H_2O \xrightarrow[\substack{-HX\ +PPh_3 \\ slow}]{-CO_2} [PdH(PPh_3)_3]X \xleftarrow[fast]{PPh_3} [Pd(PPh_3)_4] + HX$$

Scheme 32. Origins of $[PdH(PPh_3)_3]^+$ in ethene–CO–H_2O system.

$$[Pd(PPh_3)_2X_2] + H_2 \xrightarrow{PPh_3} [PdH(PPh_3)_3]X + HX$$

Scheme 33. Origins of $[PdH(PPh_3)_3]^+$ in ethene–CO–H_2 system.



Scheme 34. Three possible modes of termination producing 3-pentanone.

Three termination mechanisms producing 3-pentanone (DEK) from the 3-oxopentyl intermediate were possible and are described in Scheme 34. Chelation of the 3-oxopentyl chain through the carbonyl oxygen was proposed, forming the four coordinate complex, $[Pd(C_2H_4C(O)C_2H_5)(PPh_3)_2]^+$.

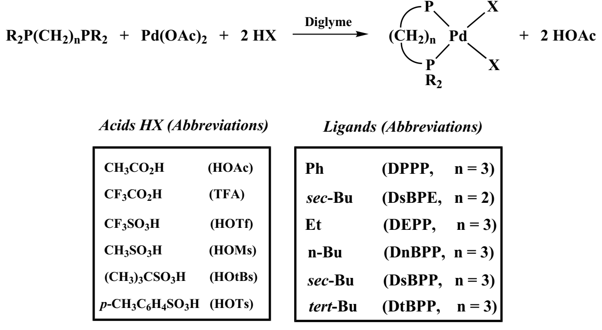
The likelihood of (A) being the operative mechanism was slim as the system was able to produce 3-pentanone in the absence of H_2. The keto–enol isomerisation mechanism, (C), was more complex and involved a 1,2-H shift in the keto alkyl chain, rupture of the Pd–C bond and formation of a Pd–O σ bond. 3-Pentanone could then be quickly released by protonolysis of the resulting enolate complex. To elucidate whether mechanism (B) or (C) was operative, deuteriation studies were carried out using H_2/D^+ and D_2/D^+ systems. The nature of the labelled products unambiguously demonstrated that termination was via the enolate mechanism (C).

Analogous platinum(II) triphenylphosphine complexes showed minimal catalytic activity in the hydrocarbonylation of ethene and the nature of the catalyst precursor was highly important [57]. Only $[Pt(PPh_3)_2X_2]$–CF_3CO_2H–H_2O ($X = CF_3CO_2^-$) was found to produce 3-pentanone in low yields, with the $[Pt(PPh_3)_4]$–CF_3CO_2H–H_2O system being completely inactive under the same conditions.

Drent has made numerous contributions to the field of ethene–CO copolymerisation using cationic Pd(II) complexes based on bidentate aryl phosphine ligands [1,2]. More recently, his attention has turned to the hydrocarbonylation of aliphatic and functionalised alkenes, using palladium(II) complexes with more electron donating bidentate ligands, in combination with a variety of acid promoters [60]. The catalyst precursors were prepared in situ as described in Scheme 35 and aprotic solvents such as diglyme were typically used.

Three possible catalysed reactions can occur for $RCH{=}CH_2/CO$ and H_2. Scheme 36 describes the mechanisms by which hydroformylation, hydroacylation and co-oligomerisation occur in the system. The application of hydrogen gas prevents copolymerisation and allows production of aldehydes/alcohols, monoketones or short chain co-oligomers in preference. Tailoring the choice of both the neutral ligand and the anion allows careful control of the chemoselectivity of the hydrocarbonylation process.

An active hydride species is formed from the precursor by reaction with hydrogen gas. The hydroacylation and hydroformylation mechanisms diverge beyond formation of the acyl intermediate formed from alkene and CO insertion into Pd–H. If the palladium centre is not strongly electrophilic and the anions are moderately coordinating, hydroformylation occurs selectively. For example, the combination of DtBPP, a highly basic ligand, and TFA, a weak acid, led to selective aldehyde/alcohol production. As the coordination ability of the anion increased, the selectivity to hydroformylation increased. However, this was at the expense of the overall rate, presumably due to the more difficult displacement of the anion by the monomers. The manner in which the coordinating anion favours hydroformylation was proposed to involve anion assistance in the heterolytic dissociation of H_2. The coordinating anion may be able temporarily to bind H^+. As a result, non-coordinating anions that are more remote from the Pd centre, cannot assist hydrogenolysis of the acyl species. Instead the second insertion of alkene is favoured over formation of the aldehyde. Monoketones are selectively formed in a similar system using the



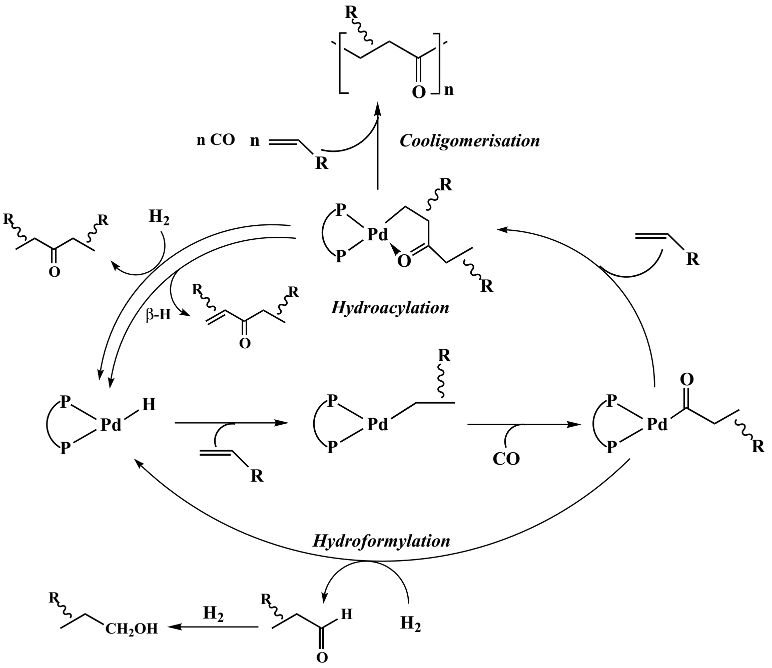
Acids HX (Abbreviations)

CH_3CO_2H	(HOAc)
CF_3CO_2H	(TFA)
CF_3SO_3H	(HOTf)
CH_3SO_3H	(HOMs)
$(CH_3)_3CSO_3H$	(HOtBs)
p-$CH_3C_6H_4SO_3H$	(HOTs)

Ligands (Abbreviations)

Ph	(DPPP, n = 3)
sec-Bu	(DsBPE, n = 2)
Et	(DEPP, n = 3)
n-Bu	(DnBPP, n = 3)
sec-Bu	(DsBPP, n = 3)
tert-Bu	(DtBPP, n = 3)

Scheme 35. In situ preparation of Pd(II) complexes for alkene hydrocarbonylation.



Scheme 36. Mechanisms of co-oligomerisation, hydroacylation and hydroformylation.

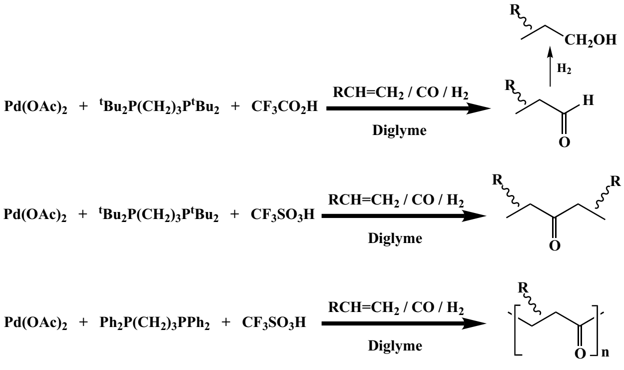
same basic diphosphine ligand, DtBPP, but replacement of TFA with a stronger acid such as HOTf. The palladium centre is more electrophilic and internal coordination of the chain results producing a five membered ring. In a similar manner, the carbonyl group of the chelate ring may assist hydrogenolysis of the alkyl intermediate by temporarily binding H^+ from the heterolytic dissociation of H_2. Further chain growth is thus prevented producing the monoketone product selectively.

However, if the palladium centre is highly electrophilic such as in the $Pd(OAc)_2$/DPPP/HOTf system, termination seems to be more difficult and multiple CO/alkene insertions can occur prior to termination. Higher oligoketones are thus produced. Although no direct mention was made of ethene hydrocarbonylation in particular, these findings are very interesting. Selective production of 3-pentanone, ethene–CO co-oligomers or propanal by tailoring the ligand and acid components of the system could soon be a commercial reality (Scheme 37).

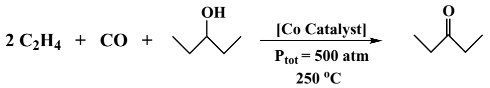
Various transition metal heterogeneous catalyst systems have been described which show activity in the synthesis of 3-pentanone from either C_2H_4–CO–H_2O [61] or C_2H_4–CO–H_2 [62–65]. However, many of these systems were not highly selective to 3-pentanone due to the production mainly of propanal and/or ethane. The best catalytic system for 3-pentanone production was based on a carbon supported Co catalyst [61]. An unusual change in selectivity from ethane to 3-pentanone was noted when $[Co_2(CO)_8]$ was adsorbed on a carbon support rather than on oxide supports.

5. Use of alcohols as the source of hydrogen in the transformation of ethene–carbon monoxide mixtures

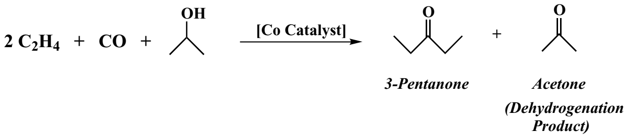
An early patent by Gresham and Brooks described the selective synthesis of 3-pentanone from ethene and CO in 3-pentanol using a variety of typical hydrogenation catalysts [66] (Scheme 38). Systems based on cobalt produced the best results, but high temperatures and



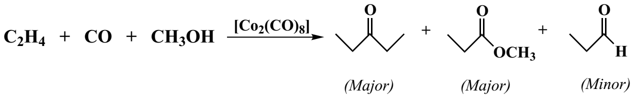
Scheme 37. Selective formation of aldehydes/alcohols, monoketones or oligoketones from alkene carbonylation by careful choice of ligand/acid components.



Scheme 38. Selective production of 3-pentanone from ethene and CO in 3-pentanol.



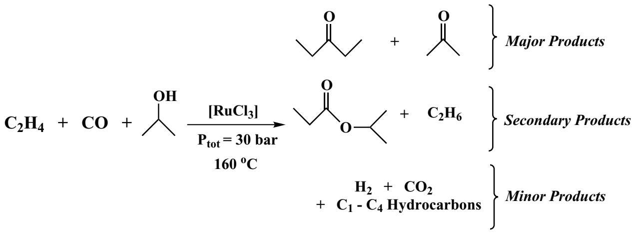
Scheme 39. Production of 3-pentanone (and acetone byproduct) from ethene and CO in isopropanol.



Scheme 40. Production of 3-pentanone and methyl propanoate from ethene, CO and methanol in addition to minor quantities of propanal.

$$2\,CH_3OH \longrightarrow CH_3OCH_3 + H_2O$$
$$H_2O + CO \longrightarrow H_2 + CO_2$$

Scheme 41. Production of water from the dehydration of methanol and generation of H_2 via the WGSR.



Scheme 42. Various products formed from the ruthenium catalysed transformation of ethene–CO mixtures in isopropanol.

pressures were required. Typically conditions of 500 atm and 250 °C were applied.

The alcohol solvent, 3-pentanol, provided the two hydrogen atoms necessary for formation of 3-pentanone by undergoing hydrogen transfer via dehydrogenation. In this particular solvent, the product of alcohol dehydrogenation is itself 3-pentanone, resulting in the observed high selectivity. The use of more common secondary alcohols, such as isopropanol, resulted in formation of acetone alongside 3-pentanone (Scheme 39).

Subsequently, Natta et al. demonstrated that $[Co_2(CO)_8]$ could catalyse the production of 3-pentanone (and 2-butanone) from ethene, CO and 2-butanol under milder conditions (210 °C and 250 atm) [17]. However, reactions performed in methanol were less selective due to the formation of methyl propanoate and propanal in addition to 3-pentanone. Similarly, Gresham et al. had briefly noted the loss of selectivity to the ketone product using primary alcohols and suggested that near exclusive formation of the ester could be achieved [66] (Scheme 40).

Formaldehyde was expected as the dehydrogenation product from methanol. However, no appreciable quantity was detected at the end of the reaction, but dimethyl ether was found unexpectedly in the gas phase. This volatile product was explained as arising from dehydration of two methanol molecules. The water thus formed then produced the necessary hydrogen atoms for formation of the ketone via the WGSR (Scheme 41).

A slightly different result was reported by Sneeden et al. in the ruthenium catalysed synthesis of ketones from alkene–CO mixtures in alcohols [67]. In secondary alcohols, 3-pentanone was not formed in the same selective manner due to the production of major quantities of the alkyl propanoate and ethane as secondary products. Scheme 42 shows the various products formed from ethene–CO mixtures in isopropanol. H_2, CO_2 and C_1–C_4 hydrocarbons were also detected as minor products. Exceptionally mild conditions were used in comparison to the systems previously described. Temperatures of 160 °C and pressures as low as 15 bar could be employed.

In primary alcohols, such as ethanol, the ester product, ethyl propanoate, was favoured over 3-pentanone. In contrast to the cobalt catalysed methanolic system [17], which did not appear to involve dehydrogenation of the alcohol as the hydrogen source, acetaldehyde was indeed proposed as a reaction byproduct in this ethanolic system. However, further reaction of acetaldehyde with ethanol resulted in the direct formation of acetaldehyde diethyl acetal in preference.

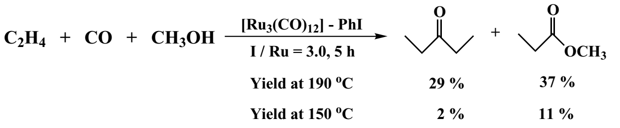
Suitable ruthenium catalysts for this reaction were $[RuCl_3]$ or base promoted $[Ru_3(CO)_{12}]$. The nature of the active species was not defined but was proposed to involve mono- or binuclear entities. The yield of 3-pentanone was found to be inversely proportional to the concentration of the $[Ru_3(CO)_{12}]$ catalyst but directly proportional to the concentration of the $[RuCl_3]$ catalyst. The yield and selectivity to 3-pentanone was improved by using a 2:1 ratio of ethene to CO at elevated pressures between 20 and 40 bar. Temperatures around 190–200 °C were ideal for high yields of 3-pentanone but higher temperatures resulted in transfer of selectivity to the hydrogenation of ethene.

An improvement in the synthesis of esters and ketones from ruthenium catalysed alkene–CO–ROH systems was reported by Hidai et al. some years later [68]. The use of iodide promoters with $[Ru_3(CO)_{12}]$ led to higher activities than the ruthenium systems previously reported by Sneeden et al. [67]. Moreover, control over the selectivity could be achieved by application of a covalent or ionic iodide. The covalent iodides, such as CH_3I or PhI, were found to promote the formation of both the ester and ketone (Scheme 43). The distribution of these products greatly depended on the I/Ru ratio.

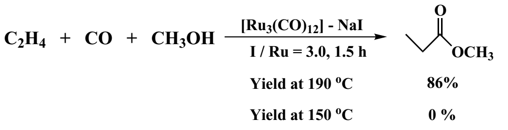
Low ratios, e.g. 1:1, favoured the ester product such as methyl propanoate from ethene–CO–MeOH mixtures, whilst high ratios (10:1) favoured the ketone product, 3-pentanone. The temperature of the reaction also altered the product distribution. The ester was the preferred product at 150 °C, whereas both products were formed in near equal amounts at 190 °C. The quantity of covalent iodide added was not found to influence greatly the reaction rate.

In contrast, the quantity of ionic iodide added, such as NaI, ^{n}Bu$_4$NI or Ph$_4$PI, was found to affect the rate dramatically. Increasing quantities of these promoters resulted in a steady increase in rate. With I/Ru ratios of 10:1, the rate was found to be ten times faster than using [Ru$_3$(CO)$_{12}$] alone. Use of ionic iodides also allowed preferential formation of methyl propanoate from ethene–CO–MeOH mixtures, due to enhancement of the hydroesterification of ethene. (Scheme 44). 3-Pentanone was not generated in this case and temperatures of 190 °C were required for activity. Free iodide anion was thought to be crucial to the enhancement of methyl propanoate synthesis.

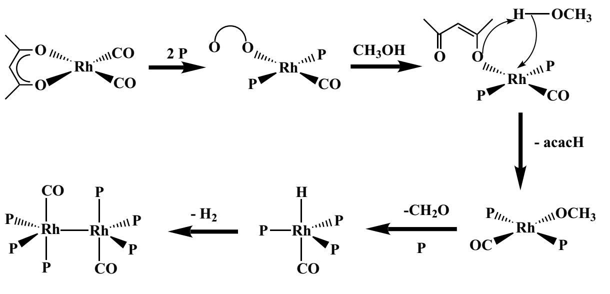
Smaller quantities of the alkane from hydrogenation were sometimes observed. In systems using the secondary alcohol, the ketone produced from of the alcohol was also noted. For example, acetone was observed as a byproduct in the [Ru$_3$(CO)$_{12}$]–PhI system in isopropanol. However, formaldehyde was not detected in the equivalent experiment in methanol and no attempts to explain this observation were made.



Scheme 43. Product distribution from ethene–CO–MeOH mixtures using 3:1 ratio of covalent iodide to [Ru] at 150 and 190 °C.



Scheme 44. Selective synthesis of methyl propanoate from ethene–CO–MeOH mixtures using 3:1 ratio of ionic iodide to [Ru] at 190 °C.



Scheme 45. Formation of the active hydride and resting dimer from [Rh(acac)(CO)$_2$] and PEt$_3$ (P) in methanol.

Propene reacted much more slowly than ethene and gave poorer results overall. In contrast to the ketone and ester products observed using ethene, products from the propene reaction under the same conditions were propane and methyl butyrate ($n/i = 1{:}1$).

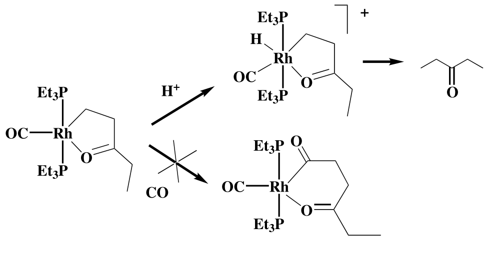
The active ruthenium species were proposed to be [Ru$_3$(H)(CO)$_{11}$]$^-$ and [Ru(CO)$_3$I$_3$]$^-$. Insertion of ethene and CO into the Ru–H bond of the former hydride species would form an acyl intermediate. Formation of methyl propanoate was thought to occur via reaction of MeOH with EtC(O)I, the latter being produced from the bimolecular reductive elimination of the acyl intermediate with [Ru(CO)$_3$I$_3$]$^-$.

More recently, Robertson et al. have investigated rhodium triethylphosphine complexes for reactions of CO with ethene in methanol and other alcohols [69]. Selectivities of up to 85% for 3-pentanone can be observed under relatively mild conditions (70 bar, 110 °C). The other product is methyl propanoate, with only traces of longer chain products being observed. The catalyst precursor can be [RhH(PEt$_3$)$_4$] or the catalyst can be made in situ from [Rh(acac)(CO)$_2$] and PEt$_3$, with no significant difference in the product selectivity except for slightly increased chain growth for the in situ prepared catalyst. Higher temperatures increased the reaction rate but reduced the selectivity to 3-pentanone. Unlike the studies of Sen [12] (see Section 2) using Rh/PPh$_3$ complexes, neither hydrogen nor water were required for reactivity, indeed water reduced the overall yield. By using ^{13}C labelled methanol, it was demonstrated that the source of the two extra H atoms required for the formation of 3-pentanone was methanol, which was converted into methyl formate rather than formaldehyde or dimethoxymethane.

The catalytic precursor was shown to be [RhH(CO)(PEt$_3$)$_3$], which was formed (Scheme 45) from [Rh(acac)(CO)$_2$] and PEt$_3$ via the crystallographically characterised [Rh(η^1-acac)(CO)(PEt$_3$)$_2$]. In the absence of ethene, [RhH(CO)(PEt$_3$)$_3$] degrades to [Rh$_2$(CO)$_2$(PEt$_3$)$_6$], which is also the resting state of the catalyst [70].

The high selectivity to 3-pentanone was explained [69,70] in terms of coordination of the carbonyl O atom of the 3-oxopentyl intermediate creating an 18 electron Rh centre and hence reducing the tendency for migratory insertion of CO into the Rh–C bond which would expand the ring from five- to six-membered (Scheme 46).

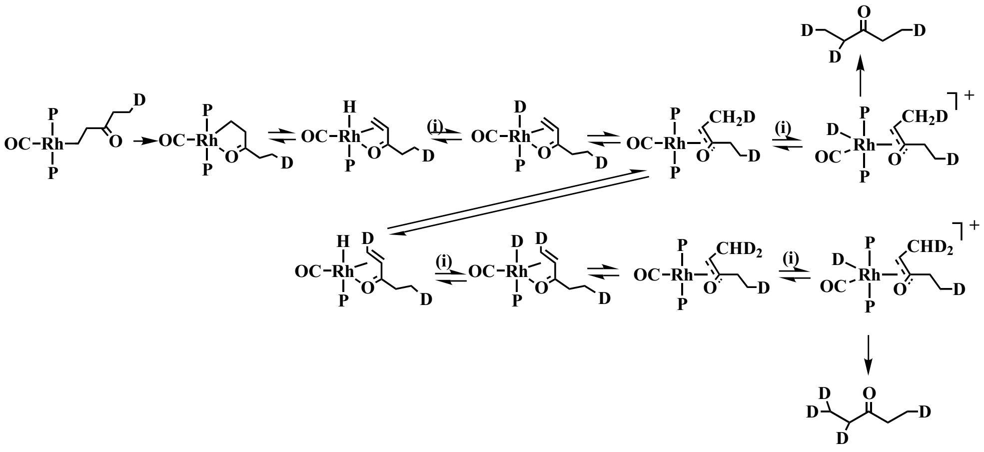
Reactions using CD$_3$OD produced 3-pentanone with up to 2 D atoms in one Me group and 1 in the other and methyl propanoate with 0 or 1 D atom in the methyl group of the ethyl moiety. Post reaction exchange into the methylene groups of each product



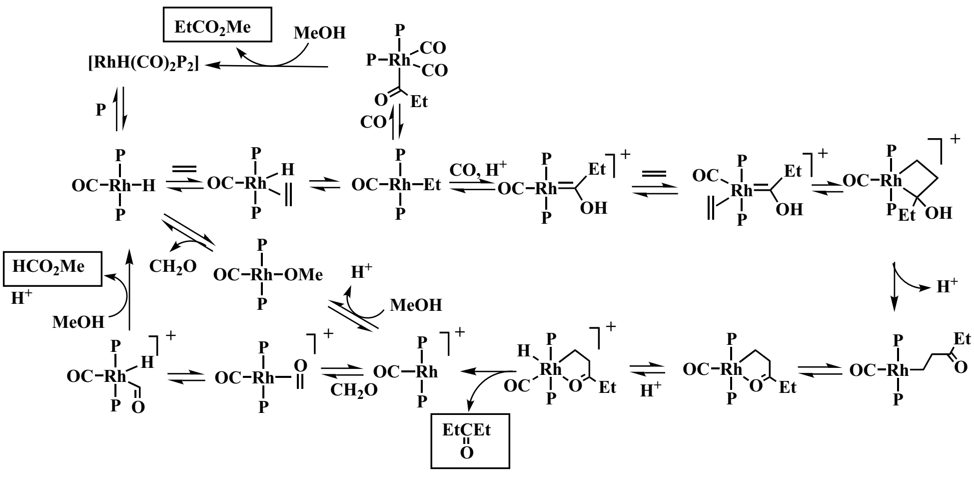
Scheme 46. Selective formation of 3-pentanone caused by chelation of the η²-oxopentyl intermediate to form an 18 e complex.

meant that their labelling patterns were not mechanistically important. The fact that a significant proportion of both products contained no D atoms was interpreted as meaning that hydride (deuteride) migration onto the coordinated ethene molecule and exchange of free and bound ethene were reversible and rapid compared with migratory insertion of CO into the Rh–Et bond or H/D exchange with the solvent. Multiple incorporation of D into one Me group of 3-pentanone was explained by the enolate mechanism shown in Scheme 47, which is similar to that previously demonstrated in Pd systems by Zudin et al. [56] and van Leeuwen and coworkers [71]. It could not have occurred by reversible migration of D onto coordinated ethene and facile H/D exchange since this would also have led to multiple incorporation into the Me group of the ethyl moiety of methyl propanoate, since both products come from the same initial Rh–Et complex. The fact that multiple D incorporation into the Me group of the ethyl moiety of methyl propanoate was not observed was interpreted as ruling out a carbomethoxy intermediate in this system.

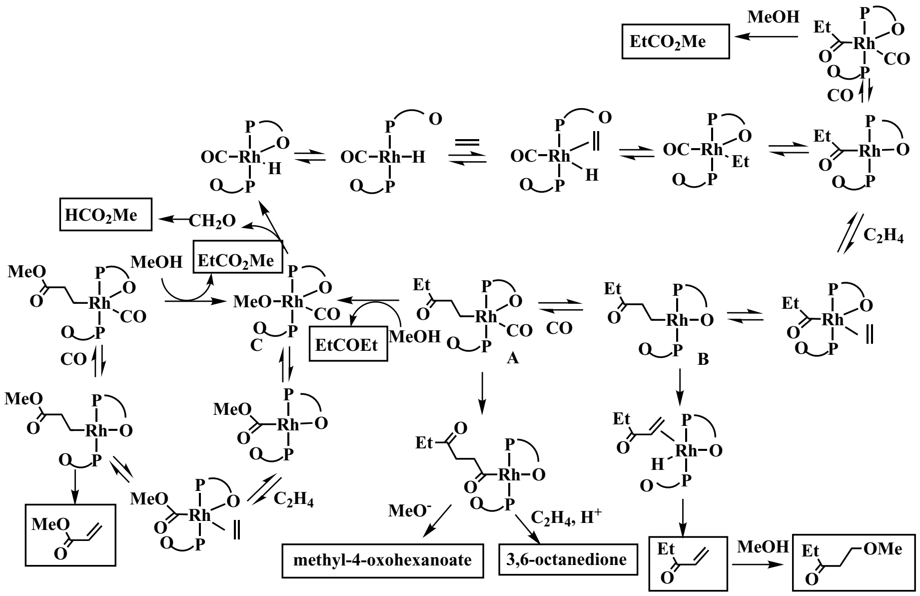
The overall mechanism for the production of the various products is then as shown in Scheme 48. The proposed carbene complex has been shown to be present in this system both spectroscopically and by synthesis and full spectroscopic characterisation of the



Scheme 47. Enolate mechanism accounting for the multiple incorporation of D into 1-methyl group of 3-pentanone. (i) CD_3OD, $P = PEt_3$ from Ref. [69]. Reproduced by permission of the Royal Society of Chemistry.



Scheme 48. Mechanism for the production of 3-pentanone, methyl propanoate and methyl formate (in boxes) from CO, ethene and MeOH catalysed by PEt_3 complexes of rhodium. $P = PEt_3$. From Ref. [69]. Reproduced by permission of the Royal Society of Chemistry.



Scheme 49. Proposed mechanism for the formation of all the products listed in Table 3 using catalysts based on the phosphines with γ-O atoms (P–O) listed in Table 3. From Ref. [73]. Reproduced by permission of the Royal Society of Chemistry.

Table 3

Products obtained from the carbonylation of ethene catalysed by rhodium complexes of β-ketophosphines and related ligands, from Ref. [73] [a]. Reproduced by permission of the Royal Society of Chemistry

Ligand	MA	MP	EVK	DEK	1M3P	M4OH	OD	Total turnover	MCP (%)
$Et_2PCH_2C(O)Ph$	4.4	4.4	2.0	24.0	12.5	2.4	9.0	58.7	40.7
$Et_2PCH_2C(O)Et$	6.7	7.8	3.1	23.4	12.0	2.6	7.1	62.7	34.6
$Et_2PCH_2C(O)OEt$	12.2	6.8	3.7	38.2	14.3	5.8	9.7	90.7	32.9
$Et_2PCH(CH_3)C(O)CH_3$	7.2	6.9	1.4	39.7	6.7	2.5	3.1	67.5	18.2
$Cy_2PCH_2C(O)Ph$	–	4.0	–	0.5	1.2	2.0	0.7	8.4	46.4
$^tBu_2PCH_2C(O)OEt$	–	2.1	1.7	7.7	11.2	–	4.4	27.1	57.6
$^tBu_2PCH_2C(O)Ph$	–	–	–	–	–	–	–	0	–
$Et_2PC_2H_4OMe$	4.1	15.0	1.5	37.3	17.8	3.0	9.2	87.9	34.1
$Et_2PC_2H_4NEt_2$	–	26.9	trace	41.1	3.3	–	4.4	75.7	10.2
$Me_2PCH_2P(O)Me_2$	–	10.7	0.9	3.5	3.7	–	2.9	21.7	30.4
$Me_2PCH_2P(O)Me_2$ [b]	4.4	5.1	3.4	24.9	13.4	2.9	14.3	68.4	44.7

[a] $[Rh(acac)(CO)_2]$ (0.1 mmol), phosphine (0.4 mmol), CO (35 bar), ethene (35 bar), methanol (10 cm^3), 110 °C, 24 h. Amounts expressed as catalyst turnovers.

[b] Two equivalents of ligand used—i.e. (0.2 mmol). MA (methyl propenoate, methyl acrylate), MP (methyl propanoate), EVK (penten-3-one, ethyl vinyl ketone), DEK (pentan-3-one, diethyl ketone), 1M3P (1-methoxy-3-pentanone), M4OH (methyl 4-oxohexanoate), OD (3,6-octanedione), MCP (medium chain products, 7+ atoms in backbone).

analogue with methyl replacing ethyl on the hydroxycarbene ligand [69,72].

In order to attempt to encourage chain growth in this system, it was reasoned that the η^2-binding of the 3-oxopentyl intermediate would have to be frustrated, for example by forming intermediate **A** in Scheme 49. The use of ligands containing carbonyl groups β to the P atom in the phosphine ligand was investigated in the anticipation that the O atom of this carbonyl group might bind to the Rh atom in preference to the O atom of the 3-oxopentyl intermediate. The results in Table 3 show that chain growth was increased, but that other products, methyl propenoate and penten-3-one also became significant [73]. 1-Methoxypentan-3-one, which was also observed, was shown to have been formed from addition of methanol to penten-3-one in an uncatalysed reaction. The selectivity to products with > 7 C or O atoms could be as high as 58%. Since the products contain two or more O atoms, the product mixture has the potential to be a low volatility solvent with good solvating power.

Reactions in CD_3OD gave 3-pentanone and methyl propanoate with a maximum of one D in the end methyl groups, indicating that the enolate mechanism was not operating. This is presumably because of η^1 binding of the 3-oxopentyl intermediate (**B** in Scheme 49) so that β-H abstraction leads to penten-3-one coordinated only through the double bond and this decoordinates rather than reinserting to give the enolate complex.

It might be expected that the pendant oxygen atom from the growing chain in intermediate **B** in Scheme 49 might coordinate to give an intermediate similar to that proposed for the PEt_3 system (Fig. 7) and hence to give high selectivity to 3-pentanone.

However, the proposed η^1-3-oxopentyl intermediates differ in that the one derived from the β-ketophosphine ligand does not contain CO and the rhodium centre will be more electron rich than that derived from PEt_3, which does contain CO. The more electron rich intermediate will favour CO coordination over binding of the keto group from the growing chain, since back bonding into the π^*-orbitals of CO will help to reduce the electron density on Rh whilst the keto O atom of the growing chain is mainly a σ donor. For the PEt_3 complex, the CO is already lowering the electron density at Rh so that binding of the keto O atom from the growing chain will occur more readily and will be favoured on entropic grounds, hence the high selectivity to 3-pentanone.

The observation of methyl propenoate as a product shows that a carbomethoxy cycle must be operating in this case and this is again explained by the coordination of the γ-O atom in the ligand. The methoxy complex, **C** in Scheme 49, is then an 18 electron complex and more readily undergoes migratory insertion to give the carbomethoxy complex than β-H abstraction to re-enter the hydride cycle.

Bis(dimethylphosphino)methane oxide behaves similarly to ligands containing a CO group β to the P atom, as does diethyl(2-methoxyethyl)phosphine, but a ligand such as diethyl(2-dimethylaminoethyl)phosphine, with a γ-N atom behaves more like PEt_3 (Table 3). The proposed mechanism for the formation of all of the observed products is shown in Scheme 49, which relies heavily on the proposal that the γ-O atom of the phosphine ligand does coordinate to the rhodium throughout most of the cycle.

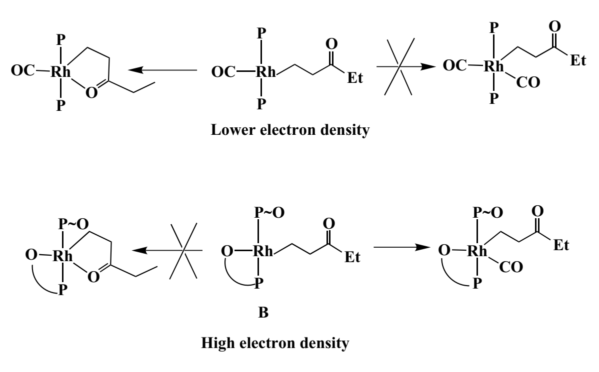


Fig. 7. η^1-3-Oxopentyl intermediates from PEt_3 (P) and β-ketophosphine (P–O) complexes of rhodium and the effect of coordinated CO on the metal electron density and hence reactivity.

6. Conclusions

A wide diversity of products is available from reactions of carbon monoxide with ethene in alcohols or other solvents. Perfectly alternating copolymers and propanal from hydroformylation have already been commercialised, whilst the formation of methyl propanoate is currently being scaled up in industry, particularly as part of a route to methyl methacrylate via condensation with formaldehyde. Other short chain oligoketones, for which the first member is 3-pentanone, or oligoketoesters are becoming of interest because they have the potential to provide good solvents with low volatilities and hence to contribute to the greening of Chemistry by reducing emissions of volatile organic compounds (VOCs).

The most used metal for CO–ethene reactions is palladium and the products obtained are determined by the ligand and the solvent. In general, complexes containing unidentate phosphines lead to high selectivities to methyl propanoate for reactions carried out in methanol, whilst bidentate ligands give oligo or polyketones (Section 1).

For palladium complexes of triphenylphosphine, the product is methyl propanoate (Section 3) but changing the alcohol (Section 3) from methanol leads to oligoketones because the insertion of ethene into the key acyl intermediate becomes competitive with nucleophilic attack of the alcohol. For ethanol, the reduced rate of alcoholysis is attributed to steric effects, but the longer chain growth observed when using trifluoroethanol is assumed to arise because of the lower nucleophilicity of trifluoroethanol.

For simple diphosphines of formula $Ph_2P(CH_2)_n$-PPh_2, the molecular weight of the oligoketones and the reactivity of the system vary with the length of the spacer group between the P atoms, with both peaking when $n = 3$ (Section 2). Oligoketoesters are formed at low temperatures, but statistical mixtures of oligoketoesters and compounds with two ketonic end groups or two ester end groups are formed at higher temperatures showing that crossover between the hydride and the carbomethoxy mechanisms only occurs at higher temperatures. Bidentate ligands containing P,P; P,S or P,O donor sets in which both donor atoms remain coordinated to the metal throughout the catalytic cycle all give polyketones, but hemilabile P,O or P,S ligands give unsaturated oligoketones, presumably because they act like unidenate phosphines and the presence of multiple vacant sites on Pd allows facile β-hydrogen abstraction in the growing chain.

Exceptionally, rigid bidentate ligands with P atoms separated by 4 C atoms give methyl propanoate as the sole product, despite evidence that both P atoms are coordinated to the palladium at least for part of the cycle (Section 3). The most spectacular example of this

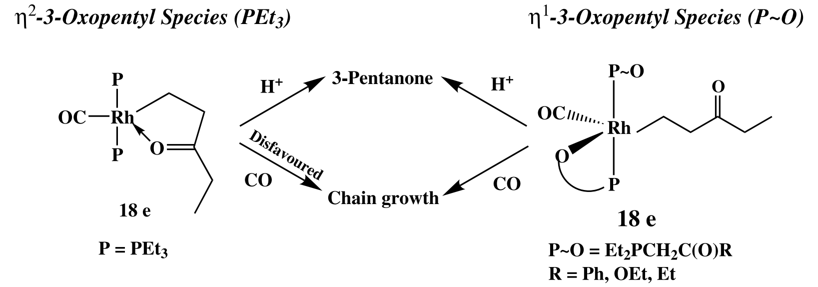


Fig. 8. Difference in structure and reactivities of the 3-oxopentyl intermediate in Rh/PEt_3 and β-ketophosphine systems.

is the system based on *o*-bis(ditertiarybutylphosphinomethyl)benzene, which gives very high activity and selectivity to methyl propanoate.

If hydrogen or water is added to the Pd/PPh_3 system, the selectivity of the reaction changes so that 3-pentanone is the major product (Section 4). The presence of CO and water allows the formation of hydrogen by the WGSR. Larger excesses of water, however, lead to propanoic acid by nucleophilic attack of water onto the acyl intermediate. Cobalt complexes, which are also capable of promoting the WGSR, again give 3-pentanone selectively from CO, ethene and water or secondary alcohols. In the case of alcohols, the two hydrogen atoms required are obtained by dehydrogenation of the alcohol.

Rhodium complexes containing CO or PPh_3 give the co-oligomerisation products, oligoketones and oligoketoesters, but water must be present, either added or formed in situ, e.g. from methanol and ethanoic acid (Section 3). Addition of pyridine changes the selectivity towards methyl propanoate because the coordinated pyridine blocks sites to which ethene would otherwise coordinate for chain growth. Triethylamine, on the other hand favours 3-pentanone, apparently because it helps to promote the WGSR, thus increasing the concentration of hydrido rhodium species and increasing the rate of bimolecular reductive elimination.

Rhodium complexes of more basic phosphines do not require the presence of water, the extra hydrogen atoms required for 3-pentanone formation being derived from the alcohol solvent (Section 5). When this is methanol, the dehydrogenation product is methyl formate. If PEt_3 is the ligand, the major product is 3-pentanone with smaller amounts of methyl propanoate and only traces of longer chain products being formed. This selectivity is attributed to the binding of the keto oxygen atom of the growing chain to the rhodium, thus preventing ethene coordination and CO insertion since this would lead to the stable five-membered ring expanding to a less stable six membered ring. In addition, the high electron density in the metal makes protonation of the Rh–C bond facile. Using β-keto and related phosphine ligands, the keto group in the ligand binds in preference to that in the growing chain (see Fig. 8 for the comparative intermediates) and so CO migratory insertion can occur more readily (no ring expansion is required) and increased chain growth is observed.

In addition, β-hydrogen abstraction from the growing chain leading to 3-pentenone also becomes significant, because this is not constrained by chelate binding of the growing chain. Finally, a carbomethoxy mechanism leading to methyl propenoate and possibly methyl propanoate also becomes operative, presumably because binding of the ligand O atom to form an 18 e intermediate reduces the rate of β–H abstraction from the methoxy intermediate and allows migration onto coordinated CO to become competitive (Fig. 9).

For square planar palladium complexes, polyketone formation only occurs when a diphosphine ligand occupies adjacent (*cis*) coordination sites on the metal. This orientation favours migratory insertion and chain growth. With unidentate phosphines, the high *trans* influence of the growing chain causes rapid isomerisation to place the phosphines mutually *trans* and early termination is favoured because migratory insertion of mutually *trans* ligands cannot occur. For rhodium complexes, which have five- and six-coordinate geometries, sites *cis* to the growing chain are always available so it would be expected that chain growth would predominate. However, this is not the case, particularly when electron donating phosphines like PEt_3 are employed. It is instructive, therefore, to compare the key intermediates in the palladium and rhodium catalysed systems.

The selectivity towards chain growth or diethylketone formation is determined by the reactivity of the 3-oxopentyl intermediates, which for Pd and Rh are shown in Fig. 10.

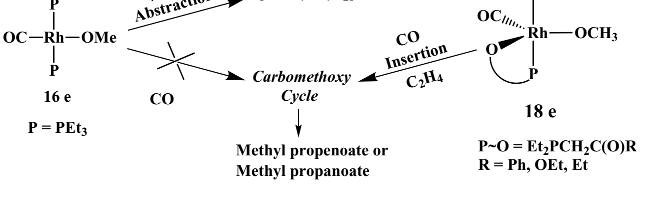


Fig. 9. Difference in structure and reactivities of the methoxy intermediates in PEt_3 and β-ketophosphine systems.

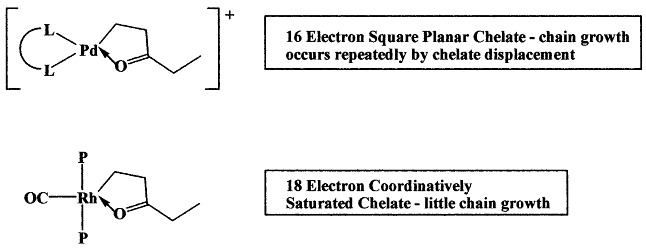


Fig. 10. Structures of proposed intermediates formed in the Pd catalysed copolymerisation and Rh catalysed co-oligomerisation of CO and ethane.

In comparison to the cationic Pd/phenyl phosphine systems such as $[Pd(Ph_2P(CH_2)_3PPh_2)(MeCN)_2][BF_4]_2$ or $[Pd(PPh_3)_n(MeCN)_{4-n}][BF_4]_2$ ($n = 1$–3), the Rh metal centre is substantially more electron rich due to the strong σ donor nature of the PEt_3 ligands and the overall neutral charge of the complex. This means that the electrostatic interaction between the oxygen atom of the chain and the rhodium should be less, forming a weaker chelate which should therefore be displaced more easily and allow chain growth. However, only limited chain growth is observed.

The lack of copolymerisation and limited extent of co-oligomerisation for Rh/PEt_3 complexes must result from the rapid protonation of the chelate complex giving 3-pentanone in preference to reaction with CO. The 18 electron η^2-3-oxopentyl species would be readily protonated due to the electron rich metal centre. The addition of H^+ does not involve an increase in the electron count, unlike the insertion of CO, which would require either ring expansion via intramolecular CO insertion (within the coordination sphere) or displacement of the chelate and coordination of CO from the gas phase. The former step is rather unlikely because a favoured five membered ring would be converted into a disfavoured six-membered ring. Because the rhodium complex has 18 e, the rate of displacement of the chelating carbonyl by CO will be less than the rate of protonation, thus causing termination after only the second insertion of ethene. In contrast, CO insertion into the 16 electron $[RhEt(CO)(PEt_3)_2]$ complex must occur faster than protonation, which prevents the observation of ethane gas as a product. Interception of the resulting $[Rh(COEt)(CO)(PEt_3)_2]$ complex by methanol before the rate limiting step of ethene insertion, results in methyl propanoate as a secondary product.

For the palladium based diphosphine systems, the key η^2-3-oxopentyl species is a 16 electron complex so it has the ability to coordinate CO and this CO must displace the oxygen atom prior to migratory insertion so that the migratory insertion occurs without direct ring expansion. A similar conclusion has been reached by Drent as a result of in situ reflection absorption infra-red spectroscopic studies of surface bound catalysts for CO–ethene polymerisation reactions [74]. Protonation of the five-membered palladacycle can also occur giving the saturated diketone and ketoester as products of termination. However, the rate of termination must be slower than that of propagation, so that polymeric products predominate rather than 3-pentanone and methyl propanoate. This may be because the palladium centre is cationic and the ligands are less electron donating, thus reducing the susceptibility to protonation. The 16 electron Pd(II) centre will also bind the next monomer more readily than the 18 electron Rh(I) centre.

The Pd based copolymerisation reactions are often carried out in dilute methanol solutions, e.g. CH_3NO_2–CH_3OH (2:1, v/v) or in aprotic solvents such as $CHCl_3$ or CH_2Cl_2. The rhodium catalytic reactions are typically carried out in pure methanol, which has been shown to cause a faster rate of termination than higher alcohols such as ethanol due to its smaller steric bulk. In general, the smaller the alcohol, the greater the termination rate. Hence, the use of undiluted methanol rather than diluted methanol or bulkier alcohol solvents would also aid early termination.

Therefore, the difference in chemoselectivity between the cationic Pd/DPPPr and neutral Rh/PEt_3 systems for reactions of CO–ethene systems lies mainly in the electronic nature of the intermediates and the nature of the solvent system employed.

Viable routes to a variety of useful compounds from CO and ethene in the presence of alcohols or water are now becoming available and a fuller understanding of the mechanisms involved is beginning to allow the tuning of the reactions towards the highly selective production of individual compounds. Current research is focussed on improving both the selectivity and activity of the catalytic systems still further.

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