(54) NOVEL RUTHENIUM CARBONYL COMPLEX HAVING A TRIDENTATE LIGAND AND MANUFACTURING METHOD AND USAGE THEREOF

(57) The present invention relates to a ruthenium carbonyl complex that is represented by the following Formula (1):

\[ \text{RuXY(CO)(L)} \]  \hspace{1cm} (1)

(in the Formula (1), X and Y, which may be the same or different from each other, represent an anionic ligand and L represents a tridentate aminodiphosphine ligand which has two phosphino groups and a -NH- group), its production method, and a method for production of alcohols by hydrogenation-reduction of ketones, esters, and lactones using the complex as a catalyst.

The ruthenium carbonyl complex of the invention has a high catalytic activity and it can be easily prepared and handled.
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Description

TECHNICAL FIELD

[0001] The present invention relates to a novel ruthenium carbonyl complex having a tridentate ligand which contains two phosphino groups and a -NH- group, its production method, and a method for production of alcohols by hydrogenation-reduction of ketones, esters, or lactones using the complex as a catalyst.

BACKGROUND ART

[0002] A method of obtaining alcohols by reducing ketones, esters, and lactones is important in chemical synthesis. In terms of reduced by-product formation, good operability, and work safety, etc., reduction by catalytic hydrogenation is useful as a method for production of alcohols. Further, optically active alcohols are important as physiologically active materials such as pharmaceuticals, agrochemical agents, and aromachemicals, etc. and also as their synthetic intermediates. Asymmetric hydrogenation of ketones or hydrogenation-reduction of optically active esters is useful as a method for production of optically active alcohols. Ruthenium complexes having polydentate ligands are one of such reducing catalysts.

[0003] As for the ruthenium complex having a tridentate ligand which contains two phosphino groups and a -NH- group, a dichloro complex is described in Patent Document 1. Further, in Non-patent Document 1, a dichloro complex or a hydride complex having a trimethyl phosphate as a ligand is described. However, these complexes do not have a carbonyl ligand. Further, although a ruthenium complex having a tridentate ligand which contains two phosphino groups and a pyridine ring and a carbonyl ligand has been reported in Non-patent Documents 2, 3 and 4, no -NH- group is contained in the tridentate ligand.

[0004] With regard to the ruthenium dichloro complex disclosed in Patent Document 1, it is reported that ketones are hydrogenated and reduced in the presence of a base to give alcohols. However, no description is included regarding the reduction of esters or lactones. The ruthenium phosphate complex disclosed in Non-patent Document 1 is reported as a catalyst for dehydrogenation of ammonia-borane. However, hydrogenation-reduction of ketones, esters, and lactones is not described. Further, as the ruthenium phosphate complex has been reported to be unstable, its industrial application is difficult due to disadvantage in handling. Further, although it has been reported that the ruthenium complex having a pyridine ring as disclosed in Non-patent Document 2 or Non-patent Document 3 can catalyze the hydrogenation-reduction of esters or the ester synthesis reaction based on dehydrogenation of alcohols, there is a problem in that not only low temperature is required for the synthesis of the complex but also complicate procedures and the radical reaction using a tin compound, which is undesirable in terms of industrial application, are used for the synthesis of the ligand, etc. In particular, because the ruthenium complex having a pyridine ring described in Non-patent Document 2 has low catalytic activity for hydrogenation-reduction of esters, development of a catalyst having higher catalytic activity has been waited for.

PRIOR ART DOCUMENTS

PATENT DOCUMENTS


NON-PATENT DOCUMENTS

SUMMARY OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0007] An object of the invention is to provide a novel ruthenium complex which can be prepared and handled easily and obtained with relatively low cost, its production method, and a technique of producing alcohols by hydrogenation-reduction of ketones, esters, and lactones using the complex as a catalyst.

MEANS FOR SOLVING THE PROBLEMS

[0008] Under the circumstances, as a result of intensive studies, the inventors of the invention developed a novel ruthenium complex having a tridentate ligand which contains two phosphino groups and an -NH- group and a carbonyl ligand. The ligands and the complex can be easily synthesized, have high stability, and can be easily handled.

[0009] Further, the inventors found that the ruthenium complex developed according to the invention has high catalytic activity for the hydrogenation-reduction of ketones, esters, and lactones, and therefore completed the invention.

[0010] In more detail, the invention is related to the following [1] to [18].

[1] A ruthenium carbonyl complex that is represented by the following Formula (1):

\[
\text{RuXY(CO)(L)} \quad (1)
\]

(in the Formula (1), X and Y, which may be the same or different from each other, represent an anionic ligand and L represents a tridentate aminodiphosphine ligand represented by the following Formula (2):

\[
\begin{align*}
\text{H} & \quad \text{Q}^1 & \quad \text{Q}^2 \\
\text{PR}^1 \text{R}^2 & \quad \text{PR}^3 \text{R}^4
\end{align*}
\]  

(2)

[0011] (in the Formula (2), R^1, R^2, R^3, and R^4, which may be the same or different from each other, represent a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkyloxy group, a cycloalkyloxy group, an aralkyloxy group, a heterocyclic group, or a substituted amino group, and R^1 and R^2 or R^3 and R^4 may bind to each other to form a ring with an adjacent phosphorus atom. Further, the alkyl group, cycloalkyl group, aryl group, aralkyl group, alkyloxy group, cycloalkyloxy group, aralkyloxy group, heterocyclic group, and substituted amino group may have a substituent group. Q^1 and Q^2, which may be the same or different from each other, represent a divalent alkylene group which may have a substituent group, a divalent cycloalkylene group which may have a substituent group, or a divalent aralkylene group which may have a substituent group or a divalent aralkylene group which may have a substituent group).

[2] The ruthenium carbonyl complex according to [1], wherein the tridentate aminodiphosphine ligand L is represented by the following Formula (3):

\[
\begin{align*}
\text{R}^5 & \quad \text{R}^6 & \quad \text{R}^7 & \quad \text{R}^8 \\
\text{PR}^1 \text{R}^2 & \quad \text{PR}^3 \text{R}^4
\end{align*}
\]  

(3)

[0012] (in the Formula (3), R^5, R^6, R^7, and R^8, which may be the same or different from each other, represent a hydrogen atom, an alkyl group which may have a substituent group, a cycloalkyl group which may have a substituent group, an aryl group which may have a substituent group, an aralkyl group which may have a substituent group, or an aralkyl group which may have a substituent group. n represents an integer of 0 to 3).

[3] The ruthenium carbonyl complex according to [1], wherein the tridentate aminodiphosphine ligand L is represented by the following Formula (4):

[0013]
[0016] (in the Formula (4), Ar1, Ar2, Ar3, and Ar4, which may be the same or different from each other, represent an aryl group or an aromatic heterocyclic group. The aryl group and aromatic heterocyclic group may have a substituent group).

[04] The ruthenium carbonyl complex according to [3], wherein Ar1, Ar2, Ar3, and Ar4 in the Formula (4) is a phenyl group which may have a substituent group.

[05] The ruthenium carbonyl complex according to any one of [1] to [4], wherein the tridentate aminodiphosphine ligand L is represented by the following Formula (5):

[0017]

[0018] (in the Formula, Ph represents a phenyl group).

[06] The ruthenium carbonyl complex according to [1] or [2], wherein the tridentate aminodiphosphine ligand L is optically active.

[07] The ruthenium carbonyl complex according to any one of [1] to [6], wherein the anionic ligand X is a hydride and the anionic ligand Y is a chloride ion in the Formula (1).

[08] The ruthenium carbonyl complex according to any one of [1] to [6], wherein the anionic ligand X is a hydride and the anionic ligand Y is BH4 in the Formula (1).

[09] A method of producing the ruthenium carbonyl complex represented by the Formula (1) by reacting the tridentate aminodiphosphine ligand L represented by the Formula (2) and RuXY (CO) (P(Ar5)3)3 (in the formula, Ar5 may be the same or different from each other and represents an aryl group which may have a substituent group).

[10] The method according to [9], wherein Ar5 is a phenyl group.

[11] The method according to [9] or [10], wherein the tridentate aminodiphosphine ligand L represented by the Formula (2) is a tridentate aminodiphosphine ligand L represented by the Formula (5).

[12] The method according to any one of [9] to [11], wherein RuXY(CO)(P(Ar5)3)3 is RuHCl(CO) (PPh3)3.

[13] A method of producing a ruthenium carbonyl complex represented by the following Formula (6) by reacting RuHCl (CO)(PPh3)3 and a tridentate aminodiphosphine ligand L represented by the Formula (5):

[0019]

[0020] A method of producing a ruthenium carbonyl complex represented by the following Formula (7) by reacting the ruthenium carbonyl complex represented by the Formula (6) and NaBH4:

[0021]
A method of producing alcohols according to the hydrogenation-reduction of ketones by using a hydrogen
donor in the presence of the ruthenium carbonyl complex according to any one of [1] to [8].

A method of producing optically active alcohols according to the asymmetric hydrogenation-reduction of ketones
by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to any one of [6] to [8].

A method of producing alcohols according to the hydrogenation-reduction of esters or lactones by using a hydrogen
donor in the presence of the ruthenium carbonyl complex according to any one of [1] to [8].

A method of producing optically active alcohols according to the hydrogenation-reduction of optically active esters
or optically active lactones by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to
any one of [1] to [8] while maintaining the optical activity of the esters or the lactones.

EFFECTS OF THE INVENTION

The novel ruthenium carbonyl complex of the invention can be easily prepared from a tridentate aminodiphosphine
ligand and a precursor ruthenium carbonyl complex, and the tridentate aminodiphosphine ligand can be easily
prepared by reacting a bisalkylamine having a leaving group with a phosphine compound in the presence of a base.
Further, the precursor ruthenium carbonyl complex can be easily prepared from an inorganic ruthenium compound that
is easily obtainable. Accordingly, the ruthenium carbonyl complex of the invention can be easily prepared and has high
stability and good handleability, and therefore it is suitable for industrial application. The ruthenium carbonyl complex of
the invention exhibits high catalytic activity even under a relatively mild reaction condition, and it can catalyze the
hydrogenation-reduction of ketones, esters, or lactones in the presence of a hydrogen donor to produce alcohols with
high yield. Further, if an optically active ligand is used, optically active alcohols can be synthesized according to asym-
metric hydrogenation-reduction of ketones. Still further, even when the esters or lactones to be hydrogenated and reduced
are optically active substances, they can be reduced to optically active alcohols without being accompanied with a
significant decrease in the optical purity.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 represents a schematic drawing of the chemical structure of the ruthenium carbonyl complex 18 of the
invention based on the X-ray structure analysis of the complex 18.

MODES FOR CARRYING OUT THE INVENTION

First, the ruthenium carbonyl complex of the invention that is represented by the following Formula (1) will be
explained.

\[ \text{RuXY(CO)(L)} \] (1)

(in the Formula (1), X and Y, which may be the same or different from each other, represent an anionic ligand and L
represents a tridentate aminodiphosphine ligand that is represented by the following Formula (2)).

\[ \text{Q}^1 \text{N} \text{Q}^2 \]
\[ \text{PR}^1 \text{R}^2 \text{PR}^3 \text{R}^4 \] (2)

(in the Formula (2), R^1, R^2, R^3, and R^4, which may be the same or different from each other, represent a
hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkoxy group, a cycloalkyloxy
group, an aryloxy group, an aralkyloxy group, a heterocyclic group, or a substituted amino group, and R^1 and R^2 or R^3
and R^4 may bind to each other to form a ring with an adjacent phosphorus atom. Further, the alkyl group, cycloalkyl
group, aryl group, aralkyl group, cycloalkyloxy group, aryloxy group, aralkyloxy group, and heterocyclic
group may have a substituent group, respectively. Q^1 and Q^2, which may be the same or different from each other,
represent a divalent alkylene group which may have a substituent group, a divalent cycloalkylene group which may have
a substituent group, or a divalent aralkylene group which may have a substituent group).
Explanations will be given to the tridentate aminodiphosphine ligand that is used in the invention. Examples of the tridentate aminodiphosphine ligand, that is expressed as L in the Formula (1), include a ligand which contains two phosphino groups and a -NH- group. Specific examples of the tridentate aminodiphosphine ligand include the ligand that is represented by the above Formula (2).

Examples of the substituent group which may be included in the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group in the substituted amino group may have an additional substituent group.

Examples of the substituent group which may be included in the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group may have an additional substituent group.

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Examples of the substituent group which may be included in the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group may have an additional substituent group.

Examples of the substituent group which may be included in the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group may have an additional substituent group.

Examples of the substituent group which may be included in the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group may have an additional substituent group.
Examples of the halogen atom as a substituent group for R1, R2, R3, and R4 include a fluorine atom, a chlorine atom, a bromine atom, and an iodine atom.

Examples of the silyl group as a substituent group for R1, R2, R3, and R4 include a group in which three hydrogen atoms of the silyl group are substituted with the alkyl group, cycloalkyl group, aryl group, or aralkyl group described above. Specific examples include a trimethylsilyl group, a triethylylsilyl group, a tert-butyldimethylsilyl group, and a triphenylsilyl group.

Examples of the hydroxy group which is optionally protected as a substituent group for R1, R2, R3, and R4 include a non-protected hydroxy group, or a silyl group such as a trimethylsilyl group, a tert-butyldimethylsilyl group, and a tert-butyldiphenylsilyl group, or a hydroxy group which may be protected with a typical hydroxy-protecting group that is generally used for peptide syntheses, etc. as described in Reference 1 (Protective Groups in Organic Synthesis Second Edition, JOHN WILEY & SONS, INC. 1991), such as a benzyl group and a methoxymethyl group.

Examples of the divalent alkylene group include a linear or branched divalent alkyl chain which contains 1 to 20 carbon atoms, preferably 1 to 10 carbon atoms, and more preferably 1 to 6 carbon atoms. Specific examples include a methylene group, an ethylene group, a trimethylene group, and a tetramethylene group.

Further, examples of the divalent cycloalkylene group include a divalent group made of a monocyclic, polycyclic, or condensed-cyclic cycloalkyl group which contains 3 to 15 carbon atoms, preferably 3 to 10 carbon atoms, and more preferably 3 to 6 carbon atoms such as a cyclopentylenegroup, a cyclobutylene group, a cyclohexylene group, and a cyclohexylenegroup.

Further, examples of the divalent aralkylene group include a divalent group containing 7 to 11 carbon atoms in which one hydrogen atom is removed from the aryl group of the aralkyl group such as a benzyl group and a phenethyl group.

Examples include a benzylene group (−Ph−CH2−), a 2-phenylethylene group (−Ph−CH2CH2−), a 1-naphthylmethylene group (−Np−CH2−), and a 2-naphthylmethylene group (−Np−CH2−) (in the formulae, −Ph−represents a phenylene group and −Np− represents a naphthylene group).

Examples of the substituent group which may be included in the divalent alkylene group, divalent cycloalkylene group, or divalent aralkylene group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkyloxy group, a cycloalkyoxy group, an aralkyloxy group, a heterocyclic group, and a halogen atom, a silyl group, a substituted amino group, and a hydroxy group which is optionally protected, which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2).

Examples of the divalent anionic ligand that is represented by X or Y in the Formula (1) will be explained.

Examples of the monovalent anionic ligand include a hydride, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an hydroxy group, an acyloxy group, an alkoxy group, an aryloxy group, an aralkyloxy group, an amino group, a substituted amino group, and an hydroxy group which is optionally protected, which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2).

Examples of the acyloxy group include those expressed as (RaCO2). Examples of Ra in the acyloxy group R aCO2 include a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, and an aralkyl group. Examples of the alkyl group, cycloalkyl group, aryl group, and aralkyl group which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2)

Examples of the amino group which is optionally protected as a substituent group for R8 include a non-protected amino group; a mono- or dialkylamino group such as a N-methylamino group, a N,N-dimethylamino group, a N,N-diethylamino group, a N,N-disopropylamino group, and a N-cyclohexylamino group; a mono- or diarylamino group such as a N-phenylamino group, a N,N-diphenylamino group, a N-naphthylamino group, and a N,N-diphenyl-N-phenylamino group; a mono- or diarylalkylamino group such as a N-benzylamino group and a N,N-dibenzylamino group; an acyloxymine group such as a formylamino group, an acetylaminogroup, a propionyl amino group, a pivaloylamino group, a pentanoylamino group, a hexanoylamino group, and a benzoyl amino group; an alkoxycarbonylamino group such as a methoxycarbonylamino group, an ethoxy carbonylamino group, a n-propoxycarbonylamino group, a n-butoxycarbonylamino group, a tert-butoxycarbonylamino group, a pentyloxy carbonylamino group, and a hexyloxycarbonylamino group; an arloxycarbonylamino group such as a phenyloxycarbonylamino group; and an aralkyloxycarbonylamino group such as a benzy-
loxycarbonylamino group. Examples of the amino group which may be further protected include an amino group that is protected with a typical amino-protecting group generally used for peptide synthesis, etc. as described in the above Reference 1.

Examples of Rα include a methyl group, an ethyl group, a propyl group, a tert-butyl group, a trifluoromethyl group, a phenyl group, and a pentafluorophenyl group.

[0040] Examples of the sulfonyleoxy group include those that are expressed as (RβSO3). Examples of Rβ in the sulfonyleoxy group RβSO3 include those which are the same as Rα of the acyloxy group. Examples of the halogen ion include a fluoride ion, a chloride ion, a bromide ion, and an iodide ion. Preferably, it is a chloride ion and a bromide ion, and more preferably it is a chloride ion.

[0041] Examples of the preferred tridentate aminophosphine ligand include those that are represented by the following Formula (3).

\[ \text{Formula (3)} \]

\[
\begin{align*}
R^1 & \quad R^2 \quad P \\
R^3 & \quad R^4
\end{align*}
\]

[0042] (in the Formula (3), R5, R6, R7 and R8, which may be the same or different from each other, represent a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, or an aralkyl group, and R5 and R6 and R7 or R5, R6 and R7 or R8 may bind to each other to form a ring with an adjacent carbon atom. n represents an integer of 0 to 3. Further, the alkyl group, cycloalkyl group, aryl group, and aralkyl group may have a substituent group).

[0044] Examples of the alkyl group, cycloalkyl group, aryl group, and aralkyl group that are expressed as R5, R6, R7 and R8 in the Formula (3) include an alkyl group, a cycloalkyl group, an aryl group, and an aralkyl group which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2). Further, examples of the substituent group that may be contained in these alkyl group, cycloalkyl group, aryl group, and aralkyl group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkyloxy group, a cycloalkyloxy group, an aryloxy group, an aralkyloxy group, a heterocyclic group, and a halogen atom, a silyl group, a substituted amino group, and a hydroxy group which is optionally protected, which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2).

[0045] Examples of the preferred tridentate aminodiphosphine ligand include those that are represented by the following Formula (4).

\[ \text{Formula (4)} \]

\[
\begin{align*}
\text{PH} & \quad \text{N} \\
\text{Ar}^1 & \quad \text{Ar}^2 \\
\text{Ar}^3 & \quad \text{Ar}^4
\end{align*}
\]

[0046] In the Formula (4), Ar1, Ar2, Ar3, and Ar4, which may be the same or different from each other, represent an aryl group or an aromatic heterocyclic group. Further, the aryl group and the aromatic heterocyclic group may have a substituent group.

[0048] Examples of the aryl group and aromatic heterocyclic group in the Formula (4) include an aryl group that is the same as the one described with regard to R1, R2, R3 and R4 of the above Formula (2) or an aromatic heterocyclic group that is the same as the one described for the heterocyclic group. Further, examples of the substituent group that may be contained in these aryl group or aromatic heterocyclic group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkyloxy group, a cycloalkyloxy group, an aryloxy group, an aralkyloxy group, and a heterocyclic group, a silyl group, a substituted amino group, and a hydroxy group which is optionally protected, which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2).

[0049] Further, examples of the still more preferred tridentate aminodiphosphine ligand include those that are represented by the following Formula (5).
Further, the tridentate aminodiphosphine ligand that is represented by the Formula (2) or (3) may be used as a ligand for the ruthenium carbonyl complex represented by the Formula (1) as an optically active substance depending on the substituent group on Q1 or Q2, or R1 to R8.

Examples of the ruthenium compound that is a starting material for producing the ruthenium carbonyl complex of the invention include, although not specifically limited, an inorganic ruthenium compound such as RuCl$_3$ hydrate, RuBr$_3$ hydrate, and RuI$_3$ hydrate, RuCl$_2$(DMSO)$_4$, [Ru(cod)Cl$_2$]$_n$, [Ru(nbd)Cl$_2$]$_n$, (cod)Ru(2-methallyl)$_2$, [Ru(benzene)Cl$_2$]$_2$, [Ru(benzene)Br$_2$]$_2$, [Ru(benzene)I$_2$]$_2$, [Ru(p-cymene)Cl$_2$]$_2$, [Ru(p-cymene)Br$_2$]$_2$, [Ru(p-cymene)I$_2$]$_2$, [Ru(hexamethylbenzene)Cl$_2$]$_2$, [Ru(hexamethylbenzene)Br$_2$]$_2$, [Ru(hexamethylbenzene)I$_2$]$_2$, RuCl$_2$(PPh$_3$)$_3$, RuBr$_2$(PPh$_3$)$_3$, RuI$_2$(PPh$_3$)$_3$, RuH$_2$(PPh$_3$)$_3$, RuClH(PPh$_3$)$_3$, RuH(OAC)(PPh$_3$)$_3$, and RuH$_2$(PPh$_3$)$_3$. In the exemplified compounds, DMSO, cod, nbd, and Ph represents dimethyl sulfoxide, 1,5-cyclooctadiene, norbornadiene, and a phenyl group, respectively.

The ruthenium carbonyl complex represented by the Formula (1) can be easily prepared from the tridentate aminodiphosphine ligand and the precursor ruthenium carbonyl complex.

The tridentate aminodiphosphine ligand can be easily prepared by reacting bis(substituted alkyl)amine having a leaving group with an alkali metal phosphido compound of lithium, sodium, and potassium, etc.

The precursor ruthenium carbonyl complex can be obtained in accordance with the method described in Inorg. Synth., 1974, 15, 45, for example. By reacting the obtained precursor ruthenium carbonyl complex with the tridentate aminodiphosphine ligand, the ruthenium carbonyl complex of the invention having the tridentate aminodiphosphine ligand can be provided.

Examples of the precursor ruthenium carbonyl complex include carbonyl(dihydride) tris(triphenylphosphine) ruthenium (II), carbonylchlorohydride tris(triphenylphosphine) ruthenium(II), and carbonyldichlorohydride tris(triphenylphosphine) ruthenium(II).

For example, the ruthenium carbonyl complex represented by the Formula (1) can be produced by reacting the tridentate aminodiphosphine ligand L represented by the Formula (2) with RuXY(CO)(P(Ar$_5$)$_3$)$_3$ (in the formula, Ar$_5$ may be the same or different from each other and represents an aryl group which may have a substituent group). Examples of the aryl group or the substituent group in Ar$_5$ include those described above. Preferred examples of Ar$_5$ include a phenyl group which may have a substituent group, in particular a phenyl group.

Further, the ruthenium carbonyl complex in which X in the ruthenium carbonyl complex represented by the Formula (1) is BH$_4^-$ can be produced by reacting the ruthenium carbonyl complex having a chloride ion as X with NaBH$_4$.

The complex produced by the above described method may result in a stereoisomer depending on the coordination type or the conformation of a ligand. However, the complex used for the reaction can be a mixture of the stereoisomers or a pure isomer.

Further, the ruthenium carbonylhydride borohydride complex having the tridentate aminodiphosphine ligand, X = H$_2$ (hydride) and Y = BH$_4^-$, can be obtained according to the method described in J. Am. Chem. Soc. 2005, 127, 516, for example. Such complex is relatively stable, and therefore can be easily handled.

Examples of the preferred complex include a complex that is represented by the following Formula (8)

\[ \text{RuHCl(CO)(L)} \] (8)

(in the Formula, (L) represents the tridentate aminodiphosphine represented by the above Formula (5)), and this complex is easily prepared by stirring the tridentate aminodiphosphine ligand L represented by the Formula (5) and RuClH(CO)(PPh$_3$)$_3$ in a suitable solvent.

Further, examples of the preferred complex include a complex represented by the following Formula (9)

\[ \text{RuH(BH}_4^-)(CO)(L) \] (9)

(in the Formula, (L) represents the tridentate aminodiphosphine represented by the above Formula (5)), and this complex is easily prepared by stirring the ruthenium carbonyl complex represented by the Formula (8) and NaBH$_4$ in a suitable solvent.

By using the ruthenium carbonyl complex as a catalyst, it becomes possible to produce alcohols from esters, lactones, and ketones with high yield and high catalytic efficiency under relatively low hydrogen pressure and reaction temperature which are industrially advantageous.
In the present invention, esters, lactones, or ketones are used as a substrate for hydrogenation of reacting materials. However, the esters, lactones, or ketones may have a substituent group which does not exhibit any adverse effect on the hydrogenation method of the invention.

The method for producing alcohols by hydrogenation-reduction of ketones according to the invention is a method that is represented by the following reaction scheme (10), that is carried out by using the ruthenium carbonyl complex represented by the Formula (1) and a hydrogen donor.

![Reaction Scheme](image)

\[ \text{R}^9 \quad \text{O} \quad \text{R}^{10} \rightarrow \text{R}^9 \quad \text{OH} \quad \text{R}^{10} \]

(in the scheme, \( \text{R}^9 \) and \( \text{R}^{10} \), which may be the same or different from each other, represent a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, a heterocyclic group, an alkenyl group, an alkynyl group, a cycloalkenyl group, or a keto group that is represented by the following Formula (I). Further, \( \text{R}^9 \) and \( \text{R}^{10} \) may bind to each other to form a ring with an adjacent carbon atom. Further, the alkyl group, cycloalkyl group, aryl group, aralkyl group, heterocyclic group, alkenyl group, alkynyl group, and cycloalkenyl group may have a substituent group).

Further, \( \text{R}^9 \) and \( \text{R}^{10} \) in the reaction scheme (10) will be explained. Examples of the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, and a heterocyclic group which are the same as those described with regard to \( \text{R}^1 \), \( \text{R}^2 \), \( \text{R}^3 \) and \( \text{R}^4 \) of the above Formula (2). Further, the alkyl group may be linear or branched, and examples include an alkyl group having 2 to 20 carbon atoms, preferably 2 to 15 carbon atoms, and more preferably 2 to 10 carbon atoms. Specific examples include an ethyl group, a propyl group, a butyl group, an isobutyl group, a pentyl group, a hexyl group, an octyl group, a nonyl group, and a decyl group. Examples of the alkynyl group include a linear or branched alkynyl group which contains 2 to 20 carbon atoms, preferably 2 to 15 carbon atoms, and more preferably 2 to 10 carbon atoms. Specific examples include an ethynyl group, a 1-propynyl group, a 2-propynyl group, a 1-butynyl group, a 3-butynyl group, a pentynyl group, and a hexynyl group. Examples of the cycloalkenyl group include a 4 to 10-membered mono- to tricyclic aliphatic hydrocarbon group having 1 or 2 double bonds in the ring. Specific examples include a cyclobutenyl group, a cyclopentenyl group, a cyclohexenyl group, a cycloheptenyl group, or a cyclooctenyl group.

Examples of the keto group include those represented by the following Formula (I)

\[ \text{O} \quad \text{R}^k \]

(in the Formula (I), \( \text{R}^k \) represents a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, a heterocyclic group, an alkenyl group, an alkynyl group, or a keto group. Further, the alkyl group, cycloalkyl group, aryl group, aralkyl group, heterocyclic group, alkenyl group, alkynyl group, and cycloalkenyl group may have a substituent group).

Further, examples of the substituent group which may be included in \( \text{R}^9 \), \( \text{R}^{10} \) in the reaction scheme (10), and \( \text{R}^k \) in the keto group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, a heterocyclic group, an alkenyl group, an alkynyl group, a cycloalkenyl group, an aryloxy group, an aralkyloxy group, an alkenyloxy group, an alkynyloxy group, an amino group which is optionally protected, a hydroxy group which is optionally protected, which are the same as those described with regard to \( \text{R}^1 \), \( \text{R}^2 \), \( \text{R}^3 \) and \( \text{R}^4 \) of the Formula (2), or an alkyl group, an aryl group, an aralkyl group, a heterocyclic group, and a keto group which are the same as those described for \( \text{R}^9 \) and \( \text{R}^{10} \) in the reaction scheme (10).

When \( \text{R}^9 \) and \( \text{R}^{10} \) are a keto group or have a keto group as a substituent group, polyhydric alcohol is obtained as a product.

When the reaction represented by the reaction scheme (10) is carried out by using a ruthenium carbonyl complex represented by the Formula (1) in which \( \text{R}^9 \) and \( \text{R}^{10} \) are different from each other and the tridentate amido-phosphine ligand represented by the Formula (2) or (3) is an optically active substance, an alcohol with one enantiomer present in excess is obtained as a product.

A method for producing alcohols by hydrogenation-reduction of esters or lactones according to the invention will be explained.
The method for producing alcohols by hydrogenation-reduction of esters according to the invention is a method that is carried out by using the ruthenium carbonyl complex represented by the Formula (1) and a hydrogen donor, in which alcohols are produced from esters according to the following reaction scheme (11):

\[ R^{11} \cdot CH_2OH + R^{12} OH \]  

(in the scheme, \( R^{11} \) and \( R^{12} \), which may be the same or different from each other, represents an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, a heterocyclic group, an alkenyl group, an alkynyl group, a cycloalkenyl group, or a keto group that is represented by the above Formula (I), provided that \( R^{11} \) may be a hydrogen atom. Further, the alkyl group, cycloalkyl group, aryl group, aralkyl group, heterocyclic group, alkenyl group, alkynyl group, and cycloalkenyl group may have a substituent group).

The method for producing alcohols by hydrogenation-reduction of lactones according to the invention is a method that is carried out by using the ruthenium carbonyl complex represented by the Formula (1) and a hydrogen donor, in which the method is represented by the following reaction scheme (12):

\[ HO\underbrace{-Q^8}_{(Q^9-X^{12})} \rightarrow CH_2OH \]  

(in the scheme, \( Q^8 \) represents a divalent alkylene group, a divalent cycloalkylene group, a divalent aralkylene group, or a divalent arylene group, \( (Q^9-X^{12}) \) represents a bonding arm, or a group in which \( Q^9 \) is a divalent alkylene group, a divalent cycloalkylene group, a divalent aralkylene group, or a divalent arylene group and \( X^{12} \) is a heteroatom such as oxygen, nitrogen, and sulfur. Further, the divalent alkylene group, divalent cycloalkylene group, divalent aralkylene group, or divalent arylene group in \( Q^8 \) and \( Q^9 \), and \( X^{12} \) as a nitrogen atom may have a substituent group).

Explanations will be given to \( R^{11} \) and \( R^{12} \) in the reaction scheme (11). Examples of the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group expressed as \( R^{11} \) and \( R^{12} \) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, and a heterocyclic group which are the same as those described with regard to \( R^1 \), \( R^2 \), \( R^3 \) and \( R^4 \) of the above Formula (2). Further, examples of the alkenyl group, alkynyl group, cycloalkenyl group, and keto group include an alkenyl group, an alkynyl group, a cycloalkenyl group, and a keto group which are the same as those described with regard to \( R^9 \) and \( R^{10} \) in the above reaction scheme (10).

Examples of the substituent group which may be included in \( R^{11} \) and \( R^{12} \) in the reaction scheme (11) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkenyl group, an alkynyl group, an aralkenyloxy group, a cycloalkenyloxy group, an aralkyloxycarbonyl group, an aralkynoxycarbonyl group, an alkenyloxy group, an alkynoxycarbonyl group, and a cycloalkynoxycarbonyl group, which are the same as those described for \( R^9 \) and \( R^{10} \) in the reaction scheme (10). However, when the protecting group for the hydroxy group which is optionally protected is an acyl group, a product with a reduced protecting group can be obtained. In addition, when \( R^{11} \) and \( R^{12} \) are a keto group, or when a keto group, an alkenyloxy group, a cycloalkenyloxy group, an aralkyloxycarbonyl group, an aralkynoxycarbonyl group, an alkenyloxycarbonyl group, an alkynoxycarbonyl group, or a cycloalkynoxycarbonyl group is present as a substituent group, polyhydric alcohols in which these groups are hydrogenated and reduced can be obtained depending on the situation.

Examples of the alkoxycarbonyl group, cycloalkyloxycarbonyl group, aralkyloxycarbonyl group, aralkynoxycarbonyl group, alkynloxycarbonyl group, and cycloalkynoxycarbonyl group as a substituent group include those that are represented by the following Formula (13):
Explanations will be given to R13 of the Formula (13). Examples of the alkyl group, cycloalkyl group, aryl group, aralkyl group, and heterocyclic group include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, and a heterocyclic group which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2). Further, examples of the alkenyl group, alkynyl group, and cycloalkenyln group include an alkenyl group, an alkynyl group, and a cycloalkenyln group which are the same as those described with regard to R9 and R10 in the reaction scheme (10). Examples of the substituent group which may be included in R13 of the Formula (13) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, and a heterocyclic group which are the same as those described with regard to R1, R2, R3 and R4 of the above Formula (2), an alkenyl group, an alkynyl group, and a cycloalkenyln group which are the same as those described with regard to R9 and R10 in the reaction scheme (10). Preferred examples of R12 include an alkyl group having 1 to 10 carbon atoms. Specific examples include a methyl group, an ethyl group, and an isopropyl group. More preferably, it is a methyl group.

Explanations will be given to Q8 and Q9 in the reaction scheme (12). Examples of the divalent alkylene group, divalent cycloalkylene group, and divalent aralkylene group that are represented by Q8 and Q9 include a divalent alkenyl group, a divalent cycloalkylene group, and a divalent aralkylene group which are the same as those described with regard to Q3 and Q4 of the above Formula (2). Examples of the divalent arylen group include a divalent group made of a monocyclic or condensed-cyclic aryl group having 6 to 12 carbon atoms such as phenylene group and 2,3-naphthalenediy1 group. Examples of the phenylene group include o- or m-phenylene group.

Examples of the substituent group which may be included in Q8 and Q9 in the reaction scheme (12) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkenyl group, an alkynyl group, a cycloalkenyln group, an alkenyl group, an alkynyl group, an alkenyln group, and cycloalkenyln group, which are the same as those described with regard to Q3 and Q4 of the above Formula (2). Examples of the substituent group which may be included in Q8 and Q9 include a divalent group made of a monocyclic or condensed-cyclic aryl group having 6 to 12 carbon atoms such as phenylene group and 2,3-naphthalenediy1 group. Examples of the phenylene group include o- or m-phenylene group.

Examples of the substituent group which may be included in Q8 and Q9 in the reaction scheme (12) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkenyl group, an alkynyl group, a cycloalkenyln group, an alkenyl group, an alkynyl group, an alkenyln group, and cycloalkenyln group, which are the same as those described with regard to Q3 and Q4 of the above Formula (2). Examples of the substituent group which may be included in Q8 and Q9 include a divalent group made of a monocyclic or condensed-cyclic aryl group having 6 to 12 carbon atoms such as phenylene group and 2,3-naphthalenediy1 group. Examples of the phenylene group include o- or m-phenylene group.

Examples of the substituent group which may be included in Q8 and Q9 in the reaction scheme (12) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkenyl group, an alkynyl group, a cycloalkenyln group, an alkenyl group, an alkynyl group, an alkenyln group, and cycloalkenyln group, which are the same as those described with regard to Q3 and Q4 of the above Formula (2). Examples of the substituent group which may be included in Q8 and Q9 include a divalent group made of a monocyclic or condensed-cyclic aryl group having 6 to 12 carbon atoms such as phenylene group and 2,3-naphthalenediy1 group. Examples of the phenylene group include o- or m-phenylene group.

Examples of the substituent group which may be included in Q8 and Q9 in the reaction scheme (12) include an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkenyl group, an alkynyl group, a cycloalkenyln group, an alkenyl group, an alkynyl group, an alkenyln group, and cycloalkenyln group, which are the same as those described with regard to Q3 and Q4 of the above Formula (2). Examples of the substituent group which may be included in Q8 and Q9 include a divalent group made of a monocyclic or condensed-cyclic aryl group having 6 to 12 carbon atoms such as phenylene group and 2,3-naphthalenediy1 group. Examples of the phenylene group include o- or m-phenylene group.

According to the hydrogenation-reduction of optically active esters or lactones in which R11, Q8, or Q9 is a group having a chiral center by following the method of the invention, alcohols with the original stereochemistry of the esters or lactones maintained can be obtained without having a significant reduction in optical purity.

The method for producing alcohols of the invention may be appropriately carried out in the presence or absence of a solvent. However, it is preferable to use a solvent. Preferably, the solvent to be used can dissolve the substrate and catalyst, and it is used either singly or as a mixture of the solvents. Specific examples of the solvent include an aromatic hydrocarbon such as toluene and xylene, an aliphatic hydrocarbon such as hexane and heptane, a halogenated hydrocarbon such as methylene chloride and chlorobenzene, ethers such as diethyl ether, tetrahydrofuran, methyl tert-butyl ether, and cyclopentyl methyl ether, alcohols such as methanol, ethanol, isopropanol, n-butanol, 2-butanol, and tert-butanol, and polyhydric alcohols such as ethylene glycol, propylene glycol, 1,2-propane diol, and glycerin. Among them, ethers or alcohols are preferable, and examples of a particularly preferred solvent include tetrahydrofuran, methanol, or isopropanol. The amount of the solvent to be used can be appropriately selected depending on the reaction condition, etc. If necessary, the reaction is carried out under stirring.

Examples of the hydrogen donor that is used for the method of the invention include molecular hydrogen, formic acid, primary alcohol (methanol, ethanol, and butanol, etc.), and secondary alcohol (isopropanol, etc.). Preferred examples include molecular hydrogen and secondary alcohol.
The amount of the catalyst to be used varies depending on the substrate to be hydrogenated, reaction condition, and type of the catalyst, etc. However, in terms of the molar ratio of the ruthenium complex to the substrate to be hydrogenated, it is generally within the range of 0.0001 mol% to 10 mol%, and preferably 0.005 mol% to 5 mol%. According to the method of the invention, the reaction temperature for carrying out the hydrogenation-reduction is 0°C to 180°C, and preferably 0°C to 120°C. If the reaction temperature is too low, a large amount of raw materials may remain as unreacted material. On the other hand, if the temperature is too high, decomposition of the raw materials and catalyst, etc. may occur, which is undesirable. According to the invention, the hydrogen pressure for carrying out the hydrogenation-reduction is 0.1 MPa to 10 MPa, and preferably 3 MPa to 6 MPa. Further, with the reaction time of 30 min to 72 hrs, and preferably 2 hrs to 48 hrs, sufficient high conversion rate of the raw materials can be obtained.

After the completion of the reaction, the desired alcohols can be obtained by following a purification method that is generally used such as extraction, filtration, crystallization, distillation, and various chromatographies, etc., either singly or in combination thereof.

The hydrogenation-reduction of the invention may be carried out with addition of an appropriate additive. Examples of the additive include a basic compound or a metal hydride, etc. Specific examples of the basic compound include amines such as triethylamine, disopropylethylamine, N,N-dimethylaniline, pyridine, 4-dimethylaminopyridine, 1,5-diazabicyclo[4.3.0]nona-5-ene, 1,8-diazabicyclo[5.4.0]undec-7-ene, tri-n-butylamine, and N-methylmorpholine, alkali metal carbonates such as potassium carbonate, sodium carbonate, lithium carbonate, and cesium carbonate, alkali earth metal carbonates such as magnesium carbonate and calcium carbonate, alkali metal hydrogen carbonates such as sodium hydrogen carbonate and potassium hydrogen carbonate, alkali metal hydrides such as sodium hydride, potassium hydride, and lithium hydride, alkali earth metal hydrides such as magnesium hydride and calcium hydride, alkali metal alkoxides such as sodium methoxide, sodium ethoxide, sodium isopropoxide, sodium tert-butoxide, potassium methoxide, potassium ethoxide, potassium isopropoxide, potassium tert-butoxide, lithium methoxide, lithium isopropoxide, and lithium tert-butoxide, alkali earth metal alkoxides such as magnesium methoxide and magnesium ethoxide, and metal hydrides such as sodium hydride and calcium hydride. Examples of a particularly preferred base include sodium methoxide or potassium tert-butoxide.

Examples of the metal hydride include lithium borohydride, sodium borohydride, potassium borohydride, and lithium aluminum hydride. These metal hydrides can yield sufficient high conversion rate even when they are used in an amount of 10 mol% of the esters or less, lactones, or ketones which are the substrate to be hydrogenated.

The present invention is hereinafter explained in more detail by means of the following Examples, to which, however, the invention is never limited.

Further, measurement of conversion rate, selectivity, and optical purity was performed by gas chromatography (GC) and liquid chromatography (LC). The instruments used are as follows.

**Conversion rate · selectivity**

**Analysis condition A:**
GC; capillary HP-INNOWax
Injection temperature 250°C, detection temperature 250°C
80°C (1 min.) - 10°C/min - 250°C (12 min.)

**Analysis condition B:**
GC; capillary RTx-5
Injection temperature 250°C, detection temperature 250°C
80°C (10 min.) - 10°C/min - 270°C (1 min.)

**Analysis condition C:**
GC; capillary TC-WAX
Injection temperature 250°C, detection temperature 250°C
80°C - 10°C/min - 200°C (2 min.)

**Analysis condition D:**
GC; capillary CP-CHIRASIL-DEX-CB
Injection temperature 250°C, detection temperature 250°C
115°C (12 min.)

The optical purity of the each product was determined according to the following methods.

**Optical purity: optical purity analysis of 1,2-propane diol**
Analysis was carried out after conversion into propylene carbonate.
Optical purity: optical purity analysis of 2-(Boc-amino)propan-1-ol
Analysis was carried out after conversion into p-nitrobenzoic acid ester.
HPLC; column DAICEL CHIRALCEL OD-H
170°C (30 min.)
Optical purity: optical purity analysis of 2-(benzyloxy)propan-1-ol
HPLC; column DAICEL CHIRALCEL AD-H

Optical purity: optical purity analysis of 3-(Boc-amino)butan-1-ol
Analysis was carried out after conversion into p-nitrobenzoic acid ester.
HPLC; column DAICEL CHIRALCEL AD-H

Optical purity: optical purity analysis of 3-(phenylamino)butan-1-ol
HPLC; column DAICEL CHIRALCEL AS-H

Optical purity: optical purity analysis of 3-(tert-butyldimethylsilyloxy)butan-1-ol
GC; capillary CP-CHIRASIL-DEX-CB

Optical purity: optical purity analysis of 1-phenylethanol
GC; capillary CP-CHIRASIL-DEX-CB

[Example 1]

According to the following reaction scheme, the ruthenium carbonyl complex 1a and 1b were produced.

Under a nitrogen stream, the amine hydrochloride 8 (4.18 mmol) was added to a 100 mL flask and suspended in toluene (33 mL). After adding 15% aqueous NaOH solution (14 mL), it was stirred at room temperature until the solids disappear. After the fractionation of the solution, the organic layer was washed with distilled water (14 mL x 2) and the aqueous layer was extracted with toluene (14 mL x 2). The combined organic layer was dried over sodium sulfate and the solvent was removed by distillation to obtain the amine 9.

The ruthenium carbonyl complex 7 (4.18 mmol) was added to a 200 mL flask, purged with nitrogen gas, and added with the amine 9 dissolved in toluene (33 mL). The mixture was refluxed with heating for 60 min. After cooling, hexane (82 mL) was added to the reaction solution and the crystals precipitated under the nitrogen atmosphere were filtered. The...
crystals thus obtained were washed with hexane (10 mL) and ethanol (40 mL). After drying under reduced pressure, 1.4 g (2.3 mmol) of the ruthenium complex 1a was obtained.

**[0098]** ¹H-NMR (300MHz CD₂Cl₂) : δ = -15.23(t, J = 29.3Hz, 1H), 2.40-2.65(m, 4H), 2.90-3.05(m, 2H), 3.30-3.55(m, 2H), 3.92(bs, 1H), 7.08-7.34(m, 4H), 7.38-7.46(m, 8H), 7.40-7.88(m, 8H) ³¹P-NMR (121.5MHz CD₂Cl₂) : δ = 52.8(d, J = 14Hz)

**[0099]** Under a nitrogen stream, the complex 1a (2.22 mmol) produced above was added to a 1000 mL flask and suspended in toluene (222 mL). After adding NaBH₄ (60.0 mmol) dissolved in ethanol (222 mL) thereto, the suspension was stirred at 65°C for 30 min and at room temperature for 30 min. The solvent was then distilled off under reduced pressure. Hexane (220 mL) and distilled water (110 mL) were added to the residue. After stirring for 15 min, the precipitated crystals were filtered. The crystals thus obtained were washed with distilled water (110 mL x 2) and hexane (110 mL x 2). After drying under reduced pressure, 1.05 g (1.79 mmol) of the target ruthenium complex 1b was obtained.

**[0100]** ¹H-NMR(300MHz CD₂Cl₂) : δ = -12.36(t, J = 28.5Hz, 1H), -2.80-1. 70 (bs, 4H), 2.40-2.78(m, 4H), 2.90-3.05(m, 2H), 3.32-3.60(m, 2H), 4.20-4.40(m, 1H), 6.92-7.28(m, 4H), 7.38-7.46(m, 8H), 7.70-7.82(m, 8H) ³¹P-NMR (121.5MHz CD₂Cl₂) : δ = 56.6(s)

**Example 2**

**[0101]** Hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme.

**[0102]**

![Reaction Scheme](image)

**[0103]** A solution of methyl (R) -lactate (10 mmol) having optical purity of 99.3%ee, the complex 1a (0.01 mmol) produced in Example 1, methanol (7.6 mL), and 0.5 M of sodium methoxide in methanol (0.4 mL) was added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation-reduction was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, the conversion rate was 96.3%. Optical purity of the alcohol obtained was 99.1%ee.

**Example 3**

**[0104]** Hydrogenation of methyl L-Boc-alanine ester was carried out according to the following reaction scheme.

**[0105]**

![Reaction Scheme](image)

**[0106]** Methyl L-Boc-alanine ester (5 mmol), the complex 1b (0.01 mmol) produced in Example 1, and tetrahydrofuran (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (S) -2-(Boc-amino)propan-1-ol was produced with the conversion rate of 100% and the selectivity of 100%. Optical purity of the alcohol obtained was 99%ee or higher.
Hydrogenation of methyl (S)-2- (benzyloxy) propionate was carried out according to the following reaction scheme.

Methyl (S)-2- (benzyloxy) propionate (5 mmol) with optical purity of 98.5%ee, the complex 1b (0.01 mmol) produced in Example 1, and tetrahydrofuran (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (S)-2- (benzyloxy)propan-1-ol was obtained with the conversion rate of 100% and the selectivity of 99%. Optical purity of the alcohol obtained was 98.5%ee.

Hydrogenation of methyl (R)-3-(Boc-amino)butanoate was carried out according to the following reaction scheme.

The complex 1b (0.02 mmol) produced in Example 1 was added to a 100 mL autoclave equipped with a stirrer and purged with nitrogen gas. Tetrahydrofuran (4 mL) and methyl (R)-3-(Boc-amino) butanoate (5 mmol) with 99%ee or higher were added thereto, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (R)-3- (Boc-amino)butan-1-ol was obtained with the conversion rate of 95.9%. Optical purity of the alcohol obtained was 99%ee or higher.

Hydrogenation of methyl (S)-3-(phenylamino)butanoate was carried out according to the following reaction scheme.

The complex 1b (0.02 mmol) produced in Example 1 was added to a 100 mL autoclave equipped with a stirrer and purged with nitrogen gas. Tetrahydrofuran (4 mL) and methyl (S)-3-(phenylamino) butanoate (5 mmol) with 99%ee or higher were added thereto, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (S)-3- (phenylamino)butan-1-ol was obtained with the conversion rate of 95.9%. Optical purity of the alcohol obtained was 99%ee or higher.
Methyl (S)-3-(phenylamino)butanoate (5 mmol) with optical purity of 93.9%ee, the complex 1b (0.01 mmol) produced in Example 1, and tetrahydrofuran (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (3S)-3-(phenylamino)butan-1-ol was obtained with the conversion rate of 86.4%. Optical purity of the alcohol obtained was 91.1%ee.

Hydrogenation of methyl (R)-3-(tert-butyldimethylsilyloxy)butanoate was carried out according to the following reaction scheme.

Methyl (3R)-3-tert-butyldimethylsilyloxy butanoate (5.0 mmol) with optical purity of 99%ee, the complex 1b (0.02 mmol) produced in Example 1, and tetrahydrofuran (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that (R)-3-(tert-butyldimethylsilyloxy)butan-1-ol was obtained with the reaction conversion rate of 87.9%. Optical purity of the alcohol obtained was 99%ee.

Hydrogenation of methyl benzoate was carried out according to the following reaction scheme.

Methyl benzoate (10.0 mmol), the complex 1a (0.01 mmol) produced in Example 1, sodium methoxide (0.5 mmol), and tetrahydrofuran (5 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 13.5 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that benzyl alcohol was obtained with the reaction conversion rate of 96%. 

Methyl benzoate (10.0 mmol), the complex 1a (0.01 mmol) produced in Example 1, sodium methoxide (0.5 mmol), and tetrahydrofuran (5 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 13.5 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that benzyl alcohol was obtained with the reaction conversion rate of 96%. 

Methyl benzoate (10.0 mmol), the complex 1a (0.01 mmol) produced in Example 1, sodium methoxide (0.5 mmol), and tetrahydrofuran (5 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 13.5 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that benzyl alcohol was obtained with the reaction conversion rate of 96%.
[Example 9] Hydrogen-transfer type reduction of isopropyl benzoate was carried out according to the following reaction scheme.

[0124] Isopropyl benzoate (6.15 mmol), the complex 1a (0.06 mmol) produced in Example 1, and 0.1 M of potassium tert-butoxide solution in isopropanol (12.3 mL), and isopropanol (8 mL) were added to a 100 mL autoclave equipped with a stirrer, and then stirred at 80°C for 16 hrs. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that benzyl alcohol was obtained with the reaction conversion rate of 21.0% and selectivity of 47.0%.

[Example 10] Hydrogenation of acetophenone was carried out according to the following reaction scheme.

[0127] Acetophenone (20.1 mmol), the complex 1a (0.01 mmol) produced in Example 1, potassium tert-butoxide (0.1 mmol), and isopropanol (11.5 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 40°C for 17.5 hrs with hydrogen pressure of 3 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that 1-phenylethanol was produced with the reaction conversion rate of 100%.

[Example 11] Asymmetric hydrogenation of acetophenone was carried out according to the following reaction scheme by using the ruthenium carbonyl complex containing an optically active tridentate aminodiphosphine ligand.
(1) Production of ruthenium carbonyl complex containing optically active tridentate aminodiphosphine ligand

[0130] The desired ruthenium carbonyl complex 1a' containing an optically active tridentate aminodiphosphine ligand was produced in the same manner as Example 1 except that, as a tridentate aminodiphosphine ligand, N,N-bis[(S)-2-diphenylphosphino-propyl]amine was used instead of the amine 9 described in Example 1.

(2) Asymmetric hydrogenation of acetophenone

[0131] Acetophenone (20 mmol), the complex 1a' (0.01 mmol) containing an optically active ligand, potassium tert-butoxide (0.1 mmol), and isopropanol (11.5 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 40°C for 5 hrs with hydrogen pressure of 3 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that 1-phenylethanol was obtained with the reaction conversion rate of 100%. Optical purity of the alcohol thus obtained was 54.0%ee.

[Example 12]

[0132] Hydrogen-transfer type asymmetric reduction of acetophenone was carried out according to the following reaction scheme.

[Example 13]

[0133] Acetophenone (20 mmol), the complex (0.01 mmol) 1a' containing an optically active ligand that is produced in Example 11, 0.1 M of solution of potassium tert-butoxide in isopropanol (1 mL), and isopropanol (10.5 mL) were added to a 20 mL flask equipped with a stirrer, and the mixture was stirred at 40°C for 8.5 hrs under a nitrogen stream. As a result of the analysis of the reaction solution according to gas chromatography, it was found that 1-phenylethanol was obtained with the reaction conversion rate of 72%. Optical purity of the alcohol thus obtained was 40.0%ee.

[Example 13]

[0134] Hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme.

[0135] Hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme.
Methyl (R)-lactate (50 mmol), the complex 1a (0.01 mmol) produced in Example 1, sodium methoxide (0.5 mmol), and tetrahydrofuran (19 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 95%.

**Example 14**

Hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme.

**Example 15**

The reaction was performed in the same manner as Example 14 except that isopropanol was changed to toluene. As a result, the conversion rate was 88.2%. Optical purity of the alcohol thus obtained was 88.8%ee.

**Example 16**

The reaction was performed in the same manner as Example 14 except that isopropanol was changed to ethanol. As a result, the conversion rate was 98.3%. Optical purity of the alcohol thus obtained was 93.7%ee.

**Example 17**

The ruthenium carbonyl complex 14 of the invention was produced in accordance with the following procedure.
Under a nitrogen stream, potassium tert-butoxide (22.3 mmol) was added to a 100 mL flask and suspended in tetrahydrofuran (40 mL). Subsequently, after adding bis (3,5-dimethylphenyl) phosphine (11.0 mmol) and the amine 12 (5.5 mmol) thereto, the mixture was refluxed for 6hrs, then stirred at 50°C for 12hrs and further refluxed for 2hrs. After that, the reaction solution was diluted with ethyl acetate and washed with 15% aqueous NaOH solution and distilled water. The aqueous layer was extracted with diethyl ether. The combined organic layer was dried over magnesium sulfate and subjected to drying under reduced pressure to obtain a crude product, which was then purified by base-treated silica gel column chromatography to give 1.63 g (54%) of the bisphosphinoamine 13.

\[ \text{[0145]} \]

1H-MNR (300MHz CDCl₃): \( \delta = 2.27 \) (s, 24H), 2.19-2.34 (m, 4H), 2.68-2.80 (m, 4H), 6.93 (s, 4H), 7.02 (d, J=8.1Hz, 8H)

31P-NMR (121.5MHz CDCl₃): \( \delta = -22.89 \) (s)

Subsequently, under a nitrogen stream, the bisphosphinoamine 13 (0.72 mmol) was added to a 50 mL flask, added with toluene (8.5 mL) and the complex 7 (0.60 mmol), and then refluxed with heating for 5 hrs. After that, the reaction solution was purified by silica gel column chromatography to obtain the complex 14.

\[ \text{[0146]} \] 1H-MNR (300MHz CD₂Cl₂): \( \delta = -15.37 \) (t, J=29.1Hz, 1H), 2.34 (s, 12H), 2.36 (s, 12H), 2.40-2.50 (m, 4H), 2.80-3.20 (m, 2H), 3.30-3.50 (m, 2H), 3.75-3.95 (bs, 1H), 7.05-7.80 (m, 4H), 7.36-7.46 (m, 8H)

31P-NMR (121.5MHz CD₂Cl₂): \( \delta = 51.68 \) (d, J=11.7Hz)

[Example 18]

Hydrogenation of methyl (R)-lactate was carried out.

\[ \text{[0149]} \] Methyl lactate (20.0 mmol), the complex 14 (0.01 mmol) produced in Example 17, sodium methoxide (0.2 mmol), and methanol (8 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that the conversion rate was 48% and the selectivity was 98%. Optical purity of the alcohol thus obtained was 99.1%ee.

[Example 19]

\[ \text{[0150]} \] The ruthenium carbonyl complex 18 of the invention was produced in accordance with the following procedure.

\[ \text{[0151]} \]
Under a nitrogen stream, potassium tert-butoxide (8.0 mmol) was added to a 100 mL flask and suspended in tetrahydrofuran (40 mL). After adding di(p-tolyl)phosphine (4.0 mmol) and the amine 12 (2.0 mmol) thereto, the mixture was reacted for 14 hrs at room temperature and refluxed with heating for 5 hrs. The reaction solution was then diluted with ethyl acetate (40 mL) and washed with 15% aqueous NaOH solution, distilled water, and saturated brine. The aqueous layer was extracted with ethyl acetate and the combined organic layer was dried over sodium sulfate and subjected to drying under reduced pressure. After that, hexane (40 mL) and 1 N HCl were added to the mixture, which was then reacted for 30 min at room temperature. The precipitated solids were filtered, washed with hexane, and dried under reduced pressure to obtain the amine hydrochloride 17 as a mixture.

Subsequently, under a nitrogen stream, the amine hydrochloride 17 (0.36 mmol) was added to a 20 mL flask and suspended in toluene (5.0 mL). After adding 15% aqueous NaOH solution thereto, the reaction was carried out at room temperature for 30 min. After separating into two layers, the organic layer was washed with saturated brine and the aqueous layer was extracted with toluene (1 mL). The combined organic layer was prepared as a toluene solution of the amine. Under a nitrogen stream, the toluene solution of the amine just prepared and the complex 7 (0.30 mmol) were added to a 20 mL flask and refluxed with heating for 5 hrs. After that, the reaction solution was filtered and then recrystallized by adding hexane to the filtrate. The precipitated crystals were filtered and washed with toluene: hexane = 1 : 1. Thereafter, the resultant was dried under reduced pressure to give the complex 18.

1H-MNR (300MHz CD2Cl2): δ =-15.35 (t, J=19.5Hz, 1H), 2.35 (s, 12H), 2.42-2.52 (m,4H), 2.88-3.00 (m,2H), 3.30-3.52 (m, 2H), 3.74-3.88 (m, 1H), 7.18-7.27 (m, 8H), 7.60-7.40 (m, 8H)

31P-NMR (121.5MHz CD2Cl2): δ = 50.93 (d, J=14.2Hz)

MS: as C33H38ClNOP2Ru,
Calculated value: (MH+) = 663.12
Measured value: (MH+) = 663.07

The complex 18 obtained from Example 19 was prepared as a monocrystal by using toluene - hexane, and the X ray structure analysis was carried out by using Rigaku Mercury CCD, Crystal Clear. The analysis was made by using SHELX97 of Crystal Structure3.8.

The results of X ray structure analysis of the monocrystal are as follows.
Crystal system: monoclinic system.
Space group: P121/c1.
Lattice constant a = 12.5423(13), b = 14.5907(11), c = 18.0776(15) (unit is Å (angstrom)), β = 102.131(4), V = 3234.3 (Å³ (cubic angstrom)).
The bond length around the Ru is as follows. 1.65 Å (angstrom) for Ru-H; 1.834 Å (angstrom) for Ru-C; 2.191 Å (angstrom) for Ru-N; 2.3358 Å (angstrom) and 2.3068 Å (angstrom) for Ru-P, respectively.
The schematic drawing of the chemical structure of the complex 18 according to the results above is shown in FIG. 1.
Hydrogenation of methyl (R)-lactate was carried out.

Methyl lactate (10.0 mmol), the complex 18 (0.005 mmol) produced in Example 19, sodium methoxide (0.1 mmol), and methanol (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the reaction conversion rate was 70% and the selectivity was 94%.

The ruthenium carbonyl complex 16 was produced in accordance with the following procedure.

Under a nitrogen stream, potassium tert-butoxide (2.2 mmol) was added to a 20 mL flask and suspended in tetrahydrofuran (10 mL). After adding bis(3,5-bis(trifluoromethyl)phenyl)phosphine (1.09 mmol) and the amine 12 (0.55 mmol) thereto, the mixture was refluxed with heating for 4 hrs. After that, the reaction solution was distilled off under reduced pressure, and the residues were added with ethyl acetate and washed with 15% aqueous NaOH solution and saturated brine. The obtained organic layer was dried over sodium sulfate and subjected to drying under reduced pressure to yield the amine 15 as a crude product.

\[ \text{31P-NMR (121.5 MHz CDCl}_3\text{): } \delta = -14.67 \text{ (s)} \]

Subsequently, under a nitrogen stream, the amine 15 (0.55 mmol) was added to a 50 mL flask and suspended in toluene (6.6 mL). After adding the complex 7 (0.46 mmol) thereto, the mixture was refluxed with heating for 4 hrs. After that, the reaction solution was cooled to room temperature, and the precipitated crystals were filtered. The crystals were washed with toluene and diethyl ether followed by drying under reduced pressure to obtain the complex 16.

\[ \text{1H-NMR (300MHz CD}_2\text{Cl}_2\text{): } \delta = -14.59 \text{ (t, } J = 18.6\text{ Hz, 1H), 2.35-2.60(m, 2H), 2.65-2.85(m, 2H), 3.02-3.18(m, 2H), 3.35-3.65(m, 2H), 3.80-4.20(m, 1H), 8.04(d, } J = 21.6\text{Hz, 4H), 8.18-8.26(m, 4H), 8.36-8.44(m, 4H) } \text{31P-NMR (121.5MHz CD}_2\text{Cl}_2\text{): } \delta = 60.18 \text{ (s)} \]

Hydrogenation of methyl maleate was carried out according to the following reaction scheme.
Methyl maleate (4.0 mmol), the complex 1a (0.01 mmol) produced in Example 1, sodium methoxide (0.2 mmol), and methanol (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 8 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that the reaction conversion rate was 100% and the selectivity was 100%.

Example 23

Hydrogenation of methyl methoxyacetate was carried out according to the following reaction scheme.

Methyl methoxyacetate (5.0 mmol), the complex 1a (0.01 mmol), sodium methoxide (0.2 mmol), and methanol (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 8 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction for the reaction solution according to gas chromatography, it was found that the reaction conversion rate was 100% and the selectivity was 100%.

(Comparative example 1)

By using the dichlororuthenium complex described in Patent Document 1, hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme in the presence of added base.

Methyl (R)-lactate (50 mmol), the complex 10 (0.01 mmol), sodium methoxide (0.5 mmol), and tetrahydrofuran (19 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 31%.
Hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme by using the dichlororuthenium complex that is described in Patent Document 1.

Methyl (R)-lactate (9.95 mmol), the complex 10 (0.01 mmol), sodium methoxide (0.2 mmol), and methanol (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 3.5%.

By using the ruthenium carbonyl complex containing an aminodiphosphine ligand in which an ethyl group, instead of a hydrogen atom, is present on the N, hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme in the presence of added base.

Methyl (R)-lactate (9.95 mmol), the complex 11 (0.01 mmol), sodium methoxide (0.2 mmol), and methanol (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 1.2%.

By using the ruthenium carbonyl complex containing an aminodiphosphine ligand in which an ethyl group, instead of a hydrogen atom, is present on the N, hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme in the presence of added base.
Methyl (R)-lactate (9.95 mmol), the complex 11 (0.002 mmol), sodium methoxide (0.1 mmol), tetrahydrofuran (4 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 80°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 1.1%.

(Comparative example 5)

By using the ruthenium carbonyl complex 19 (commercially available from Strem Chemicals Inc.) that is described in Non-patent Document 2, hydrogenation of methyl (R)-lactate was carried out according to the following reaction scheme.

Methyl (R)-lactate (10 mmol), the complex 19 (0.01 mmol), and methanol (8 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 2.6% and the selectivity was 0%.

(Comparative example 6)

By using the ruthenium carbonyl complex 19 (commercially available from Strem Chemicals Inc.) that is described in Non-patent Document 2, hydrogenation of methyl (R)-lactate was carried out according to the above reaction scheme in the presence of added base.

Methyl (R)-lactate (10 mmol), the complex 19 (0.01 mmol) sodium methoxide (0.2 mmol), and methanol (8 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 30°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate was 5.8% and the selectivity was 21.5%.

(Comparative example 7)

By using the ruthenium carbonyl complex 19 (commercially available from Strem Chemicals Inc.) that is described in Non-patent Document 2, hydrogenation of methyl (R)-lactate was carried out according to the above reaction scheme while using tetrahydrofuran (THF) instead of methanol as a solvent.

Methyl (R)-lactate (10 mmol), the complex 19 (0.01 mmol), and tetrahydrofuran (8 mL) were added to a 100 mL autoclave equipped with a stirrer, and the hydrogenation was carried out at 100°C for 16 hrs with hydrogen pressure of 5 MPa. As a result of the analysis of the reaction solution according to gas chromatography, it was found that the conversion rate
was 7.4% and the selectivity was 40.7%.

INDUSTRIAL APPLICABILITY

[0183] The invention is to provide a novel ruthenium carbonyl complex having a tridentate aminodiphosphine ligand that can be conveniently prepared from an easily obtainable inorganic ruthenium compound. The novel ruthenium carbonyl complex of the invention catalyzes the hydrogenation-reduction of ketones, esters, and lactones in the presence of a hydrogen donor, has high catalytic activity even under a relatively mild reaction condition, and also allows the asymmetric hydrogenation-reduction of a carbonyl group. Further, the novel ruthenium carbonyl complex of the invention has high stability and good handleability, and therefore it is suitable for industrial application. Therefore, the ruthenium carbonyl complex of the invention and the method for hydrogenation-reduction of ketones, esters, and lactones using the same are useful in the field of industrial organic chemistry.

Claims

1. A ruthenium carbonyl complex that is represented by the following Formula (1):

   \[ \text{RuXY(CO)(L)} \]  
   \[ (1) \]

   (in the Formula (1), X and Y, which may be the same or different from each other, represent an anionic ligand and L represents a tridentate aminodiphosphine ligand represented by the following Formula (2):

   \[ \begin{align*} 
   H & \\
   Q^1 & \\
   Q^2 & \\
   PR^1R^2 & \\
   PR^3R^4 & 
   \end{align*} \]  
   \[ (2) \]

   (in the Formula (2), R^1, R^2, R^3, and R^4, which may be the same or different from each other, represent a hydrogen atom, an alkyl group, a cycloalkyl group, an aryl group, an aralkyl group, an alkylxy group, a cycloalkyloxy group, an aroxyl group, an aralkyloxy group, a heterocyclic group, or a substituted amino group, and R^1 and R^2 or R^3 and R^4 may bind to each other to form a ring with an adjacent phosphorus atom. Further, the alkyl group, cycloalkyl group, aryl group, aralkyl group, alkxy group, cycloalkyloxy group, aryloxy group, aralkyloxy group, heterocyclic group, and substituted amino group may have a substituent group. Q^1 and Q^2, which may be the same or different from each other, represent a divalent alkylene group which may have a substituent group, a divalent cycloalkylene group which may have a substituent group, or a divalent aralkylene group which may have a substituent group).

2. The ruthenium carbonyl complex according to Claim 1, wherein the tridentate aminodiphosphine ligand L is represented by the following Formula (3):

   \[ \begin{align*} 
   R^5 & \\
   R^6 & \\
   R^7 & \\
   R^8 & \\
   R^9 & \\
   PR^3R^4 & 
   \end{align*} \]  
   \[ (3) \]

   (in the Formula (3), R^5, R^6, R^7 and R^8, which may be the same or different from each other, represent a hydrogen atom, an alkyl group which may have a substituent group, a cycloalkyl group which may have a substituent group, an aryl group which may have a substituent group, or an aralkyl group which may have a substituent group. n represents an integer of 0 to 3).

3. The ruthenium carbonyl complex according to Claim 1 or 2, wherein the tridentate aminodiphosphine ligand L is
represented by the following Formula (4):

\[ \text{PaR}^1\text{Ar}^2 \quad \text{PaR}^3\text{Ar}^4 \]  

(in the Formula (4), Ar\(^1\), Ar\(^2\), Ar\(^3\), and Ar\(^4\), which may be the same or different from each other, represent an aryl group or an aromatic heterocyclic group. The aryl group and aromatic heterocyclic group may have a substituent group).

4. The ruthenium carbonyl complex according to Claim 3, wherein Ar\(^1\), Ar\(^2\), Ar\(^3\), and Ar\(^4\) in the Formula (4) is a phenyl group which may have a substituent group.

5. The ruthenium carbonyl complex according to any one of Claims 1 to 4, wherein the tridentate aminodiphosphine ligand L is represented by the following Formula (5):

\[ \text{PPh}_2 \quad \text{PPh}_2 \]  

(in the Formula, Ph represents a phenyl group).

6. The ruthenium carbonyl complex according to Claim 1 or 2, wherein the tridentate aminodiphosphine ligand L is optically active.

7. The ruthenium carbonyl complex according to any one of Claims 1 to 6, wherein the anionic ligand X is a hydride and the anionic ligand Y is a chloride ion in the Formula (1).

8. The ruthenium carbonyl complex according to any one of Claims 1 to 6, wherein the anionic ligand X is a hydride and the anionic ligand Y is BH\(_4^+\) in the Formula (1).

9. A method of producing the ruthenium carbonyl complex represented by the Formula (1) by reacting the tridentate aminodiphosphine ligand L represented by the Formula (2) and RuXY(CO) (P(Ar\(^5\))\(_3\)) (in the Formula, Ar\(^5\) may be the same or different from each other and represents an aryl group which may have a substituent group).

10. The method according to Claim 9, wherein Ar\(^5\) is a phenyl group.

11. The method according to Claim 9 or 10, wherein the tridentate aminodiphosphine ligand L represented by the Formula (2) is a tridentate aminodiphosphine ligand L represented by the Formula (5).

12. The method according to any one of Claims 9 to 11, wherein RuXY (CO) (P (Ar\(^5\))\(_3\)) is RuHCl (CO) (PPh\(_3\))\(_3\).

13. A method of producing a ruthenium carbonyl complex represented by the following Formula (6) by reacting RuHCl (CO)(PPh\(_3\))\(_3\) and a tridentate aminodiphosphine ligand L represented by the Formula (5):
14. A method of producing a ruthenium carbonyl complex represented by the following Formula (7) by reacting the ruthenium carbonyl complex represented by the Formula (6) and NaBH₄:

15. A method of producing alcohols according to the hydrogenation-reduction of ketones by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to any one of Claims 1 to 8.

16. A method of producing optically active alcohols according to the asymmetric hydrogenation-reduction of ketones by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to any one of Claims 6 to 8.

17. A method of producing alcohols according to the hydrogenation-reduction of esters or lactones by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to any one of Claims 1 to 8.

18. A method of producing optically active alcohols according to the hydrogenation-reduction of optically active esters or optically active lactones by using a hydrogen donor in the presence of the ruthenium carbonyl complex according to any one of Claims 1 to 8 while maintaining the optical activity of the esters or the lactones.
**INTERNATIONAL SEARCH REPORT**

A. CLASSIFICATION OF SUBJECT MATTER
   See extra sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C07F9/50, C07F15/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2010
Kohai Jitsuyo Shinan Koho 1971-2010 Toroku Jitsuyo Shinan Koho 1994-2010

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Cplus(STN), REGISTRY(STN), JSTPlus(JDreamII), JMEDPlus(JDreamII), JST7580(JDreamII)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>A</td>
<td>US 2005/0107638 A1 (K.ABDUR-RASHID), 19 May 2005 (19.05.2005), paragraph [0154], example 7.2; paragraphs [0193] to [0201], examples 19 to 21; paragraph [0217], table 16; claims &amp; WO 2004/096735 A2 &amp; CA 2565130 A1</td>
<td>1-18</td>
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[X] Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
  "E" earlier application or patent but published on or after the international filing date
  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
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  "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
  "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
  "&" document member of the same patent family

Date of the actual completion of the international search
02 September, 2010 (02.09.10)

Date of mailing of the international search report
21 September, 2010 (21.09.10)

Name and mailing address of the ISA/
Japanese Patent Office

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Authorized officer

TelephoneNumber
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<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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Continuation of A. CLASSIFICATION OF SUBJECT MATTER

(International Patent Classification (IPC))

C07F9/50(2006.01)i, C07C29/145(2006.01)i, C07C29/149(2006.01)i,
C07C31/20(2006.01)i, C07C33/20(2006.01)i, C07C33/22(2006.01)i,
C07C41/26(2006.01)i, C07C43/178(2006.01)i, C07C213/00(2006.01)i,
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REFERENCES CITED IN THE DESCRIPTION

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