Selected recent developments in organo-cobalt chemistry

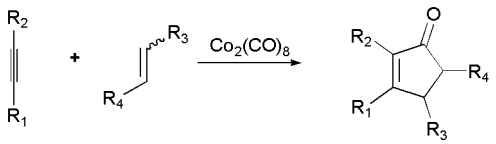
Caroline J. Scheuermann née Taylor*[a] and Benjamin D. Ward[b]

Received (in Durham, UK) 15th February 2008, Accepted 23rd April 2008
First published as an Advance Article on the web 1st July 2008
DOI: 10.1039/b802689k

Organometallic complexes of cobalt continue to find application in a wide variety of contexts, from fundamental organometallic and coordination chemistry, to the metal-mediated synthesis of organic compounds. The research outlined in this review reports on the use of organo-cobalt chemistry for the synthesis of organic compounds and cobalt containing metallocenes, particularly those cases which involve a formal cycloaddition between alkynes, with or without carbon monoxide, forming π-coordinated cyclopentenones or cyclobutadienes, respectively. Particular focus is given to the various methods available for the formation of organo-cobalt metallocenes, and their application as versatile reagents in organic synthesis is discussed.

1.1 Pauson–Khand reaction (PKR)

The Pauson–Khand reaction (PKR) is possibly the most widely studied reaction in cobalt-mediated chemistry.[1–4] First discovered in 1971 by Pauson and Khand, the reaction is a three component [2 + 2 + 1] cycloaddition between an alkyne and an alkene, with the insertion of carbon monoxide. It is one of the most useful reactions for the formation of cyclopentenones **1**, and is often used in natural product synthesis, Scheme 1.[5,6]



1

Scheme 1 Typical Pauson–Khand reaction.

The generally accepted mechanism of the PKR was proposed by Magnus, and is outlined in Scheme 2.[6–9] A problem with determining the absolute mechanism is the isolation of intermediates, which are all unstable. The first step, after complexation of the alkyne, involves the loss of a carbon monoxide ligand from octacarbonyl dicobalt. This is reversible, and is the rate limiting step.[10] The loss of two CO ligands produces the dicobalt carbonyl alkyne complex **3**, which has two σ-Co–C bonds, one to each Co atom. This intermediate complex then loses another CO ligand to form a pentacarbonyl complex which is coordinatively unsaturated.

The alkene then coordinates to this pentacarbonyl alkyne dicobalt complex. The formation of the cobaltacycle **5**, *via* the coordination of the olefin to the unsaturated cobalt and the insertion to form a new Co–C bond, determines the regio- and stereoselectivity. The energy required for this step is considerable, and may explain why strained (often cyclic) olefins are good substrates, with the relief of strain driving the reaction. Theoretical calculations for the formation of the cobaltacycle have been carried out and show that the C–Co bonds form only at one Co centre, while the other metal centre merely exerts electronic influence through the Co–Co bond.[11,12] The cyclopentenone annulation is also regioselective with the larger group of the alkene ending up adjacent to the carbonyl

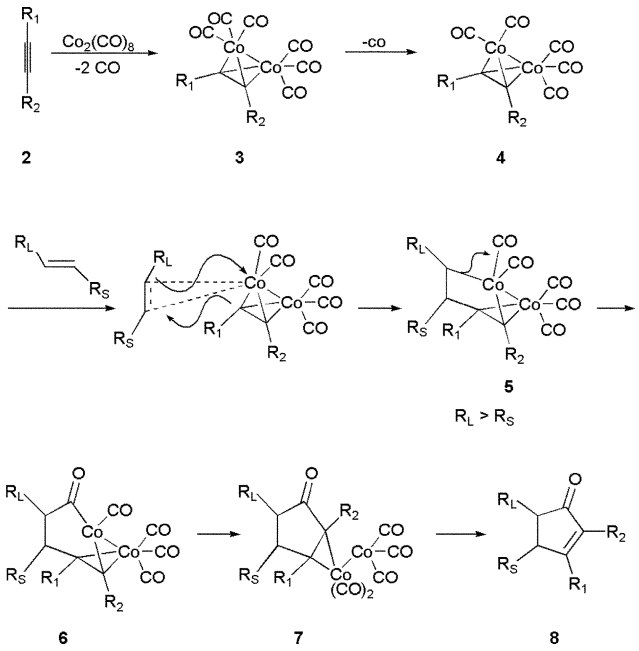
[a] *Universität Stuttgart, Institute für Organische Chemie, Pfaffenwaldring 55, 70569 Stuttgart, Germany. E-mail: caroline.scheuermann@oc.uni-stuttgart.de*
[b] *School of Chemistry, Cardiff University, Main Building, Park Place, Cardiff, UK CF10 3AT*

Caroline Scheuermann

Caroline Scheuermann did her MSci at Queen Mary College, London and remained there for her PhD in the group of Dr Richards, working on the synthesis of planar chiral Fe and Co metallocenes. She moved to Germany to take up a postdoctoral fellowship at CaRLa and currently works at the University of Stuttgart. Her research interests include asymmetric catalysis using chiral organometallic complexes of first row elements

Ben Ward

Ben Ward graduated from Nottingham with an MSci and studied for his DPhil under Prof Mountford at the University of Oxford. He moved to the Université Louis Pasteur to work with Prof Gade and was awarded a Marie Curie fellowship to continue his research in Heidelberg. He moved to Cardiff as a lecturer in 2007; his research includes syntheses and applications of organometallic compounds in asymmetric catalysis

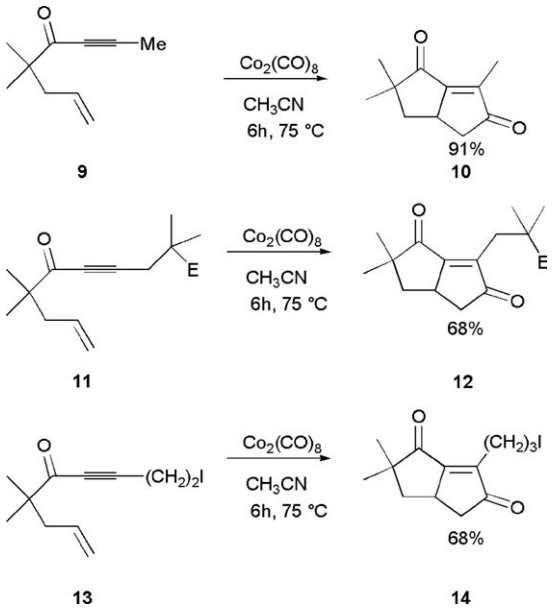


Scheme 2 The mechanism of the PKR.[6–9]

in the product.[6] The migration of the CO ligand is stereospecific with retention of absolute stereo-chemistry. Recently, Greene and co-workers have used density functional theory (DFT) calculations to study the regioselectivity of the PKR.[13] Their investigations focused on the theory that differences in the electron density at the acetylenic carbons have an effect on the regio-chemical preferences of the PKR. From the study it was found that the backbonding of the six carbonyl groups in **3** is heavily influenced by the substituents attached to the alkyne. Additionally, it was found that the two pseudoaxial CO groups were bound more strongly than the pseudo-equatorial ones. They concluded that for some cases, the observed regioselectivity in the PKR is entirely governed by electronic differences *via* discriminant carbon monoxide loss which results in the regioselective cyclopentenone formation. Similar work had been carried out by Gleiter and co-workers again using DFT calculations, though on this occasion supplemented with experimental data.[14] The DFT calculations showed that the *trans*- relationship between the positively polarized carbon atom of the alkyne and the weakened pseudoequitorial Co–CO bond, described by Greene and co-workers discussed above, only existed for one example, where in **3** R_1 = Me, R_2 = CO_2Et. They conclude that at present it is not possible to predict the regio-chemical outcome of the PKR and that a significant theoretical study should be conducted before any general conclusions can be drawn.

All simple alkynes are suitable substrates in the PKR. The yields of the reaction are dependent on the degree of substitution and bulkiness of the substituents, with ethyne or other simple terminal alkynes giving the highest yields. Electron deficient alkynes are poor substrates for these reactions as this disfavours complexation to the Co metal centre.

Hoye reported the PKR of electron deficient alkynones **9**, **11** and **13**, which are usually poor substrates due to the close proximity of the polar ketone. In this case the PKR reaction was effected with moderate to excellent yields.[15] The successful use of these substrates was shown to be highly dependent on the solvent. The reaction times were considerably longer (2–3 days) and the yields disappointing (30–45%) when using ether, THF or heptane as the solvent. In comparison reactions carried out in acetonitrile with 1.1 eq. of $Co_2(CO)_8$ at 75 °C show much improved yields (68–91%) and reduced reaction times, as shown in Scheme 3.[15] It was observed that polar groups remote from the triple bond, such as halides, have little or no effect; however, polar groups nearby often have a detrimental effect on the reaction.



Scheme 3 PKR of electron deficient alkynones.[15]

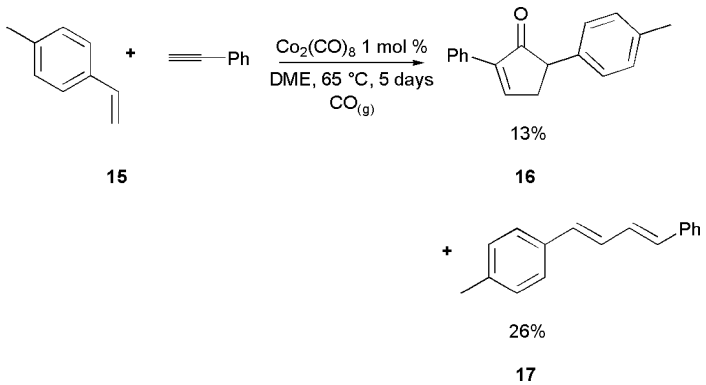
Strained cyclic alkenes, such as cyclobutenes, are suitable candidates for these reactions (*vide supra*). However, the best substrates are cyclopentene, cyclohexene and simple acyclic alkenes. Unsuitable substrates often lead to the formation of aromatics, produced by alkyne trimerisation.[16]

Alkenes, such as **15**, with electron withdrawing groups are unsuitable substrates. As the alkene becomes more electron deficient the formation of a diene by alkyne–alkene coupling (*i.e.* without carbon monoxide insertion), becomes competitive giving rise to compounds such as **17** (Scheme 4).

1.2 Promotion of the PKR

Due to the energetically demanding first step the PKR is notorious for poor yields and long reaction times.[1] Acceleration of the reaction can be achieved with the use of additives (or promoters) that encourage the labile CO ligands to dissociate, thus creating a vacant site for the incoming alkene. These promotors include a range of chemical additives,[17–20] or the use of external stimuli, *e.g.* irradiation either with microwaves, visible light or ultrasonication.[20–22]

Another advantage of the use of promoters is the possibility to use catalytic amounts of the toxic and expensive $Co_2(CO)_8$.[23] Historically, high pressures of CO have been used to regenerate the reactive cobalt species in the catalytic PKR. This was both an expensive and environmentally unfriendly



Scheme 4 Formation of a diene by alkyne–alkene coupling.[16]

method for the regeneration of the reactive cobalt species, not to mention the health hazards associated with the use of CO. Also the catalytic PKR was initially restricted to the use of highly strained alkenes, such as norbornene, in order to synthesise cyclopentenones.

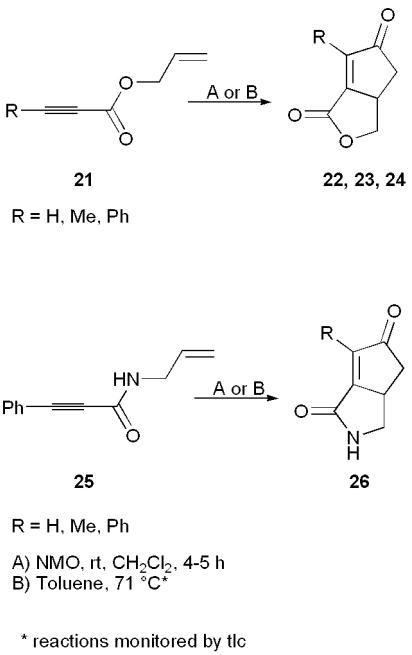
Finally, the enantio- or regio-selective PKR has been developed for the synthesis of enantiopure cyclopentenones, making this reaction attractive for natural product synthesis.[24] A number of different methods have also been employed to provide asymmetric induction in the products.[25–28]

1.2.1 Chemical additives

Many different oxidants have been used, that include amine oxides, amine phosphines, phosphine oxides and sulfoxides. These additives have had varied success, but amine oxides are the most efficient by far. Recently, the promotion of the PKR has been observed in the presence of the radical initiator TEMPO (2,2,6,6-tetramethylpiperidine *N*-oxide),[17] in combination with amine oxides, giving rise to the PKR product in excellent yields. TEMPO has also been shown to facilitate the PKR of more demanding substrates, such as *tert*-butylacetylene and trimethylsilylacetylene, where steric bulkiness can affect the ability of the complex to form the cobaltacycle.[17]

The use of amine oxides was first reported by Jeong[29] and Schreiber,[30] and has possibly become the most popular method for promotion of the PKR. The mechanism by which it works is to provide a vacant site in the cobalt cluster by oxidatively removing one of the CO ligands as CO_2. The most common amine oxides for this use are *N*-morpholine *N*-oxide (NMO) and trimethylamine *N*-oxide (TMANO). All side products from the reaction are either gaseous or volatile (Scheme 5).[30,31]

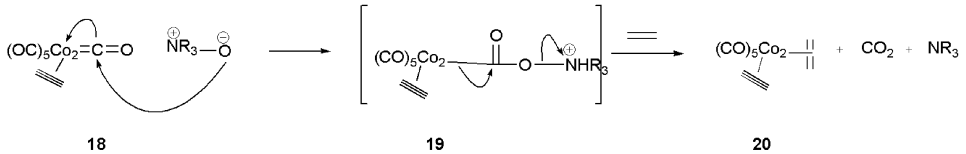
Krafft *et al.* have reported the synthesis of inter- and intramolecular cyclopentenones (**22–24** and **26**).[32] The best results were obtained for the intramolecular cycloaddition



Scheme 6 Intramolecular PKR promoted by NMO at ambient temperature.[32]

using NMO at ambient temperature (Scheme 6). The yields of these reactions decreased when repeated at elevated temperatures without NMO, as shown in Table 1. Interestingly, **25** has been shown to be inert to cycloaddition at ambient temperature in THF. However, the reaction proceeds easily in the presence of NMO.

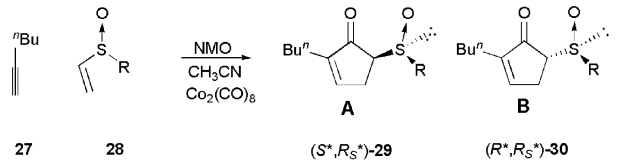
Another benefit of the use of NMO as a promoter is that faster reaction times are often observed and that lower temperatures can be employed, consequently, the reactions are often cleaner and occur in good yields under these milder conditions. Additionally, these additives allow the use of



Scheme 5 Mechanism of promotion of the PKR using amine oxides.[30,31]

Table 1 Intramolecular PKR of electron deficient promoted by NMO at ambient temperature[32]

Entry	Method	Cyclopentenone	Yield (%)
1	A	**22**	66
2	B	**22**	14
3	A	**23**	26
4	A	**24**	66
5	A	**26**	59
6	B	**26**	18



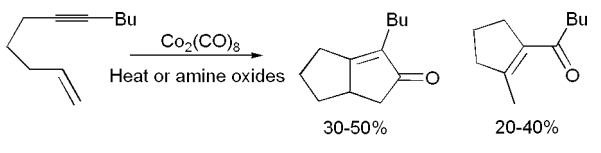
Scheme 7 The use of electron deficient alkenes in the PKR promoted by NMO.[33]

Table 2 The use of electron deficient alkenes in the PKR promoted by NMO[33]

Entry	R	*t*/h	A : B Ratio	Yield (%)
1	*p*-Tol	2	74 : 26	68
2	*o*-Tol	24	90 : 10	28
3	*o*-BrC_6H_4	24	86 : 14	30
4	2,4,6(*i*-Pr)$_3C_6H_2$	24	96 : 4	24
5	*t*-Bu	24	>98 : <2	20
6	*o*-$(Me_2N)C_6H_4$	1	92 : 2	63
7	*o*-$(Me_2N)C_6H_4$	4	93 : 7	74

electron deficient alkenes as substrates in the PKR, Scheme 7 and Table 2.[33]

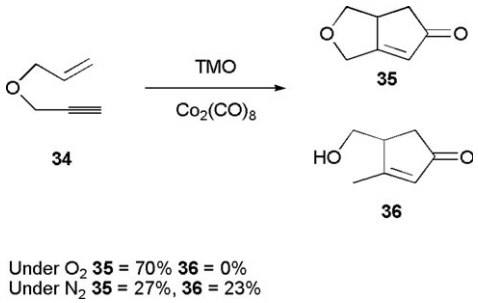
Krafft *et al*. have reported that in an interrupted PKR, the thermolysis of enyne **31** under a nitrogen atmosphere gave the expected bicyclic enone product **32** and the unexpected monocyclic product **33**.[34] Closer inspection of **33** revealed the insertion of oxygen instead of carbon monoxide (Scheme 8). Although the mechanism of the reaction is unclear, it is suggested that molecular oxygen is responsible for the change in outcome of the reaction.[34] When the reaction was carried out in the open air, there was an almost exclusive synthesis of **33**; however, the insertion of oxygen to give **33** could be



Scheme 8 A thermolysis-interrupted PKR.[34]

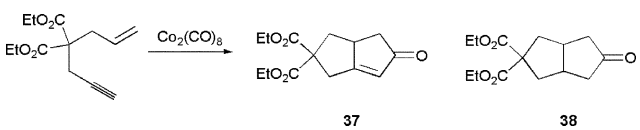
suppressed by carrying out the reaction under a nitrogen atmosphere, thus giving an improved yield of **32**.

This result is contradictory to those reported by Schreiber and co-workers, who reported the TMO (trimethylamine *N*-oxide) promotion of the PKR, shown in Scheme 9.[30] They suggest that the presence of molecular oxygen is essential for the formation of **35** in good yields.



Scheme 9 TMO Promotion of the PKR.[30]

DMSO (dimethyl sulfoxide) has also been used as a promoter of the PKR.[18,35–37] It is generally accepted that its method of action is similar to that of NMO, namely the removal of one of the CO groups of the intermediate alkyne–Co complex by oxidation to carbon dioxide. It was thought that DMSO would be more effective at promoting the PKR than phosphine oxides, and not cause any oxidative destruction of the cobalt complexes, as observed with TMANO. This would provide the possibility of a catalytic version of the reaction. Pauson and co-workers compared the effect of DMSO promotion directly with TMANO in the PKR, Table 3 and Scheme 10.[18] They found the yield of the resulting cyclopentenones was similar to the reactions promoted by TMANO, but that the DMSO variant required higher reaction temperatures. Additionally, an increase in the amount of DMSO, when the reaction was carried out in dichloromethane, lead to an increase in the undesirable saturated cyclopentanone **38**, Scheme 10. This problem was overcome by changing the reaction solvent to benzene, however, this had the effect of extending the reaction time from 4 to 24 h. Unfortunately, when the PKR was carried out using a chiral sulfoxide, (−)-methyl-*p*-tolylsulfoxide, as the promoter no asymmetry was observed in the products.

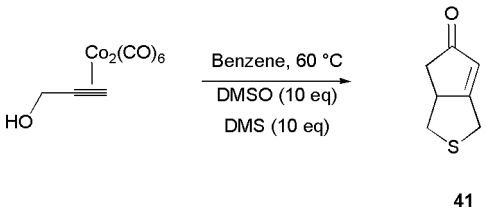


Scheme 10 Comparison of the effect of DMSO and TMANO promotion.[18]

Table 3 Comparison of the effect of DMSO and TMANO promotion[18]

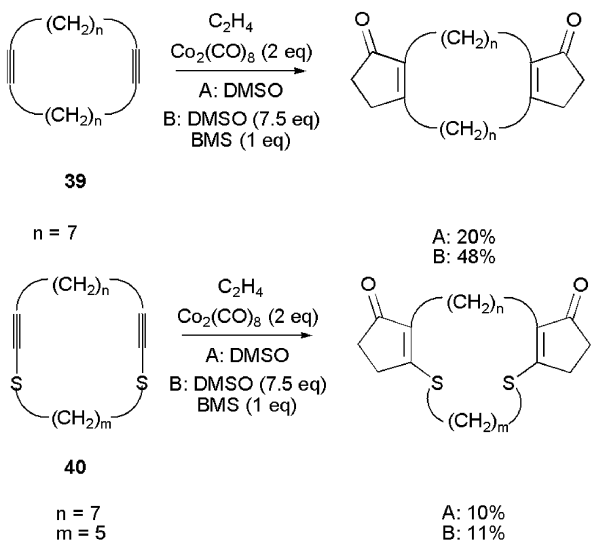
Promoter (eq.)	Solvent	*T*/°C	*t*/h	**37**	**38**
TMANO (−)	CH_2Cl_2	20	3	90	0
DMSO (1)	CH_2Cl_2	40	4	85	1
DMSO (2)	CH_2Cl_2	40	4	84	2
DMSO (3)	CH_2Cl_2	40	4	83	3
DMSO (3)	C_6H_6	40	24	90	0

Stumpf *et al*. noticed a synergistic effect for the intramolecular PKR, during the synthesis of 3-thiabicyclo-[3,3,0]-oct-5-en-7-ones, when the reaction was promoted by DMSO in combination with DMS (dimethyl sulfide).[37] The reaction proceeded with a moderate yield (48%) of **39** at high temperature, in refluxing benzene and DMSO (10 eq.), without the addition of DMS. However, when the reaction was repeated at 60 °C, also using benzene as the solvent, with DMSO (10 eq.), and DMS (10 eq.) the yield increased (65%). It is thought that the role the DMS plays is to ligate the coordinatively unsaturated metal fragment directly after the reaction cycle, Scheme 11.



Scheme 11 Synergistic effect for the intramolecular PKR when promoted by DMSO and DMS.[37]

Gleiter *et al*. have also reported a synergistic effect of oxidative and coordinative promoters for the two fold PKR of cyclic diynes **40** and dithiadiynes **41**, Scheme 12.[35] The promoters used in these reactions were DMSO and BMS (*n*-butylmethyl sulfide). They found that for dithiadiynes there was little difference in the low yield of the reaction regardless of the ratio of the two promoters, *i.e*. DMSO and BMS. However, for the diynes, *i.e*. with no sulfur present in the starting alkyne, significant differences in the yield were observed depending on the ratio of the promoters used. The best yields (48%) of the desired cyclopentenones were achieved when 7.5 eq. of DMSO and 1 eq. of BMS were used in comparison to a significantly lower yield (20%) when DMSO was used as the sole promoter. The increase in yield of the reaction is ascribed to transannular Co–S interactions. Co–S bonds are presumed to be relatively strong. For the dithiadiynes there is a transannular Co–S bond therefore preventing closure of the synthetic cycle leading to the observed low product yield. For the diynes, containing no sulfur, the observed differences in the yield are explained by a synergistic effect. It is proposed that DMSO generates a free oxidation site at one cobalt nucleus. The vacant site can then be occupied, in a reversible manner, by BMS, however, if BMS is present in excess then dissociation is no longer functionally reversible and the yield of the reaction is reduced.

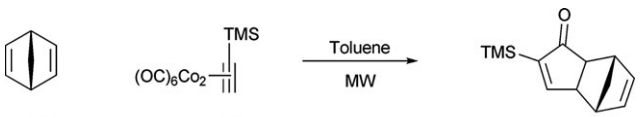


Scheme 12 Synergistic effect for the PKR when promoted by DMSO and BMS.[35]

In conclusion, the use of amine oxides has reduced reaction times and improved yields. However, stoichiometric amounts of octacarbonyl dicobalt in the presence of chemical additives alone are still necessary to produce reasonable yields of cyclopentenones.

1.2.2 External promotion

Evans and co-workers have used microwave irradiation to affect the PKR. This has been shown to significantly reduce reaction times and the amount of $Co_2(CO)_8$ required.[20] Using toluene as the solvent for an intermolecular PKR between **42** and cobalt complex **43**, excellent yields of the cyclopentenone were achieved after 5 min of irradiation, Scheme 13. There were however, some problems associated with the purification of the product due to the side reactions of the norbornadiene. Improvements to the reaction were made by changing the solvent to 1,2-dichloroethane (DCE), giving cleaner reactions with higher selectivity. DCE has a larger dielectric constant than toluene (10.2 and 2.4, respectively). Solvents with low dielectric constants are almost "invisible" to microwave irradiation,[38] consequently, when solvents with a low dielectric constant are used, the energy applied to the reaction is almost quantitatively absorbed by the reagents. When DCE is used, much of the energy applied is absorbed by the solvent. However, to achieve comparable yields to those reactions in toluene longer reaction times were required (Table 4). With DCE, less than stoichiometric amounts of octacarbonyl dicobalt (0.5 eq.) were required. Presumably the cobalt carbonyl complex can be regenerated due to the high pressure of carbon monoxide produced during the reaction. The high pressure arises since microwave vessels are often sealed tubes, thus



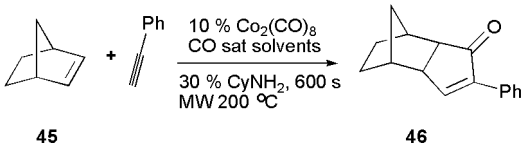
Scheme 13 Microwave promotion of the PKR.[20]

Table 4 Microwave promotion of the PKR[20]

Entry	Solvent	*T*/°C	*t*	Yield **44** (%)
1	Toluene	90	5 min	97
2	DCE	90	20 min	98
3	DCE	180	100 s	91
4	DCE	120	200 s	93
5	Toluene	110	16 h	99
6	Dichloromethane	25	16 h	50

preventing the escape of CO and allowing the use of sub-stoichiometric amounts of carbonyl cobalt complex.

At the same time, Groth and co-workers published the use of microwave radiation for the promotion of the catalytic PKR in solvents saturated with CO.[21] The influence of the microwave radiation on the PKR is unclear but the fast heating of solvents, often above their boiling point, in closed systems, is believed to increase the rate of the reaction. The choice of solvent seems to be crucial for the success of this reaction. The use of polar solvents, such as DMSO, had a detrimental effect on the reaction, whereas apolar solvents, such as toluene, gave improved yields. The reaction shown in Scheme 14 was carried out in the presence of the PKR promoter cyclohexylamine, the results are summarised in Table 5. A metallic lustre was noticed on the inside of the reaction vessel, suggesting that the cobalt reagent is significantly decomposed by microwave irradiation.



45 46

Scheme 14 PKR carried out in the presence of microwave irradiation and cyclohexylamine promoter.[21]

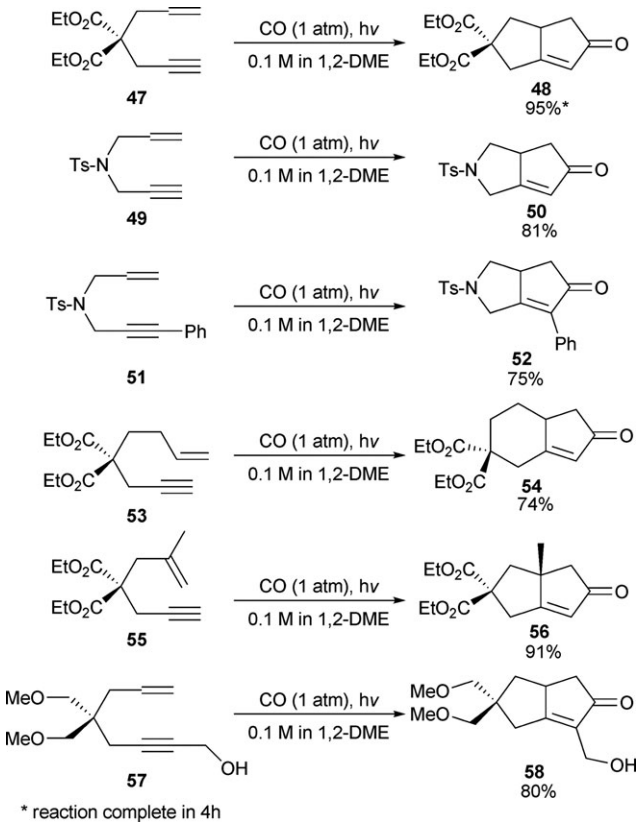
Table 5 PKR carried out in the presence of microwave irradiation and cyclohexylamine promoter[21]

Entry	Solvent	Dielectric constant	Yield **46** (%)
1	DMSO	46.7	5
2	Acetonitrile	37.5	16
3	Dichloromethane	9.0	21
4	Tetrahydrofuran	7.6	38
5	1,2-Dimethoxyethane	7.2	41
6	Diglet[a]	5.7	44
7	Toluene	2.4	44
8	Toluene	2.4	43[b]
9	Dioxane	2.2	41
10	Heptane	1.9	20

[a] Diethylene glycol diethyl ether. [b] Reaction using solvent without CO (g) saturation.

Lower reaction temperatures affected the yields of the catalytic PKR substantially, with the most dramatic effect noticed with heptane, where the yield increased from 20% (200 °C) to 49% (100 °C). It was found that lowering the temperature of the reaction led to improved yields in all cases. This indicates decomposition of the cobalt catalyst at high temperatures. The best results for the catalytic PKR promoted by microwave radiation are obtained for those reactions carried out in toluene at 100 °C with 20% $Co_2(CO)_8$ and 6 eq. of amine, when irradiated for 300 seconds.

The external promotion of the PKR has been shown to be efficient in the presence of less than stoichiometric amounts of the reactive cobalt species. Similarly, the photochemical promotion of the intramolecular PKR with 5 mol% of $Co_2(CO)_8$ has been used to obtain cyclopentenones in up to 95% yield, Scheme 15.[22] In addition, the light source was also of great



Scheme 15 Photochemical promotion of the intramolecular PKR.[22]

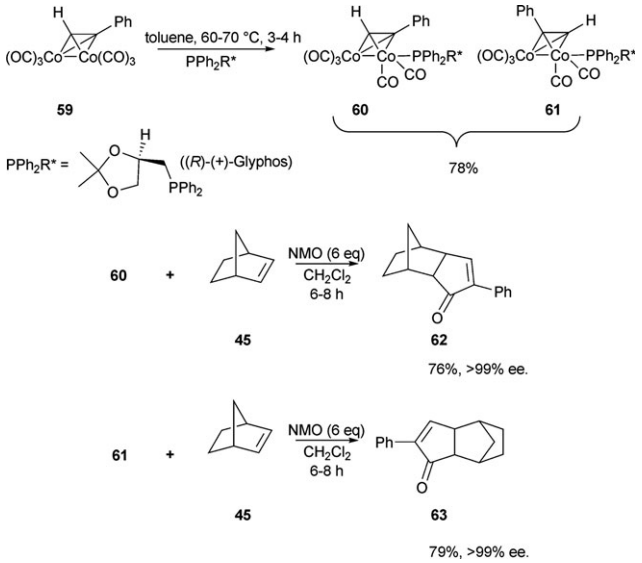
importance. The most effective light source was found to be Q-Beam MAX MILLION 10^6 candle power spot light as it gave astonishing rates of photoinitiation. The reactions were run in the temperature range of 50–55 °C at a concentration of 0.1 M in 1,2-DME, under 1 atm of CO for 12 h giving good to excellent yields of the PKR products. The only drawback for this method of promotion is the narrow temperature range (50–55 °C), which must be strictly adhered to. Temperatures outside of this range have a detrimental effect by destroying the cobalt cluster. A solution to this is the use of chemical additives that can stabilise the short-lived intermediates formed during the reaction, therefore allowing a broader range of temperatures to be employed.[17,29–32]

1.2.3 Stereoselective PKR

The PKR is a very useful tool for the enantioselective synthesis of natural products.[5,24] There are several approaches that can be employed with the PKR. These include the diastereoselective approach, where chirality from a co-ligand is transferred to the substrates; the chiral auxiliary approach *via* an auxiliary directly bound to either the reacting alkyne or alkene; and finally a combination of these two approaches.

The chiral monodentate phosphine ligand Glyphos® has been used to substitute one of the carbonyl ligands to give two diastereomeric complexes **60** and **61** (78% combined yield) thus, creating a chiral cobalt cluster (Scheme 16).[39]

These complexes, *i.e.* **60** and **61**, can be easily separated by preparative liquid chromatography (LC). The optically pure diastereoisomers were used to prepare optically pure

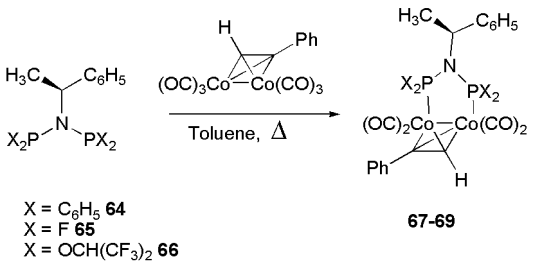


Scheme 16 Preparation of a chiral cobalt source and its use in the stereoselective PKR using Glyphos®.[39]

cyclopentenones **62** and **63**. However, the substitution of a carbonyl ligand with Glyphos® reduces the yield and the rate of the reactions, additionally the reactions had to be carried out at lower temperatures to prevent epimerisation of the pentacarbonyl-Glyphos® complex. The limitations impressed on the reaction temperature are almost certainly responsible for the reduction in yield.[40]

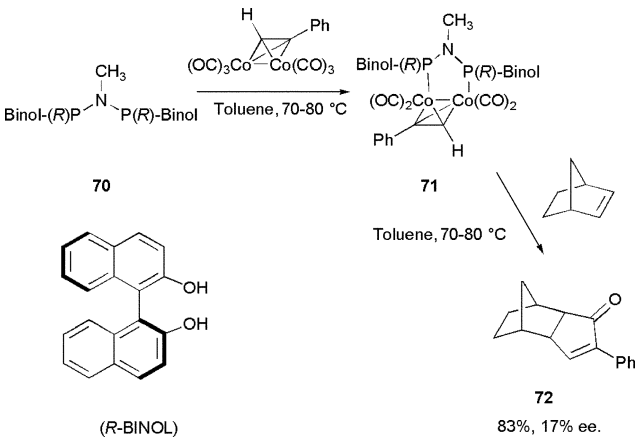
Other limitations are associated with the production of enantiopure sources of cobalt for use in the PKR by the complexation of a chiral ligand, namely the production of two diastereoisomers which have to be separated if any enantioselectivity is to be observed in the products. Greene and co-workers have tried to overcome some of the problems associated with the chiral cobalt cluster approach by the use of chiral diphosphinoamines.[25] Pauson and co-workers reported that the use of achiral diphosphines had a markedly deleterious effect on the yield when norbornene and phenylacetylene were employed.[18] Greene and co-workers have shown that *via* an electronic modification of phosphine substituents, the yields can be significantly improved, 98% compared with 24%.[25] These phosphines improve the yields by increasing the ease of dissociation of the first CO ligand by an increase in back-bonding, whilst protecting the alkyne from oxidation. The diphosphinoamines have been synthesised by placing a chiral substituent on the nitrogen. Electron withdrawing substituents on chiral diphosphines are not only expected to increase the yield but also the asymmetric induction of the reaction due to the close proximity of the chiral ligand to the cobalt centres, Scheme 17.

Using complexes **67–69** only in the PKR of norbornene with phenylacetylene gave a high yield of the PKR product (90–99%), although the products were devoid of any asymmetry. The asymmetric induction is dependent on the ligands ability to provide a chiral environment close to the reaction centre. The distance of the chiral centre from the active site is quite large, Greene and co-workers proposed that asymmetric induction could occur through a spatial orientation imposed



Scheme 17 Chiral cobalt cluster approach by use of chiral diphosphinoamines.[25]

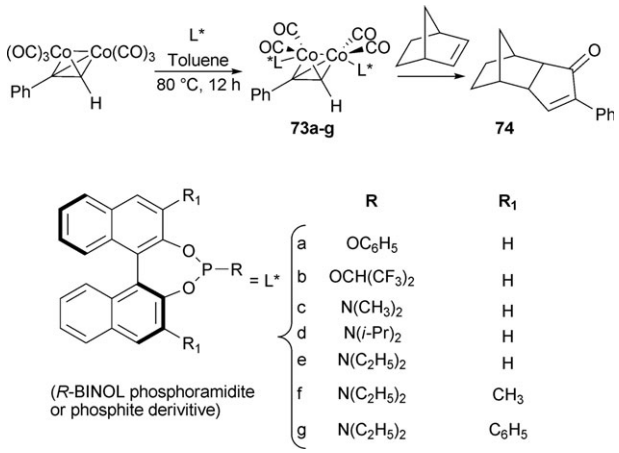
on the phenyl groups by the phosphorus. However, exchanging the phenyl groups for smaller electron withdrawing groups, such as fluorine, had no effect on the asymmetric outcome of the reaction. Increasing the size of the amine moiety was also not a workable solution since it encouraged the formation of side products, such as cyclodiphosphazanes. It was thought asymmetric induction could be gained if the chiral groups were brought closer to the reacting centre; complex **71** was reacted with norbornene. The yield was a respectable 83%; unfortunately asymmetric induction was low giving an ee of only 17%, Scheme 18.[25]



Scheme 18 The use of a chiral cobalt cluster in the asymmetric PKR.[25]

Another approach has been the attachment of identical chiral phosphine ligands to each cobalt atom but without bridging the two metals. This negates the need for high Co discrimination during the reaction. The choice of the electron withdrawing binol phosphoramidite (**73**) and phosphite derivatives enhanced the yield of these reactions (Scheme 19). The yields were comparable to the bidentate chiral diphosphine ligands, however, chiral induction was significantly improved. For entry E in Table 6 it was noticed that a change in the reaction conditions led to improved asymmetric induction to 56% *ee* albeit in a reduced yield, 60% *vs.* 70%. This was achieved by changing the solvent from toluene at 80 °C to DME at 60 °C. This also had the effect of increasing the reaction time, 96 h *vs.* 12 h, Table 6.[25]

Chiral auxiliaries attached directly to the starting materials have been well studied.[41–44] The synthesis of a diastereomeric mixture of alkyne pentacarbonyl dicobalt complexes was



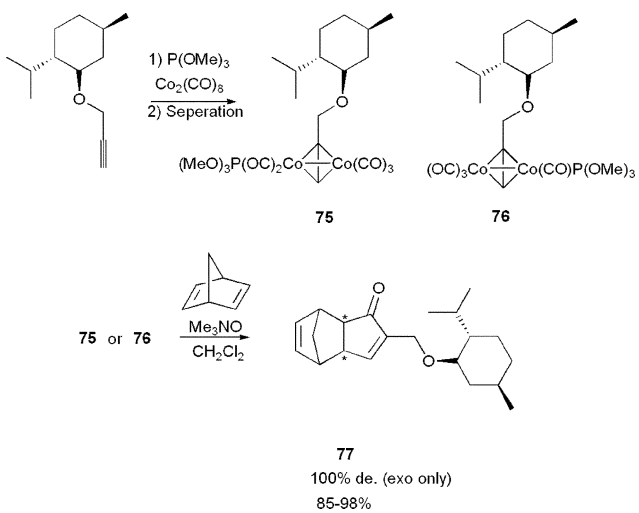
Scheme 19 The synthesis and use of chiral bis(BINOL phosphoramidite)cobalt cluster in the asymmetric PKR.[25]

Table 6 The synthesis and use of chiral bis(BINOL phosphoramidite)-cobalt cluster in the asymmetric PKR[25]

Entry	R	R_1	Yield (%) **74**	ee (%)
73a	OC_6H_5	H	65	24
73b	$OCH(CF_3)_2$	H	75	36
73c	$N(CH_3)_2$	H	75	13
73d	$N(i\text{-}Pr)_2$	H	60	21
73e	$N(C_2H_5)_2$	H	70	38
73f	$N(C_2H_5)_2$	CH_3	40	30
73g	$N(C_2H_5)_2$	C_6H_5	30	16
73h[a]	$N(C_2H_5)_2$	H	60	56

[a] Solvent changed from toluene to DME, reaction time increased to 96 h at 60 °C.

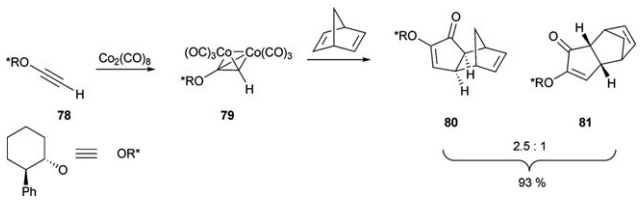
achieved by the reaction of (−)-menthol propargyl ether with $Co_2(CO)_8$ followed by the replacement of a carbonyl with phosphate (Scheme 20).[44]



Scheme 20 Synthesis of a chiral cobalt cluster where the chirality resides on the starting material and its application in the asymmetric PKR.[44]

The asymmetric induction relies on the synthesis of diastereoisomers which may be separated by chromatography. The products were obtained, after treatment with Me_3NO, in an 85–98% yield with 100% diastereomeric excess, Scheme 20. This excellent diastereoselectivity arises from the chiral cobalt core; however, the synthesis and separation of diastereoisomers is time consuming and expensive.

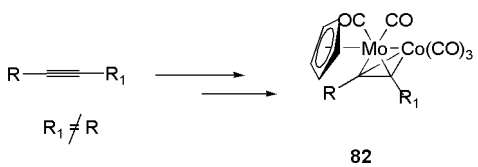
Greene and co-workers have reported an asymmetric PKR for the synthesis of the natural product Brefeldin A.[5] This was achieved using an enantiopure chiral alcohol attached to the alkyne, which was then complexed with $Co_2(CO)_8$ to give a chiral hexacarbonyl dicobalt complex **79** (Scheme 21). The chiral hexacarbonyl complex was then reacted with norbornadiene. This gave the PKR products in excellent yields (93%), and the two diastereoisomers formed, in a 2.5 : 1 ratio, were separable by flash chromatography.



Scheme 21 Asymmetric induction in the PKR using a chiral dicobalt hexacarbonyl complex.[5]

Christie and co-workers have explored the use of mixed metal alkyne complexes, such as **82**, for the synthesis of enantiopure cyclopentenone compounds, Scheme 22.[3,45] When unsymmetrical alkynes are employed, the corners of the metal alkyne core are chiral. The different electronic properties of the two metals encourage discrimination allowing cyclisation at the preferential metal centre, producing a highly diastereoselective reaction.

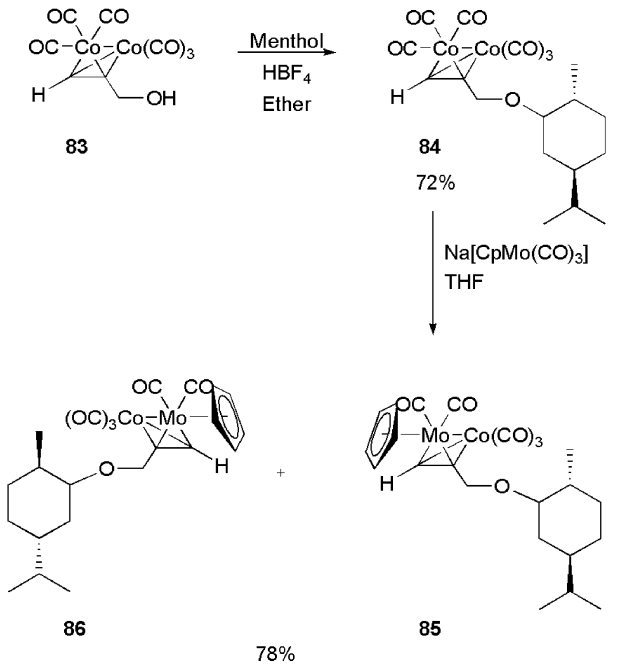
The use of menthol as the chiral auxiliary enabled the separation of diastereomeric hetero metal complexes; these complexes were stable to silica gel, Scheme 23.[3,45]



Scheme 22 Synthesis of mixed metal alkyne complexes for use in the asymmetric PKR.[3,45]

The separated complexes were then used in the PKR with norbornadiene, the cyclopentenones **87** from **85** and **88** from **86** were obtained in good yield (61 and 67%, respectively), Scheme 24. The diastereomerically pure metal alkyne complexes gave rise to a single diastereoisomer in both cases; this has been attributed to the chirality about the metal core.[45]

It is assumed that cyclisation occurs about only one of the two possible metal centres, giving rise to the asymmetric induction. When the experiments were repeated with the alkyne dicobalt complex, only a slight diastereomeric excess was observed which was attributed to the presence of the menthyl group.[45]



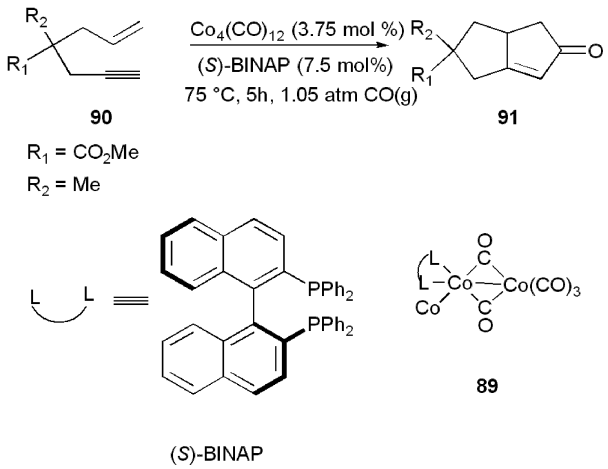
Scheme 23 Separation of mixed metal alkyne complexes by complexation with menthol.[3,45]

Recently the synthesis and isolation of hexadicarbonyl dicobalt(0) complex **89** has been achieved using (*S*)-BINAP, which was bound to one of the two cobalt atoms (Scheme 25).[27] This shows catalytic activity as opposed to a complex in which (*S*)-BINAP is added after the alkyne has been coordinated, which shows no catalytic activity at all. This suggests that the complex **89** is the structure of the precatalyst. Initially the PKR of **90** in the presence of (*S*)-BINAP was examined, Scheme 25. Only diphosphine ligands with axial chirality led to a significant chiral induction, Table 7.[27]

In summary the PKR is an important tool for the synthesis of cyclopentenones. Recent advances have enabled the catalytic variant to be accessible. However, there is still scope for the production of a generally applicable catalyst that can be applied to the synthesis of asymmetric products.

2.0 Cobalt mediated cyclotrimerisation (Vollhardt trimerisation)

Cyclotrimerisation utilizes cobalt (among other metals) to combine three alkynes into an aromatic ring system (Scheme 26).[46]

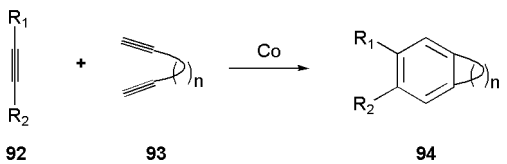


Scheme 25 Catalytic PKR in the presence of diphosphine ligands displaying axial chirality.[27]

Table 7 Catalytic PKR in the presence of several different diphosphine ligands displaying axial chirality[27]

Entry	Ligand	Conversion	Yield **91** (%)	ee
1	(*S*)-BINAP	100	70	89 (+)
2	(*R*)-Noriphos	0	—	—
3	(*S*)-TolBINAP	100	85	96 (+)
4	(*R*)-HEXAPHEMP	95	75	93 (−)

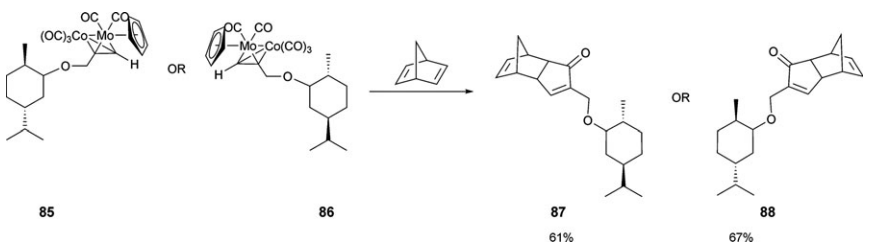
[a] Noriphos = 2,3-bis(diphenylphosphino)bicyclo[2.2.1]hept-5-ene. HEXAPHEMP = 6,6′-bis(diphenylphosphanyl)-2,3,4,2′,3′,4′-hexamethylbiphenyl.



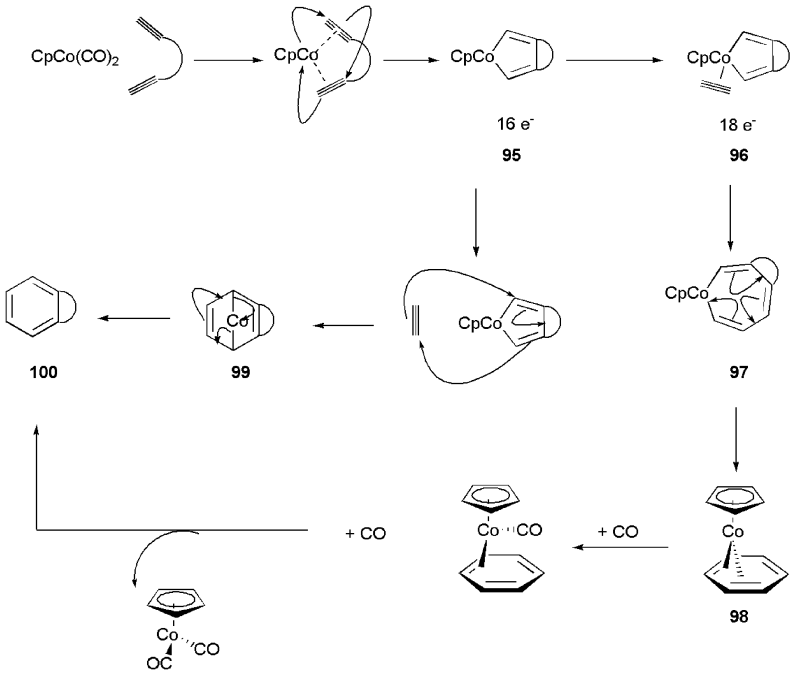
Scheme 26 The cyclotrimerisation reaction.[46]

The cobalt-mediated reaction usually employs $CoCp(CO)_2$ as the cobalt source. Two of the alkynes first replace the two CO ligands. The resulting π complex rearranges to give a double σ-complex *via* cycloaddition forming a new C–C σ-bond as it does so, Scheme 27. This produces a metallocyclopentene **95**.[46,47]

The instability of complex **95** facilitates the addition of the remaining alkyne to give an 18-electron complex **96**. There are two possible routes to the final product. The first is the insertion of an alkyne into one of the C–Co bonds to form a

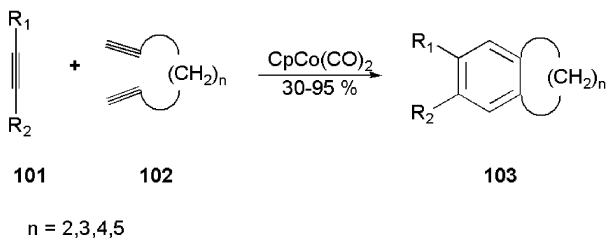


Scheme 24 The use of diastereomerically pure mixed metal alkyne complexes in the PKR.[45]



Scheme 27 Reaction mechanism of the Vollhardt cyclotrimerisation.[46,47]

new seven-membered heterocycle **97**. This would rearrange in an electrocyclic reaction *via* the bicyclic intermediate **98** to give the new six-membered ring **100**. The alternative route would involve a Diels–Alder reaction of the alkyne with the five-membered cobalt heterocycle, yielding a bridged six-membered ring **99** that would extrude cobalt to give the six-membered benzene complex **100**. The cyclopentadienyl cobalt moiety can form a stable complex with only four of the benzene electrons; these can be exchanged for two molecules of carbon monoxide, thereby regenerating the catalyst.[46] Cyclopentadienyl dicarbonyl cobalt has been found to catalyze a variety of [2 + 2 + 2] cyclotrimerisations to form benzene rings from linked alkynes, as exemplified by the general reaction given in Scheme 28. The best results for the synthesis of compounds of type **103** are obtained for $n = 3$ or 4 when linked intermediates, such as **102** are used.[48]



Scheme 28 The formation of aromatic compounds *via* the [2 + 2 + 2] cyclotrimerisation of linked alkynes.[48]

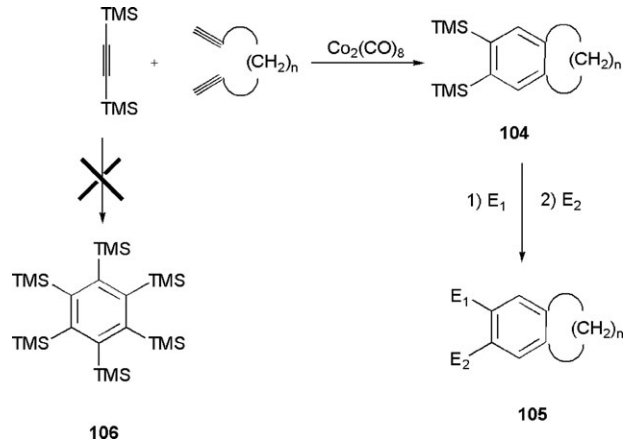
2.1 Functional group tolerance, chemo- and regioselectivity

This reaction is tolerant to a variety of functional groups on the alkyne **101**, including R = H, alkyl, aryl, CO_2R', CH_2OH, CH_2OR', COR' and groups where C is replaced by a heteroatom, such as NOR', NR_2', SR' and TMS. However, problems with chemo-selectivity are often encountered when alkynes of considerable bulk or a certain electronic makeup are used, as they tend to undergo other cyclisation side reactions. The presence of bulky substituents, such as TMS groups, at the terminal position of the diyne may also lead to diminished yields.

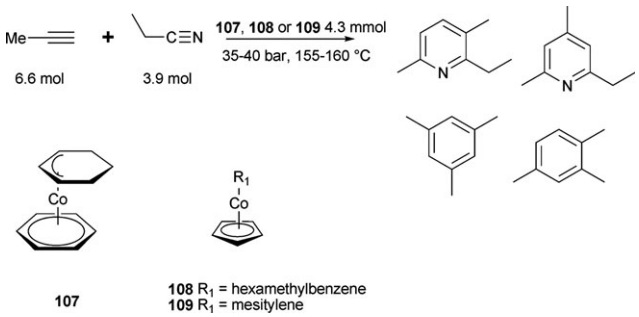
Functional groups that have a detrimental effect on the catalyst include NO_2, alkyl halides, reactive vinyl and acyl halides. This is possibly due to oxidative side reactions facilitated by the presence of such functionalities. However, chlorophenylalkynes are readily cyclised by $Co_2(CO)_8$.[46]

The problem of steric and electronic effects observed with some alkynes has been overcome with the use of trimethylsilyl alkynes to give benzene derivatives, such as **104**. These compounds are too sterically hindered to autocyclise to give ring systems, of the type **106**, but not so much as to co-cyclise to give compounds of the type **104**. The TMS group in **104** is easily removed *via* electrophilic aromatic substitution reactions to give benzene derivatives of the type **105**. This has been shown to be particularly important when employing bis-(trimethylsilyl)acetylene (BTMSA) in cyclisation reactions since it is easily removed and can be selectively substituted in a stepwise approach giving high yields of compounds with the general structure of **105**, Scheme 29.

More functionalised Co catalysts are also available for the cyclotrimerisation of alkynes. Bönnemann *et al.* have described the cyclotrimerisation of alkynes with nitriles for the synthesis of pyridines using catalytic amounts η^6-arene cobalt complexes **107**, **108** and **109**, Scheme 30.[49] The initial step is proposed to be the dissociation of the neutral ligand, generating the catalytically active species, whilst a univalent anionic ligand acts as a steering ligand and remains bound



Scheme 29 Cyclotrimerisation of linked alkynes with BTMSA.[46]



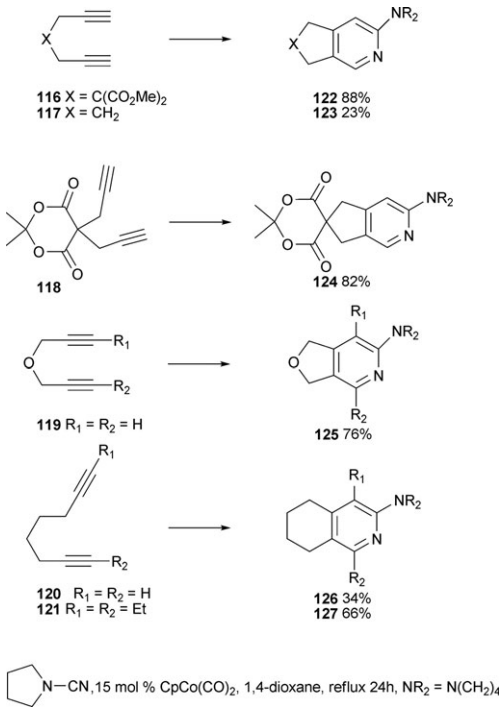
Scheme 30 The cobalt-catalyzed cyclotrimerisation of alkynes with nitriles for the synthesis of pyridines.[49]

to the metal throughout the catalytic cycle. They found that (η^6-benzene)(η^8-cyclohexenyl)cobalt **107** had a lower reactivity and chemoselectivity (0.43) compared to (η^3-cyclopentenyl)cobalt complexes **108** (1.54) and **109** (1.38). The difference in catalytic activity and chemoselectivity suggests that the cyclopentenyl-Co compounds undergo partial dehydrogenation to form Cp–Co catalysts. This implies that in the reaction mixture both the active species from the original cyclopentenyl complex and [CpCo] are present. Unfortunately, no control of the products from the reactions could be gained using these catalysts.

In spite of intensive research into the transition metal catalysed cyclotrimerisation of alkynes, the intermolecular version of this process suffers from poor regio- and chemoselectivity. Reactions of α,ω-diynes with an excess of alkyne which can be considered as partially intramolecular have been successfully employed to overcome this problem.[48] Recently the use of a silicon tether in the catalytic regio- and chemoselective cobalt cyclisation has been reported, Scheme 31.[48]

The advantage of this route is selective removal of the silicon tether after completion of the reaction leading to highly functionalised arenes **114** and **115**.

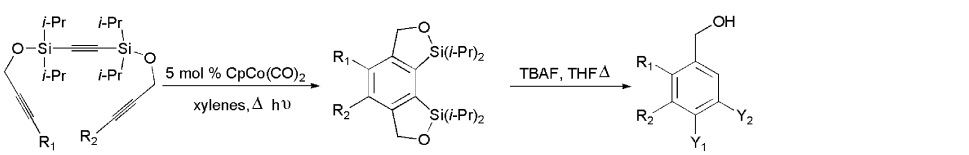
Cyclotrimerisation is an important organometallic tool for the synthesis of natural products.[50–52] The extension of the reaction to form heterocyclic ring systems makes it invaluable for the formation of natural products containing pyridines and ethers. The cyclotrimerisation of various bis-alkynes with cyanamides catalyzed by $CoCp(CO)_2$ under thermal conditions without photo-activation, undergo a co-cyclotrimerisation with *N*-cyanopyrrolidine in moderate to excellent yields (Scheme 32).[53]



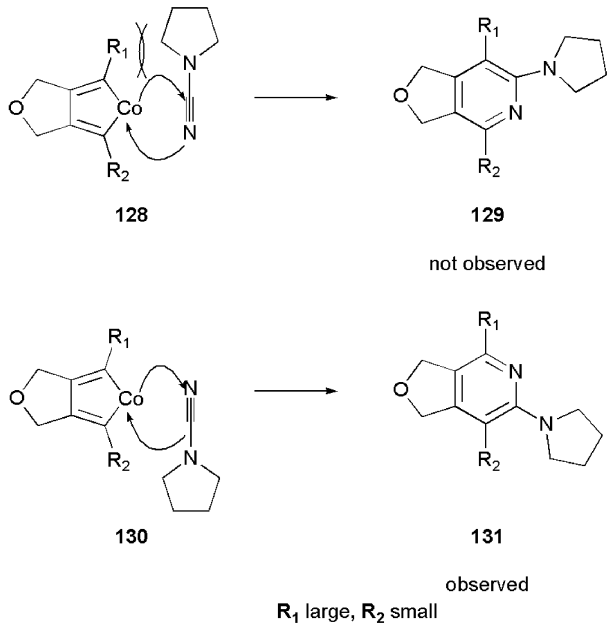
Scheme 32 Co-cyclotrimerisation with *N*-cyanopyrrolidine.[53]

The observed regiochemical outcome can be understood when the cyclopentadienyl cobalt intermediates are examined more closely, Scheme 33. In intermediate **128** there is significant steric hindrance that impedes the formation of **129**, whereas in **130** there is significantly less steric hindrance thus, facilitating the formation of pyridine **131**.

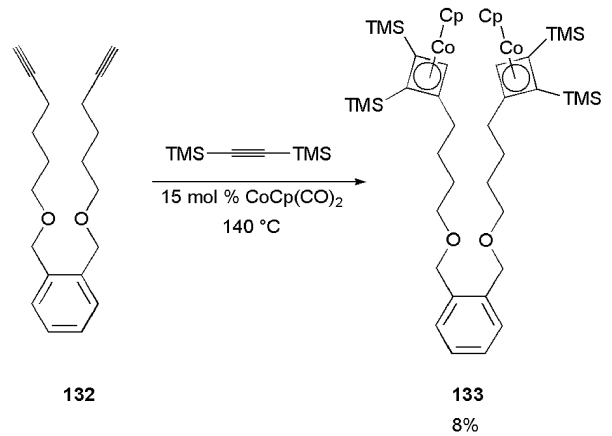
A protocol for the synthesis of pyridine containing macrocycles has also been established.[54] Initial reactions of bis-alkyne **132** with an excess of BTMSA gave interesting results. There was no detectable macrocycle formed in this reaction at



Scheme 31 The use of a silicon tether in the intermolecular cyclotrimerisation reaction.[48]



Scheme 33 The nitrile incorporation step for co-cyclotrimerisation with *N*-cyanopyrrolidine.[53]

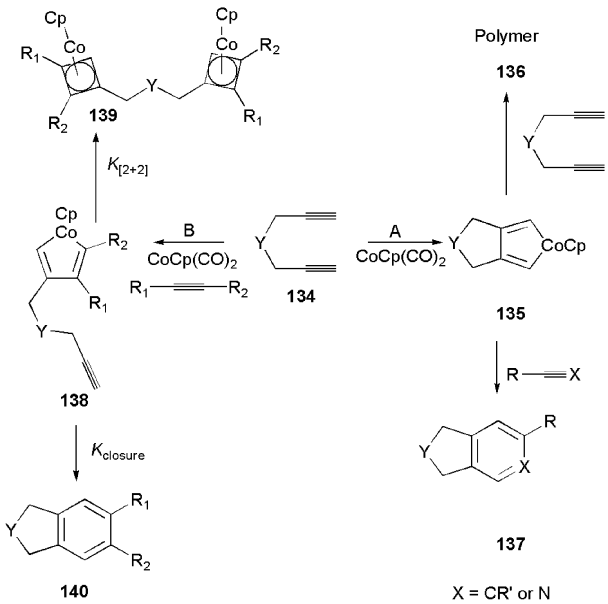


Scheme 34 Reaction of a bis-alkyne with an excess of BTMSA under cyclotrimerisation conditions.[54]

140 °C under visible light, only exclusive formation of the bis-cyclobutadiene-cobalt complex **133**, Scheme 34.

The yield of the cyclobutadiene complex **133**, is only 8% based on the bisalkyne compound **132**, it, however, increases to 100% when the yield is based on the amount of cobalt added. The result from the reaction can be appreciated when the mechanism for the reaction is considered, Scheme 35.

If route A is taken the intermediate cobaltacycle **135** will be formed. This would coordinate to an alkyne monomer to give the desired product **137**, where X = CR′ or N, or it could also polymerise to give **136**. If route B is taken, the intermediate **138** is formed, which can react to form a stable cyclobutadiene complex, *e.g.* **139**. It appears that the rate of formation of this complex is greater than that of the formation of the benzene derivative **140**. Pathway B dominates for the above example giving rise to the cyclobutadiene complex **139**. It is possible to block pathway B by using a nitrile in place of an alkyne.



Scheme 35 Proposed mechanism for the synthesis of cyclobutadiene complexes.[54]

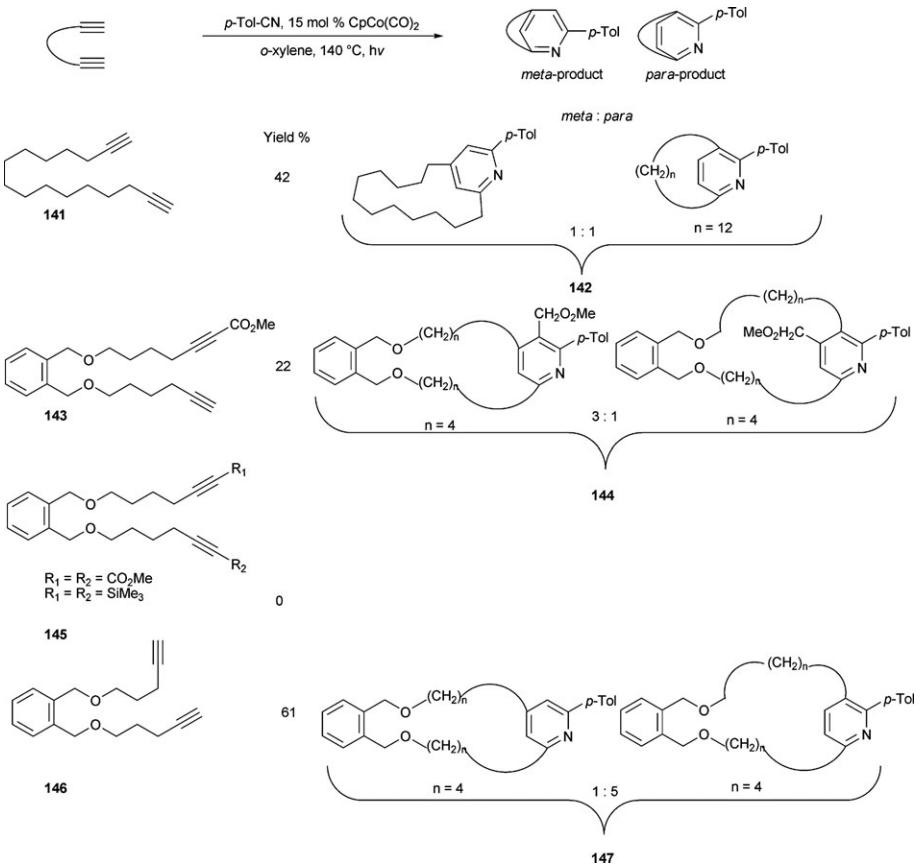
Pathway B it is made inaccessible as the nitrogen lone pair of the nitrile prevents coordination to the cobalt(I) species. After coordination of the bis-alkyne the oxidation state of the metal atom changes to Co(III) allowing the nitrile to coordinate and insert. The successful synthesis of pyridine macrocycles **142–147** has been achieved using this strategy, Scheme 36.[54]

Under suitable conditions, and with the right substrates, carbonyls can be incorporated into the cobalt catalysed cyclotrimerisation for the synthesis of 2*H*-pyrans, *e.g.* **149**, Scheme 37.[55,56]

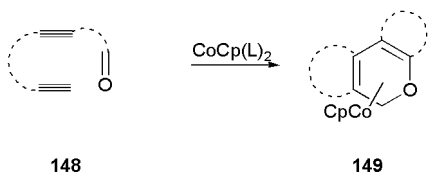
When employing $CoCp(C_2H_4)_2$ as the cobalt source, Scheme 38, the competition of the alkene ligands attached to the cobalt with the oxo function in the cyclisation reaction can be suppressed successfully by using the aldehyde or ketone component in a large excess. The mechanism of this reaction is unknown, however, it is postulated that three-, five- and seven-membered cobaltacycles function as crucial intermediates.[55]

2.2 Aqueous solutions

Cyclotrimerisation can occur in aqueous solutions, hydrophobic effects in organic reactions can also provide substantial rate enhancements and influence the chemo- and stereoselectivity. The synthesis of several benzenes *via* cyclotrimerisation in aqueous solutions has been achieved under mild conditions with no protection of functional groups, furnishing the desired products in moderate to excellent yields.[57] To achieve the reaction in an aqueous environment, the modified catalysts such as, **171** and **172**, must be employed. Furthermore, carbonyl cobalt complexes, such as $CoCp(CO)_2$, are unsuitable catalysts for the reaction. This is due to the fact that carbonyl replacement becomes more difficult as a consequence of enhanced back-bonding (as a result of the increased polarity of the solvent). A CpCo(COD) complex, in which the cyclopentadienyl moiety is modified so that it is more soluble in



Scheme 36 Synthesis of pyridine macrocycles using nitriles.[54]

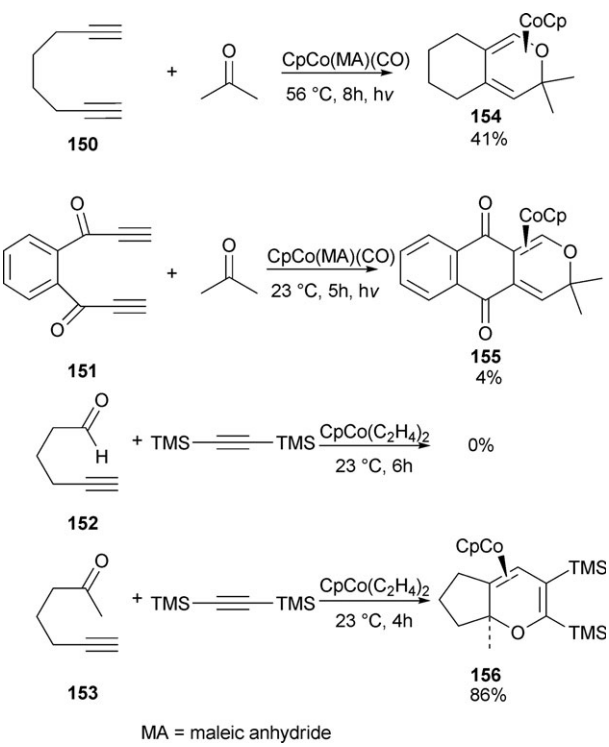


Scheme 37 Carbonyl incorporation using cyclotrimerisation.[55,56]

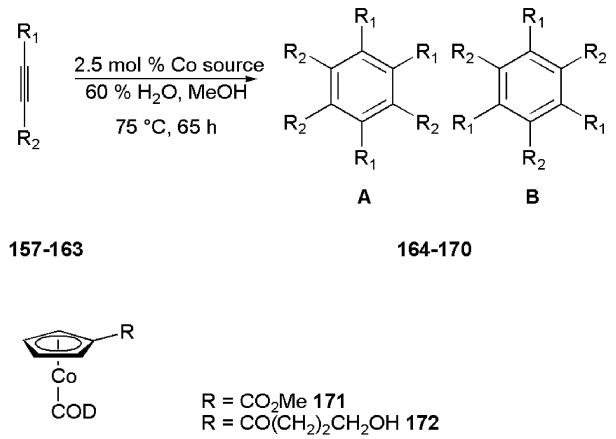
aqueous media, is more convenient for the transformation in this media. The COD moiety furthermore allows controlled access to the cobalt coordination sphere. However, complexes of this type have a short life span due to degradation at high temperatures. Another interesting feature is that protection of functional groups was found to be unnecessary in all cases, Scheme 39, Table 8.[58]

Another catalyst that may be used for the cobalt catalysed cyclotrimerisation of acetylenes in water is the di-*tert*-butylphosphanylethylcyclopentadienyl cobalt(I) chelate **173**. This complex is unstable in air but stable in water.[58] Using **173** as the cobalt source, the reaction was complete in 8 h at room temperature with no photo-activation necessary (Scheme 40).

The construction of an AB taxane ring system *via* cobalt cyclotrimerisation was attempted by Malacria and co-workers.[59] The attempted formation of the taxane ring used the linked chiral trialkyne **174** mixed with cyclopentadienyl dicarbonyl cobalt, in benzene. Exposure of this mixture to light was expected to afford the cyclotrimerisation product. Unfortunately, all attempts of this reaction only gave the metallocene



Scheme 38 Examples of carbonyl incorporation using cyclotrimerisation.[55]

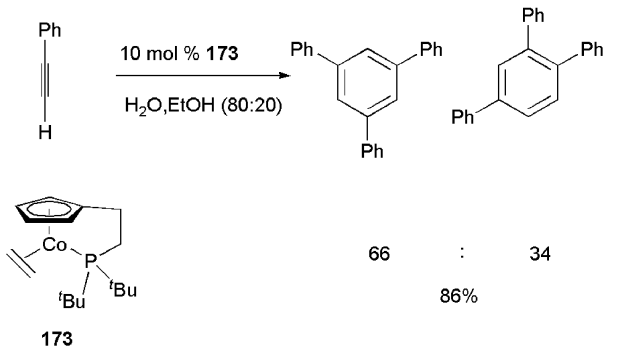


Scheme 39 Cyclotrimerisation of unsymmetrical alkynes mediated by CoCp(COD) **171**.[58]

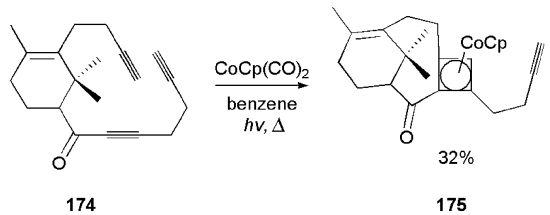
175. This cyclobutadiene complex **175** was obtained as a single diastereoisomer in 32% yield, Scheme 41.

Other metals besides cobalt have been used for the cyclotrimerisation of alkynes, these include Ru(II) species amongst others.[60] Initially, the cyclotrimerisation reactions of diynes and alkynes required stoichiometric amounts of the Ru source, though since these early investigations catalytic versions have been developed.[61,62] An advantage of this method is the large variety of mono and di-alkynes that may be employed. However, these types of cyclotrimerisations are hampered by a facile side reaction, *i.e.* the dimerisation of the diyne. Elimination of the side reaction requires a large excess of the mono-alkyne species. Yamamoto *et al.* have reported the synthesis of benzo-fused lactams *via* Ru(II) catalysed cyclotrimerisation, Scheme 42 and Table 9.[63]

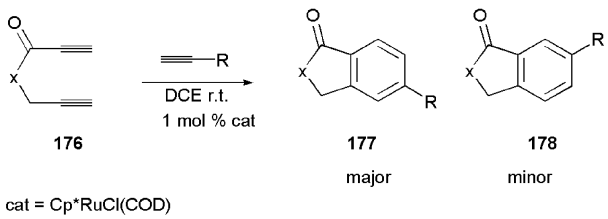
The observed regioselectivities are explained by the X group which has a large effect on the electron withdrawing ability of the carbonyl group. The stronger the electron withdrawing ability of the carbonyl the more the major isomer is favoured, therefore X = NBn ≈ O < CMe_2 which is indicative of a carbonyl group with stronger electron withdrawing ability.[64] In conclusion the use of Ru(II) species as an alternative to Co(I) for the cyclotrimerisation of alkynes is successful. There are problems associated with side reactions, however, these may be suppressed with an excess of the alkyne. Good to excellent regioselectivity has been achieved, with low catalyst loading (1%) and in good to excellent yields (63–93%). The best selectivity was observed when the carbonyl group alpha to the alkyne had a stronger electron withdrawing ability.



Scheme 40 The use of di-*tert*-butylphosphanylethylcyclopentadienyl cobalt(I) chelate in the cyclotrimerisation of phenylacetylene.[58]



Scheme 41 The attempt to use cyclotrimerisation for the formation of the taxane ring.[59]



Scheme 42 Synthesis of benzo-fused lactams *via* Ru(II) catalyzed cyclotrimerisation.[63]

Table 9 Synthesis of benzo-fused lactams *via* Ru(II) catalyzed cyclotrimerisation[63]

X	R	*t*/h	Yield (%)	**177** : **178**
NBn	Ph	2	93	80 : 20
NBn	CH_2OMe	1	90	64 : 36
NBn	CH_2NMe_2	1	63	64 : 36
O	Ph	2	87	75 : 25
CMe_2	*t*-Bu	0.5	70	78 : 22

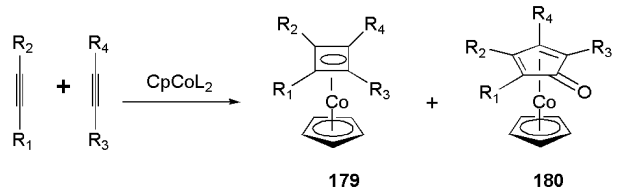
Table 8 Cyclotrimerisation of unsymmetrical alkynes mediated by CoCp(COD) **171**[58]

Entry	Alkyne	R_1	R_2	Yield (%)	A : B
1	**157**	H	$COCH_3$	44 (**164**)	0[a] : 44
2	**158**	H	CO_2CH_3	67 (**165**)	47 : 20
3	**159**	H	$(CH_2)_2OH$	85 (**166**)	62 : 23
4	**160**	H	CH_2NHCH_3	73 (**167**)	47 : 26
5	**161**	H	$C(CH_3)_2OH$	81 (**168**)	53 : 28
6	**162**	H	$CH_2N(CH_3)_2$	78 (**169**)	51 : 27
7	**163**	H	$(CH_2)_2CO_2H$	56 (**170**)	36 : 20

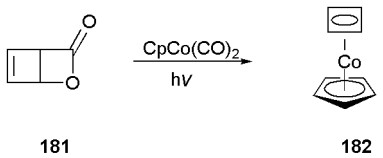
[a] Minor isomer not isolated.

3.0 Synthesis of (η^4-cyclobutadiene)(η^5-cyclopentadienyl)cobalt(I) and (η^4-cyclopentadienone)-(η^5-cyclopentadienyl)cobalt(I) metallocenes

(η^4-Cyclobutadiene)(η^5-cyclopentadienyl)cobalt(I) complexes **179**, Scheme 43, were first reported in the 1960s.[65] One of the earliest reports describes the synthesis of an unsubstituted cyclobutadiene complex *via* the exposure of the strained lactone photo-α-pyrone **181** to light in the presence of dicarbonyl cyclopentadienyl cobalt $CoCp(CO)_2$, Scheme 44.[66]



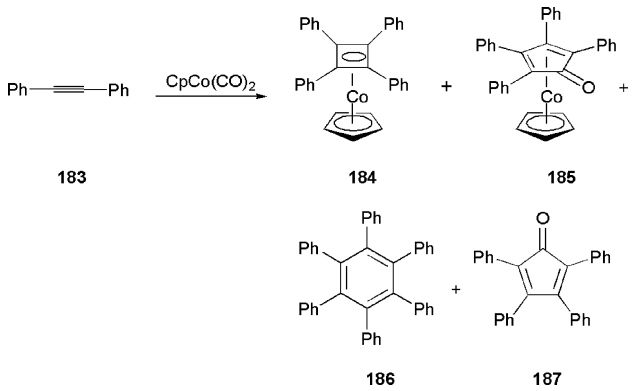
Scheme 43 (η^4-Cyclobutadiene)(η^5-cyclopentadienyl)cobalt(I) and (η^4-cyclopentadienone)(η^5-cyclopentadienyl)cobalt(I) metallocenes.[66]



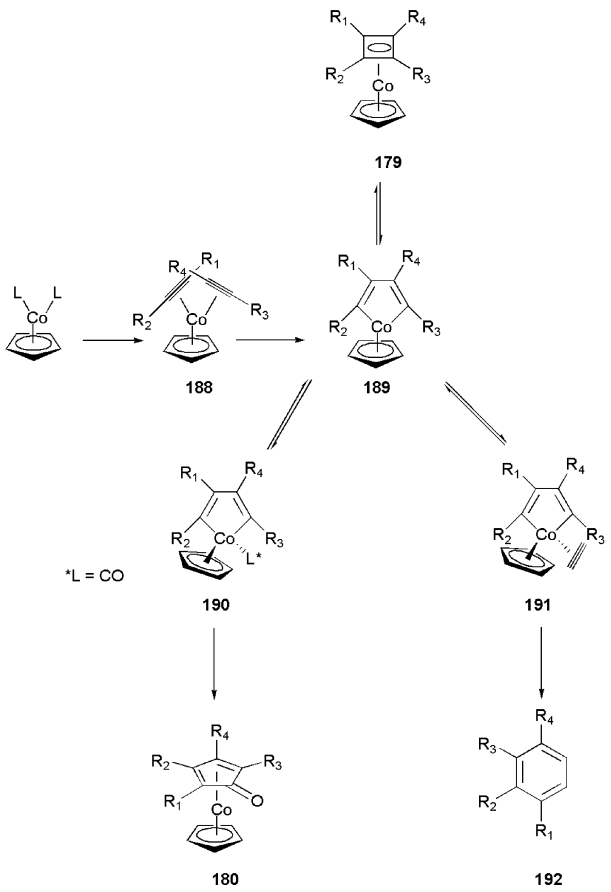
Scheme 44 Synthesis of an unsubstituted cyclobutadiene complex *via* exposure of photo-α-pyrone to light.[66]

It was noticed that the metallocene **183** was an air-stable crystalline solid (mp 88.5–89.0 °C) and that it had a very similar infrared spectrum to ferrocene. The presence of the cyclobutadiene ring was supported by the ^{1}H NMR spectrum which showed two peaks at δ 4.90 and 3.66 ppm with a ratio of 5 : 4, respectively. Over the years, a large number of complexes of type **179** and **180** have been synthesised (Scheme 43). Most of these complexes are air-stable, since they are 18-electron complexes, and the chemistry of their synthesis is vast and varied. For complexes, such as **179**, many different cobalt sources have been used including $CoCp(C_2H_4)_2$,[67–69] CoCp(COD),[70–72] $CoCl(PPh_3)_3$[73] and $CoCp(CO)_2$.[74] For the synthesis of complexes with the general structure of **180** the only available cobalt source is $CoCp(CO)_2$, the same source of cobalt as is used for the Vollhardt cyclotrimerisation.[46] The use of this complex can therefore be used for the formation of any (or a mixture) of the type of compounds shown in Scheme 45, depending on the conditions employed.

The mechanism in Scheme 46 is generally accepted for the synthesis of cyclobutadiene cobalt complexes of type **179**.[75] During the first step, the two labile CO ligands dissociate allowing two alkynes to coordinate to the cobalt species giving rise to **188**. Compound **188** is unstable and has never been isolated. It quickly undergoes an oxidative coupling to give the 16-electron metallacycle **189** which has been isolated when stabilised by a donor ligand. The final step is a reductive elimination to form the desired cyclobutadiene complex.



Scheme 45 The use of $CoCp(CO)_2$ in the formation of organic and organometallic compounds.

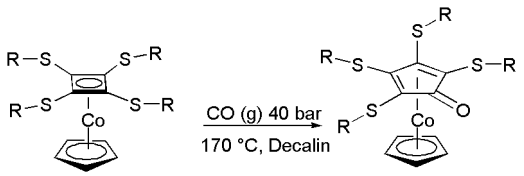


Scheme 46 Mechanism for the formation of (η^4-cyclobutadiene)-(η^5-cyclopentadienyl)cobalt(I) **179** and (η^4-cyclopentadienone)-(η^5-cyclopentadienyl)cobalt(I) **180**.

As mentioned above, the formation of these compounds is not exclusive since various side reactions can occur. These include the Vollhardt cyclotrimerisation, to form **192**, a cyclobutadiene cobalt metallocene, to give complex **179**, and decomplexation as well as the synthesis of the metallocene **180**, depending on the cobalt source employed.[75,76] In the case of linked cyclic diynes cyclobutadiene formation is dominant over the Vollhardt cyclotrimerisation.[77]

3.1 Synthesis of (η^4-cyclobutadiene)-(η^5-cyclopentadienyl)cobalt(I) metallocenes

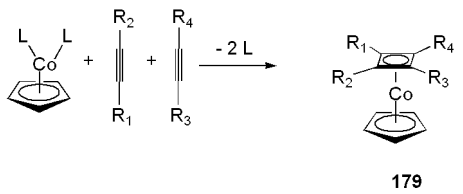
It has been reported that cyclobutadiene cobalt complexes, such as **193**, with electron-rich substituents, such as thioethers, can be transformed into the cyclopentadienones of type **180**. This conversion is effected by heating the complex under high pressure of CO (Scheme 47).[78]



Scheme 47 Conversion of a cyclobutadiene cobalt complex to a cyclopentadienone complex.[78]

These findings indicated that the cyclopentadienone synthesis could only occur when there were thioether groups attached directly to the cyclobutadiene ring. The studies also showed that a large R group, attached to the thioether, *e.g.* Ph, inhibited the reaction, giving lower yields of the desired cyclopentadienone. DFT calculations have shown that electron-donating substituents favour intermediates of the type **189**. The electron-donating substituents lower the transition state energy, therefore accounting for the greater reactivity of the thioether-substituted cyclobutadiene complex.[75]

Many interesting and useful cyclobutadienes have been synthesised since the first discovery of $CoCp(CO)_2$ in the 1950s.[79] Since this time there have been a range of cobalt(I) sources developed for use in the synthesis of cyclobutadiene complexes with the general structure **179**, Scheme 48.

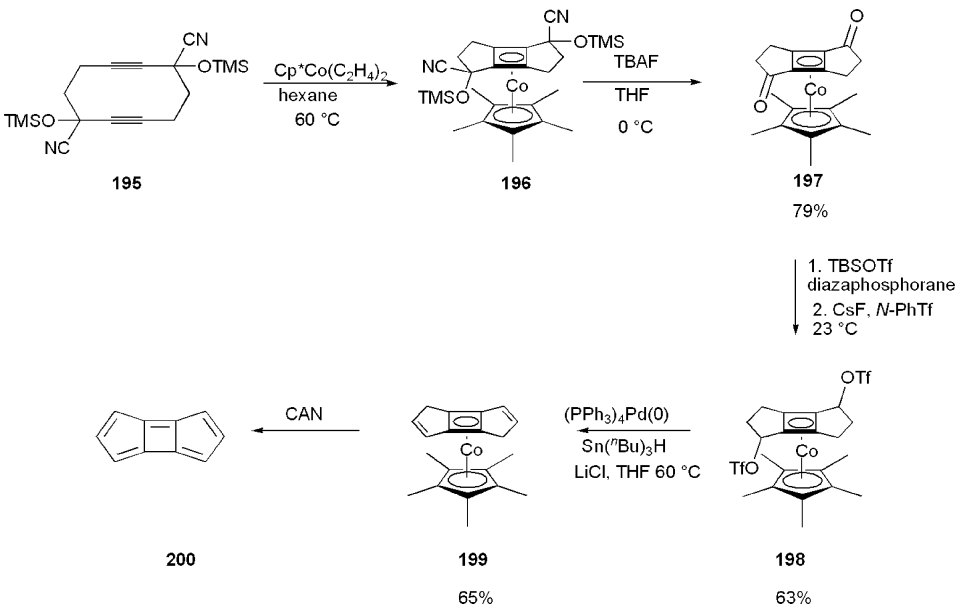


Scheme 48 Synthesis of (η^4-cyclobutadiene)(η^5-cyclopentadienyl)-cobalt(I) complexes.

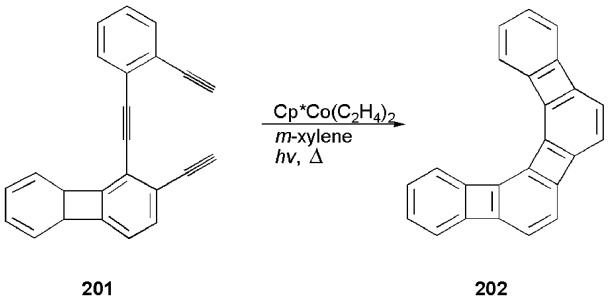
Myers *et al.* have synthesised strained cyclobutadienes using $CoCp^*(C_2H_4)_2$. They found this a useful precursor for the synthesis of strained cyclic alkenes.[69] Metal cyclobutadiene complexes can produce free cyclobutene *via* an oxidative decomplexation in the presence of ceric ammonium nitrate (CAN). They achieved the synthesis of the metallocene **196** by heating diyne **195** in hexane at 60 °C, Scheme 49.

Vollhardt has also synthesised strained cyclobutadienes by forming a cyclobutadiene cobalt complex from $CoCp^*(C_2H_4)_2$, followed by a decomplexation to give the desired product **202**.[69] Unusually this synthesis was accomplished photolytically. They found $CoCp^*(C_2H_4)_2$ a better source of cobalt(I) than $CoCp(C_2H_4)_2$, giving the decomplexed cyclobutadiene in greater yield (51% *vs.* 30%). The use of light obviated the use of ceric ammonium nitrate for the decomplexation, Scheme 50.

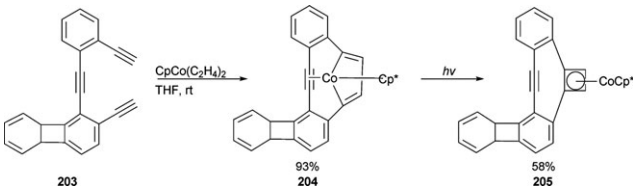
In the process of the afore-mentioned studies, the metallacycle **204** was isolated in 93% yield, as a thermally unstable material. Photochemical attempts to improve the yield of **202** led to the isolation of the bright orange cyclobutadiene complex **205** in 58% yield, Scheme 51.[69] The authors observed that whilst cyclobutadiene complexes are commonly synthesised from $CoCp^*(C_2H_4)_2$, none had ever been detected during the synthesis of phenylenes.



Scheme 49 Synthesis of strained cyclobutadienes using $CoCp^*(C_2H_4)_2$.[69]



Scheme 50 Synthesis of a strained cyclobutadiene.[69]



Scheme 51 Photochemical synthesis of a cyclobutadiene complex.[69]

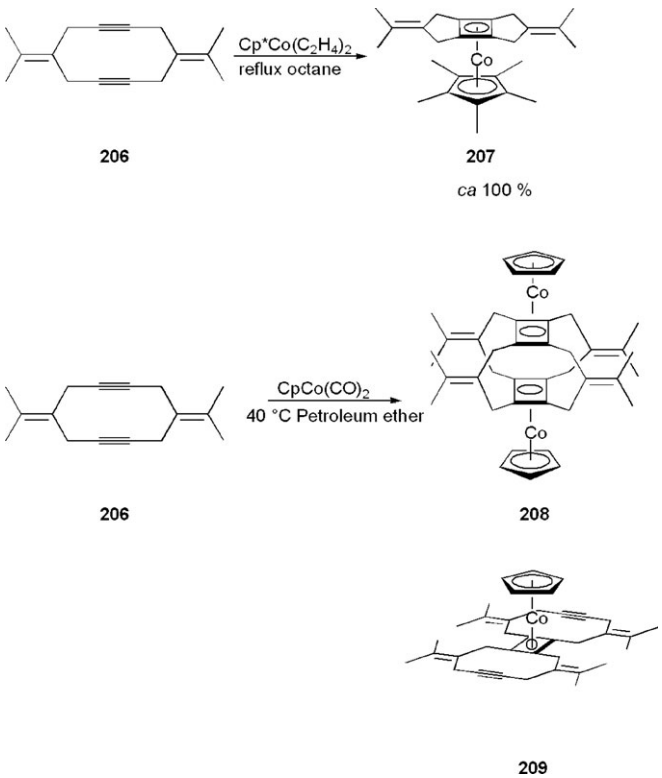
The inter- *vs.* intramolecular cyclobutadiene cobalt(I) complex formation from 1,6-cyclodecadiyne derivatives with $CoCp^*(C_2H_4)_2$ and $CoCp(CO)_2$ has also been investigated.[67] The two complexes gave different results: the ethylene complex gave the intramolecular complex **207** in almost quantitative yield, whereas the carbonyl cobalt gave the intermolecular metallocenes **208** and **209**, Scheme 52.[80]

The difference in reactivity was rationalised by the formation of a loose coordination with the isopropylidene double bond. This would favour a perpendicular approach of the Co complex giving rise to **208** and **209**.

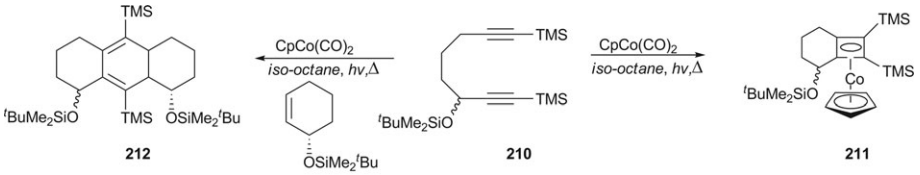
Dicarbonyl cyclopentadienyl cobalt(I) can be used for the synthesis of two different cobalt metallocenes, *i.e.* cobalt cyclobutadienes and cyclopentadienones. $CpCo(CO)_2$ is also used in the Vollhardt cyclotrimerisation of alkynes and is often used in the synthesis of natural products.[59] Another example of inadvertent cyclobutadiene synthesis was from the photolysis of a linked diyne **210**.[81] The intended reaction was the Vollhardt cyclotrimerisation reaction, to form **212**. In fact the only product obtained was the cyclobutadiene complex **211** in a 76% yield. It was suggested that the selectivity in this reaction is kinetically, rather than thermodynamically, controlled, Scheme 53.

The reaction most likely proceeds *via* the photochemical removal of the carbonyl ligands, followed by coordination of the diyne to the cobalt and subsequent oxidative addition to form the metallacycle. The next step would be an intramolecular Diels–Alder type reaction to give the trimerisation product *via* a bicycloheptenecobalt, which rearranges to give **212**. In an attempt to suppress the synthesis of the undesired cyclobutadiene, the substrate was modified to the silicon tethered dialkyne **213**. It was thought this would force the reaction to commence in an intramolecular manner. Indeed, the desired product **214** was obtained in 76% yield using this procedure, Scheme 54.

Sterically hindered diynes have been converted into cyclobutadiene-CpCo complexes using $CoCp(CO)_2$ in refluxing decalin.[82,83] The inertness of the cobalt precursor towards

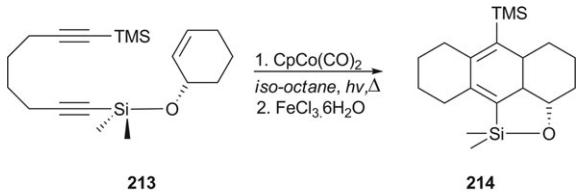


Scheme 52 Inter- *vs.* intramolecular cyclobutadiene cobalt(I) complex formation using $CoCp^*(C_2H_4)_2$ and $CoCp(CO)_2$.[80]



212 0% 210 211 76%

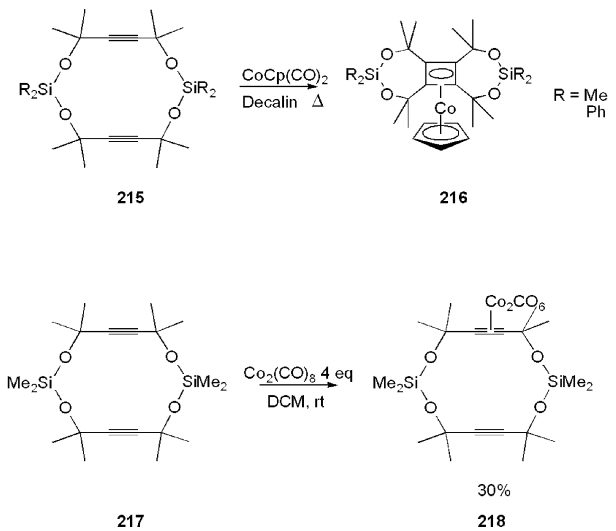
Scheme 53 Synthesis of cobalt(I) cyclobutadiene cyclopentadienyl from a linked diyne.[81]



213 214 76%

Scheme 54 Suppression of cyclobutadiene cobalt(I) metallocene formation using a silicon tethered dialkyne.[81]

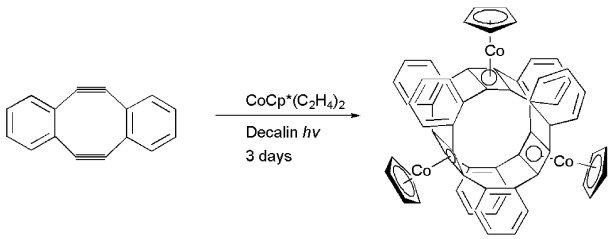
complexation of the alkynes was suggested by the fact that even a four fold excess of octacarbonyl dicobalt gave only a 30% yield of the mono-complexed product.[84] This is due to the methyl groups which make attack at the triple bonds difficult. It was concluded that the steric hindrance of the triple bonds greatly affects their reactivity towards complexation, requiring a large excess of the reacting cobalt species to give **218** even in poor yields. This possibly explains the forcing conditions necessary for the synthesis of cyclobutadiene **216**, with the dialkyne **217** being refluxed in decalin, Scheme 55.



215 216 217 30% 218

Scheme 55 The synthesis of a hindered Co-cyclobutadiene cyclopentadienyl complex.[84]

The synthesis of highly strained cyclobutadiene "beltlike" macrocycles **220** has been achieved under mild photolytic conditions, Scheme 56. The reaction was slow (3 days) and the yields were poor (14%).[85] The choice of cobalt source was found to be of great importance for the synthesis. Pentamethylcyclopentadienyl cobalt ($CoCp^*L_2$) complexes are too large to give rise to superphane compounds. Synthesis of

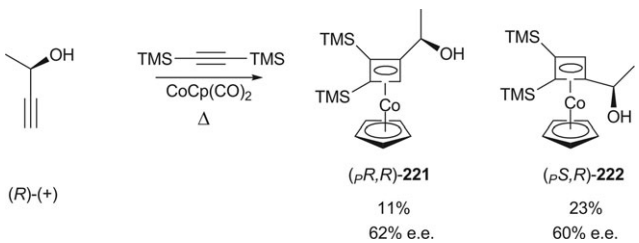


219 220 14%

Scheme 56 Synthesis of highly strained cyclobutadiene "beltlike" macrocycles.[85]

trimers and tetramers has been achieved with strained cyclic diynes in the presence of $CoCp(C_2H_4)_2$.[67] Dicarbonyl cyclopentadienyl cobalt was chosen to effect the tri- or tetramerisation of a dialkyne with even greater strain, Scheme 56.[85]

The first optically enriched cyclobutadiene complexes were synthesised by Vollhardt and co-workers in the early 1980s.[76] This was achieved by complexing optically enriched (*R*)-1-butyn-3-ol with BTMSA in the presence of $CoCp(CO)_2$ which gave the optically active diastereoisomers ($_PS,R$)-**221** and ($_PR,R$)-**222** in a 34% overall yield with 62 and 60% ee, respectively, as determined by NMR spectroscopy, Scheme 57.

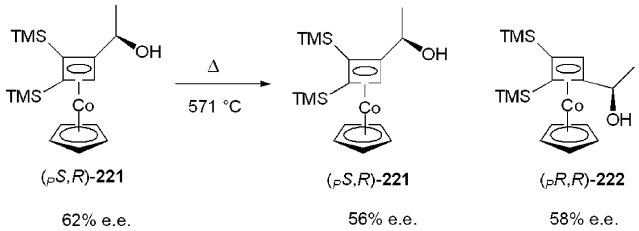


(*R*)-(+) ($_PR,R$)-**221** 11% 62% e.e. ($_PS,R$)-**222** 23% 60% e.e.

Scheme 57 The first optically enriched cyclobutadiene complexes.[76]

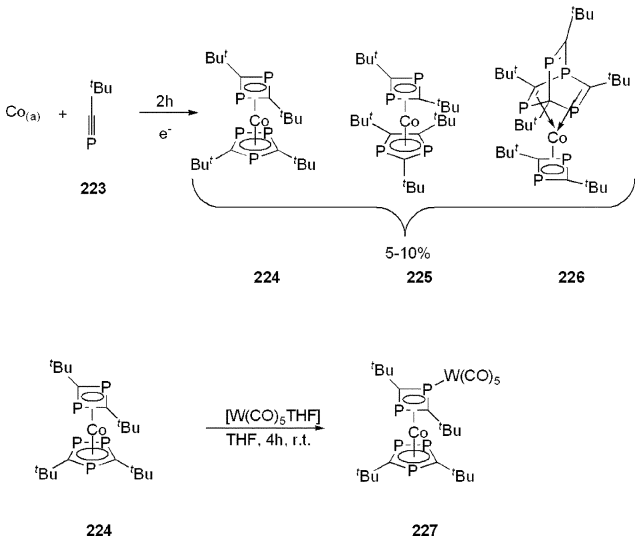
Vollhardt and co-workers also investigated the mechanism by which cyclobutadiene cobalt complexes were formed.[76,86] In the course of these explorations it was discovered that at high temperatures the epimerisation of complex **221** occurs. When an optically enriched sample of predominantly ($_PS,R$)-**221** was heated to 571 °C a mixture of ($_PS,R$)-**221** and ($_PR,R$)-**222** was obtained in a 65.6 : 34.4 ratio with 56 and 58% ee, respectively. The diastereomeric ratio of **221** and **222** after the pyrolysis was the same as that produced by the initial complexation; which indicates that diastereoracemerisation occurs at the cobalt centre, Scheme 58.

Recently, much effort has been invested into the synthesis of cyclobutadiene cobalt complexes containing a heteroatom, such as silicon or phosphorus, either in the cyclobutadiene



Scheme 58 Epimerization of cyclobutadiene cobalt complexes at high temperature.[76,86]

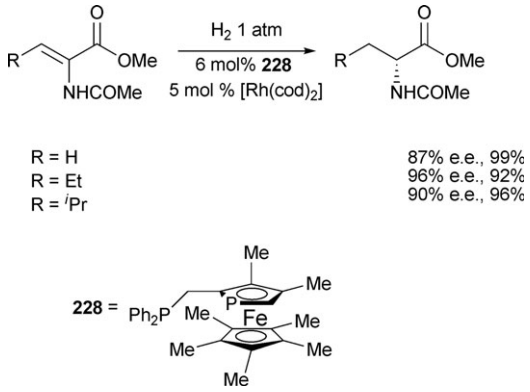
or in the cyclopentadienyl ring.[87,88] The synthesis of cyclobutadiene cobalt complexes containing phosphorus atoms within both the cyclopentadienyl and cyclobutadienyl ring has been achieved. The bonding in these complexes mimics that of "traditional" cyclopentadienyl and cyclobutadiene species to give rise to metallocene-like sandwich structures. The synthesis of these complexes is achieved by the co-condensation of cobalt atoms with *t*-BuCP (**223**), Scheme 59. The black mass obtained from the reaction mixture was purified on alumina giving the three metallocenes **224**, **225** and **226**, albeit in low yields.[88]



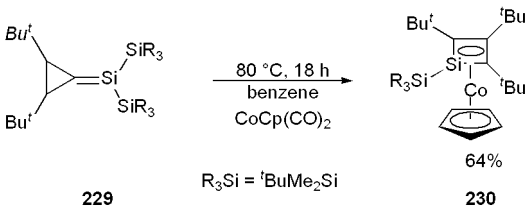
Scheme 59 The co-condensation of cobalt atoms and *t*-BuCP, and the coordination of a heteroatom-containing cyclobutadiene cobalt complex to tungsten.[87,88]

The compounds (**224**, **225** and **226**) have all demonstrated an ability to coordinate to other metals to form complexes, such as **227**. An indication of the potential of such compounds comes from the work of Qiao and Fu, where a phosphorus atom is placed directly in a ferrocene ring **228**. This ligand has been used to great effect in asymmetric catalysis, giving up to 96% ee in good yields (92–100%), as shown in Scheme 60.[89]

Recently, a silacyclobutadiene cobalt complex has been synthesised in moderate yield by heating 4-silatriafulvene **229** with dicarbonyl cyclopentadienyl cobalt at 80 °C (Scheme 61).[87] This crystalline red compound **230** is thermally stable under an inert atmosphere; however, it is air- and moisture-sensitive.



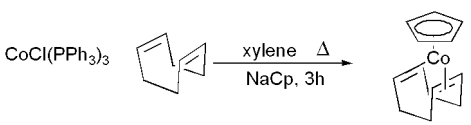
Scheme 60 The enantioselective hydrogenation of double bonds.[89]



Scheme 61 Synthesis of a silicon containing cyclobutadiene cobalt(I) complex.[87]

3.1.2 Synthesis using cyclopentadienyl 1,5-cyclooctadiene (COD) cobalt(I) complexes

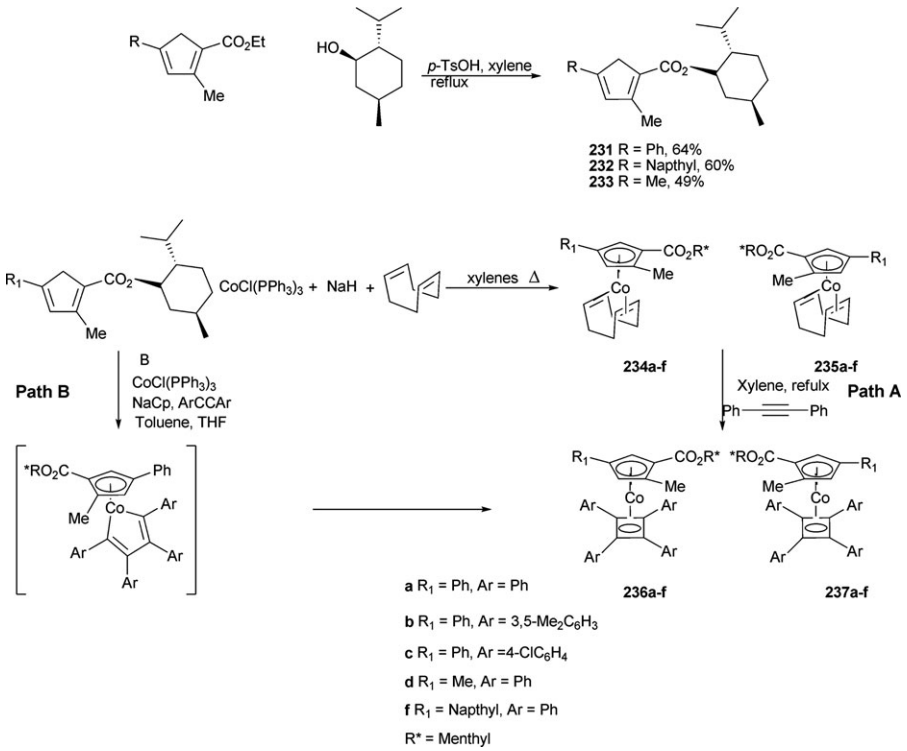
Cyclopentadienyl 1,5-cyclooctadiene (COD) cobalt(I) complexes are easily synthesised. This is achieved by mixing COD and dicarbonyl cyclopentadienyl cobalt and irradiating with a mercury lamp.[90] An alternative synthesis involves refluxing a mixture of cobalt chloride tris-triphenylphosphine and COD with sodium cyclopentadienylide in xylene for 3 h, Scheme 62.[72]



Scheme 62 Synthesis of cobalt cyclopentadienyl 1,5-cyclooctadiene.[72]

In the early 1990s the syntheses of the first optically pure planar chiral cyclobutadiene complexes was reported using trisubstituted cyclopentadienyls.[72] The cyclopentadienyl ring was first functionalised *via* an ester linkage to a (−)-menthyl group, Scheme 63. The chiral cyclopentadienyls **231**, **232** and **233** were then converted into cyclooctadiene cobalt complexes, as shown in Scheme 63.

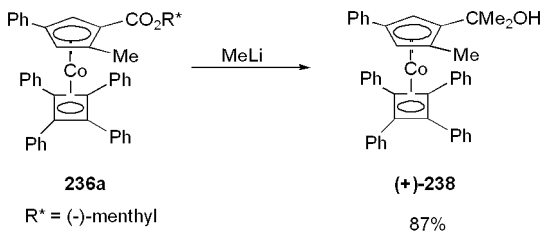
The functionalised CpCo(COD) complexes were synthesised as two diastereoisomers and were easily purified as a mixture on silica *via* column chromatography, but could not be separated by HPLC, with the exception of the cyclopentadienyls **234a** and **235a**. The COD complexes **234** and **235** were then used to synthesise the cyclobutadiene compounds without purification. Pathway B is a more convenient and direct



Scheme 63 The use of functionalised cyclopentadienyl 1,5-cyclooctadiene cobalt complexes for the synthesis of cyclobutadiene cyclopentadienyl cobalt metallocenes.[72]

method for the synthesis of the cyclobutadiene compounds; however, only moderate yields were obtained using this procedure. A summary of the results is shown in Table 10.

For all compounds both diastereoisomers were isolated and separated by flash chromatography, with the exception of entry 5, Table 10, where no cyclobutadiene complexes were obtained from the reaction. The reason for the lack of cyclobutadiene formation is attributed to the steric hindrance of the two methyl groups in the *ortho*-position. The conversion of the separated diastereoisomers **236a** and **237a** into optically pure complexes was achieved *via* removal of the (−)-menthyl group on the cyclopentadienyl moiety. The optical purity of the complexes was determined by ^{1}H NMR spectroscopy, and the circular dichroism spectra of the two separate complexes. The reaction of **236a** with methyllithium in tetrahydrofuran gave enantiomer (+)-**238** in good yield (87%), Scheme 64.



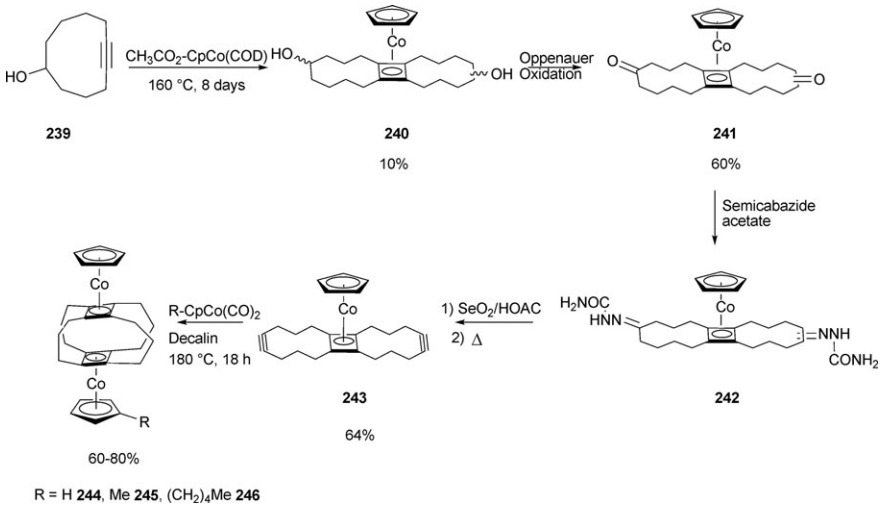
Scheme 64 Synthesis of optically pure cyclopentadienyl cyclobutadiene cobalt(I) complex *via* removal of the menthyl auxiliary.[72]

The generation of strained cobalt dicyclobutadienophanes has been achieved with CoCp(COD). These compounds are of special interest as they allow the exploration of the electron delocalisation over two metal centres.[70,71] Using a cyclic alkyne **239**, containing a hydroxyl moiety, the cyclobutadiene-cobalt metallocene **240** was furnished, giving a mixture of inseparable

Table 10 Synthesis of functionalised cyclopentadienyl cobalt(I) cyclobutadiene cobalt complexes from functionalised CpCo(COD) complexes[72]

Entry	Path	Product	Ar	Yield (%)	$[\alpha]_D$ in $CHCl_3$
1	A	**236a**	Ph	28[a]	+46
		237a		36[a]	−5.6
2	B	**236a**	Ph	27[b]	—
		237a		35[b]	—
3	B	**236b**	3,5-$Me_2C_6H_4$	29[b]	+93
		237b		32[b]	–32
4	B	**236c**	4-ClC_6H_4	16[b]	+7
		237c		18[b]	–2
5	B	**236**	2,4,6-$Me_3C_6H_2$	0	—
		237		0	—

[a] Isolated yield based on **236a–f**. [b] Isolated yield based on $CoCl(PPh_3)_2$.



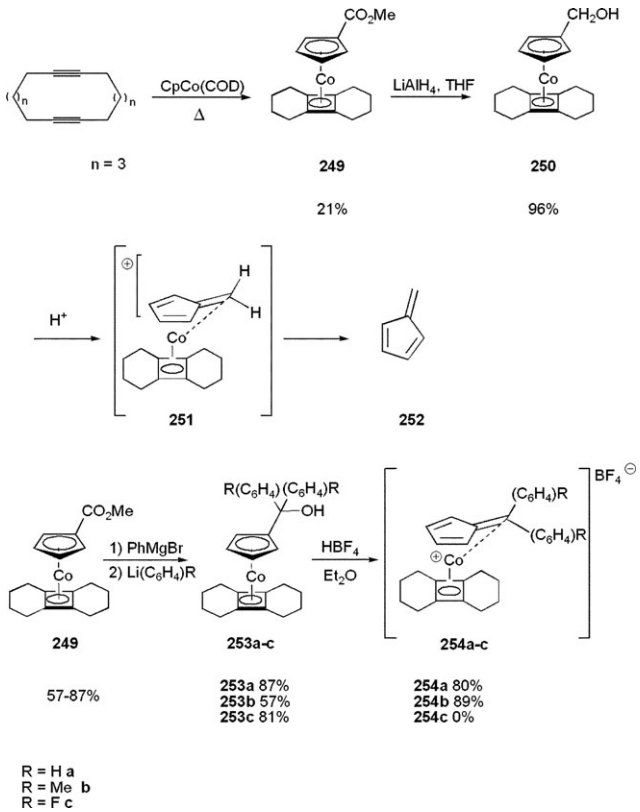
Scheme 65 The generation of strained dicyclobutadienophanes using modified CoCp(COD) complexes.[70,71]

diastereoisomers. This mixture was oxidised to give the diketone **241**; transformation of the diketone species to the bis-(semicarbazone) species **242** was achieved using the Lalezari protocol. Selenium dioxide furnished the bis(selenadiazoles), however, the yields were disappointing (15–19%). The cyclobutadiene alkyne complex **243** was finally synthesised after heating to 180 °C for 10 min at 0.1 bar, giving the desired product in a 64% yield, Scheme 65. The cobalt source was altered to allow the synthesis of a second cyclobutadiene ring; this was probably necessary since the COD moiety would be too bulky to allow attack from the second set of alkynes. Also COD ligands are not as labile as their CO counterparts.

The stability of ferrocenylcarbocations, such as **247** shown in Fig. 1, has been widely investigated.[91] Gleiter *et al.* have investigated the stability of the related cobalt cyclobutadiene cyclopentadienyl carbocations **248**.[92]

In studies to investigate the stability of cationic cyclobutadiene complexes, complex **249** was chosen as a model system, partially for its ease of synthesis, but also for the facile conversion of the ester moiety into an alcohol group to give the primary alcohol **250**, Scheme 66.

Alcohol **250** was treated with acid, but the only product from this reaction was pentafulvene **252**. To stabilize the carbocationic complex of the type **251**, derivatives with benzene and *para*-substituted benzene rings (**254a–c**) were synthesised. Alcohols **253a–c** were treated with different acids and in each case an immediate colour change from yellow to deep violet–blue was observed. The most successful acid was HBF_4, since in this case the cationic products **254a** and **254b** were isolated and



Scheme 66 Synthesis of a cyclobutadiene cobalt(I) complex suitable for conversion to a cyclobutadiene cyclopentadienyl carbocation.[92]

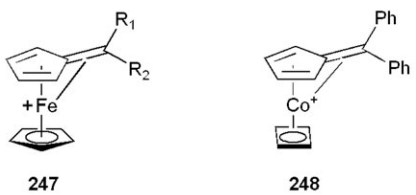
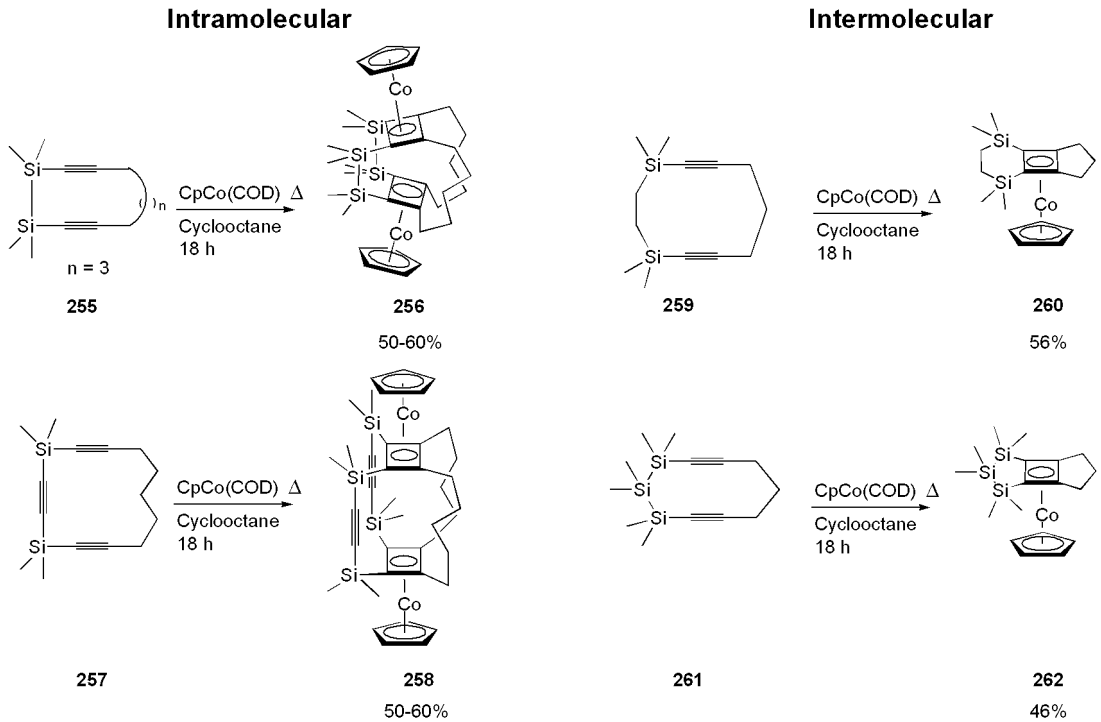


Fig. 1 A ferrocenylcarbocation and a cyclobutadiene cyclopentadienyl carbocation

characterised, whereas other acids gave cationic complexes which could be observed but were unable to be isolated. Cyclic voltammetry experiments showed that in contrast with ferrocene analogues where 85% of the positive charge resides on the iron, 96% of the positive charge resides on the cobalt.[92] They also stated that the positive charge at the exo-methylene carbon is smaller (+0.28) for the cobalt species **248** than for its ferrocene counterpart **247**, where the positive charge is +0.31. This suggests that there is a stronger metal-fulvene interaction in complex **247** compared to **248**, which is due to the higher



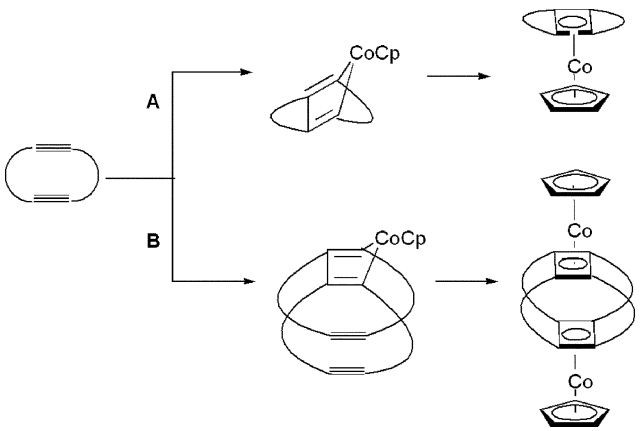
Scheme 67 Synthesis of cyclobutadiene cobalt metallocenes from sterically congested diynes giving both the inter- and intramolecular products.[82]

stability of the cyclobutadiene-cobalt cationic unit. This stability is traced back to the better distribution of positive charge in the $CoCb^+$ (cobalt cyclobutadiene) fragment over the Cb ring compared to that of the $FeCp^+$ fragment.

Sterically congested cyclic diynes have been successfully converted into cyclobutadiene compounds *via* complexation with CoCp(COD) in refluxing cyclooctane.[82] The synthesis of sterically hindered cyclobutadiene systems has also been achieved using $CoCp(CO)_2$ in refluxing decalin.[82,83] Sterically congested diynes react differently with $CoCp(L)_2$, giving both the inter- and intramolecular products. The difference in reactivity was attributed to the possible formation of strained cyclobutadienes in the case where the intramolecular reaction is disfavoured; this would make the intermolecular pathway considerably lower in energy, giving rise to cyclobutadiene compounds, such as **256** and **258**. However, if the bridge containing the trimethylsilyl groups is larger or less rigid, the intramolecular pathway is more energetically favourable giving rise to products such as **260** and **262**, shown in Scheme 67.

When linked cyclic diynes are employed, the cyclobutadiene cobalt complex synthesised is directly related to the chain length that separates the alkynes.[77] There are two types of complex that can be synthesised, cyclobutadiene complexes, such as **260** and **262**, which arise from an intramolecular pathway, or superphanes, such as **256** and **258**, which arise from an intermolecular pathway A, Scheme 68. In general, small rings or those that contain a silyl-bridge favour the formation of superphane whereas larger rings, *i.e.* more than three methylene units between the triple bonds, favour the intermolecular pathway A, (Scheme 68).

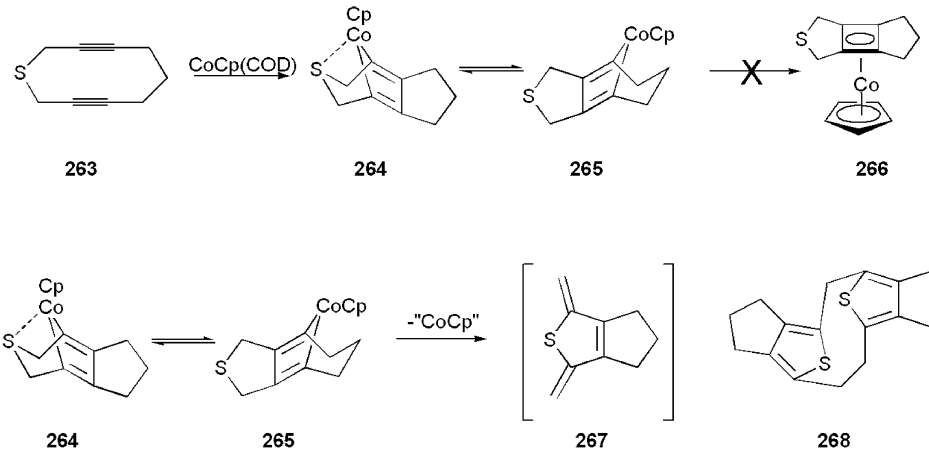
The mechanism by which the two types of product are made has been examined.[93] A number of cyclic thiadiynes containing a sulfur moiety in the propargylic position with respect to



Scheme 68 Inter- and intramolecular pathways for the formation of cyclobutadiene cobalt complexes.[77]

both triple bonds were reacted with CoCp(COD). The sulfur atom was expected to stabilize the intermediate metallacycles **264** and **265**, Scheme 69.

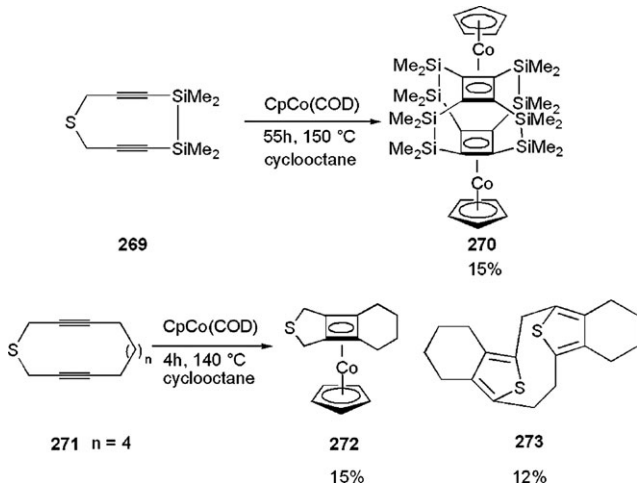
Thioenophane **268** was isolated, Scheme 69, where the CoCp fragment and the sulfur had exchanged places. The mechanism suggests an equilibrium between cobaltols **264** and **265**. The stability of these intermediates depends mostly on the sulfur-cobalt interaction, and any steric hindrance that might arise in the transition states.[93] Gleiter and co-workers were unable to analyse intermediates **264** and **265** due to their instability. The geometry of non-sulfur containing analogues in the transition state was correlated with the triple bond distances of their respective starting materials, and compared to those compounds containing sulfur. The results suggest that in cycles with sulfur in the propargylic position, the distance between the alkyne units in the starting material is large, which



Scheme 69 Attempted synthesis of sulfur containing cobalt cyclobutadiene complexes from thiadiynes.[93]

favours the formation of metallacycle **265** and the course of the reaction follows intramolecular pathway A, Scheme 68. When the distance between the two alkyne units is smaller, metallacycle **264** is favoured, and this preferentially gives rise to the intermolecular pathway B.

For thiacycle **269** the intermolecular product superphane **270** was synthesised in 15% yield, Scheme 70. Both the intramolecular product **272** and the thioenophane **273** were isolated from the reaction of **271** with CoCp(COD), this is due to the formation of cobaltacycles, of the type **264** and **265**, where neither pathway is favoured, hence the mixture of products.

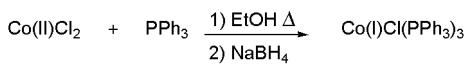


Scheme 70 Synthesis of sulfur containing cobalt cyclobutadiene complexes from thiadiynes.[93]

3.3.1 Synthesis using $(PR_3)_3CoCl$ complexes

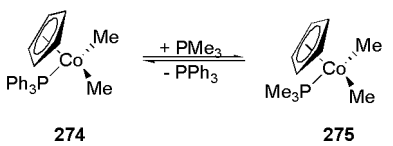
$CoCl(PPh_3)_3$ is used in conjunction with sodium cyclopentadienyl for the formation of cyclobutadiene cobalt complexes. It is made by stirring cobalt(II) chloride in ethanol in the presence of triphenylphosphine, the metal is then reduced using sodium borohydride to give $CoCl(PPh_3)_3$ as an air- and moisture-sensitive brown precipitate, Scheme 71.

There are several examples, spanning over 20 years, where this complex has been used in the synthesis of cyclobutadiene



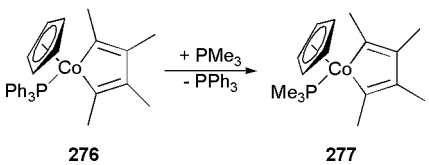
Scheme 71 Synthesis of $CoCl(PPh_3)_3$.

cobalt complexes.[73,94] Cyclopentadienyl dimethyl triphenylphosphine cobalt(III) **274** has also been shown to produce cyclobutadiene cobalt(I) complexes in the presence of two equivalents of diphenylacetylene.[73] The substitutional lability of the triphenyl phosphine ligand in complex **274** was demonstrated in toluene-d_8 in the presence of trimethyl phosphine, which gave complex **275**, Scheme 72.



Scheme 72 Cyclopentadienylcobalt(III) dimethyl(trimethylphosphine).[73]

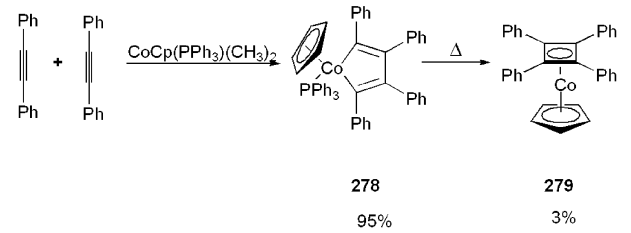
Cobaltacycle **276** has also been shown to undergo phosphine replacement to give cobaltacycle **277**, although the rate of this transformation is much slower, Scheme 73. The slower rate is presumed to be a reflection of the ability of the conjugated ''cyclic dialkenyl'' moiety to remove electron density from the metal centre more effectively than the two methyl groups in **275**.



Scheme 73 Phosphine substitution of a cyclopentadienylcobalt(III) cobaltacycle.[73]

As stated above, **274** reacts with diphenylacetylene to give the 18-electron cobaltacycle **277**, and then reductive elimination occurs giving ring closure to yield the cyclobutadiene

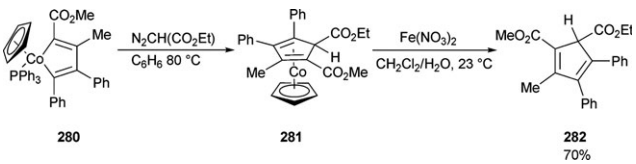
cobalt complex **278**. The major product is found to be the 18-electron species **278** (95%) with only small amounts of the cyclobutadiene complex (3%) formed, Scheme 74.[73]



Scheme 74 Synthesis of a cobalt(I) cyclobutene metallocene from cyclopentadienylcobalt(III) cobaltacycle.[73]

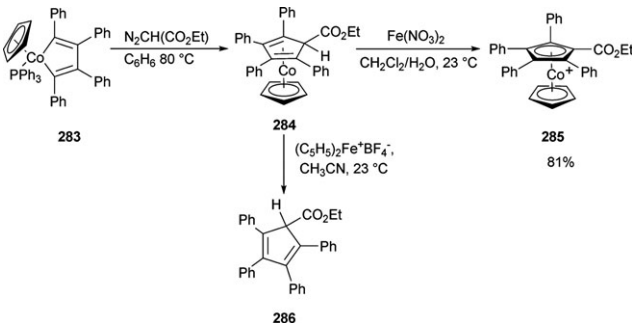
It was noticed that in the presence of an excess of diphenylacetylene and triphenyl phosphine the rate of reaction, and the yield of **279** was increased and the rate of formation of **278** was impeded.[73]

Highly substituted cobaltocenium complexes **281** have been synthesised by exposure of $CpCo(PPh_3)_2$ to alkynes and ethyl diazoacetate, Scheme 75.[95] The function of the ethyl diazoacetate is to liberate triphenyl phosphine from the 16-electron cobaltacycle intermediate, furnishing a η^4-cyclopentadienyl complex. Decomplexation is observed when **281** is treated with $Fe(NO_3)_2{\cdot}9H_2O$ in wet dichloromethane at room temperature giving the cyclopentadienyl **282** in good yields (70%).



Scheme 75 Decomplexation of a cobaltocenium species by treatment with $Fe(NO_3)_2{\cdot}9H_2O$.[95]

However, when the 18-electron complex **283**, (Scheme 76) was treated with a variety of oxidizing agents the cobaltocenium species **285** was isolated in good yields (60–81%), the results are shown in Table 11.

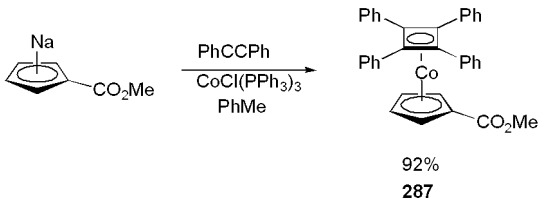


Scheme 76 Synthesis of cobaltocenium species by treatment with a variety of oxidizing agents.[95]

Cyclobutadiene cobalt metallocenes have also been synthesised using $CoCl(PPh_3)_3$ as the cobalt source, in the presence of sodium cyclopentadienylide and diphenylacetylene (Scheme 77).[94] The cyclobutadiene compound **287** was synthesised in excellent yields (92%), with no cobaltacycle **276** detected.

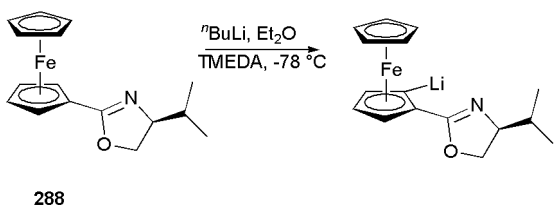
Table 11 Synthesis of cobaltocenium species by treatment with a variety of oxidizing agents

Oxidant (eq.)	Solvent	*t*/h	Product (yield %)
$Fe(NO_3)_2{\cdot}9H_2O$ (10)	Dichloromethane	15	**282** (80)
$Fe(NO_3)_2{\cdot}9H_2O$ (10)	CH_3CN	15	**282** (78)
$(NH_4)_2Ce(NO_3)_6$ (3)	$(CH_3)_2CO$	20	**282** (81)
I_2 (1.5)	C_6D_6	1	**282** (80)
$(C_5H_5)_2Fe^+BF_4^-$ (2)	$(CH_3)_2CO$	0.5–1	**283** (38)
$(C_5H_5)_2Fe^+BF_4^-$ (2)	CH_3CN	15	**283** (70)
$(C_5H_5)_2Fe^+BF_4^-$(2)	CH_3CN	2.5	**283** (74)



Scheme 77 Synthesis of cyclobutadienyl cobalt metallocenes using $CoCl(PPh_3)_3$.[94]

The ester **289** was transformed into the chiral oxazoline **290** in 47% overall yield, (Scheme 79).[96] This compound is similar to its ferrocene analogue (Scheme 78), which has been shown to give stereocontrol during deprotonation with organo-lithium species.



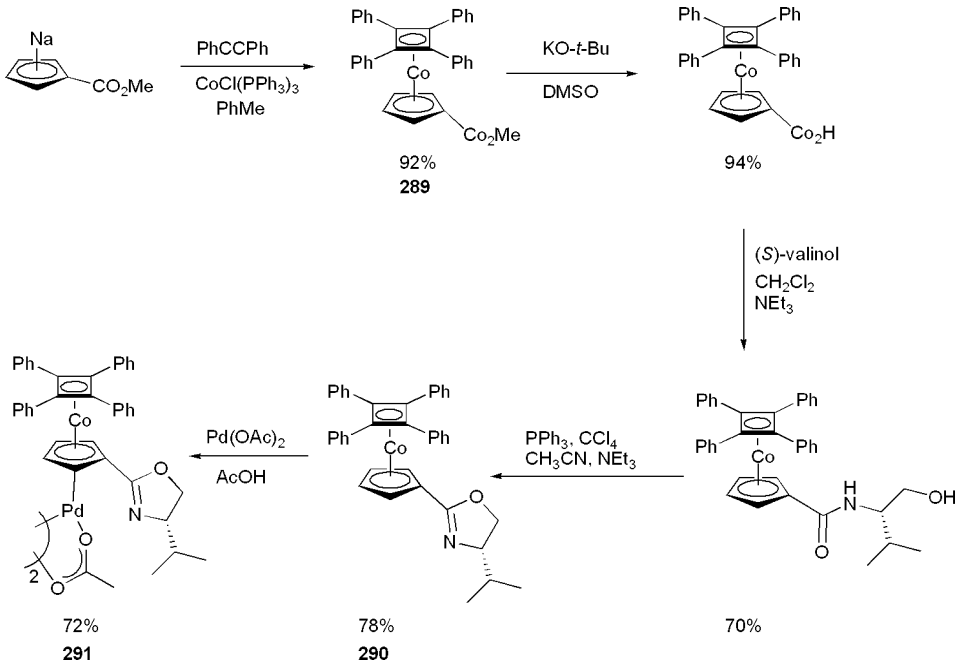
Scheme 78 Synthesis of a chiral cobalt cyclobutadiene cyclopentadienyl oxazoline metallocene.[94,96]

The stereocontrol during deprotonation derives from the isopropyl group that is orientated towards the unsubstituted part of the cyclopentadienyl ring, providing a stabilizing effect. Richards has shown this is the opposite case for the cyclobutadiene species **290**.[94]

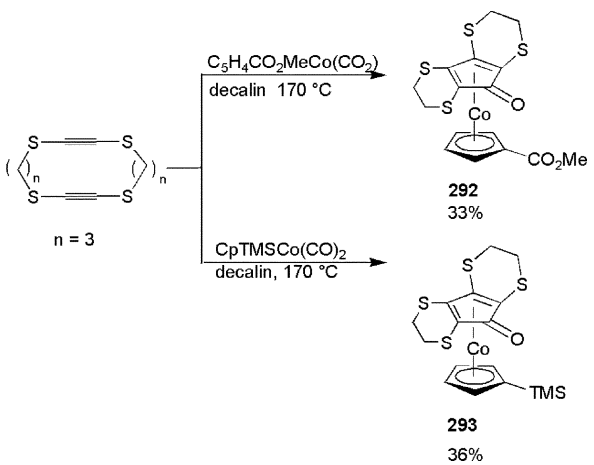
The palladacycle **291** was then synthesised as a single diastereoisomer, as demonstrated by ^{1}H NMR spectroscopy, as only one set of signals was observed. This is one of the first reports of complete *ortho*-palladation of a metallocene with complete stereocontrol.[94] It was proposed that the other diastereoisomer is inaccessible due to steric hindrance from the phenyl groups attached to the cyclobutadiene ring.

As previously stated, this chemistry is perhaps more complex due to the side reactions observed in the synthesis of cyclopentadienone cobalt metallocenes. Depending on the reaction conditions used, cyclobutadiene and cyclopentadienone metallocenes, or benzene derivatives can be obtained.

The synthesis of cyclopentadienone **292** was achieved in a 6% yield in toluene; however, the yields were improved to 33% when the reaction was carried out at a higher



Scheme 79 Stereochemical control during deprotonation of chiral cobalt cyclobutadiene cyclopentadienyl oxazoline metallocene to give a palladacycle.[94]

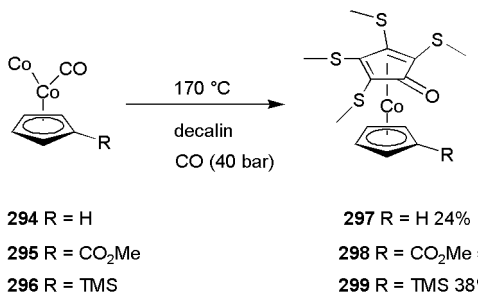


Scheme 80 Synthesis of a cyclopentadienone cobalt metallocene in decalin.[78]

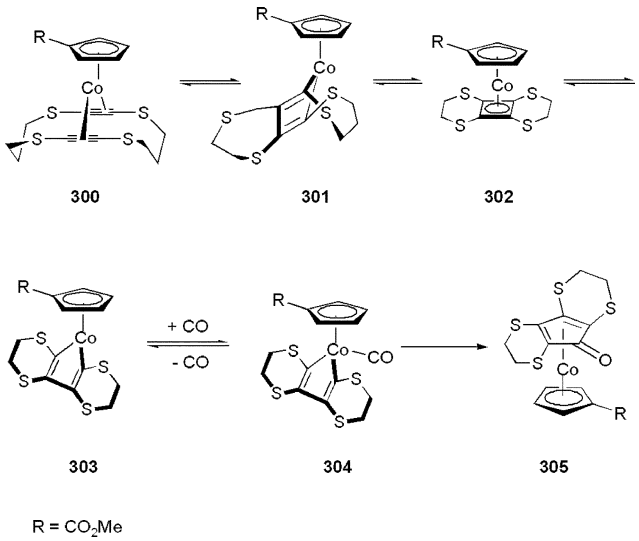
temperature in decalin.[78] Using the same methodology, the synthesis of cyclopentadienone **293** was achieved in decalin in a 36% yield, Scheme 80.

Investigations into whether the cyclopentadienone formation was dependent on the substituent attached to the Cp ring were performed, in which different Cp derivatives were used under otherwise identical conditions; it was found that the ester group gave the best yields of the corresponding cyclopentadienone **297–299**, Scheme 81.[78]

The bis(alkyne) complex **300** was employed in this reaction, which gave the cobaltacycle **301**, reductive elimination followed to give the intermediate cyclobutadiene complex **302**. The cobaltacycle **303** must be an intermediate in the reaction pathway towards **292**, in **303** the triple bond is broken and CO insertion gives the 18-electron species **304** which can lead to the cyclopentadienone complex **292**, Scheme 82.[78]

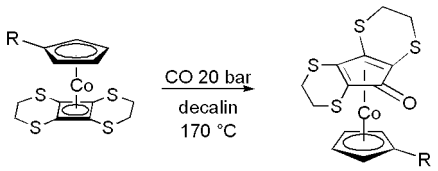


Scheme 81 Dependency of the formation of cyclopentadienone cyclopentadienyl cobalt metallocenes on substituents attached to the cyclopentadienyl ring.[78]



Scheme 82 Synthesis of sulfur-containing cyclopentadienone cobalt complex.[78]

Proof that the cyclobutadiene complex **302** is an intermediate in the formation of the cyclopentadienone complex **292** was obtained by heating compound **302** in the presence of CO at high pressures. This gave the corresponding cyclopentadienone complex in 42% yield as the only product, Scheme 83.[78]



302 **292**

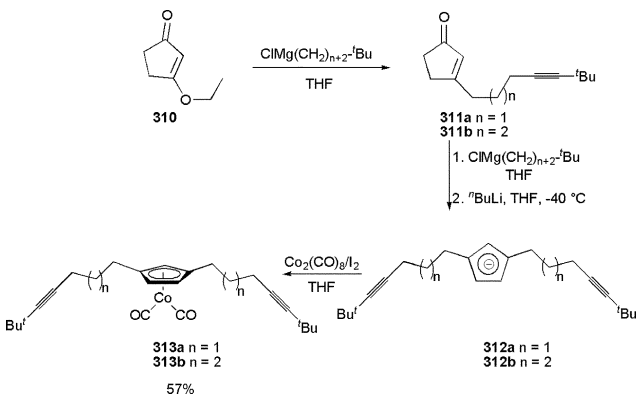
42%

Scheme 83 Conversion of a cobalt cyclobutadiene metallocene into the corresponding cyclopentadienone.[78]

Cyclopentadienone cobalt stabilised superphanes have been synthesised and their properties examined.[97] Examples of superphane cyclobutadiene complexes have been discussed previously. In general small rings favour the formation of superphane whereas larger rings, *i.e.* more than three methylene units between the triple bonds, favour the intermolecular pathway A. The synthesis of cyclopentadienone superphane analogues of the cyclobutadiene complexes (*vide supra*), used a similar approach.[93,98] The superphane was built up in a stepwise fashion from a medium sized cyclic alkyne bearing a ketone group, **305**. The generation of the first cyclopentadienone **306** from two of the alkyne-ketone units was achieved by refluxing in decalin for 5 days (Scheme 84). Milder conditions have been used to synthesise cyclopentadienone complexes previously, which include irradiation; however this only gave a 4% yield of the desired compound.[97,98]

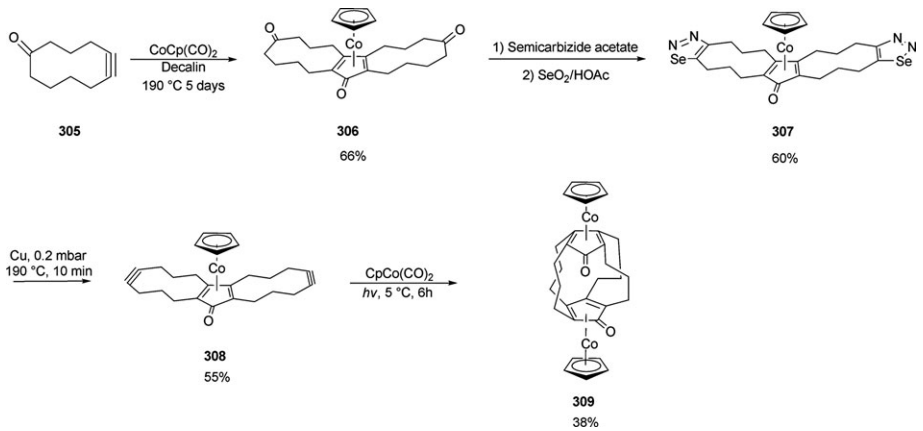
Three different regioisomers were generated from this reaction. The ketone **306** is then converted to the selenadiazole **308** *via* treatment with semicarbazide acetate followed by selenium dioxide and acetic acid. This gave the selenadiazole **308** in 60% yield as a mixture of inseparable regioisomers. Treatment with copper at elevated temperatures gave the tricyclic alkyne complex **308** in a 55% yield.[97] The intramolecular cyclisation of **308** to **309** was first attempted in decalin at 190 °C, but was unsuccessful and gave only 2% of the product. The cyclisation was effected *via* irradiation in THF at 5 °C, which gave 38% of the superphane **309** as the major product. Only the *syn* isomer of **309** was generated, which was ascribed to steric effects. It is assumed that the triple bonds in **308** are orientated parallel to the double bonds in the cyclopentadienyl unit. Superphane **309** has also been synthesised using a one-pot procedure.[98] This was not however, a successful preparation, yielding only 5% of the desired product.

An alternative method for the synthesis of superphanes or metallocenophanes uses a functionalised metal cyclopentadienyl complex, *e.g.* Cp^*CoL_2.[74,99] For the synthesis of cyclopentadienone systems, a metal supported [2 + 2 + 1] cycloaddition of two alkyne units and one CO group was employed. This system can also be used for the generation of cyclopentadienone or cyclobutadiene endohedral metallocenophanes by using a modified version of $CoCp(CO)_2$. Modified cyclopentadienyl anions **312a,b**, bearing long alkyl chains with terminal acetylene groups, were synthesised in three steps, these were then complexed to metal carbonyls **313** by treatment with octacarbonyl dicobalt and iodine in THF, Scheme 85.



Scheme 85 An alternative method for the synthesis of cobalt containing superphanes or metallocenophanes.[74,99]

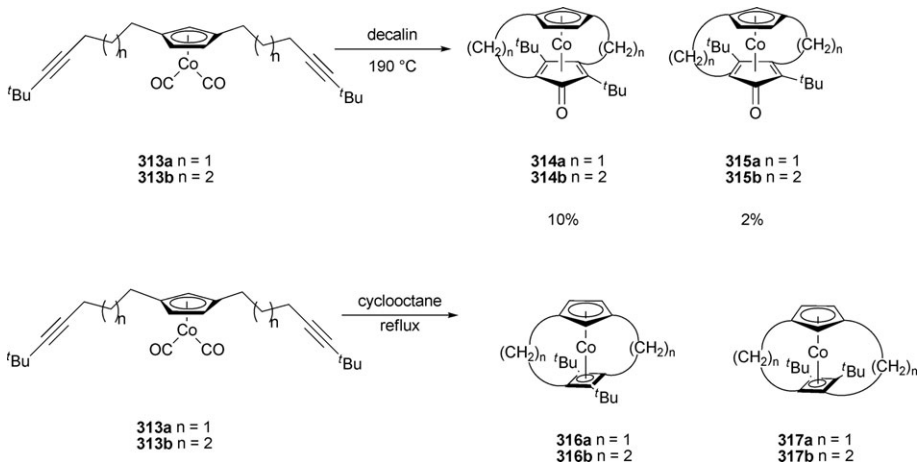
The modified cyclopentadienyl cobalt carbonyl complexes were then heated to 190 °C in decalin, this gave the cyclopentadienones **314–315a–b** in 2–10% yields. The C_1-symmetric



305 **306** 66% **307** 60%

308 55% **309** 38%

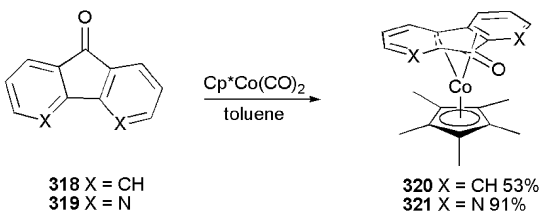
Scheme 84 The generation of the first superphane cyclopentadienone from two of the alkyne–ketone units.[97,98]



Scheme 86 The synthesis of cobalt containing superphanes or metallocenophanes bearing cyclopentadienone or cyclobutadiene rings.[74,99]

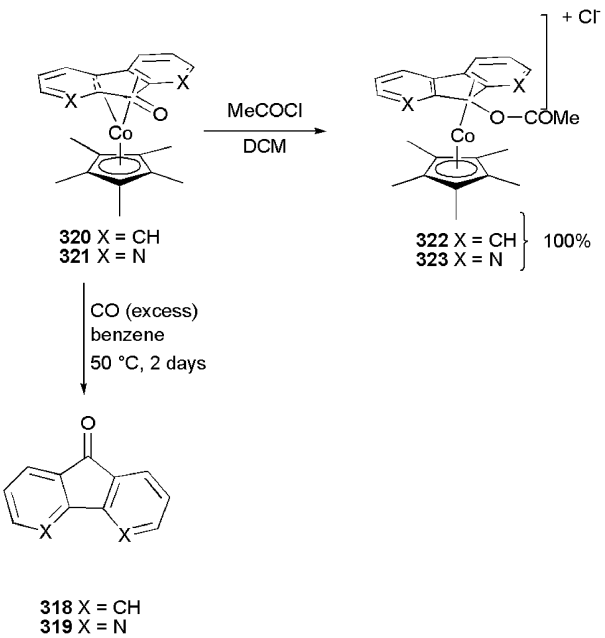
complex **314a** was synthesised in a 10% yield, and was spectroscopically indistinguishable from **314b**. Treatment of **313b** under the same conditions gave only a 2% yield of **315a** and **315b**, Scheme 86. Synthesis of the cyclobutadiene analogues was achieved by heating **313a,b** in cyclooctane at reflux this gave rise to only one of the intramolecular products **316** and **317a,b** in good yields (35 and 39%, respectively), Scheme 86.

It was found that when lower temperatures (120 °C) were used only the corresponding cyclobutadiene complexes were synthesised.[100] More recently there has been a report describing the cyclopentadienone-like behaviour of fluorinone compounds in the presence of pentamethylcyclopentadienyl cobalt dicarbonyl.[101] These compounds gave the air-stable cyclopentadienone compounds **320** and **321**, Scheme 87.



Scheme 87 Cyclopentadienone-like behaviour of fluorinone compounds.[101]

The synthesis of these compounds is quite unique. As in all other cases the cyclopentadienone is formed as a direct result of the [2 + 2 + 1] cycloaddition of alkynes with carbon monoxide. Strictly speaking, compounds **318** and **319** do not possess a cyclopentadienone functionality; the bonding in complexes **320** and **321** is perhaps most accurately described as η^2-cobalt complexes with respect to each of the aromatic rings. Compounds **320** and **321** have also been transformed into their cobaltocenium salts *via* treatment with acetyl chloride in dichloromethane to give brown-yellow compounds. Decomplexation has been achieved giving quantitative amounts of the $CoCp^*(CO)_2$ complex and the starting arene, however, these reactions were laboriously slow (Scheme 88).[101]

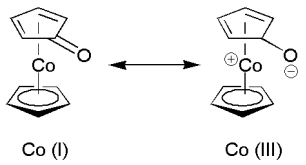


Scheme 88 Decomplexation of cyclopentadienone-like fluorinone compounds.[101]

Electronic properties of cyclopentadienone cobalt metallocenes and their *o*-alkylated or protonated congeners has been described by Gleiter *et al.*[102] Stability of cyclopentadienone metallocenes originates from the occupation of the LUMO of the cyclopentadienone ring, leading to an 18-electron complex. The electronic structure of the complexes is best described by resonance structures **324** and **325**, Fig. 2.

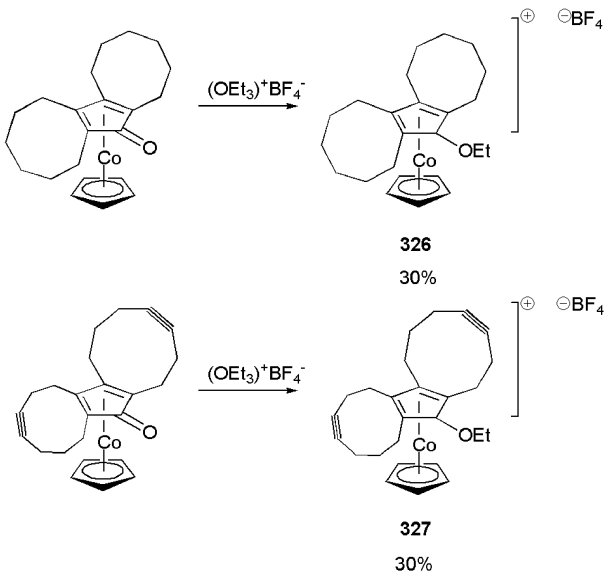
A feature of these compounds is the higher electron density at the oxygen atoms, which shows up in the ease of protonation and alkylation of such metallocenes. Protonation and alkylation experiments were carried out on a number of metallocenes, the NMR spectra of the derived species **326** and **327** were scrutinised closely, Scheme 89.[103]

The yellow cobaltocenium ions **326** and **327**, Scheme 89, showed significant differences to their starting materials. Examination of the ^{1}H NMR spectra showed a shift in the



324 325

Fig. 2 Cyclopentadienone cobalt metallocenes and the *o*-alkylated congeners.[102]



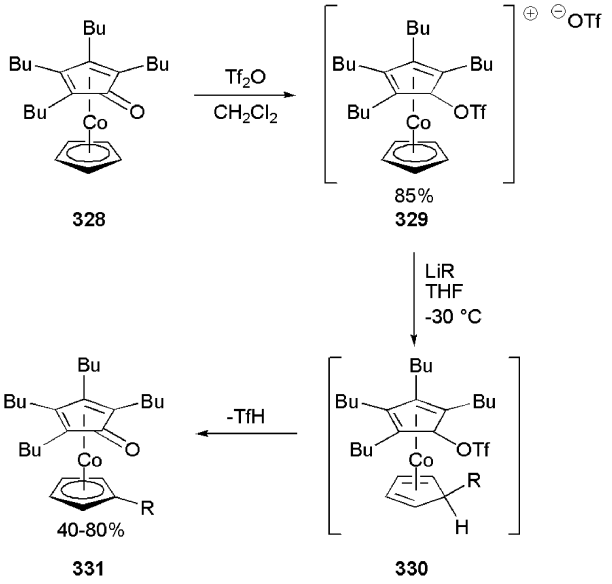
Scheme 89 *o*-Alkylated congeners of cyclopentadienone cobalt metallocenes.[103]

Cp peak by almost 1 ppm downfield.[102] The addition of triflate to the cyclopentadienone complex **328** has also been investigated, and this gives the cobaltocenium salt **329** in an 85% yield.[104] It was shown that further reaction with nucleophiles, such as MeLi or PhLi, does not yield the direct substitution product of the triflate, Scheme 90.

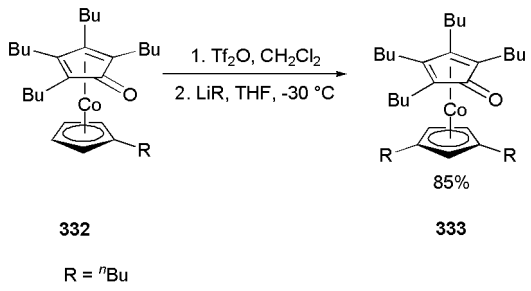
Instead, the reaction yields the product from attack on the lower unsubstituted Cp ring, eliminating the triflate and regenerating the carbonyl complex. Overall, complex **331** with a substituted cyclopentadienyl ring is formed. This is the simplest process to introduce a substituent into the Cp ring. A second substitution in the β-position with respect to the first may be achieved by repeating the procedure, Scheme 91.

The results from DFT calculations show that triflate, compared to protonated cyclopentadienone species, changes the charge distribution within the complex. In the cobaltocenium triflate species **329** the net charges on the cyclopentadienyl carbon atoms were shown to be positive. In the cyclopentadienone complex **328** the net charges are negative; this is also the case for the protonated cobaltocenium species. Therefore, attack on the lower unsubstituted cyclopentadienyl **329** is favoured over substitution of the triflate group.

Recently Richards and Taylor have reported the microwave assisted one-pot synthesis of planar chiral cobalt cyclopentadienones **336** in moderate yield and diastereoselectivity.[105]

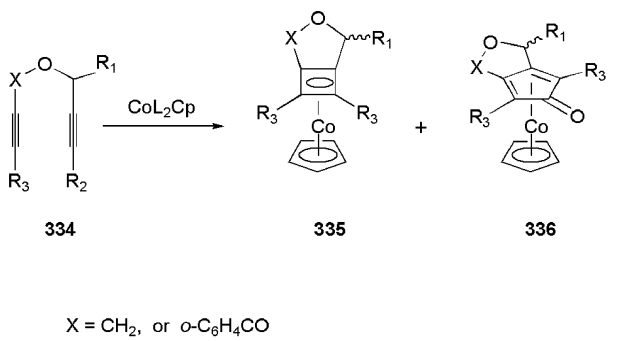


Scheme 90 Synthesis and reactions of *o*-alkylated congeners of cyclopentadienone cobalt metallocenes.[104]



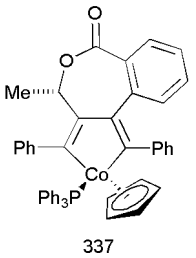
Scheme 91 Alkylation of cyclopentadienone cobalt metallocenes.[104]

This is the first known example of the synthesis of a metallocene under microwave irradiation using a metal carbonyl as the starting material. The control during the complexation was achieved by linking a diyne of the type **334**, shown in Scheme 92.



Scheme 92 One-pot procedure for the preparation of cobalt containing cyclopentadienones.[105]

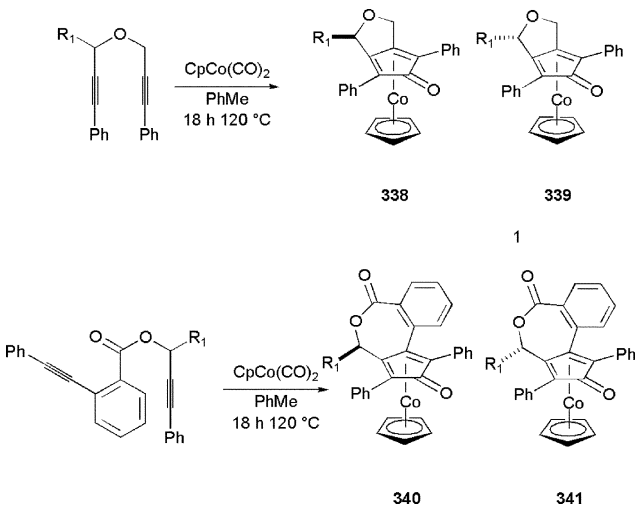
Interestingly there was no cyclobutadiene formed under the reaction conditions. Attempts to synthesise the cyclobutadiene using cobalt(I) chloride tris(triphenylphosphine) as the cobalt source failed, yielding only crystalline phosphine cobaltacycle **337**, as shown in Scheme 93, and attempts to force the synthesis of the corresponding cyclobutadiene complex failed.



337

Scheme 93 Phosphine cobaltacycle which is chiral at cobalt.[105]

Complexation of the racemic diynes **334** was investigated under a variety of conditions using either $Co(CO)_2Cp$ or $Co_2(CO)_8$ as the cobalt source. In all cases, the major diastereoisomer was the one where the R^1 group points up away from the cyclopentadienone ring with no cyclobutadiene cobalt complex observed, Scheme 94.



Scheme 94 One-pot procedure for the preparation of diastereoisomeric of cobalt containing cyclopentadienones.[105]

The optimal conditions using normal thermal methods were found to be toluene at 120 °C for 18 h, since this gave the highest yields and diastereoselectivity; the synthesis of the product was sluggish at lower temperatures and after 84 h at 70 °C it only gave 11% of **338** and **339** (where R^1 = Me). The complexations where then repeated with microwave irradiation in decalin using either $Co(CO)_2Cp$ or $Co_2(CO)_8$ as the cobalt source with little erosion of the selectivity but a significant reduction in the reaction time, *i.e.* from 18 h to 10 min. The results from the complexations are shown in Tables 12 and 13. The authors illustrate the viability of this protocol for the synthesis of non racemic metallocenes, by employing an optically enriched propargylic (*S*)-alcohol with 72% ee which was transformed into the corresponding linked diyne with no erosion of ee. They then converted this optically enriched diyne into the metallocenes **340** and **341** (R^1 = Me) *via* microwave-assisted complexation with $CpCo(CO)_2$ this gave a 4 : 1 ratio of diastereoisomers **340** : **341** (R^1 = Me) in 38% yield. The major and minor isomers were shown by HPLC to have ee of 74 and 72%, respectively. This shows that this procedure is suitable for the synthesis of scalemic complexes containing both central and planar elements of chirality in one-pot as there was not deleterious effect on the ee during the conversion of the diyne to the metallocene.

Table 12 One-pot procedure for the preparation of diastereoisomeric of cobalt containing cyclopentadienones[105]

Entry	R^1	Conditions[b]	Yield (%)	**338** : **339**[a]
1	Me	A	61	4 : 1
2	Me	B	68	3 : 1
3	^{i}Pr	A	47	5 : 1
4	^{i}Pr	B	49	5 : 1
5	^{i}Pr	C	34	4 : 1

[a] Ratio determined by ^{1}H NMR spectroscopy. [b] Conditions A: Cp–$Co(CO)_2$, toluene, 120 °C, N_2, 18 h. Conditions B: $CpCo(CO)_2$, decalin, 190 °C, N_2, microwave, 10 min. Conditions C: $Co_2(CO)_8$ (0.5 eq.) C_5H_6 (2 eq.), decalin, 5 min at 40 °C, 10 min at 190 °C.

Table 13 One-pot procedure for the preparation of diastereoisomeric of cobalt containing cyclopentadienones[105]

Entry	R^1	Conditions[b]	Yield (%)	**340** : **341**[a]
1	Me	A	21	3 : 1
2	Me	B	29	3 : 1
3	*i*-Pr	A	33	4 : 1
4	*i*-Pr	B	57	3 : 1
5	*i*-Pr	C	11	5 : 1

[a] Ratio determined by ^{1}H NMR spectroscopy. [b] Conditions A: Cp–$Co(CO)_2$, toluene, 120 °C, N_2, 18 h. Conditions B: $CpCo(CO)_2$, decalin, 190 °C, N_2, microwave, 10 min. Conditions C: $Co_2(CO)_8$ (0.5 eq.), C_5H_6 (2 eq.), decalin, 5 min at 40 °C, 5 min at 190 °C.

Concluding remarks

In conclusion organo-cobalt chemistry continues to be an important area of research providing facile routes towards the directed synthesis of a range of carbocycles from simple and inexpensive precursors under relatively mild conditions, which can (and often do) find use in the synthesis of natural products.

Acknowledgements

The authors are very grateful to Dr Anne-Sophie Rodriguez for helpful discussions.

References

1 S. E. Gibson and A. Stevenazzi, *Angew. Chem., Int. Ed.*, 2003, **42**, 1800–1810.
2 Y. K. Chung, *Coord. Chem. Rev.*, 1999, **188**, 297–341.

3 A. J. Fletcher and S. D. R. Christe, *J. Chem. Soc., Perkin Trans. 1*, 2000, 1657–1668.
4 J. Blanco-Urgoiti, L. Anorbe, L. Pérez-Serrano, G. Dominguez and J. Pérez-Castells, *Chem. Soc. Rev.*, 2004, **33**, 32–42.
5 V. Bernardes, N. Kann, A. Riera, A. Moyano, M. A. Pericas and A. E. Greene, *J. Org. Chem.*, 1995, **60**, 6670.
6 C. Exon and P. Magnus, *J. Am. Chem. Soc.*, 1983, **105**, 2477.
7 P. Magnus and L. M. Principe, *Tetrahedron Lett.*, 1985, **26**, 4851–4854.
8 E. V. Banide, H. Müller-Bunz, A. R. Manning, P. Evans and M. J. McGlinchey, *Angew. Chem., Int. Ed.*, 2007, **46**, 2907.
9 D. B. Werz, J. H. Schulte, B. J. Rausch, R. Gleiter and F. Rominger, *Eur. J. Inorg. Chem.*, 2004, 2585.
10 Y. Gimbert, D. Lesage, A. Milet, F. Fournier, A. E. Greene and J.-C. Tabet, *Org. Lett.*, 2003, **5**, 4073–4075.
11 M. Yamanaka and E. Nakamura, *J. Am. Chem. Soc.*, 2001, **123**, 1703–1708.
12 T. J. de Bruin, M., A. Milet, F. Robert, Y. Gimbert and A. E. Greene, *J. Am. Chem. Soc.*, 2001, **123**, 7184–7185.
13 F. Robert, A. Milet, Y. Gimbert, D. Konya and A. E. Greene, *J. Am. Chem. Soc.*, 2001, **123**, 5396.
14 J. H. Schulte, R. Gleiter and F. Rominger, *Org. Lett.*, 2002, **4**, 3301.
15 T. R. Hoye and J. A. Suriano, *J. Org. Chem.*, 1993, **58**, 1659–1660.
16 N. E. Schore, B. E. La Belle, M. J. Knudsen, H. Hope and X.-J. Xu, *J. Organomet. Chem.*, 1984, **272**, 435.
17 A. Lagunas, A. M. I. Payeras, C. Jimeno and M. A. Pericas, *Org. Lett.*, 2005, **7**, 3033–3036.
18 Y. K. Chung, B. Y. Lee, N. Jeong, M. Hudecek and P. L. Pauson, *Organometallics*, 1993, **12**, 220–223.
19 T. Sugihara, M. Yamada, Y. Yamaguchi and M. Nishizawa, *Synlett*, 1999, 771–773.
20 M. Iqbal, N. Vyse, J. Dauvergne and P. Evans, *Tetrahedron Lett.*, 2002, **43**, 7859–7862.
21 S. Fischer, U. Groth, M. Jung and A. Schnider, *Synlett*, 2002, **12**, 2023–2026.
22 B. L. Pagenkopf and T. Livinghouse, *J. Am. Chem. Soc.*, 1996, **118**, 2285–2286.
23 S.-W. Kim, S. U. Son, S. I. Lee, T. Hyeon and Y. K. Chung, *J. Am. Chem. Soc.*, 2000, **122**, 1550–1551.
24 K. M. Brummond, J. Lu and J. Petersen, *J. Am. Chem. Soc.*, 2000, **122**, 4915–4920.
25 D. Konya, F. Robert, Y. Gimbert and A. E. Greene, *Tetrahedron Lett.*, 2004, **45**, 6975–6978.
26 M. E. Krafft, C. Hirosawa and L. V. R. Bonaga, *Tetrahedron Lett.*, 1999, **40**, 9177–9181.
27 S. E. Gibson, S. E. Lewis, J. A. Loch, J. W. Steed and M. J. Tozer, *Organometallics*, 2003, **22**, 5382–5384.
28 J. Castro, A. Moyano, M. A. Pericas, A. Riera, A. Alvarez-Larena and J. F. Piniella, *J. Am. Chem. Soc.*, 2000, **122**, 7944–7952.
29 J. Nakcheol, C. Young Keun, L. Bun Yeoul, L. Sang Hee and Y. Sung-Eun, *Synlett*, 1991, 204.
30 S. Shambayani, W. E. Crowe and S. L. Schreiber, *Tetrahedron Lett.*, 1990, **31**, 5289.
31 J. Shen, Y. Gao, Q. Shi and F. Basolo, *Organometallics*, 1989, **8**, 2144.
32 M. E. Krafft, R. H. Romero and I. L. Scott, *J. Org. Chem.*, 1992, **57**, 5277.
33 M. Rodriguez Rivero, J. C. de la Rosa and J. C. Carretero, *J. Am. Chem. Soc.*, 2003, **125**, 14992.
34 M. E. Krafft, A. M. Wilson, O. A. Dasse, B. Shao, Y. Y. Cheung, Z. Fu, L. V. R. Bonaga and M. K. Mollman, *J. Am. Chem. Soc.*, 1996, **118**, 6080–6081.
35 R. Gleiter, J. H. Schulte and D. B. Werz, *Eur. J. Org. Chem.*, 2004, 4077.
36 M. E. Krafft, I. L. Scott, R. H. Romero, S. Feibelmann and C. E. Van Pelt, *J. Am. Chem. Soc.*, 1993, **115**, 7199.
37 A. Stumpf, N. Jeong and H. Sunghee, *Synlett*, 1997, 205.
38 B. L. Hayes, *Aldrichimica Acta*, 2004, **37**, 66–76.
39 A. M. Hay, W. J. Kerr, G. G. Kirk and D. Middlemiss, *Organometallics*, 1995, **14**, 4986–4988.
40 R. P. Elliott, G. W. J. Fleet, K. Vogt, F. X. Wilson, Y. Wang, D. R. Witty, R. Storer, P. L. Myers and C. J. Wallis, *Tetrahedron: Asymmetry*, 1990, **1**, 715.
41 M. Poch, E. Valentí, A. Moyano, M. A. Pericàsa, J. Castro, A. DeNicola and A. E. Greene, *Tetrahedron Lett.*, 1990, **31**, 7505.
42 X. Verdaguer, A. Moyano, M. A. Pericàs, A. Riera, A. E. Greene, J. F. Piniella and A. Alvarez-Larena, *J. Organomet. Chem.*, 1992, **433**, 305.
43 V. Bernardes, X. Verdaguer, N. Kardos, A. Riera, A. Moyano, M. A. Pericàs and A. E. Greene, *Tetrahedron Lett.*, 1994, **35**, 575.
44 H.-J. Park, B. Y. Lee, Y. K. Kang and Y. K. Chung, *Organometallics*, 1995, **14**, 3104.
45 D. T. Rutherford and S. D. R. Christie, *Tetrahedron Lett.*, 1998, **39**, 9805–9808.
46 K. P. C. Vollhardt, *Angew. Chem., Int. Ed. Engl.*, 1984, **23**, 539–644.
47 N. E. Schore, *Chem. Rev.*, 1988, **88**, 1081.
48 G. Chouraqui, M. Petit, C. Aubert and M. Malacria, *Org. Lett.*, 2004, **6**, 1519–1521.
49 H. Bönnemann, R. Goddard, J. Grub, R. Mynott, E. Raabe and S. Wendel, *Organometallics*, 1988, **8**, 1941.
50 B. Heller, B. Sundermann, H. Buschmann, H.-J. Drexler, H. You, U. Holzgrabe, E. Heller and G. Oehme, *J. Org. Chem.*, 2002, **67**, 4414–4422.
51 D. Péréz, B. A. Siesel, M. J. Malaska, E. David and K. P. C. Vollhardt, *Synlett*, 2000, 306–310.
52 A. Bradley, W. B. Motherwell and F. Ujjainwalla, *Chem. Commun.*, 1999, 917–918.
53 L. V. R. Bonaga, H. C. Zhang and B. E. Maryanoff, *Chem. Commun.*, 2004, 2394–2395.
54 A. F. Moretto, H. C. Zhang and B. E. Maryanoff, *J. Am. Chem. Soc.*, 2001, **123**, 3157–3158.
55 D. F. Harvey, B. M. Johnson, C. S. Ung and K. P. C. Vollhardt, *Synlett*, 1989, 15–18.
56 R. Gleiter and V. Schehlmann, *Tetrahedron Lett.*, 1989, **30**, 2893.
57 M. S. Sigman, A. W. Fatland and B. E. Eaton, *J. Am. Chem. Soc.*, 1998, **120**, 5130–5131.
58 L. Yong and H. Butenschön, *Chem. Commun.*, 2002, 2852–2853.
59 P. Phansavath, C. Aubert and M. Malacria, *Tetrahedron Lett.*, 1998, **39**, 1561–1564.
60 Y. Yamamoto, T. Arakawa and K. Itoh, *Organometallics*, 2004, **23**, 3610–3614.
61 Y. Yamamoto and S. Saito, *Chem. Rev.*, 2000, **100**, 2901–2915.
62 K. P. C. Vollhardt and R. G. Bergman, *J. Am. Chem. Soc.*, 1974, **96**, 4996–4998.
63 Y. Yamamoto, K. Kinpara, T. Saigoku, H. Nishiyama and K. Itoh, *Org. Biomol. Chem.*, 2004, 1287–1294.
64 Y. Yamamoto, T. Saigoku, T. Ohgai, H. Nishiyama and K. Itoh, *Chem. Commun.*, 2004, 2702–2703.
65 A. Nakamura and H. Hagihara, *Bull. Chem. Soc. Jpn.*, 1961, **34**, 452.
66 J. A. Howard and K. U. Ingold, *J. Am. Chem. Soc.*, 1968, **90**, 1060.
67 R. Gleiter, R. Merger, H. Irngartinger and B. Nuber, *J. Org. Chem.*, 1993, **58**, 2025–2028.
68 P. I. Dosa, G. D. Whitener, K. P. C. Vollhardt, A. D. Bond and S. J. Teat, *Org. Lett.*, 2002, **4**, 2075–2078.
69 A. G. Myers, M. Sogi, M. A. Lewis and S. P. Arvedson, *J. Org. Chem.*, 2004, **69**, 2516–2525.
70 R. Gleiter, H. Langer, V. Schehlmann and B. Nuber, *Organometallics*, 1995, **14**, 975–986.
71 R. Gleiter, R. Roers, J. Classen, A. Jacobi, G. Huttner and T. Oeser, *Organometallics*, 2000, **19**, 147–151.
72 M. Uno, K. Ando, N. Komatsuzaki, T. Tsuda, T. Tanaka, M. Sawada and S. Takahashi, *J. Organomet. Chem.*, 1994, **473**, 303–311.
73 E. R. Evitt and R. G. Bergman, *J. Am. Chem. Soc.*, 1980, **102**, 7003–7011.
74 G. Scholz, C. Schaefer, F. Rominger and R. Gleiter, *Org. Lett.*, 2002, **4**, 2889–2892.
75 R. Gleiter and D. B. Werz, *Organometallics*, 2005, **24**, 4316–4329.
76 G. A. Ville, K. P. C. Vollhardt and M. J. Winter, *Organometallics*, 1984, **3**, 1177–1187.
77 V. Wolfart, M. Ramming, R. Gleiter, B. Nuber, H. Pritzkow and F. Rominger, *Eur. J. Inorg. Chem.*, 1999, 499–504.
78 C. Schaefer, D. B. Werz, T. H. Staeb, R. Gleiter and F. Rominger, *Organometallics*, 2005, **24**, 2106–2113.

79 T. S. Piper, F. A. Cotton and J. Wilkinson, *J. Inorg. Nucl. Chem.*, 1955, **1**, 165–174.
80 R. Gleiter, R. Merger and B. Nuber, *J. Am. Chem. Soc.*, 1992, **114**, 8921–8927.
81 P. Eckenberg and U. Groth, *Synlett*, 2003, 2188–2192.
82 R. Gleiter, H. Stahr and B. Nuber, *Organometallics*, 1997, **16**, 646–650.
83 C. Schaefer, R. Gleiter and F. Rominger, *Organometallics*, 2004, **23**, 2225–2227.
84 C. Schaefer, R. Gleiter and F. Rominger, *Eur. J. Org. Chem.*, 2003, 3051–5059.
85 B. Hellbach, F. Rominger and R. Gleiter, *Angew. Chem., Int. Ed.*, 2004, **43**, 5846–5849.
86 G. A. Ville, K. P. C. Vollhardt and M. J. Winter, *J. Am. Chem. Soc.*, 1981, **103**, 5267–5269.
87 Y. Kon, K. Sakamoto, C. Kabuto and M. Kira, *Organometallics*, 2005, **24**, 1407–1409.
88 N. G. F. Cloke, P. B. Hitchcock, J. F. Nixon and D. M. Vickers, *J. Organomet. Chem.*, 2001, **635**, 212–221.
89 S. Qiao and G. C. Fu, *J. Org. Chem.*, 1998, **63**, 4168–4169.
90 H. Schimanke and R. Gleiter, *Organometallics*, 1998, **17**, 275–277.
91 W. E. Watts, *Organomet. Chem. Rev., 1979*, 1979, **7**, 399.
92 R. Gleiter, H. Schimanke, S. J. Silvero, M. Buchner and G. Huttner, *Organometallics*, 1996, **15**, 5635–5640.
93 R. Gleiter, J. Classen, B. J. Rausch, T. Oeser and F. Rominger, *J. Organomet. Chem.*, 2002, **641**, 3–8.
94 A. M. Stevens and C. J. Richards, *Organometallics*, 1999, **18**, 1346–1348.
95 J. M. O'Connor and J. A. Johnson, *Synlett*, 1989, 57–59.
96 C. J. Richards, T. Damalidis, D. E. Hibbs and M. B. Hursthouse, *Synlett*, 1995, 74.
97 R. Roers, F. Rominger, B. Nuber and R. Gleiter, *Organometallics*, 2000, **19**, 1578–1588.
98 R. Roers, F. Rominger and R. Gleiter, *Tetrahedron Lett.*, 1999, **40**, 3141–3144.
99 G. Scholz, R. Gleiter and F. Rominger, *Angew. Chem., Int. Ed.*, 2001, **40**, 2477.
100 C. Schaefer, G. Scholz, R. Gleiter, T. Oeser and F. Rominger, *Eur. J. Org. Chem.*, 2005, 1274–1281.
101 U. Siemeling, I. Scheppelmann, B. Neumann, H.-G. Stammler and W. W. Schoeller, *Organometallics*, 2004, **23**, 626–628.
102 R. Gleiter, R. Roers, F. Rominger, B. Nuber and I. Hyla-Kryspin, *J. Organomet. Chem.*, 2000, **610**, 80–87.
103 M. D. Rausch and R. A. Genetti, *J. Org. Chem.*, 1970, **35**, 3888–3897.
104 M. von der Gruen, C. Schaefer and R. Gleiter, *Organometallics*, 2003, **22**, 2370–2372.
105 C. J. Taylor, M. Motevalli and C. J. Richards, *Organometallics*, 2006, **25**, 2899–2902.

