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REVIEWS

Organic Syntheses by Means of Metal Carbonyls

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This review surveys the reactions of metal carbonyls with organic halides or organolithium compounds and some carbonylation reactions using metal carbonyls; these reactions appear to be novel and of practical synthetic importance:

1. Reactions of Organic Monohalides with Metal Carbonyls,
2. Reactions of Organomercury Compounds with Metal Carbonyls,
3. Synthesis of Ketones using Lithium Acylmetal Carbonylates,
4. Carbonylation of Olefins or Acetylenes using Metal Carbonyls,
5. Reactions of Nitrogen Compounds with Metal Carbonyls.

Es wird eine Übersicht über die Reaktionen von Metallcarbonylen mit C-Halogen-Verbindungen und Organolithium-Verbindungen gegeben; darüber hinaus werden einige Carbonylierungsreaktionen mit Metallcarbonylen besprochen. Diese noch nicht lange bekannten Reaktionen besitzen beträchtliches präparatives Interesse:

1. Reaktionen von C-Halogen-Verbindungen mit Metallcarbonylen,
2. Reaktionen von Organoquecksilber-Verbindungen mit Metallcarbonylen,
3. Synthese von Ketonen mit Lithium-acylmetallcarbonylaten,
4. Carbonylierung von Olefinen und Acetylenen mit Metallcarbonylen,
5. Reaktionen von Stickstoff-Verbindungen mit Metallcarbonylen.

During the last two decades, carbon monoxide has become one of the important starting materials for organic synthesis because of its availability and unique reactivity. A number of synthetic reactions have been reported and some of them have found technical application.

Recently, it has become apparent that unstable organometallic complexes are formed as intermediates in the reactions of carbon monoxide using metal complexes as catalysts or stoichiometric reagents and that the application of carbon monoxide in organic synthesis may be achieved effectively by using metal complexes. Carbonylation reactions using noble metal compounds have been extensively studied and many of them have been found to be useful in organic synthesis[1]. Carbonylation using various metal carbonyls has also been studied extensively and the results have been summarized in recent reviews[2,3,4].

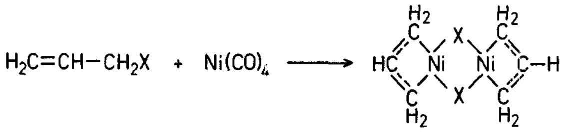
Metal carbonyls exhibit unique reactivities towards various organic reagents. This is due to their low oxidation state, easy replacibility of carbon monoxide ligands, reducibility and oxidizibility, and their good solubility in organic solvents. Thus, metal carbonyls have become very important as catalysts or stoichiometric reagents in many organic reactions.

In a previous review[4] by one of the present authors, the reactions of metal carbonyls were described. To avoid duplication, this review deals only with typical examples of organic synthesis and recent advances in this area.

1. The Reaction of Organic Monohalides with Metal Carbonyls

Monohalides tend to add oxidatively to metal carbonyls to form unstable organometallic complexes, the decomposition of which yields coupling products and/or ketones. The reactivity of monohalides towards metal carbonyls is remarkably affected by the organic halide moieties. Thus, halides which are reactive towards nickel carbonyl or iron pentacarbonyl contain unsaturated bonds (e.g. $>C=C<$, $>C=O$, $-C\equiv N$) at the β,γ-position of the halide. In general, alkyl halides or aliphatic acid halides are relatively unreactive towards neutral metal carbonyls; in such cases, anionic metal carbonylate species such as sodium cobalt tetracarbonyl, lithium acylmetal carbonylates, and the reagent from nickel carbonyl and potassium *t*-butoxide, are frequently reactive.

The reactions of allyl halides with nickel carbonyl have been thoroughly studied. It was confirmed that allyl halides (**1**) add to nickel replacing carbon monoxide to form π-allylnickel halides (**2**):


1 **2**

Organic syntheses with π-allylnickel complexes have been extensively studied by Chiusoli et al.; the results have been described in detail in his review[5].

1.1. Coupling Reaction using π-Allylnickel Complexes

Corey et al. discovered a coupling reaction involving π-allylnickel complexes and halides[6]; in coordinating media, e.g., dimethylformamide, N-methylpyrrolidone, or hexamethylphosphortriamide, a facile reaction occurs between the nickel complexes (**3**) and a wide variety of halides (**4**) as shown in the following scheme:

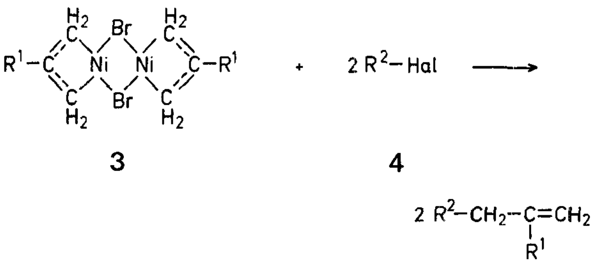
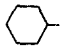
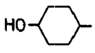
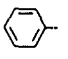
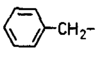
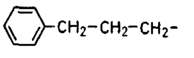
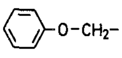
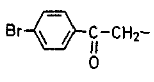

3 **4** **5**

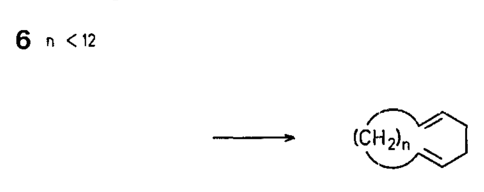
Table 1 gives the results obtained in reactions between π-methallylnickel bromide (**3**, $R^1=CH_3$) and diverse substrates.

Table 1. Coupling of π-Methallylnickel Bromide with Alkyl and Aryl Halides in Dimethylformamide[6] (**3**+**4**→**5**)

R^1	R^2	Hal	Yield %
$-CH_3$	H_3C-	J	90
	H_3C-	Br	90
		J	91
		J	88
	$t-C_4H_9$	J	25
		J	98
	$H_2C=CH-$	Br	70
		Br	91
		Br	92
		Cl	50
		Br	75
	 $H_3C-C(=O)-CH_2-$	Cl	46

The data in Table 1 indicate that the presence of carbonyl or hydroxy functions in the halide need not interfere with coupling. Dihalides undergo disubstitution with the appropriate quantity of nickel complex, as shown by the conversion of 1,6-diiodohexane into 2,11-dimethyl-$\Delta^{1,11}$-dodecadiene (95% yield) and 1,4-dibromobenzene into 1,4-dimethallylbenzene (97%).

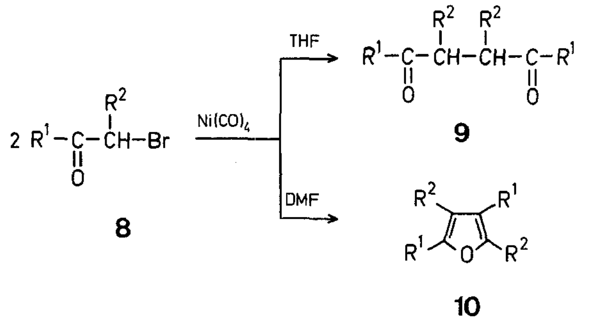
Syntheses of humulene and santalenes were achieved by using this coupling reaction[7]. Furthermore, intramolecular coupling of dibromides (**6**) by means of nickel carbonyl provides an unusually efficient route for the formation of large rings (cyclic 1,5-dienes, **7**)[8], which are difficultly accessible via the acylation reaction, currently the only commonly used general approach to large rings:


6 n < 12

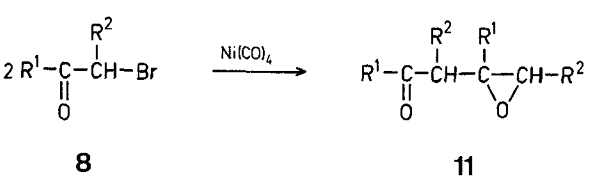
7

1.2. Synthesis of β,γ-Epoxyketones

α-Bromoketones (**8**) are reactive toward nickel tetracarbonyl. In this reaction, the solvent plays a significant role. Thus, when dimethylformamide is used as a solvent, the reaction between phenacyl bromide (**8**, $R^1 = C_6H_5$, $R^2 = H$) and nickel carbonyl proceeds at 30° to give 2,4-diphenylfuran (**10**, $R^1 = C_6H_5$, $R^2 = H$) but in tetrahydrofuran, the reaction occurs at 50–60° giving 1,4-dioxo-1,4-diphenylbutane (**9**, $R^1 = C_6H_5$, $R^2 = H$). The furan-producing reaction has been successfully extended to other aryl or alkyl α-bromoketones[9].



In the reaction of α-bromoketones (**8**) with nickel tetracarbonyl to give substituted furans (**10**), β,γ-epoxyketones have been shown to be isolable intermediates. In general, β,γ-epoxyketones can be prepared by epoxidation of β,γ-unsaturated ketones with perbenzoic acid[11]. However, the starting β,γ-unsaturated ketones are not always easily accessible due to their facile rearrangement to the more stable α,β-unsaturated isomers. Thus, the reaction of α-bromoketones (**8**) with nickel carbonyl is a convenient method for the preparation of β,γ-epoxyketones (**11**):



Data on the formation of β,γ-epoxyketones from several α-bromoketones are given in Table 2[10].

Preparation of β,γ-Epoxyketones: The reaction of an α-bromoketone (0.1 mol) with nickel carbonyl (0.06 mol) was carried out in dimethylformamide (30 ml) under argon at 30° for 5 hr. The reaction mixture was poured into dilute aqueous hydrochloric acid which was then extracted with ether. The ether extract was washed with water and dilute sodium hydrogen carbonate solution and then dried over anhydrous sodium sulfate. After removal of ether, the residue was distilled and the product characterized by I.R. and N.M.R. spectra, elemental analysis, and chemical reactions.

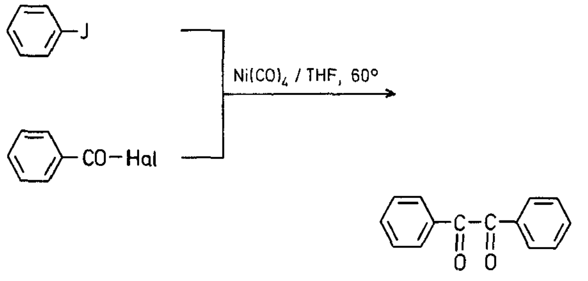
Thus, the reaction of bromomethyl *t*-butyl ketone with nickel carbonyl gave 2-*t*-butyl-5,5-dimethyl-1,2-epoxy-4-oxohexane, b.p. 94°/9 mm. When this compound was heated above 130°, dehydration occured to give 2,4-di-*t*-butylfuran.

Table 2. Formation of β,γ-Epoxyketones (**11**) from α-Bromo Ketones (**8**) and Nickel Tetracarbonyl

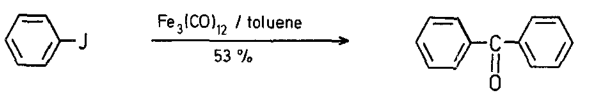
R^1	R^2	Yield %
C_2H_5	H	52
t-C_4H_9	H	61
CH_3	CH_3	70
C_2H_5	CH_3	84

1.3. Ketone Formation and Related Reactions

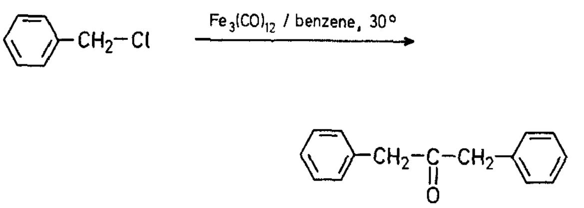
The reaction of mononuclear metal carbonyls with halides such as aroyl halides, aryl iodides, or benzyl halides, affords aroylmetal or acylmetal carbonyl derivatives as intermediates, the decomposition of which yields the corresponding symmetrical ketones. Thus, iodobenzene or benzoyl halide reacts with nickel carbonyl at 50–60° in tetrahydrofuran to give benzil[12]:



Triiron dodecacarbonyl reacts with iodobenzene in refluxing toluene to give benzophenone



and with benzyl halide to give dibenzyl ketone[13],



but the formation of α-diketones has not been observed. These reactions depend markedly not only on the properties of the halides used but also on the reaction media. For example, aryl iodides are readily carbonylated by nickel carbonyl even in nonpolar solvents (e.g. benzene) to give α-diketones,

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[1] J. Tsuji, *Organic Synthesis by Noble Metal Compounds*, Advan. Org. Chem. **6**, 109 (1969).
R. Hüttel, *Palladiumsalze und Palladium-Komplexe in der präparativen organischen Chemie*, Synthesis **1970**, 225.

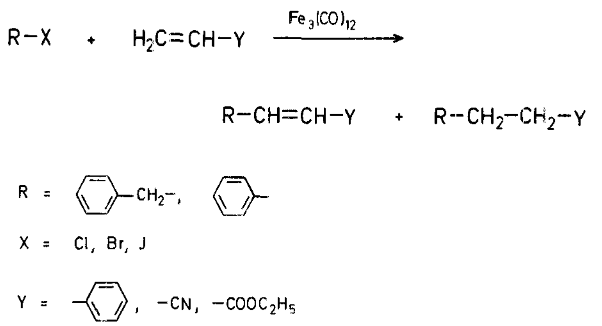
[2] I. Wender, P. Pino (Editors), *Organic Synthesis via Metal Carbonyls*, Vol. 1, Interscience Publishers, New York, 1968.

[3] C. W. Bird, *Transition Metal Intermediates in Organic Synthesis*, Logos Press, Academic Press, London, 1967.

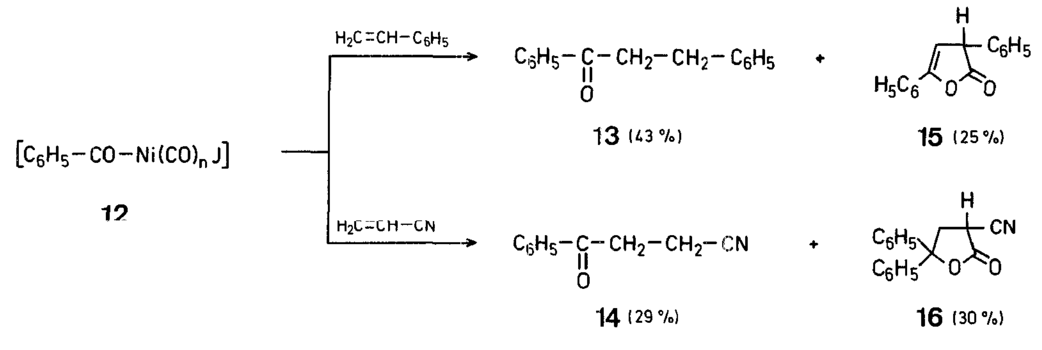
but carbonylation of benzyl halides (to give dibenzyl ketone or ethyl phenylacetate) is only possible in polar solvents[14] such as dimethylformamide (in which case the yield of ketone is 95%), tetrahydrofuran, and ethanol. On the other hand, when cyclohexane is used as the solvent, reaction does not occur and in benzene solution, Friedel-Crafts type reaction takes place instead of CO insertion and benzylated products of benzene are isolated.

Organotransition metal σ-complexes are known to add readily to unsaturated bonds, e.g. $>C{=}C<$, $-C{\equiv}C-$, $>C{=}O$, in synthetically useful reactions. Since unstable organotransition metal σ-complexes are believed to be intermediates in many reactions of organic halides with metal carbonyls, it is considered reasonable that organic reactions of metal carbonyls with unsaturated compounds proceed at least partly via these unstable σ-complexes.

Thus, although acylcobalt tetracarbonyls do not undergo olefin insertion reactions, the σ-complexes, which are presumed to be intermediates in the oxidative addition reaction of monohalides to metal carbonyls, should be reactive towards olefins because of the relatively positive character of the metal atom compared to that of acylcobalt carbonyls. In fact, the reaction of organic halides with metal carbonyls in the presence of olefins does give addition products. When benzyl halides or iodobenzene are used as partners for the reaction with triiron dodecacarbonyl in the presence of olefins, benzylation or phenylation, respectively, of the alkenes occurs[13]:



Similarly, aroylnickel carbonyl iodides, prepared from aryl iodides and nickel carbonyl, react readily even in nonpolar solvents with olefins such as styrene, acrylonitrile, and ethyl acrylate to give benzoyl adducts of olefins or γ-lactones[15]:

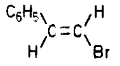
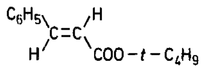
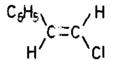
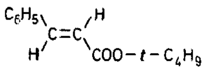
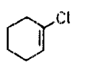
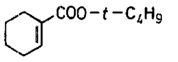
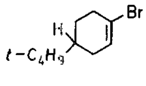
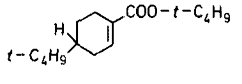


1.4. The Reaction of Alkyl-, Vinyl-, or Acyl Halides with Metal Carbonyls

Alkyl or vinyl halides are generally inactive towards nickel carbonyl in ordinary organic solvents. However, it was recently reported that treatment of alkenyl halides or alkyl iodides with several equivalents of nickel carbonyl in *t*-butanol containing 2–3 equivalents of sodium or potassium *t*-butoxide results in the formation of *t*-butyl esters (Table 3)[16]:

$$R{-}Hal \xrightarrow{Ni(CO)_4\ /\ t{-}C_4H_9OH,\ t{-}C_4H_9O^{\ominus}} R{-}COO{-}t{-}C_4H_9$$

Table 3. *t*-Butyloxycarbonylation of Organic Halides[16]

R-Hal	Reaction Product	Yield %
		60
		50
		64
		76
$H_3C{-}(CH_2)_6{-}J$	$H_3C{-}(CH_2)_6{-}COO{-}t{-}C_4H_9$	66
$J{-}(CH_2)_6{-}J$	$t{-}C_4H_9O{-}CO{-}(CH_2)_6{-}COO{-}t{-}C_4H_9$	61

Addition of *t*-butoxide to a solution of nickel carbonyl in *t*-butanol at 20° produces an immediate deep red coloration, which suggests the formation of an anionic nickel carbonylate species due to the basic reduction of nickel carbonyl.

A similarly prepared reagent from a methoxide and nickel carbonyl in methanol is useful for methoxycarbonylation of alkenyl halides or iodobenzene; however alkyl halides, including iodides, do not undergo methoxycarbonylation by the reagent. Hence, it appears that a halogen atom attached to saturated carbon is less reactive than one bonded to a trigonal carbon atom.

The reaction of acyl halides with metal carbonyls is very complicated and has not yet been completely elucidated.

Acyl halides may be decarbonylated using coordinately unsaturated transition metal compounds such as chloro-tris-[triphenylphosphine]-rhodium (**18**) in aromatic hydrocarbons or dichloromethane. The first step of the decarbonylation reaction involves oxidative addition of the acyl halide to the transition metal complex. In the case of the reaction of **18** with 3-phenylpropanoyl chloride (**17**) in toluene[17], a crystalline acyl complex (**19**) can be isolated:

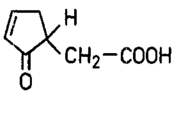
$$\underset{\textbf{17}}{C_6H_5{-}CH_2{-}CH_2{-}COCl} + \underset{\textbf{18}}{RhCl[P(C_6H_5)_3]_3} \longrightarrow$$

$$\underset{\textbf{19}}{C_6H_5{-}CH_2{-}CH_2{-}CO{-}RhCl_2[P(C_6H_5)_3]_2} + P(C_6H_5)_3$$

Oxidative addition of some acyl halides to metal carbonyls such as iron pentacarbonyl or nickel carbonyl does not, however, proceed smoothly in tetrahydrofuran or in hydrocarbon solvents. Benzoyl chloride and bromide react with nickel carbonyl in aprotic solvents such as tetrahydrofuran or hexane to give 1,2-dibenzoyloxystilbene but the conversion of benzoyl chloride is low (40%)[12].

Aliphatic acid halides are inactive towards nickel carbonyl in tetrahydrofuran or hydrocarbon solvents but display considerably increased reactivity in ketonic solvents. Thus, the reaction of hexadienoyl chloride (**20**) with nickel carbonyl and acetylene in acetone produces cyclopentenone derivatives (**21** and **22**) in good yields[19], whereas the same reaction in tetrahydrofuran gives a very low yield of ketonic products:

$$\underset{\textbf{20}}{H_2C{=}CH{-}CH_2{-}CH{=}CH{-}COCl} + HC{\equiv}CH \xrightarrow{Ni(CO)_4/acetone}$$



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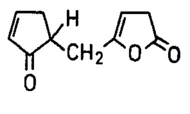

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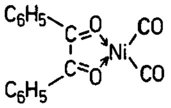
The reaction of benzil and nickel carbonyl in tetrahydrofuran at reflux temperature affords a transient red complex; if benzoyl chloride is added to the resultant solution, 1,2-dibenzoyloxy stilbene is produced. The above results suggest that acetone and benzil exert an activating effect on nickel carbonyl somewhat resembling the effect of alkoxide ion on the alkoxycarbonylation reaction of alkenyl halides or alkyl iodides. In the case of benzil, complex **23** probably is an active intermediate.

It has been proposed[19] that ketonic solvents, $R^2{-}CO{-}R^2$, promote the reaction between acyl groups, $R^1{-}CO{-}$, and metal carbonyls (**23**) via complexes such as **24**:



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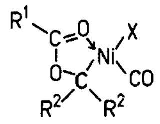

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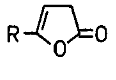
Although an exact explanation for this activation effect can not be given, it is a fact that acyl halides react with nickel carbonyl in ketonic solvents, thus permitting the reaction to be used as one of the routes to acyl nickel complexes.

Carbonylation of acyl halides in the presence of acetylene and carbon monoxide in acetone containing 0.1% water produces lactones (**25**):

$$R{-}COCl + HC{\equiv}CH + Ni(CO)_4 + H_2O \longrightarrow$$

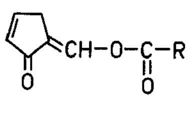


+ NiOHCl + 3 CO

25

Addition of α,β-unsaturated aldehydes such as acrolein to this reaction system results in the formation of cyclopentenone derivatives, esters of oxocyclopentylidenemethanol (**26**), or oxocyclopentenylmethanol (**27**)[5]:

$$R{-}COCl + H_2C{=}CH{-}CHO + HC{\equiv}CH + Ni(CO)_4 \longrightarrow$$



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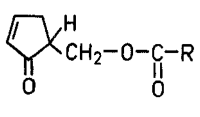

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[6] E.J. Corey, M.F. Semmelhack, J. Amer. Chem. Soc. **89**, 2755 (1967).

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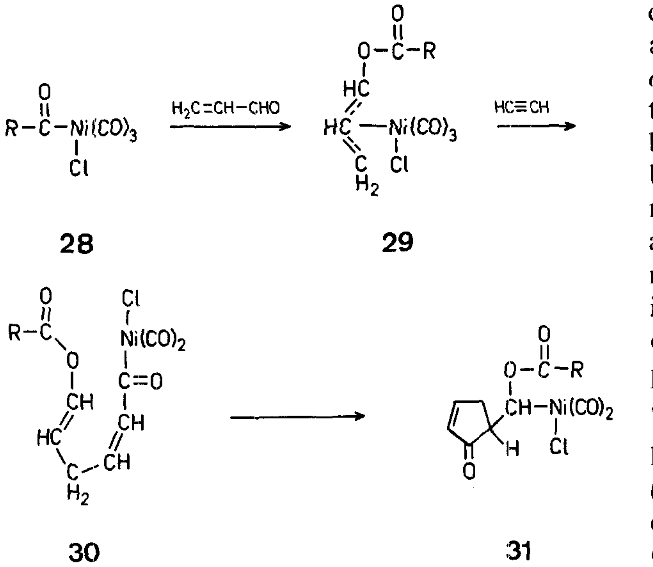
[11] For example, see H. Freitel, P. Baranger, Compt. Rend. Acad. Sci. Paris **241**, 674 (1955).

[12] N.L. Bauld, Tetrahedron Letters **1963**, 1841.

[13] I. Rhee, M. Ryang, S. Tsutsumi, J. Organometal. Chem. **9**, 361 (1967).

[14] E. Yoshisato, S. Tsutsumi, J. Org. Chem. **33**, 869 (1968).

This reaction can be interpreted in terms of insertion of the carbonyl group of acrolein into the carbon-nickel bond of the acylnickel complex **28** formed by the reaction between acid halide and nickel carbonyl. The nickel complex formed (**29**, structure does not consider possible participation of acetone and water) undergoes acetylene insertion to yield *the cyclopentenone derivatives via intermediates* **30** and **31**:



28 **29**

30 **31**

The reaction of benzoyl chloride with iron carbonyls is complex. Thus, iron pentacarbonyl does not react with benzoyl chloride in dry benzene, and, when tetrahydrofuran is used as a solvent, cleavage of the tetrahydrofuran ring occurs to give 4-chlorobutyl benzoate in 83.5% yield.

The reaction of triiron dodecacarbonyl with benzoyl chloride in dimethylformamide solution affords the dimethyl-aminoiron carbonyl complex[18]:

$HFe_3(CO)_{10}CN(CH_3)_2$

In benzene solution, the product is triphenylmethane. Details of the reaction of benzoyl chloride with iron carbonyls or dicobalt octacarbonyls in several media are given in Table 4[20]:

Table 4. The Reaction of Benzoyl Chloride with Metal Carbonyls in Several Media[20]

Metal Carbonyl	Solvent	Product	Yield %
$Fe(CO)_5$	THF	$C_6H_5{-}CO{-}(CH_2)_4{-}Cl$	84
$Fe(CO)_5$	benzene	none	
$Fe_3(CO)_{12}$	dimethyl-formamide	$HFe_3(CO)_{10}CN(CH_3)_2$	23
		$C_6H_5{-}CO{-}N(CH_3)_2$	38
$Fe_3(CO)_{12}$	benzene	$(C_6H_5)_3CH$	23
$Co_2(CO)_8$	benzene	$C_6H_5CCo_3(CO)_9$	10

2. The Reaction of Organomercury Compounds with Metal Carbonyls

Many organomercuric halides react with dicobalt octacarbonyl in tetrahydrofuran at room temperature to give symmetrical ketones in high yields, $Hg[Co(CO)_4]_2$, cobalt(II)-halide, and carbon monoxide[21,22]. This reaction proceeds rapidly and is of preparative utility. A wide variety of symmetrical diaryl ketones may be thus prepared; however, the aryl groups must not be greatly hindered at the *o*-position and should not be of such a nature that the electrophilic cleavage from mercury is hindered because of electronic factors. Dialkyl ketones may be similarly obtained from the reaction using alkylmercuric halides. However, in the case of most alkylmercuric halides, carbon-skeletal rearrangements of the intermediates lead to a mixture of isomeric ketones. If the ratio of $Co_2(CO)_8$: R—HgX exceeds 1, aldehydes are also found among the products.

The following mechanism of ketone formation was proposed:

(1) Solvent-induced redox disproportionation of dicobalt octacarbonyl to give $THF{\cdot}Co(CO)_4^{\oplus}$ and $Co(CO)_4^{\ominus}$;

(2) Nucleophilic displacement of halide ion from mercury by the cobalt carbonyl anion;

(3) Electrophilic cleavage of the C—Hg bond in the $R{-}HgCo(CO)_4$ formed (or in its disproportionation product, R—Hg—R) by $THF{\cdot}Co(CO)_4^{\oplus}$ to give $R{-}Co(CO)_4$;

(4) Organic group migration in $R{-}Co(CO)_4$, producing $R{-}CO{-}Co(CO)_3$;

(5) Reaction of this intermediate with $R{-}Co(CO)_4$ to give the ketone and dicobalt octacarbonyl.

Diphenylmercury also reacts with dicobalt octacarbonyl in tetrahydrofuran to give benzophenone and $Hg[Co(CO)_4]_2$:

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[15] E. Yoshisato, M. Ryang, S. Tsutsumi, J. Org. Chem. **34**, 1500 (1969).

[16] E. J. Corey, L. S. Hegedus, J. Amer. Chem. Soc. **91**, 1233 (1969).

[17] J. Tsuji, K. Ohno, J. Amer. Chem. Soc. **88**, 3452 (1966).

[18] I. Rhee, M. Ryang, Chem. Commun. **1968**, 455. The structure of this hydride complex was established by means of Mössbauer and mass spectra; R. Greatrex, N. N. Greenwood, I. Rhee, M. Ryang, S. Tsutsumi, Chem. Commun. **1970**, 1193.

[19] L. Cassar, G. P. Chiusoli, Tetrahedron Letters **1966**, 2805.

[20] I. Rhee, M. Ryang, S. Tsutsumi, unpublished work.

[21] D. Seyferth, R. J. Spohn, J. Amer. Chem. Soc. **90**, 540 (1968).

[22] D. Seyferth, R. J. Spohn, J. Amer. Chem. Soc. **91**, 3037 (1969).

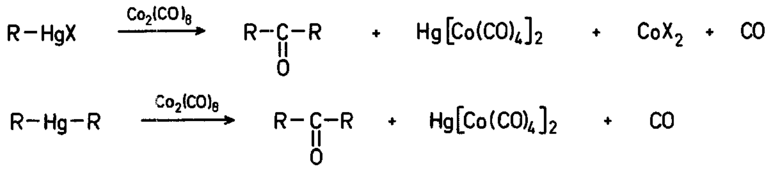
[23] D. Seyferth, R. J. Spohn, J. Amer. Chem. Soc. **91**, 6192 (1969).

[24] Y. Hirota, M. Ryang, S. Tsutsumi, unpublished work.

[25] Y. Sawa, I. Hashimoto, M. Ryang, S. Tsutsumi, J. Org. Chem. **33**, 2159 (1968).

[26] E. J. Corey, L. S. Hegedus, J. Amer. Chem. Soc. **91**, 4926 (1969).

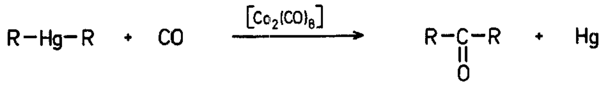
[27] G. M. Whitesides, W. F. Fischer, J. S. Filippo, R. W. Bashe, H. O. House, J. Amer. Chem. Soc. **91**, 4871 (1969).



$$R{-}HgX \xrightarrow{Co_2(CO)_8} R{-}\underset{\overset{\|}{O}}{C}{-}R + Hg[Co(CO)_4]_2 + CoX_2 + CO$$

$$R{-}Hg{-}R \xrightarrow{Co_2(CO)_8} R{-}\underset{\overset{\|}{O}}{C}{-}R + Hg[Co(CO)_4]_2 + CO$$

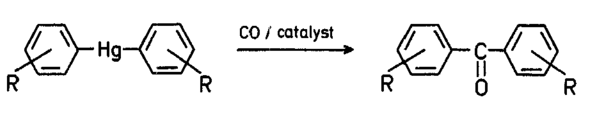
In the above equations, stoichiometric amounts of dicobalt octacarbonyl are required. However, a novel ketone synthesis was reported, in which carbon monoxide is used in stoichiometric amounts, and the relatively expensive dicobalt octacarbonyl is employed in only catalytic quantities[23]:



$$R{-}Hg{-}R + CO \xrightarrow{[Co_2(CO)_8]} R{-}\underset{\overset{\|}{O}}{C}{-}R + Hg$$

Thus, it was found that irradiative carbonylation of diarylmercury with carbon monoxide is catalyzed by dicobalt octacarbonyl. By using this method[23], various diaryl ketones have been prepared in excellent yields as shown in Table 5. This new catalytic reaction does not appear to be applicable to the synthesis of dialkyl ketones from dialkylmercury compounds, most likely because of the well-known photolability of the alkyl-Hg bond.

Table 5. Cobalt Carbonyl-Catalyzed Carbonylation of Diarylmercury Compounds[23].

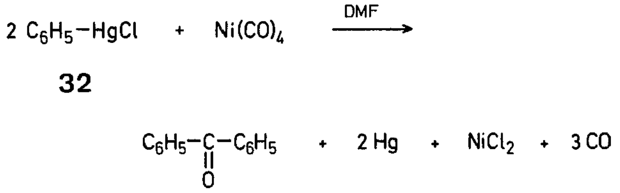


R	Catalyst	Diarylmercury/Catalyst molar ratio	Reaction time hr	Yield %
H	$Co_2(CO)_8$	37.3	123	91
H	$Hg[Co(CO)_4]_2$	94	141	88
		470	21 days	74
4-F	$Co_2(CO)_8$	46	120	87
4-Cl	$Co_2(CO)_8$	22.4	233	85
4-CH_3	$Hg[Co(CO)_4]_2$	88	36.5	62
4-OCH_3	$Hg[Co(CO)_4]_2$	48	113	52

The following procedure is typical of the method described.

Benzophenone[23]: A 150-ml quartz flask is charged with diphenylmercury (10.0 g, 28.2 mmol) and dry tetrahydrofuran (100 ml). The system is flushed with carbon monoxide, and dicobalt octacarbonyl (0.5 g, 1.46 mmol) is added. While the reaction mixture is stirred and carbon monoxide continously and slowly introduced the flask is irradiated externally with a Hanovia utility (100 W) high-pressure U.V. lamp. After 123 hr at room temperature, the flow of carbon monoxide is stopped. The reaction mixture is flushed with nitrogen and decanted from metallic mercury. From the solution, after removal of $Hg[Co(CO)_4]_2$ as the triphenylphosphine adduct, 4.7 g (91 %) of benzophenone is obtained.

The mode of reaction between phenylmercuric chloride (**32**) and nickel tetracarbonyl is considerably affected by solvent[24]. When dimethylformamide, dimethyl sulfoxide, or acetonitrile is used as the solvent, benzophenone is produced in 85–95 % yield and quantitative amounts of metallic mercury are separated in the course of the reaction, thus making the work-up of the reaction mixture simple:



32

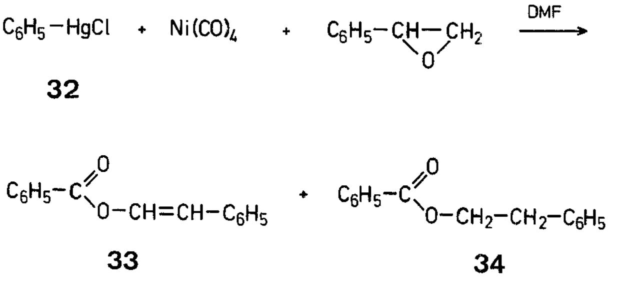
$$2\,C_6H_5{-}HgCl + Ni(CO)_4 \xrightarrow{DMF} C_6H_5{-}\underset{\overset{\|}{O}}{C}{-}C_6H_5 + 2\,Hg + NiCl_2 + 3\,CO$$

On the other hand, the same reaction in benzene, tetrahydrofuran, ethanol, or aniline yields diphenylmercury and no significant amount of carbonylated product.

Phenylmercuric acetate also reacts with nickel tetracarbonyl to give diphenylmercury in 91 % yield.

The reaction of iron pentacarbonyl with phenylmercuric chloride or phenylmercuric acetate in dimethylformamide gives diphenylmercury in good yield, but benzophenone is not obtained.

In the presence of styrene oxide, the reaction of phenylmercuric chloride (**32**) with nickel tetracarbonyl in dimethylformamide affords styryl benzoate (**33**) and 2-phenylethyl benzoate (**34**):



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33

34

3. Syntheses of Ketones using Lithium Acylmetal Carbonylates

Organolithium compounds add reductively to metal carbonyls to form rather stable anionic metal carbonylates. The lithium acylmetal carbonylates thus prepared have been found to be useful reagents for organic synthesis because of their tendency to decompose readily even under mild conditions to give organic compounds, and because of their reactivity in organic reactions, considered to be due to the nucleophilicity of the anionic complexes[4].

3.1. Synthesis of 1,4-Dicarbonyl Compounds

In reactions with acetylenic compounds, iron or chromium carbonylates are unreactive even at elevated temperatures. However, the nickel carbonylate is very reactive toward acetylene or monosubstituted acetylenes even at −70° whereby two aroyl or acyl groups are introduced into the acetylenes[25], forming a wide variety of 1,4-diketones as shown in Table 6. When the same reaction is carried out at higher temperature (−30°), γ-lactones are also produced as by-products in 2–24% yield.

1,2-Bis-[4-methylbenzoyl]-propane[25]: Propyne (2.0 g, 0.05 mol) was added to an ether solution of lithium 4-methylbenzoylnickel tricarbonylate (0.05 mol) prepared from equimolar amounts of 4-methylphenyllithium and nickel tetracarbonyl. The mixture was stirred for 5 hr at −70°, hydrolyzed with 4 *N* hydrochloric acid (50 ml), and subsequently brought slowly to room temperature. The organic layer which separated was treated with three successive 30-ml portions of 5% aqueous sodium hydroxide; the resultant mixture was separated into an organic layer and aqueous solution. The organic layer was washed with water and dried over magnesium sulfate. After removal of the solvent, the residual oil was distilled under reduced pressure to give the following fractions:

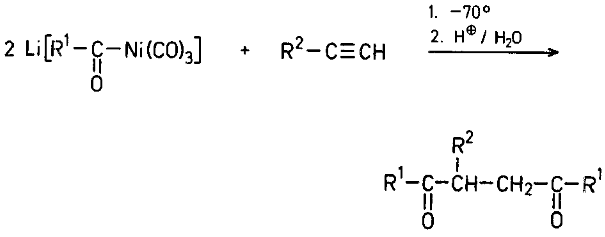
1. b.p. 70–100°/1.1 mm; 0.3 g,
2. b.p. 130–195°/1.0 mm; 5.3 g.

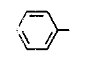
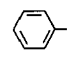
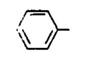
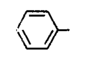
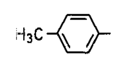
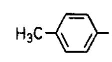
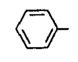
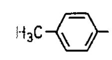
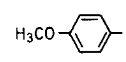
The second fraction crystallized on standing, and the crystals were recrystallized from ethanol; yield: 4.8 g colorless needles; m.p. 118–119°.

The complexes of nickel tetracarbonyl with organolithium compounds, generated at −50°, also react with a variety of α,β-unsaturated carbonyl compounds to form 1,4-dicarbonyl compounds[26]. For example, from mesityl oxide and the reagent prepared from equimolar amounts of butyllithium and nickel tetracarbonyl there is obtained 2,5-dioxo-4,4-dimethylnonane in 89% yield using the following procedure.

2,5-Dioxo-4,4-dimethylnonane[26]: To a solution of the complex prepared from nickel tetracarbonyl (5.0 mmol in 10 ml of dry argon-saturated ether) and butyllithium (5.0 mmol, 3.85 ml of 1.3 *M* solution in pentane) was slowly added and with stirring, at −50°, mesityl oxide (0.294 g, 3.0 mmol). Stirring was continued at the same temperature for 16 hr, the reaction mixture quenched by addition of aqueous ammonium chloride (10 ml of a saturated solution), and then allowed to warm to room temperature. Excess nickel tetracarbonyl and nickel complexes were decomposed by careful addition of iodine in ether until the brown color of iodine persisted. The mixture was extracted with ether, and the ether extract washed until colorless with 10 ml of saturated sodium chloride solution containing sodium sulfate, dried over magnesium sulfate, and concentrated. The crude product was separated from impurities by preparative T.L.C.; yield: 0.49 g (89%).

Table 6. 1,4-Diketones from Lithium Acylnickel Carbonylates and Acetylenes[25].



R¹	R²	Yield %
		74
	CH₃	44
	H	50
	CH₃	69
		47
	H	56
	H	31
n-C₄H₉	H	24

3.2. The Reaction of Lithium Acylmetal Carbonylates with Organic Halides[31]

As described in Section 3.1., lithium acylmetal carbonylates react with acetylenes or α,β-unsaturated carbonyl compounds to form acylated products of the unsaturated compounds. Moreover, these acylmetal carbonylates serve as effective reagents in the formation of a C—C bond by the nucleophilic displacement at a C-Hal bond in an organic halide.

Many commonly encountered organometallic compounds, such as organic derivatives of alkali metals, magnesium, zinc, and aluminum, appear in general to be unsatisfactory reagents in nucleophilic displacements with organic halides forming C—C

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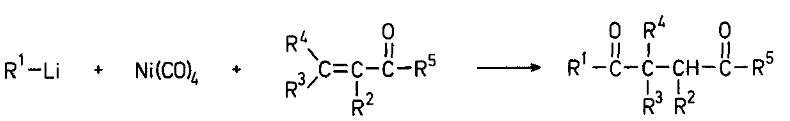
[28] H. O. House, W. F. Fischer, J. Org. Chem. 34, 3626 (1969).

[29] H. Bock, K. L. Kompa, Angew. Chem. 78, 114 (1966); Angew. Chem., Internat. Edit. 5, 123 (1966).

[30] I. Hashimoto, M. Ryang, S. Tsutsumi, Tetrahedron Letters 1969, 3291.

Table 7. Conjugate Addition of Acyl Groups to α,β-Unsaturated Carbonyl Compounds[26].



$$R^1\text{-Li} + Ni(CO)_4 + R^4R^3C{=}C(R^2){-}C(=O){-}R^5 \longrightarrow R^1{-}C(=O){-}C(R^4)(R^3){-}CH(R^2){-}C(=O){-}R^5$$

R^1	R^2	R^3	R^4	R^5	Ratio RLi : $Ni(CO)_4$: substrate	Reaction conditions		Yield[a] %
						Temperature	Time (hr)	
CH_3	H	H	C_6H_5	CH_3	4:4:3	-78°	5	82
n-C_4H_9	H	H	C_6H_5	CH_3	4:4:3	-78°	20	92
C_6H_5	H	H	C_6H_5	CH_3	5:5:3	-50°	4	42
CH_3	H	H	C_6H_5	OCH_3	2:2:1	-30°	8	71
n-C_4H_9	H	H	C_6H_5	OCH_3	4:4:3	-50°	12	59
CH_3	H	H	$-CH_2-CH_2-CH_2-$		4:4:3	-50°	12	35
n-C_4H_9	H	H	$-CH_2-CH_2-CH_2-$		4:4:3	-50°	12	64
CH_3	CH_3	H	CH_3	CH_3	4:4:3	-50°	7.5	50
n-C_4H_9	CH_3	H	CH_3	CH_3	4:4:3	-50°	7	64
CH_3	H	CH_3	CH_3	CH_3	5:5:3	-50°	16	60
n-C_4H_9	H	CH_3	CH_3	CH_3	5:5:3	-50°	16	89
n-C_4H_9	H	H	H	CH_3	5:5:3	-50°	5	64
CH_3	H	H	CH_3	OCH_3	4:4:3	-50°	4.5	49
n-C_4H_9	H	H	CH_3	OCH_3	4:4:3	-50°	4.5	76

[a] Yields refer to purified product.

bonds. However, in recent years, a variety of anionic organometallic complexes have been shown to be excellent nucleophilic reagents in various synthetic reactions, e.g.

lithium dialkylcuprate[27,51] in the reaction with organic halides or α,β-unsaturated ketones;

sodium dicyanocuprate[28] for cyanation of alkenyl halides;

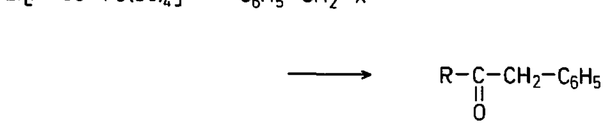
potassium hexacyanodinickelate(I)[16,30] for coupling, cyanation, or carbonylation of organic halides;

reagents from nickel tetracarbonyl and alkali metal alkoxides for alkoxycarbonylation of alkenyl or alkyl halides[30].

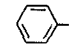
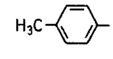
Lithium acylmetal carbonylates are also reagents useful in allowing the nucleophilic addition of the acyl group to the carbon atom of organic halides. The displacement reactions using the carbonylate complex derived from iron pentacarbonyl and that derived from nickel tetracarbonyl follow different courses. Thus, the reaction of lithium acyliron tetracarbonylates with benzyl halides or acid halides yields unsymmetrical ketones, whereas lithium acylnickel tricarbonylates give α-benzyl-α-hydroxyketones or stilbenediol diesters (**38**, **40**) in the reaction with benzyl halides or acid halides, respectively.

Synthesis of Unsymmetrical Ketones[31]: To a solution of the lithium acyliron carbonylate prepared by the reaction of equimolar amounts of organolithium compound and iron pentacarbonyl in ether/benzene, is added at −50° 1 equivalent of benzyl halide. The reaction mixture is then warmed to reflux temperature for 2 hr. The mixture is hydrolyzed with 4 *N* hydrochloric acid and the product isolated. The results are listed in Table 8.

Table 8. Benzyl Ketones from Lithium Acyliron Carbonylates and Benzyl Halides.



$$Li[R{-}CO{-}Fe(CO)_4] + C_6H_5{-}CH_2{-}X \longrightarrow R{-}C(=O){-}CH_2{-}C_6H_5$$

R	X	Yield %[a]
	Br	73
	Br	67
n-C_4H_9	J	50

[a] Yields are based on the amount of benzyl halide used.

When acid chlorides are used instead of benzyl halides, unsymmetrical ketones (**35**) are formed as the main products and α-diketones (**36**) as by-products (Table 9).

Contrary to the case of acyliron carbonylate complexes, in which benzyl alkyl (or aryl) ketones are formed, treatment of acylnickel tricarbonylates with

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[31] Y. Sawa, M. Ryang, S. Tsutsumi, Tetrahedron Letters **1969**, 5189, and unpublished work.

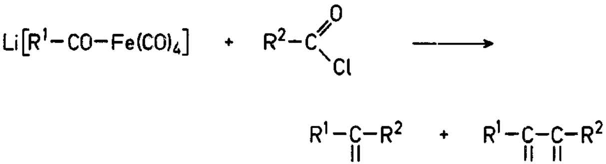
[32] N. Kutepov, H. Kindler, Angew. Chem. **72**, 802 (1960).

[33] T. Susuki, J. Tsuji, Tetrahedron Letters **1968**, 913.

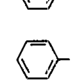
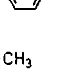
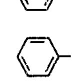
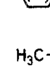
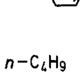
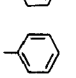
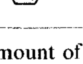
[34] German Patent (DBP) 1215139 (1962), W. Reppe, A. Magin (BASF); C. A. **65**, 8766 (1966).

benzyl halides results in the formation of α-hydroxy-α-benzylketones (α-benzylacyloins) and no significant amounts of benzyl ketones are obtained (Table 10).

Table 9. Unsymmetrical Ketones (35) and α-Diketones (36) from Lithium Acyliron Carbonylates and Acyl Chlorides.

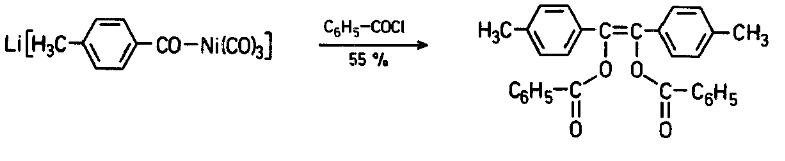


35 36

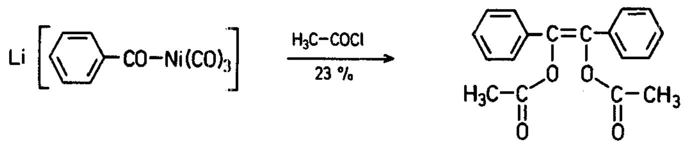
<table>
<tr><th rowspan="2">R¹</th><th rowspan="2">R²</th><th colspan="2">Yield %ᵃ</th></tr>
<tr><th>35</th><th>36</th></tr>
<tr><td></td><td></td><td>22</td><td>10</td></tr>
<tr><td></td><td>-CH₃</td><td>54</td><td>trace</td></tr>
<tr><td></td><td>-CH=CH-C₆H₅</td><td>22</td><td>21</td></tr>
<tr><td></td><td></td><td>21</td><td>trace</td></tr>
<tr><td>n-C₄H₉</td><td></td><td>36</td><td></td></tr>
</table>

ᵃ Yields are based on the amount of acid halide used.

Nucleophilic displacement of the halogen atom in acid halides with aroylnickel tricarbonylate leads to the formation of stilbenediol diesters instead of unsymmetrical ketones. Thus, the reaction of lithium 4-methylbenzoylnickel tricarbonylate (**37**) with benzoyl chloride yields 4,4′-dimethyl-α,β-dibenzoyloxy-stilbene (**38**), and that of lithium benzoylnickel tricarbonylate (**39**) with acetyl chloride gives 1,2-diacetoxy-*cis*-stilbene (**40**):

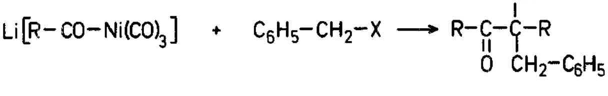


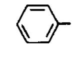
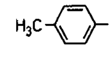
37 **38**



39 **40**

Table 10. α-Hydroxy-α-benzylketones from Lithium Acylnickel Tricarbonylates and Benzyl Halides.



<table>
<tr><th>R</th><th>X</th><th>Yield %ᵃ</th></tr>
<tr><td></td><td>Br</td><td>41</td></tr>
<tr><td></td><td>Cl</td><td>73</td></tr>
<tr><td>n-C₄H₉</td><td>Br</td><td>58</td></tr>
</table>

ᵃ Yields are based on the amount of organolithium compound used.

4. Carbonylation of Olefins or Acetylenes using Metal Carbonyls as Catalysts

Carbonylation reactions of olefins or acetylenes have been extensively studied and a number of synthetically useful reactions discovered. Some of these have found technical applications, e.g., the production of aldehydes from olefins (Oxo-process)[3] and the synthesis of acrylic acid derivatives or butanol from acetylenes or propene, respectively (Reppe-process)[32].

This Section deals with typical examples of recently published carbonylation reactions of olefins and acetylenes which promise to be applicable to organic synthesis.

Carbonylation of Δ^1-olefins in carbon tetrachloride using binuclear metal-carbonyl complexes as catalysts offers a convenient preparative method for

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[35] P. Pino, G. Braca, G. Sbrana, A. Cuccuru, Chem. & Ind. **1968**, 1732.

[36] S. Murahashi, S. Horiie, T. Joh, Bull. Chem. Soc. Japan **33**, 81 (1960).

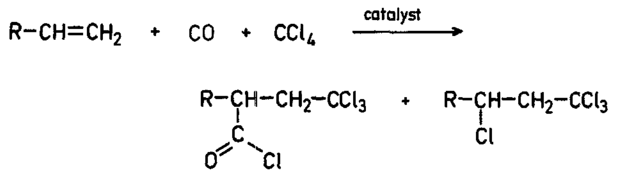
the production of 2-alkyl-4,4,4-trichlorobutanoyl chloride (**41**, R=H), from which various bifunctional compounds can be derived[33]. The following catalysts are used: dicyclopentadienyldiiron tetracarbonyl, $[C_5H_5Fe(CO)_2]_2$ (I); dicyclopentadienyldimolybdenum hexacarbonyl, $[C_5H_5Mo(CO)_3]_2$ (II); dicobalt octacarbonyl, $Co_2(CO)_8$ (III). A typical example is the following.

4,4,4-Trichlorobutanoyl Chloride (41, R = H)[33]: Ethylene (30 atm.), carbon monoxide (170 atm.), and carbon tetrachloride (40 ml) are allowed to react in a stainless steel autoclave (300 ml) at 120° in the presence of catalyst II (1 g). After 12 hr, 4,4,4-trichlorobutanoyl chloride is isolated as by distillation; yield: 15.5 g.

Other reactions of this type are summarized in Table 11.

One mol of nickel tetracarbonyl reacts with 4–18 mol of acetylene. The main product is the diester of $\Delta^{3,5}$-octadienedioic acid (**43**, n = 3); the diester of $\Delta^{3,5,7}$-decatrienedioic acid (**43**, n = 4) is obtained as a by-product.

Table 11. 4,4,4-Trichlorobutanoyl Chlorides (**41**) and 1,1,1,3-Tetrachloroalkanes (**42**) from the Carbonylation of Δ^1-Olefins in the Presence of Carbon Tetrachloride and Metal Carbonyl Catalysts[33].



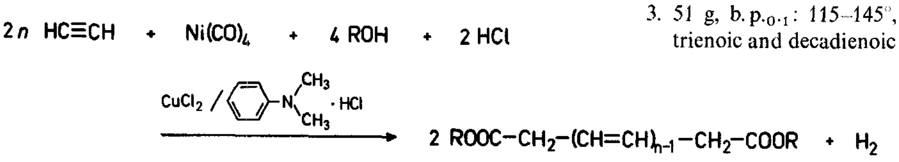
41 **42**

R	Reaction conditions				Yield g	
	Catalyst (1 g)	CO pressure atm.	Temperature	Time hr	**41**	**42**
H	II	170	120°	15	15.4	
CH_3	III	200	140°	15	11.1	6.6
n-C_4H_9	III	200	125°	15	4.9	3.6
n-C_6H_{13}	I	200	118	15	7.6	3.5

The first step of the reaction was proposed to proceed via cleavage of the metal-metal bond of the binuclear complexes with carbon tetrachloride, followed by insertion of olefin into the metal-carbon bond:

$$CCl_4 + Co_2(CO)_8 \longrightarrow Cl{-}Co(CO)_4 + Cl_3C{-}Co(CO)_4$$

Carbonylation of acetylene with nickel tetracarbonyl in acidic alcohol solution yields esters of acrylic acid. Addition of copper(II)-chloride and N, N-dimethylaniline hydrochloride to the reaction mixture leads to the formation of unsaturated dicarboxylic acids (**43**) containing 6–20 carbon atoms[34]:



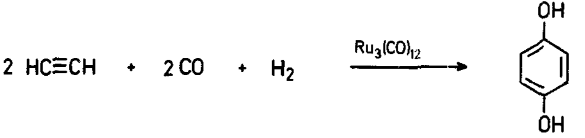
$$2n\ HC{\equiv}CH + Ni(CO)_4 + 4\ ROH + 2\ HCl \xrightarrow{CuCl_2\ /\ C_6H_5N(CH_3)_2 \cdot HCl} 2\ ROOC{-}CH_2{-}(CH{=}CH)_{n-1}{-}CH_2{-}COOR + H_2$$

43

Diethyl $\Delta^{3,5}$-Octadienedioate (43, $n = 3$)[34]: To a flask cooled to 0 to −20° were added under nitrogen absolute ethanol (1800 g), dry copper(II)-chloride (25.5 g), and N,N-dimethylaniline hydrochloride (60 g). To this mixture was added a mixture of nickel tetracarbonyl (20 g) and ethanol (12 g), followed by 9,3 l of carbon monoxide. During 6.5 hr (at 64–66°), a mixture of nickel tetracarbonyl (277 g) and ethanol (180 g) as well as ethanolic hydrogen chloride (405 g, 14.8% HCl), acetylene (345 l), and carbon monoxide (61.1 l) were added. The mixture was thereafter distilled at 50–60° at moderate pressure to yield 159 g of ethyl acrylate and 10 g of diethyl pentadienoate. The residue was extracted with ether and distilled to give the fractions:

1. 92 g, b.p.$_{0\cdot1}$: 26–100°, a mixture of unsaturated monoethyl esters;
2. 369 g, b.p.$_{0\cdot1}$: 100–115°, nearly pure diethyl $\Delta^{3,5}$-octadienedioate;
3. 51 g, b.p.$_{0\cdot1}$: 115–145°, a mixture of diethyl esters of decatrienoic and decadienoic acids.

The reaction of acetylene with a stoichiometric amount of iron pentacarbonyl in 96% ethanolic solution gives hydroquinone in 20–30% yield. However, using a catalytic amount of triruthenium dodecacarbonyl, easily prepared from ruthenium tris-acetylacetonate, acetylene reacts under anhydrous conditions in either tetrahydrofuran or dioxan to give higher yields of hydroquinone[35]:



Hydroquinone[35]: The reaction is carried out in a steel autoclave at 200°; reaction time: 268 min. The components are: acetylene (0.248 mol), carbon monoxide (120 atm. at 20°), hydrogen (10 atm. at 20°), triruthenium dodecacarbonyl (0.1 g), and tetrahydrofuran (177 g); yield: 0.075 mol (58.5%).

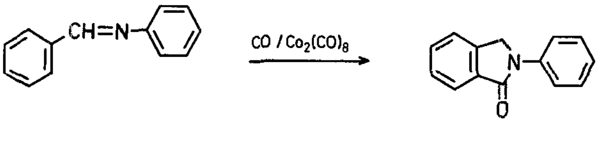
The yield of hydroquinone is markedly dependent on the partial pressure of hydrogen, the best yields being obtained at a hydrogen partial pressure of 5–10 atm. Furthermore, the yield appears to depend upon the ratio water:acetylene and upon the temperature; the partial pressure of carbon monoxide and the concentration of acetylene appears to be of less importance.

5. Reaction of Nitrogen Compounds with Metal Carbonyls.

During the last decade, considerable research on the reactions of nitrogen compounds with metal carbonyls has been carried out. In particular, cyclization of imino or azo compounds to yield heterocyclic substances and carbonylation of amines to ureas, formamides, or oxamides have been successfully achieved. The reaction of carbon monoxide with various unsaturated nitrogen compounds, such as Schiff bases, azo compounds, aromatic ketoximes or aldoximes, etc., using metal carbonyls as catalysts represents a valuable method for the preparation of a variety of heterocyclic compounds. However, since an excellent review relating to these reactions has recently been published[43], advances in this field will be described only briefly in this article.

5.1. Reactions of Compounds Containing C—N or N—N Multiple Bonds

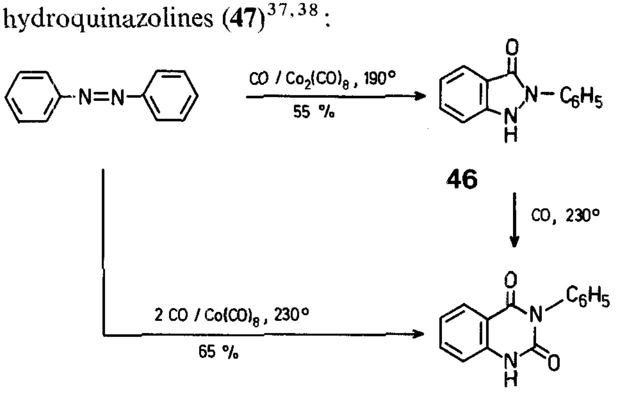
Benzaldehyde phenylimines (e.g. **44**) may be cyclized with carbon monoxide under a pressure of 100–200 atm. at 200–230° in the presence of dicobalt octacarbonyl in benzene to yield N-phenylphthalimides (e.g. **45**)[36]:



44 **45**

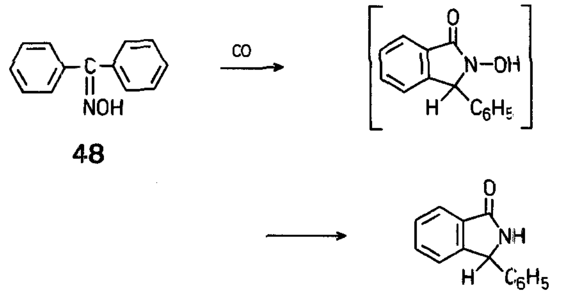
Iron pentacarbonyl is less effective than dicobalt octacarbonyl in catalyzing this reaction.

Azo compounds react similarly with carbon monoxide in the presence of dicobalt octacarbonyl to yield cyclization products such as 3-oxo-2-phenyldihydroindazoles (**46**) or 2,4-dioxo-3-phenyltetrahydroquinazolines (**47**)[37,38]:



47

The cyclization reaction also takes place, but with lower yield, when iron pentacarbonyl is used as catalyst. The presence of polar substances such as water or alcohols inhibits the reaction. If one of the phenyl rings contains an electron-repelling group, ring closure occurs to the ring having this substituent; if an electron-attracting group is present, cyclization does not take place. Carbonylation of aromatic ketoximes (e.g. **48**) produces substituted phthalimidines (e.g. **49**)[39,40]:



49

Under similar reaction conditions, aryl alkyl ketoximes afford only complex mixtures of products.

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[37] S. Horiie, S. Murahashi, Bull. Chem. Soc. Japan 33, 88 (1960).

[38] S. Horiie, S. Murahashi, Bull. Chem. Soc. Japan 33, 247 (1960).

[39] A. Rosenthal, A. Hubscher, J. Org. Chem. 25, 1562 (1960).

[40] A. Rosenthal, J. Org. Chem. 26, 1638 (1961).

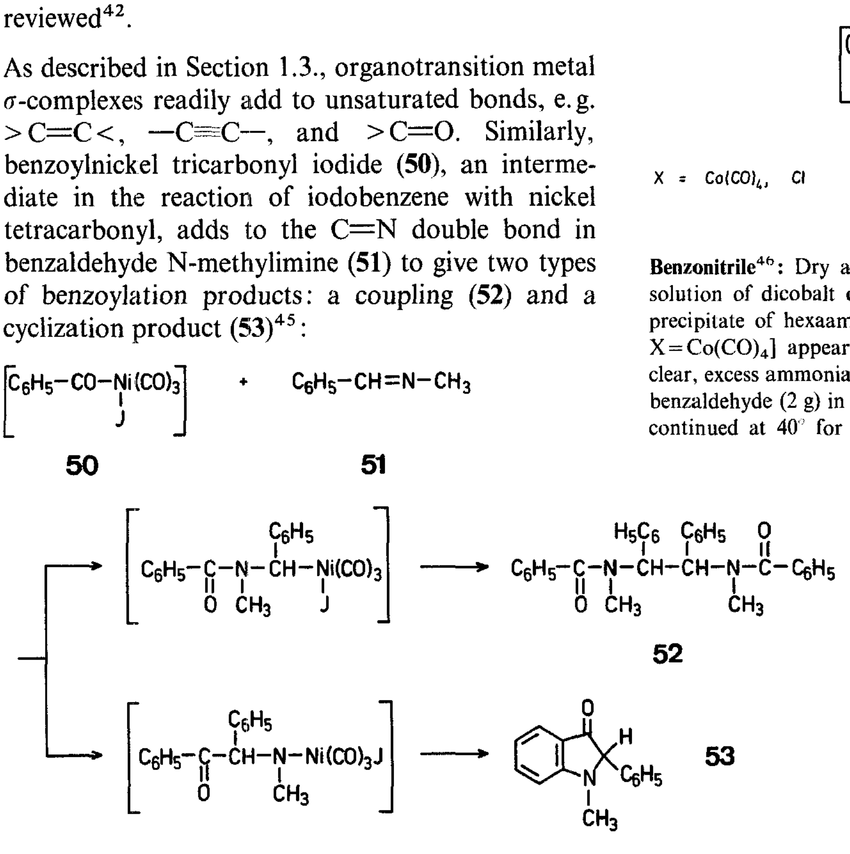
[41] J. Falbe, F. Korte, Angew. Chem. 74, 291 (1962); Angew. Chem., Internat. Edit. 1, 266 (1962).

[42] J. Falbe, Angew. Chem. 78, 532 (1966); Angew. Chem., Internat. Edit. 5, 435 (1966).

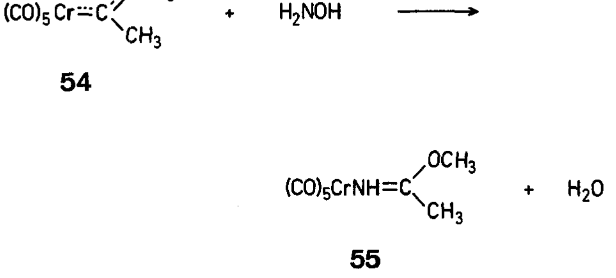
Aromatic ketone or aldehyde phenylhydrazones (or semicarbazones) also undergo carbonylation and cyclization to give heterocyclic compounds; the nature of the products and the yields depend upon reaction temperature and upon the substituent at the carbon atom of the imino group.

Aliphatic α,β-unsaturated carboxylic acid amides react with carbon monoxide at a pressure of 100–300 atm. at 160–280° in the presence of dicobalt octacarbonyl to give succinimides[41]. A similar type of reactions involving unsaturated amines or alcohols has been systematically studied and reviewed[42].

As described in Section 1.3., organotransition metal σ-complexes readily add to unsaturated bonds, e.g. $>C{=}C<$, $-C{\equiv}C-$, and $>C{=}O$. Similarly, benzoylnickel tricarbonyl iodide (**50**), an intermediate in the reaction of iodobenzene with nickel tetracarbonyl, adds to the C=N double bond in benzaldehyde N-methylimine (**51**) to give two types of benzoylation products: a coupling (**52**) and a cyclization product (**53**)[45]:

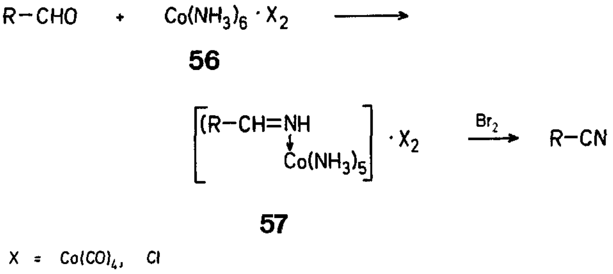


Imines which contain no substituent on nitrogen are readily formed by addition of ammonia to aldehydes but have received only limited attention in synthetic organic chemistry because of their instability. However, it was recently reported that the reaction of anhydrous hydroxylamine with methylmethoxycarbene-chromium pentacarbonyl (**54**) in ether at room temperature produces yellow (methyl-acetimidato)-chromium pentacarbonyl (**55**) in almost quantitative yield[44]:



This result indicates the stabilization of N-substituted imines by complex formation with transition metal, thus suggesting a possibility for various imines to be utilized in organic synthesis.

Thus, nitriles may be synthesized from aldehydes using a procedure involving formation of an imine-cobalt complex (**57**), which is subsequently oxidized[46]:



Benzonitrile[46]: Dry ammonia is bubbled into a stirred hexane solution of dicobalt octacarbonyl (5 g, 14.6 mmol); a colorless precipitate of hexaamminecobalt bis-[cobalt tetracarbonyl] [**56**, $X=Co(CO)_4$] appears. After the hexane solution has become clear, excess ammonia and hexane are completely removed. Then benzaldehyde (2 g) in acetonitrile (50 ml) is added and stirring is continued at 40° for 15 hr. The I.R. spectrum of the reaction mixture shows the presence of N—H (3480, 3300 cm^{-1}), Co—CO (1840–1930 cm^{-1}), and C=N groups (1630 cm^{-1}). The solvent is removed; analysis of the benzene extract of the residue indicates small amounts of benzaldehyde to be present, but no imine derivatives or cyclized products. This result suggests that benzaldehyde reacts readily with **56** to form benzaldimine as a stable complex with cobalt (**57**). Decomposition of the above reaction mixture with bromine affords 1 g of benzonitrile.

Nitriles are also produced by the reaction of hexaammine-cobalt dichloride (**56**, X=Cl) with aldehydes.

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[43] A. ROSENTHAL, *Reactions of Nitrogen Compounds*, in I. WENDER, P. PINO, *Organic Synthesis via Metal Carbonyls*, Vol. 1, p. 405, Interscience Publishers, New York, 1968.

[44] E.O. FISCHER, R. AUMANN, Angew. Chem. **79**, 191 (1967); Angew. Chem., Internat. Edit. **6**, 181 (1967).

[45] Y. TOYODA, I. RHEE, M. RYANG, S. TSUTSUMI, unpublished work.

[46] I. RHEE, M. RYANG, S. TSUTSUMI, Tetrahedron Letters **1970**, 3419.

Table 12. Nitriles from Aldehydes by Reaction with Hexaamminecobalt Dicobalt Octacarbonyl[46].

$$R{-}CHO + Co(NH_3)_6[Co(CO)_4]_2 \longrightarrow \mathbf{56}$$

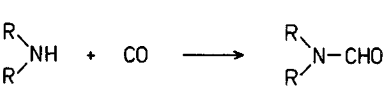
$$\mathbf{57} \xrightarrow{Br_2} R{-}CN$$

R	Reaction conditions			Yield[a] %
	Solvent	Temperature	Time hr	
C_6H_5	DMSO	40°	6	20
	DMF	40°	6	42
	acetonitrile	40°	6	52
	acetonitrile	40°	15	70
	acetonitrile	30°	100	77
	acetonitrile	50°	100	110
$C_6H_5{-}CH{=}CH{-}$	acetonitrile	15°	15	21
$C_6H_5{-}CH_2{-}CH_2{-}$	acetonitrile	0–5°	6	70

[a] Based on complex **56**

5.2. Carbonylation of Amines

Amines react with carbon monoxide in the presence of catalytic amounts of either metal carbonyls or the halides of metal carbonyl-forming metals to yield N-formyl derivatives and substituted ureas[2,4,43]. The overall equation for the formation of substituted formamides from primary and secondary amines may be written as follows:



$$RR'NH + CO \longrightarrow RR'N{-}CHO$$

Urea formation involves the elimination of one mole of hydrogen from two moles of amine; the hydrogen is often transferred to an organic acceptor. The reactions of carbonyl sulfide or carbonyl selenide with amines also afford ureas.

The reaction of primary amines with sulfur and carbon monoxide at temperatures of ~100° gives the corresponding ureas in high yields[46]. This reaction is widely applicable to aliphatic amines, and high yields of 1,3-disubstituted ureas are obtained.

Aromatic amines react only slightly under the conditions employed for the synthesis of dialkyl ureas. However, high yields of several diaryl ureas were achieved by using tertiary amines as catalysts in the absence of solvent. In this carbonylation reaction, carbonyl sulfide was found to be the active species. N,N'-Disubstituted ureas (**59**) may also be produced in very good yields under milder reaction conditions by treating amines with carbonyl selenide (**58**)[48]:

$$SeCO + 2\,R{-}NH_2 \longrightarrow R{-}NH{-}C(=O){-}NH{-}R + H_2Se$$

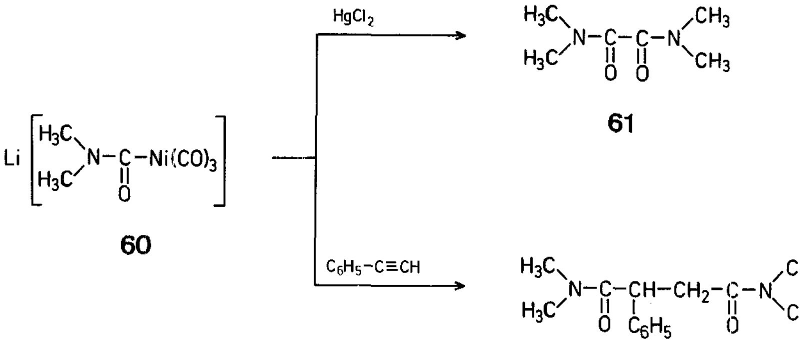
58 **59**

$$2\,H_2Se + O_2 \longrightarrow 2\,Se + 2\,H_2O$$

The selenohydride produced in the reaction is decomposed by oxygen to give metallic selenium.

Amines are also carbonylated in the presence of catalytic amounts of metallic selenium to give quantitative yields of 1,3-dialkyl ureas.

Lithium dimethylamide adds reductively to nickel tetracarbonyl to afford lithium dimethylcarbamoylnickel tricarbonylate[49] (**60**) in a reaction similar to the synthesis of lithium acylnickel carbonylates. The complex in turn undergoes decomposition with mercury(II)-chloride in tetrahydrofuran to give tetramethyloxamide (**61**) and metallic mercury, and adds to phenylacetylene to yield N,N,N',N'-tetramethylsuccindiamide (**62**):



60 **61** **62**

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[47] R.A. Frantz, F. Applegath, F.V. Morriss, F. Baiocchi, J. Org. Chem. **26**, 3304, 3306, 3309 (1961).

[48] N. Sonoda, T. Yasuhara, S. Tsutsumi, unpublished work.

[49] S. Fukuoka, M. Ryang, S. Tsutsumi, J. Org. Chem. **33**, 2973 (1968).

As mentioned in Section 1., several organic monohalides which contain unsaturated bonds at the β,γ-position to the halogen atom add oxidatively to metal carbonyls to give cationic alkylmetal or acylmetal carbonyls, which decompose to give either coupling products or ketones.

On the other hand, only a few studies on the reaction of N-haloamines with metal carbonyls have been reported. One of these involves the reaction of N-dichloroamine with nickel tetracarbonyl in wet benzene to yield N,N'-dialkyl ureas[29]. In addition, several monochloroamines react with nickel tetracarbonyl to form unstable alkylcarbamoylnickel complexes, which immediately decompose to give ureas as main products and carbamoyl chlorides as minor products[50].

Although α-haloketones react with nickel tetracarbonyl without CO insertion to give 1,4-diketones (in tetrahydrofuran) and/or β,γ-epoxyketones (in dimethylformamide), N-chlorobenzamide, a nitrogen compound corresponding in some respect to an α-haloketone, reacts with nickel tetracarbonyl to give the CO insertion product N,N'-dibenzoylurea in 53% yield[50].

Received: June 4, 1970

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[50] S. Fukuoka, M. Ryang, S. Tsutsumi, Tetrahedron Letters **1970**, 2553.

[51] E. J. Corey, G. H. Posner, Tetrahedron Letters **1970**, 315, and references cited therein.