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References and Notes

(1) Author to whom correspondence should be addressed.
(2) T. B. Eames and B. M. Hoffman, *J. Am. Chem. Soc.*, **93**, 3141 (1971).
(3) A. L. Buchachenko et al., *Radiospectrosk. Kvantovokhim. Metody Strukt. Issled.*, 124 (1967).
(4) E. G. Janzen et al., *J. Phys. Chem.*, **74**, 3025 (1970).
(5) P. Ashkenazi and M. Cais, *Angew. Chem., Int. Ed. Engl.*, **11**, 1027 (1972).
(6) R. West and P. Boudjouk, *J. Am. Chem. Soc.*, **95**, 3983 (1973).
(7) G. A. Abakumov, V. D. Tikhonov, and G. A. Razuvaev, *Dokl. Akad. Nauk SSSR*, **187**, 571 (1969).
(8) R. Briere, H. Lemaire, and A. Rassat, *Bull. Soc. Chim. Fr.*, 3273 (1965).
(9) P. Legzdins, R. W. Mitchell, G. L. Rempel, J. D. Ruddick, and G. Wilkinson, *J. Chem. Soc. A*, 3322 (1970).
(10) F. A. Cotton and J. G. Norman, Jr., *J. Coord. Chem.*, 1, 161 (1971).
(11) Computer program from J. Fritsch, Thesis, University of Kansas.
(12) M. A. Porai-Koshits and A. S. Antsyshkima, *Dokl. Akad. Nauk SSSR*, **146**, 1102 (1962).
(13) L. Dubicki and R. L. Martin, *Inorg. Chem.*, **9**, 673 (1970).
(14) R. M. Richman, S. P. Tanner, and R. S. Drago, to be submitted.
(15) D. Kivelson, *J. Chem. Phys.*, **33**, 1094 (1960).
(16) J. E. Wertz and J. R. Bolton, "Electron Spin Resonance, Elementary Theory and Practical Applications", McGraw-Hill, New York, N.Y., p 465.
(17) A. H. Cohen and B. M. Hoffman, *J. Phys. Chem.*, **78**, 1313 (1974) and references therein.
(18) Y. Y. Lim and R. S. Drago, *J. Am. Chem. Soc.*, **93**, 891 (1971).
(19) T. Kawamura, S. Matsunami, and T. Yonezawa, *Bull. Chem. Soc. Jpn.*, **40**, 1111 (1967).
(20) B. R. McGarvey, *J. Phys. Chem.*, **71**, 51 (1967).
(21) B. A. Goodman and J. B. Raynor, *Adv. Inorg. Chem. Radiochem.*, **13**, 135 (1970).

Stereochemistry of the Hydroformylation of Olefinic Hydrocarbons with Cobalt and Rhodium Catalysts

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Abstract: (*E*)- and (*Z*)-3-methyl-2-pentene, the three isomeric methylcyclohexenes, as well as 1,2-dimethylcyclohexene and 2-methyl-1-methylidenecyclohexane have been hydroformylated in the presence of rhodium or cobalt catalysts in order to investigate the stereochemistry of the reaction. Conclusive evidence is provided that both catalytic systems promote cis addition of hydrogen and formyl group to the olefins. Some aspects of the isomerization phenomena accompanying the hydroformylation have been clarified, and two different mechanisms responsible for the formation of isomeric aldehydes have been proved.

Although the hydroformylation of olefins has been extensively investigated, experimental evidence concerning the stereochemistry of the addition of hydrogen and a formyl group to the double bond is still scarce.[1] Prevailing cis addition has been ascertained in the cobalt-catalyzed hydroformylation of 3β,20β-diacetoxy-Δ^5-pregnene[2] and of 3,4,6-tri-*O*-acetyl-D-glucal.[3] Contrasting evidence exists in the literature in the case of the stoichiometric synthesis of aldehydes from olefinic substrates and hydrido- or deuteridotetracarbonylcobalt.[1] The stereochemistry of the hydroformylation catalyzed by other metals has not been previously investigated. We became interested in the steric aspects of the hydroformylation and particularly in the degree of stereospecificity of the reaction in connection with our research on the asymmetric hydroformylation catalyzed by cobalt and rhodium complexes containing chiral ligands;[4] in a preliminary communication we have shown that in the case of hydridocarbonyltris(triphenylphosphine)rhodium as the catalyst, the reaction proceeds with cis stereochemistry.[5] Similar results have been achieved by other authors using rhodium supported on alumina as the catalyst.[6] The analogous investigation carried out with cobalt catalyst is complicated by the hydrogen shift reactions occurring in the substrate during the hydroformylation[7] and this is probably the main reason for the lack of quantitative data in this field.

In the present paper the hydroformylation of (*E*)- and (*Z*)-3-methyl-2-pentene, as well as of the three isomeric methylcyclohexenes, of 1,2-dimethylcyclohexene, and of 2-methyl-1-methylidenecyclohexane is described. Conclusive evidence is provided that both rhodium and cobalt catalysts promote a stereospecific cis addition of carbon monoxide and hydrogen to the double bond. From the results obtained a deeper insight has been achieved for the isomerization phenomena accompanying the hydroformylation. Furthermore the existence of at least two different mechanisms responsible for the formation of isomeric aldehydes, other than those predicted from the direct hydroformylation of the double bond, has been proved.

Results and Discussion

(A) Hydroformylation of (*E*)- and (*Z*)-3-Methyl-2-pentene with Hydridocarbonyltris(triphenylphosphine)rhodium or Dicobalt Octacarbonyl as Catalyst Precursors. The absolute predominance of the threo or of the erythro isomer, obtained in the hydroformylation of (*E*)- or (*Z*)-3-methyl-2-pentene (Table I), indicates, beyond any doubt, the overwhelming cis stereochemistry of the rhodium-catalyzed hydroformylation.

The relatively small amounts of erythro or threo epimer obtained from (*E*) and (*Z*) substrate, respectively, might be accounted for by either a trans hydroformylation of the original olefin or a cis hydroformylation of the cis–trans isomerized substrate. Beside the already published results,[5] the following points should be mentioned: (a) The degree of deuteration of the substrate skeleton, as shown by the analysis of the methyl esters obtained from the primary reaction products, is the following: methyl *threo*-2,3-dimethylpentanoate was monodeuterated ($d_1 > 90\%$), methyl *erythro*-2,3-dimethylpentanoate, methyl 3-ethylpentanoate, and methyl 4-methylhexanoate were dideuterated ($d_2 > 90$, 80, and 85%, respectively). (b) No deuterium scrambling seems to occur during the reaction. Within the limits of NMR analysis, deuterium occupies only position 3 in methyl *threo*-2,3-dimethylpentanoate and only positions 3 and 4 in methyl 3-ethylpentanoate and methyl

Table I. Conditions and Reaction Mixture Composition at 50% Conversion,[a] of Rhodium- and Cobalt-Catalyzed Hydroformylation of (*E*)- and (*Z*)-3-Methyl-2-pentene

Substrate config	Catalyst precursor	Initial pressure[b] ($CO:H_2$ = 1:1), atm	Temp, °C	% aldehydes: 2,3-Dimethylpentanal Erythro	2,3-Dimethylpentanal Threo	4-Methylhexanal	3-Ethylpentanal	% residual olefins 3-methyl-2-pentene: (*E*)	(*Z*)
(*E*)	$HRhCO(PPh_3)_3$	80	80	5	81	11	3	94	6
(*Z*)				78	7	12	3	8	92
(*E*)	$Co_2(CO)_8$	180	115	2.5	3.5	76	18	91	9
(*Z*)				3	4	76	17	14	86

[a] Based on gas absorption. [b] Measured at room temperature.

4-methylhexanoate. The deuterium position in methyl *erythro*-2,3-dimethylpentanoate was not determined.

The results provide therefore the evidence for a complete cis stereochemistry of the rhodium-catalyzed hydroformylation. However, in view of the fact that the "oxo" reaction is a multistep process,[8] the question whether the observed cis addition to the double bond is the overall result of a double trans addition, was not solved by the above experiment.

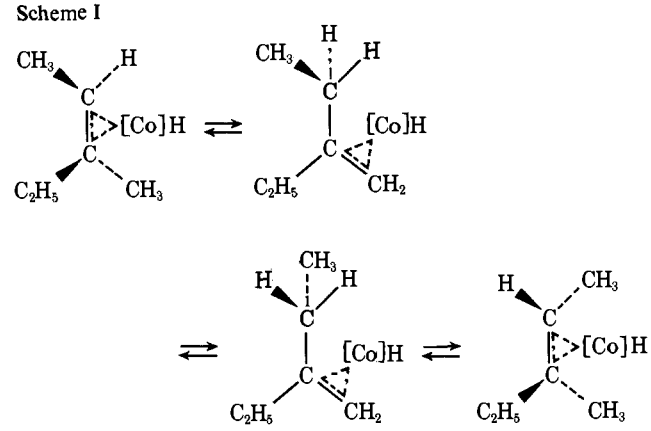
Furthermore, the amount and position of deuterium incorporated can be taken as an indication that formylation at positions 4 and 5 is indeed negligible.

The small extent of substrate isomerization accompanying hydroformylation indicates that carbon monoxide insertion in the intermediate secondary alkylrhodium complex is considerably faster than rhodium–hydride elimination. The formation of the tertiary alkyl–rhodium intermediate is considerably less preferred than that of the secondary one, but not negligible, as shown by the cis–trans substrate isomerization, and by the formation of 3-ethylbutanal. Therefore, the fact that 2-methyl-2-ethylbutanal has not been detected among the products, must be largely ascribed to a very low ratio between carbon monoxide insertion and rhodium hydride elimination in the case of the tertiary alkylrhodium intermediate.

A completely different picture was obtained in the cobalt-catalyzed hydroformylation of the same olefins (Table I). The conditions used, viz., moderate temperature and high carbon monoxide pressure, were such as to minimize isomerization of the substrate,[9] and indeed the residual olefins after partial hydroformylation contained only a small amount of isomers. The extent of cis–trans isomerization is similar to that observed in the rhodium-catalyzed reactions. Nevertheless isomerization, apparently without the intermediacy of free isomerized olefin, was very extensive, as more than 90% of the formylation occurred at the terminal positions of the substrate. The 2,3-dimethylpentanal consisted of approximately the same epimeric composition, with a slight predominance of the threo form, when either (*E*)- or (*Z*)-3-methyl-2-pentene was used as substrate. However, this result cannot be assumed as evidence for the lack of stereospecificity of the cobalt-catalyzed hydroformylation. In fact the well-known hydrogen shift phenomena[7,10] occurring more rapidly than carbon monoxide insertion in the intermediate alkyl–cobalt complex can cause the formation of both epimeric secondary alkyl–cobalt complexes. Therefore similar epimeric composition of the products can be obtained, irrespective of the geometry of the original double bond in the substrate.[11]

A possible way to explain both the cis–trans isomerization of the substrate and the lack of stereospecificity in the formation of the two diastereomeric 2,3-dimethylpentanals is to postulate that the change in the stereochemistry of the II-complexes, generally assumed as intermediates, is more rapid than complex dissociation and aldehyde formation. A possible path for the above change is shown in Scheme I, in which only two of the five possible II-complexes are shown.

Scheme I



Taking into account the results obtained in the hydroformylation of 3-methyl-2-pentene, it appeared that, in order to give information on the stereochemistry of the reaction, the substrate should fulfill the following conditions: (a) Two new asymmetric carbon atoms must arise from the reaction, as in the case of 3-methyl-2-pentene. (b) No cis–trans isomerization must be possible. (c) No double bond shift must be possible, or, if it is, it must occur through a stereospecific hydrogen shift.

The first two conditions can be satisfactorily fulfilled by 1-alkyl-substituted cycloolefins. Concerning condition c, it has already been shown that, at high carbon monoxide pressure, double bond shift can occur without dissociation of the unsaturated substrate from the catalyst,[1] and that, at least when a tertiary carbon atom is involved in the double bond shift, the reaction is largely stereospecific.[10,12]

In view of the above considerations, 1-methylcyclohexene was chosen as the substrate for further investigation. In fact, the direct hydroformylation of the double bond, occurring with cis stereochemistry, would yield in this case *trans*-2-methylcyclohexanecarboxaldehyde. If double bond shift occurs in the ring through a stereospecific hydrogen shift, the isomeric aldehydes formed should have trans configurations as well.

(B) Hydroformylation of Methylcyclohexenes with Rhodium(III) Oxide or Dicobalt Octacarbonyl as Catalyst Precursors. The three isomeric cyclohexenes were first hydroformylated with a rhodium catalyst, to check how the already proved cis stereochemistry of the hydrogen and carbon monoxide addition, and the accompanying substrate isomerization, would operate with the above substrates.

1-Methylcyclohexene gave no reaction with carbon monoxide and hydrogen in the presence of the Wilkinson catalyst even using more vigorous conditions than usual (up to 150 °C, under 160 atm total pressure of a 1:1 mixture of CO and H_2). However, hydroformylation occurred at 100 °C and 100 atm using Rh_2O_3 as a catalyst precursor. Under the same conditions 3- and 4-methylcyclohexene were hydroformylated. The

Table II. Reaction Conditions and Product Composition of Rhodium- and Cobalt-Catalyzed Hydroformylation of Methyl-Substituted Cyclohexenes

Cyclohexene derivative	Catalyst precursor	Initial pressure,[a] atm CO	Initial pressure,[a] atm H_2	Temp, °C	Hydroformylation products, % Cyclohexanecarboxaldehyde -2-Methyl Trans	-2-Methyl Cis	-3-Methyl Trans	-3-Methyl Cis	-4-Methyl Trans	-4-Methyl Cis	Cyclohexaneacetaldehyde
1-Methyl	Rh_2O_3	50	50	100	85	1.5	2.5	3.5	—	—	7.5
3-Methyl	Rh_2O_3	50	50	100	25.5	6	19	45	3.5	<1	<1
4-Methyl	Rh_2O_3	50	50	100	1	<0.5	21	29	29	19	—
1-Methyl	$Co_2(CO)_8$	100	50	120	28	<0.5	10	4	36	<1	20
3-Methyl	$Co_2(CO)_8$	100	50	120	19	<1	8	43.5	20	3	5.5
4-Methyl	$Co_2(CO)_8$	100	50	120	11	<1	6	51	24.5	4	3
1-Methyl	$Co_2(CO)_8$	5	100	120	17	1	9	22	16	4	31

[a] Measured at room temperature.

results are summarized in Table II along with those obtained from the cobalt-catalyzed reactions.

As generally observed with rhodium catalysts, hydroformylation occurred mainly at the position of the double bond in the starting substrate (>86% in 1-methyl-, and >95% in 3- and 4-methylcyclohexene). The formylation at initially saturated carbon atoms being a minor phenomenon, the mechanism of isomerization involved was not investigated.

The large prevalence of *trans*-2-methylcyclohexanecarboxaldehyde in the hydroformylation products of 1-methylcyclohexene is in agreement with the expected cis stereochemistry. The stereospecificity of the reaction, as in the case of 3-methyl-2-pentene, is probably complete. In fact the small amount of *cis*-2-methylcyclohexanecarboxaldehyde arises presumably from the hydroformylation of small amounts of 3-methylcyclohexene formed by isomerization of the original substrate.

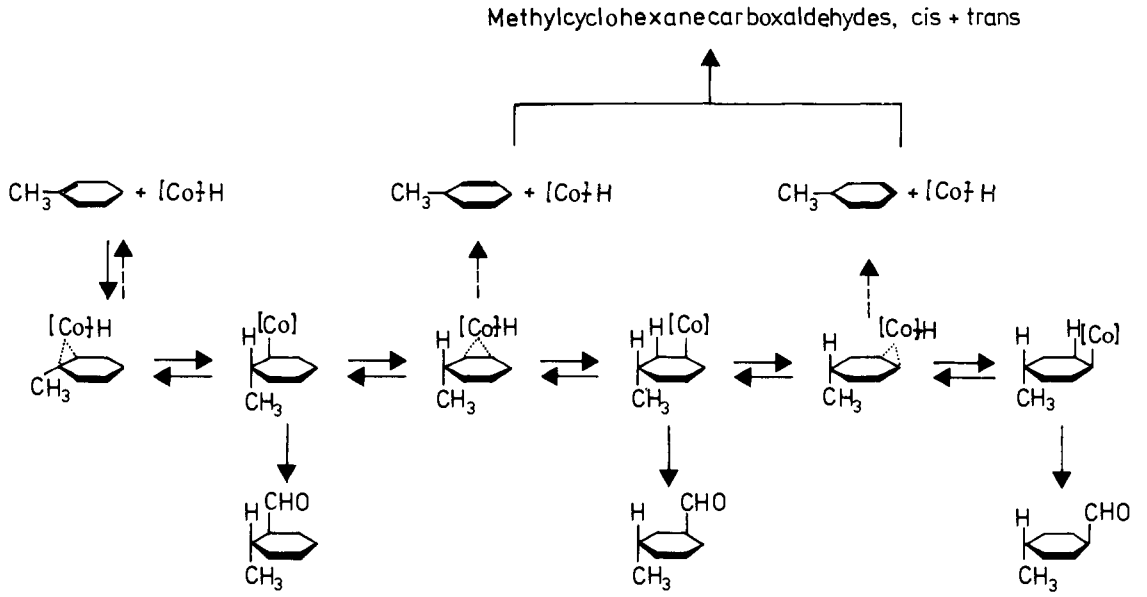
The hydroformylation of 3- and 4-methylcyclohexene did not display a significant diastereoselectivity, the ratio between the *cis*- and *trans*-methylcyclohexanecarboxaldehydes being very close to unity in both cases. However, regioselectivity on the two faces of the cyclohexane ring is remarkably different. On the cis side, with respect to the methyl group, the formation of 3-methylcyclohexanecarboxaldehyde is preferred over the other two isomers. On the trans side the formation of the above compound is disfavored with respect to the alternate expected product (2-methyl- or 4-methylcyclohexanecarboxaldehyde). In each case, between the two alternative products, the isomer prevails which, by analogy with the corresponding dimethylcyclohexanes,[13] should have the higher thermodynamic stability. As the hydroformylation is not a reversible reaction, thermodynamic control of the product composition must be excluded. The present data are not sufficient to establish whether the observed regularity is occasional or reflects an influence of thermodynamic factors on the kinetically controlled product composition.[14]

When dicobalt octacarbonyl was used as catalyst precursor, the hydroformylation of the methyl-substituted cyclohexenes afforded, as expected, quite a different picture. Inspection of the results obtained at high carbon monoxide partial pressure (Table II) reveals the following: (a) Contrary to the general experience that the cobalt-catalyzed hydroformylation of internal olefins gives predominantly carbon monoxide insertion at the terminal ends of the substrate,[15] in the case of the cycloolefins investigated, only a minor amount of the products arises from the formylation of the methyl group, the amount decreasing by increasing the distance between methyl group and double bond in the substrate. (b) A comparable extent of formylation occurs at the nonsubstituted ring positions, independently of the olefin used. (c) More than 90% of the methylcyclohexanecarboxaldehydes obtained from 1-methylcyclohexene have trans configuration. (d) The cis/trans ratio, calculated for the same products obtained from both 3- and 4-methylcyclohexene, is not far from unity, showing, as in the case of the rhodium-catalyzed hydroformylation, no significant diastereoselectivity of the reaction. (e) In any case the formylation takes place on the cis or trans side of the cyclohexane ring with a well-defined regioselectivity, which is influenced only to a small extent by the original position of the double bond; the extent of carbon monoxide addition to the different positions decreases in the order 4 > 2 > 3, with respect to the methyl group, when leading to products having trans configuration, and in the order 3 > 4 > 2 when leading to products having cis configuration.

The favorable trans/cis ratio of the 2-methylcyclohexanecarboxaldehyde, considered as the direct hydroformylation product of 1-methylcyclohexene, cannot be taken by itself as sufficient evidence for the stereochemistry of the reaction; in fact the formation of the cis isomer by hydroformylation is highly unfavorable, as shown by the products obtained from 3-methylcyclohexene.

The fact that, in the absence of diastereoselectivity in the hydroformylation of 3- and 4-methylcyclohexene, an overwhelming amount of isomeric *trans*-methylcyclohexanecarboxaldehydes is obtained in the hydroformylation of 1-methylcyclohexene, shows that a stereospecific migration of the catalyst occurs along the substrate skeleton, without substantial dissociation of isomerized olefin. A possible mechanism that could explain the observed phenomenon is illustrated in Scheme II,[16] in which the double arrows indicate the reversibility of the reaction, but not the reaching of the equilibrium between the intermediates involved; in fact the product composition depends appreciably on the original position of the double bond. The stereospecificity of the cobalt-promoted hydrogen shift, already proved in the case involving an optically active tertiary carbon atom,[10,12] has thus been more generally confirmed also in the case in which secondary carbon atoms are involved. Sound evidence for the type of stereochemistry in the cobalt-catalyzed hydroformylation can be obtained from the ratio between the sums of the isomeric *cis*- or *trans*-methylcyclohexanecarboxaldehydes obtained from 1-methylcyclohexene; the large prevalence of the *trans*-methylcyclohexanecarboxaldehydes (93:7) leaves no doubt that hydrogen and formyl group add to the cyclohexane ring almost completely from the same side. Therefore the cis stereochemistry is highly prevailing. It is not unreasonable to assume that the cobalt-catalyzed hydroformylation occurs with a completely cis stereochemistry, as in the case of the rhodium-catalyzed reaction. In fact, the methylcyclohexanecarboxaldehydes having cis configuration, formed in small quantities in the hydroformylation of 1-methylcyclohexene, probably originate from minor amounts of isomerized olefin released from the catalytic complex (Scheme II). On this basis, in view of the insignificant diastereoselectivity displayed in the

Scheme II[a]



[a] [Co]–H represents the catalytic system. Dotted arrows indicate slow reactions. Double arrows do not imply achievement of equilibrium conditions.

hydroformylation of 3- and 4-methylcyclohexenes, the total amount of isomerized olefin released from the catalytic complex prior to hydroformylation can be estimated at about 10–15%.

As far as the regioselectivity of the reaction is concerned, the composition of the reaction products as in the case of the rhodium-catalyzed hydroformylation, qualitatively reflects their relative thermodynamic stability evaluated on the basis of the data concerning the dimethylcyclohexanes. However, in this case the choice of the position for the carbon monoxide insertion is not limited to the two carbon atoms engaged in the original double bond.

The hydroformylation of olefins in the presence of cobalt catalysts under low carbon monoxide partial pressure[17] shows many peculiar features in comparison with the hydroformylation at high pressure. It was therefore interesting to investigate the hydroformylation of 1-methylcyclohexene at low pressure. The result obtained is summarized in the last line of Table II: in comparison with the data relative to the analogous reaction under higher pressure, a drastic reduction of the ratio between *trans*- and *cis*-methylcyclohexanecarboxaldehydes, and a higher percentage of cyclohexaneacetaldehyde can be noticed. Whether these differences are due to a change of the reaction mechanism and lack of stereospecificity or simply to the higher rate of substrate isomerization prior to hydroformylation cannot be established from the available data. However, on the basis of the present knowledge of hydroformylation at low carbon monoxide pressure, the second hypothesis seems more probable.

(C) Hydroformylation of 1,2-Dimethylcyclohexene and 2-Methyl-1-methylidenecyclohexane with Rhodium(III) Oxide or Dicobalt Octacarbonyl as Catalyst Precursors. A further contribution to the knowledge of the stereochemistry of hydroformylation arises from experiments carried out on 1,2-dimethylcyclohexene and 2-methyl-1-methylidenecyclohexane. Both olefins were hydroformylated in the presence of rhodium or cobalt catalyst under the conditions used for the hydroformylation of tetrasubstituted ethylenes.[18] In the case of the rhodium catalyst, the conditions were vigorous enough to reduce the aldehydes formed to alcohols. The isomeric composition of the reaction products (Table III) has not been fully investigated, since instead our attention was focused on the comparison between the diastereomeric compositions of 2-methyl-1-cyclohexaneacetaldehyde generated from the two substrates. With the rhodium catalyst, both olefins afforded *trans*- and *cis*-2-methyl-1-cyclohexaneacetaldehyde. The trans/cis ratio (~4) is practically identical in the two cases, in agreement with the fact that isomerization of the substrate should precede the hydroformylation (see section A), and 2-methyl-1-methylidenecyclohexane is the common precursor of the two aldehydes (Scheme III).

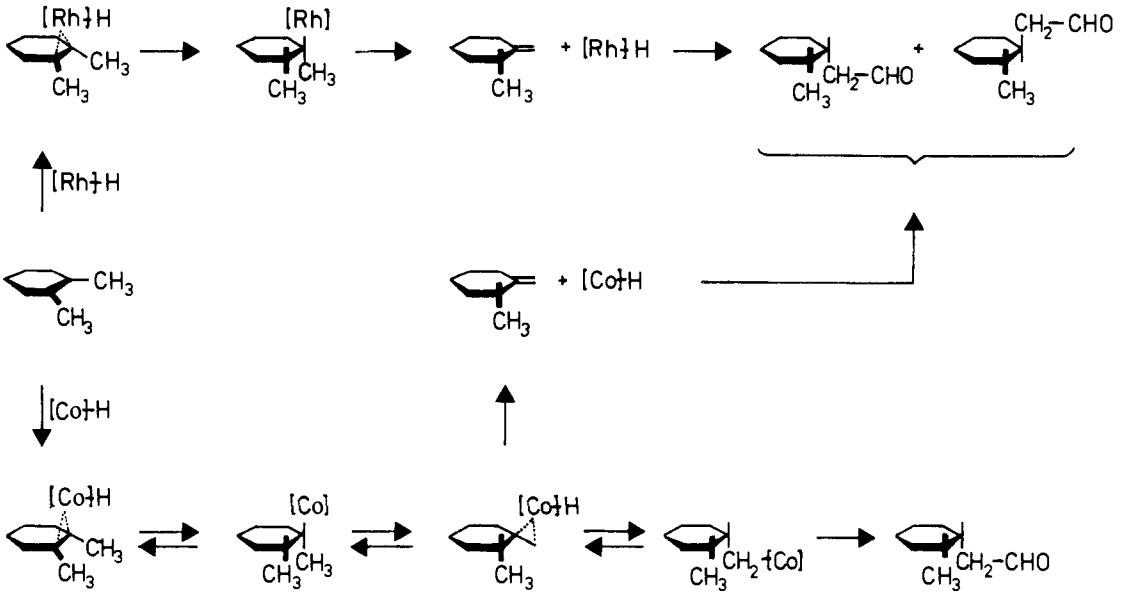
With cobalt catalyst, at high carbon monoxide pressure, the same products were obtained with substantially different diastereomeric compositions from the two substrates: the trans configuration prevails by a factor of 2, in the products obtained from 2-methyl-1-methylidenecyclohexane, while the cis configuration dominates (cis/trans ~ 7) in the 2-methyl-1-cyclohexaneacetaldehyde obtained from 1,2-dimethylcyclo-

Table III. Reaction Conditions and Product Composition of Rhodium- and Cobalt-Catalyzed Hydroformylation of 1,2-Dimethylcyclohexene and 2-Methyl-1-methylidenecyclohexane

Substrate	Catalyst precursor	Initial pressure,[a] atm CO	Initial pressure,[a] atm H_2	Temp, °C	Primary hydroformylation products, % 2-Methyl-1-cyclohexane-acetaldehyde (cis:trans)	Primary hydroformylation products, % Dimethyl-cyclohexane-carboxal-dehydes
1,2-Dimethylcyclohexene	Rh_2O_3	50	50	120	78 (21:79)	22
2-Methyl-1-methylidenecyclohexane	Rh_2O_3	50	50	120	94 (20:80)	6
1,2-Dimethylcyclohexene	$Co_2(CO)_8$	100	50	100	56 (88:12)	44
2-Methyl-1-methylidenecyclohexane	$Co_2(CO)_8$	100	50	100	94 (34:66)	6

[a] Measured at room temperature.

Scheme III[a]



[a] [Rh]–H and [Co]–H represent the two catalytic systems.

hexene. This fact confirms once more the existence, along with the substrate isomerization, of an independent mechanism actively operating with cobalt catalysts at high carbon monoxide pressure, responsible for the formation of isomeric aldehydes, in which the formyl group occupies initially saturated positions. As already pointed out in the previous discussion, such a reaction occurs through the stereospecific migration of the cobalt atom of the catalytic complex along the skeleton of the substrate; therefore, as illustrated in the Scheme III, in the reaction with 1,2-dimethylcyclohexene, the configuration of the two carbon atoms originally involved in the double bond is fixed by the addition of the cobalt and hydrogen atoms and maintained throughout the isomerization process.[19] Thus the prevailing cis configuration found in the hydroformylation product reflects the cis stereochemistry of the initial cobalt-hydride addition to the double bond, ruling out, in the case of the cobalt catalyst, the possibility, mentioned in the foregoing discussion, that the observed cis stereochemistry of the hydroformylation reaction might be the overall result of a double trans addition. According to the mechanism illustrated in the Scheme III, the amount of *trans*-2-methyl-1-cyclohexaneacetaldehyde obtained from the cobalt-catalyzed hydroformylation of 1,2-dimethylcyclohexene allows an estimation of the accompanying substrate isomerization: taking into account the observed diastereoselectivity of the reaction with 2-methyl-1-methylidenecyclohexane (Table III), the extent of olefin isomerization can be estimated at 18%.

Conclusions

The present investigation has brought some interesting contributions to the knowledge of both the stereochemistry and the mechanism of the rhodium- and cobalt-catalyzed hydroformylation.

As far as the stereochemistry of the reaction is concerned, conclusive evidence has been found that the addition of carbon monoxide and hydrogen to the double bond occurs according to a cis stereochemistry with both catalytic systems. The possibility that the observed cis stereochemistry might be the overall result of a double trans addition has been ruled out at least in the case of the cobalt.

No conclusion has been reached concerning the stereochemistry of the cobalt-catalyzed hydroformylation, at low carbon monoxide partial pressure, although no evidence against a cis stereochemistry has been found.

Very low diastereoselectivity has been observed in the hydroformylation of 3- and 4-methylcyclohexene in the presence of either catalyst. In the case of 2-methyl-1-methylidenecyclohexane as the substrate, however, diastereoselectivity favored the product with trans configuration. Two times higher diastereoselectivity was observed with rhodium than with cobalt.

A peculiar regioselectivity has been observed in the rhodium- and cobalt-catalyzed hydroformylation of the methylcyclohexenes: the relative abundances of the products obtained seem to reflect, in a qualitative way, the respective thermodynamic stabilities.

Concerning the isomerization phenomena accompanying the hydroformylation, the existence of two different mechanisms for the formation of aldehydes, in which an originally saturated carbon atom bears the formyl group, has been proved. The one involves double bond shift in the substrate with formation of free isomerized olefin through consecutive additions and eliminations of metal hydride: this mechanism is operative with rhodium catalyst and prevails with cobalt catalyst at low, while playing a minor role at high, carbon monoxide pressure. The second one, prevailing with cobalt catalyst at high carbon monoxide pressure, involves a stereospecific migration of the metal atom along the skeleton of the substrate, accompanied by 1,2 hydrogen shifts: in this case, speaking about olefin isomerization[7] may be misleading, as actually an intramolecular isomerization of the catalyst-olefin complex, without formation of free isomerized olefin is taking place. The mechanism of the stereospecific migration of the cobalt along the olefin skeleton is still open to discussion. Besides a series of cobalt hydride additions and eliminations with intermediate Π olefin complexes formation (see reference in the note 7), an interconversion of the Π-complexes, involving 1,2 hydrogen shifts but not the intermediate formation of alkyl-cobalt species, should be considered.[20]

Experimental Section

VPC analyses were made on a Perkin-Elmer vapor fractometer 990; preparative separations were performed on a Perkin-Elmer gas chromatograph F21. Mass spectra were measured with an Hitachi mass spectrometer RMU-6L at 70 eV. NMR spectra at 100 MHz were obtained with a Varian spectrometer HA-100.

Hydroformylation Reactions. The reactions were carried out according to standard procedures[17] in stainless steel autoclaves using

benzene as the solvent. The conditions of pressure and temperature used in each reaction are reported in the tables. Dicobalt octacarbonyl prepared according to Orchin et al.,[21] hydridocarbonyltris(triphenylphosphine)rhodium prepared according to Wilkinson et al.,[22] or commercial rhodium(III) oxide (Fluka AG, Switzerland) were used as catalysts. The hydroformylations of (*E*)- and (*Z*)-3-methyl-2-pentene were stopped when the drop of pressure indicated 50% conversion. Conversions between 50 and 75% were obtained in the cobalt-catalyzed, and between 80 and 95% in the rhodium-catalyzed, hydroformylation of the other substrates.

Analysis of the Reaction Mixtures. (A) From Hydroformylation of 3-Methyl-2-pentenes. The reaction mixtures were analyzed as described in a previous communication.[5]

(B) From the Deuterioformylation of (*E*)-3-Methyl-2-pentene in the Presence of Hydridocarbonyltris(triphenyphosphine)rhodium. Qualitative and quantitative determination of the reaction mixture composition was made with the same procedure used for the hydroformylation mixtures. The deuterium content in each component was determined by gas chromatography–mass spectrometry. The methyl esters derived from the deuterioformylation products[9] were separated by preparative VPC (4.50 m × 9.5 mm column packed with polypropylene glycol 20% on Chromosorb A) and pure samples of methyl 4-methylhexanoate-*3,4*-d_2 (isotopic purity >85%) and methyl 3-ethylpentanoate-*3,4*-d_2 (isotopic purity >80%), along with a mixture containing 94% methyl *threo*-2,3-dimethylpentanoate-*3*-d_1 (isotopic purity >90%) and 6% methyl *erythro*-2,3-dimethylpentanoate-d_2 (isotopic purity >90%), were obtained. The isotopic purities were determined by mass spectral analysis, and the positions of the deuterium atoms by comparison of the NMR spectra of the deuterated esters with those of undeuterated samples.

(C) From Hydroformylation of Methylcyclohexenes. The mixture of aldehydes obtained in each experiment was converted to a mixture of methyl esters of the corresponding acids according to a procedure described elsewhere.[9] VPC analysis of the esters was performed on a 50 m × 0.25 mm column coated with Apiezon L at 90 °C; the single components were identified against standards with the aid of combined VPC–MS analysis, and quantitative determinations were made on the basis of the chromatograms. Possible alterations of the compositions throughout the transformations and handling of the products were minimized by paying particular care at driving to completeness the reactions and avoiding the isolation of the products from the mixtures. Good reproducibility (within 5% approximation) was observed in repeated experiments. Standard samples of the expected methyl esters were prepared by catalytic hydrogenation (Raney nickel, 150 atm, 120 °C) of *o*-, *m*-, or *p*-toluic acid and phenylacetic acid methyl esters, respectively. Cis and trans isomers obtained in unequal amounts from the hydrogenations were identified after conversion of the isomer pairs to the corresponding dimethylcyclohexanes, in essentially quantitative yields, by consecutive treatments with $LiAlH_4$, methanesulfonyl chloride, and $LiAlH_4$.[23] Authentic samples of the six dimethylcyclohexanes were used as standard for the identifications. The transformation of the ester functions to methyl groups did not alter the cis/trans ratios of the pair of isomers, thus giving the clue for the correct assignment of the configuration to each ester.

VPC analysis under the above specified conditions, of a mixture containing all the seven methyl esters, gave six peaks, corresponding, in the order of elution, to *trans*-2-methyl-, *trans*-3-methyl-, *cis*-4-methyl-, *cis*-2-methyl-, *cis*-3-methyl- + *trans*-4-methylcyclohexanecarboxylic acid, and cyclohexaneacetic acid. The relative contribution of *cis*-3-methyl- and *trans*-4-methylcyclohexanecarboxylic acid methyl esters to the fifth peak was determined in each case after treatment of the mixture with an excess of methylmagnesium iodide to give the corresponding alkyl-dimethylcarbinols: isolated peaks were obtained on VPC (same column, 100 °C) for *cis*-3-methylcyclohexyl- and *trans*-4-methylcyclohexyldimethylcarbinol.

(D) From Hydroformylation of 1,2-Dimethylcyclohexene and 2-Methyl-1-methylidenecyclohexane. *cis*- and *trans*-2-methyl-1-cyclohexaneacetaldehyde as well as the corresponding alcohols obtained in the rhodium catalyzed hydroformylation of 1,2-dimethylcyclohexene, were easily separated and quantitatively evaluated, by VPC, having the cis isomer, in both cases, higher retention time on Carbowax 20 M: this was determined after conversion to the corresponding methylethylcyclohexanes, by a procedure analogous to that used for the conversion of esters to hydrocarbons (section C), and comparison of the products with authentic samples of *cis*- and *trans*-2-methylethylcyclohexane. No attempt was made to identify the single isomeric dimethylcyclohexanecarboxaldehydes obtained from the hydroformylation of 1,2-dimethylcyclohexene and 2-methyl-1-methylidenecyclohexane. Their presence did not interfere, in the gas chromatographic analysis, with the methyl-1-cyclohexaneacetaldehydes.

References and Notes

(1) M. Orchin and W. Rupilius, *Catal. Rev.*, **6**, 85 (1972).
(2) A. L. Nussbaum, T. L. Popper, E. P. Oliveto, S. Friedman, and I. Wender, *J. Am. Chem. Soc.*, **81**, 1228 (1959).
(3) A. Rosenthal, *Adv. Carbohyd. Chem.*, **23**, 59 (1968).
(4) P. Pino, G. Consiglio, C. Botteghi, and C. Salomon, *Adv. Chem. Ser.*, **No. 132**, 295 (1974).
(5) A. Stefani, G. Consiglio, C. Botteghi, and P. Pino, *J. Am. Chem. Soc.*, **95**, 6504 (1973).
(6) R. Lai and E. Ucciani, *Adv. Chem. Ser.*, **No. 132**, 1 (1974).
(7) Usually the hydrogen shift reactions, evidenced by the isomeric products composition, are referred to as "olefin isomerization" (C. P. Casey and C. R. Cyr, *J. Am. Chem. Soc.*, **95**, 2240 (1973)); however, hydrogen shift reactions can occur also independently of the olefin isomerization. In particular, under high carbon monoxide pressure, they proceed even more rapidly than olefin dissociation, and are connected with the isomerization of the olefin–catalyst complex.
(8) G. Yagupsky, C. K. Brown, and G. Wilkinson, *J. Chem. Soc. A*, 1392 (1970).
(9) P. Pino, S. Pucci, F. Piacenti, and G. Dell'Amico, *J. Chem. Soc. C*, 1640 (1971).
(10) F. Piacenti, S. Pucci, M. Bianchi, R. Lazzaroni, and P. Pino, *J. Am. Chem. Soc.*, **90**, 6847 (1968).
(11) Similar ratio between *erythro*- and *threo*- 2,3-dimethylpentanal was observed in the hydroformylation product of 3-methyl-1-pentene.[9]
(12) F. Piacenti, M. Bianchi, and P. Frediani, *Adv. Chem. Ser.*, **No. 132**, 283 (1974).
(13) E. L. Eliel "Stereochemistry of Carbon Compounds", McGraw-Hill, New York, N.Y., 1962, p 211ff.
(14) W. J. le Noble and T. Asano, *J. Am. Chem. Soc.*, **97**, 1778 (1975).
(15) J. Falbe "Carbon Monoxide in Organic Synthesis", Springer-Verlag, Berlin, 1970, p 38.
(16) Other mechanisms can be conceived, in which Π-complex interconversion, accompanied by 1,2-hydrogen shifts, occurs without the formation of intermediate alkyl–cobalt complexes.
(17) F. Piacenti, P. Pino, R. Lazzaroni, and M. Bianchi, *J. Chem. Soc. C*, 488 (1966).
(18) W. Rupilius, Thesis, Technische Hochschule Aachen, 1969.
(19) Analogous stereospecificity has been observed when 1,2-dimethylcyclohexene was hydroborated, and the product made to rearrange: B. Rickborn and S. E. Wood, *J. Am. Chem. Soc.*, **93**, 3940 (1971).
(20) M. Bianchi, P. Frediani, U. Matteoli, A. Girolla, and F. Piacenti, *Chim. Ind. (Milan)*, **58**, 223 (1976).
(21) I. Wender, H. W. Sternberg, S. Metlin, and M. Orchin, *Inorg. Synth.*, **5**, 190 (1957).
(22) D. Evans, G. Yagupsky, and G. Wilkinson, *J. Chem. Soc. A*, 2660 (1968).
(23) C. Büchi, W. Hofheinz, and J. V. Paukstelis, *J. Am. Chem. Soc.*, **88**, 4113 (1966).