Chapter 1

Studies on the preparation of alkyne-Co$_2$(CO)$_6$ complexes for applications in Pauson-Khand cyclopentenone synthesis
1.1 Introduction

In recent years, there has been increasing interest in the application of transition metal mediated transformations in organic synthesis. The use of transition metal reagents in organic synthesis gives the strategic advantage primarily because of unusual selectivity and reactivity realized over classical organic reaction counterparts. However, if the transition metal mediated organic reactions are to find widespread general use, it is essential that they simplify complicated problems, and of course, be experimentally convenient. The Pauson-Khand reaction is one such reaction that has been intensively studied in recent years. A brief review of the reports on this reaction will be helpful for the discussion.

The Pauson-Khand reaction, first reported in 1973,\textsuperscript{1} involves the dicobalt octacarbonyl mediated cocyclization of alkynes with alkenes and carbon monoxide to synthesize cyclopentenone derivatives (eq 1). Excellent reviews by Pauson,\textsuperscript{2} de Meijere,\textsuperscript{3} Schore\textsuperscript{4} and more recently, by Schmalz\textsuperscript{5} have been published on this reaction.

The Pauson-Khand reaction shows high degree of both regio- and stereoselectivity.\textsuperscript{6} The mechanism of this reaction has not been established fully (Scheme 1).\textsuperscript{2-4} Generally, it is assumed that the reaction proceeds through the insertion
of alkene to one of the cobalt atoms via a dissociative mechanism involving the initial loss of CO. Subsequent insertion of the complexed face of the alkene π-bond into one of the formal cobalt-carbon bonds of the alkyne complex occurs, followed by the addition of the CO to the coordinatively unsaturated cobalt atom. The metallocycle thus formed leads to standard sequence of steps migratory insertion of a cobalt bound CO, addition of another CO molecule and finally reductive elimination of the cobalt carbonyl moiety to give the cyclopentenone derivative (Scheme 1).

Scheme 1
In recent years, considerable efforts were made by several groups to optimize the reaction conditions using various additives as promoters. First such modification has been made by Smit and Caple et al.\textsuperscript{7} These authors reported that the use of adsorbents such as SiO$_2$, Al$_2$O$_3$ and MgO.SiO$_2$ facilitates the reaction (Scheme 2).

Scheme 2

Later, Pauson et al.\textsuperscript{8} studied the effect of ultrasound, phosphine and phosphine-oxides. Whereas the ultrasonic irradiation of the reaction mixture allows the reactions to proceed considerably faster at lower temperatures, it has little effect on the yields. Addition of phosphine oxides leads to significant yield enhancement in intramolecular Pauson-Khand reaction.

First significant modification has been reported by Shambayati\textsuperscript{9} and Joeng\textsuperscript{10} using N-oxides as promoter in both intra and inter molecular versions of the Pauson-Khand reaction at room temperature (eq 2).
Kraft et al. observed that the presence of ligands such as sulfur, nitrogen in side chain lead to increase in both the reaction rates and yields (eq 3).

It has been also reported that the dimethylsulphoxide (DMSO) promotes the Pauson-Khand reaction (Scheme 3).

Scheme 3

Kraft et al. observed that the presence of ligands such as sulfur, nitrogen in side chain lead to increase in both the reaction rates and yields (eq 3).

Also, these authors observed that the use of oxygenated atmosphere causes a change in the normal Pauson-Khand reaction pathway leading to monocyclic enones 6 instead of the anticipated bicyclic enones (eq 4).
More recently, Kerr et al\textsuperscript{14} developed a novel method in which vinyl esters are utilized as non-gaseous ethylene equivalents in Pauson-Khand annulation using NMO as a promoter at room temperature (eq 5).

Also, it was observed that the polymer supported N-oxide \textsuperscript{15a} is useful as a promoter under mild conditions, affording good to excellent yields of cyclopentenones (eq 6). The advantage in this method is that the amine oxide supported on solid phase is found to be highly efficient and reusable, affording cyclopentenones in high purity without the need for purification by chromatography.
Further, it has been reported that the cobalt carbonyl complexes immobilised onto a polymer bound triphenylphosphine solid support are effective, practical catalysts for Pauson-Khand reaction (eq 7).\textsuperscript{15b}

\begin{center}
\begin{equation}
\text{TsN} \begin{array}{c}
\text{Cat (5 mol\%)} \\
70 ^\circ C
\end{array} \rightarrow \text{TsN} \begin{array}{c}
\text{Cat} = \begin{array}{c}
\Phi \\
\Phi
\end{array} \\
\begin{array}{c}
\Phi \\
\Phi \\
\Phi \\
\Phi
\end{array}
\end{array} \begin{array}{c}
\begin{array}{c}
\text{C} \\
\text{O}
\end{array} \\
\begin{array}{c}
\text{C} \\
\text{O}
\end{array}
\end{array} \begin{array}{c}
\text{10} \\
(66\%)
\end{array}
\end{equation}
\end{center}

Also, it was observed that the NMO promotes the Pauson-Khand reaction of alkynes with electron deficient olefins at 0-20 °C (eq 8).\textsuperscript{16}

\begin{center}
\begin{equation}
\begin{array}{c}
\text{R} \\
\text{Co} \begin{array}{c}
\text{C} \\
\text{O}
\end{array} \begin{array}{c}
\text{C} \\
\text{O}
\end{array} \begin{array}{c}
\text{C} \\
\text{O}
\end{array} \begin{array}{c}
\text{C} \\
\text{O}
\end{array} \begin{array}{c}
\text{C} \\
\text{O}
\end{array} \begin{array}{c}
\text{C} \\
\text{O}
\end{array}
\end{array}
\end{array} + \begin{array}{c}
\text{EWG}
\end{array} \begin{array}{c}
\text{NMO}
\end{array} \begin{array}{c}
\text{CH}_2\text{Cl}_2 - \text{THF}
\end{array} \begin{array}{c}
\text{0-20 } ^\circ C
\end{array} \rightarrow \text{R} \begin{array}{c}
\text{11}
\end{array} \begin{array}{c}
\text{EWG}
\end{array}
\end{equation}
\end{center}

The methylenecyclopropenes can function as a simple olefin component in the intra molecular Pauson-Khand reaction to give the product 12 or it can give rearranged hydroindenones 13 in which neither of the two carbon atoms of the alkyne component form part of the cyclopentenone moiety in the product (Scheme 4).\textsuperscript{17}
The use of stoichiometric amounts of the transition metals is not acceptable commercially. Therefore, several groups focussed research efforts on the development of catalytic variants of the Pauson-Khand reaction.

Pauson and Khand \textsuperscript{1c} reported the catalytic version but the first success was achieved by Rautenstrauch\textsuperscript{10} using 0.22 mol\% of Co$_2$(CO)$_8$ (Scheme 5).

Later, Joeng \textit{et al.}\textsuperscript{19} observed the catalytic version of Pauson-Khand reaction using the phosphites as co-ligands (eq 9).
Further, not only $\text{Co}_2(\text{CO})_8$ but also other cobalt complexes were employed successfully for the catalytic Pauson-Khand reaction (eq 10).\(^{20}\)

Livinghouse\(^{21}\) reported the photochemical method of promotion of the catalytic intramolecular Pauson-Khand reaction (eq 11).

Supercritical $\text{CO}_2$ has been used for catalytic Pauson-Khand reaction (eq 12).\(^{22}\)

Sugihara and Yamaguchi\(^{23}\) observed that the Pauson-Khand reaction could be catalyzed using catalytic amounts of alkylidynetricobalt nonacarbonyls (eq 13).
Also, it was observed that the catalytic Pauson-Khand reaction could be employed for the synthesis of cis-fused decalins (eq 14).\textsuperscript{24}

More recently, phosphane sulfide catalyzed Pauson-Khand reaction was observed under atmospheric pressure of CO.\textsuperscript{25} In this way, both intra- and intermolecular catalytic versions of Pauson-Khand reaction take place (eq 15).

Considerable efforts have been made to develop asymmetric variants of the classical Pauson-Khand reaction. Initially, it was observed that the chiral phosphane (glyphos) ligands give high enantioselectivity (eq 16).\textsuperscript{26}
Kerr et al.\textsuperscript{27} achieved significant enantioselectivities by employing the chiral amine-oxides as promoters (eq 17).

Pericas et al.\textsuperscript{28} used chirally modified substrates to obtain asymmetric induction in Pauson-Khand reaction. The potential of this method was demonstrated in total syntheses of natural products.\textsuperscript{29}

Also, the use of t-butylsulfinyl group as a highly efficient chiral auxiliary in asymmetric Pauson-Khand reaction has been reported (eq 18).\textsuperscript{30}
Buchwald developed the first catalytic asymmetric Pauson-Khand type cyclization of enynes using a titanocene catalyst. A variety of 1,6-enynes were converted to corresponding cyclopentenones in high yield (70-94%) with excellent ees (87-96%) (eq 19).

These authors also devised an outstanding procedure for the direct, titanocene catalyzed cyclocarbonylation of enynes. This catalytic method has a number of advantages, it occurs at low CO pressure, tolerates a variety of functional groups including disubstituted alkenes and gives the cyclopentenones in high yields (>85%) (eq 20).
Apart from cobalt and titanium complexes, several other transition metals such as ruthenium, rhodium, were employed in catalytic Pauson-Khand reaction. Also, carbonyls such as Fe(CO)$_5$, W(CO)$_6$, Cp$_2$Mo$_2$(CO)$_4$, Mo(CO)$_6$, are useful as catalysts in Pauson-Khand reaction. In addition, reagent systems such as Cp$_2$TiCl$_2$/CO, Cp$_2$ZrCl$_2$/CO, Cp$_2$TiCl$_2$-Mg-BTC, Cp$_2$Ti(PMe$_3$)/R$_3$SiCN, Ni(COD)$_2$ and Ni(CO)$_4$ have been shown to be effective for the conversion of enynes to bicyclic octenone derivatives.

In recent years, several new convenient procedures have been developed in this laboratory for the preparation of cobalt carbonyls in situ through reduction of CoCl$_2$ or CoBr$_2$ using various reducing agents. For example, it was found that the reduction of CoCl$_2$ with MgH$_2$ at 0 °C under CO atmosphere gives Co$_2$(CO)$_8$. Reaction of an alkyne and norbornylene with the reagent prepared in this way gives the corresponding cyclopentenone at 70 °C (Scheme 6).

Scheme 6

It was also observed that the reduction of anhydrous CoBr$_2$ with Zn under CO atmosphere in THF at room temperature followed by reaction with alkynes, gives the corresponding (alkyne)Co$_2$(CO)$_6$ complexes. These complexes on reaction with olefins give the corresponding cyclopentenones in moderate to good yields (eq 21).
It was observed that the \((\text{alkyne})\text{Co}_2(\text{CO})_6\) complexes prepared in situ using 
\(\text{CoBr}_2, \text{Zn}\) under CO atmosphere in THF, on reaction with norbornylene in presence of 
\(\text{CF}_3\text{COOH} (\text{TFA})\) gives the reduced Pauson-Khand cyclopentanones (Scheme 8).^{45d}
In continuation of these studies, we have undertaken further investigations on the preparation of these complexes \textit{in situ} in solvents like CH$_2$Cl$_2$ and toluene. We have also examined the applications of the complexes prepared in this way in Pauson-Khand reaction. The results are described in this chapter.
1.2 Results and Discussion

1.2.1 Studies on the preparation and utilization of (alkyne)Co$_2$(CO)$_6$ complexes

As outlined in the introductory section, methods have been developed in this laboratory for the preparation of (alkyne)Co$_2$(CO)$_6$ complexes *in situ* in THF through the reaction of CoCl$_2$ or CoBr$_2$ with different reducing agents under CO atmosphere. Since THF promotes the disproportionation of Co$_2$(CO)$_8$,\textsuperscript{46} we have been looking for an alternative solvent system for the preparation of such complexes.

It has been reported that the reduction of CoI$_2$ in toluene/t-BuOH solvent mixture by Zn metal in presence of CO at atmospheric pressure, gives Co$_2$(CO)$_8$ in 38% yield after 24h (eq 22).\textsuperscript{47}

\[
\text{CoI}_2 + \text{Zn} \xrightarrow{\text{t-BuOH, toluene}} \text{CO, r.t., 24 h} \rightarrow \text{Co}_2(\text{CO})_8
\]

[22]

We have observed that the (alkyne)Co$_2$(CO)$_6$ complexes can be prepared *in situ* by the reduction of CoBr$_2$ by Zn dust in the CH$_2$Cl$_2$ and t-BuOH solvent mixture while bubbling CO at 25 °C for 6-8h. Since solubility of CoBr$_2$ in CH$_2$Cl$_2$ is less, to enhance the solubility 1-2 mL of t-BuOH was added. The formation of (alkyne)-Co$_2$(CO)$_6$ complex was confirmed by carrying out the reaction of diphenylacetylene with CoBr$_2$ and Zn in CH$_2$Cl$_2$/t-BuOH while bubbling CO for 8h at 25 °C. After workup, (PhC≡CPh)Co$_2$(CO)$_6$\textsuperscript{28} was isolated (eq 23).
The IR spectra of the isolated complex 28 showed the absorptions at 2000, 2050, 2100 cm\(^{-1}\) (terminal CO), and the absence of absorption at 1910 cm\(^{-1}\) (bridging carbonyl).\(^{48}\)

The (alkyne)Co\(_2\)(CO)\(_6\) complexes prepared in this way, undergo Pauson-Khand reaction with norbornylene, upon heating to give the corresponding cyclopentenones in 75-80% yield in toluene/t-BuOH solvent system (Scheme 10).

**Scheme 10**

1.2.2 Reactions of (alkyne)Co\(_2\)(CO)\(_6\) complexes with olefins in presence of amine/amide in CH\(_2\)Cl\(_2\)/t-BuOH solvent system

As discussed earlier, in the presence of additives such as amine oxides and DMSO, the Pauson-Khand reaction can be carried out under ambient conditions.\(^{9-11}\)
For example, amine oxides react with \((\text{alkyne})\text{Co}_2(\text{CO})_6\) complex to create a vacant coordination site in the \((\text{alkyne})\text{Co}_2(\text{CO})_6\) complex through the oxidation of CO to \(\text{CO}_2\) (Scheme 11).\(^6\) Hence, reactions that require initial dissociation of CO are facilitated in this way.

Scheme 11

Similar reaction of amine oxides with \(\text{Fe}(\text{CO})_5\) gives coordinatively unsaturated iron carbonyl species.\(^{49}\)

The metal carbonyl complexes also react with amines to give carbomyl complexes (eq 24).\(^{50}\) The reactions are rapid and essentially quantitative at room temperature. This reaction was observed with many transition metal carbonyls.
It was also observed that the Lewis bases disproportionate \( \text{Co}_2(\text{CO})_8 \) (eq 25).\(^{51}\)

\[
3 \text{Co}_2(\text{CO})_6 + 2n \text{B} \longrightarrow 2 [\text{Co(B)}_3][\text{Co(CO)}_4]_2 + 8 \text{CO}
\]

\( \text{B} = \text{Lewis base} \)  \(\ldots \ldots \) [25]

Reaction of aliphatic and alicyclic primary and secondary amines with \( \text{Co}_2(\text{CO})_8 \) bring about carbonylation of the amine to the corresponding formamide (eq 26).\(^{52}\)

\[
3[\text{Co(CO)}_4] + 20(\text{CH}_2)_2\text{NH} \longrightarrow 2[\text{Co(NH(CHA)}_2]_2[\text{Co(CO)}_4]_2 + 8\text{HCON(CHA)}_2
\]

As outlined in Scheme 11, the elimination of CO from (alkyne)\( \text{Co}_2(\text{CO})_6 \) complex is the key step in the Pauson-Khand reaction. Hence, we have examined the effect of amines on the reaction of (alkyne)\( \text{Co}_2(\text{CO})_6 \) complexes with olefins. We have carried out the reaction of (C\(_5\)H\(_{11}\)C=CH)\( \text{Co}_2(\text{CO})_6 \) complex generated \( \text{in situ} \) using 1-heptyne, \( \text{CoBr}_2 \), Zn and CO in \( \text{CH}_2\text{Cl}_2/t\text{-BuOH} \) solvent system with norbornylene and TMEDA at 25°C (Scheme 12). It has been observed that the corresponding cyclopentenone 29 is obtained in 53% yield besides some unreacted cobalt carbonyl complexes under these conditions.

This observation prompted us to further investigate the effect of different amines in the presence of olefins. The experiments were carried out using (alkyne)\( \text{Co}_2(\text{CO})_6 \) complexes and norbornylene and cyclopentene employing amines and amides such as TMEDA, \( \alpha\)-methylbenzylamine and DMF. The results are summarized in Table 1.\(^{53}\) The cyclopentenones were obtained in somewhat lower yields than that obtained under refluxing conditions in THF or toluene (Scheme 10).
It is evident from the Table 1, the yields of the cyclopentenones obtained are similar with different promoters. As expected, the yields are better with norbornylene and lower yields were realized in the case of the less reactive cylopentene. Also, a slight increase in yield of the cyclopentenones was observed when the reaction was carried out in open air after the complex formation (entries 3 and 7, Table 1).
Table 1: Reactions of (alkyne)Co₂(CO)₈ Complexes with olefin in presence of amine/amide in CH₂Cl₂/t-BuOH

<table>
<thead>
<tr>
<th>No.</th>
<th>alkyne</th>
<th>alkene</th>
<th>amine/amide</th>
<th>Product</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C₅H₁₁C≡CCH</td>
<td></td>
<td>TMEDA</td>
<td><img src="image1" alt="Image" /></td>
<td>53%</td>
</tr>
<tr>
<td>2</td>
<td>PhC≡CCH</td>
<td></td>
<td>C₆H₅CH(CH₃)NH₂</td>
<td><img src="image2" alt="Image" /></td>
<td>55%</td>
</tr>
<tr>
<td>3</td>
<td>PhC≡CCH</td>
<td></td>
<td>C₆H₅CH(CH₃)NH₂</td>
<td><img src="image3" alt="Image" /></td>
<td>58%</td>
</tr>
<tr>
<td>4</td>
<td>C₅H₁₁C≡CCH</td>
<td></td>
<td>DMF</td>
<td><img src="image4" alt="Image" /></td>
<td>52%</td>
</tr>
<tr>
<td>5</td>
<td>C₅H₁₁C≡CCH</td>
<td></td>
<td>TMEDA</td>
<td><img src="image5" alt="Image" /></td>
<td>30%</td>
</tr>
<tr>
<td>6</td>
<td>PhC≡CCH</td>
<td></td>
<td>C₆H₅CH(CH₃)NH₂</td>
<td><img src="image6" alt="Image" /></td>
<td>32%</td>
</tr>
<tr>
<td>7</td>
<td>PhC≡CCH</td>
<td></td>
<td>C₆H₅CH(CH₃)NH₂</td>
<td><img src="image7" alt="Image" /></td>
<td>35%</td>
</tr>
<tr>
<td>8</td>
<td>C₅H₁₁C≡CCH</td>
<td></td>
<td>DMF</td>
<td><img src="image8" alt="Image" /></td>
<td>32%</td>
</tr>
</tbody>
</table>
Foot notes to Table 1

a) All reactions were carried out using CoBr$_2$ (20 mmol), Zn (20 mmol), alkyne (10 mmol) in CH$_2$Cl$_2$ (50 mL)/t-BuOH (1.5 mL), olefin (15 mmol), amine (30 mmol) at 25 °C for 3h.

b) Products were identified by analysis of spectral data (IR, $^1$H, $^{13}$C NMR) and in comparison with the data available in the literature.

c) Yields reported are for products separated by column chromatography on silica gel using ethyl acetate in hexane as eluent and calculated on the basis of amount of alkyne used.

d) Reaction was carried out in open air atmosphere.

The mechanism of this transformation is not clear. Presumably, the amine may form weak complex with cobalt by eliminating CO, which could facilitate the Pauson-Khand reaction (Scheme 13). If this is so, the use of chiral amine is expected to induce asymmetric induction to some extent if it is present in the transition state of the reaction. To examine this, we have briefly investigated the reaction of (PhC=CH)Co$_2$(CO)$_6$ with norbornylene in the presence of the chiral a-methylbenzylamine at room temperature and 0 °C.

Scheme 13
We have not observed any asymmetric induction in the cyclopentenone formed. Presumably, the amine moiety is not present in the transition state after elimination of CO from (alkyne)Co₂(CO)₆ complex (Scheme 13).

It may be of interest to note here that when these studies on the effect of amines on Pauson-Khand reaction were in progress in this laboratory, a report appeared describing the role of primary amines on the rate enhancement of Pauson-Khand reaction at 83 °C (eq 27)⁵⁴

These authors observed that the cyclopentenone is obtained in only 46% yield at 25 °C after 25 days, besides unidentified polar by-products. At 83 °C, the conversion is complete within 5 minutes. The desired cyclopentenone was obtained in 99% yield.

### 1.2.3 Reactions of (alkyne)Co₂(CO)₆ complexes with olefins in CH₂Cl₂/amine solvent system

We have observed that the (alkyne)Co₂(CO)₆ complexes can be also prepared using amines in CH₂Cl₂ without using t-BuOH. The Pauson-Khand reaction of the complex prepared in this way using 1-heptyne, CoBr₂, Zn and CO in CH₂Cl₂/TMEDA
Table 2 Reactions of (alkyne)Co$_2$(CO)$_6$ complexes with olefin in CH$_2$Cl$_2$/amine

<table>
<thead>
<tr>
<th>No.</th>
<th>alkyne</th>
<th>alkene</th>
<th>amine</th>
<th>Product</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C$<em>5$H$</em>{11}$C≡CH</td>
<td>PhC($CH_2$)NH$_2$</td>
<td>TMEDA</td>
<td><img src="29" alt="Image" /></td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>C$<em>6$H$</em>{17}$C≡CH</td>
<td>PhC($CH_2$)NH$_2$</td>
<td></td>
<td><img src="31" alt="Image" /></td>
<td>52%</td>
</tr>
<tr>
<td>3</td>
<td>PhC≡CH</td>
<td>PhC($CH_2$)NH$_2$</td>
<td></td>
<td><img src="33" alt="Image" /></td>
<td>32%</td>
</tr>
</tbody>
</table>

a) All reactions were carried out using CoBr$_2$ (20 mmol), Zn (20 mmol), alkyne (10 mmol) in CH$_2$Cl$_2$ (50 mL)/amine (1.5 mL), olefin (15 mmol), amine (30 mmol) at 25 °C for 3h.
b) Products were identified by analysis of spectral data (IR, $^1$H, $^{13}$C NMR) and comparison with the data available in the literature.
c) Yields reported are for products separated by column chromatography on silica gel using ethyl acetate in hexane as eluent and calculated on the basis of amount of alkyne used.

with norbornylene as an olefin was then carried out. The corresponding cyclopentenone 29 is obtained in 50% yield (Scheme 14). The yield of cyclopentenone is similar to that obtained in the reaction carried out using of t-BuOH. The results are summarized in Table 2.

Scheme 14
1.2.4 Reactions of (alkyne)Co$_2$(CO)$_6$ complexes prepared *in situ* using sub-stoichiometric amounts of CoBr$_2$, Zn and CO with olefins in toluene/t-BuOH solvent system

We then turned our attention towards the catalytic version of the Pauson-Khand reaction. A catalytic Pauson-Khand reaction that would allow the use of free alkyne and CO would be of great interest, especially for large scale synthetic operations. As discussed in the introductory section, there are several methods reported for the catalytic version of the Pauson-Khand reaction. However, several of these reactions were carried out under high pressure of CO. We were interested in developing a simple method that can be carried out at atmospheric pressure of CO.

We have attempted the reaction of (C$_5$H$_{11}$C=CH)Co$_2$(CO)$_6$ complex prepared *in situ* using sub-stoichiometric amounts of CoBr$_2$ and Zn under CO atmosphere with norbornylene in the presence of TMEDA in CH$_2$Cl$_2$/t-BuOH solvent system (Scheme 15). The desired cyclopentenone (29) was obtained in somewhat lower yield (30%).

Scheme 15
Since catalytic reactions are generally carried out at higher temperatures, we have examined the reaction under refluxing conditions in toluene. The \((\text{C}_5\text{H}_5\text{C}≡\text{CH})-\text{Co}_2(\text{CO})_6\) complex was prepared in situ using 0.4 equivalents each of \(\text{CoBr}_2\) and \(\text{Zn}\) under CO atmosphere in toluene/t-BuOH solvent system. After the complex formation, the norbornylene was added and the contents were stirred at 110 °C while bubbling CO for 24h. After the workup, the cyclopentenone 29 was obtained in 88% yield (Scheme 16). Since the desired product is obtained in good yield at atmospheric pressure of CO, the reaction was carried out using different alkynes. The results are summarized in Table 3.\(^{55}\)

Scheme 16

We have carried out experiments under different conditions so as to optimize the reaction conditions. For example, in a run using 0.2 equivalents each of \(\text{CoBr}_2\) and \(\text{Zn}\) with phenylacetylene (1 equiv) and norbornylene (1.5 equiv), after refluxing the contents for 24h, the desired cyclopentenone 30 was obtained in 40% yield.
Table 3 Sub-Stoichiometric reactions of (alkyne)Co$_2$(CO)$_6$ complexes with olefins

<table>
<thead>
<tr>
<th>No.</th>
<th>alkyne</th>
<th>alkene</th>
<th>time</th>
<th>Product $^a$</th>
<th>Yield $^{b,c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C$<em>5$H$</em>{11}$C≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 29" /></td>
<td>88%</td>
</tr>
<tr>
<td>2</td>
<td>PhC≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 30" /></td>
<td>83%</td>
</tr>
<tr>
<td>3</td>
<td>PhC≡CH</td>
<td></td>
<td>12h</td>
<td><img src="image" alt="Product 30" /></td>
<td>67%</td>
</tr>
<tr>
<td>4</td>
<td>C$<em>8$H$</em>{17}$C≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 31" /></td>
<td>85%</td>
</tr>
<tr>
<td>5</td>
<td>PhC≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 33" /></td>
<td>32%</td>
</tr>
<tr>
<td>6</td>
<td>C$<em>8$H$</em>{17}$C≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 34" /></td>
<td>35%</td>
</tr>
<tr>
<td>7</td>
<td>C$<em>6$H$</em>{13}$C≡CH</td>
<td></td>
<td>24h</td>
<td><img src="image" alt="Product 35" /></td>
<td>30%</td>
</tr>
</tbody>
</table>

a) All reactions were carried out using CoBr$_2$ (4 mmol), Zn (4.3 mmol), alkyne (10 mmol), olefin (15-20 mmol), in toluene (50 mL)t-BuOH (1.5 mL) at 110 °C.

b) Products were identified by analysis of spectral data (IR, $^1$H, $^{13}$C NMR) and in comparison with the data available in the literature.

c) Yields reported are for products separated by column chromatography on silica gel using ethyl acetate in hexane as eluent and calculated on the basis of amount of alkyne used.
In a run, using 0.4 equivalents each of CoBr₂ and Zn with phenylacetylene (1 equiv) and norbornylene (1.5 equiv), under the above conditions for 12h, the cyclopentenone 30 was obtained in 67% yield. We have also carried out the reaction by replacing TMEDA in place of t-BuOH. In this case also, the cyclopentenone 30 was obtained in 67% yield.

Further, when the reaction of (PhC=CH)Co₂(CO)₆ complex, prepared using sub-stoichiometric amounts of CoBr₂ and Zn, was performed with norbornylene in CH₂Cl₂/t-BuOH solvent system at 45 °C under atmospheric pressure of CO for 24h, the cyclopentenone 30 was obtained in lower in yields (48%) compared to that obtained at 110 °C in toluene (entry 2 in Table 3). This indicates that the catalytic Pauson-Khand reaction requires higher temperature to recycle the catalyst.

We have also carried out an intramolecular version of Pauson-Khand reaction using sub-stoichiometric amounts of CoBr₂ and Zn at atmospheric pressure of CO. Unfortunately, the corresponding cyclopentenone was not formed even after heating the contents at 110 °C for 24h (Scheme 17).

Scheme 17
It appears that it is important to have a reactive olefin moiety for the Pauson-Khand reaction under the present conditions.
1.2.5 Conclusions

A simple and convenient method of preparation of \((\text{alkyne})\text{Co}_2(\text{CO})_6\) complexes has been developed through the reduction of \(\text{CoBr}_2\) in \(\text{CH}_2\text{Cl}_2\) and toluene with \(\text{Zn}\) and \(\text{CO}\) in the presence of alkynes. The complexes prepared in this way undergo Pauson-Khand reaction in the presence of amines and amides at room temperature in \(\text{CH}_2\text{Cl}_2\) to give the corresponding cyclopentenones in moderate to good yields. The Pauson-Khand reaction of \((\text{alkyne})\text{Co}_2(\text{CO})_6\) complexes was also carried out using sub stoichiometric amounts of \(\text{CCBr}_2\) and \(\text{Zn}\) at atmospheric pressure of \(\text{CO}\) with olefins. Again, the corresponding cyclopentenones were obtained in moderate to good yields under these conditions.
1.3 Experimental Section

1.3.1 General Information

Melting points reported in this thesis are uncorrected and were determined using a Buchi-510 capillary point apparatus. Infrared spectra were recorded on Perkin-Elmer IR spectrometer Model JASCO FT 5300 with polystyrene as reference. \( ^1\text{H} \) (200 MHz) and \( ^{13}\text{C} \) NMR (50 MHz) spectra were taken in CDCl3 unless otherwise stated and TMS as reference (\( \delta = 0 \, \text{ppm} \)). The \( ^{13}\text{C} \) chemical shifts are reported in ppm on the \( \delta \) scale relative to CDCl3 (77.0 ppm) and coupling constants are reported in hertz. Elemental analyses were performed on a Perkin-Elmer elemental analyzer model-240 C. Column chromatography was carried out using Acme's silica gel (100-200 mesh).

All glassware were predried at 140 °C in hot air oven for 4h, assembled in hot and cooled under a stream of dry nitrogen. Unless otherwise mentioned, all the operations and transformations of reagents were carried out using standard syringe, septum technique recommended for handling air sensitive organometallic compounds. In all experiments, a round bottom flask of appropriate size with a side arm, a side septum, a magnetic stirring bar, a condenser and a connecting tube attached to a mercury bubbler were used. The outlet of the mercury bubbler was connected to a long tube to the atmosphere. All dry solvents and reagents (liquids) used were distilled from appropriate drying agents just before use. Toluene was distilled over bezophenone/sodium. CH\(_2\)Cl\(_2\) was washed successively with H\(_2\)SO\(_4\) and water then distilled over CaH\(_2\). As a routine practice, all organic extracts were
concentrated on Buchi-EL-rotary evaporator. All yields reported are isolated yields of material judged homogenous by TLC, IR and NMR spectroscopy. The phenyl-acetylene, 1-decyne and 1-octyne were prepared following the reported procedures. The 1-heptyne was supplied by Fluka, Switzerland. Norbornylene and cyclopentene used were supplied by Aldrich CoBr$_2$ was prepared from cobalt carbonate using 48% HBr solution. The CoBr$_2$.H$_2$O was dehydrated initially on hot plate for 2h and then in hot air oven at 150 °C for 5-6h. It was further dried at 150 °C for 4h under vacumm and kept in a desiccator under nitrogen. Zinc dust was supplied by Ranbaxy, India. Activated Zn dust was prepared by treating the commercial Zn dust with 1% H$_2$SO$_4$, then washing with water, acetone and dried at 150°C for 4h under vacuum. Carbon monoxide was generated by slow addition of formic acid (98%) to concentrated H$_2$SO$_4$ (96%) at 80-90 °C using an apparatus recommended for utilization in the carbonylation of organoboranes. It was predried by passing through anhydrous KOH pellets before bubbling into reaction mixture.

1.3.2 Reaction of (C$_5$H$_{11}$C=CH)Co$_2$(CO)$_6$ complex with Norbornylene in toluene/t-BuOH solvent system.

The (C$_5$H$_{11}$C=CH)Co$_2$(CO)$_6$ complex was prepared by reducing CoBr$_2$ (2.36 g, 20 mmol) with Zn (1.35 g, 20 mmol) and C$_5$H$_{11}$C=CH (1.3 mL, 10 mmol) in toluene (50 mL)/ t-BuOH(1.5 mL) while bubbling CO at 25°C for 8h. The CO atmosphere was replaced by dry static nitrogen. The norbornylene (1.4 g, 15 mmol) was added. The contents were stirred at 110 °C for 8h and brought to room temperature. The reaction mixture was successively washed with water and brine solution. The organic layer was extracted with ether (2x25 mL) and dried over anhydrous MgSO$_4$ and concentrated.
The crude product was subjected to column chromatography on a silica gel using hexane/ethyl acetate as eluent. The cyclopentenone 29 (80%, 1.74g) was isolated and identified by IR, $^1$H and $^{13}$C NMR spectral data. The spectral data obtained for product 29 are summarized below.

Yield 80% (1.74 g)

IR (neat) 2957, 2872, 1699, 1456, 1186, 1053 cm$^{-1}$

$^1$H NMR 8 ppm 0.9 (t, 2.8 Hz, 3H), 1.1-1.7 (m, 14H), 2.1 (m, 2H), 2.3(bs, 1H), 2.5 (bs, 1H), 7.1(bs, 1H) (Spectrum number 1)

$^{13}$C NMR 8 ppm 13.9, 22.3, 24.6, 27.5.8, 28.4, 29.0, 30.9, 31.5, 38.0, 38.9, 48.1, 53.8, 149.5 (quaternary), 158.4, 210.9 (CO) (Spectrum number 2)

The spectral data are in 1:1 correspondence with the data reported in the literature.$^{45}$

The above procedure was followed for the reaction of (PhC≡CH)Co$_2$(CO)$_6$ with norbornylene.
Yield 78% (1.74 g)

**M.P.** 92-94 °C (Lit. m.p. 93-95 °C)

IR(KBr) 3025, 3040, 3025, 2950, 1695, 1610, 1600, 765, 700 cm⁻¹

¹H NMR δ ppm 0.9-1.1 (m, 2H), 1.1-1.8 (m, 4H), 2.3 -2.5 (m, 3H), 2.6 (m, 1H), 7.2-7.8 (m, 6H)

¹³C NMR δ ppm 28.4, 29.1, 31.2, 38.3, 39.4, 47.7, 54.9, 127.1, 128.4, 131.6, 146.1 (quaternary), 160.3, 209.1(CO)

The spectral data show 1:1 correspondence with the data previously reported from this laboratory.

1.3.3. **Reaction of (C₅H₅C≡CH)Co₂(CO)₆ complex with Norbornylene in presence of TMEDA in CH₂Cl₂/t-BuOH : A representative procedure**

The (C₅H₅C≡CH)Co₂(CO)₆ complex was prepared by reducing CoBr₂ (2.36 g 20 mmol) with Zn (1.35 g, 20 mmol) and C₅H₅C≡CH (1.3 mL, 10 mmol) in CH₂Cl₂ (50 mL)/t-BuOH (1.5 mL) while bubbling CO at 25 °C for 8h. The CO atmosphere was replaced by dry static nitrogen. The norbornylene (1.4 g, 15 mmol), TMEDA (4.5 mL, 30 mmol) were added. The contents were stirred at 25 °C for 3h. The mixture was
successively washed with dil. HCl, water and brine solution. The organic layer was extracted with CH$_2$Cl$_2$ and dried over anhydrous MgSO$_4$ and concentrated. The crude product was subjected to column chromatography on silica gel using hexane/ethyl acetate as eluent. The cyclopentenone 29 (53%, 1.15 g) was isolated and identified by IR, $^1$H, $^{13}$C NMR spectral data.

Yield 53% (1.15 g)

The spectral data were identical to the data of 29 obtained in the previous experiment.

The above procedure was followed for other (alkyne)Co$_2$(CO)$_6$ complexes with different olefins in the presence of different amines/amides. The results are summarized in Table 1.

Yield 55% (1.23 g)

The spectral data were identical to the data of 30 obtained in the previous experiment.
Yield 52\% (1.35 g)

**IR (neat)\)** 2950, 1705, 1630, 1440, 1040 cm$^{-1}$

$^1$**H NMR\)** 6 ppm 0.8 (t, 2.5 Hz, 3H), 1.0-1.6 (m, 20H), 2.1 (m, 2H), 2.3 (bs, 1H), 2.5 (bs, 1H), 7.0 (bs, 1H)

$^{13}$**C NMR\)** 8 ppm 13.6, 22.2, 24.3, 27.4, 28.0, 28.6, 28.8, 30.5, 31.4, 37.7, 38.5, 47.7, 53.4, 149.4 (quaternary), 158.1, 210.3 (CO)

The spectral data show 1:1 correspondence with the data previously reported from this laboratory.$^{45}$

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Yield 30\% (0.57 g)

**IR (neat)\)** 2929, 2862, 1701, 1631 1458, 1259 cm$^{-1}$

$^1$**H NMR\)** 8 ppm 0.8 (t, 3 Hz, 3H), 1.0-2.0 (m, 14 H), 2.0-2.7 (m, 1H), 3.2 (bs, 1H), 7.1 (bs, 1H)
**$^{13}$C NMR**

6 ppm 13.8, 22.4, 23.3, 24.5, 27.6, 28.8, 30.0, 31.4, 43.7, 49.9, 146.6 (quaternary), 159.9, 212.4 (CO)

The spectral data show 1:1 correspondence with the data previously reported from this laboratory.  

Yield 32% (0.63 g)

M. P 40-42 °C (Lit. 6 m.p. 40-44 °C)

IR(KBr) 690, 755, 1290, 1600, 1620, 1695, 2950, 3025, 3040 cm$^{-1}$

**^1H NMR** 5 ppm 1.1-2.0, (m, 6H), 2.9-3.4 (m, 2H), 7.2-7.8 (m, 6H)

**$^{13}$C NMR** 6 ppm 23.3, 29.4, 30.2, 42.2, 50.9, 126.9, 127.7, 128.1, 129.6, 143.2 (quaternary), 161.8, 210.7 (CO)

The spectral data show 1:1 correspondence with the data previously reported from this laboratory.  

Yield 32% (0.74 g)

IR (neat) 1040, 1260, 1630, 1705, 2950 cm$^{-1}$
$^1$H NMR  
8 ppm 0.6-0.9 (t, 3 Hz, 3H), 0.9-2.1 (m, 20H), 2.5-2.8 (m, 1H), 3.2 (bs, 1H), 7.0 (bs, 1H)

$^{13}$C NMR  
δ ppm 13.9, 22.5, 23.4, 24.6, 27.8, 29.2, 29.6, 30.1, 31.5, 31.8, 43.8, 50.1, 147.0 (quaternary), 160.2, 212.9 (CO)

The spectral data show 1:1 correspondence with the data previously reported from this laboratory.48

1.3.4. Reaction of (C$_5$H$_{11}$C=CH)Co$_2$(CO)$_6$ complex with Norbornylene in CH$_2$Cl$_2$/TMEDA solvent system

The (C$_5$H$_{11}$C=CH)Co$_2$(CO)$_6$ complex was prepared by reducing CoBr$_2$ (2.36 g, 20 mmol) with Zn (1.35 g, 20 mmol) and C$_5$H$_{11}$C=CH (1.3 mL, 10 mmol) in CH$_2$Cl$_2$ (50 mL)/TMEDA (1.5 mL) while bubbling CO at 25°C for 8h. The CO atmosphere was replaced by dry static nitrogen. The norbornylene (1.4 g, 15 mmol), TMEDA (4.5 mL, 30 mmol) were added. The contents were stirred at 25°C for 3h. The mixture was successively washed with dil. HCl, water and brine solution. The organic layer was extracted with CH$_2$Cl$_2$ dried over anhydrous MgSO$_4$ and concentrated. The crude product was subjected to column chromatography on silica gel using hexane/ethyl acetate as eluent. The cyclopentenone 29 (50%, 1.09 g) was isolated and identified by IR, $^1$H, $^{13}$CNMR spectral data. The results are summarized in Table 2.
1.3.5. Sub-stoichiometric reaction of (PhC=CH)Co$_2$(CO)$_6$ complex with Norbornylene: A representative procedure

The (PhC=CH)Co$_2$(CO)$_6$ complex was prepared by reducing CoBr$_2$ (0.88 g, 4 mmol) with Zn (0.28 g, 4.3 mmol) and PhC=CH (0.2 mL, 2 mmol) in toluene (50 mL)/t-BuOH (1.5 mL) while bubbling CO at 25 °C for 5h. After the complex formation, PhC=CH (0.8 mL, 8 mmol) and norbornylene (1.4 g, 15 mmol) were added. The contents were stirred at 110 °C for 24h while bubbling CO at atmospheric pressure and brought to room temperature, water (20 mL) was added and the organic layer was separated. The aqueous layer was extracted with ether (50 mL). The combined organic extract was washed successively with water (20 mL), brine solution (10 mL) and dried over anhydrous MgSO$_4$ and concentrated. The crude product was subjected to column chromatography on silica gel using hexane/ethyl acetate as eluent. The cyclopentenone 30 (83%, 1.85 g) was isolated and identified by IR, $^1$H, $^{13}$C NMR spectral data and comparison with reported data.
Yield 83% (1.85 g)

The spectral data were identical to the data of 30 obtained in the previous experiments.

The above procedure was followed for other (alkyne)Co$_2$(CO)$_6$ complexes with different olefins and the results are summarized below (also in Table 3).

Yield 88% (1.91 g)

The spectral data were identical to the data of 29 obtained in the previous experiments.
Yield 85% (2.21 g)

The spectral data were identical to the data of 31 obtained in the previous experiments.

Yield 32% (0.63 g)

The spectral data were identical to the data of 33 obtained in the previous experiments.
Yield 35% (0.81 g)

The spectral data were identical to the data of 34 obtained in the previous experiments.

Yield 30% (0.61 g)

IR(neat) 2929, 2862, 1701, 1631, 1453, 1259 cm⁻¹

¹H NMR δ ppm 0.8 (t, 2.8 Hz, 3H), 1.0-2.0 (m, 16H), 2.7 (m, 1H), 3.2 (bs, 1H), 7.1 (bs, 1H). (Spectrum number 3)
$^3$C NMR δppm 13.8, 22.3, 23.3, 24.5, 27.6, 28.8, 29.5, 30.0, 31.4, 43.7, 49.9, 146.6 (quaternary), 159.9, 212.4 (CO) (Spectrum number 4)
1.4 References


