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Metal catalyzed carbonylation and oxidation-reduction reactions

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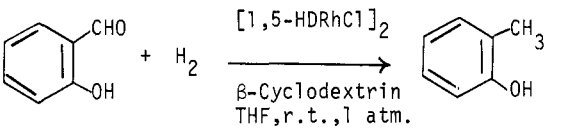
Abstract - By the use of rhodium, rhenium, or palladium complexes as catalysts, and cyclodextrins or polyethylene glycols as phase transfer catalysts, the selective reduction or oxidation of carbonyl compounds, as well as the synthesis of the latter from olefins, occurs under remarkably mild conditions. Homogeneous or phase transfer catalyzed carbonylation of olefins, epoxides and thiiranes to acids, esters, and lactones are described, using cobalt or palladium catalysts. The rhodium(I) catalyzed carbonylation of aziridines to β-lactams is a stereospecific and enantiospecific process. The presence of d or l-menthol results in high asymmetric induction using racemic aziridines as substrates.

INTRODUCTION

Three important processes in organic chemistry are reduction, oxidation, and carbonylation reactions. Significant progress has been made in recent years in the development of new chemistry, or the improvement of known reactions, using homogeneous and phase transfer catalysis. This account describes some of the author's recent results in these areas.

REDUCTION REACTIONS

In 1983, it was reported that chloro(1,5-hexadiene)rhodium(I) dimer is an effective catalyst for the phase transfer catalyzed hydrogenation of aromatic hydrocarbons and heterocyclic compounds using hexane as the organic phase, an aqueous buffer of pH 7.4-7.6 and either cetyltrimethylammonium bromide or tetrabutylammonium hydrogen sulfate as the phase transfer agent (ref. 1). This reaction proceeds at room temperature and atmospheric pressure, and the same transformation can also be realized by means of rhodium trichloride and Aliquat 336 (ref. 2). The arene reduction shows good functional group selectivity since the following groups are unaffected: ether, ester, amide, and carbonyl. Concerning the latter, it seemed conceivable that, under modified conditions, one could achieve preferential reduction of the carbonyl moiety in the presence of the arene. It is known that aryl ketones form 1:1 complexes with β-cyclodextrin, the carbonyl group probably located in an exposed position with the arene ring inside the cavity and thus protected from reaction (ref. 3, 4). β-Cyclodextrins constitute one of three classes of cycloamyloses [the others being α and γ]. When an aryl alkyl ketone or aromatic aldehyde is treated with hydrogen in the presence of a catalytic quantity of the rhodium dimer and β-cyclodextrin in tetrahydrofuran at room temperature, hydrocarbons are formed in excellent yields. What is particularly attractive about this reaction, in comparison to existing methodology for reducing a carbonyl to a methylene group, is the ability to effect reduction in the case of acidic (eq. 1) or basic substrates, and under exceptionally mild conditions (ref. 5).



(1)

OXIDATION REACTIONS

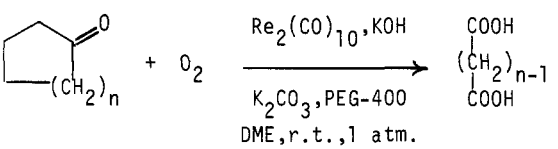
Two industrially valuable oxidation reactions are the conversion of cyclic ketones to diacids, and the formation of ketones from olefins [the simplest example being the conversion of ethylene to acetaldehyde - the Wacker process]. By the use of phase transfer catalysis, one can achieve both reactions under remarkably mild conditions. The most effective class of phase transfer agents for this reaction are polyethylene glycols (PEG's) which can be regarded as acyclic analogs of crown ethers. Reactions where PEG's are of genuine benefit include the dehydrohalogenation of (2-bromoethyl)benzene (ref. 6) and palladium(0) catalyzed carbonylation of vinylic dibromides to monocarboxylic acids, a formal oxidative homologation reaction (ref. 7). Exposure of a cyclic ketone to rhenium carbonyl (100/1 ratio of substrate/rhenium),

TABLE 1. Oxidation of Ketones by $Re_2(CO)_{10}$-K_2CO_3-PEG-400[a]

Reactant	Reaction time, hr.	Product	Yield, %
Cyclohexanone	24	adipic acid	74
Cyclohexanone[b]	24	adipic acid	12
Cyclohexanone[c]	24	adipic acid	24
Cyclohexanone[d]	24	adipic acid	11
Cyclohexanone[e]	24	adipic acid	41
Cycloheptanone	24	$HOOC(CH_2)_5COOH$	80
Cyclooctanone	48	$HOOC(CH_2)_6COOH$	82
Cyclododecanone	96[f]	$HOOC(CH_2)_{10}COOH$	86
4-t-Butylcyclohexanone	24	$HOOC(CH_2)_2\underset{\displaystyle C(CH_3)_3}{\underset{\vert}{C}}HCH_2COOH$	36
1-tetralone	6	2-hydroxy-1,4-naphthoquinone	93
2-tetralone	8	2-hydroxy-1,4-naphthoquinone	63
Dibenzyl ketone	6	benzoic acid	72
1-Phenyl-2-butanone	24	benzoic acid	74

[a] 10 mmol of substrate, 0.1 mmol of $Re_2(CO)_{10}$, 40 mmol each of K_2CO_3 and KOH, 3 drops of PEG-400, 20 ml. of DME.
[b] no $Re_2(CO)_{10}$
[c] no PEG-400
[d] no K_2CO_3 or KOH
[e] Na_2CO_3 and NaOH instead of K_2CO_3 and KOH
[f] 50°C

oxygen, potassium hydroxide, potassium carbonate, and several drops of PEG-400 in 1,2-dimethoxyethane (DME), at room temperature and one atmosphere, afforded the dicarboxylic acid (eq. 2) in good yield (see Table 1 for data).



(2)

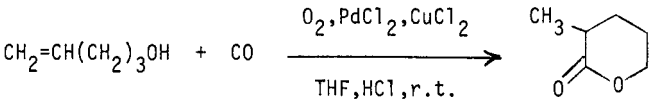
Exceptional cases are 1- or 2-tetralone, both of which give 2-hydroxy-1,4-naphthoquinone. Acyclic benzylic ketones are converted to benzoic acid while ketones such as 5-nonanone are inert. This PEG-induced route to diacids (ref. 8) occurs under milder conditions, and in better yields, than the homogeneously catalyzed reaction (ref. 9).

PEG-400 is also useful for the oxidation of isomeric butenes to butanone using palladium chloride as the catalyst and cupric chloride as the re-oxidant (ref. 10). Unfortunately, a side reaction is olefin isomerization and therefore one obtains isomeric ketones as by-products [e.g. 1-decene gives 2-decanone as the major product with 3-, 4-, 5-decanone as by-products]. This problem can be avoided by using, as the phase transfer agent, a quaternary ammonium salt containing at least one long chain alkyl group. Only terminal olefins are oxidized when such catalysts are employed, but little, if any, isomerization occurs under these conditions (ref. 11). Finally, palladium chloride catalyzes the oxidation of both terminal and internal olefins when β-cyclodextrin is the phase transfer catalyst (ref. 12).

CARBONYLATION REACTIONS

If the homogeneous Wacker reaction is run in the presence of carbon monoxide (i.e. as a so-called oxidative carbonylation reaction) and a small amount of an acid in alcohol, then regiospecific hydroesterification occurs under very gentle conditions affording branched chain esters in excellent yields (ref. 13). The carboxylic acid is formed when water in tetrahydrofuran is used as the solvent mixture instead of alcohol (ref. 14). This method is applicable to the synthesis of ibuprofen, naproxen, and other non-steroidal antiinflammatory agents. An alternate route from olefins to esters involves the use of formate esters as reagents for the palladium chloride catalyzed reaction. Although nor regiospecific, the reaction displays good regioselectivity for the branched chain product (ref. 15). The intramolecular version of the hydroesterification reaction can be attained by the use of unsatu-

rated alcohols. For instance, when 4-penten-1-ol was used as the substrate, the six-membered ring lactone was obtained in 75% yield (eq. 3). Homoallylic (ref. 16) and allylic (ref. 17) alcohols give butyrolactones in good yields.



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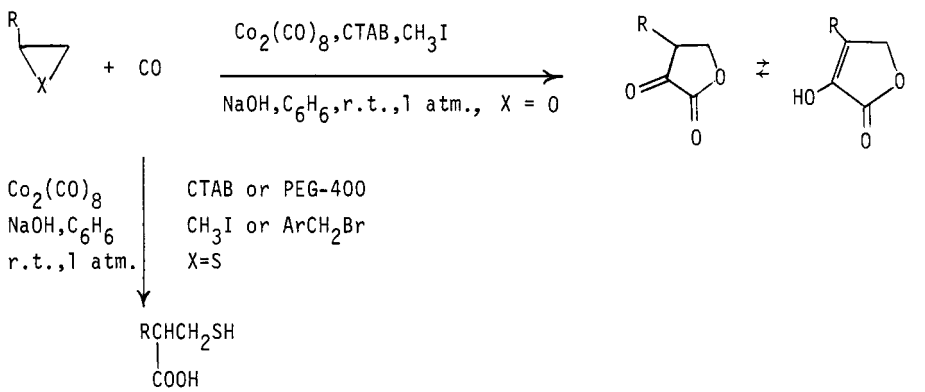
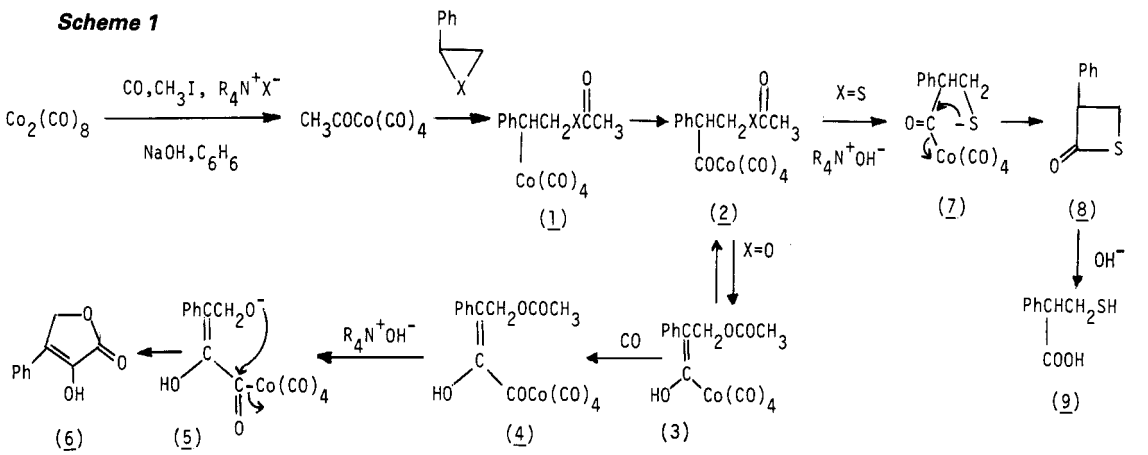
Metal catalyzed double carbonylation reactions have attracted much attention in recent years. The focus for most of this research has been in the conversion of halides to α-keto acids and their derivatives (ref. 18). Recent studies have shown that certain amines can also undergo double carbonylation under the above hydroesterification conditions affording oxamic acid esters (ref. 19). Even more fascinating is the first report of a metal catalyzed double insertion of carbon monoxide into a cyclic compound. Styrene oxides react with in situ generated acylcobalt tetracarbonyl [from methyl iodide or a benzylic bromide, cobalt carbonyl, carbon monoxide, and phase transfer conditions] to give α-keto lactones (or the enol tautomer) in good yield (eq. 4 - ref. 20). When episulfides (thiiranes) are used as the substrates,



(4)

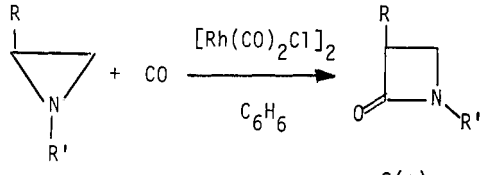
monocarbonylation occurs affording β-mercapto acids (eq. 4 - ref. 21). How can one rationalize the different behavior of epoxides and thiiranes in these reactions? Consider the pathways outlined in Scheme 1 [using methyl iodide as the halide and styrene oxide or sulfide]. Reaction of the acylcobalt carbonyl with the epoxide or thiirane would give the ester or thioester complex 1 which could insert carbon monoxide affording 2. Enolization can then occur for X=O generating 3. The latter, containing a vinyl metal-carbon bond, should experience facile insertion of carbon monoxide resulting in the formation of 4. Base induced hydrolysis of the ester would give 5 which can cyclize to give the product (6). It is known that thioesters hydrolyze more rapidly than the corresponding esters (ref. 22). Consequently, hydrolysis of 2, X=S to 7 may take precedence over enolization and carbonylation. It is the relative susceptibility to hydrolysis of 2, X=O,S which may determine the reaction course. The β-thiopropriolactone 8 could arise by intramolecular cyclization of 7, and subsequent base-induced cleavage of the heterocycle under the phase transfer conditions would give the β-mercapto acid. Solid evidence was obtained for the intermediacy of 8 in the reaction.

Scheme 1

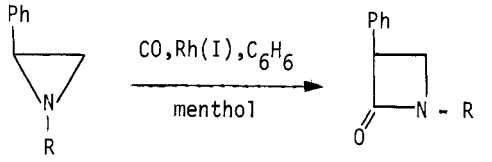


Metal catalyzed carbonylation - ring expansion reactions of heterocycles have considerable scope being applicable to α-lactams (ref. 23), azirines (ref. 24), and aziridines (ref. 25). Concerning the latter, rhodium(I) complexes are excellent catalysts for the conversion of aziridines to β-lactams. Not only is the reaction regiospecific, but it is also stereospecific and enantiospecific (eq. 5). A requirement is that the R group have available π or n electrons for stabilizing a presumed rhodacycle intermediate [i.e. R=Ph, $CH=CH_2$, $COCH_3$, $COOCH_3$, $NHCOCH_3$]. One can achieve a very high degree of asymmetric induction in the reaction, by kinetic resolution, using d or l-menthol as an added chiral ligand (eq. 6). This is an attractive route for the generation of key intermediates in the chiral synthesis of carbapenems (ref. 26). Furthermore the recovered aziridines, in the carbonylation reaction, are also obtained in high optical purity.

		menthol	
R = $C(CH_3)_3$	$[Rh(CO)_2Cl]_2$	d	+15.7
S(+) = +44.0°	[1,5-CODRhCl]$_2$	d	+38.0
R(-) = -44.0°	[1,5-CODRhCl]$_2$	l	-44.0
	[1,5-HDRhCl]$_2$	l	-38.5
R = 1-adamantyl	[1,5-CODRhCl]$_2$	d	+14.5
S(+) = +14.8°	[1,5-CODRhCl]$_2$	l	-14.6
R(-) = -14.8°			



S(-) S(+) (5)



(6)

In conclusion, homogeneous and phase transfer catalyses are useful vehicles for the realization of valuable metal catalyzed reduction, oxidation, and carbonylation reactions under exceptionally mild conditions.

Acknowledgements

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