

## Metal carbonyl complexes and chirality\*

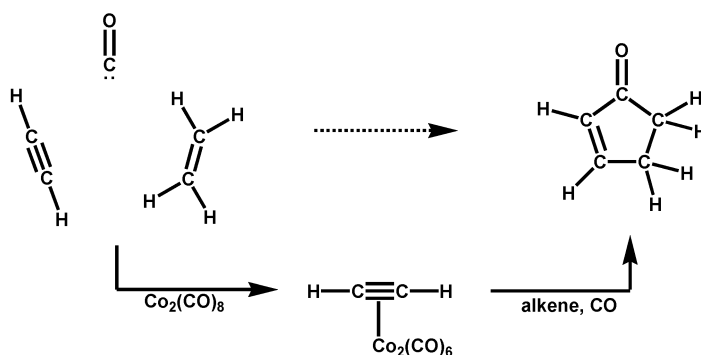
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**Abstract:** A study of the Pauson–Khand reaction (PKR) based on  $\text{Co}_2(\text{CO})_8$  and binap has revealed that a key precatalyst is  $(\text{binap})\text{Co}_2(\text{CO})_6$ , and that alkynes add to this species to generate isomers that interconvert under typical PKR conditions. A  $^{31}\text{P}$  NMR study of  $(\text{binap})(N\text{-}(\text{prop-2-enyl})\text{-}N\text{-}(\text{prop-2-ynyl})\text{-}p\text{-toluenesulfonamide})\text{Co}_2(\text{CO})_4$  revealed that heating this species gives rise to an unexpected cobalt hydride species  $(\text{binap})\text{Co}(\text{CO})_2\text{H}$  together with  $(\text{binap})\text{Co}_2(\text{CO})_6$ . Observation of a PKR reaction by  $^{31}\text{P}$  NMR spectroscopy revealed that the hydride species is generated during the course of the reaction.

**Keywords:** Pauson–Khand reaction; cyclopentenone; cobalt carbonyl; binap; asymmetric synthesis.

The Pauson–Khand reaction (PKR), first reported in 1971 [1], is an attractive carbon–carbon bond-forming reaction that converts an alkyne, an alkene, and carbon monoxide into a cyclopentenone. The majority of reports of this reaction in the 20<sup>th</sup> century involved a two-step process requiring synthesis of an intermediate alkyne cobalt complex (Scheme 1). A mechanism proposed by Magnus in 1985 is still generally accepted [2], and the stoichiometric reaction continues to form an attractive synthetic approach to complex molecules [3]. In recent years, much effort has been invested in rendering the PKR a one-step catalytic reaction. A range of metals have been investigated, including cobalt, titanium, ruthenium, rhodium, and iridium [4].

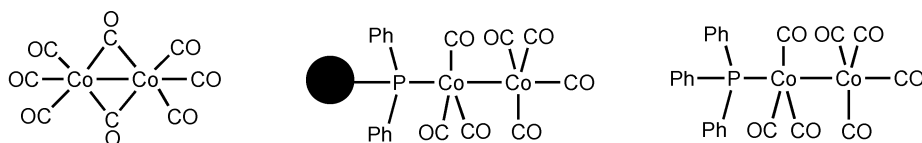


Scheme 1

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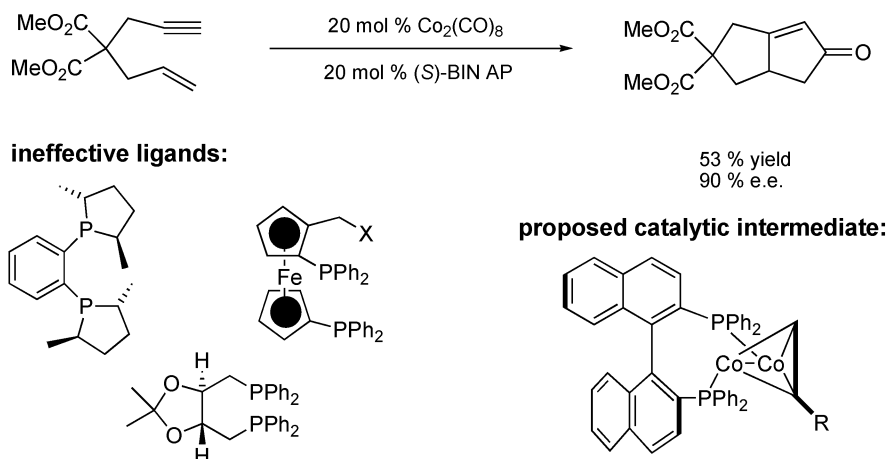
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Our interest in this area began with studies of phosphine-substituted derivatives [5,6] of the known PKR catalyst  $\text{Co}_2(\text{CO})_8$  (Scheme 2) [7]. The phosphine-substituted complexes had some handling advantages over  $\text{Co}_2(\text{CO})_8$ , but comparison of the results achieved with the different catalysts suggested that they all proceeded via a common catalytic cycle, i.e., one that did not involve phosphine-substituted species. Thus, it appeared that the phosphine-substituted complexes were essentially convenient sources of cobalt carbonyl species.



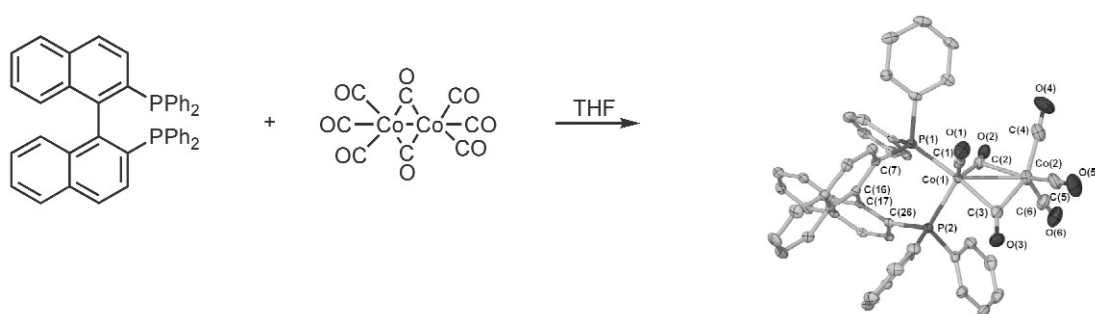
Scheme 2

We were thus intrigued by Hiroi's report [8] in 2000 that treatment of a typical PK substrate with catalytic amounts of  $\text{Co}_2(\text{CO})_8$  and the chiral ligand binap gave a cyclopentenone in high enantiomeric excess (ee), revealing that in this reaction the chiral phosphine is present on the cobalt during the step which leads to the creation of the chiral center (Scheme 3). Thus, in this case, a phosphine-substituted species is more reactive than the background  $\text{Co}_2(\text{CO})_8$  reaction.

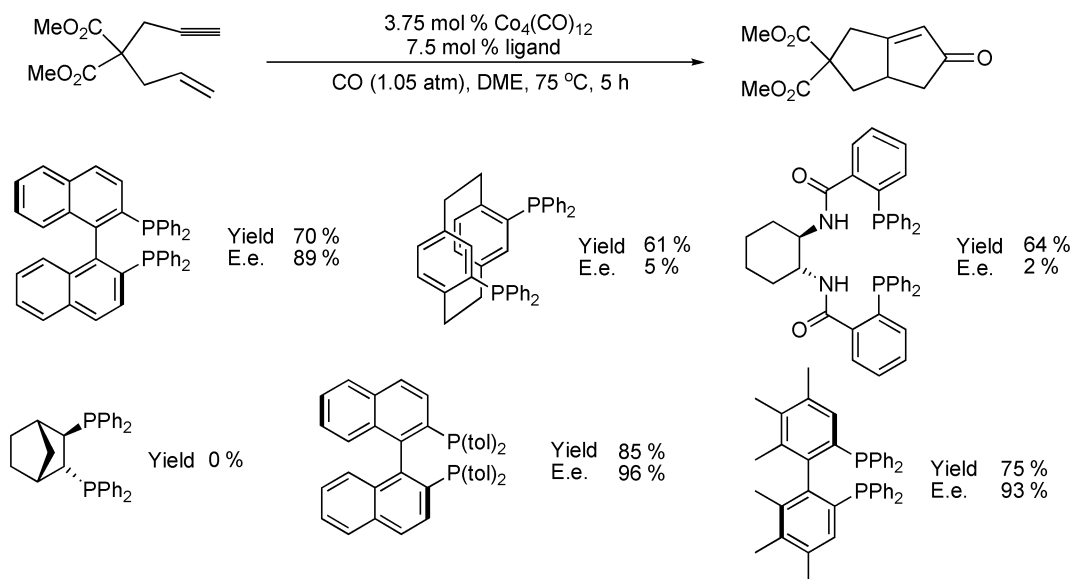


Scheme 3

Hiroi examined several other classes of phosphine ligands and found that they gave very poor ee, suggesting that for these ligands the background  $\text{Co}_2(\text{CO})_8$  reaction was faster. He proposed a catalytic intermediate in which the binap is bound to both of the cobalts of the alkyne complex (Scheme 3). In our hands, Hiroi's reaction worked well with binap and other axially chiral ligands such as tol-binap and hexaphemp, but we too found that representatives of other classes of chiral phosphines such as phanephos or a Trost ligand gave negligible ee (Scheme 5) [9].

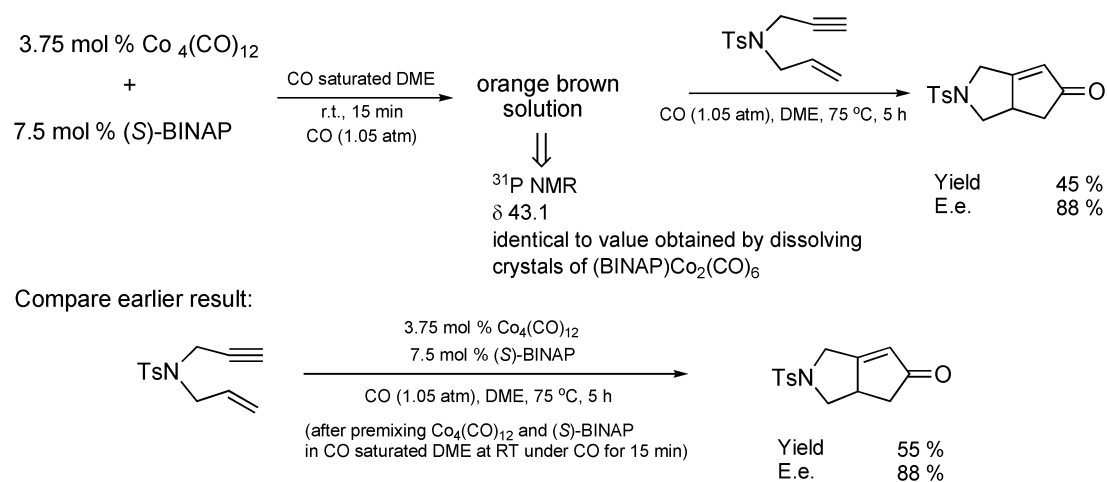


Scheme 4



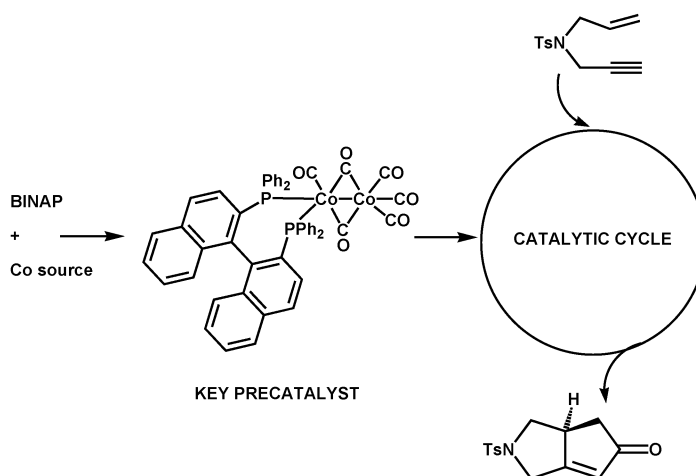
Scheme 5

In order to probe the origin of the exceptional reactivity exhibited by the axially chiral ligands, we reacted binap with  $\text{Co}_2(\text{CO})_8$ . This led to small red crystals which were identified by X-ray crystallography as a dicobalt complex bearing the binap ligand on just one of the two cobalt atoms, i.e., a chelating species (Scheme 4) [9]. In order to relate this observation to a catalytic reaction, a reaction carried out earlier was repeated and sampled before the enyne addition. The  $^{31}\text{P}$  NMR spectrum of the sample was identical to the spectrum of the crystals. On addition of the enyne, the reaction proceeded to give product of similar enantiomeric purity and yield to the original reaction (Scheme 6) [9].



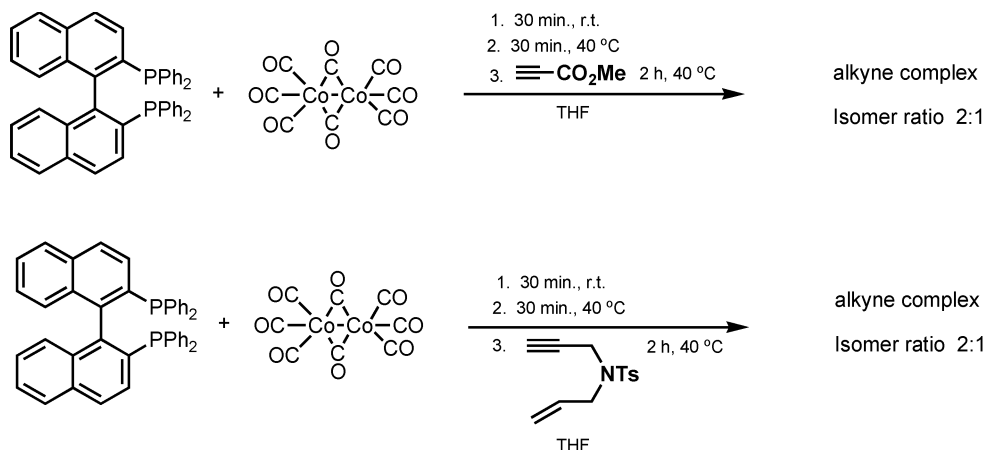
## Scheme 6

In light of the above observations, it is reasonable to assume that  $(\text{binap})\text{Co}_2(\text{CO})_6$  is a key pre-catalyst in this asymmetric PKR (Scheme 7).



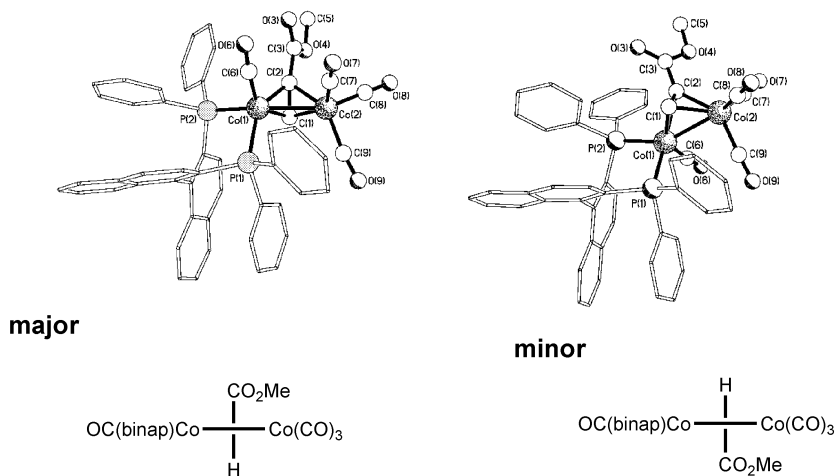
## Scheme 7

In order to probe the next stage of the reaction, samples of precatalyst were formed and treated with a range of alkynes, including the electron-deficient alkyne methyl propiolate and the typical PKR substrate *N*-(prop-2-enyl)-*N*-(prop-2-ynyl)-*p*-toluenesulfonamide (Scheme 8) [10].



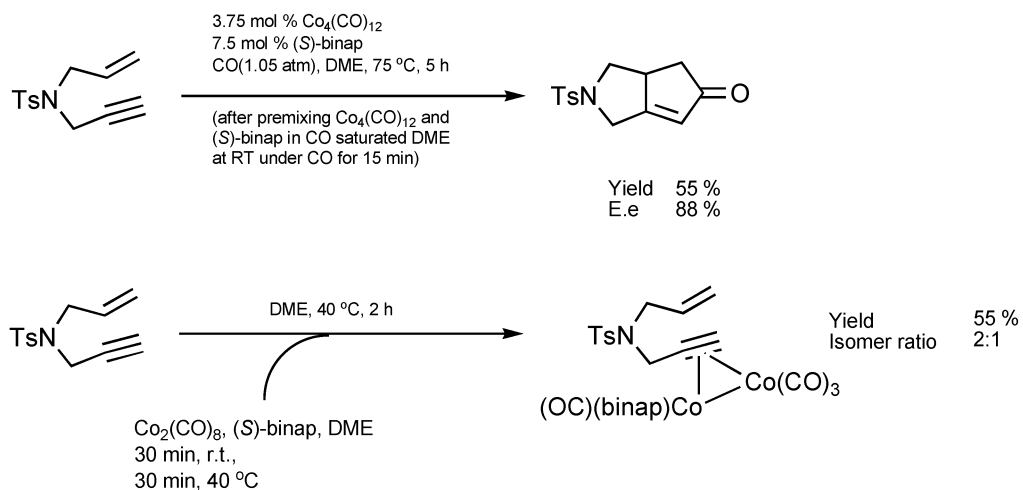
Scheme 8

The former produced a stable product that consisted of two diastereoisomers in a ratio of 2:1 according to  $^{31}\text{P}$  NMR spectroscopy. The isomers proved separable by column chromatography and amenable to crystallization. X-ray crystallography revealed that both isomers contained a chelating binap ligand and differed only in the orientation of the alkyne ligand (Scheme 9) [10].



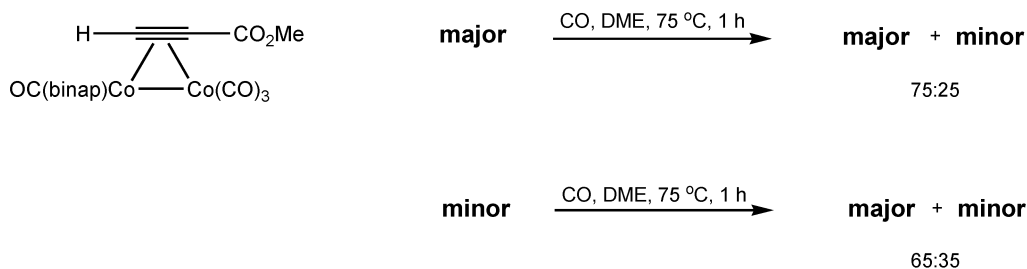
Scheme 9

The enantioselectivities observed in the PKRs and the isomer ratio of the alkyne complex generated by stirring with the precatalyst indicate that the enantioselectivity of the reaction is not a function of the orientation of the alkyne ligand with respect to the binap ligand (Scheme 10).



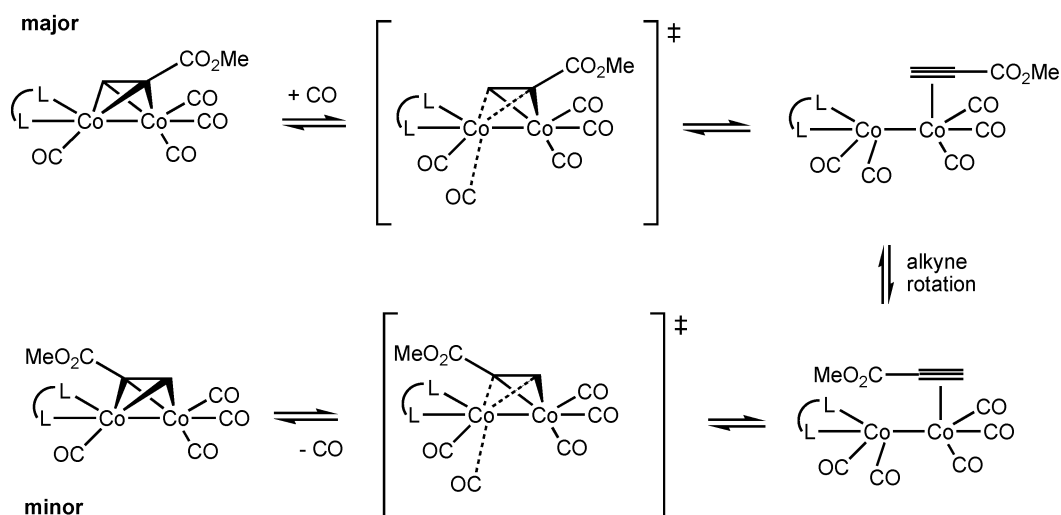
Scheme 10

On comparing the reaction conditions for the PKR and the alkyne complex synthesis (Scheme 10), it was apparent that a significant difference between the two sets of conditions was the reaction temperature (75 °C for the PKR; 40 °C for alkyne complex formation). Thus, samples of each of the isomers of the methyl propiolate were subjected to typical PKR conditions. After 1 h, both of the samples contained a mixture of isomers, indicating that isomer interconversion was occurring under typical PKR conditions (Scheme 11) [10].



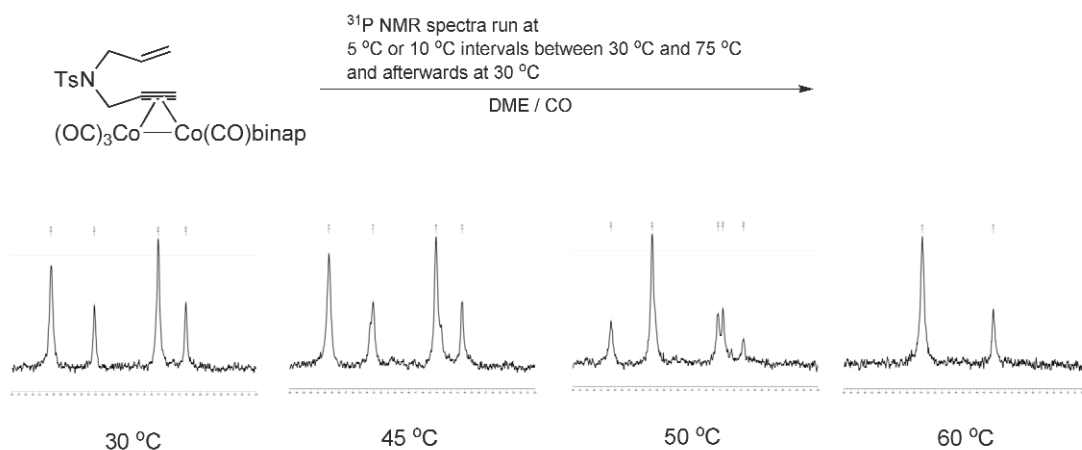
Scheme 11

Further  $^{31}\text{P}$  NMR experiments revealed that the interconversion is faster under a carbon monoxide atmosphere than under a nitrogen atmosphere [10]. A possible pathway for the interconversion of the isomers is illustrated in Scheme 12. Carbon monoxide addition displaces the alkyne ligand from one of the two cobalt atoms to effectively lower the barrier to alkyne rotation. It is of note that at this point an alternative pathway for isomer interconversion that involves binap migration from one cobalt to the other cannot be ruled out.



Scheme 12

As the cobalt binap complex of the enyne *N*-(prop-2-enyl)-*N*-(prop-2-ynyl)-*p*-toluenesulfonamide was much less stable than the complex of methyl propiolate, it was decided to study its chemistry by NMR spectroscopy. The  $^{31}\text{P}$  NMR spectrum at 30 °C displayed resonances typical of the two isomers of all the alkyne complexes synthesized. On raising the temperature, changes were evident between 45 and 60 °C (Scheme 13). The resulting spectrum, which remained unchanged up to 75 °C, contained resonances at  $\delta$  43 and 54 [11]. The former resonance was attributed to the precatalyst,  $(\text{binap})\text{Co}_2(\text{CO})_6$ , leaving a question mark over the latter resonance.



Scheme 13

Fortunately, on one occasion, brown crystals were observed in the NMR tube at the end of the variable-temperature (VT) sequence. X-ray crystallography revealed that they were the trigonal bipyramidal cobalt hydride depicted in Fig. 1. Repetition of the VT  $^{31}\text{P}$  NMR experiment followed by examination of the  $^1\text{H}$  NMR spectrum of the product mixture revealed a broad resonance at  $\delta$  -11.6, thus providing a correlation between the solid-state structure and the solution observations [11].

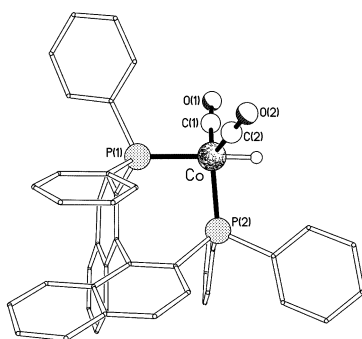
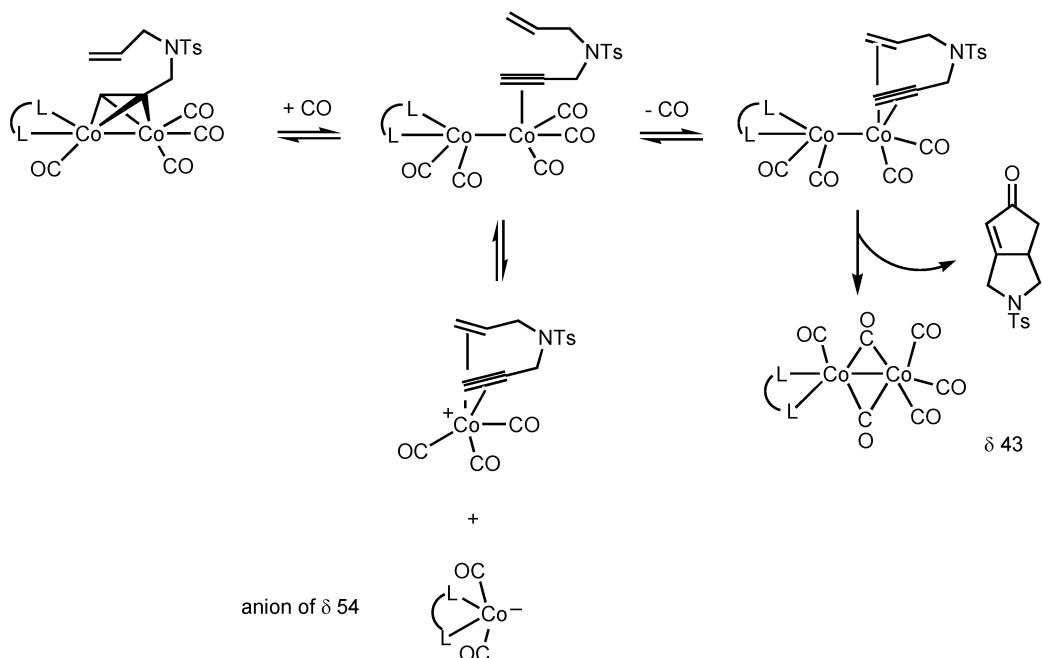


Fig. 1

One explanation for the formation of the resonances at  $\delta$  43 and 54 is depicted in Scheme 14. After carbon monoxide-induced dissociation of the alkyne, binding of the alkene may either rupture the cobalt–cobalt bond [a process which has precedent [12] in phosphine additions to  $\text{Co}_2(\text{CO})_8$ ] to give a hitherto unobserved enyne cation and the anion of the hydride depicted in Fig. 1 ( $\delta$  54), or if carbon monoxide dissociation occurs first, binding of the alkene proceeds via the PKR pathway to generate cyclopentenone product and precatalyst ( $\delta$  43).



Scheme 14

Finally, in order to relate the observations described above to catalytic PKR conditions, a series of constant-temperature NMR experiments were performed using substoichiometric amounts of octacarbonyldicobalt(0) and binap (25–50 mol %) with the standard PKR enyne, *N*-(prop-2-enyl)-*N*-(prop-2-ynyl)-*p*-toluenesulfonamide. These revealed that the binap cobalt hydride species identified and characterized in this work is generated under substoichiometric PKR conditions [11].

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