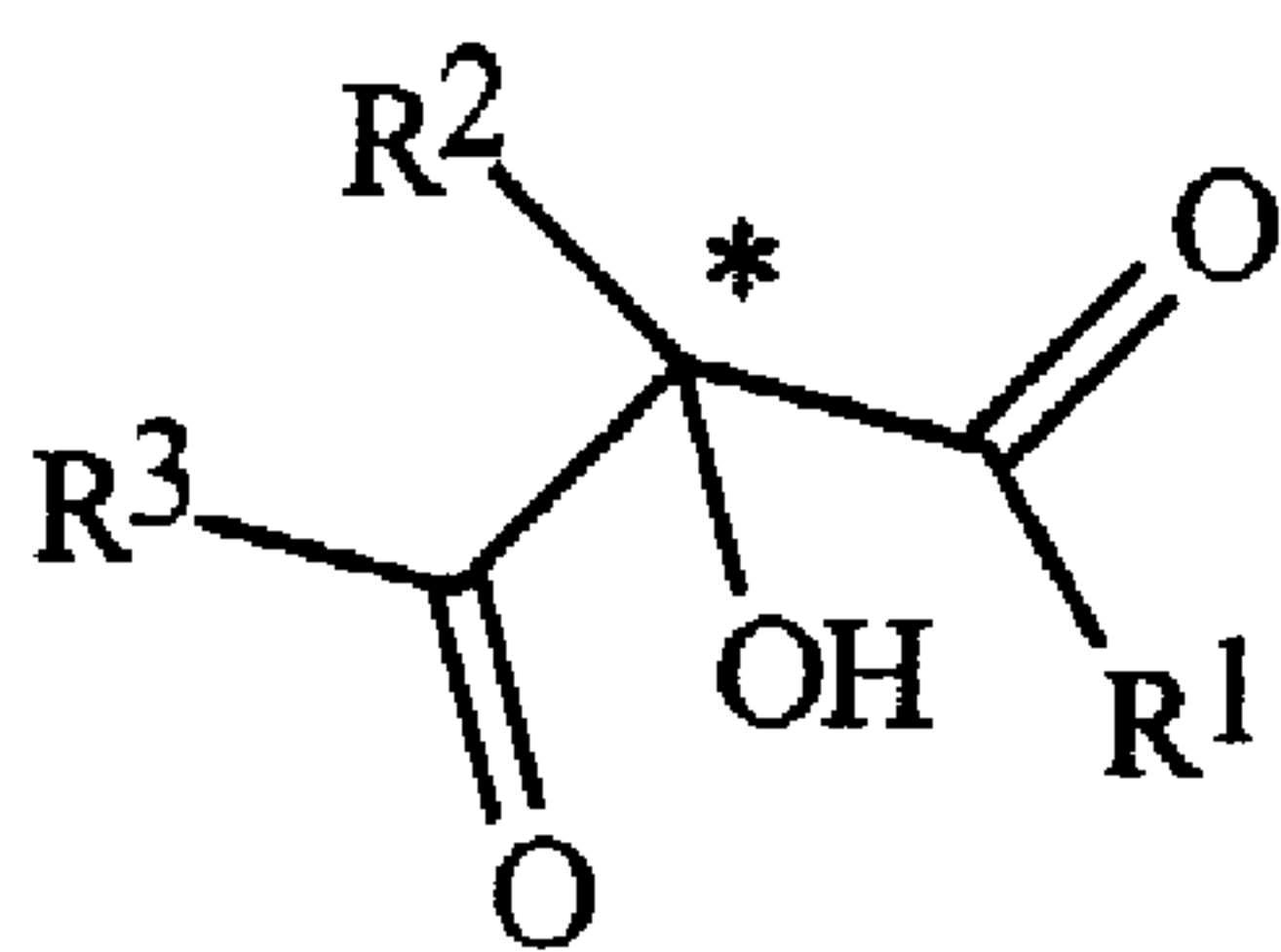




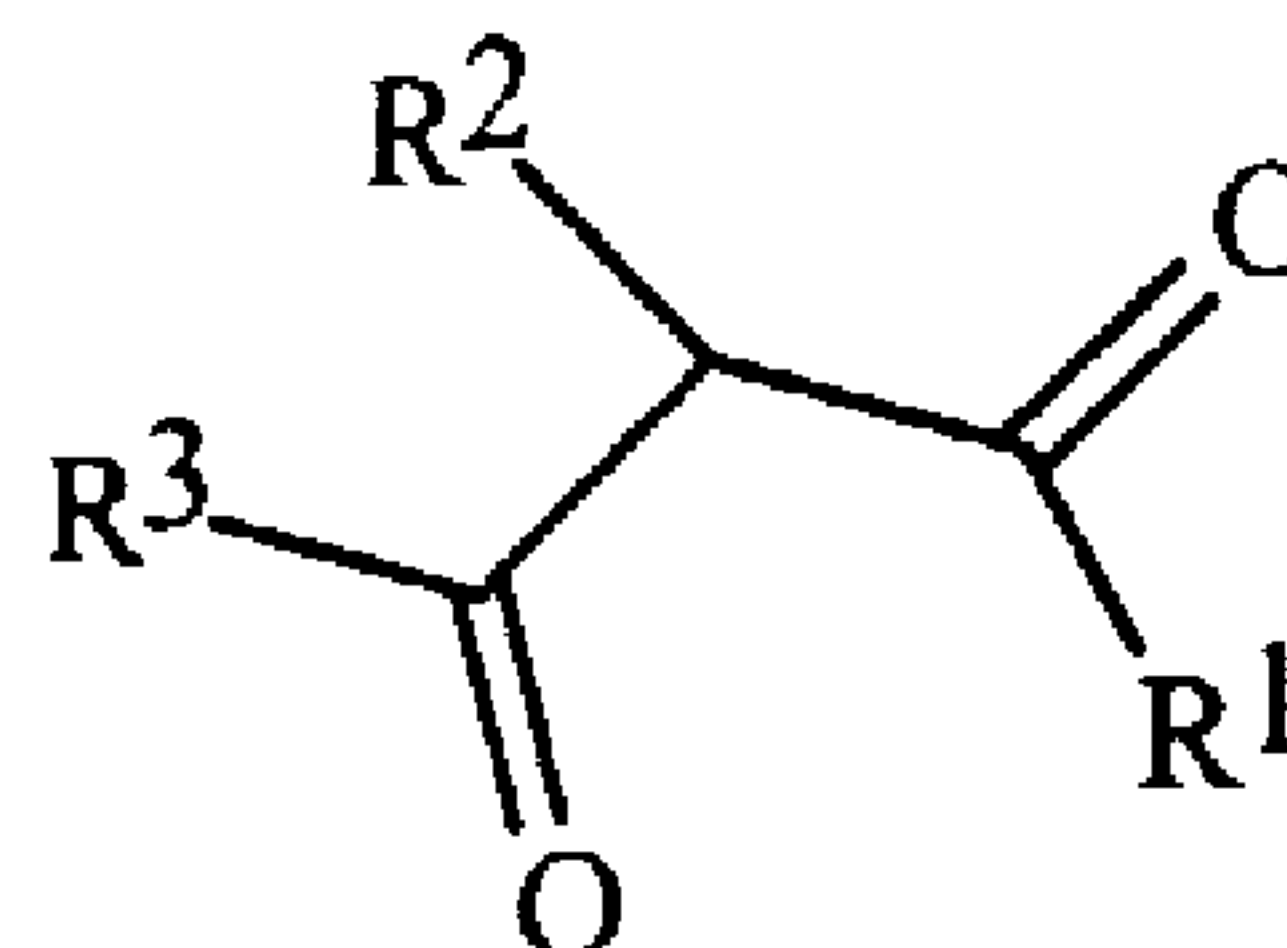
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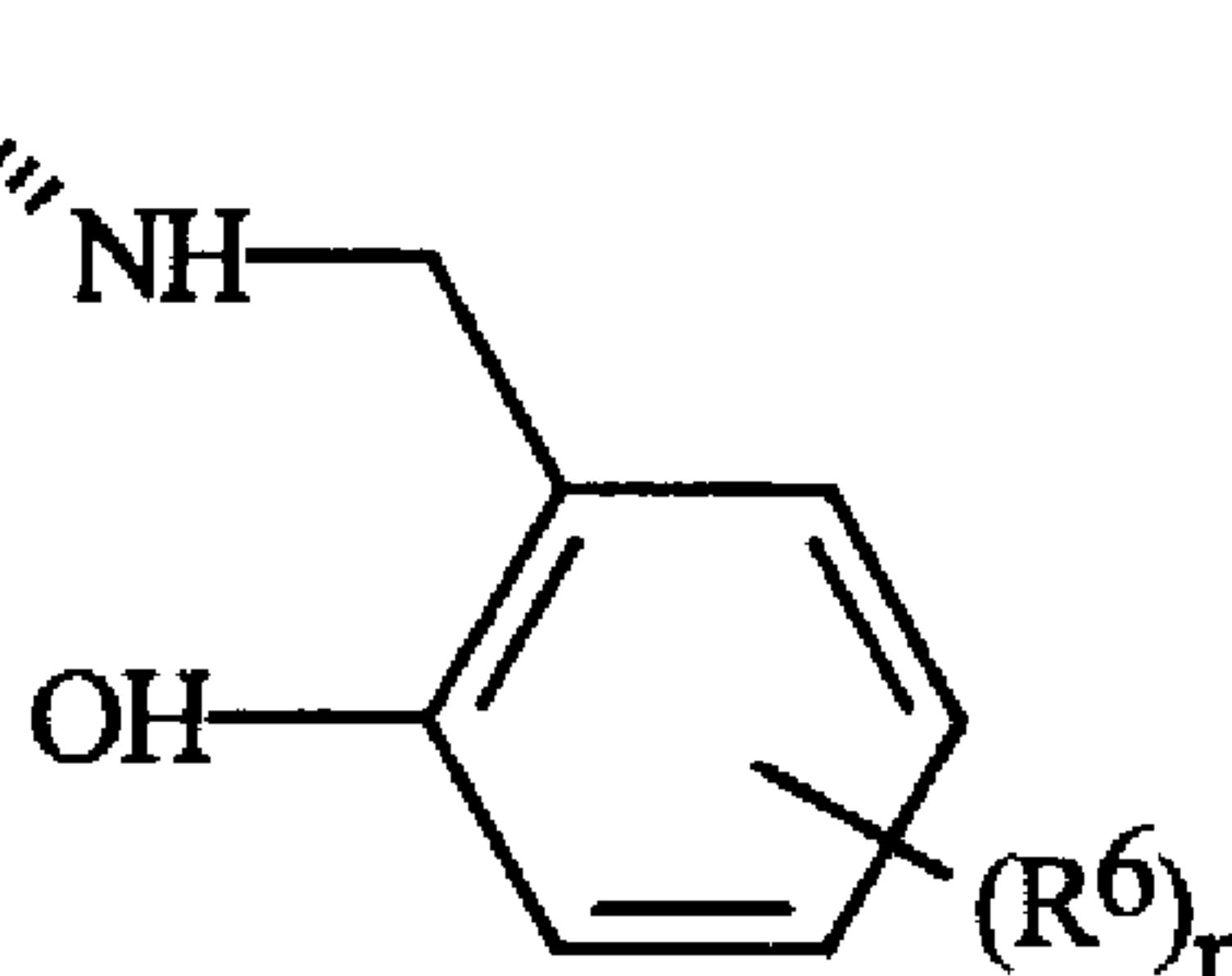
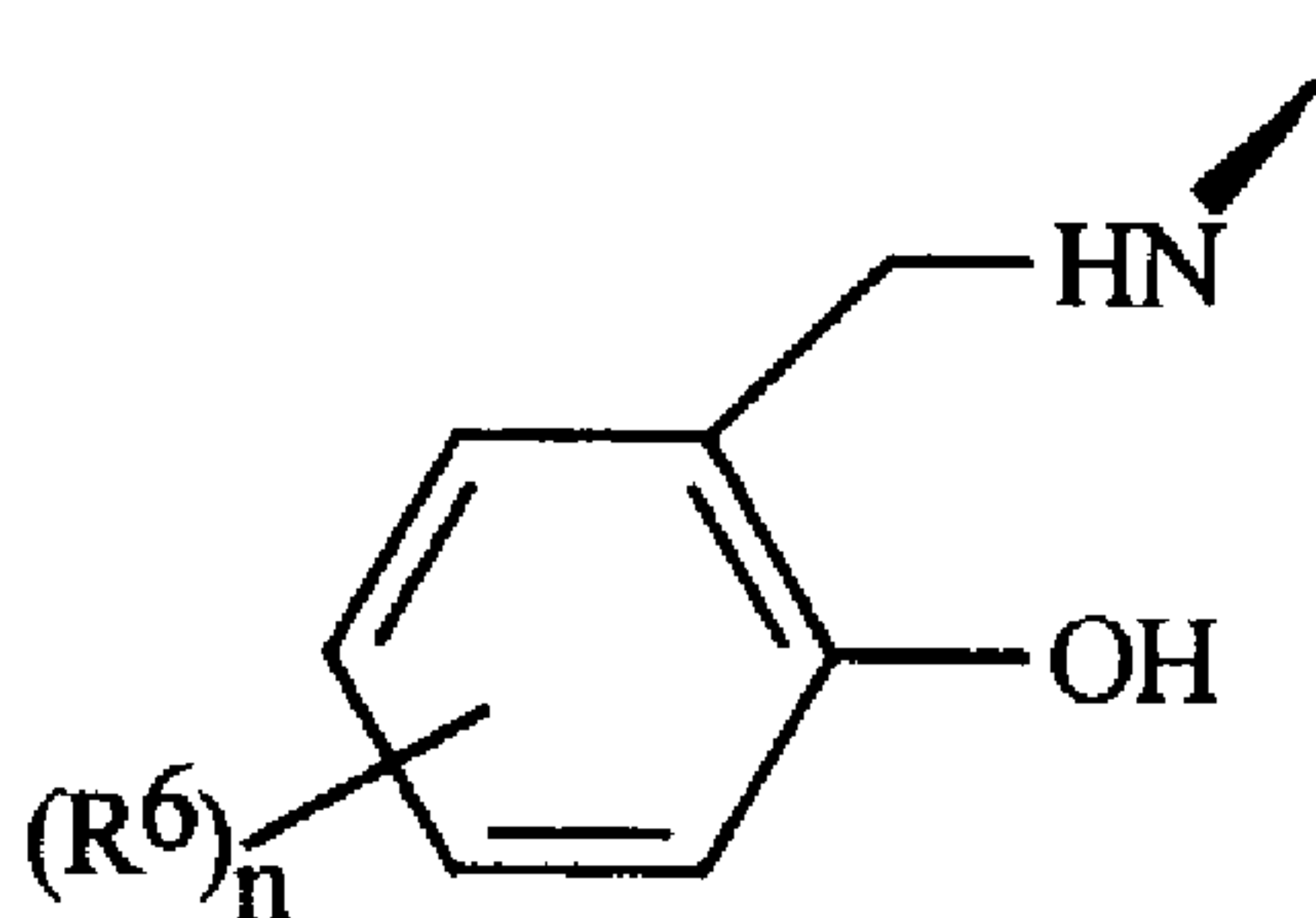
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 (54) Title: HYDROXYLATION OF BETA-DICARBONYLS WITH ZIRCONIUM CATALYSTS



(I)



(II)



(III)

(57) Abrégé/Abstract:

The present invention pertains to a process for preparing a compound of Formula I that is achiral, racemic or enantiomerically enriched at the hydroxylation center indicated by comprising contacting a compound of Formula II with an oxidant selected from oxygen, hydrogen peroxide, peracids or alkyl hydroperoxides in the presence of a zirconium complex, wherein R¹, R² and R³ are as defined in the disclosure. This invention also pertains to zirconium complexes useful in this procedure comprising zirconium and a ligand of Formula III or its enantiomer wherein J, R⁶ and n are as defined in the disclosure. This invention further pertains to a compound of Formula III or its enantiomer.

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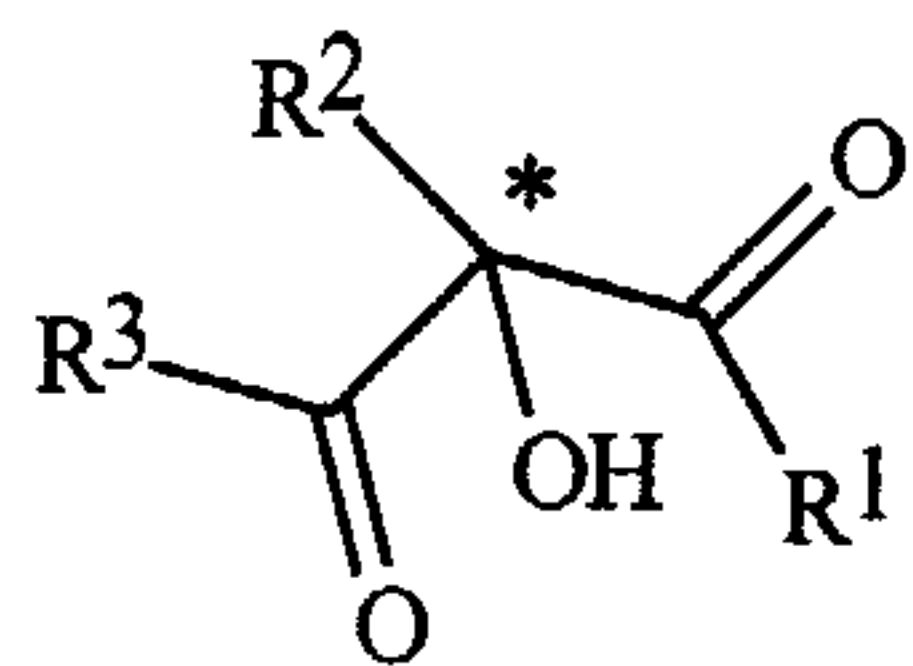
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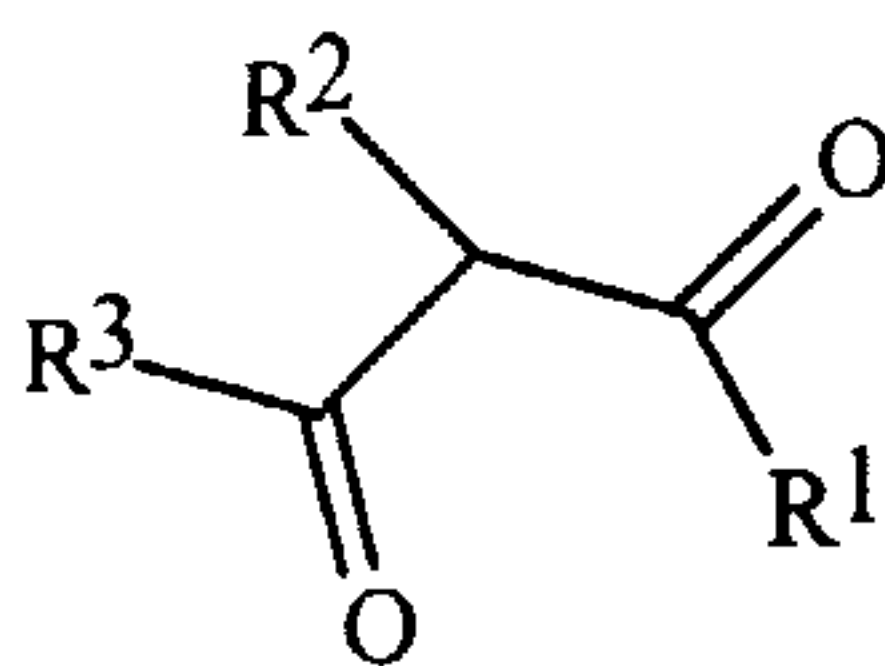
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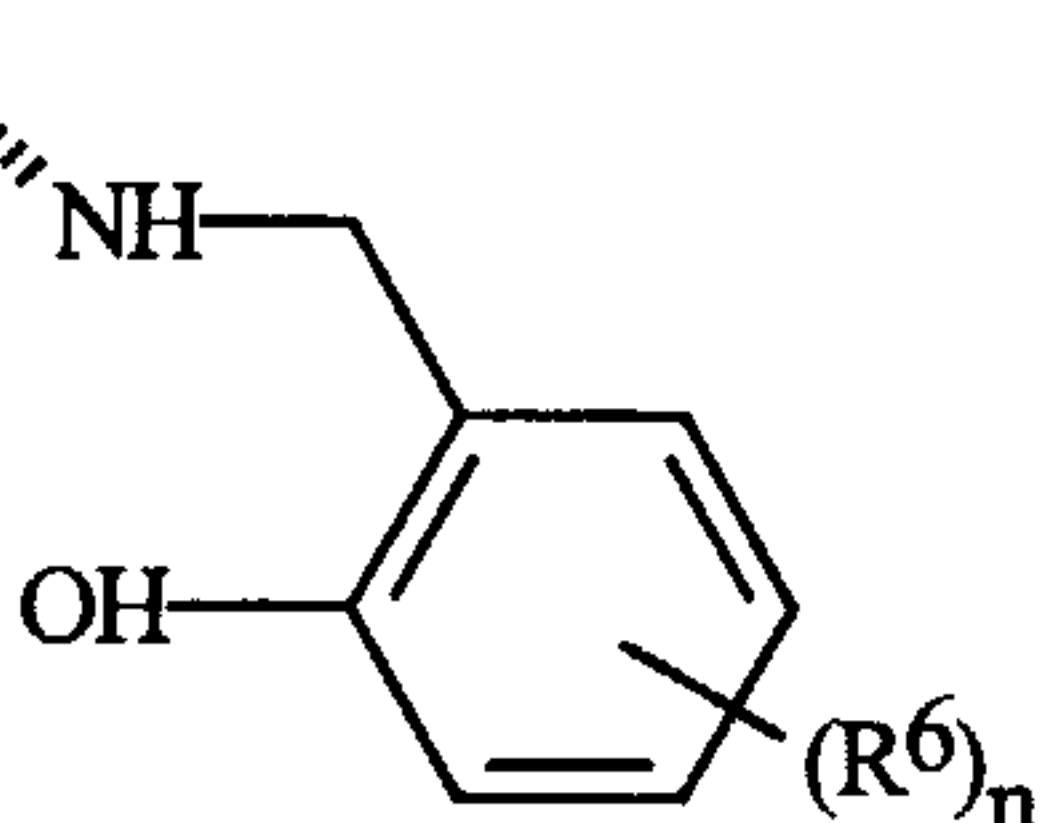
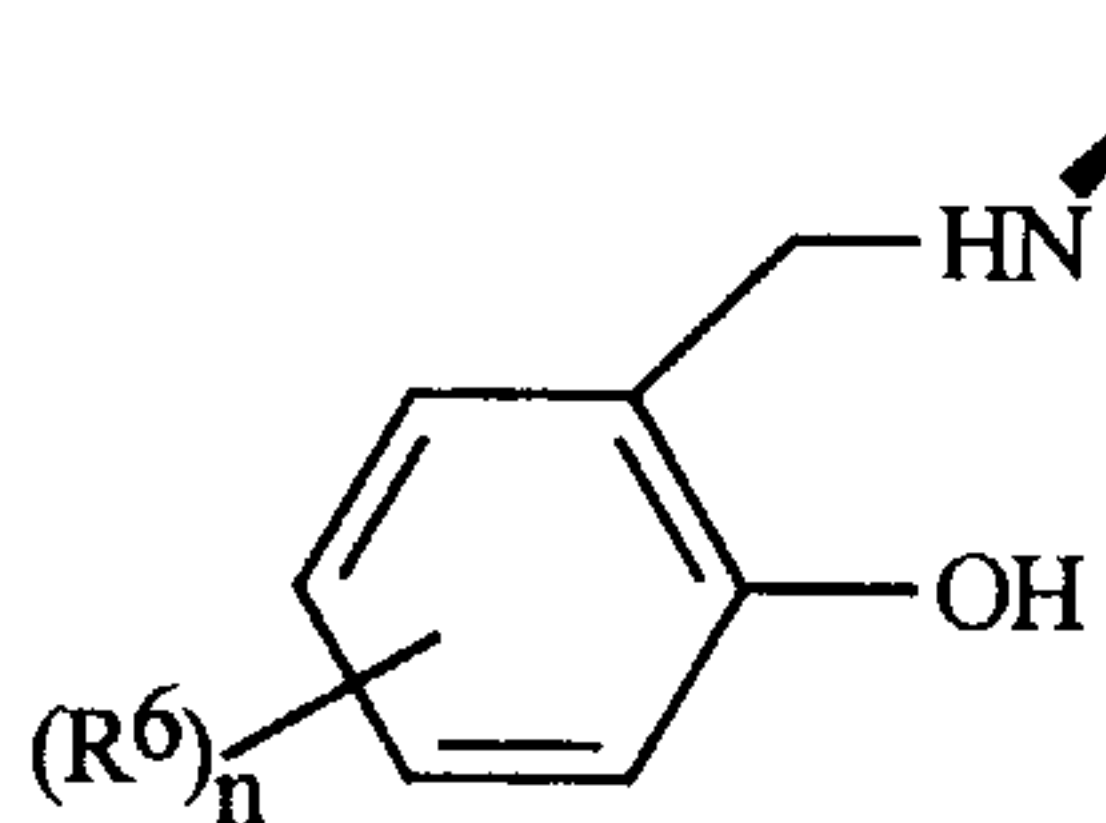
(54) Title: HYDROXYLATION OF BETA-DICARBONYLS WITH ZIRCONIUM CATALYSTS



(I)



(II)



(III)

(57) Abstract: The present invention pertains to a process for preparing a compound of Formula I that is achiral, racemic or enantiomerically enriched at the hydroxylation center indicated by comprising contacting a compound of Formula II with an oxidant selected from oxygen, hydrogen peroxide, peracids or alkyl hydroperoxides in the presence of a zirconium complex, wherein R¹, R² and R³ are as defined in the disclosure. This invention also pertains to zirconium complexesuseful in this procedure comprising zirconium and a ligand of Formula III or its enantiomer wherein J, R⁶ and n are as defined in the disclosure. This invention further pertains to a compound of Formula III or its enantiomer.

WO 03/002255 A1

HYDROXYLATION OF BETA-DICARBONYLS WITH ZIRCONIUM CATALYSTS

FIELD OF THE INVENTION

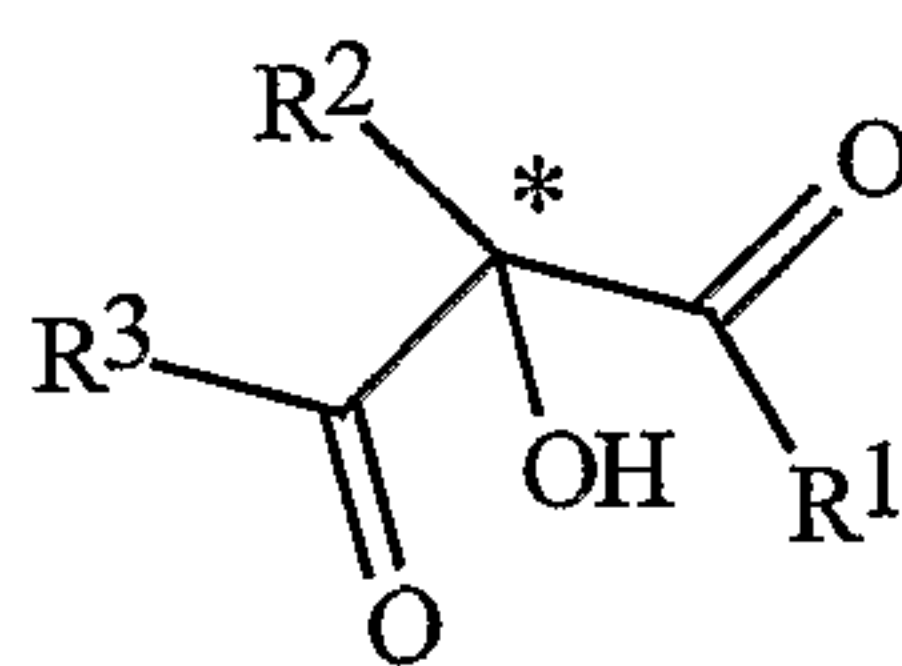
The present invention pertains to a process for the hydroxylation of β -dicarbonyl
5 compounds.

BACKGROUND OF THE INVENTION

Certain β -dicarbonyl compounds (i.e. β -keto esters and their hydroxylated derivatives)
are useful as intermediates for the preparation of fine chemicals, pharmaceuticals and plant
protection products such as arthropodocidal oxadiazines. Arthropodocidal oxadiazines are
10 disclosed in PCT Publications WO 92/11249 and WO 93/19045. Methods of preparing these
compounds have also been reported in WO 95/29171, including a preparative step involving
the hydroxylation of β -keto esters. However, improved preparative methods for these
compounds are desirable for more economic commercial operation. Accordingly, the
present invention provides an improved process to prepare hydroxylated β -dicarbonyl
15 compounds, including those useful in preparing arthropodocidal oxadiazines.

SUMMARY OF THE INVENTION

The present invention pertains to a process for preparing a compound of Formula I
that is achiral, racemic or enantiomerically enriched at the hydroxylation center indicated by
*

**I**

20

wherein

R^1 is H; or alkoxy, alkyl, cycloalkyl, cycloalkoxy, a phenyl ring, a phenoxy ring or a
5- or 6-membered heteroaromatic ring, each optionally substituted;

R^2 is H; or alkyl, cycloalkyl, a phenyl ring, or a 5- or 6-membered heteroaromatic ring,
25 each optionally substituted;

R^3 is H; or alkoxy, alkyl, cycloalkyl, cycloalkoxy, a phenyl ring, a phenoxy ring or a
5- or 6-membered heteroaromatic ring, each optionally substituted; or

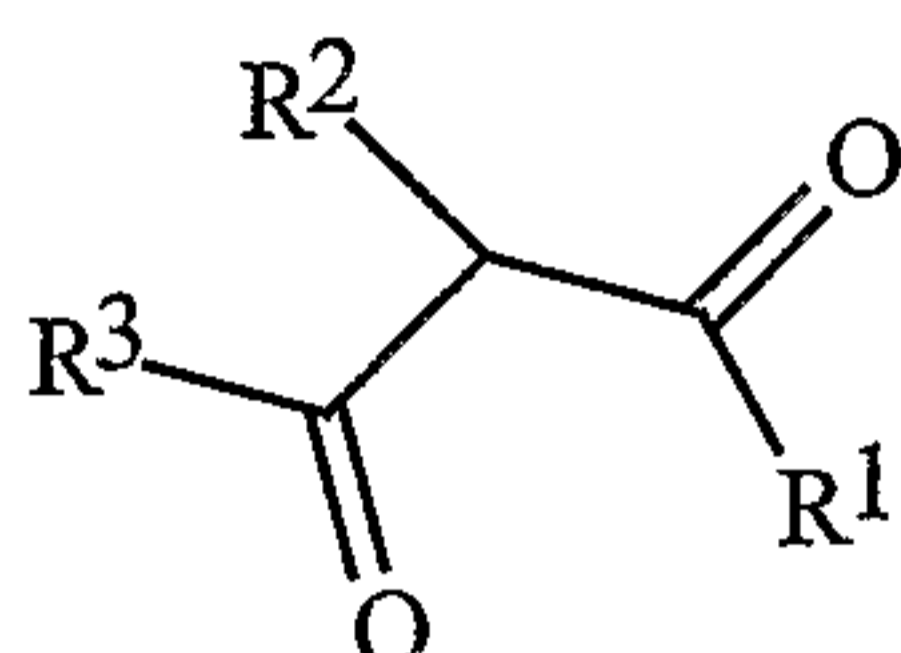
R^2 and R^3 can be taken together to form an optionally substituted linking chain of 3 to
6 members including at least one carbon member, optionally including no more
30 than two carbon members as C(=O), optionally including one member selected

from nitrogen and oxygen, and optionally fused to a phenyl ring or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; or

R¹ and R³ can be taken together to form an optionally substituted linking chain of 2 to 5 members including at least one carbon member, optionally including no more than one carbon member as C(=O), and optionally fused to a phenyl ring or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted;

comprising:

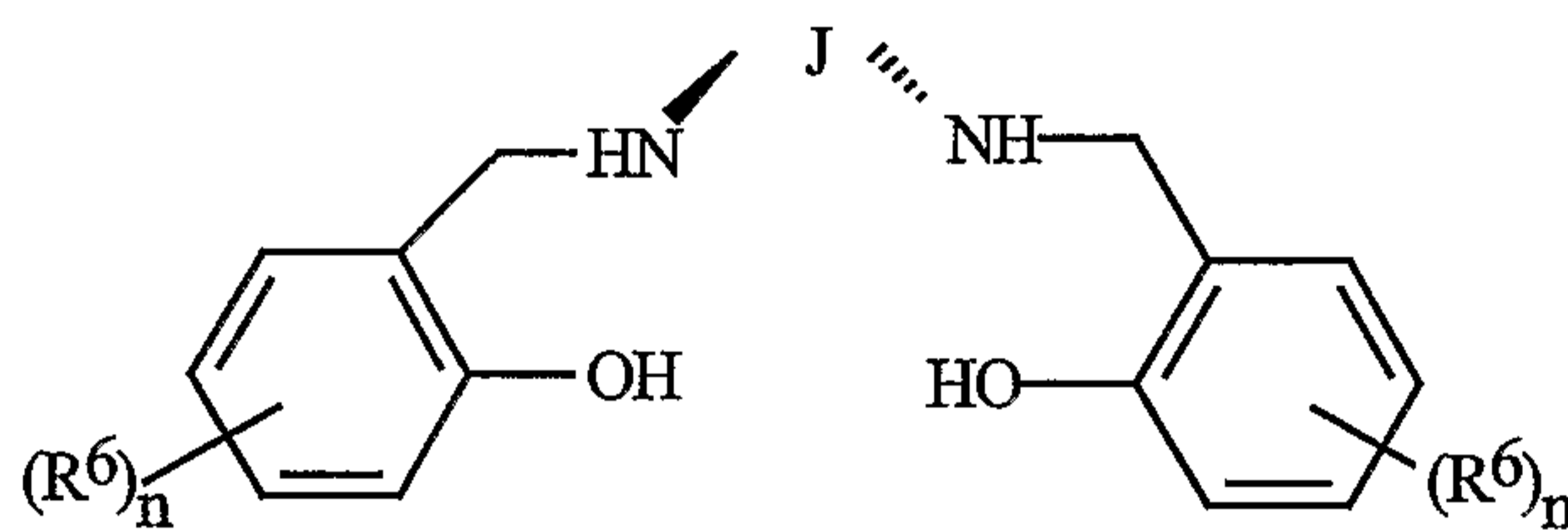
contacting a compound of Formula II



II

10 wherein R¹, R² and R³ are as defined above, with a zirconium complex and an oxidant.

This invention also pertains to a chiral zirconium complex comprising zirconium and a chiral ligand of Formula III



III

15 wherein

J is an optionally substituted linking chain of 2 to 4 members consisting of at least one carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as C(=O); the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a C₃-C₈ cycloalkyl ring, a C₃-C₈ nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

25 each R⁶ is independently selected from the group consisting of halogen; NO₂; cyano; C₂-C₅ alkoxy carbonyl; N(C₁-C₄ alkyl)₂; CON(C₁-C₄ alkyl)₂; C₁-C₄ alkoxy; C₂-C₅ alkyl carbonyloxy; C₂-C₅ alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; (C₁-C₄ alkyl)silyl; tri(C₁-C₄ alkyl)siloxy; C₁-C₄ alkyl

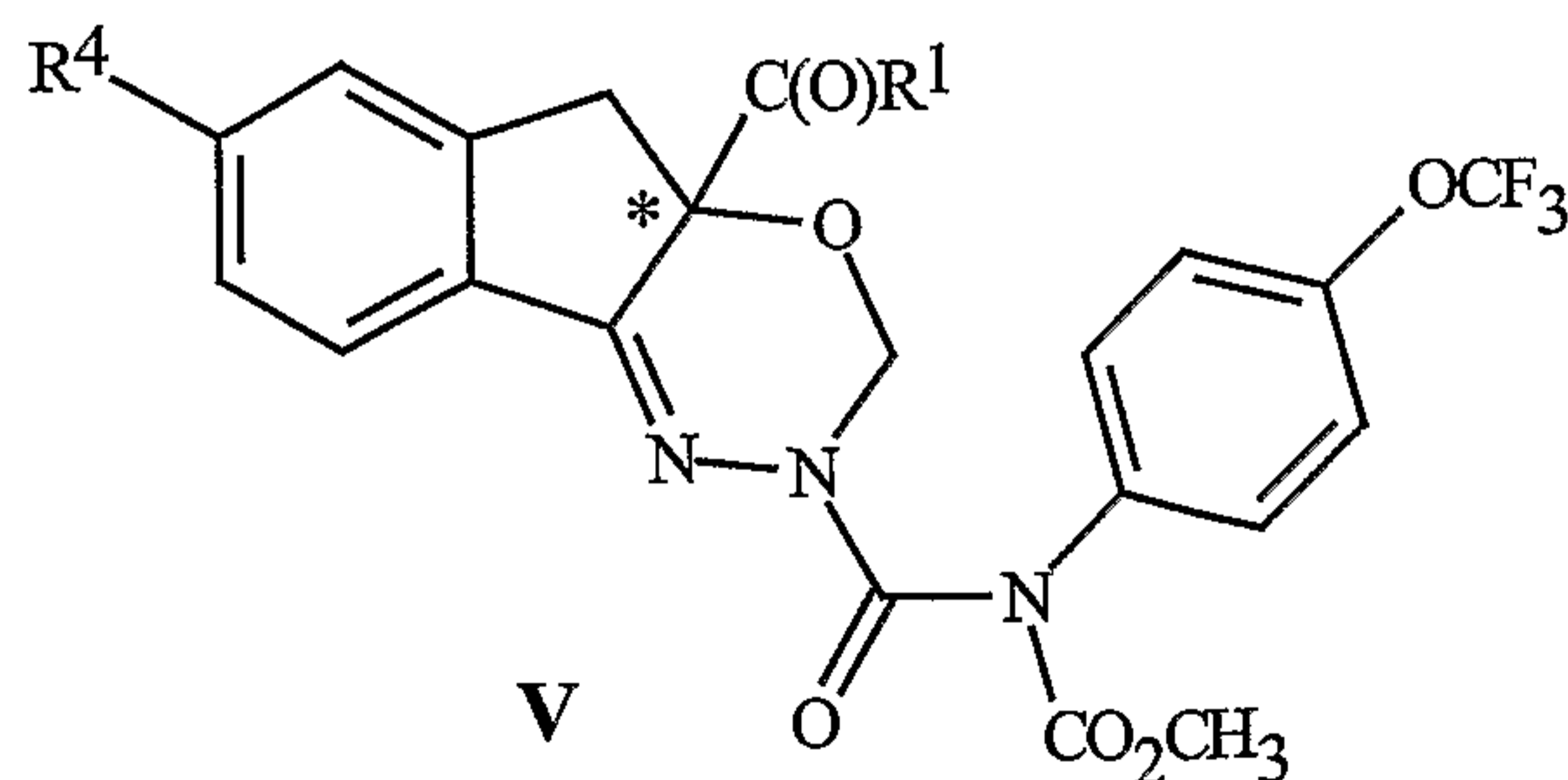
optionally substituted with 1–3 phenyl rings; C₃–C₆ cycloalkyl optionally substituted with C₁–C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and each n is independently an integer from 0 to 4.

This invention also pertains to a chiral zirconium complex comprising zirconium and a ligand that is the enantiomer of Formula **III**, said enantiomer designated Formula **ent-III**.

This invention also pertains to a compound of Formula **III** as defined above, provided that (a) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **III**, then at least one n is an integer from 1 to 4; (b) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **III**, on one phenyl ring n is 2 and (R⁶)_n is 3-*t*-butyl-5-methyl, then (R⁶)_n on the other phenyl ring is other than 3-*t*-butyl-5-methyl; and (c) when J is a 1,1'-binaphthalenyl ring system connected via the 2 and 2' positions to the remainder of Formula **III**, then at least one n is an integer from 1 to 4.

This invention also pertains to the enantiomer of the compound of Formula **III** (designated Formula **ent-III**), provided that (a) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **ent-III**, then at least one n is an integer from 1 to 4; (b) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **ent-III**, on one phenyl ring n is 2 and (R⁶)_n is 3-*t*-butyl-5-methyl, then (R⁶)_n on the other phenyl ring is other than 3-*t*-butyl-5-methyl; (c) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **ent-III**, on one phenyl ring n is 2 and (R⁶)_n is 3-*t*-butyl-5-*t*-butyl, then (R⁶)_n on the other phenyl ring is other than 3-*t*-butyl-5-*t*-butyl; and (d) when J is a 1,1'-binaphthalenyl ring system connected via the 2 and 2' positions to the remainder of Formula **ent-III**, then at least one n is an integer from 1 to 4.

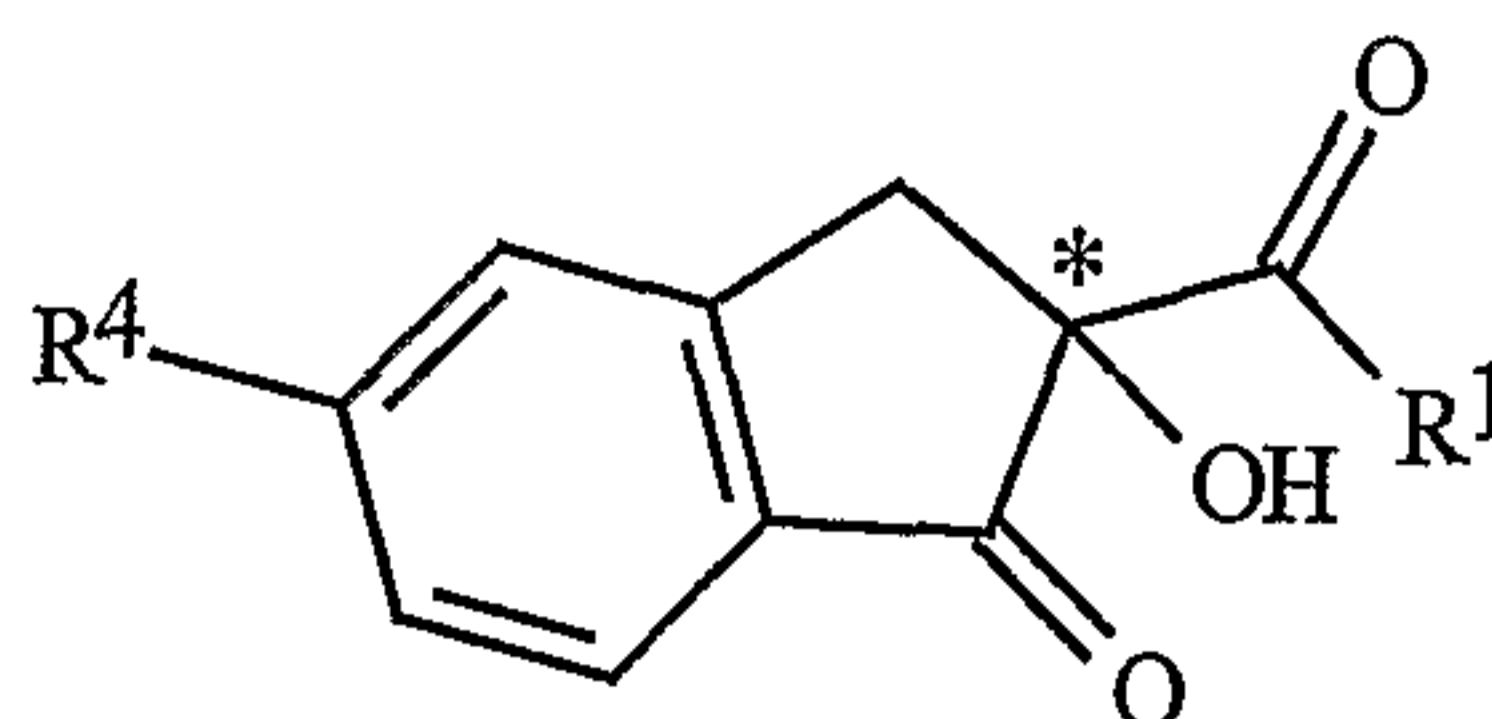
This invention also involves a method of preparing a compound of Formula **V**,



wherein

R¹ is C₁–C₃ alkoxy; and

R⁴ is F, Cl or C₁-C₃ fluoroalkoxy;
using a compound of Formula **Ia**

**Ia**

wherein Formulae **V** and **Ia** are racemic or enantiomerically enriched at the chiral center
5 indicated by *; characterized by:

preparing said compound of Formula **Ia** by the method indicated above.

DETAILED DESCRIPTION OF THE INVENTION

In the recitations herein, the term “alkyl”, used either alone or in compound words
such as “alkylthio” or “haloalkyl” includes straight-chain or branched alkyl, such as, methyl,
10 ethyl, *n*-propyl, *i*-propyl, or the different butyl, pentyl or hexyl isomers. “Alkenyl” includes
straight-chain or branched alkenes such as ethenyl, 1-propenyl, 2-propenyl, and the different
butenyl, pentenyl and hexenyl isomers. “Alkenyl” also includes polyenes such as
1,2-propadienyl and 2,4-hexadienyl. “Alkynyl” includes straight-chain or branched alkynes
such as ethynyl, 1-propynyl, 2-propynyl and the different butynyl, pentynyl and hexynyl
15 isomers. “Alkynyl” can also include moieties comprised of multiple triple bonds such as
2,5-hexadiynyl. “Alkoxy” includes, for example, methoxy, ethoxy, *n*-propyloxy,
isopropyloxy and the different butoxy, pentoxy and hexyloxy isomers. “Alkylamino”,
“alkenylthio”, “alkenylsulfinyl”, “alkenylsulfonyl”, “alkynylthio”, “alkynylsulfinyl”,
“alkynylsulfonyl”, and the like, are defined analogously to the above examples.
20 “Cycloalkyl” includes, for example, cyclopropyl, cyclobutyl, cyclopentyl, and cyclohexyl.
The term “cycloalkoxy” includes the same groups linked through an oxygen atom such as
cyclopentyloxy and cyclohexyloxy. “Cycloalkenyl” includes groups such as cyclopentenyl
and cyclohexenyl as well as groups with more than one double bond such as 1,3- and
1,4-cyclohexadienyl. Examples of “alkylcarbonyl” include C(O)CH₃, C(O)CH₂CH₂CH₃
25 and C(O)CH(CH₃)₂. Examples of “alkoxycarbonyl” include CH₃OC(=O),
CH₃CH₂OC(=O), CH₃CH₂CH₂OC(=O), (CH₃)₂CHOC(=O) and the different butoxy- or
pentoxy carbonyl isomers. Other groups are defined analogously.

The term “halogen”, either alone or in compound words such as “haloalkyl”, includes
fluorine, chlorine, bromine or iodine. Further, when used in compound words such as
30 “haloalkyl”, said alkyl may be partially or fully substituted with halogen atoms which may
be the same or different. Examples of “haloalkyl” include F₃C, ClCH₂, CF₃CH₂ and
CF₃CCl₂. The terms “haloalkenyl”, “haloalkoxy” and the like, are defined analogously to

the term "haloalkyl". Examples of "haloalkenyl" include $(\text{Cl})_2\text{C}=\text{CHCH}_2$ and $\text{CF}_3\text{CH}_2\text{CH}=\text{CHCH}_2$. Examples of "haloalkoxy" include CF_3O , $\text{CCl}_3\text{CH}_2\text{O}$, $\text{HCF}_2\text{CH}_2\text{CH}_2\text{O}$ and $\text{CF}_3\text{CH}_2\text{O}$.

5 The total number of carbon atoms in a substituent group can be indicated by the "C_i-C_j" prefix where, for example, i and j are numbers from 1 to 8. For example, C₁-C₃ alkyl designates methyl through propyl. When a compound is substituted with a substituent bearing a subscript that indicates the number of said substituents can exceed 1, said substituents (when they exceed 1) are independently selected from the group of defined substituents.

10 The term "member" in the description of a chain or ring refers to an atom forming part of the backbone structure of said chain or ring. If said chain or ring is said to be optionally substituted, the atom members are optionally substituted with one or more substituent groups, consistent with the atom members' free valency remaining after bonding of the atom members to form the chain or ring.

15 The term "optionally substituted" refers to a chain, ring or other group that is unsubstituted or substituted with at least one moiety other than hydrogen by replacement of said hydrogen.

The term "carbocyclic ring" denotes a ring wherein the atoms forming the ring backbone are selected only from carbon. The term "heterocyclic ring" denotes a ring
20 wherein at least one atom forming the ring backbone is carbon and at least one other atom forming the ring backbone is other than carbon. The term "aryl" refers to an aromatic carbocyclic or heterocyclic ring to which is optionally fused one or more aromatic or nonaromatic rings. Aromatic indicates that each of ring atoms is essentially in the same plane and has a *p*-orbital perpendicular to the ring plane, and in which $(4n + 2) \pi$ electrons,
25 when *n* is 0 or a positive integer, are associated with the ring to comply with Hückel's rule. A "ring system" refers to two or more fused rings. Examples of aromatic carbocyclic ring and ring systems include benzene, naphthalene, anthracene and the like. The term "heteroaromatic ring" means an aromatic heterocyclic ring. Examples of aromatic heterocyclic rings include thiophene, pyridine, pyridazine, pyrazine, pyrimidine, pyrrole,
30 triazine, triazole and furan. A "nonaromatic heterocyclic ring" generally is a single ring with a backbone containing at least one carbon atom and one to four heteroatoms independently selected from the group nitrogen, oxygen and sulfur, provided that each ring contains no more than four nitrogens, no more than two oxygens and no more than two sulfurs. Said rings can be fully saturated heterocycles as well as partially or fully unsaturated heterocycles
35 in which the Hückel rule for aromaticity is not satisfied by the ring. Examples of nonaromatic heterocyclic rings include tetrahydrofuran, thiolane, pyrrolidine, 1,3-dioxolane, 1,3-dithiolane, 1,3- and 1,4-dioxane, 4,5,6,7-tetrahydro-1,3-dioxepin and the like. Hetero-

cyclic ring systems can be attached to other groups through any available carbon or nitrogen by replacement of a hydrogen on said carbon or nitrogen.

One skilled in the art will appreciate that not all nitrogen-containing heterocycles can form *N*-oxides, because the nitrogen requires an available lone pair for oxidation to the oxide; one skilled in the art will recognize those nitrogen containing heterocycles which can form *N*-oxides. One skilled in the art will also recognize that tertiary amines can form *N*-oxides. Synthetic methods for the preparation of *N*-oxides of heterocycles and tertiary amines are very well known by one skilled in the art including the oxidation of heterocycles and tertiary amines with peroxy acids such as peracetic and *m*-chloroperbenzoic acid (MCPBA), hydrogen peroxide, alkyl hydroperoxides such as *t*-butyl hydroperoxide, sodium perborate, and dioxiranes such as dimethyldioxirane. These methods for the preparation of *N*-oxides have been extensively described and reviewed in the literature, see for example: T. L. Gilchrist in *Comprehensive Organic Synthesis*, vol. 7, pp 748–750, S. V. Ley, Ed., Pergamon Press; M. Tisler and B. Stanovnik in *Comprehensive Heterocyclic Chemistry*, vol. 3, pp 18–20, A. J. Boulton and A. McKillop, Eds., Pergamon Press; M. R. Grimmett and B. R. T. Keene in *Advances in Heterocyclic Chemistry*, vol. 43, pp 149–161, A. R. Katritzky, Ed., Academic Press; M. Tisler and B. Stanovnik in *Advances in Heterocyclic Chemistry*, vol. 9, pp 285–291, A. R. Katritzky and A. J. Boulton, Eds., Academic Press; and G. W. H. Cheeseman and E. S. G. Werstiuk in *Advances in Heterocyclic Chemistry*, vol. 22, pp 390–392, A. R. Katritzky and A. J. Boulton, Eds., Academic Press.

Molecular depictions drawn herein follow standard conventions for depicting stereochemistry. To indicate stereoconfiguration, bonds rising from the plane of the drawing and towards the viewer are denoted by solid wedges wherein the broad end of the wedge is attached to the atom rising from the plane of the drawing towards the viewer. Bonds going below the plane of the drawing and away from the viewer are denoted by dashed wedges wherein the narrow end of the wedge is attached to the atom further away from the viewer. Constant width lines indicate bonds with a direction opposite or neutral relative to bonds shown with solid or dashed wedges; constant width lines also depict bonds in molecules or parts of molecules in which no particular stereoconfiguration is intended to be specified.

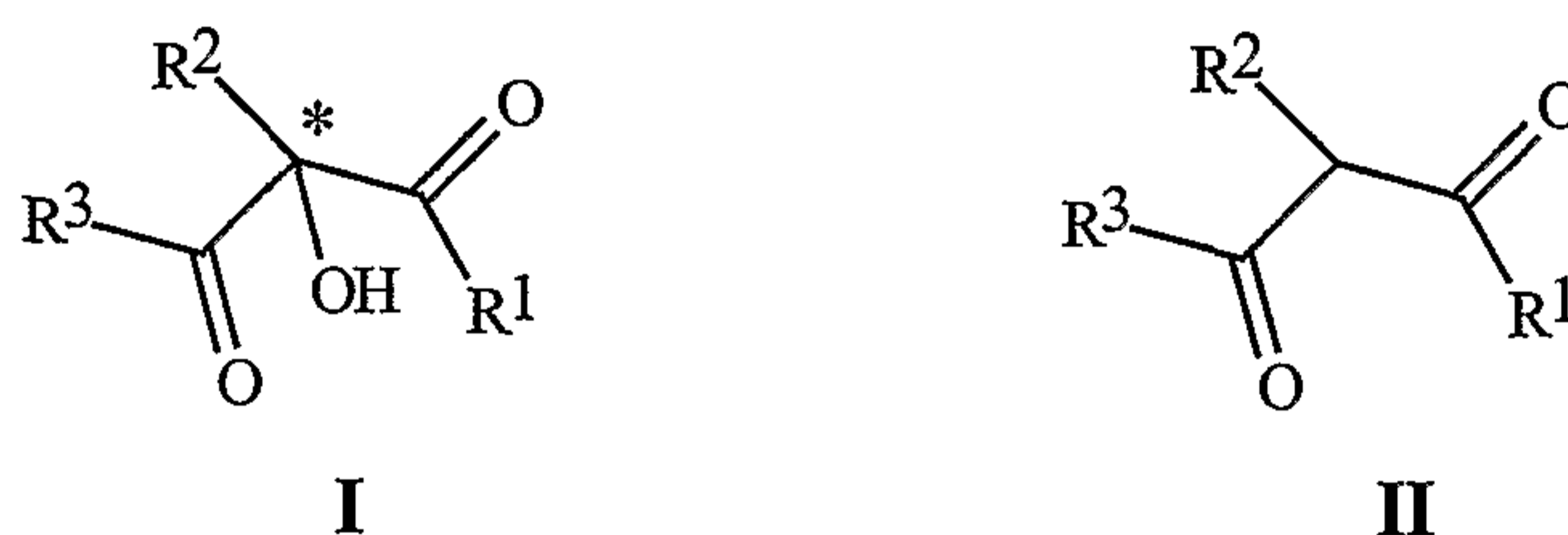
An asterisk (*) is used to indicate the Formula I hydroxylation center comprising the hydroxy group introduced by a process of this invention. When two of the groups attached to the hydroxylation center are identical a mirror plane of symmetry exists through the hydroxylation center. In this situation the hydroxylation center is achiral. If no mirror plane of symmetry exists through the hydroxylation center, then the hydroxylation center is a chiral center, resulting in two possible enantiomers corresponding to the two possible configurations at the chiral center. When the enantiomers are present in equal amounts the Formula I compound is racemic at the hydroxylation center; otherwise one enantiomer is

present in excess and the Formula I compound is described as enantiomerically enriched at the hydroxylation center.

Furthermore, R¹, R² and R³ of Formulae I and II can optionally comprise one or more additional chiral centers. R⁶ of Formulae III and IV can also optionally comprise one or more chiral centers. A statement that Formula I is achiral, racemic or enantiomerically enriched at the hydroxylation center indicated by * refers only to that center. For example, a compound of Formula I that is racemic at the chiral center indicated by * can at the same time be enantiomerically enriched at other chiral centers.

For a general reference regarding enantiomers and enantioselective processes, see E. L. Eliel, S. H. Wilen and L. N. Mander, *Stereochemistry of Organic Compounds*, Wiley-Interscience, New York, 1994.

This invention pertains to a process for preparing compounds of Formula I by contacting a compound of Formula II with an oxidant and a zirconium complex, optionally in the presence of an inert solvent



wherein * indicates the hydroxylation center, and R¹, R² and R³ are as defined in the Summary of the Invention.

More specifically in this process, the compound of Formula I is prepared by contacting a compound of Formula II with generally about 0.9 to 10.0 equivalents or more of an oxidant in the presence of about 0.001 to 1.5 equivalents of a zirconium complex, and optionally an inert solvent. Typical reaction conditions include reaction temperatures in the range of about -5 to 100 °C and reaction times of about 2 hours to 8 days. Suitable oxidants include oxygen (e.g., air), hydrogen peroxide, monoethers of hydrogen peroxide including *tert*-butyl hydroperoxide, cumene hydroperoxide and combinations thereof, peracids such as peracetic acid or *m*-chloroperbenzoic acid, hypochlorites such as sodium hypochlorite, monopersulfates such as potassium monopersulfate (e.g., Oxone®), and dioxiranes such as dimethyldioxirane. A particularly useful oxidant for this process is hydrogen peroxide or a mono ether of hydrogen peroxide. A preferred oxidant is *tert*-butyl hydroperoxide. Suitable solvents include aliphatic hydrocarbons such as cyclohexane, aromatic hydrocarbons such as toluene, xylenes, ethylbenzene, mesitylene and cumene, halogenated hydrocarbons such as dichloromethane, dichloroethane and *ortho*-dichlorobenzene, ketones such as methyl ethyl ketone, methyl isobutyl ketone and methyl isopropyl ketone, esters such as methyl acetate,

ethyl acetate, isopropyl acetate, alcohols such as methanol and 2-methyl-2-propanol, or ethers such as diethyl ether and tetrahydrofuran. Aromatic hydrocarbon solvents are preferred.

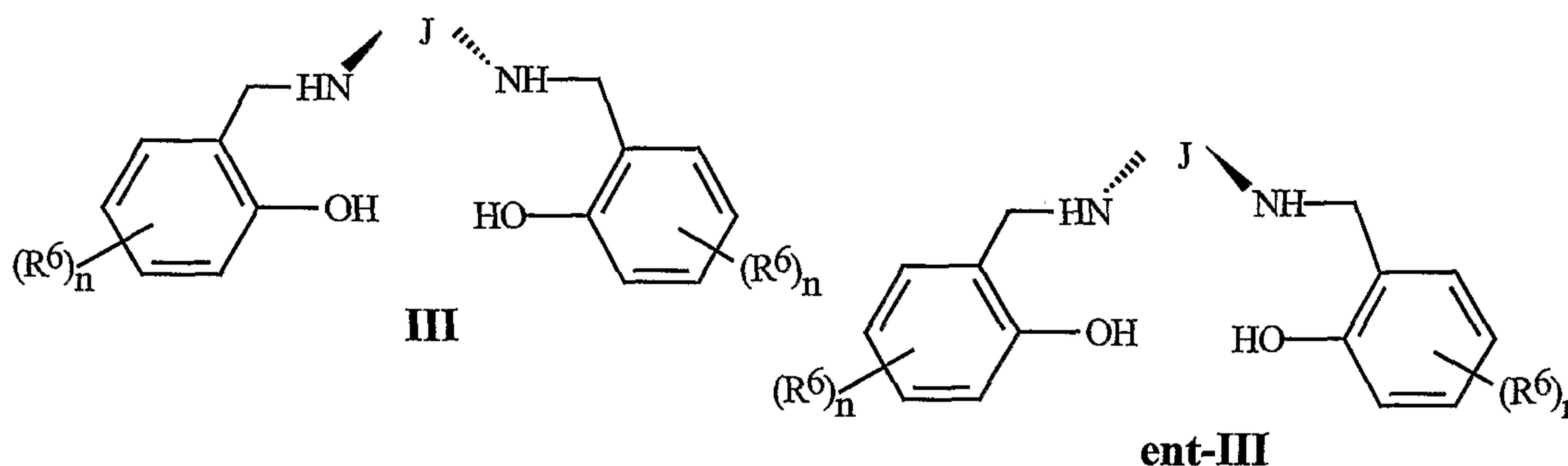
In one embodiment of this process, an achiral or racemic zirconium catalyst is used to
5 prepare a compound of Formula I in racemic form. Suitable achiral or racemic zirconium
complexes include zirconium alkoxide complexes such as zirconium(IV) isopropoxide,
zirconium(IV) butoxide, zirconium(IV) *tert*-butoxide, and zirconium(IV) propoxide,
zirconium(IV) β -dicarbonyl complexes such as zirconium(IV) acetylacetonate,
zirconium(IV) aryloxide complexes, zirconium(IV) amine complexes, or zirconium(IV)
10 amido complexes. Zirconium(IV) C₁-C₄ alkoxide and zirconium(IV) acetylacetonate are
preferred, and zirconium(IV) isopropoxide and zirconium(IV) acetylacetonate are
particularly useful. Zirconium(IV) acetylacetonate is most preferred because it is less
hygroscopic than zirconium(IV) alkoxide complexes. For this racemic embodiment,
hydrogen peroxide or a monoether of hydrogen peroxide is preferred as oxidant, and
15 *tert*-butyl hydroxide is especially preferred as oxidant.

In another embodiment of the present invention, an enantiomerically enriched
compound of Formula I is prepared by an enantioselective procedure. By "enantiomerically
enriched" it is meant that a bulk sample of the compound contains an excess of either the (+)
or (-) enantiomer and includes anything greater than a 1-to-1 (racemic) mixture of
20 enantiomers up to and including 100% of the pure enantiomer. By definition, the
enantiomeric excess (ee) of a sample is expressed as a percentage and is given by the
equation

$$\text{Enantiomeric Excess} = [(\text{En1} - \text{En2}) \cdot 100\%] / (\text{En1} + \text{En2})$$

where En1 and En2 are the amounts of the two enantiomers. Thus, for example, an enriched
25 compound having 25% (-) enantiomer and 75% (+) enantiomer is referred to as having a
50% enantiomeric excess of the (+) enantiomer. Enantiomerically enriched compounds of
Formula I can be produced, for example, by physically separating the enantiomers of a
racemic mixture according to standard methods. However, such methods are difficult to
operate on a large scale and are often wasteful, because the undesired enantiomer must be
30 discarded if it cannot be racemized. By "enantioselective" it is meant that the desired
enantiomer of the chiral product is formed preferentially, although not necessarily
exclusively. "Enantiomeric purity" is calculated the same way as enantiomeric excess; a
product of 100% enantiomeric purity has one enantiomer in 100% excess and none of the
other enantiomer; a product of 0% enantiomeric purity has equal amounts of enantiomers
35 such that neither is in excess, and therefore the product is racemic.

For the embodiment of the present invention pertaining to a process for preparing enantiomerically enriched compounds of Formula I by contacting a compound of Formula II with an oxidant and a chiral zirconium complex, a reaction temperature of about 20 to 75 °C and *tert*-butyl hydroperoxide as oxidant are preferred. Chiral zirconium complexes suitable for this process including preferred chiral complexes comprising zirconium and ligands of Formula III or its enantiomer (**ent-III**) are described in further detail below.



wherein J, R⁶ and n are as defined in the Summary of the Invention.

R¹, R² and R³ in Formulae I and II are appendages not directly involved in the hydroxylation reaction center. Because the reaction conditions of the hydroxylation process of the invention are so mild, a wide range of molecular structural features are possible for R¹, R² and R³, and only functionalities most reactive to oxidative conditions are susceptible to being affected. Therefore the substituent radicals listed for R¹, R² and R³ in the Summary of the Invention should be regarded as just describing a subgenus illustrative of the wide range of applicability of the process of this invention. Many of the radicals specified in the Summary of the Invention for R¹, R² and R³ in Formulae I and II are optionally substituted. A wide range of optional substituents are possible; illustrative optional substituents include alkyl, alkenyl, cycloalkyl, cycloalkenyl, aryl, hydroxycarbonyl, formyl, alkylcarbonyl, alkenylcarbonyl, alkynylcarbonyl, alkoxy, alkenyloxy, alkynyl-oxy, cycloalkoxy, aryloxy, alkylthio, alkenylthio, alkynylthio, cycloalkylthio, arylthio, alkylsulfinyl, alkenylsulfinyl, alkynylsulfinyl, cycloalkylsulfinyl, arylsulfinyl, alkylsulfonyl, alkenylsulfonyl, alkynylsulfonyl, cycloalkylsulfonyl, arylsulfonyl, amino, alkylamino, alkenylamino, alkynylamino, arylamino, aminocarbonyl, alkylaminocarbonyl, alkenylaminocarbonyl, alkynylaminocarbonyl, arylaminocarbonyl, alkylaminocarbonyl, alkenylaminocarbonyl, alkynylaminocarbonyl, arylaminocarbonyloxy, alkoxy, alkenyloxy, alkenyloxycarbonylamino, alkynyloxycarbonylamino and aryloxycarbonylamino, each further optionally substituted, and halogen, cyano and nitro. The optional further substituents are independently selected from groups like those illustrated above to give groups such as haloalkyl, haloalkenyl and haloalkoxy. As a further example, alkylamino can be further substituted with alkyl, giving dialkylamino. The substituents can also be tied

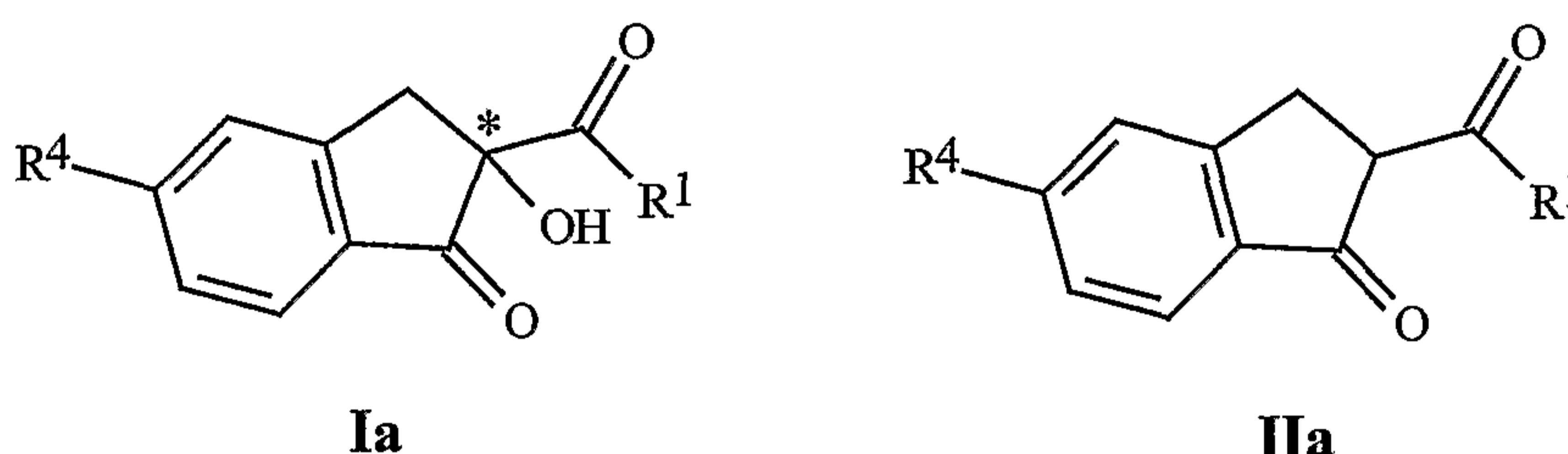
together by figuratively removing one or two hydrogen atoms from each of two substituents or a substituent and the supporting molecular structure and joining the radicals to produce cyclic and polycyclic structures fused or appended to the molecular structure supporting the substituents. For example, tying together adjacent hydroxy and methoxy groups attached to, for example, a phenyl ring gives a fused dioxolane structure containing the linking group -O-CH₂-O-. Tying together a hydroxy group and the molecular structure to which it is attached can give cyclic ethers, including epoxides. Illustrative substituents also include oxygen, which when attached to carbon forms a carbonyl function. Preferred processes of the invention are those wherein in Formulae I and II, the carbon atom of R² connected to the center indicated by * is in the form of a methyl, methylene or carbonyl unit. When the connecting carbon of R² is in the form of a carbonyl unit, it forms a tricarbonyl system with the other two carbonyls of Formula II. The enhanced acidity of the tricarbonyl system can facilitate the hydroxylation of Formula II to give Formula I.

Although there is no definite limit to the sizes of Formulae I and II suitable for the processes of the invention, typically Formula II comprises 5-100, more commonly 5-50, and most commonly 5-25 carbon atoms, and 2-25, more commonly 2-15, and most commonly 2-10 heteroatoms. The heteroatoms are commonly selected from halogen, oxygen, sulfur, nitrogen and phosphorus, and more commonly, halogen, oxygen and nitrogen. Two heteroatoms in Formula II are the β-dicarbonyl oxygen atoms. The numbers of atoms commonly in Formula I are similar to those described by Formula II, except that as result of hydroxylation, Formula I has one more heteroatom. Also, there is no definite limit to the size of the illustrative groups listed for R¹, R² and R³, but alkyl, including derivatives such as alkoxy, is commonly C₁-C₆, alkenyl and alkynyl are commonly C₂-C₆ and more commonly C₂-C₆, and cycloalkyl is commonly C₃-C₈.

One skilled in the art recognizes that sulfinyl and particularly thio moieties (in, for example, alkylthio, alkenylthio, alkynylthio, cycloalkylthio, arylthio, alkylsulfinyl, alkenylsulfinyl, alkynylsulfinyl, cycloalkylsulfinyl and arylsulfinyl substituents) are susceptible to oxidation. Thio- and sulfinyl-containing substituents in Formula II do not prevent the hydroxylation reaction of this invention, but thio can be converted to sulfinyl and sulfonyl, and sulfinyl converted to sulfonyl in the product of Formula I.

Of note are processes of this invention wherein, in Formulae I and II, R² is H, alkyl, cycloalkyl, a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and R¹ and R³ are not taken together. Of note also are processes of the invention wherein, in Formulae I and II, R¹ is H; or alkoxy, alkyl, cycloalkyl, a phenyl ring, a phenoxy ring or a 5- or 6-membered heteroaromatic ring, each optionally substituted; and R³ is alkoxy, alkyl, cycloalkyl, a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each optionally substituted.

Preferred processes of this invention are those wherein, in Formulae **I** and **II**, R¹ is alkyl or alkoxy, preferably alkoxy, more particularly C₁-C₆ alkoxy, and more preferably C₁-C₃ alkoxy, R² is preferably alkyl or alkylcarbonyl (alkyl substituted with oxygen on the linking carbon), more preferably alkyl and more particularly C₁-C₆ alkyl, R³ is optionally substituted phenyl, or R² and R³ are taken together to form an optionally substituted linking chain of 3 to 4 carbon members optionally fused to an optionally substituted phenyl ring. Preferably the optional substituents on phenyl are selected from halogen, cyano and nitro, and also alkyl, alkenyl, alkynyl, cycloalkyl, cycloalkenyl, aryl, formyl, alkylcarbonyl, alkenylcarbonyl, alkynylcarbonyl, alkoxycarbonyl, hydroxy, alkoxy, alkenyloxy, alkynyloxy, aryloxy, alkylsulfonyl, alkenylsulfonyl, alkynylsulfonyl, arylsulfonyl, amino, alkylamino, alkenylamino, alkynylamino, arylamino, aminocarbonyl, alkylaminocarbonyl, alkenylaminocarbonyl, alkynylaminocarbonyl, arylaminocarbonyl, alkylaminocarbonyloxy, alkenylaminocarbonyloxy, alkynylaminocarbonyloxy, arylaminocarbonyloxy, alkoxy-carbonylamino, the aforementioned substituents optionally tied together, the aforementioned substituents optionally substituted with halogen. Particularly preferred processes of the invention are those wherein Formula **I** is Formula **Ia** and Formula **II** is Formula **Ila**



wherein * indicates the hydroxylation center, which is a chiral center, and Formula **Ia** is racemic or enantiomerically enriched.

Formulae **Ia** and **Ila** are subsets of Formula **I** and **II**, respectively, in which R² and R³ are taken together to form a linking chain of 3 carbon members fused to a phenyl ring substituted with R⁴. In Formulae **Ia** and **Ila**, R¹ is preferably alkoxy, more particularly C₁-C₆ alkoxy, and more preferably C₁-C₃ alkoxy; and R⁴ is preferably halogen or haloalkoxy, more particularly F, Cl or C₁-C₃ fluoroalkoxy, and most particularly Cl.

Illustrating a combination of preferred R¹, R² and R³ is a process for preparing a compound of Formula **I** that is racemic or enantiomerically enriched at the chiral center indicated by *, comprising contacting a compound of Formula **II** with a zirconium complex and an oxidant, wherein in Formulae **I** and **II**

R¹ is alkoxy;

R² is alkyl;

R³ is optionally substituted phenyl, or

R² and R³ can be taken together to form an optionally substituted linking chain of 3 to 4 carbon members optionally fused to an optionally substituted phenyl ring.

Note that this preferred embodiment provides for the hydroxylation of β -keto esters.

A more preferred process of this invention is one wherein a compound of Formula **IIa** wherein R¹ is C₁–C₃ alkoxy and R⁴ is F, Cl, or C₁–C₃ fluoroalkoxy is contacted with an oxidant and a zirconium complex to prepare a compound of Formula **Ia** that is racemic or enantiomerically enriched at the chiral center indicated by *.

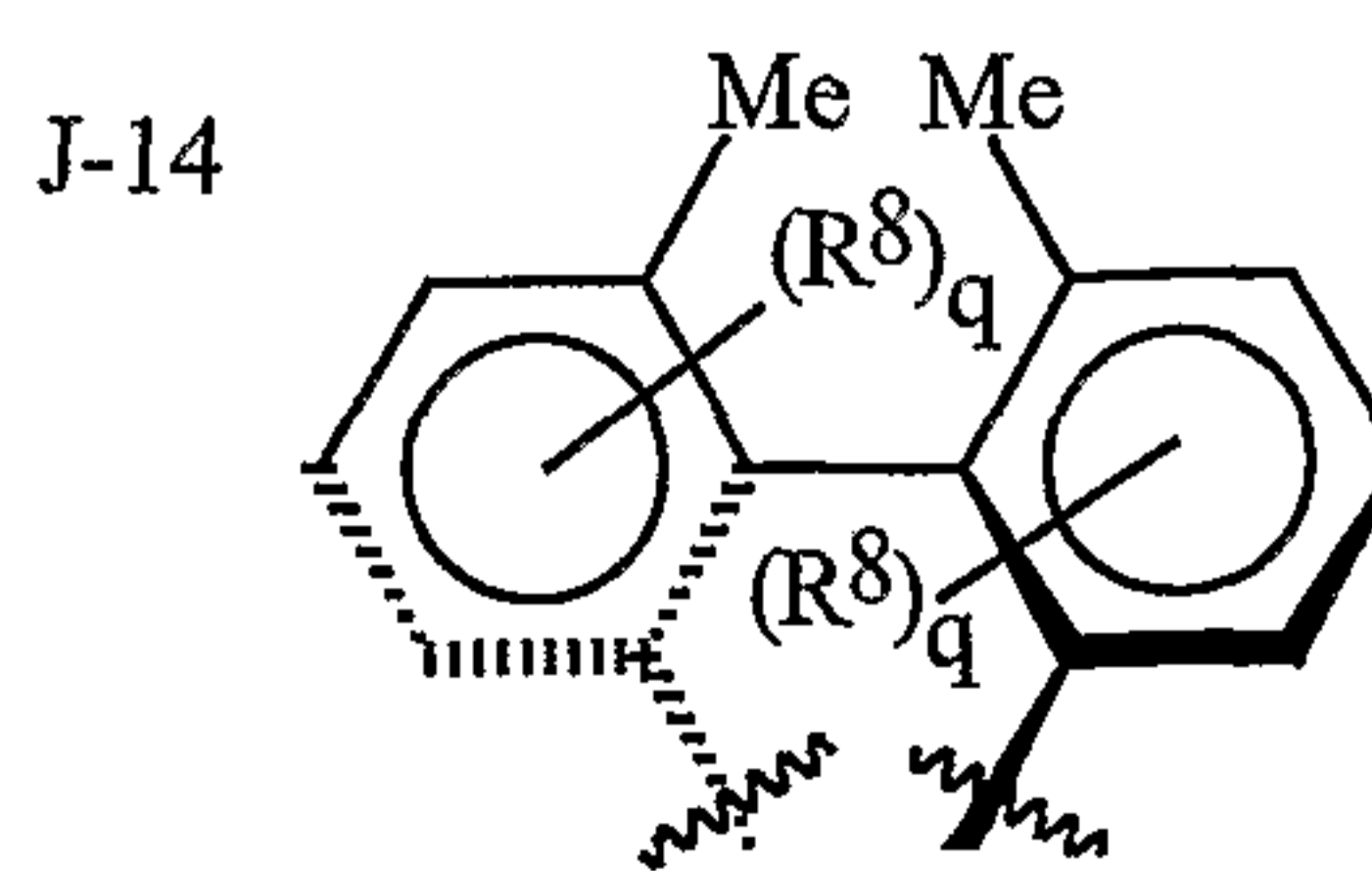
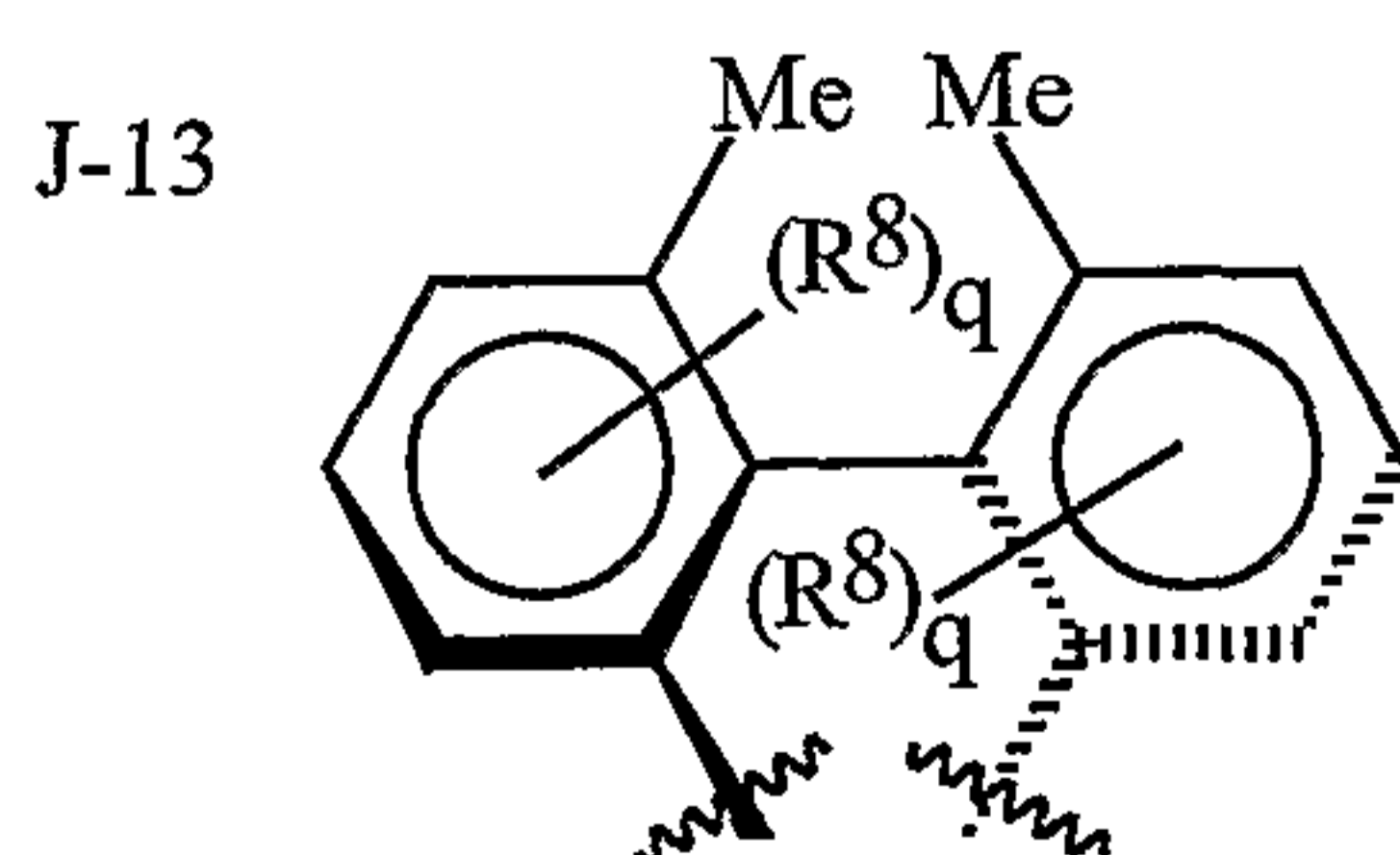
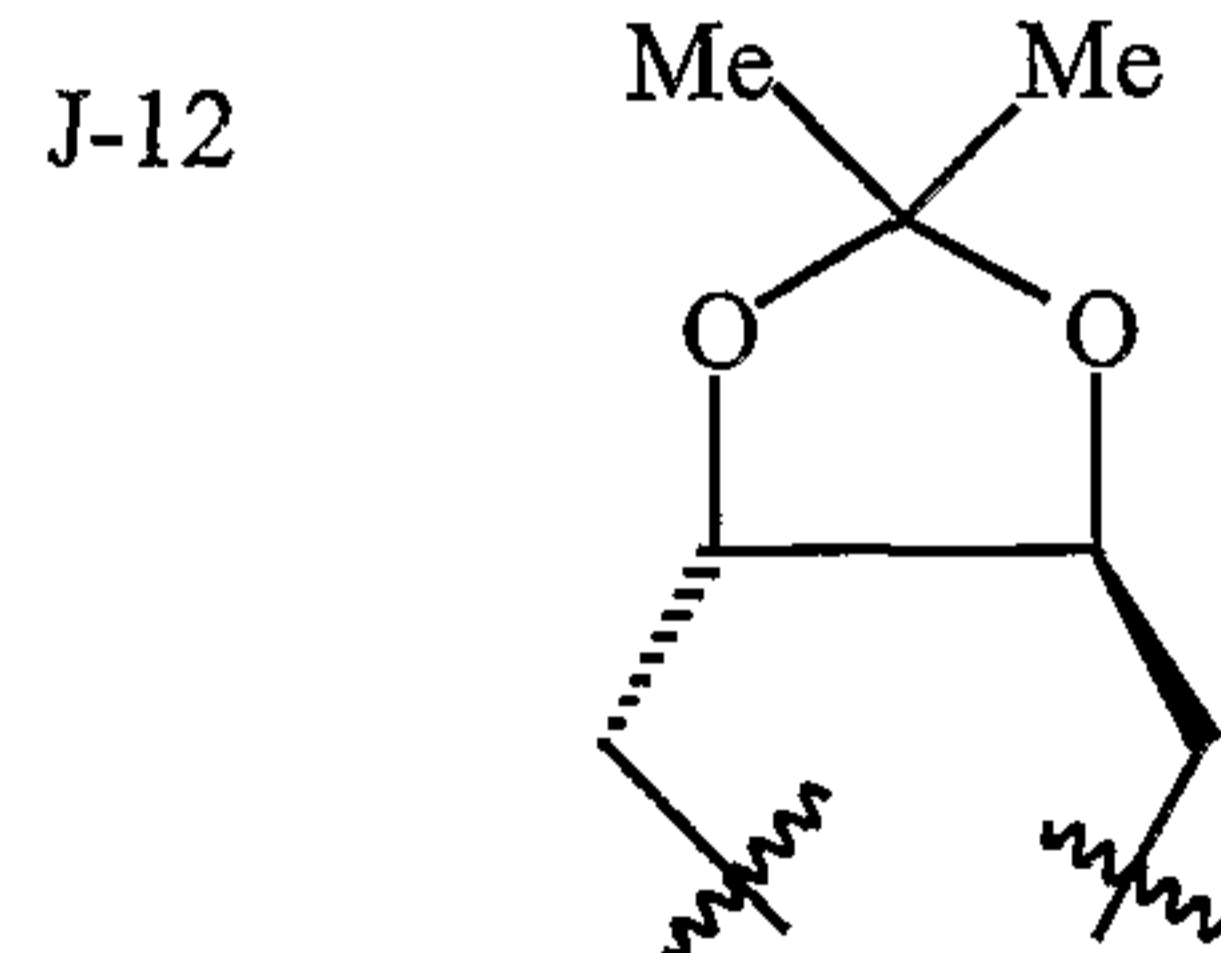
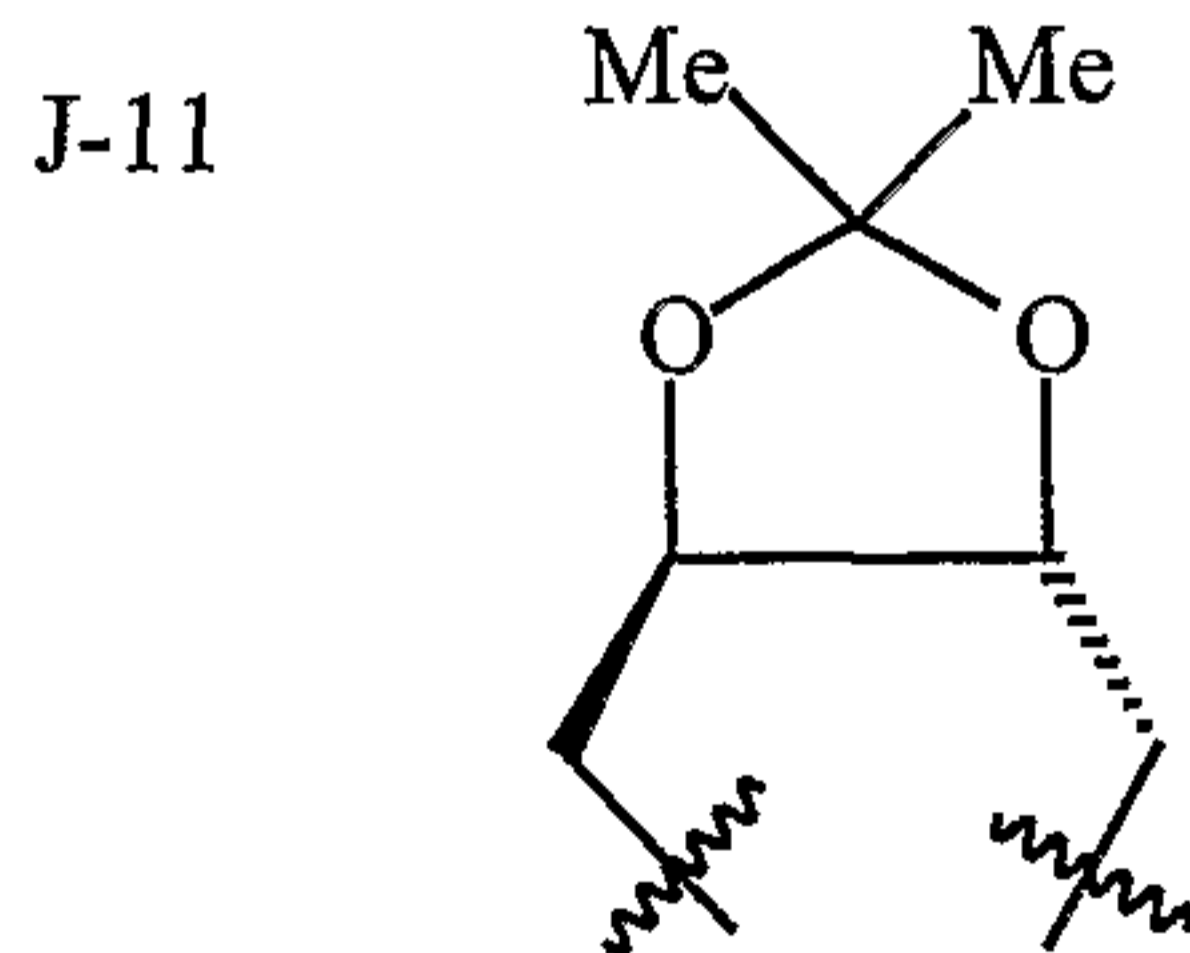
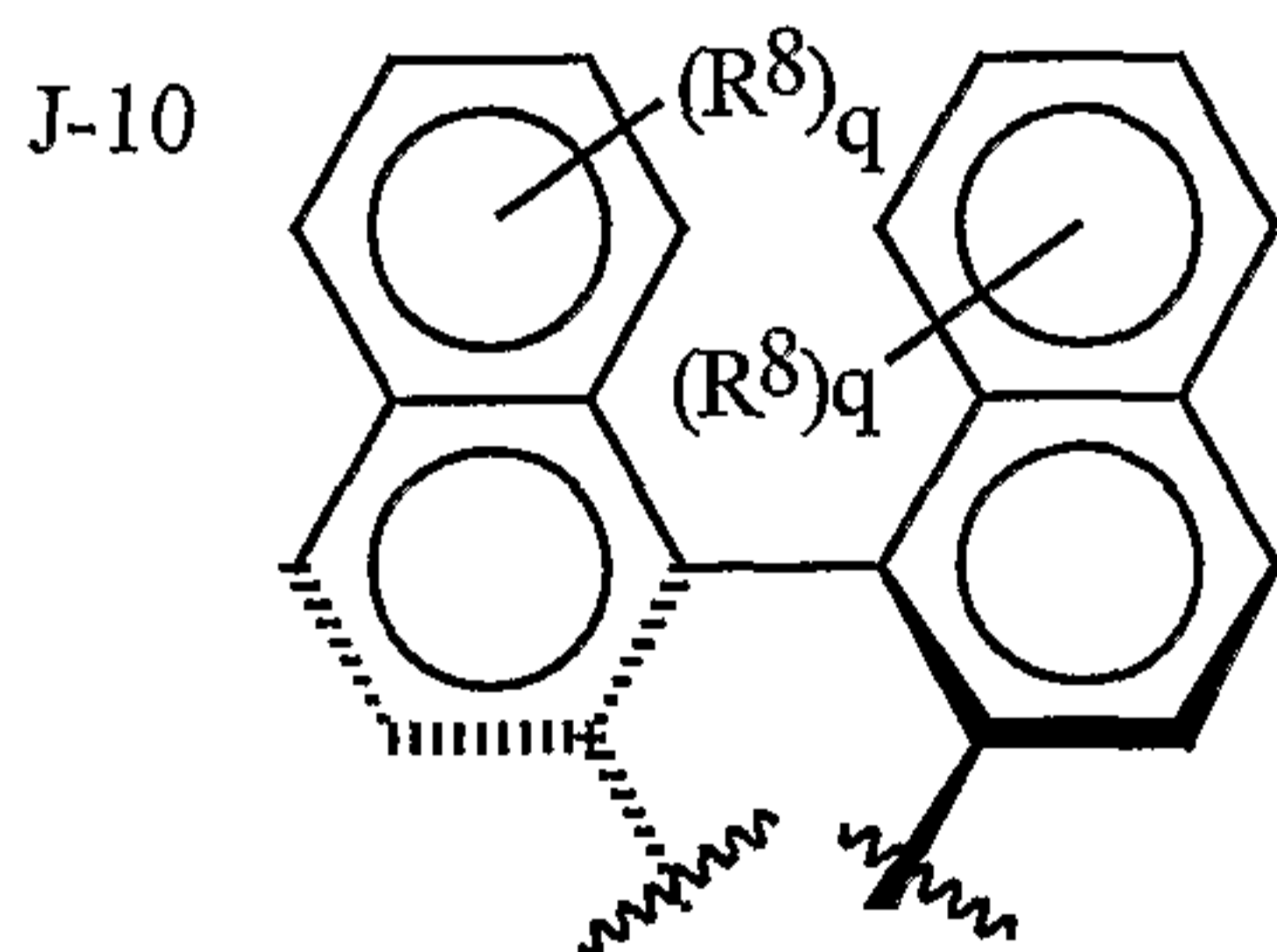
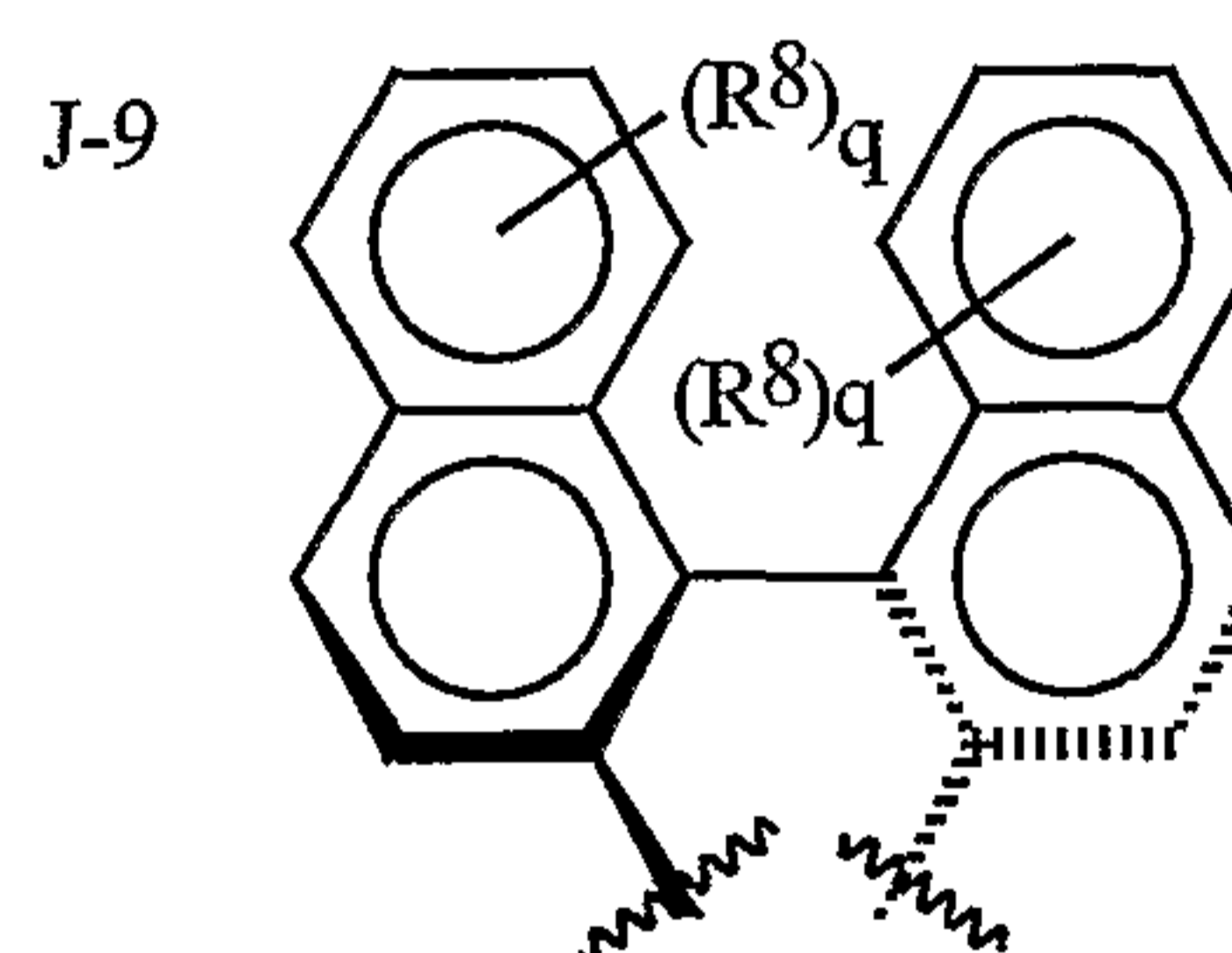
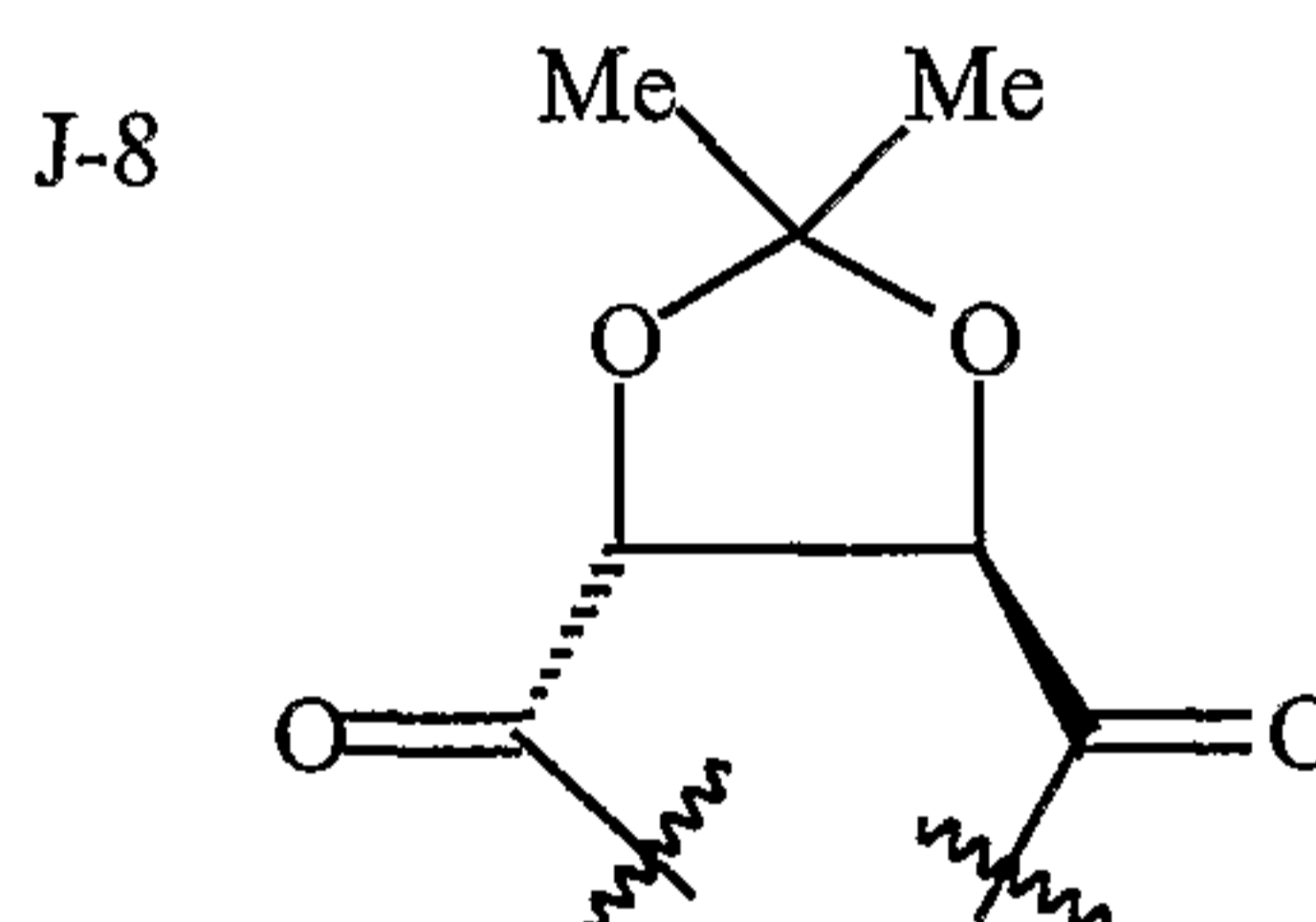
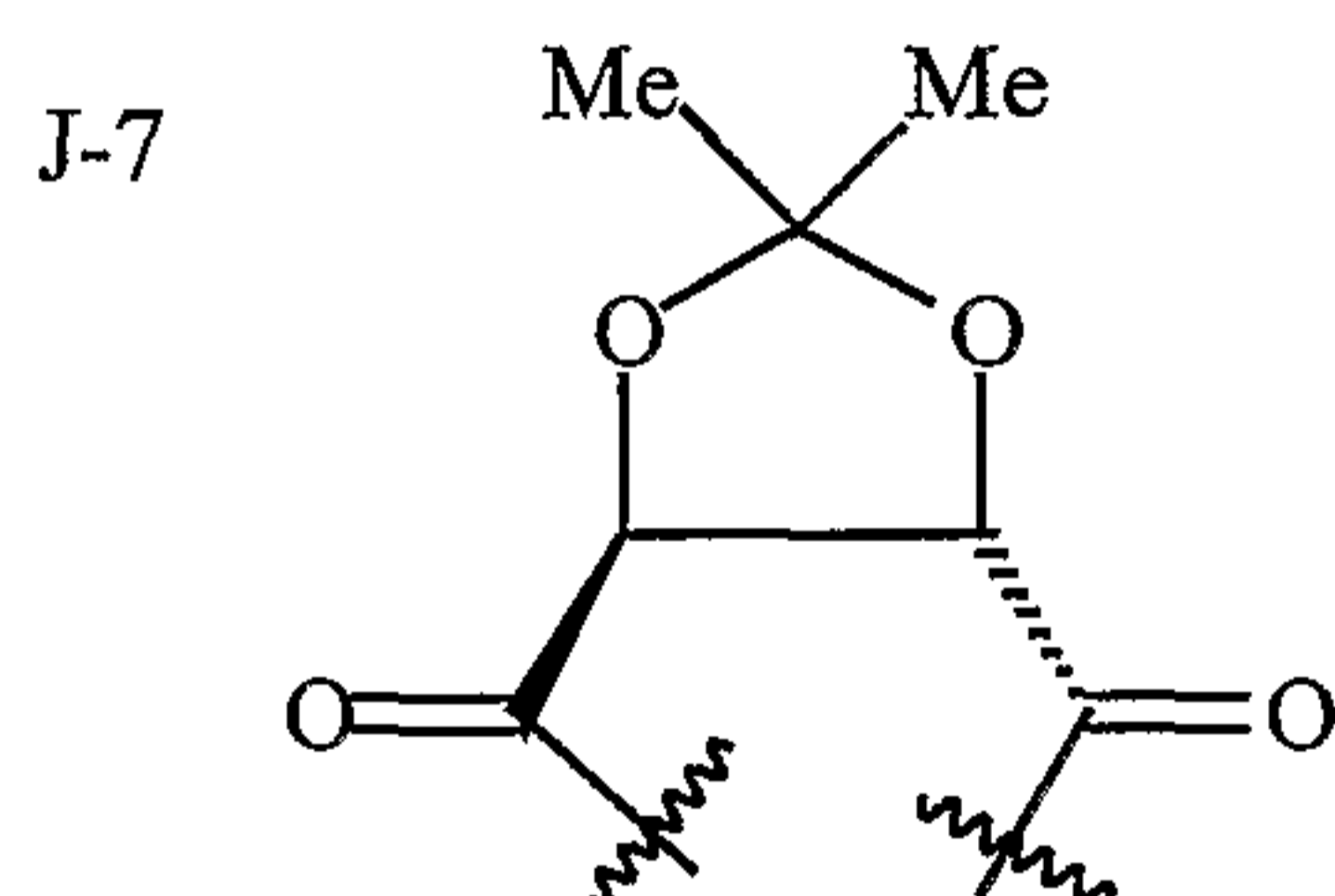
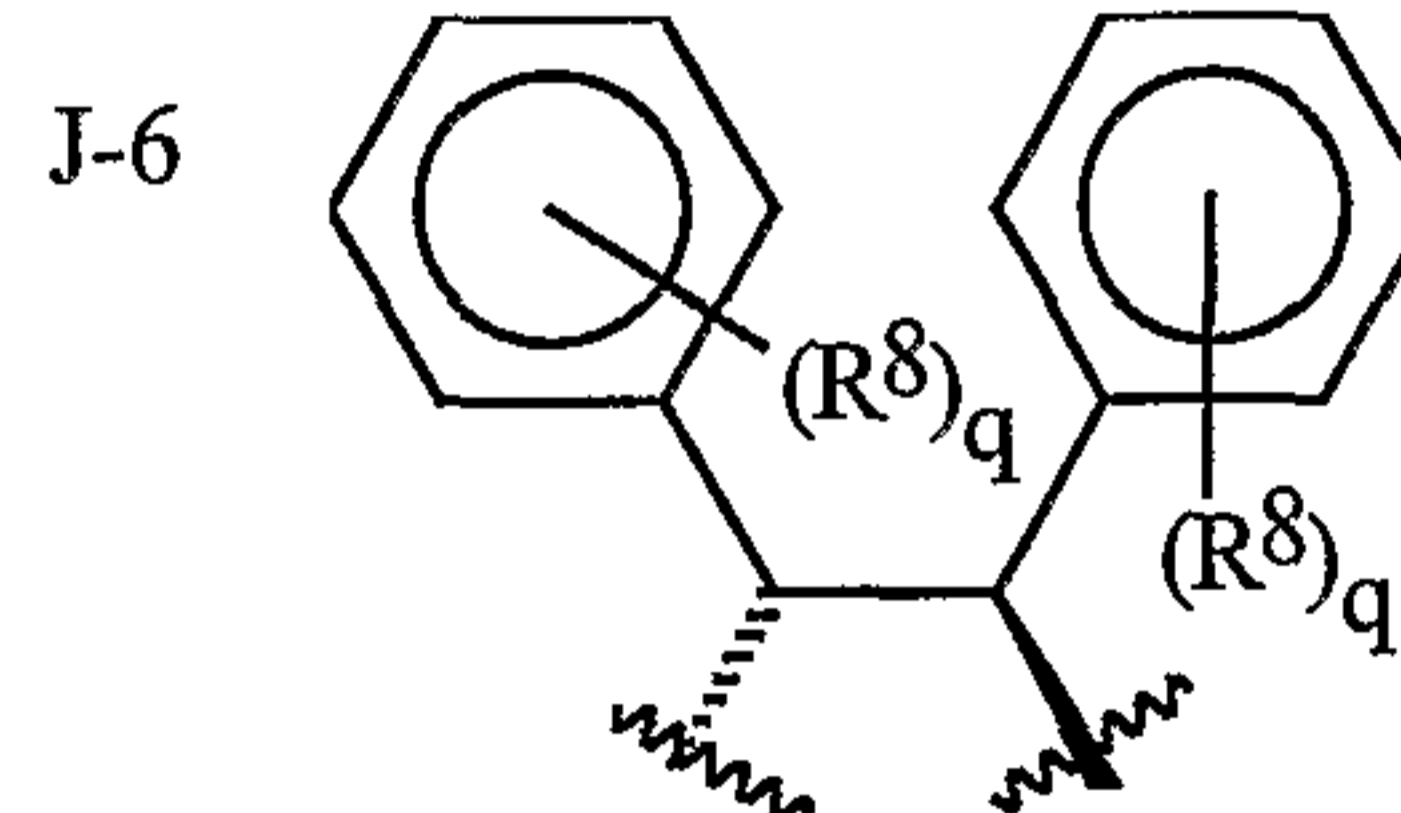
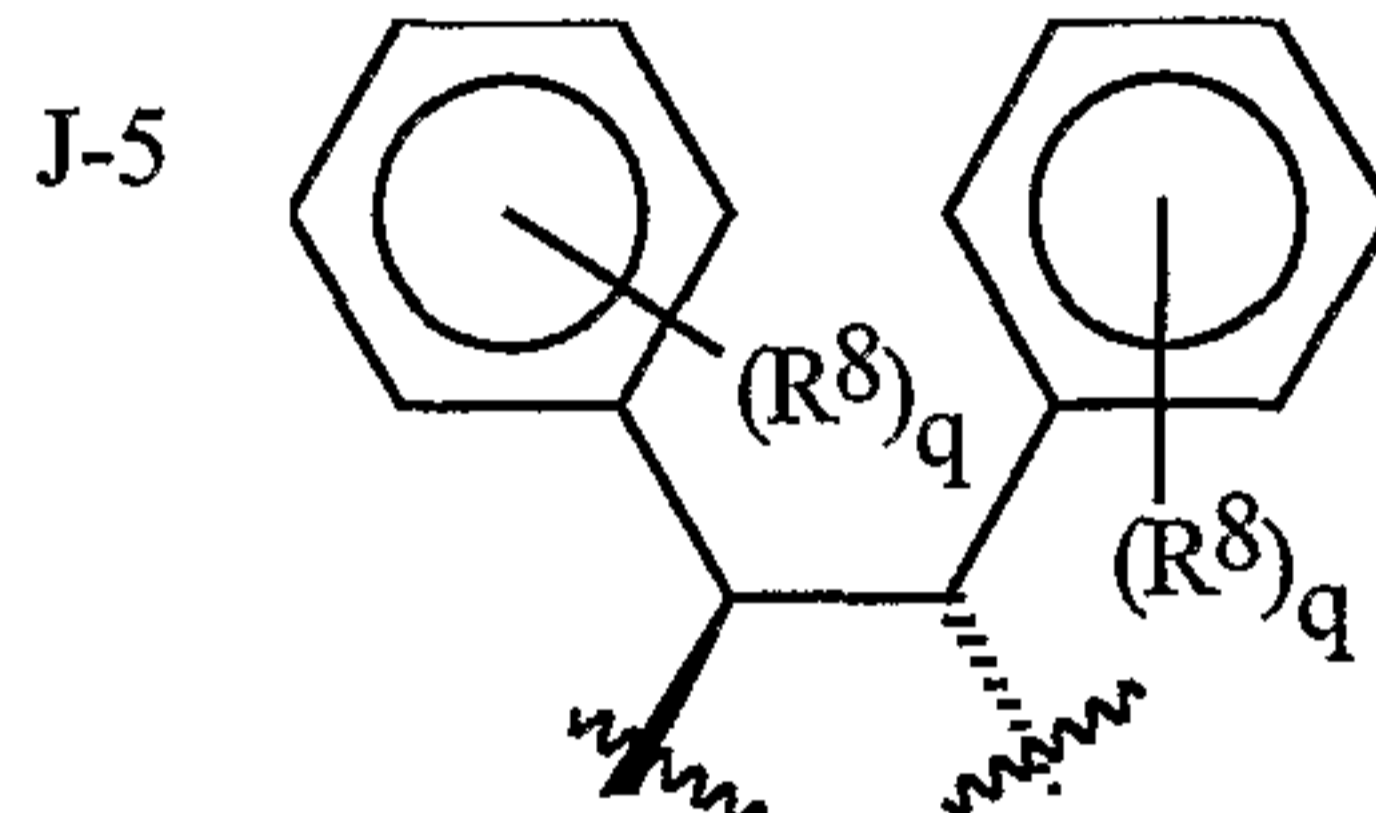
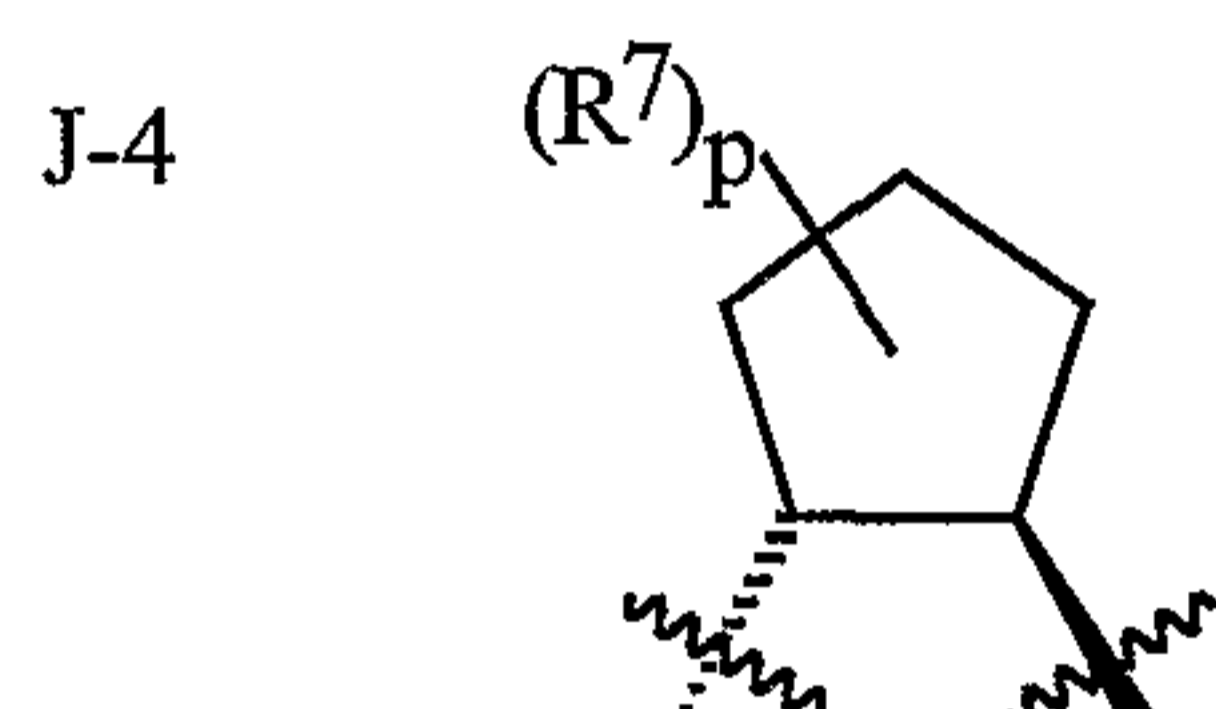
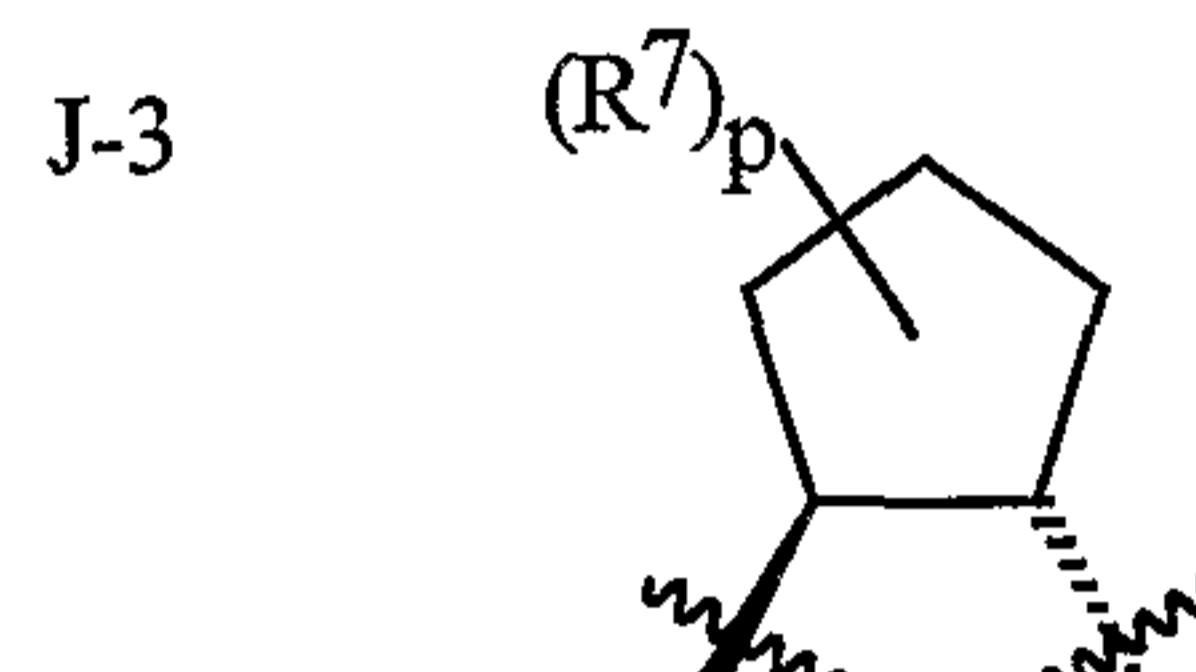
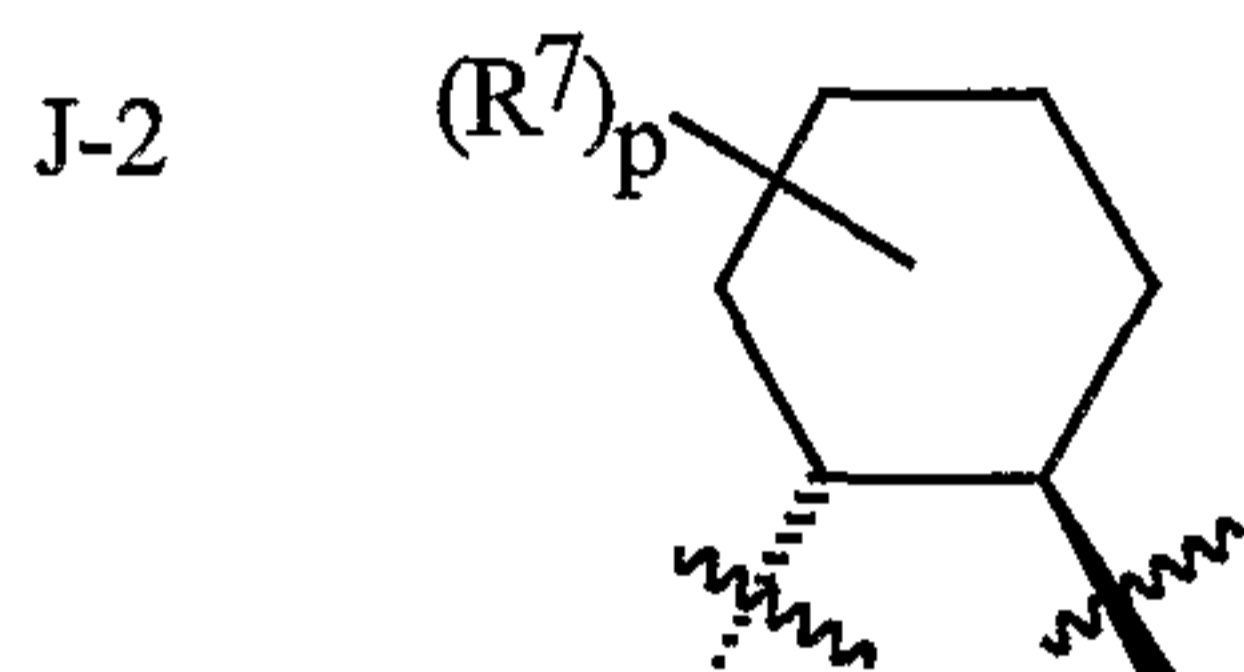
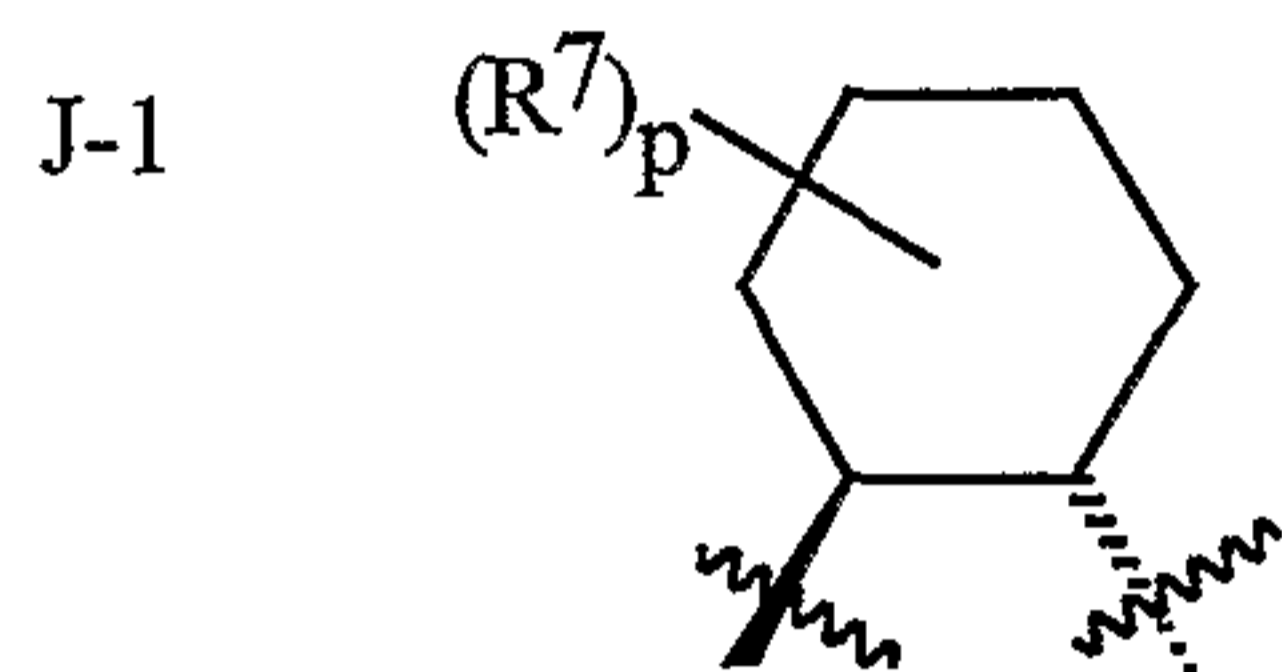
Most preferred is a process in which a compound of Formula **IIa** is contacted with an oxidant and a chiral zirconium complex comprising zirconium and a ligand of Formula **III** or its enantiomer. Preparation of compounds of Formula **Ia** from compounds of Formula **IIa** has been previously reported in WO 95/29171 using a different process. The process of the instant invention provides higher yields of Formula **Ia** and is more convenient to run compared to the previously reported process. The process of the instant invention also affords improved enantioselectivity over the enantioselective process reported in WO 95/29171.

As already described, the hydroxylation process of this invention is generally applicable to a wide range of starting compounds of Formula **II**, which are obtainable through the methodologies known in the art of synthetic organic chemistry. For example, compounds of Formula **IIa** can be prepared by the methods described by R. Shapiro et al. "Toward the Manufacture of Indoxacarb" Chapter 17 (pp. 178–185 in *Synthesis and Chemistry of Agrochemicals VI* (ACS Symposium Series 800), American Chemical Society, Washington, DC, 2002 and particularly PCT Publication WO 96/20151.

Another embodiment of this invention pertains to chiral zirconium complexes comprising zirconium and a chiral ligand of Formula **III** or its enantiomer (**ent-III**). The chiral centers of the chiral ligands of Formula **III** must provide overall chirality with the configurations of the NH linking groups as depicted, thereby excluding meso stereoisomers, which do not form enantiomers. The chiral zirconium complexes are suitable for the process for preparing enantiomerically enriched compounds of Formula **I** from Formula **II**. In the Summary of the Invention, rings (e.g., phenyl) and ring systems are described for J and R⁶ in Formulae **III** and **ent-III** as being optionally substituted. As these optional substituents are spatially separate from the region of Formulae **III** and **ent-III** complexing to zirconium(IV), a wide range of substituents are possible, but at the same time, generally do not increase the usefulness of the zirconium complexes for the hydroxylation process of the invention. Optional substituents most easily included in Formulae **III** and **ent-III** are alkyl, haloalkyl, alkoxy, haloalkoxy, halogen and nitro; more particularly, C₁–C₄ alkyl, C₁–C₄ haloalkyl, C₁–C₄ alkoxy, C₁–C₄ haloalkoxy, halogen and nitro, and more preferably C₁–C₄ alkyl, C₁–C₄ alkoxy, halogen and nitro. Preferably, the optional substituents for the rings and ring

systems described for J and R^6 are selected and positioned so that Formulae **III** and **ent-III** has a C_2 axis of symmetry. More preferably, the rings and ring systems in J and R^6 do not have optional substituents. Of note are compounds of Formulae **III** and **ent-III** wherein R^6 is other than the following: adamantyl, C_3 - C_6 cycloalkyl optionally substituted with C_1 - C_2 alkyl, C_2 - C_5 alkylcarbonyloxy, C_2 - C_5 alkoxy carbonyloxy, and optionally substituted phenylcarbonyloxy.

If the linking chain of J is fused to form a C_3 - C_8 nonaromatic heterocyclic ring, preferably said nonaromatic heterocyclic ring is fully saturated; also preferably said ring is connected through carbon atoms of said ring to the aminomethyl moieties connecting to the remainder of Formulae **III** and **ent-III**. Illustrative examples of J include:



wherein

each R⁷ is independently selected from C₁-C₄ alkyl, C₁-C₄ alkoxy and halogen;

each R⁸ is independently selected from C₁-C₄ alkyl, C₁-C₄ alkoxy, halogen and nitro;

p is an integer from 0 to 4; and

5 each q is independently an integer from 0 to 3.

Preferably, each q is the same, and each R⁷ and each R⁸ are selected and positioned so that J has a C₂ axis of symmetry. More preferably, p and q are each 0.

The phrase "C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **III** (or **ent-III**)" used herein refers to J-1 (or J-2) where p is 0. The phrase "1,1'-
10 binaphthalenyl ring system connected via the 2 and 2' positions to the remainder of Formula **III** (or **ent-III**)" used herein refers to J-9 (or J-10) where q is 0.

Accordingly, for this embodiment of the invention, the chiral zirconium complex comprises a complex prepared from a chiral ligand of Formula **III** or its enantiomer and a zirconium complex. One skilled in the art will realize that the enantioselectivity of the
15 hydroxylation reaction will generally decrease as the enantiomeric purity of the chiral ligand decreases. By the same reasoning, one skilled in the art will also realize that using a chiral ligand with greater than 0% enantiomeric purity (i.e. a chiral ligand that is enantiomerically enriched) may produce an enantiomerically enriched hydroxylation product. Preferably the enantiomeric purity of the chiral ligand is at least about 50%, more preferably at least 90%,
20 even more preferably at least 95%, even more preferably at least 98%, and most preferably at least 99%.

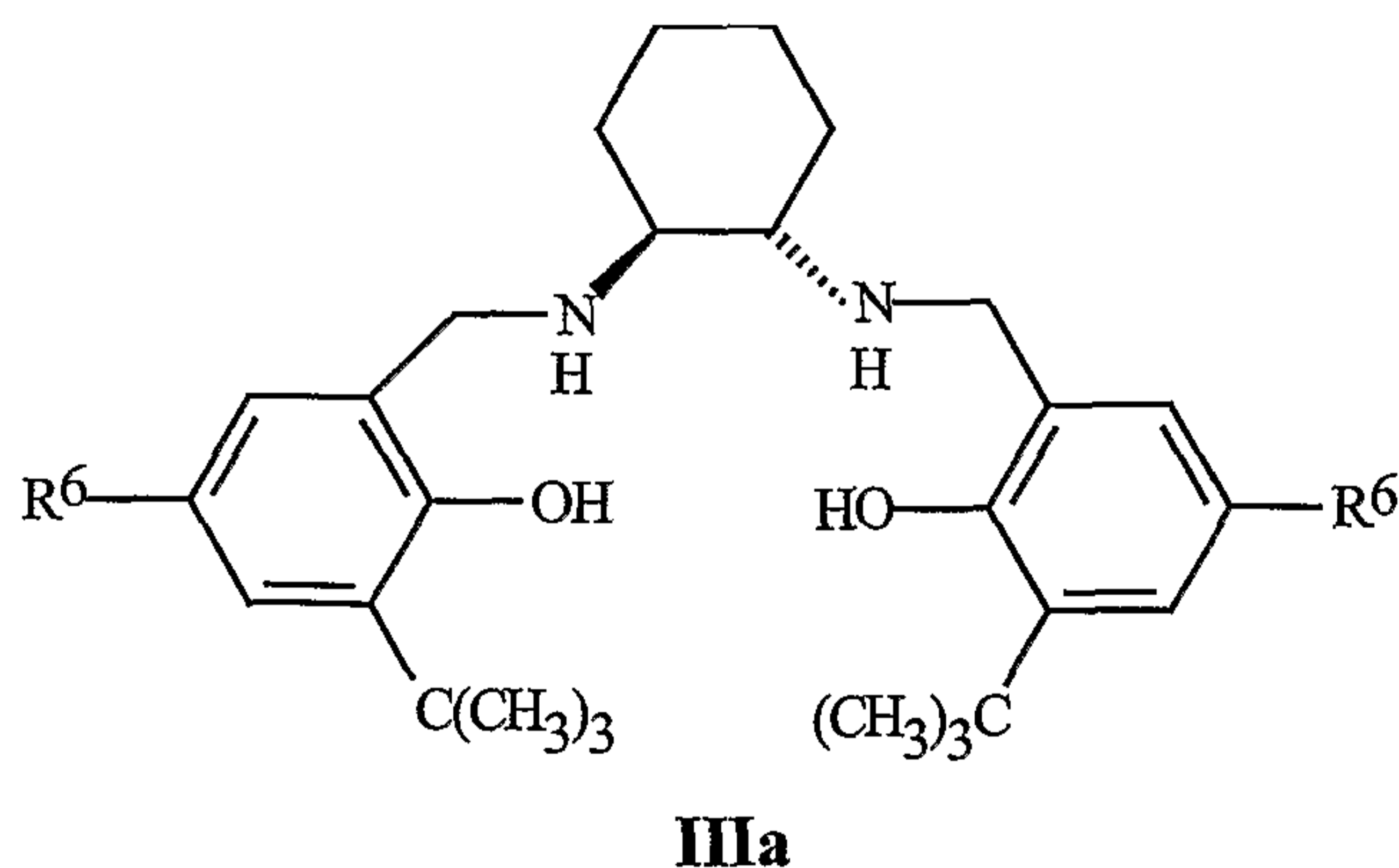
The chiral zirconium complex can be prepared by contacting the zirconium complex with 0.1 to 5 equivalents of a compound of Formula **III** or **ent-III**, optionally in the presence of a solvent. Typical reaction conditions include reaction temperatures in the range of about
25 -5 to 100 °C and reaction times of about 30 minutes to 3 days. Preferred chiral zirconium complexes comprise chiral ligands that have a C₂ axis of symmetry. As a substituent adjacent to the -OH function on each phenyl ring of Formula **III** (and **ent-III**) can promote stereoselectivity of the process, preferred are chiral zirconium complexes comprising ligands of Formula **III** or **ent-III** wherein each phenyl ring has an R⁶ substituent ortho to the -OH
30 function. More preferred are chiral zirconium complexes comprising ligands of Formula **III** or **ent-III** wherein each R⁶ substituent ortho to the -OH function is *tert*-butyl. Particularly suitable ligands of Formula **III** or **ent-III** include structures where the HN-J-NH group is the diradical of (1*S*,2*S*)- or (1*R*,2*R*)-1,2-cyclohexanediamine, (1*S*,2*S*)- or (1*R*,2*R*)-1,2-diphenyl-1,2-ethanediamine (also known as (*S,S*)- or (*R,R*)-1,2-diphenylethylenediamine), (1*S*)- or
35 (1*R*)-[1,1'-binaphthalene]-2,2'-diamine (also known as (*S*)- or (*R*)-1,1'-binaphthyl-2,2'-diamine), and (2*S*,3*S*)- or (2*R*,3*R*)-2,3-dihydroxybutanediamide (also known as (*S,S*)- or (*R,R*)-tartaric acid diamide). Preferred are chiral zirconium complexes comprising ligands

comprising the diradical independently selected from the group consisting of (*S,S*)- or (*R,R*)-1,2-cyclohexanediamine and (*S,S*)- or (*R,R*)-1,2-diphenylethylenediamine.

Suitable zirconium complexes for the preparation of chiral zirconium complexes comprising zirconium and ligands of Formula **III** or **ent-III** include zirconium alkoxide complexes such as zirconium(IV) isopropoxide, zirconium(IV) butoxide, zirconium(IV) *tert*-butoxide, and zirconium(IV) propoxide, zirconium(IV) β -dicarbonyl complexes such as zirconium(IV) acetylacetonate, zirconium(IV) aryloxide complexes, zirconium(IV) amine complexes, or zirconium(IV) amido complexes. Zirconium(IV) isopropoxide and zirconium(IV) acetylacetonate are preferred. Suitable solvents for preparing the chiral zirconium complex include aliphatic hydrocarbons such as cyclohexane, aromatic hydrocarbons such as toluene, xylenes, ethylbenzene, mesitylene and cumene, halogenated hydrocarbons such as dichloromethane, dichloroethane and *ortho*-dichlorobenzene, ketones such as methyl ethyl ketone, methyl isobutyl ketone and methyl isopropyl ketone, esters such as methyl acetate, ethyl acetate, isopropyl acetate and ethers such as diethyl ether or tetrahydrofuran. Aromatic hydrocarbon solvents are preferred.

One skilled in the art will recognize that the process of this invention may involve several different chiral complexes comprising zirconium and a chiral ligand of Formula **III** or **ent-III** including those comprising additional ligands such as, but not limited to, the oxidant, compounds of Formula **II** and compounds of Formula **I**. All such complexes involved in the process of this invention are encompassed by this embodiment of the invention.

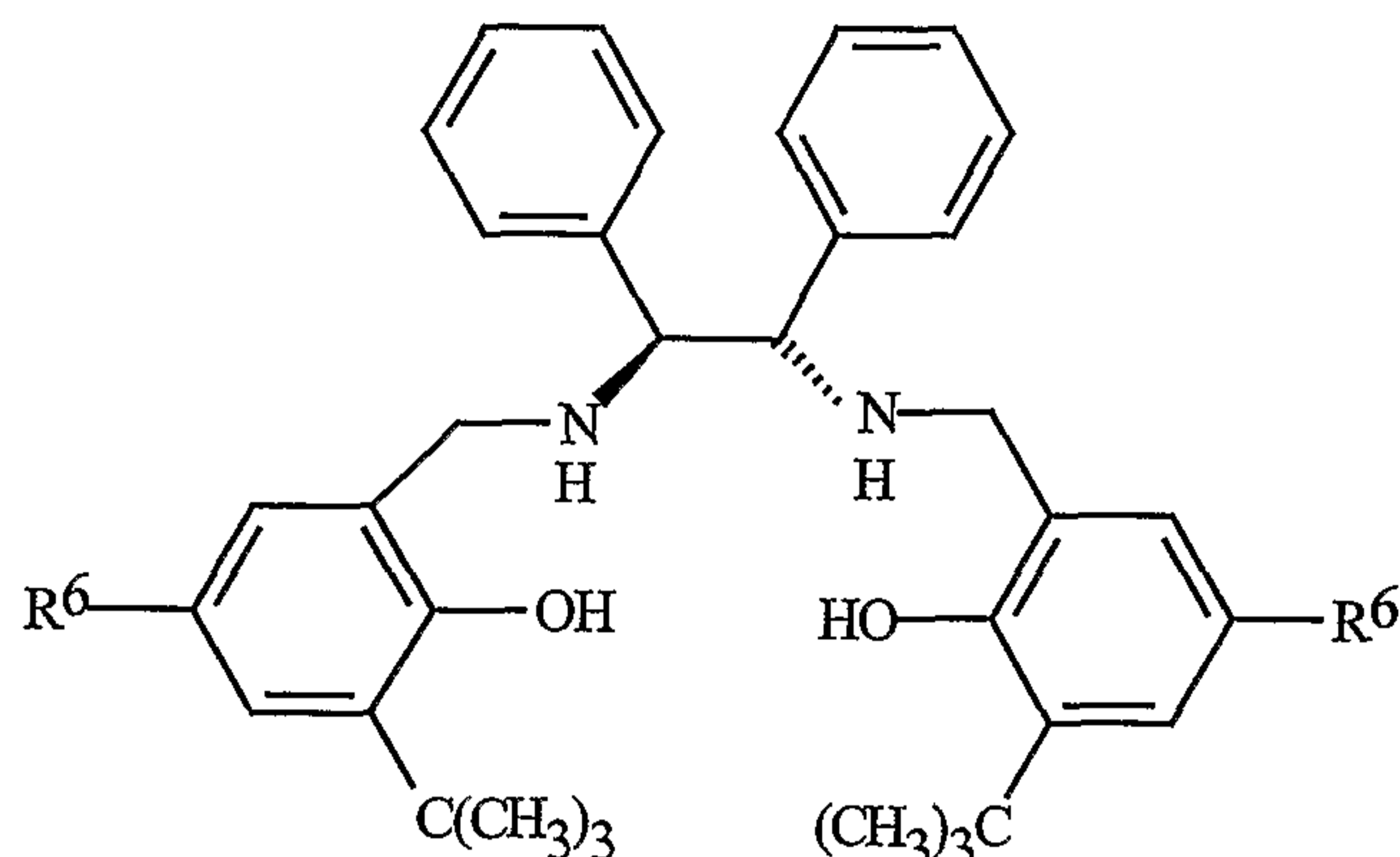
A particularly preferred complex is a complex comprising zirconium and a ligand of Formula **IIIa**



wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

The compound of Formula **IIIa** wherein R^6 is $C(CH_3)_3$ is named 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediylbis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol], and the ligand of Formula **IIIa** wherein R^6 is H is named 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediylbis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol].

A second particularly preferred complex is a complex comprising zirconium and a ligand of Formula **IIIb**

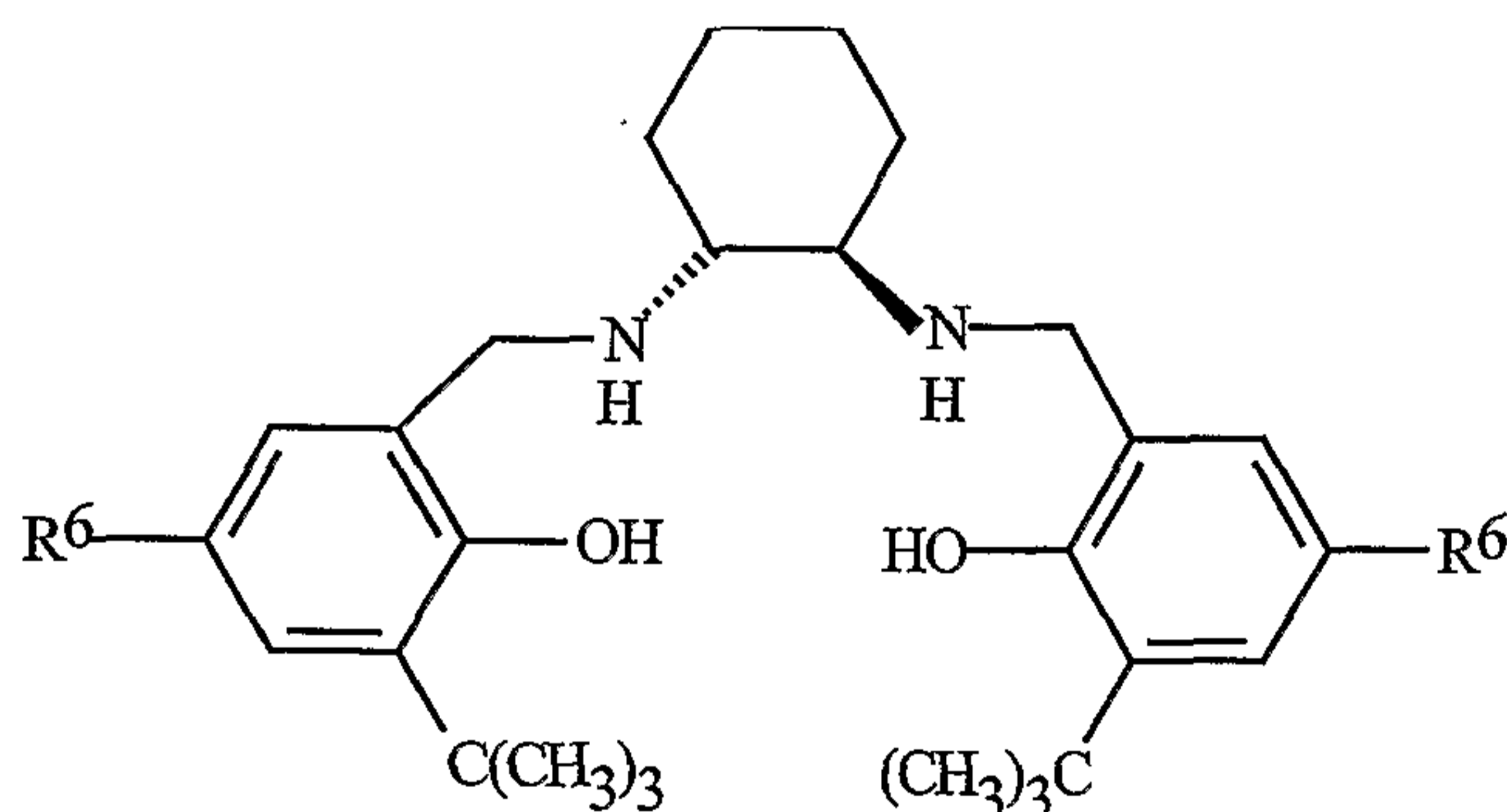


IIIb

wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

- 5 The ligand of Formula **IIIb** wherein R^6 is H is named 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol], and the ligand of Formula **IIIb** wherein R^6 is $C(CH_3)_3$ is named 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]-bis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol].

10 Other preferred complexes are complexes comprising zirconium and a ligand that is Formula **ent-IIIa** (which is the enantiomer of Formula **IIIa**)

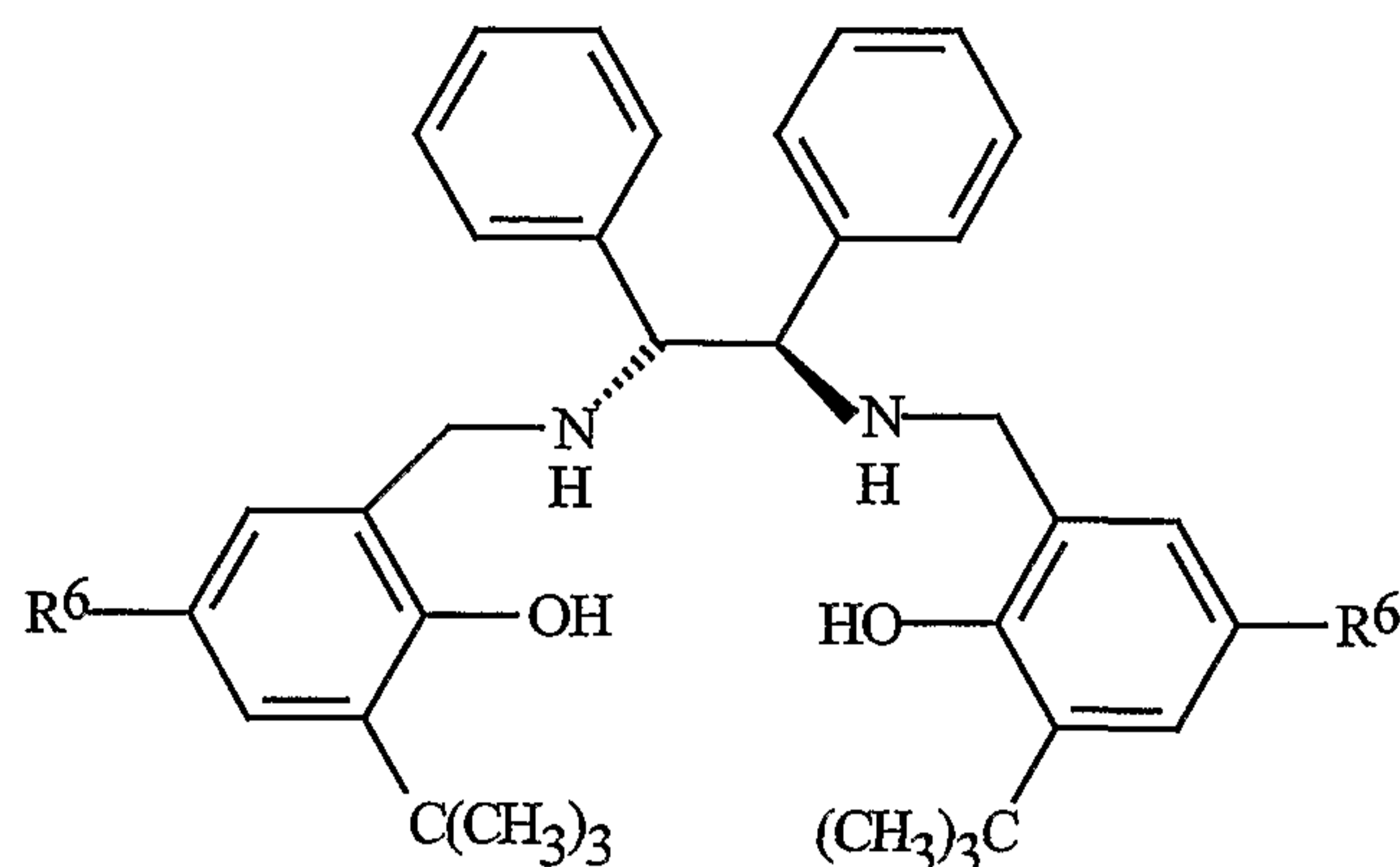


ent-IIIa

wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

- 15 The ligand of Formula **ent-IIIa** wherein R^6 is $C(CH_3)_3$ is named 2,2'-[[*(1R,2R)*-1,2-cyclohexanediyl]bis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol]), and the ligand of Formula **ent-IIIa** wherein R^6 is H is named 2,2'-[[*(1R,2R)*-1,2-cyclohexanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol].

Other preferred complexes are complexes comprising zirconium and a ligand that is Formula **ent-IIIb** (which is the enantiomer of Formula **IIIb**)

**ent-IIIb**

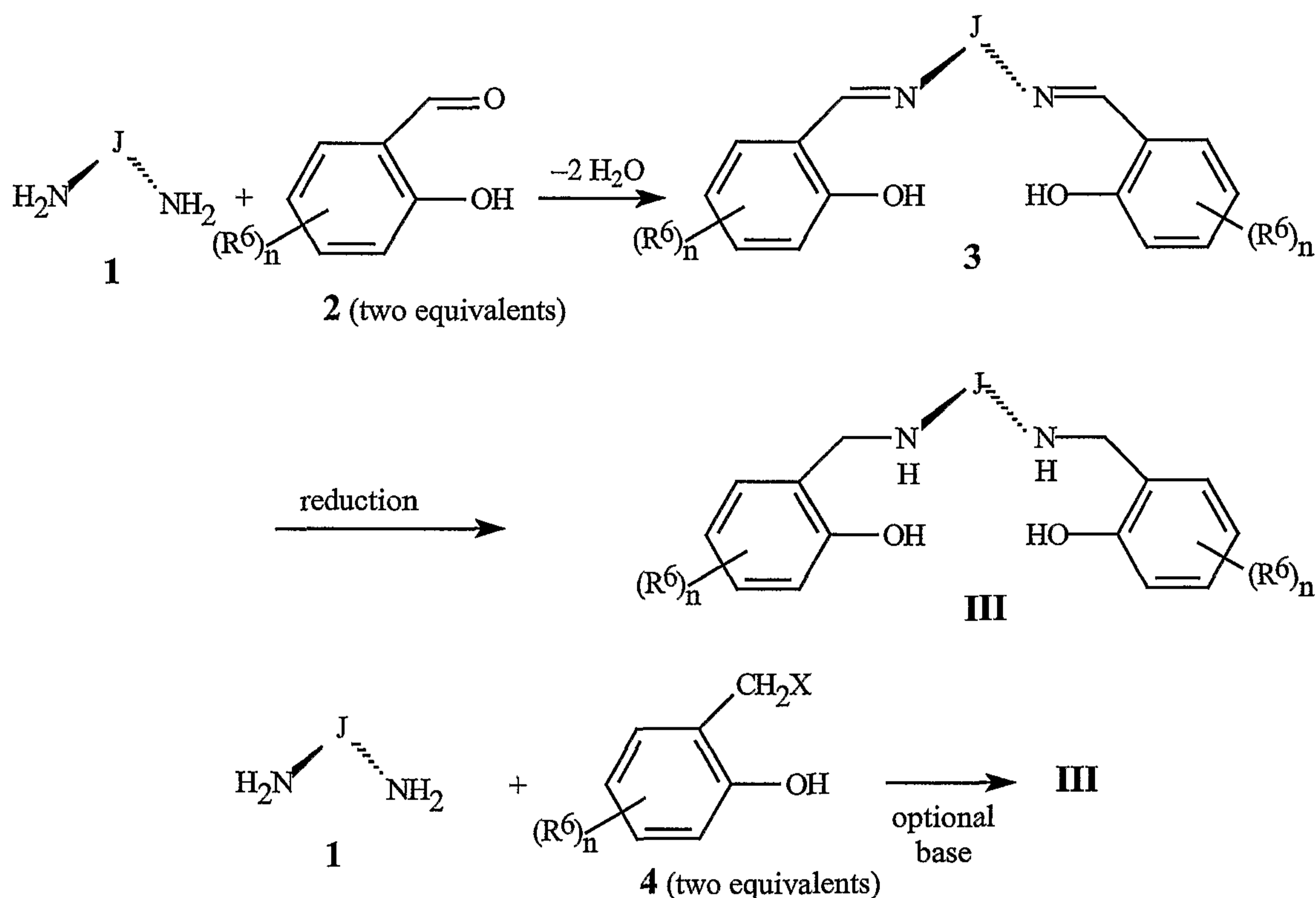
wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

The ligand of Formula **ent-IIIb** wherein R^6 is H is named 2,2'-[[$(1R,2R)$ -1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol], and the ligand of
 5 Formula **IIIb** wherein R^6 is $C(CH_3)_3$ is named 2,2'-[[$(1R,2R)$ -1,2-diphenyl-1,2-ethanediyl]-bis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol].

Another embodiment of this invention pertains to the ligand of Formula **III** or its enantiomer **ent-III**. Preferred ligands of Formulae **III** or **ent-III** are those of the preferred chiral zirconium complexes. Particularly preferred are ligands of Formulae **IIIa**, **ent-IIIa**,
 10 **IIIb** and **ent-IIIb**. Most preferred are ligands of Formulae **IIIa** and **IIIb**, as the hydroxylation reaction of the invention involving a zirconium complex comprising a ligand selected from Formulae **IIIa** and **IIIb** is particularly useful for enantioselectively preparing the more efficacious S configuration of arthropodocidal oxadiazines of Formula **V** (depicted below).

15 Ligands of Formula **III** or **ent-III** can be prepared by general methods known in the art, such as those depicted in Scheme 1. Note that Formula **III** is illustrated in Scheme 1; preparation of **ent-III** can be accomplished by using the enantiomer of compounds of Formula **1** in the syntheses illustrated.

Scheme 1



X is Cl, Br, I, OS(O)₂Z
 Z is CH₃, CF₃ or *p*-C₆H₄CH₃

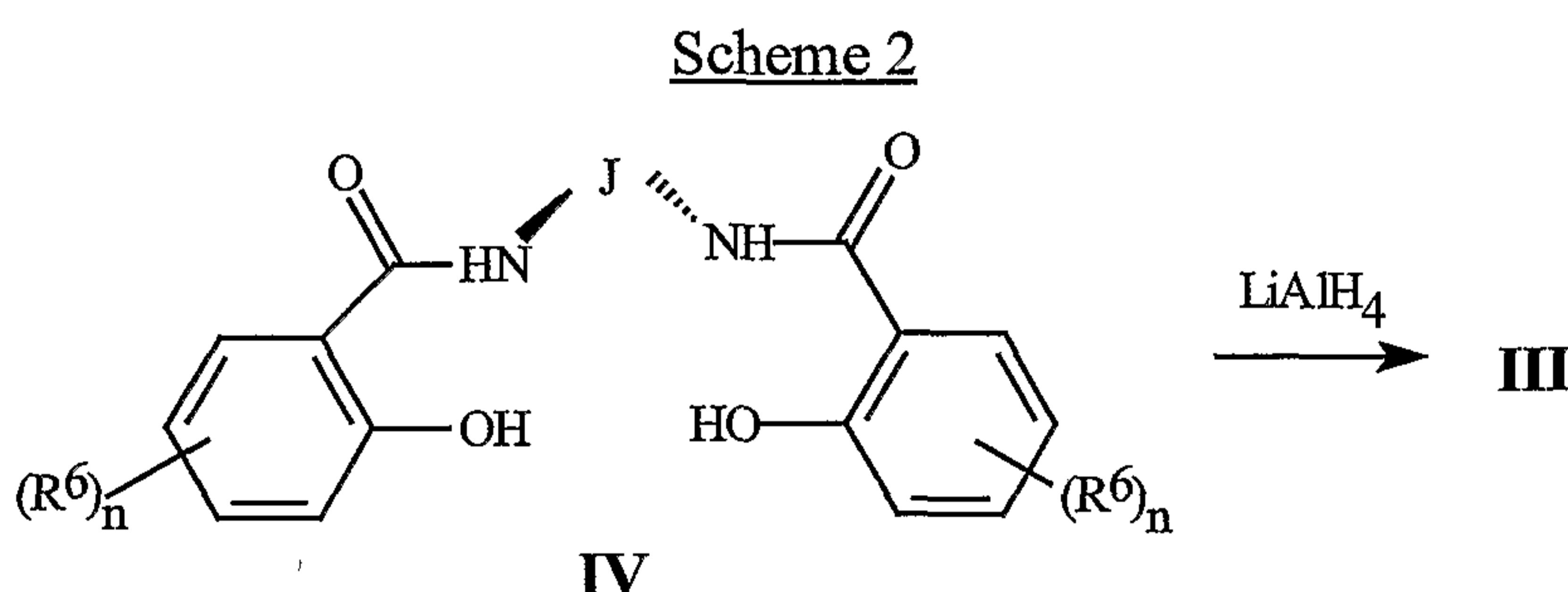
The first method involves the condensation of a chiral diamine of Formula **1**, wherein J is defined as above for Formula **III**, with two equivalents of an appropriately substituted salicylaldehyde derivative of Formula **2** to form the Schiff base (imine) adduct of Formula **3** shown in Scheme 1. Excess amounts of compounds of Formula **2** may be used to facilitate this condensation. Subsequent reduction of the Schiff base with reagents such as sodium borohydride or sodium cyanoborohydride or by catalytic hydrogenation affords the desired ligands of Formula **III**. The reduction using sodium cyanoborohydride is conducted in the presence of acid, such as hydrochloric acid, in a suitable solvent, such as a mixture of ethanol and toluene.

Catalytic hydrogenation of compounds of Formula **3** to give the corresponding ligands of Formula **III** can be carried out using supported precious metal catalysts. Palladium- and platinum-based catalysts are preferred, with platinum being most preferred. Typical catalyst supports include carbon, alumina and calcium carbonate. Amorphous carbon supports, such as charcoal, are preferred. Any solvent compatible with the reaction conditions can be used, and preferably the solvent is aprotic. Particularly suitable solvents include aromatic hydrocarbon solvents such as toluene. The reaction can be promoted by the addition of a

carboxylic acid (e.g., acetic acid) or mineral acid (e.g., sulfuric acid). Acetic acid is particularly useful because of its low corrosivity and ease of removal from the product solution. Best results are obtained when the reaction mixture is essentially free from water, which could otherwise cause hydrolysis of the Schiff base starting material. Therefore both
5 the solvent and catalyst should be anhydrous.

Salicylaldehyde derivatives of Formula 2 are either commercially available or can be prepared by methods well known in the art. Another method for the preparation of a ligand of Formula III involves the reaction of a chiral diamine of Formula 1 with two equivalents of a benzyl halide or benzyl sulfonate of Formula 4. Optionally an additional base, such as
10 organic bases such as triethylamine or inorganic bases such as sodium or potassium carbonate or sodium or potassium hydroxide may be used to facilitate this reaction. Excess amounts of compounds of Formula 4 may also be used to facilitate this reaction.

Ligands of Formula III can also be prepared from compounds of Formula IV by reduction of the C(=O)NH moiety using reducing agents such as lithium aluminum hydride
15 (Scheme 2). Enantiomers of Formula III may be prepared by reduction of the enantiomers of Formula IV. Reductions of amides to amines are well known in the art; see, for example, J. March, *Advanced Organic Chemistry: Reactions, Mechanisms and Structure*, 3rd ed., 1985, Wiley, New York, p. 1099; and R. C. Larock, *Comprehensive Organic Transformations: A Guide to Functional Group Transformations*, 1989, VCH Publishers, Inc.,
20 pp. 432-434 and the references cited therein.



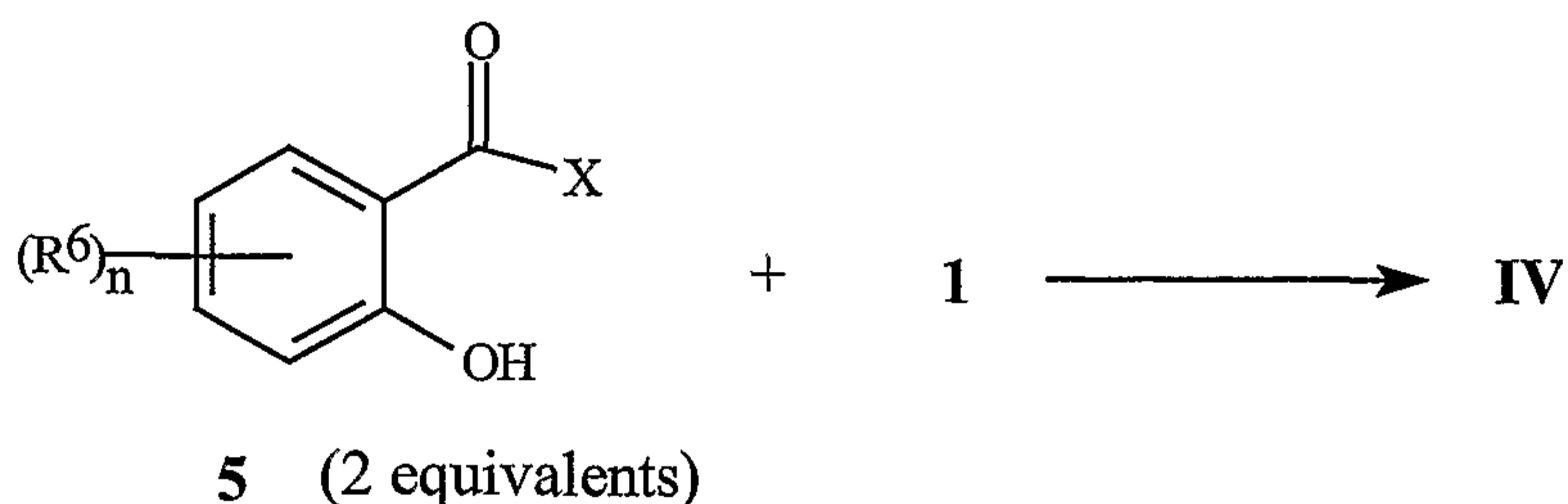
wherein J, n and R⁶ are as defined for Formula III in the Summary of the Invention.

A synthesis of the ligand of Formula IIIa wherein R⁶ is C(CH₃)₃ is described in
25 Example 1, and syntheses of the ligand of Formula IIIb wherein R⁶ is H is described in Examples 2 and 3.

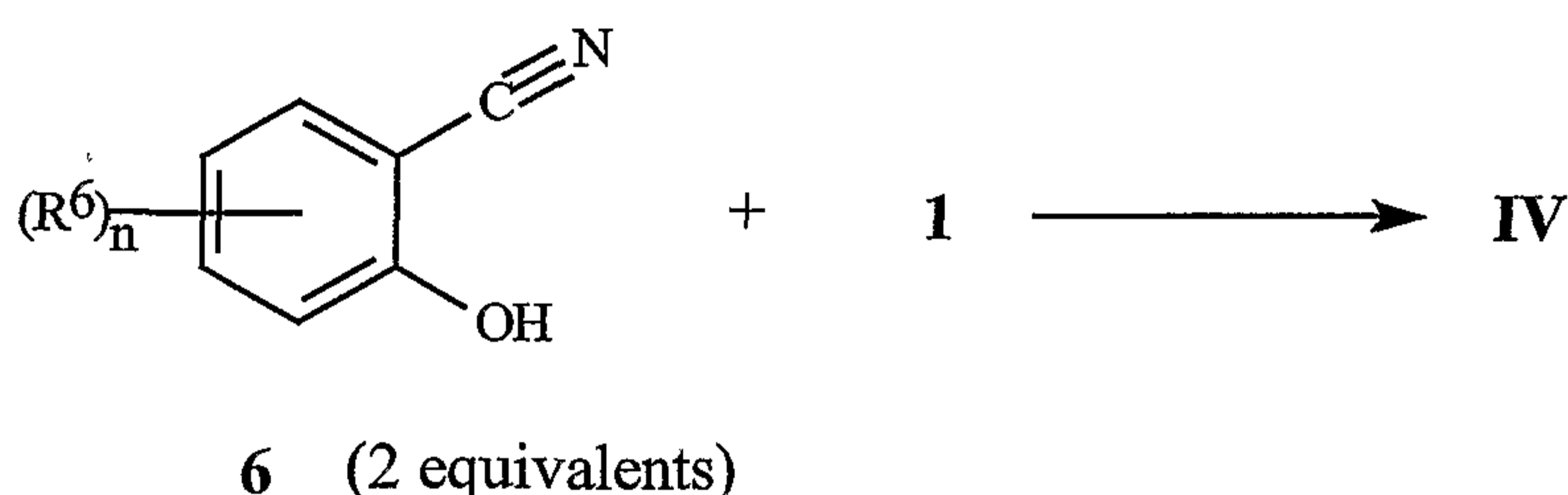
As shown in Scheme 3, compounds of Formula IV can be prepared by condensing a chiral diamine of Formula 1 with suitable carboxylic acids or carboxylic acid derivatives such as acid chlorides and amides (Formula 5) or nitriles (Formula 6) using methods known
30 to those skilled in the art, see for example, Richard C. Larock, *Comprehensive Organic*

Transformations: A Guide to Functional Group Transformations, 1989, VCH Publishers, Inc., pp. 963–994 and the references cited therein.

Scheme 3



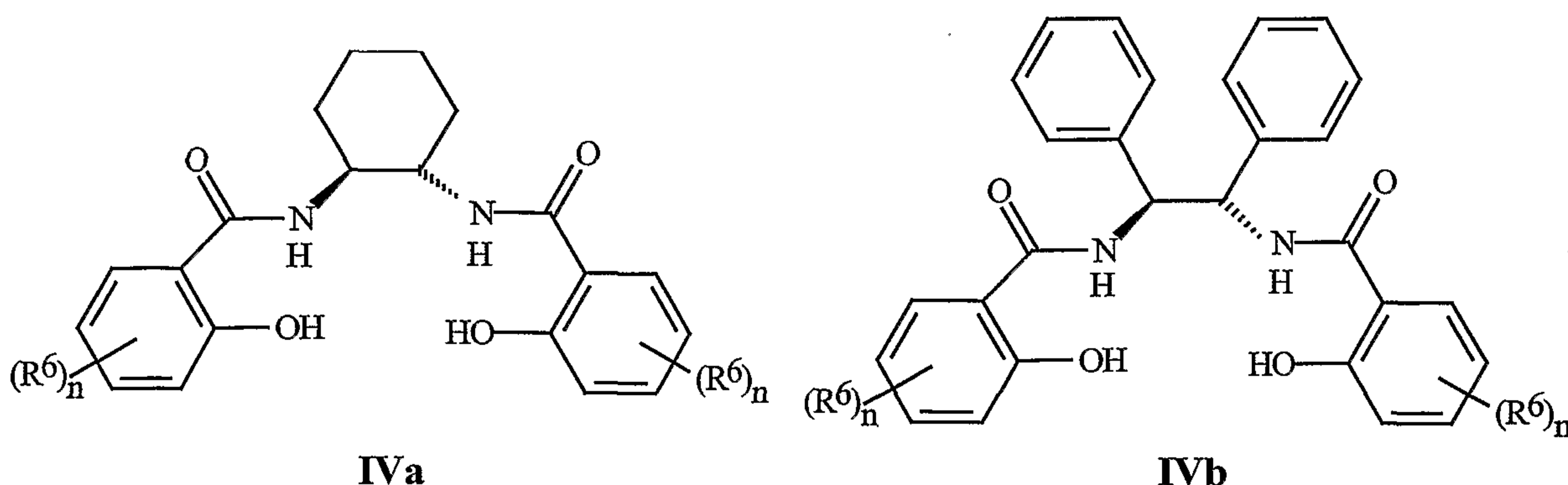
X is halide, hydroxy or amino



5 Preparation of a compound of Formula IV is illustrated in Example 4.

Carboxamide compounds of Formula IV can also be prepared by oxidizing the corresponding amine compounds of Formula III according to methods known in those skilled in the art; see for example, DE 871755, Ruhrchemie A.G., 1950; A. A. Frimer et al. *J. Org. Chem.* **1983**, 48 (10), 1700; K. Tanaka et al. *Chem. Pharm. Bull.* **1987**, 35 (1), 364; and G. Bettoni et al. *Tetrahedron* **1981**, 37 (24), 4159.

Of note are complexes comprising zirconium and ligands of Formula IV and their enantiomers. Of particular note are compounds of Formula IVa and IVb and their enantiomers and complexes comprising them.



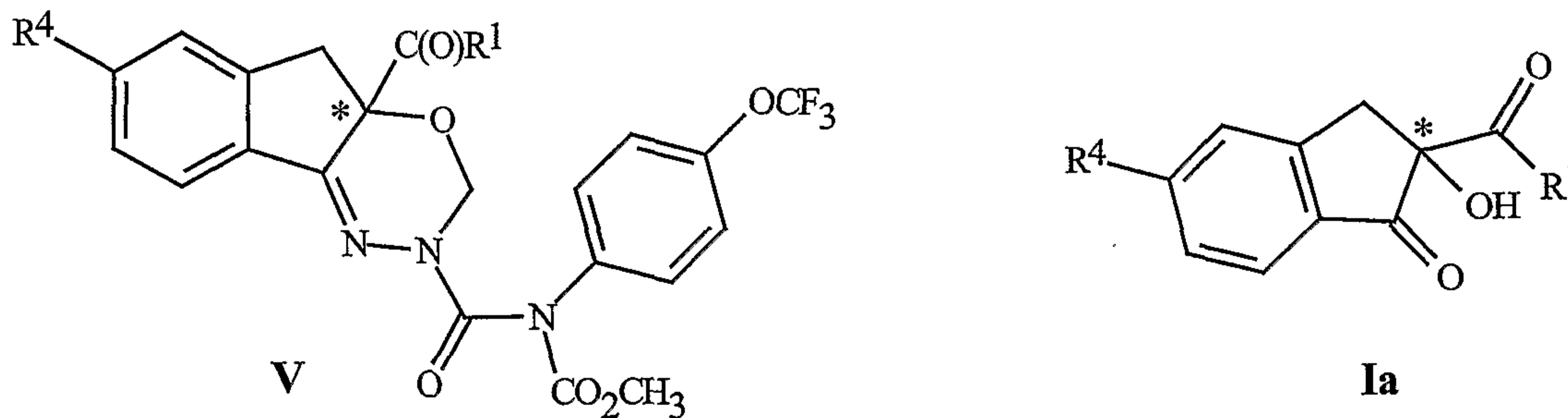
wherein n and R⁶ are as defined for Formula III in the Summary of the Invention.

Of note are the use of compounds of Formula **III** or **ent-III** in other enantioselective processes including oxidations of sulfides to chiral sulfoxides, oxidations of olefins to chiral epoxides, dihydroxy compounds or aminoalkoxy compounds, and oxidations of allylic alcohols to epoxyalcohols. Complexes comprising compounds of Formula **III** or **ent-III** may also be used in enantioselective hydrogenations or reductions.

One skilled in the art will also recognize that compounds of Formula **III** and the intermediates described herein can be subjected to various electrophilic, nucleophilic, radical, organometallic, oxidation, and reduction reactions to add substituents or modify existing substituents.

It is recognized that some reagents and reaction conditions described above for preparing compounds of Formula **III** may not be compatible with certain functionalities present in the intermediates. In these instances, the incorporation of protection/deprotection sequences or functional group interconversions into the synthesis will aid in obtaining the desired products. The use and choice of the protecting groups will be apparent to one skilled in chemical synthesis (see, for example, T. W. Greene and P. G. M. Wuts, *Protective Groups in Organic Synthesis*, 2nd ed.; Wiley: New York, 1991). One skilled in the art will recognize that, in some cases, after the introduction of a given reagent as it is depicted in any individual scheme, it may be necessary to perform additional routine synthetic steps not described in detail to complete the synthesis of compounds of Formula **III**. One skilled in the art will also recognize that it may be necessary to perform a combination of the steps illustrated in the above schemes in an order other than that implied by the particular sequence presented to prepare the compounds of Formula **III**.

The hydroxylation method of the invention is useful for preparation of an arthropodocidal oxadiazine of Formula **V**, involving as process intermediate the compound of Formula **Ia** prepared by said hydroxylation method

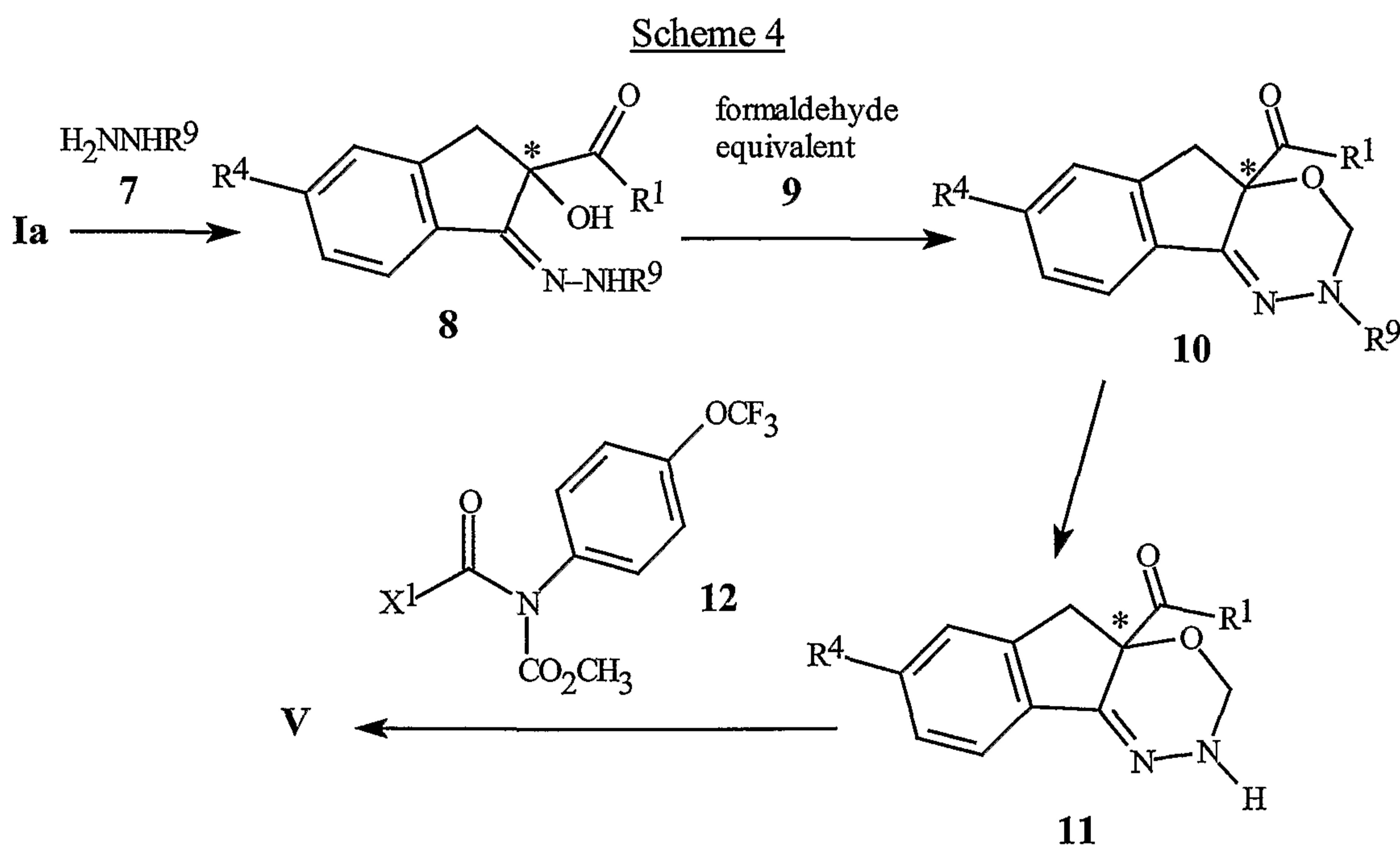


wherein Formulae **V** and **Ia** are racemic or enantiomerically enriched at the chiral center indicated by *, R^1 is C_1-C_3 alkoxy, and R^4 is F, Cl or C_1-C_3 fluoroalkoxy. Preferred because of excellent arthropodocidal efficacy of the oxadiazine product of Formula **V** is the aforementioned preparation wherein R^1 is OCH_3 and R^4 is Cl. As the enantiomer of Formula **V** having the *S* configuration has much greater arthropodocidal efficacy than does

its antipode having the *R* configuration, preferred is the preparation wherein Formulae **V** and **Ia** are enantiomerically enriched with the *S* isomer obtained by hydroxylation using a chiral zirconium catalyst.

As already discussed, the compound of Formula **Ia** can be prepared from the corresponding compound of Formula **IIa** using the hydroxylation method of the invention. The further steps leading to the preparation of the compound of Formula **V** from Formula **Ia** are disclosed by R. Shapiro et al. "Toward the Manufacture of Indoxacarb" Chapter 17 (pp. 178–185 in *Synthesis and Chemistry of Agrochemicals VI* (ACS Symposium Series 800), American Chemical Society, Washington, DC, 2002 and PCT Publications WO 92/11249, WO 95/29171, WO 96/31467 and WO 98/05656 and are depicted in Schemes 4 and 5. The reaction steps in these Schemes proceed substantially with retention of configuration at the chiral center indicated by *.

In the synthetic route shown in Scheme 4 the compound of Formula **Ia** is contacted with a protected hydrazine compound of Formula **7** to give the hydrazone of Formula **8**. This hydrazone is then contacted with a formaldehyde equivalent (Formula **9**) to form the cyclized compound of Formula **10**. The protecting group is removed from the Formula **10** compound to give the compound of Formula **11**, which is contacted with an acylating agent of Formula **12** to give the compound of Formula **V**.



20

wherein R^1 and R^4 are as previously defined, R^9 is a protecting group, and X^1 is a leaving group.

The hydrazine derivative of Formula **7** has one end protected with protecting group R^9 . A variety of amino protecting groups are known (see T. W. Greene and P. G. M. Wuts,

Protective Groups in Organic Synthesis, 2nd ed.; Wiley: New York, 1991). A protecting group that is particularly convenient in this preparation is benzyloxycarbonyl (R^9 is $C(O)OCH_2Ph$). Generally at least a molar equivalent of the hydrazine of Formula 7 is used in relation to the ketone of Formula Ia. The condensation of the hydrazine of Formula 7 with the ketone of Formula Ia is greatly facilitated by the presence of a catalyst. Useful catalysts for this condensation have acidic properties. Such catalysts include zeolites such as molecular sieves, as well as Lewis acids and, most commonly, protic acids. Useful protic acids include, for example, mixed toluenesulfonic acids, *p*-toluenesulfonic acid, sulfuric acid or acetic acid. With strong protic acids such as the toluenesulfonic acids as little as about 10–12 mol % acid can provide high conversions. As strong acids can protonate the hydrazine derivative of Formula 7, generally the molar amount of Formula 7 should at least equal the sum of the molar amount of Formula Ia and the molar equivalents of acid catalyst. The condensation can be conducted without solvent or in the presence of an inert solvent such as methanol, isopropanol, tetrahydrofuran, dichloromethane, 1,2-dichloromethane, toluene and the like. Typical reaction conditions include temperatures of about 40 to 120 °C, preferably about 65 to 85 °C for about 0.5 to 25 hours. The hydrazone of Formula 8 can be recovered by standard methods such as filtration, optionally after dilution of the reaction mixture with water. Alternatively, the reaction mixture containing the hydrazone of Formula 8 can be used directly in the next reaction step, or the hydrazone of Formula 8 can be extracted with solvent and the solvent extract used in the next reaction step.

In the next step the hydrazone of Formula 8 is cyclized using a formaldehyde equivalent (9) to give the compound of Formula 10. Formaldehyde equivalents include formaldehyde itself, but it readily polymerizes and is inconvenient to use. Other formaldehyde equivalents include halomethyl alkyl ethers. Most convenient of formaldehyde equivalents are dialkoxymethanes, preferably di(C_1 – C_3 alkoxy)methane, such as dimethoxymethane or diethoxymethane. The dialkoxymethane is preferably used in molar excess relative to Formula 8 and can also serve as the solvent. The reaction is optionally conducted using as co-solvent an inert solvent such as dichloromethane, trichloromethane, 1,2-dichloroethane, tetrahydrofuran, chlorobenzene, α,α,α -trifluorotoluene, toluene, heptane, xylenes, acetonitrile and the like. When the formaldehyde equivalent is a dialkoxymethane, the reaction is conducted in the presence of a Lewis or protic acid. Useful Lewis acids include phosphorus pentoxide, boron trifluoride or sulfur trioxide, of which 0.9 to 4.0 molar equivalents (relative to 8) is generally required for best results. Other useful Lewis acids include metal (especially scandium, ytterbium, yttrium and zinc) trifluoromethanesulfonates, which can be used in amounts of 0.1 to 0.5 molar equivalents relative to the compound of Formula 8. The most preferred Lewis acids for this step are phosphorus pentoxide and sulfur trioxide; the sulfur trioxide can be in the form of a

complex such as $\text{SO}_3 \cdot \text{DMF}$ (DMF is *N,N*-dimethylformamide), and usually there is also present a protic acid scavenger such as an amine complex (e.g., $\text{SO}_3 \cdot \text{pyridine}$). A filter aid such as Celite® (diatomaceous earth) can be advantageously added to reactions employing phosphorus pentoxide. When a Lewis acid is used, halogenated solvents are most suitable.

5 Useful protic acids include mineral acids such as sulfuric and sulfonic acids such as aromatic, aliphatic and polymeric sulfonic acids; preferred protic acids include *p*-toluenesulfonic acid, mixtures of the isomeric sulfonic acids, benzenesulfonic acid, naphthalenesulfonic acids, xylenesulfonic acids, methanesulfonic acid, sulfuric acid, and camphorsulfonic acids; most preferred are *p*-toluenesulfonic acid and mixtures of isomeric
10 toluenesulfonic acids. While stoichiometric or greater amounts of a protic acid can be employed, no more than a catalytic amount is needed. Preferably the amount of protic acid is about 0.01 to 0.20, more preferably between about 0.05 and 0.10, molar equivalents relative to the compound of Formula 8.

For the cyclization step, typical reaction conditions include temperatures of about 0 to
15 150 °C, preferably about 40 to 70 °C, more preferably about 50 to 60 °C with Lewis acids, and with protic acids such as toluenesulfonic acid preferably about 100 to 130 °C, more preferably about 110 to 115 °C, and pressures of about ambient pressure to 600 kPa above ambient pressure, preferably ambient pressure to 200 kPa above ambient pressure, and most conveniently near ambient pressure, for about 0.5 to 48 h. The byproduct alcohol is
20 preferably removed by distillation during the reaction when a non-sacrificial Lewis acid such as a rare-earth trifluoromethanesulfonate or a protic acid is employed. The cyclized product of Formula 10 can be recovered by standard methods such as concentration, optionally preceded by quenching with aqueous base and extraction of the organic material, and crystallization from a suitable solvent such as ethanol for the reactions involving protic acids
25 or liquid or gaseous Lewis acids such as sulfur trioxide or alternatively filtration, washing with aqueous base, concentration and crystallization for the phosphorus pentoxide reactions. The reaction mixture can also be filtered and used without further purification in the next reaction step. When metal trifluoromethanesulfonates are employed as the Lewis acid, the cyclized product can be recovered by concentrating the reaction mass, optionally diluting
30 with an inert, water-immiscible solvent such as ethyl acetate, washing with water to remove the metal trifluoromethanesulfonates, concentrating the organic phase and inducing the product of Formula 10 to crystallize, optionally by adding a suitable solvent such as aqueous methanol, ethanol, hexane and the like.

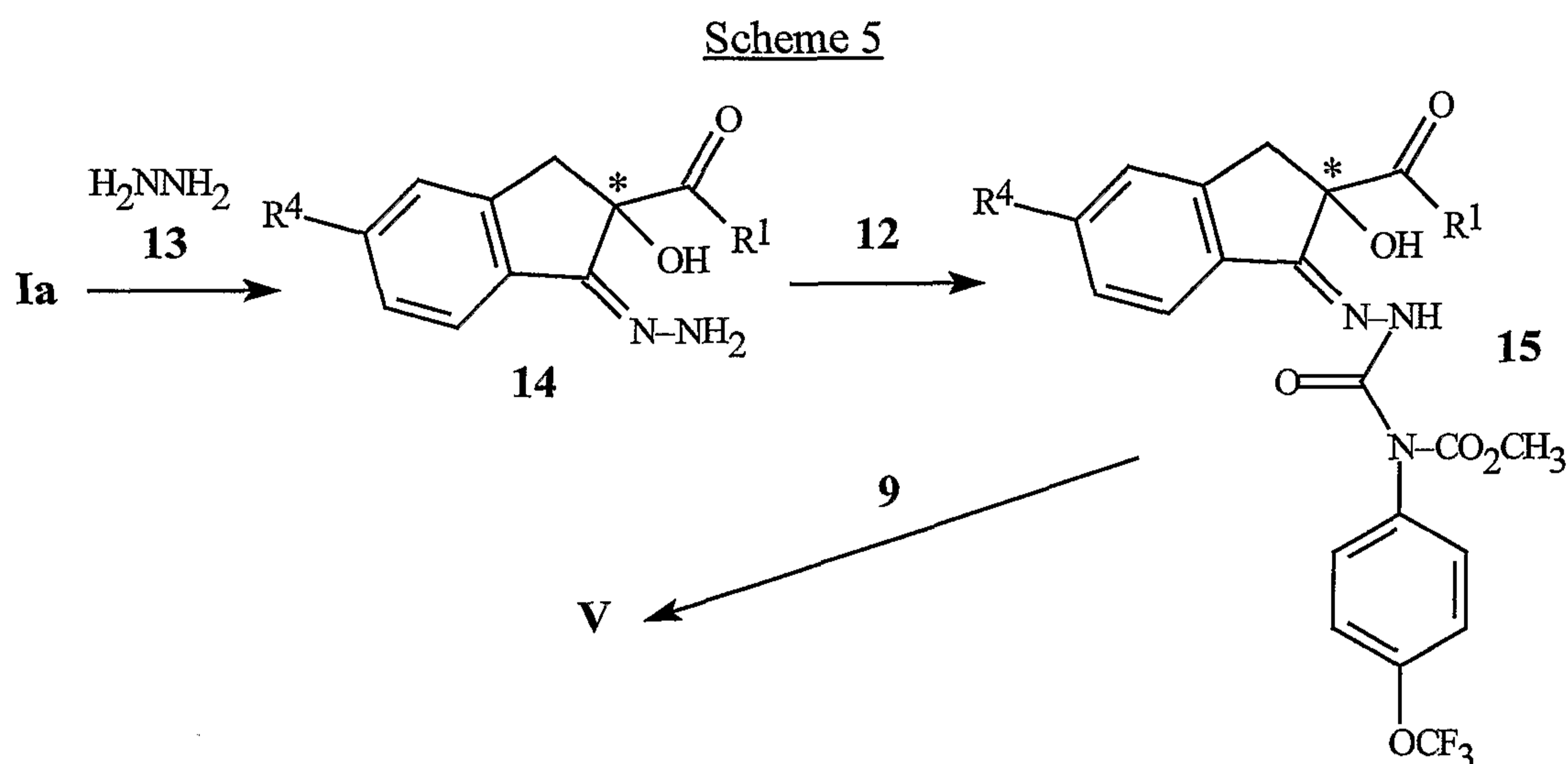
In the next step, the protecting group R^9 is removed from the compound of Formula 10
35 to give the compound of Formula 11. Conditions for cleaving amino protecting groups are well known (see T. W. Greene and P. G. M. Wuts, *Protective Groups in Organic Synthesis*, 2nd ed.; Wiley: New York, 1991). The preferred benzyloxycarbonyl protecting group is

most conveniently cleaved by hydrogenolysis. The reaction involves contacting a compound of Formula 11 wherein R⁹ is C(O)OCH₂Ph with hydrogen, from a hydrogen source or preferably molecular hydrogen itself, in the presence of a hydrogenolysis metal catalyst such as palladium, preferably supported on a substance such as charcoal, in an inert solvent such as methyl acetate, ethyl acetate, toluene or diethoxymethane. Typical reaction conditions include temperatures of about 0 °C to the boiling point of the solvent, preferably about 15 to 55 °C, more preferably about 20 to 40 °C, and pressures of close to ambient to about 350 kPa above ambient pressure, although higher pressures are also operable. The hydrogenolysis can be conveniently operated at near ambient pressure. Reaction time needed for complete conversion depends upon the usual parameters of temperature, hydrogen pressure, catalyst and reactant concentration, and typically requires 0.5 to 25 hours. The progress of the reaction can be monitored by analysis of the aliquots, or by consumption of hydrogen, as can be determined, for example, by pressure changes. The product of Formula 11 can be recovered from solution by standard methods such as filtering and collecting the metal catalyst for recycle to subsequent batches, separating the organic phase, concentrating by removing the solvent, and inducing crystallization of Formula 11, optionally by adding an aqueous C₁-C₃ alcohol, acetonitrile or an aliphatic hydrocarbon such as hexane. Preferably the compound of Formula 11 is used in the next step without isolation from the organic phase solution.

In the last step of Scheme 4, the compound of Formula 11 is contacted with about a molar equivalent of the acylating agent of Formula 12 to give the oxadiazine of Formula V. The group X¹ is selected from groups useful as leaving groups in nucleophilic displacement reactions. Considering ease of synthesis and cost, X¹ is preferably halide, and most preferably Cl. The reaction of the compound of Formula 11 with the acylating agent of Formula 12 is preferably conducted in the presence of about 1.0 to 1.5 molar equivalents (relative to Formula 11) of an acid scavenger such as a trialkylamine (e.g., triethylamine), *N,N*-dimethylaniline, pyridine or, preferably, aqueous sodium carbonate or bicarbonate, in an inert solvent such as toluene, xylene, methyl acetate, ethyl acetate, dichloromethane, trichloromethane, 1,2-dichloroethane, diethoxymethane and the like. The reaction is facile and can be conducted over a wide range of temperatures, e.g., about -10 to 60 °C. Typical reaction conditions include temperatures of about 0 to 30 °C. For convenience, the reaction can be conducted at ambient temperature (e.g., about 15 to 35 °C). The reaction is usually complete within several hours, and 1 to 2 h is typical. The product of Formula V can be recovered by standard methods such as washing the reaction mixture with aqueous acid or aqueous sodium chloride, concentrating the organic phase and inducing crystallization of V, optionally by addition of a C₁-C₃ alcohol, water, alcohol-water mixtures or an aliphatic hydrocarbon such as hexane.

The last two steps of Scheme 4 can be combined in a single reaction pot by adding the acylating agent of Formula 12 and the optional acid scavenger during the hydrogenolysis of the compound of Formula 10. In this way, the compound of Formula 11 is acylated as soon as it is formed to give the product of Formula V. Typical solvents for the combined steps are methyl acetate, ethyl acetate, toluene, xylene, dichloromethane, 1,2-dichloroethane and the like. Acid scavengers can be a tertiary amine, such as tripropylamine, tributylamine, diisopropylethylamine, *N,N*-dimethylaniline, *N,N*-diethylaniline, and the like, or a solid ionic compound such as sodium bicarbonate, calcium oxide, sodium pyrophosphate, citric acid trisodium salt and the like.

The sequence of condensation and acylation steps to convert the compound of Formula Ia to the compound of Formula V can also be conducted in other orders, as is illustrated by Scheme 5 below. In this alternate route, the compound of Formula Ia is contacted with hydrazine (13) to give the hydrazone of Formula 14. This hydrazone is then contacted with an acylating agent of Formula 12 to give the compound of Formula 15, which is then contacted with a formaldehyde equivalent (9) to give the compound of Formula V.



wherein the substituents are as defined for Scheme 4.

To prepare the hydrazone of Formula 14, the ketone of Formula Ia is contacted with preferably excess equivalents (e.g., 1.1 to 10 equivalents relative to Ia) of hydrazine, hydrazine monohydrate, hydrazine acetate, hydrazine hydrochloride and the like. The reaction is conducted in a solvent typically comprising methanol, ethanol, *n*-propanol, isopropanol and the like or acetic acid, and the reaction mixture is typically heated to the reflux temperature of the solvent. The reaction is generally complete within 24 hours. Step B of Example 2 of WO 92/11249 describes an example of this step.

The hydrazone of Formula **14** is then contacted with an acylating agent of Formula **12**. This step is conducted using reaction conditions analogous to those already described for the conversion of the compound of Formula **11** to the compound of Formula **V** in Scheme 4. The product of Formula **15** is isolated by standard methods, such as aqueous work up,
5 concentration and crystallization from a suitable solvent. Example 1 of WO 96/31467 provides an example of this step.

In the final step of Scheme 5, the compound of Formula **15** is treated with a formaldehyde equivalent of Formula **9**. This step is conducted using reaction conditions analogous to those already described for the conversion of the compound of Formula **8** to the
10 compound of Formula **10** in Scheme 4. Example 2 of WO 96/31467 provides an example of this step.

Acylating agents of Formula **12** can be prepared by contacting methyl [4-(trifluoromethoxy)phenyl]carbamate with a base such as sodium hydride, sodium methoxide and the like in a solvent comprising aromatic solvents such as benzene, toluene
15 and the like and a ethereal solvent such as 1,2-dimethoxyethane to form the corresponding salt. The salt is then treated with the appropriate compound having formula $X^1C(O)X^1$ to form Formula **12**. For the preferred acylating agent of Formula **12** wherein X^1 is Cl, the appropriate compound is phosgene ($ClC(O)Cl$) or a phosgene substitute such as triphosgene (also named bis(trichloromethyl) carbonate). Most conveniently an excess of phosgene is
20 used. Suitable temperatures for this reaction are in the range of about -10 to 100 °C, preferably about -10 to 30 °C. The reaction is usually complete within several hours. Acylating agents of Formula **12** wherein X^1 is other than Cl can be made from Formula **12** wherein X^1 is Cl by nucleophilic displacement. For example, treatment with silver fluoride can give Formula **12** wherein X^1 is F, and treatment with sodium iodide can give Formula **12**
25 wherein X^1 is I. Methyl [4-(trifluoromethoxy)phenyl]carbamate can be made from 4-(trifluoromethoxy)benzenamine by standard methods, such as contacting 4-(trifluoromethoxy)benzenamine with methyl chloroformate in the presence of an acid scavenger such as *N,N*-diethylaniline, triethylamine, aqueous potassium carbonate and the like, optionally in a solvent such as diethyl ether, dichloromethane and the like. Suitable temperatures for this
30 reaction are typically in the range of about 0 to 100 °C, with temperatures of about 20 to 70 °C being preferred. The reaction is usually complete within several hours. Example 1 of WO 96/31467 provides an example of preparation of the preferred acylating agent of Formula **12** wherein X^1 is Cl.

Without further elaboration, it is believed that one skilled in the art using the preceding
35 description can utilize the present invention to its fullest extent. The following Examples are, therefore, to be construed as merely illustrative, and not limiting of the disclosure in any way whatsoever. Percentages are by weight except for chromatographic solvent mixtures or

where otherwise indicated. Parts and percentages for chromatographic solvent mixtures are by volume unless otherwise indicated. ¹H NMR spectra are reported in ppm downfield from tetramethylsilane; “s” means singlet, “d” means doublet, “t” means triplet, “q” means quartet, “m” means multiplet, “dd” means doublet of doublets, “dt” means doublet of triplets, “br s” means broad singlet, and “br m” means broad multiplet. Chemoselectivity is the percentage of the consumed limiting reagent (i.e. **IIa** in Examples 5–11) that is converted into product.

In the Examples, quantitative HPLC analysis was used to measure the amounts of methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate and methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate present in the reaction mixture. In the examples where a chiral zirconium complex was used, a chiral HPLC method was used to determine the enantiomeric excess of methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate.

The quantitative HPLC analyses were conducted using a Supelco (595 North Harrison Road, Bellefonte, PA 16823-0048 USA) Discovery C8 (octylsilane bonded to silica) column (25 cm x 4.6 mm, 5 μ m) and a flow rate of 1.5 mL/min at 40 °C. The elution solvent was a mixture of water (pH 6.5) and acetonitrile, with the concentration of acetonitrile increased from 32% to 75% over 30 minutes to produce a solvent gradient. Detection utilized light absorption at 260 nm. The detector was calibrated using an external standard with 3-point calibration curves for methyl 5-chloro-1,3-dihydro-2-hydroxy-1-oxo-2*H*-indene-2-carboxylate and methyl 5-chloro-1-oxo-2,3-dihydroindene-2-carboxylate.

The chiral HPLC analyses were conducted using an Astec (Advanced Separation Technologies, Inc., 37 Leslie Court, Whippany, NJ 07981 USA) Chirobiotic TTM (teicoplanin glycopeptide covalently bound to 5 μ m silica gel) column and a flow rate of 1.0 mL/min at 40 °C. The elution solvent was an isocratic 80:20 mixture of hexanes and ethanol. Detection utilized light absorption at 254 and 230 nm. Calibration was not necessary as the peak areas of the two enantiomers are directly compared and the detector sensitivity does not differ between enantiomers.

EXAMPLE 1

Preparation of the 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediyl]bis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol] (Formula **IIIa** wherein R⁶ is C(CH₃)₃)

An ethanolic hydrochloric acid solution was prepared by dissolving commercial concentrated hydrochloric acid (1.596 g, 37% by weight, 16.2 mmol) in ethanol (15 mL). Solid sodium cyanoborohydride (1.850 g, 29.4 mmol) and the ethanolic hydrochloric acid were added in portions over 1.5 hours to a slurry of 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediyl]bis(nitrilomethylidene)]bis[4,6-bis(1,1-dimethylethyl)phenol] (also known as (1*S*,2*S*)-(+)-

1,2-cyclohexanediamino-*N,N*-bis(3,5-di-*t*-butylsalicylidene) (Strem, 4.026 g, 7.362 mmol) in ethanol (50 mL) and toluene (15 mL) at 65 °C. The reaction mixture changed from a cloudy, yellow suspension to a cloudy white solution during this time. The reaction mixture was stirred for an additional 30 minutes at 65 °C and then poured into a mixture of ethyl acetate and aqueous sodium bicarbonate solution. The aqueous layer was separated and extracted with more ethyl acetate. The combined organic extracts were dried (MgSO₄), filtered, and evaporated in vacuo. The remaining crude product was purified by flash chromatography over silica gel (90:10 hexanes–ethyl acetate). After drying in vacuo, the purified product was obtained as a white solid (3.262 g, 80% yield) melting 128–132 °C. ¹H NMR (CDCl₃) δ 1.279 (s, 18H, overlapped with broad resonances 1.20–1.30 ppm, approx. 6H integration), 1.42 (m, 2H), 1.375 (s, 18H), 1.70 (br m, 2H), 2.46 (br m, 2H), 2.17 (br m, 2H), 3.898 (d of AB pattern, *J* = 13.3 Hz, 2H), 4.039 (d of AB pattern), *J* = 13.3 Hz, 2H), 6.863 (d, *J* = 2.3 Hz, 2H), 7.208 (d, *J* = 2.5 Hz, 2H). LC/MS AP⁺: 8.33 min, 551 (M⁺ + 1); AP⁻: 8.35 min, 549 (M⁺ - 1).

15

EXAMPLE 2

Preparation of 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol] (**IIIb** wherein R⁶ is H) using sodium cyanoborohydride

(1S,2S)-1,2-diphenyl-1,2-ethanediamine (also known as *(1S,2S)*-(-)-1,2-diphenylethylenediamine) (2.04 g, 9.40 mmol) and 3-(1,1-dimethylethyl)-2-hydroxybenzaldehyde (also known as 3-*tert*-butyl-2-hydroxy-benzaldehyde) (3.36 g, 18.8 mmol, 2 equivalents) were heated at reflux in methanol (50 ml) for 1 hour. The mixture was then cooled to 65 °C, and sodium cyanoborohydride (1.50 g, 23.9 mmol, 2.5 mole per mole of the starting diamine) and concentrated hydrochloric acid (36.5%, 2.07 g, 20.7 mmol, 2.2 mole per mole of the starting diamine) dissolved in ethanol (10 mL) were added portionwise over 10–15 minutes. After the addition, the mixture was held at 65 °C for 30 minutes. The mixture was then cooled, poured onto a mixture of saturated aqueous sodium bicarbonate solution (40 mL) and ethyl acetate (50 mL). About 40 mL of water was added to dissolve the salt. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate (3 x 50 mL). The combined organic layer was dried (MgSO₄), and the solvent evaporated to give a glassy residue, which was triturated with absolute ethanol to give the title compound as the first crop (2.98 g). Concentration of the filtrate gave a second crop (0.45 g), for a total of the title product of 3.43 g (68.6% yield) melting at 143–145 °C. ¹H NMR (CDCl₃) δ 1.35 (s, 18H), 2.2 (br m, 2H), 3.52 (d, *J* = 13.5 Hz, 2H), 3.76 (d, *J* = 13.5 Hz, 2H), 3.92 (s, 2H), 6.5 (m, 4H), 6.8 (m, 4H), 7.0–7.2 (m, 8H), 10.4 (br s, 2H).

EXAMPLE 3

Preparation of 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol] (**IIIb** wherein R⁶ is H) using hydrogenation

Step A Preparation of 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(nitrilomethylidyne)]bis[6-(1,1-dimethylethyl)phenol]

(*1S,2S*)-1,2-diphenyl-1,2-ethanediamine (also known as (*1S,2S*)-(-)-1,2-diphenylethylenediamine) (20.8 g, 98 mmol) and 3-(1,1-dimethylethyl)-2-hydroxybenzaldehyde (also known as 3-*tert*-butyl-2-hydroxy-benzaldehyde) (35.0 g, 196 mmol, 2 equivalents) were heated in methanol (150 mL). As the mixture approached reflux temperature, a gum separated out. Methanol (50 g) and heptane (10 g) were added and the gummy solids broken up with a spatula. The mixture was heated at reflux for two hours and then allowed to cool to room temperature. The product was collected by filtration and washed with methanol to give the title product as a bright yellow solid. Concentration of the filtrate provided a second crop (8.20 g).

Step B Preparation of 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol]

A 100-mL stainless steel autoclave was charged with 2,2'-[[*(1S,2S)*-1,2-diphenyl-1,2-ethanediyl]bis(nitrilomethylidyne)]bis[6-(1,1-dimethylethyl)phenol] (i.e. the product of Step A, 5.0 g), platinum-on-carbon catalyst (Engelhard Corporation CP97 Lot # 6729-36-02, 3 weight %, 2.5 g), toluene (45.0 g), and glacial acetic acid (1.0 g). After flushing with nitrogen, the vessel was pressurized to 100 psig (690 kPa) above ambient with hydrogen and heated to 75 °C. After reaching 75 °C, the hydrogen pressure was adjusted to about 400 psig (2760 kPa) and the reaction mixture held at 75 °C and about 400 psig (2760 kPa) for 5 h. The mixture was cooled to 20 °C, and the hydrogen was vented, resulting in some loss of product. The catalyst was removed by filtration, and the reactor and catalyst were washed with toluene (300 grams). The product solution was washed successively with saturated aqueous sodium bicarbonate (2 x 100 mL) and water (150 mL) and dried over anhydrous magnesium sulfate. The organic phase was concentrated under reduced pressure to leave a dark oil (5.0 g). Addition of methanol (12 g) dissolved the oil and induced crystallization. The crystals were collected, washed with methanol (5 g) and dried in a vacuum oven at 45 °C to give the title product (3.0 g) melting at 143–144 °C.

EXAMPLE 4

Preparation of *N,N'*-(*1S,2S*)-1,2-cyclohexanediylbis[3,5-bis(1,1-dimethylethyl)-2-hydroxybenzenecarboxamide] (**IVa** wherein (R⁶)_n is 3,5-di-*tert*-butyl)

Thionyl chloride (5.95 g, 50 mmol) was added to a mixture of 3,5-bis(1,1-dimethylethyl)-2-hydroxybenzoic acid (alternatively named 3,5-di-*tert*-butylsalicylic acid)

(2.50 g, 10 mmol) and *N,N*-dimethylformamide (10 drops) in dry toluene (50 mL) at 60 °C. After 1 hour at 60 °C, the light yellow solution was evaporated in vacuo to leave a thick oil and then diluted with dry tetrahydrofuran (THF) (40 mL). After heating to 50 °C, a solution of (1*S*,2*S*)-(+)-1,2-cyclohexanediamine (0.560, 4.90 mmol) in 10 mL of dry THF was added followed by triethylamine (1.01 g, 10 mmol). After 1 h at 50 °C, the reaction mixture was quenched with water (25 mL) and then poured into ethyl acetate/water. The organic phase was separated, and the aqueous phase extracted with additional ethyl acetate (35 mL). The combined organic phase was washed once more with water and then evaporated onto silica gel. Purification by flash chromatography (hexanes–ethyl acetate, 0 to 20% ethyl acetate over 1 hour) and evaporation of the chromatography solvent in vacuo afforded the product as a foamy off-white solid (1.18 g). The product was further purified by stirring the white solid in methanol (5 mL) and then decanting the mother liquor from a small amount of insoluble, gummy solids. Evaporation of the methanol mother liquor afforded the title product as an off-white solid (1.15 g). ¹H NMR (CDCl₃) δ 1.29 (s, 18H), 1.38 (s, 18H), 1.82 (s, 2H), 2.22 (br s, 2H), 3.96 (br s, 2H), 6.95 (br s, 2H), 7.16 (d, *J* = 2 Hz, 2H), 7.41 (d, *J* = 2 Hz, 2H), 12.70 (s, 2H). MS ESI Positive: 579 (M+1), ESI Negative: 577 (M-1).

EXAMPLE 5

Preparation of racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

To a solution of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (also known as methyl 5-chloro-1-oxo-2,3-dihydroindene-2-carboxylate) (0.500 g, 2.23 mmol) (Formula **IIa** wherein R¹ is OCH₃ and R⁴ is Cl) and zirconium(IV) isopropoxide (0.0086 g, 0.022 mmol) in toluene (1.34 g, 1.56 mL) at 30 °C was added an aqueous solution of *tert*-butyl hydroperoxide (70%, 0.316 g, 2.46 mmol). The reaction mixture was stirred for 24 hours at 30 °C and then diluted with acetonitrile (about 6 mL). Quantitative HPLC analysis showed 92% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 89% yield (97% chemoselectivity).

EXAMPLE 6

Preparation of racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

The reaction described in Example 1 was carried out using zirconium(IV) acetylacetonate (0.0544 g, 0.112 mmol). Quantitative HPLC analysis showed 97% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 93% yield (96% chemoselectivity).

EXAMPLE 7

Preparation of racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

5 The reaction described in Example 5 was carried out using zirconium(IV) *tert*-butoxide (0.0428 g, 0.112 mmol). Quantitative HPLC analysis showed 94% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming racemic methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 82% yield (87% chemoselectivity).

EXAMPLE 8

10 Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (also known as (+)-methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate) (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

15 A chiral zirconium complex was prepared by stirring zirconium(IV) isopropoxide (0.0345 g, 0.089 mmol) with 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediylbis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol] (Formula **IIIa** wherein R⁶ is C(CH₃)₃, 0.0613 g, 0.11 mmol) in toluene (2 mL) at ambient temperature. After stirring overnight, the homogeneous solution was evaporated to dryness in vacuo, and the residue redissolved in toluene (1.34 g). Methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (0.250 g, 1.11 mmol) (Formula **IIa** wherein R¹ is OCH₃ and R⁴ is Cl) was added to the toluene solution, the solution was
20 heated to 55 °C, and then an aqueous solution of *tert*-butyl hydroperoxide (70%, 0.316 g, 2.46 mmol) was added. After 2 hours at 55 °C, the solution was diluted with acetonitrile (11.5 mL). Analysis by quantitative and chiral HPLC showed 100% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 84% yield (84% chemoselectivity) and 84%
25 enantiomeric excess of the *S*-enantiomer.

EXAMPLE 9

Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

30 The reaction described in Example 8 was carried out using methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (0.100 g, 0.445 mmol) (Formula **IIa** wherein R¹ is OCH₃ and R⁴ is Cl). Analysis by quantitative and chiral HPLC showed 100% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 66% yield (66% chemoselectivity) and 90% enantiomeric excess of the *S*-enantiomer.

EXAMPLE 10

Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate
(Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

5 A chiral zirconium complex was prepared by stirring zirconium(IV) isopropoxide (0.560 g, 1.44 mmol) with 2,2'-[(1*S*,2*S*)-1,2-cyclohexanediylbis(iminomethylene)]bis[4,6-bis(1,1-dimethylethyl)phenol] (Formula **IIIa** wherein R⁶ is C(CH₃)₃, 1.00 g, 1.82 mmol) for 30 minutes in toluene (25 mL) at ambient temperature. The homogeneous solution was evaporated to dryness in vacuo, and the residue redissolved in toluene (8.70 g, 10 mL). A
10 toluene solution of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (1.53 g of a 21.55% by weight toluene solution, 1.47 mmol of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate) was added to the toluene solution of the chiral zirconium complex and the reaction mixture was heated to 55 °C. Over the next 47 minutes, a toluene solution
15 of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (36.71 g of a 21.55% by weight toluene solution, 35.2 mmol of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate) and, simultaneously, an aqueous solution of *tert*-butyl hydroperoxide (70%, 4.69 g, 36.4 mmol) were co-fed to the reaction mixture at 55 °C. After the two solutions were added, the reaction mixture was heated at 55 °C for an additional 6 hours, cooled to 25 °C, and then filtered. After drying, 4.64 g (52.5%) of the *S*-enantiomer of methyl
20 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate was obtained as a white solid in ≥ 98% enantiomeric excess. Quantitative HPLC analysis of the filtrate and solids showed that the overall reaction proceeded with 85% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 74% yield (87% chemoselectivity) and 75% enantiomeric excess of the *S*-enantiomer.

25

EXAMPLE 11

Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate
(Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl)

A chiral zirconium complex was prepared by rapidly stirring (forming a vortex) a mixture of zirconium(IV) acetylacetonate (43.5 mg, 0.089 mmol) and
30 2,2'-[[[(1*S*,2*S*)-1,2-diphenyl-1,2-ethanediyl]bis(iminomethylene)]bis[6-(1,1-dimethylethyl)phenol] (Formula **IIIb** wherein R⁶ is H, 0.096 g, 0.18 mmol) in toluene (1.00 mL) at 50 °C for one hour. The resulting solution was evaporated to dryness in vacuo, then a solution of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (0.500 g, 2.23 mmol) (Formula **IIa** wherein R¹ is OCH₃ and R⁴ is Cl) in toluene (2.00 mL) was added. The reaction
35 mixture was heated to 65 °C, and then an aqueous solution of *tert*-butyl hydroperoxide (70%, 0.316 g, 0.340 mL, 2.46 mmol) was added. After 3.5 hours at 65 °C, the reaction was

quenched by adding an acetonitrile solution (7.00 mL) containing biphenyl (0.125 g) as an HPLC internal standard and cooling to ambient temperature. Analysis by quantitative and chiral HPLC showed 100% conversion of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate, forming methyl 5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate in 85% yield (85% chemoselectivity) and 94% enantiomeric excess of the *S*-enantiomer.

EXAMPLE 12

Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl) with recycle of catalyst

10 A chiral zirconium complex was prepared by stirring zirconium(IV) acetylacetonate (0.73 g, 1.5 mmol) with **IIIb** wherein R⁶ is H (1.61 g, 3.0 mmol) in toluene (5 mL) for 1 hour at 50 °C. To the resulting solution was added methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (4.5 g, 20 mmol) and additional toluene (4 mL). The temperature was increased to 65 °C, and then two separate solutions of methyl 5-chloro-2,3-dihydro-1-oxo-15 1*H*-indene-2-carboxylate (17.96 g, 80 mmol in 53 g of toluene) and a 70% by weight solution of *tert*-butyl hydroperoxide in water (11.59 g, 90 mmol) were simultaneously co-fed to the reaction mixture. The rates of addition were controlled so that the *tert*-butyl hydroperoxide feed was completed in 30 minutes and the methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate feed was completed in 2.25 hours. After both feeds were 20 complete, the reaction mixture was stirred for an additional 2 hours at 65 °C, cooled to 10 °C, and filtered. The isolated solid product of Formula **Ia** was washed with toluene (2 x 8 g) and then dried in vacuo at 45 °C.

The filtrate from the previous reaction was evaporated in vacuo at 30 °C and diluted with toluene (about 7 g) to give a total weight of 20 g. This solution was charged with 25 methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (2.25 g, 10 mmol) and toluene (6.65 g) and heated to 65 °C, and the solutions of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (20.21 g, 90 mmol, in 55.35 g of toluene) and *tert*-butyl hydroperoxide (12.88 g, 100 mmol) were co-fed as described before. After both feeds were complete, the reaction mixture was stirred for an additional 1.5 hours at 65 °C, cooled 30 to 10 °C, and filtered. The isolated solid product of Formula **Ia** was washed and dried as before.

Using the filtrate from the previous run, the recycling process was repeated a second time as described in the previous paragraph except that 13.52 g (105 mmol) of *tert*-butyl hydroperoxide was used.

The recycling process was repeated a third time as before, except that 19.31 g (150 mmol) of *tert*-butyl hydroperoxide was used and the reaction mixture was held for 3 hours at 65 °C after both feeds were completed.

The results from these reactions, reported in the Table E12 below, were determined by HPLC analysis of both the isolated solids and the filtrates from each reaction. The overall reaction enantiomeric excess (ee) refers to the net enantiomeric excess of **Ia** produced during the run and is a weighted average of the enantiomeric excess of **Ia** in the solid and filtrate phases. The enantiomeric excess of the solid, isolated **Ia** may be higher than the reaction enantiomeric excess because the crystallization of **Ia** from the reaction mixture can enrich the solid with the predominant enantiomer.

TABLE E12

Results from Recycling Catalyst **IIIb** wherein R⁶ is H

Run	IIa Conversion (%)	Ia Isolated Weight (g)	Ia Isolated Yield (%) ^a	Isolated Ia ee (%) ^b	Reaction ee (%)
Initial	83	17.52	73	>98	95.1
1st Recycle	86	19.89	82	>98	92.3
2nd Recycle	87	17.93	74	82.1	71.7
3rd Recycle	91	24.05	99	62.6	62.9

^a Yields based on **IIa** added to the reaction during that step.

^b Enantiomeric excess (ee) positive values indicate an excess of the *S* enantiomer.

EXAMPLE 13

Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl) with recycle and makeup of catalyst

A chiral zirconium complex was prepared by stirring zirconium(IV) acetylacetonate (0.73 g, 1.5 mmol) with **IIIb** wherein R⁶ is H (1.61 g, 3.0 mmol) in toluene (4.7 g) for 40 minutes at 65 °C. To the resulting solution was added methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (4.55 g, 20 mmol) and additional toluene (8.7 g). Two separate solutions of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (18.38 g, 82 mmol in 54 g of toluene) and a 70% by weight solution of *tert*-butyl hydroperoxide in water (18.02 g, 140 mmol) were simultaneously co-fed to the reaction mixture while maintaining the reaction temperature at 65 °C. The rates of addition were controlled so that the *tert*-butyl hydroperoxide feed was completed in 30 minutes and the methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate feed was completed in 2.5 hours. After both feeds were complete, the reaction mixture was stirred for an additional 2 hours at 65 °C, cooled to 10 °C, and filtered. The resulting isolated solids of **Ia** were washed with toluene

(2 x 8 g) and then dried in vacuo at 45 °C. The filtrate (reaction filtrate and toluene wash) was washed with aqueous sodium bisulfite (pH adjusted to 8.8 with sodium carbonate), separated from the aqueous phase, and then concentrated in vacuo at 30 °C to provide a liquid weighing 10.4 g.

5 A catalyst makeup solution was prepared by heating **IIIb** wherein R⁶ is H (1.07 g, 2 mmol) and zirconium(IV) acetylacetonate (0.195 g, 0.4 mmol) in toluene (2.73 g) at 50 °C for 1 hour. The concentrated filtrate from the previous run was charged with 1.0 g of the catalyst makeup solution (0.5 mmol **IIIb** wherein R⁶ is H, 0.1 mmol zirconium(IV) acetylacetonate). After heating the mixture to 65 °C, methyl 5-chloro-2,3-dihydro-1-oxo-
10 1*H*-indene-2-carboxylate (2.29 g, 10 mmol) was added and then the solutions of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (20.64 g, 92 mmol in 61 g of toluene) and *tert*-butyl hydroperoxide (18.02 g, 140 mmol) were co-fed as described before. After both feeds were complete, the reaction mixture was stirred for an additional 1 hour at 65 °C and cooled to 10 °C. After adding water (10 mL) to the reaction mixture, it was filtered and
15 the isolated solids dried as before. The filtrate was washed, separated, and concentrated as before to provide a liquid weighing 9.85 g.

Using the concentrated filtrate from the previous run, the recycling process (including catalyst makeup) was repeated a second time as described in the previous paragraph except the *tert*-butyl hydroperoxide was fed over 1.75 hours and the methyl 5-chloro-2,3-dihydro-
20 1-oxo-1*H*-indene-2-carboxylate was fed over 3 hours. The solids and filtrate were treated as before. The filtrate was concentrated to provide a liquid weighing 10.77 g.

Using the concentrated filtrate from the previous run, the recycling process (including catalyst makeup) was repeated a third time as described in the previous paragraph except the *tert*-butyl hydroperoxide was fed over 2 hours. The solids and filtrate were treated as before.

25 The results from these reactions, reported in the Table E13 below, were determined by HPLC analysis of both the isolated solids of **Ia** and the filtrates from each reaction. The overall reaction enantiomeric excess (ee) refers to the net enantiomeric excess of **Ia** produced during the run and is a weighted average of the enantiomeric excess of **Ia** in the solid and filtrate phases. The enantiomeric excess of the solid, isolated **Ia** may be higher
30 than the reaction enantiomeric excess because the crystallization of **Ia** from the reaction mixture can enrich the solid with the predominant enantiomer.

TABLE E13

Results from Recycling Catalyst **IIIb** wherein R⁶ is H with Catalyst Makeup

Run	IIa Conversion (%)	Ia Isolated Weight (g)	Ia Isolated Yield (%) ^a	Isolated Ia ee (%) ^b	Reaction ee (%)
Initial	100	20.65	85.3	100	95.2
1st Recycle	100	23.03	94.6	100	91.5
2nd Recycle	99.6	22.45	92.1	98.6	85.6
3rd Recycle	97.6	20.21	83.2	98.2	75.2

^a Yields based on **IIa** added to the reaction during that step.^b Enantiomeric excess (ee) positive values indicate an excess of the *S* enantiomer.

EXAMPLE 14

- 5 Preparation of methyl (2*S*)-5-chloro-2,3-dihydro-2-hydroxy-1-oxo-1*H*-indene-2-carboxylate (Formula **Ia** wherein R¹ is OCH₃ and R⁴ is Cl) using other ligands of Formulae **III** or **IV**

10 The reaction conditions, reagents, and reagent amounts for the following examples are shown in Tables E14A and E14B. The conversion of **IIa** (R¹ is OCH₃, R⁴ is Cl) and yield of **Ia** (R¹ is OCH₃, R⁴ is Cl) are based on the amount of the limiting reagent **IIa** used in these reactions.

15 General procedure: A chiral zirconium complex was prepared by stirring either zirconium(IV) isopropoxide or zirconium(IV) acetylacetonate with a chiral ligand in toluene (1–2 mL) at 50 °C for 1 hour. The reaction mixture was evaporated to dryness in vacuo and then a toluene solution (2.00 mL) of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate (0.250 g/mL; 0.500 g, 2.23 mmol of methyl 5-chloro-2,3-dihydro-1-oxo-1*H*-indene-2-carboxylate) was added. The resulting reaction mixture was heated to the temperature indicated in Tables E14A and E14B, and then a 70% by weight solution of *tert*-butyl hydroperoxide in water (0.316 g, 0.340 mL, 2.46 mmol (1.10 equivalents) or 0.359 g, 0.386 mL, 2.79 mmol (1.25 equivalents)) was added. After the indicated time, the reaction mixture was diluted with acetonitrile (7.0 mL). The results of analysis by quantitative and chiral HPLC are shown in Tables E14A and E14B. (R⁶)_n specified in 20 Tables E14A and E14B are the same on each phenyl ring.

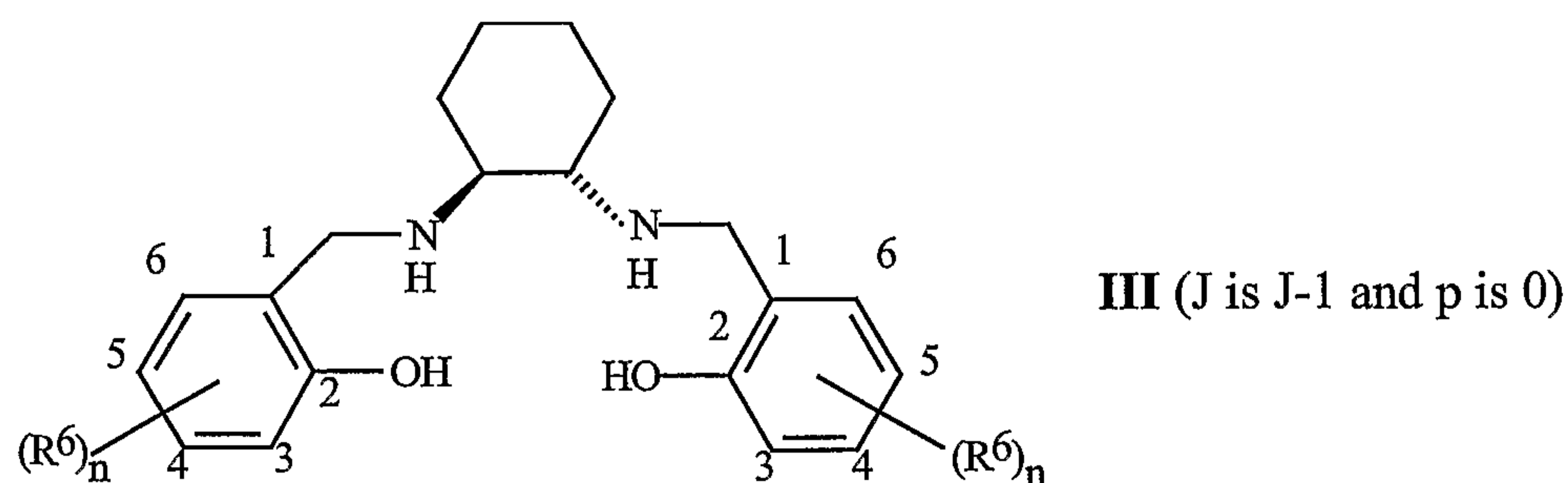


TABLE E14A

Yield and ee (enantiomeric excess) of **Ia** (R^1 is OCH_3 , R^4 is Cl) obtained with ligands of Formula **III** (J is J-1 and p is 0).

5

$(R^6)_n$	Ligand Equivalents ^a	Zr Complex Starting Material ^b	t-BuOOH Equivalents ^a	Temperature (° C)	Time (h)	IIa Conversion (%)	Ia Yield (%)	Ia ee (%) ^c
H (n is 0)	0.050	Zr(O <i>i</i> Pr) ₄	1.10	30	20	95	76	0.5
3- <i>tert</i> -butyl	0.080	Zr(acac) ₄	1.10	65	3.5	94	76	87.6
5-nitro	0.050	Zr(O <i>i</i> Pr) ₄	1.10	30	20	18	8	7.7
5-bromo	0.050	Zr(O <i>i</i> Pr) ₄	1.10	30	20	90	78	-0.2
3-bromo-5-chloro	0.050	Zr(O <i>i</i> Pr) ₄	1.10	30	20	92	81	-0.3
4,6-dichloro	0.060	Zr(acac) ₄	1.10	65	3.5	92	72	0.0
3-methoxy	0.060	Zr(acac) ₄	1.10	65	3.5	92	67	-1.3
3-methoxy-5-bromo	0.060	Zr(acac) ₄	1.10	65	3.5	91	73	-0.9
3,5-dibromo	0.060	Zr(acac) ₄	1.10	65	3.5	88	70	0.2
3,5-dichloro	0.060	Zr(acac) ₄	1.10	65	3.5	90	73	-0.5
3,4-dimethoxy	0.060	Zr(acac) ₄	1.10	65	3.5	88	70	-1.1
5-methoxy	0.060	Zr(acac) ₄	1.10	65	3.5	94	72	1.1
3- <i>tert</i> -butyl-5-bromo	0.048	Zr(acac) ₄	1.25	65	3.5	94	84	75
3- <i>tert</i> -butyl-5-chloro	0.048	Zr(acac) ₄	1.25	65	3.5	89	81	78
3- <i>tert</i> -butyl-5-methyl	0.048	Zr(acac) ₄	1.25	65	3.5	97	85	71
3- <i>tert</i> -butyl-5-methoxy	0.048	Zr(acac) ₄	1.25	65	3.5	98	73	64
3- <i>tert</i> -butyl-5-O ₂ CC(CH ₃) ₃	0.048	Zr(acac) ₄	1.25	65	3.5	95	87	49
3- <i>tert</i> -butyl-5-OSi(<i>iso</i> -Pr) ₃	0.048	Zr(acac) ₄	1.25	65	3.5	95	85	71
3- <i>tert</i> -butyl-5-O ₂ CC ₆ H ₄ (4'-OCH ₃)	0.048	Zr(acac) ₄	1.25	65	3.5	94	86	60
3- <i>tert</i> -butyl-5-O ₂ CC ₆ H ₄ (4'-NO ₂)	0.048	Zr(acac) ₄	1.25	65	3.5	97	73	66
3-(1'-adamantyl)-5-methyl	0.048	Zr(acac) ₄	1.25	65	3.5	95	86	36

- a The number of equivalents relative to the amount of **IIa** used.
 b 0.04 equivalents of Zr complex starting material were used for all runs relative to the amount of **IIa**.
 c Enantiomeric excess (ee) positive values indicate an excess of the *S* enantiomer; negative values indicate an excess of the *R* enantiomer.

5

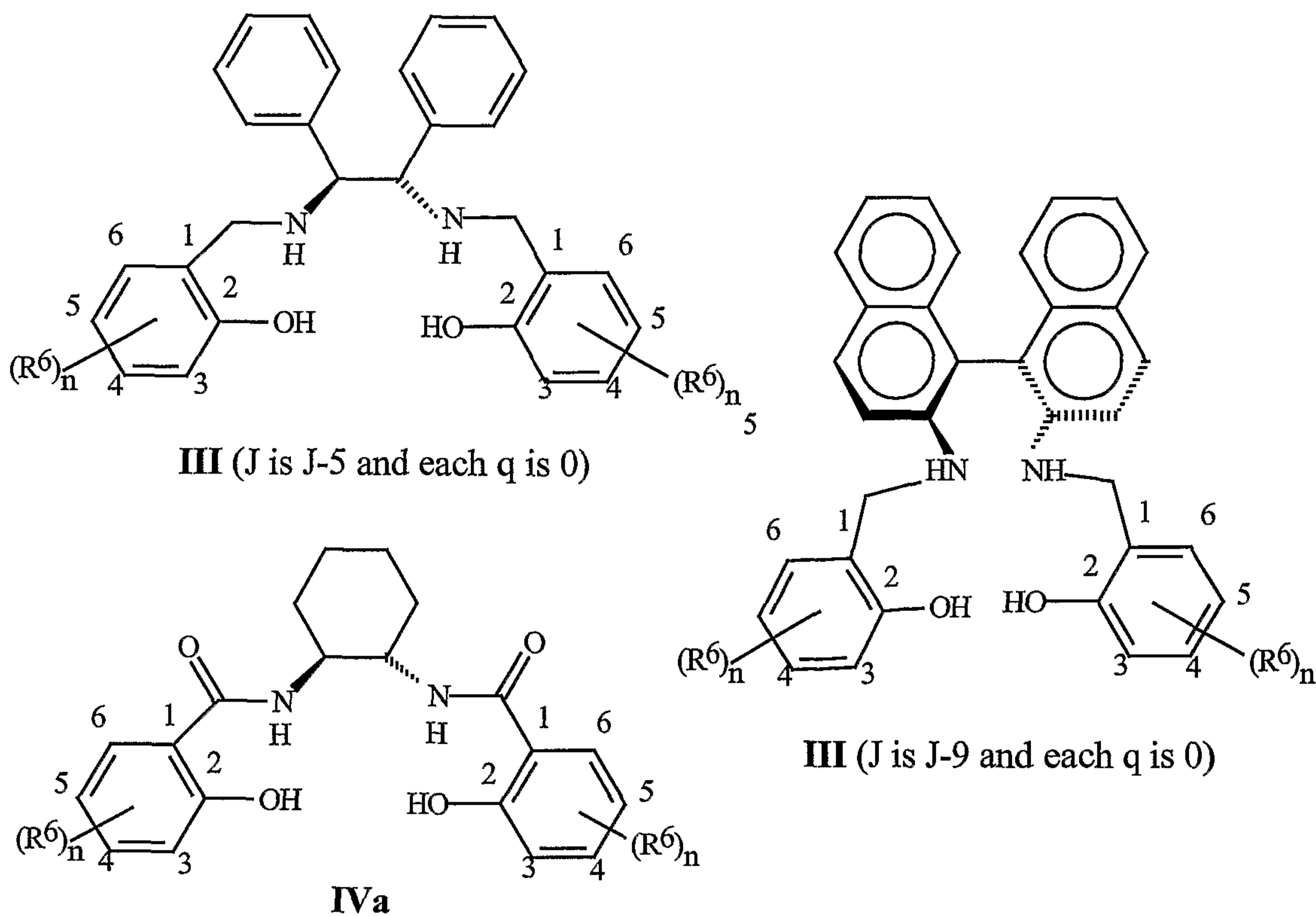


TABLE E14B

Yield and ee (enantiomeric excess) of **Ia** (R^1 is OCH_3 , R^4 is Cl) obtained with ligands of Formula **III** (J is J-5 or J-9, each q is 0) and **IVa**

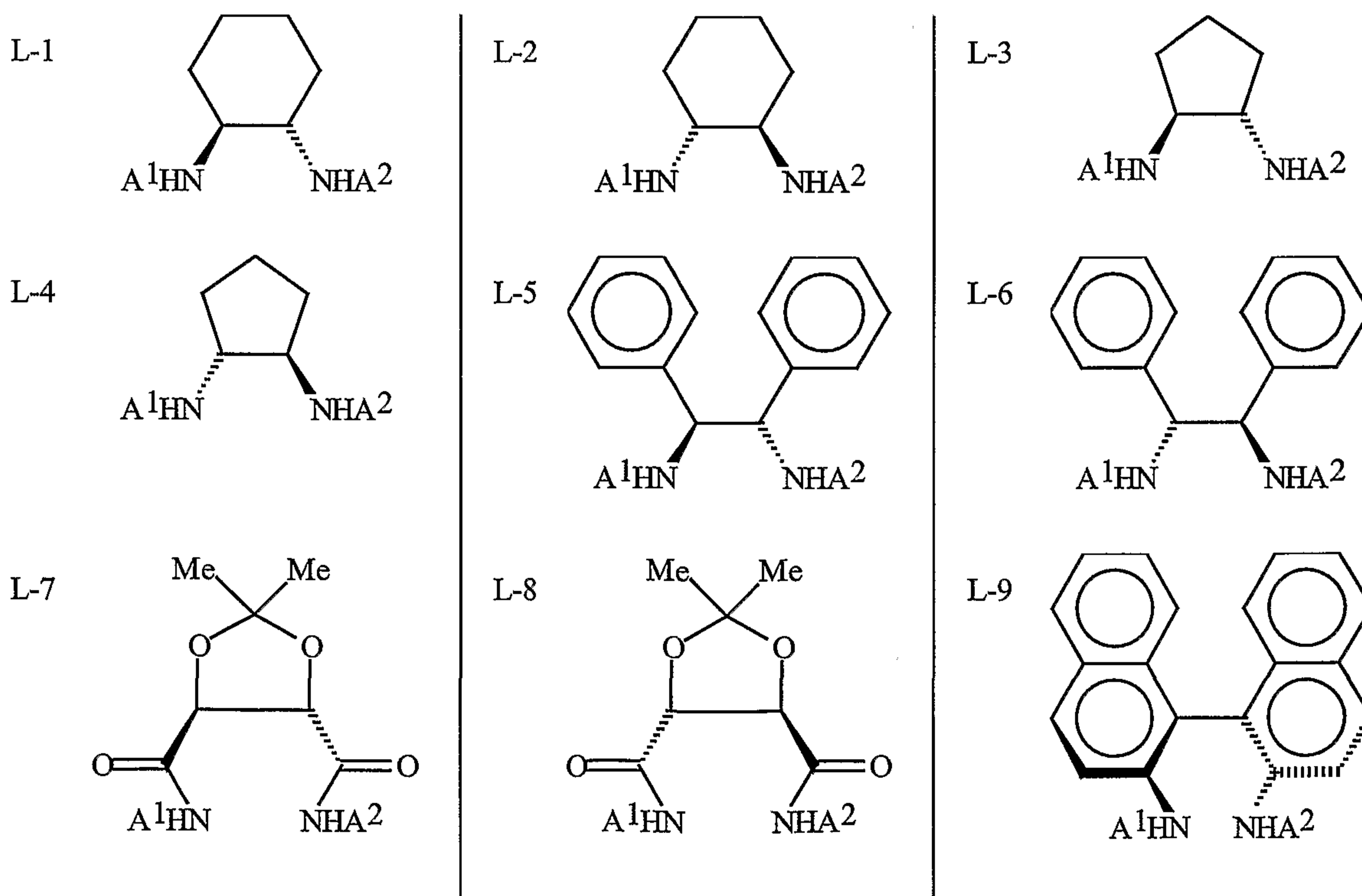
$(R^6)_n$	Ligand	Ligand Equivalents ^a	Zr Complex Starting Material	Zr Equivalents ^a	IIa Conversion (%)	Ia Yield (%)	Ia ee (%) ^b	Temperature (°C)	Time (h)
5- <i>tert</i> -butyl	III (J is J-5)	0.08	Zr(acac) ₄	0.04	59	38	12.2	65	3.5
3,5-di- <i>tert</i> -butyl	III (J is J-5)	0.08	Zr(acac) ₄	0.04	96	77	88.7	65	3.5
3,5-di- <i>tert</i> -butyl	III (J is J-9)	0.08	Zr(acac) ₄	0.04	87	67	1.0	65	3.5
3,5-di- <i>tert</i> -butyl	IVa	0.08	Zr(acac) ₄	0.04	92	71	-6.7	65	3.5

^a The number of equivalents relative to the amount of **IIa** used.

^b Enantiomeric excess (ee) positive values indicate an excess of the *S* enantiomer; negative values indicate an excess of the *R* enantiomer.

By the procedures described herein together with methods known in the art, the ligands identified in Tables 1–3 and their zirconium complexes can be prepared. Table 4 illustrates examples of hydroxylated compounds of Formula I preparable from the corresponding β -dicarbonyl compounds of Formula II according to the process of the invention. The following abbreviations are used in the Tables which follow: “*t*” means tertiary, “*s*” means secondary, “*n*” means normal, “*i*” means iso, “*c*” means cyclo, “Me” means methyl, “Et” means ethyl, “Pr” means propyl, “*i*-Pr” means isopropyl, “Bu” means butyl, “Ph” means phenyl, “OMe” means methoxy, “OEt” means ethoxy, “SMe” means methylthio, “SEt” means ethylthio, “CN” means cyano, “NO₂” means nitro, “TMS” means trimethylsilyl, “S(O)Me” means methylsulfinyl, and “S(O)₂Me” means methylsulfonyl. For clarity, examples of compounds of Formula III (or their enantiomers) are illustrated in Tables 2A and 2B and examples of compounds of Formula IV (or their enantiomers) are illustrated in Tables 3A and 3B with the stereochemical relationship between J and the connecting nitrogen-containing linkages included in L specifically depicted as L-1 through L-12 shown in Table 1. The parts of Formula III or Formula IV or their enantiomers connected to the nitrogen-containing linkages of L are denoted A¹ and A².

TABLE 1
Illustrative Examples of L



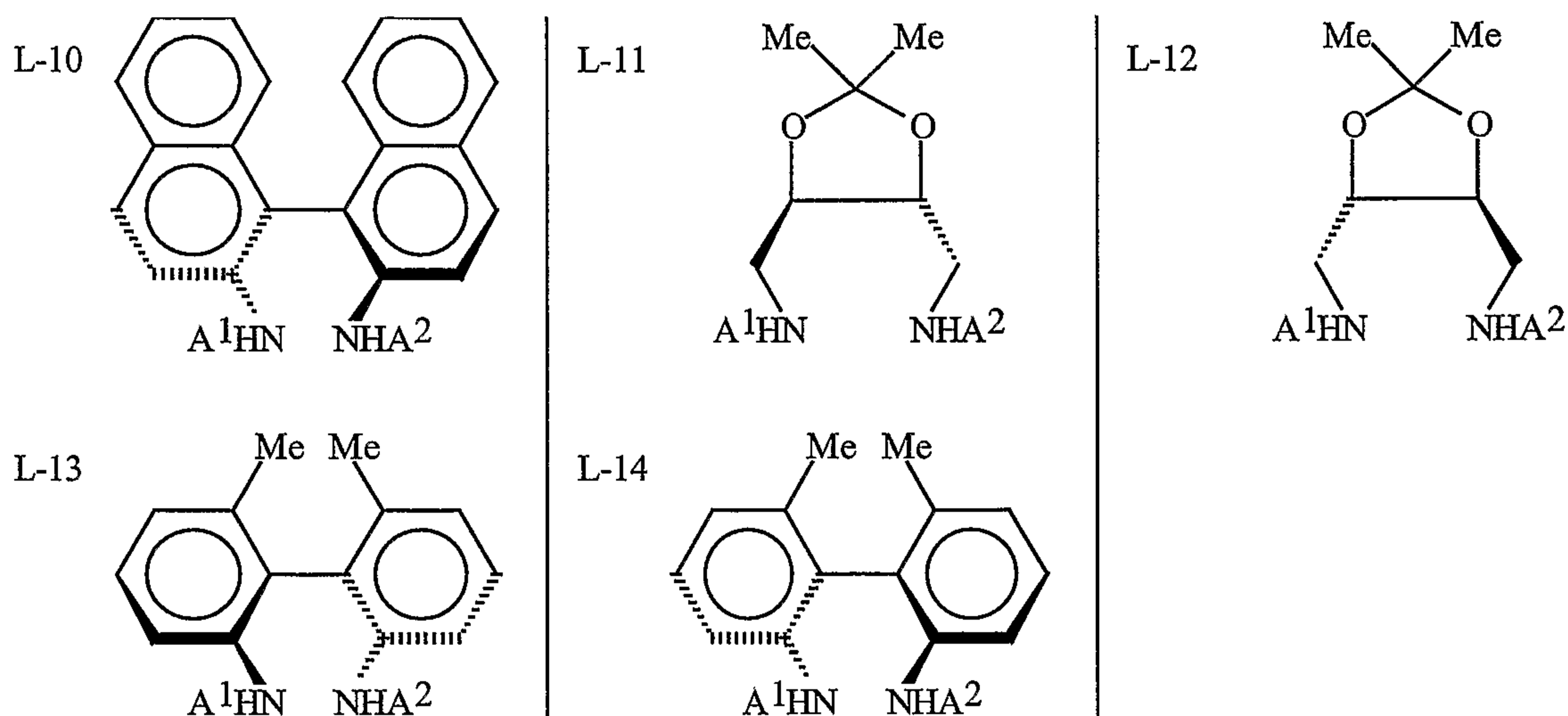
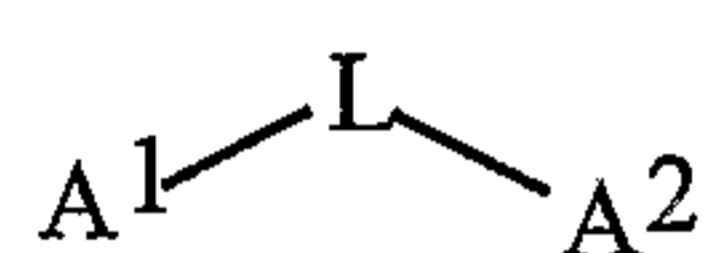
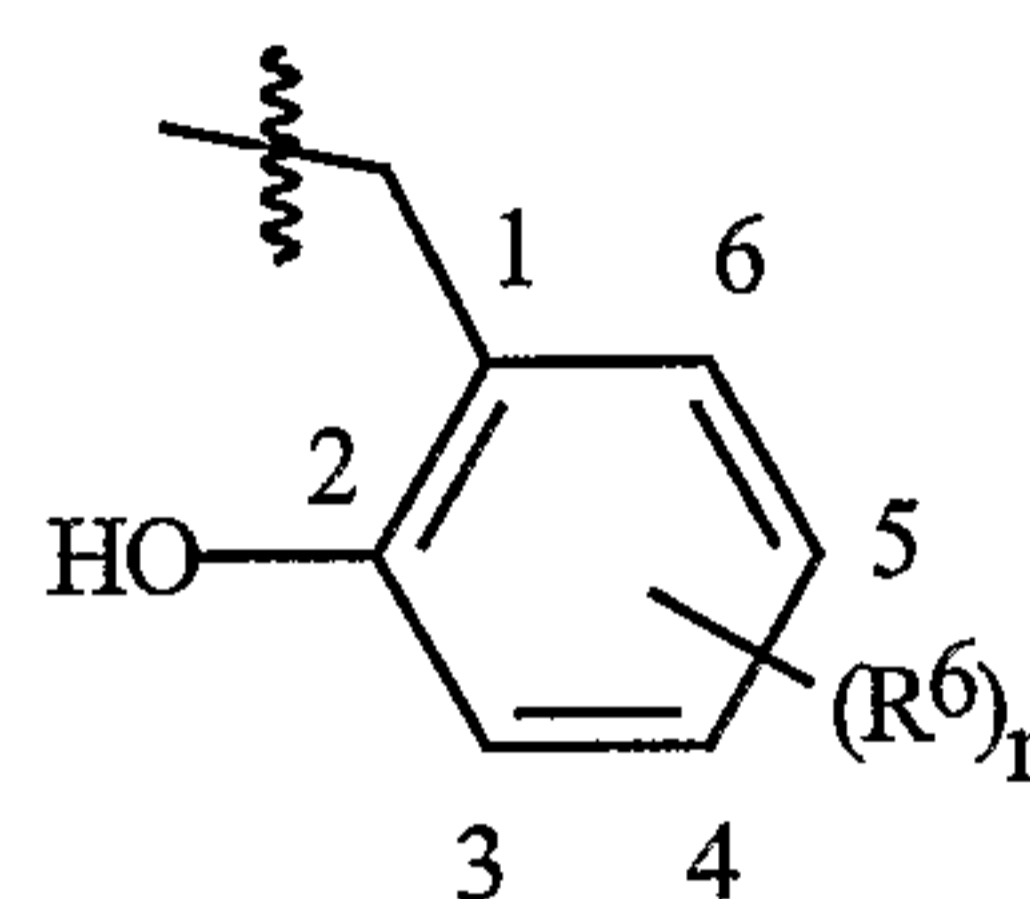


TABLE 2A



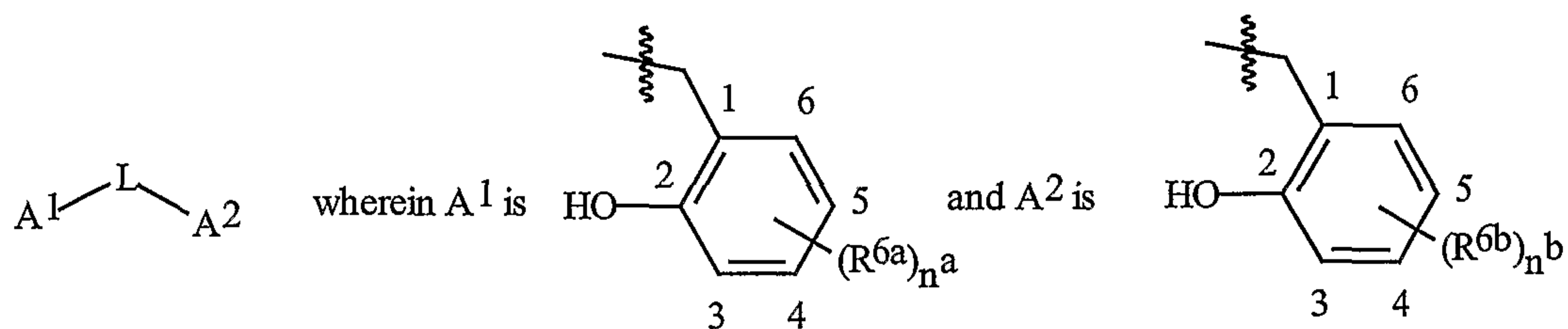
wherein A¹ and A² are both



L	(R ⁶) _n		L	(R ⁶) _n
L-1	3,5-di- <i>t</i> -Bu	(IIIa, R ⁶ is C(CH ₃) ₃)	L-7	3,5-di- <i>t</i> -Bu
L-2	3,5-di- <i>t</i> -Bu	(ent-IIIa, R ⁶ is C(CH ₃) ₃)	L-8	3,5-di- <i>t</i> -Bu
L-1	H		L-7	H
L-2	H		L-8	H
L-1	3- <i>t</i> -Bu	(IIIa, R ⁶ is H)	L-7	3,5-di-Me
L-2	3- <i>t</i> -Bu	(ent-IIIa, R ⁶ is H)	L-8	3,5-di-Me
L-1	5-NO ₂		L-7	3,5-di-TMS
L-2	5-NO ₂		L-8	3,5-di-TMS
L-1	3-Br		L-7	3,5-di-Cl
L-2	3-Br		L-8	3,5-di-Cl
L-1	3-Br, 5-Cl		L-9	3,5-di- <i>t</i> -Bu
L-2	3-Br, 5-Cl		L-10	3,5-di- <i>t</i> -Bu
L-1	3- <i>t</i> -Bu, 5-Cl		L-9	H
L-2	3- <i>t</i> -Bu, 5-Cl		L-10	H
L-1	3- <i>t</i> -Bu, 5-Br		L-9	3,5-di-Me
L-2	3- <i>t</i> -Bu, 5-Br		L-10	3,5-di-Me
L-1	3- <i>t</i> -Bu, 5-Me		L-9	3,5-di-TMS

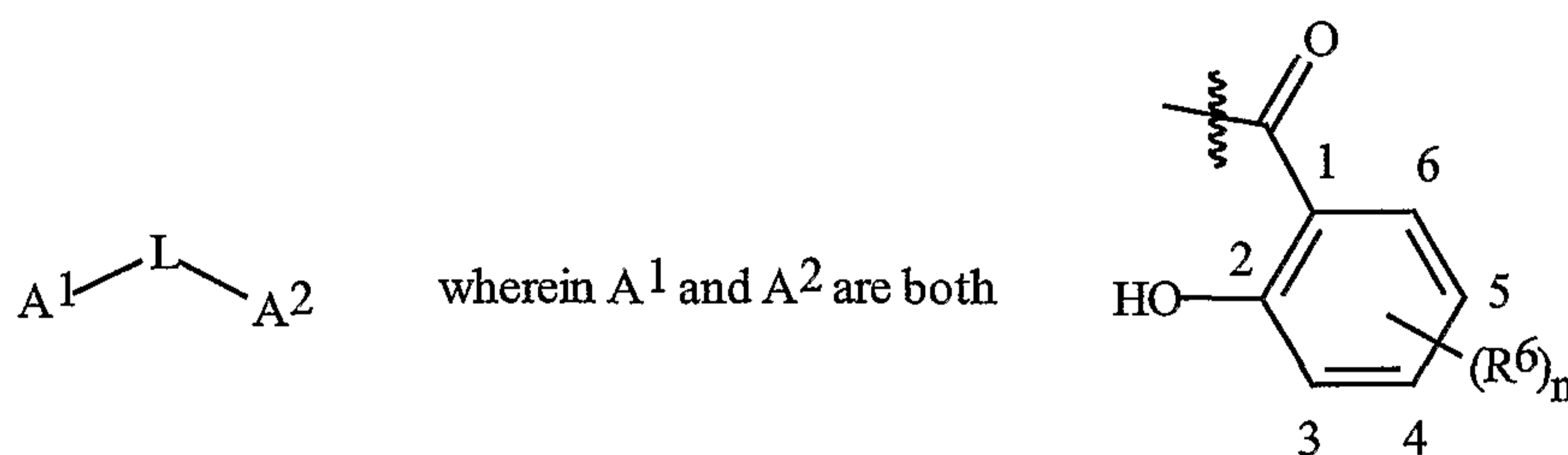
L	(R ⁶) _n		L	(R ⁶) _n	
L-2	3- <i>t</i> -Bu, 5-Me		L-10	3,5-di-TMS	
L-1	3- <i>t</i> -Bu, 5-OSi(<i>i</i> -Pr) ₃		L-9	3,5-di-Cl	
L-2	3- <i>t</i> -Bu, 5-OSi(<i>i</i> -Pr) ₃		L-10	3,5-di-Cl	
L-1	3- <i>t</i> -Bu, 5-OMe		L-11	3,5-di-TMS	
L-2	3- <i>t</i> -Bu, 5-OMe		L-12	3,5-di-TMS	
L-1	3,5-di-Me		L-11	H	
L-2	3,5-di-Me		L-12	H	
L-1	3,5-di-TMS		L-11	3,5-di-Me	
L-2	3,5-di-TMS		L-12	3,5-di-Me	
L-1	3,5-di-Cl		L-11	3,5-di-TMS	
L-2	3,5-di-Cl		L-12	3,5-di-TMS	
L-3	3,5-di- <i>t</i> -Bu		L-11	3,5-di-Cl	
L-4	3,5-di- <i>t</i> -Bu		L-12	3,5-di-Cl	
L-3	H		L-13	3,5-di- <i>t</i> -Bu	
L-4	H		L-14	3,5-di- <i>t</i> -Bu	
L-3	3,5-di-Me		L-13	H	
L-4	3,5-di-Me		L-14	H	
L-3	3,5-di-TMS		L-13	3,5-di-Me	
L-4	3,5-di-TMS		L-14	3,5-di-Me	
L-3	3,5-di-Cl		L-13	3,5-di-TMS	
L-4	3,5-di-Cl		L-14	3,5-di-TMS	
L-5	3,5-di- <i>t</i> -Bu	(IIIb , R ⁶ is C(CH ₃) ₃)	L-13	3,5-di-Cl	
L-6	3,5-di- <i>t</i> -Bu	(ent-IIIb , R ⁶ is C(CH ₃) ₃)	L-14	3,5-di-Cl	
L-5	H		L-5	3,5-di-Cl	
L-6	H		L-6	3,5-di-Cl	
L-5	3,5-di-Me		L-5	3- <i>t</i> -Bu	(IIIb , R ⁶ is H)
L-6	3,5-di-Me		L-6	3- <i>t</i> -Bu	(ent-IIIb , R ⁶ is H)
L-5	3,5-di-TMS		L-1	3- <i>t</i> -Bu, 5-Me	
L-6	3,5-di-TMS		L-2	3- <i>t</i> -Bu, 5-Me	
L-5	3- <i>t</i> -Bu, 5-Me				
L-6	3- <i>t</i> -Bu, 5-Me				

TABLE 2B



L	(R ^{6a}) _n a	(R ^{6b}) _n b	L	(R ^{6a}) _n a	(R ^{6b}) _n b
L-1	3,5-di- <i>t</i> -Bu	3- <i>t</i> -Bu	L-1	3,5-di-TMS	3- <i>t</i> -Bu
L-2	3,5-di- <i>t</i> -Bu	3- <i>t</i> -Bu	L-2	3,5-di-TMS	3- <i>t</i> -Bu
L-5	3- <i>t</i> -Bu	3,5-di- <i>t</i> -Bu	L-5	3,5-di-TMS	3- <i>t</i> -Bu
L-6	3- <i>t</i> -Bu	3,5-di- <i>t</i> -Bu	L-6	3,5-di-TMS	3- <i>t</i> -Bu

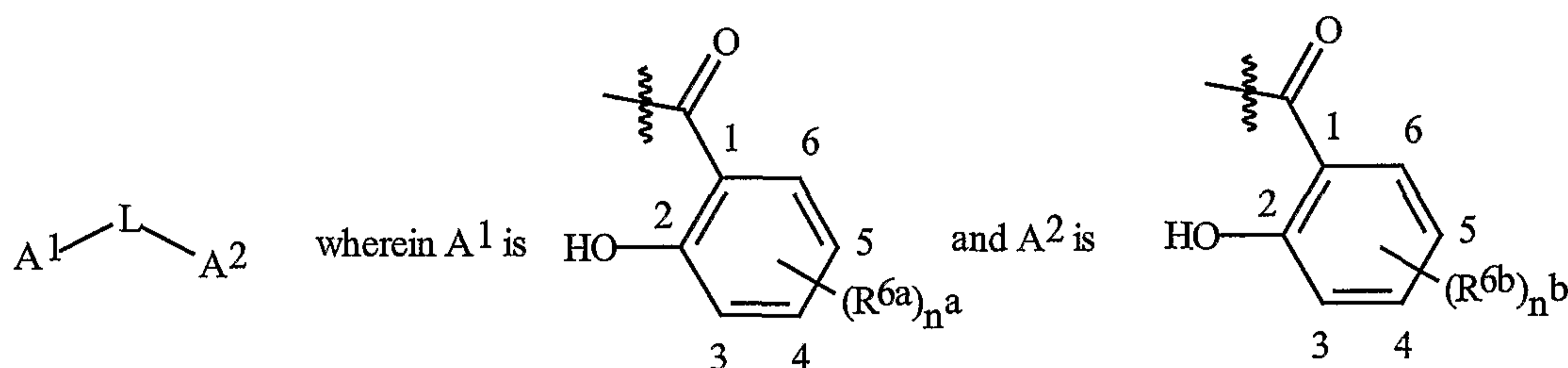
TABLE 3A



L	(R ⁶) _n	L	(R ⁶) _n	L	(R ⁶) _n
L-1	3,5-di- <i>t</i> -Bu	L-4	3,5-di- <i>t</i> -Bu	L-10	3,5-di-TMS
L-2	3,5-di- <i>t</i> -Bu	L-3	H	L-9	3,5-di-Cl
L-1	H	L-4	H	L-10	3,5-di-Cl
L-2	H	L-3	3,5-di-Me	L-11	3,5-di- <i>t</i> -Bu
L-1	3- <i>t</i> -Bu	L-4	3,5-di-Me	L-12	3,5-di- <i>t</i> -Bu
L-2	3- <i>t</i> -Bu	L-3	3,5-di-TMS	L-11	H
L-1	5-NO ₂	L-4	3,5-di-TMS	L-12	H
L-2	5-NO ₂	L-3	3,5-di-Cl	L-11	3,5-di-Me
L-1	3-Br	L-4	3,5-di-Cl	L-12	3,5-di-Me
L-2	3-Br	L-5	3,5-di- <i>t</i> -Bu	L-11	3,5-di-TMS
L-1	3-Br, 5-Cl	L-6	3,5-di- <i>t</i> -Bu	L-12	3,5-di-TMS
L-2	3-Br, 5-Cl	L-5	H	L-11	3,5-di-Cl
L-1	3- <i>t</i> -Bu, 5-Cl	L-6	H	L-12	3,5-di-Cl
L-2	3- <i>t</i> -Bu, 5-Cl	L-5	3,5-di-Me	L-13	3,5-di- <i>t</i> -Bu
L-1	3- <i>t</i> -Bu, 5-Br	L-8	3,5-di-Me	L-14	3,5-di- <i>t</i> -Bu
L-2	3- <i>t</i> -Bu, 5-Br	L-7	3,5-di-TMS	L-13	H
L-1	3- <i>t</i> -Bu, 5-Me	L-8	3,5-di-TMS	L-14	H

L	(R ⁶) _n	L	(R ⁶) _n	L	(R ⁶) _n
L-2	3- <i>t</i> -Bu, 5-Me	L-7	3,5-di-Cl	L-13	3,5-di-Me
L-1	3- <i>t</i> -Bu, 5-OSi(<i>i</i> -Pr) ₃	L-8	3,5-di-Cl	L-14	3,5-di-Me
L-2	3- <i>t</i> -Bu, 5-OSi(<i>i</i> -Pr) ₃	L-9	3,5-di- <i>t</i> -Bu	L-13	3,5-di-TMS
L-1	3- <i>t</i> -Bu, 5-OMe	L-10	3,5-di- <i>t</i> -Bu	L-14	3,5-di-TMS
L-2	3- <i>t</i> -Bu, 5-OMe	L-9	H	L-13	3,5-di-Cl
L-1	3,5-di-Me	L-10	H	L-14	3,5-di-Cl
L-2	3,5-di-Me	L-9	3,5-di-Me	L-5	3- <i>t</i> -Bu
L-1	3,5-di-TMS	L-10	3,5-di-Me	L-6	3- <i>t</i> -Bu
L-2	3,5-di-TMS	L-6	3,5-di-Me	L-5	3,5-di-Cl
L-1	3,5-di-Cl	L-5	3,5-di-TMS	L-6	3,5-di-Cl
L-2	3,5-di-Cl	L-6	3,5-di-TMS		
L-3	3,5-di- <i>t</i> -Bu	L-9	3,5-di-TMS		

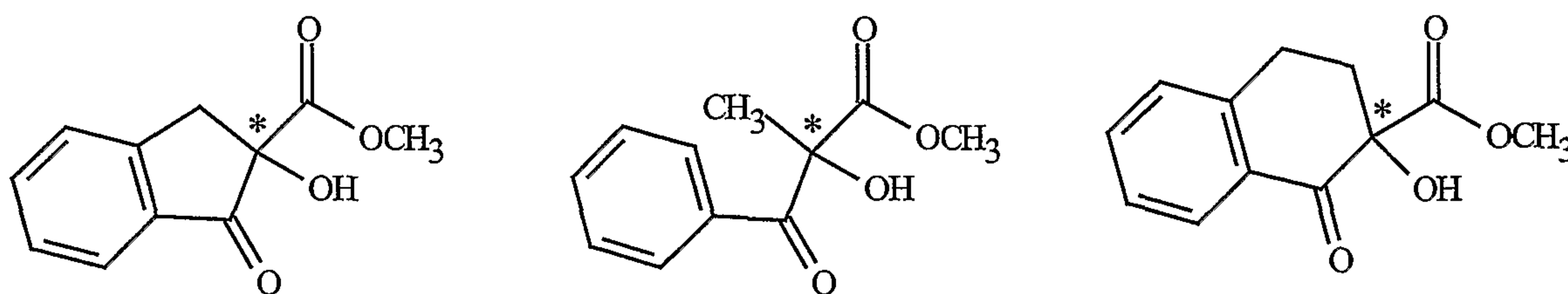
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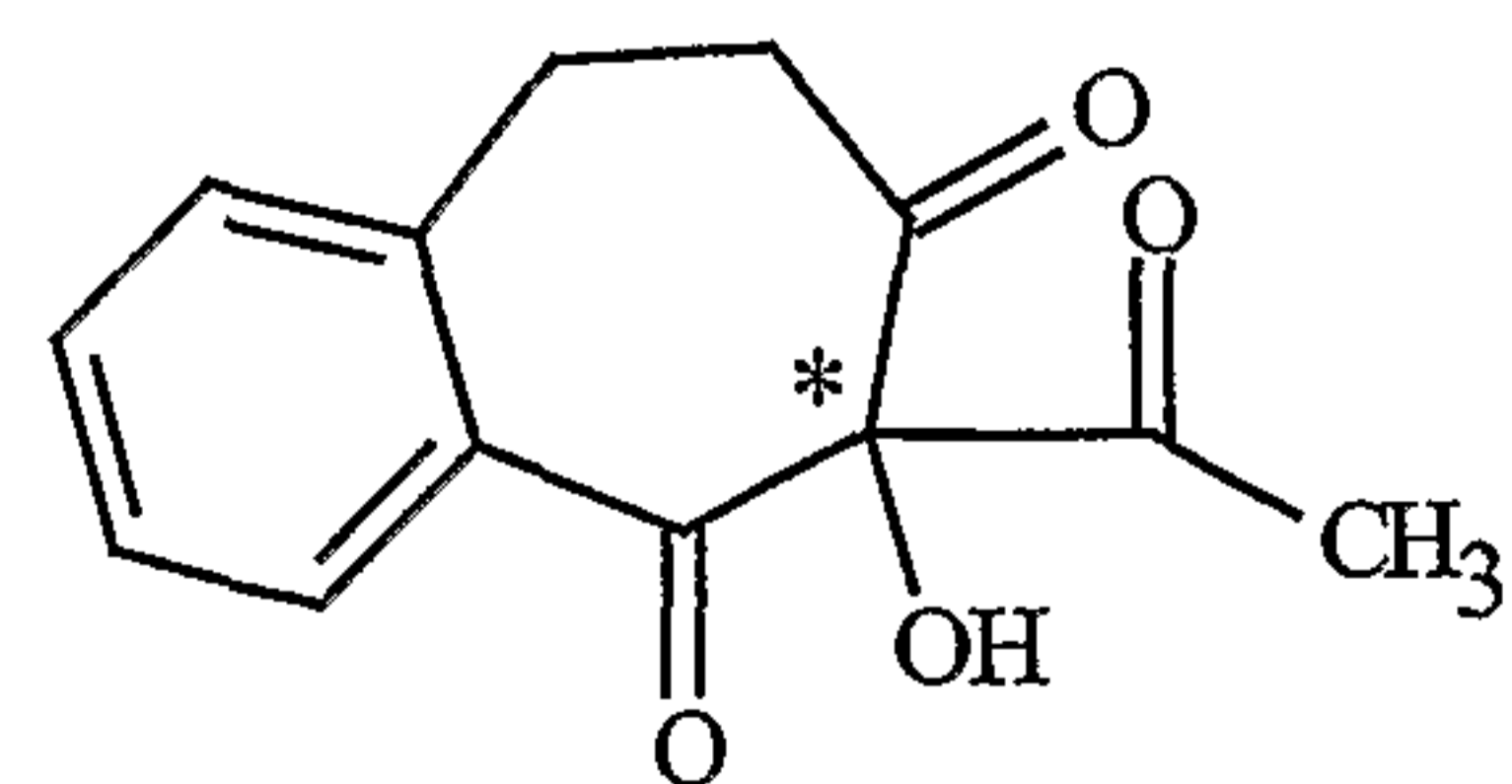
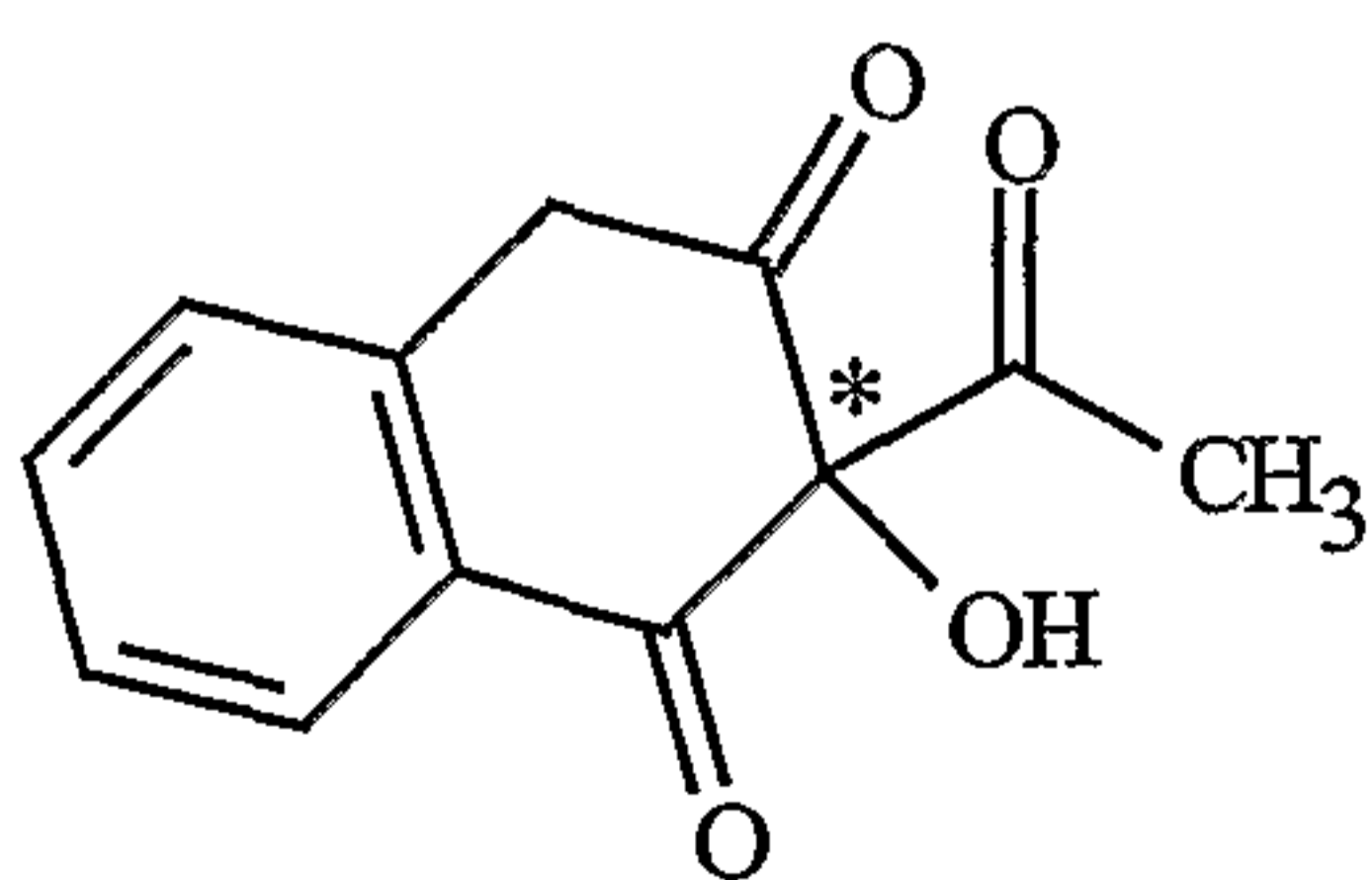
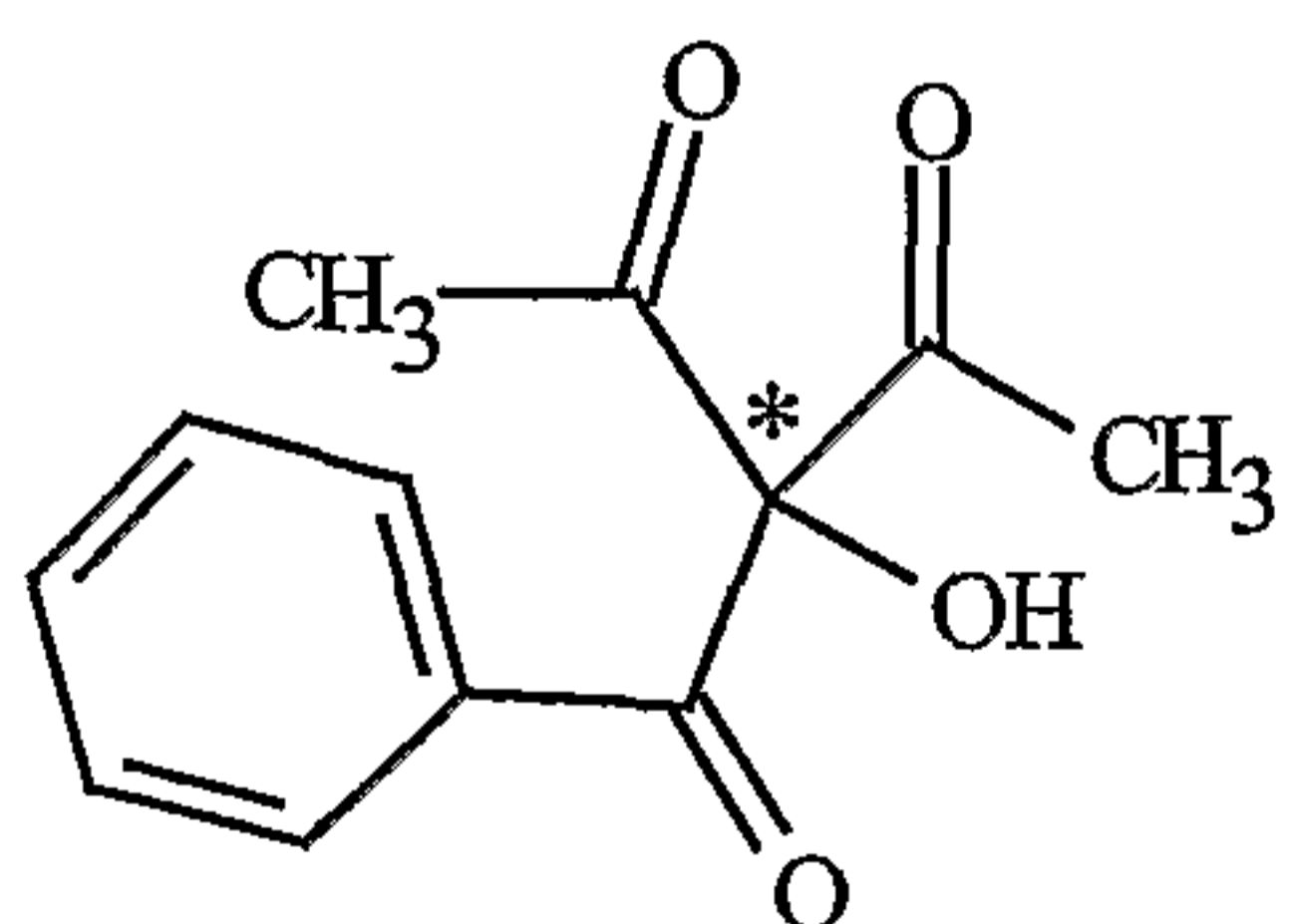
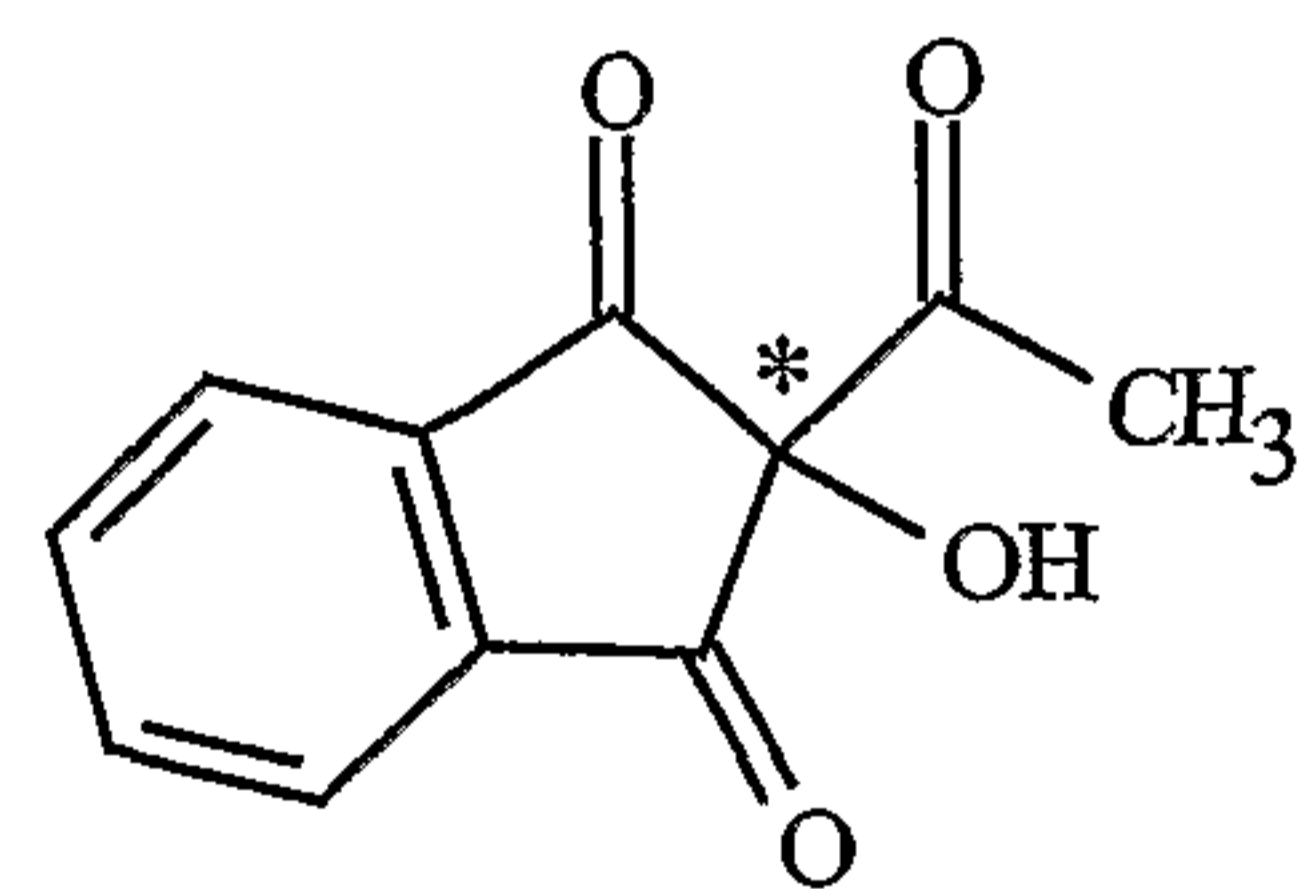
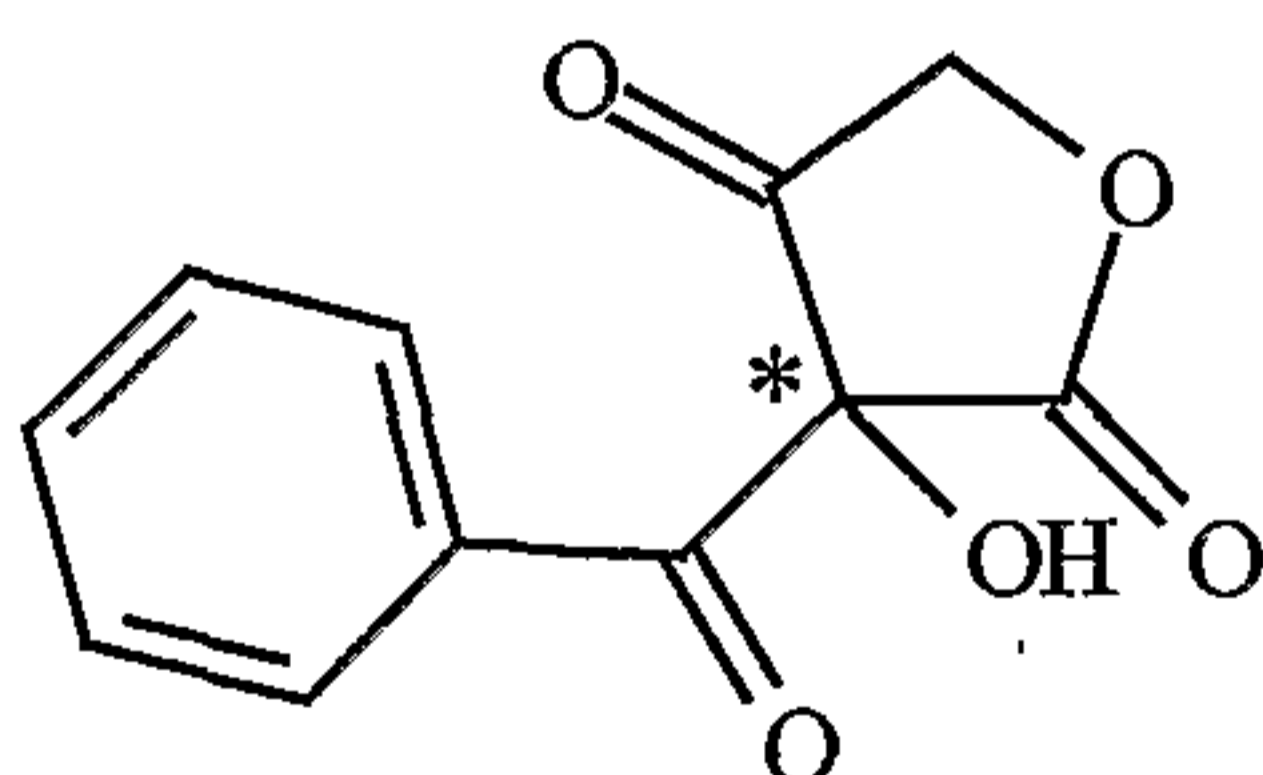
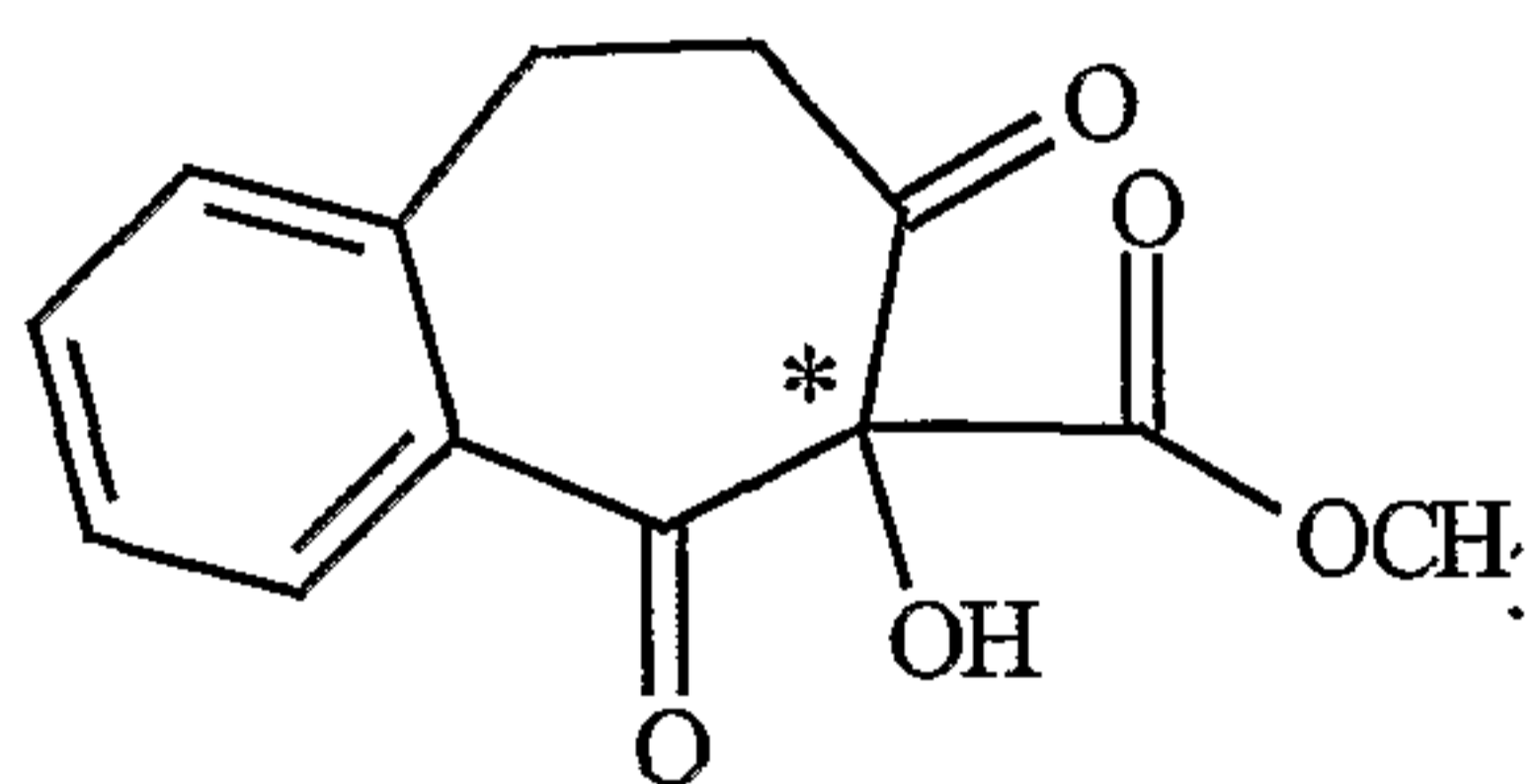
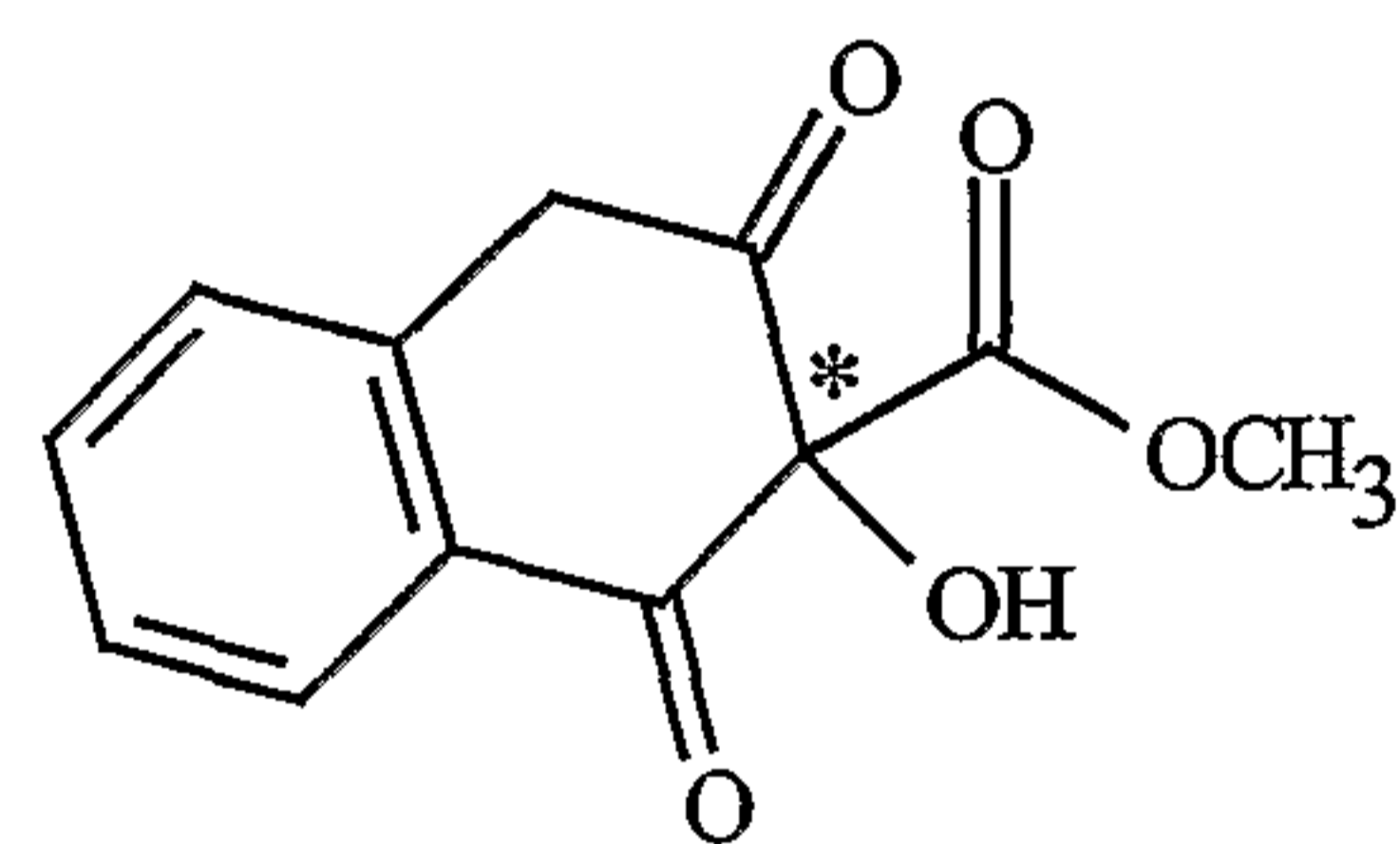
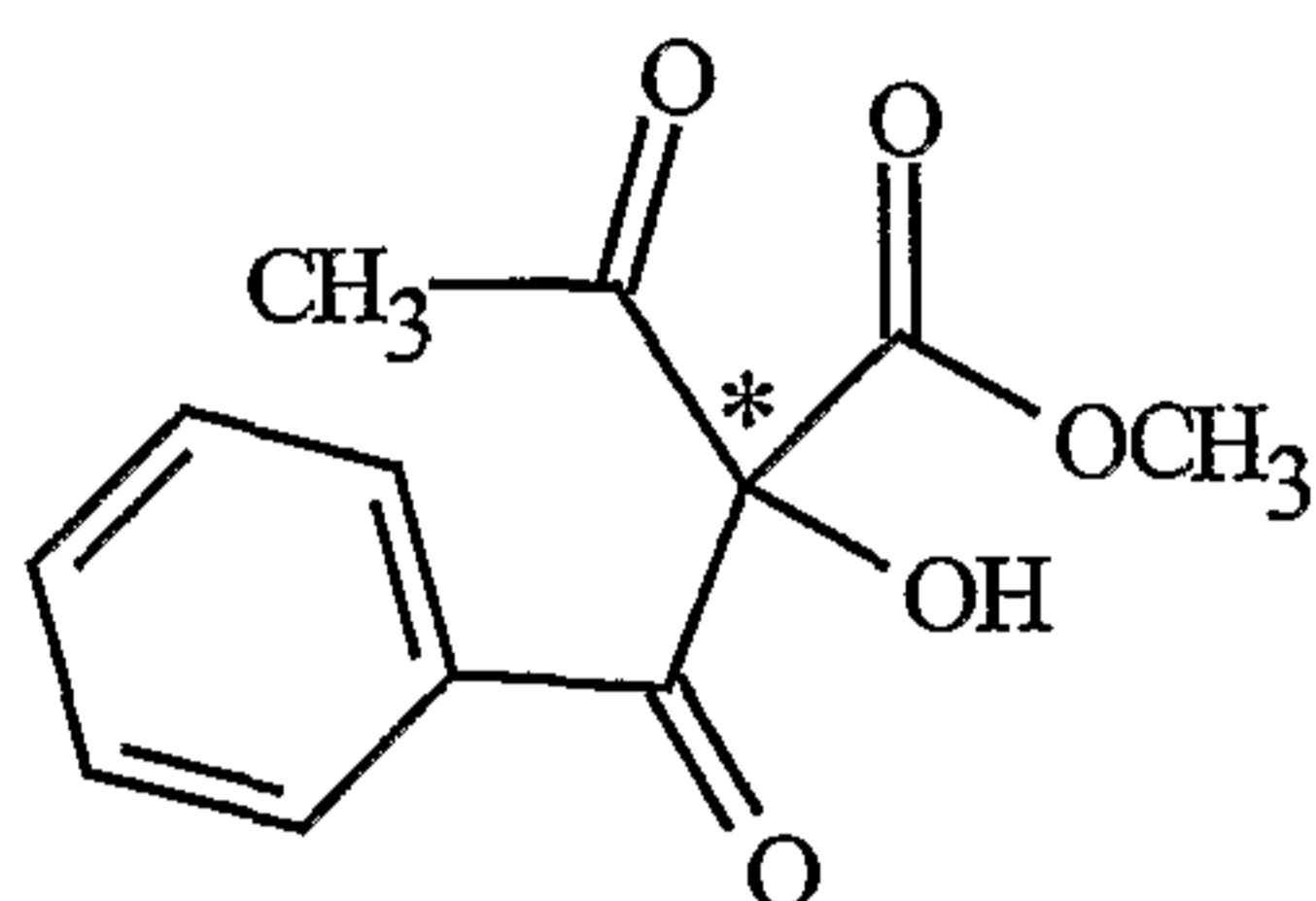
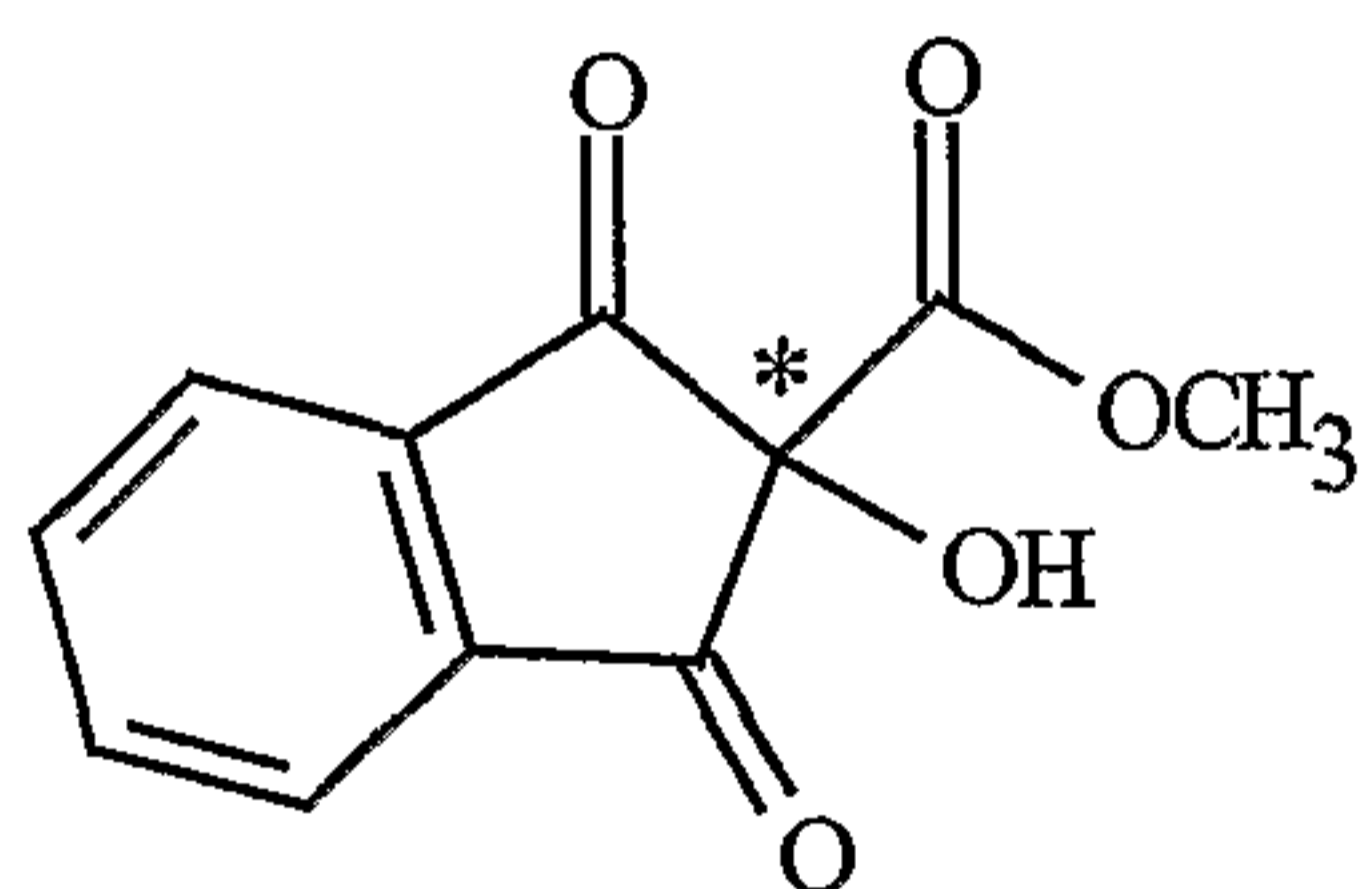
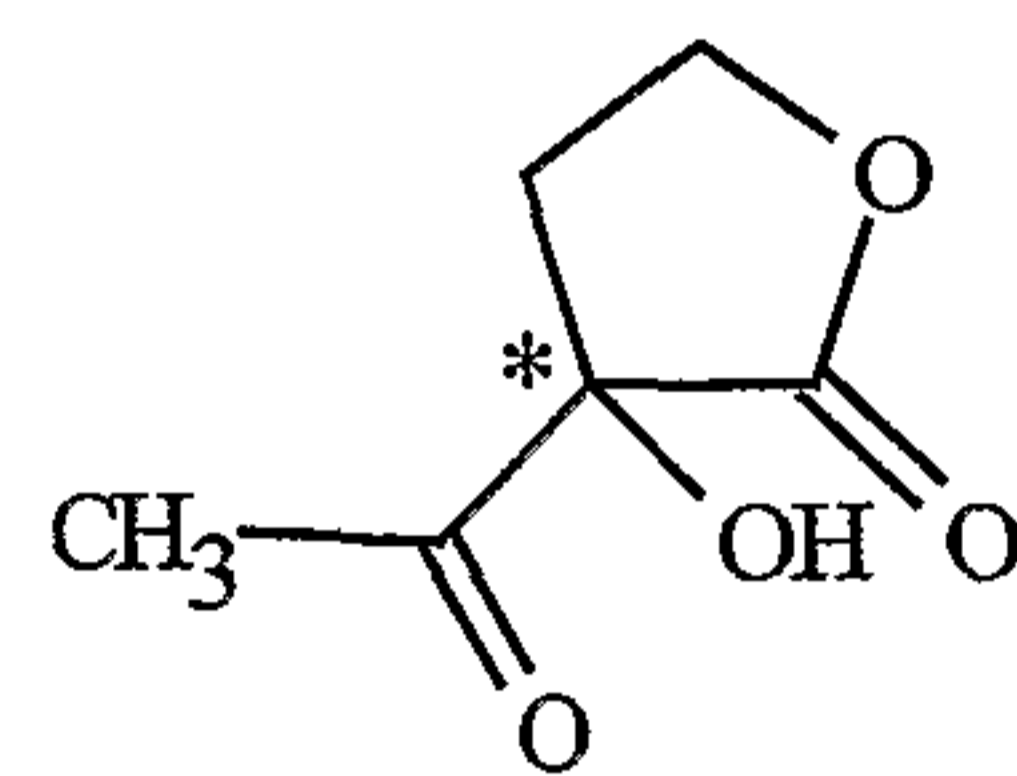
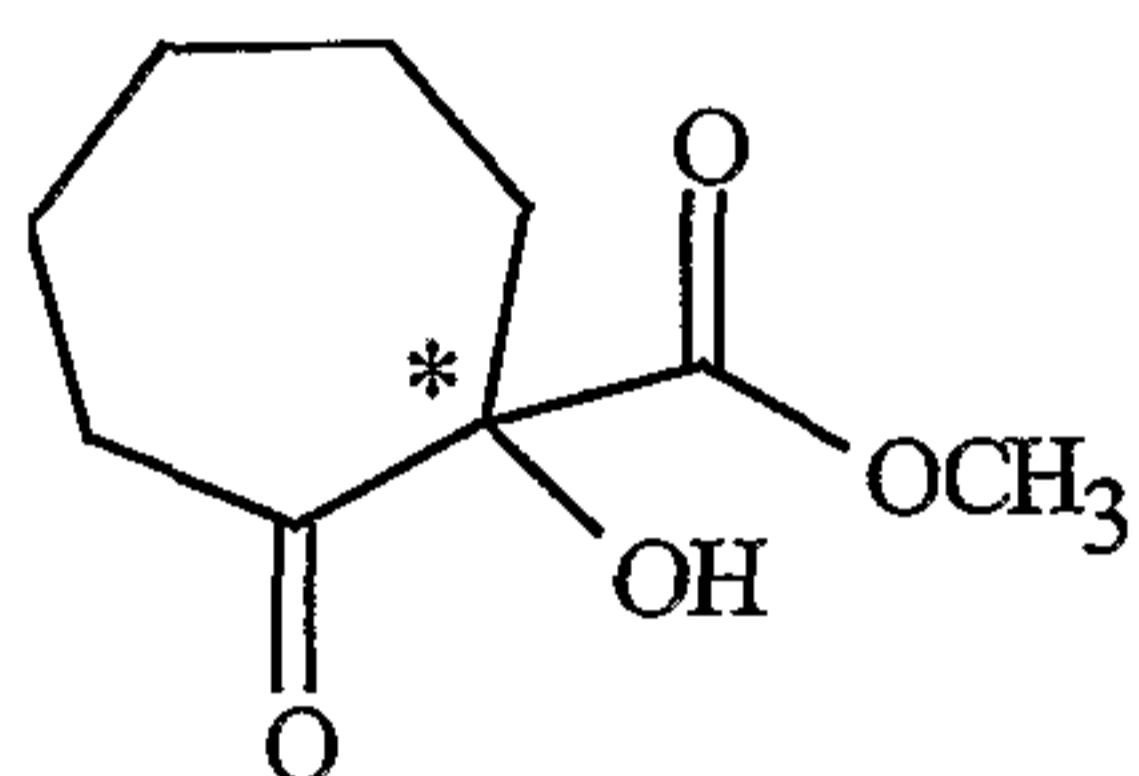
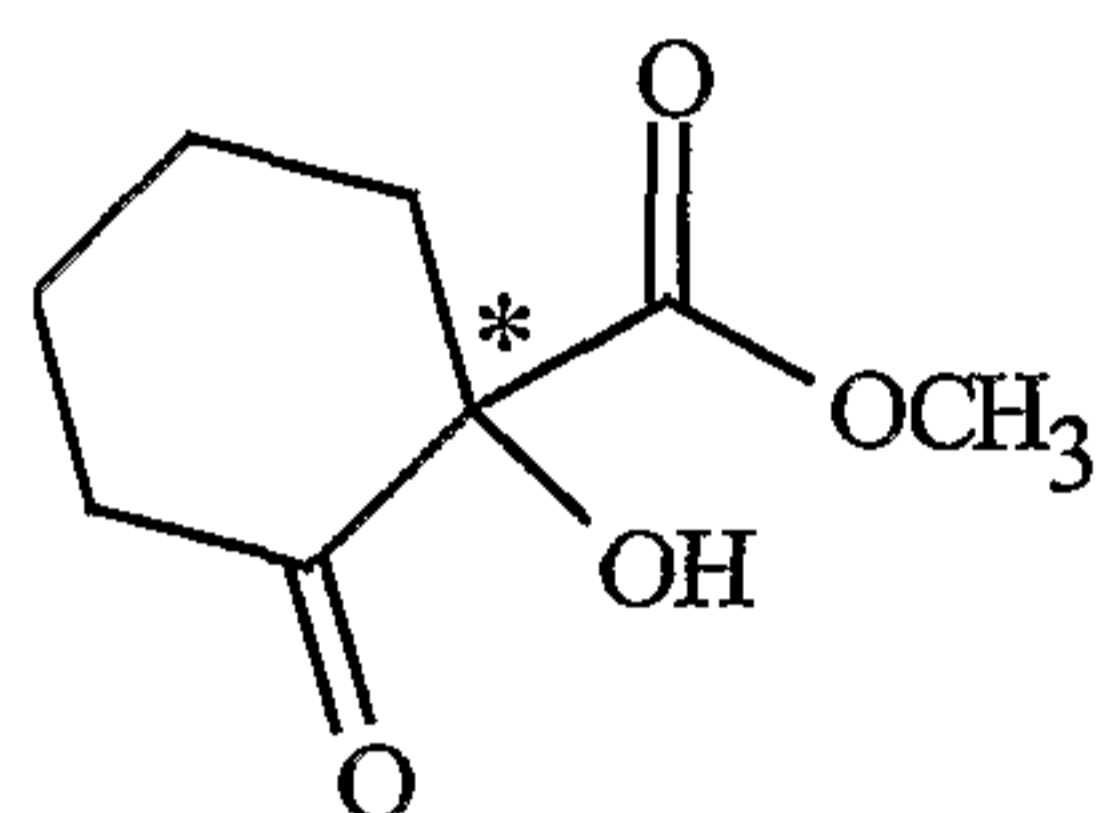
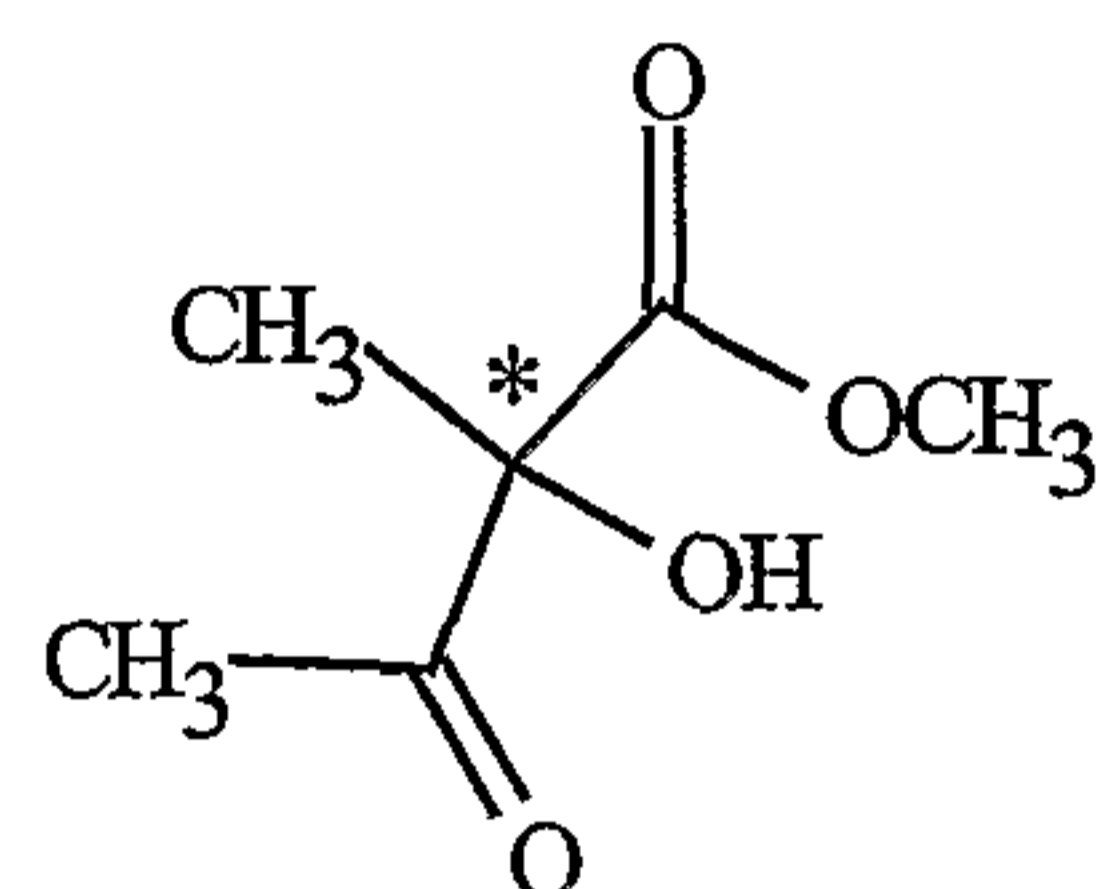
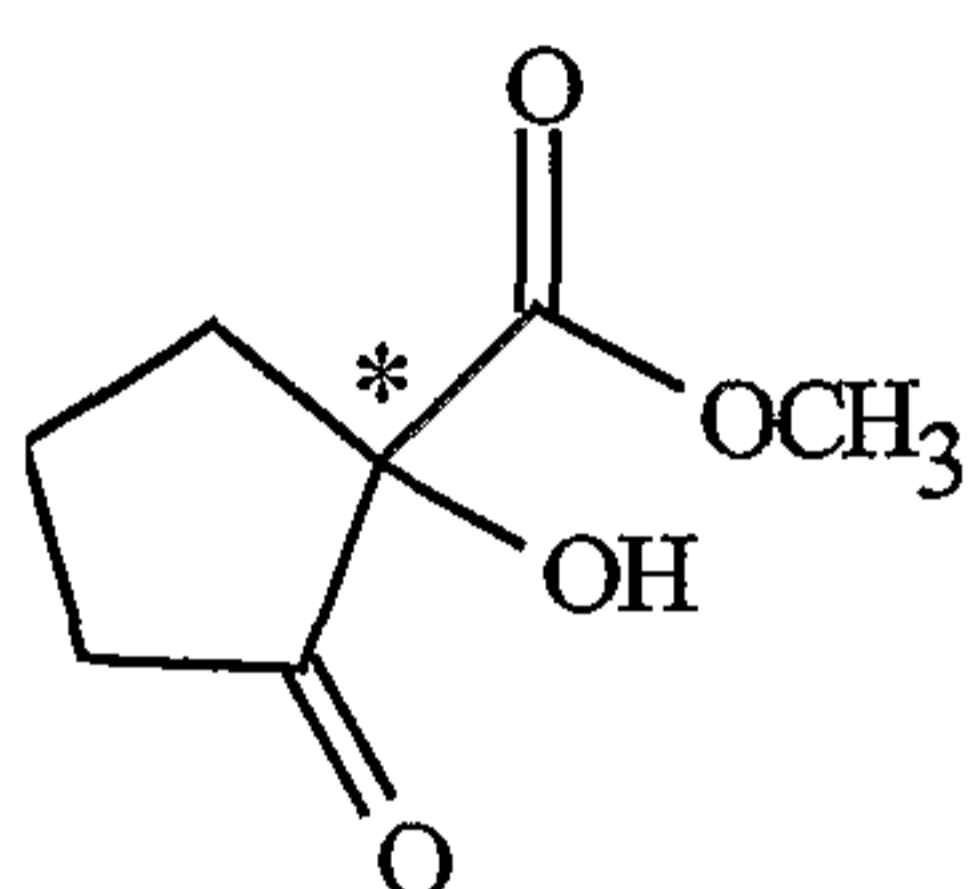
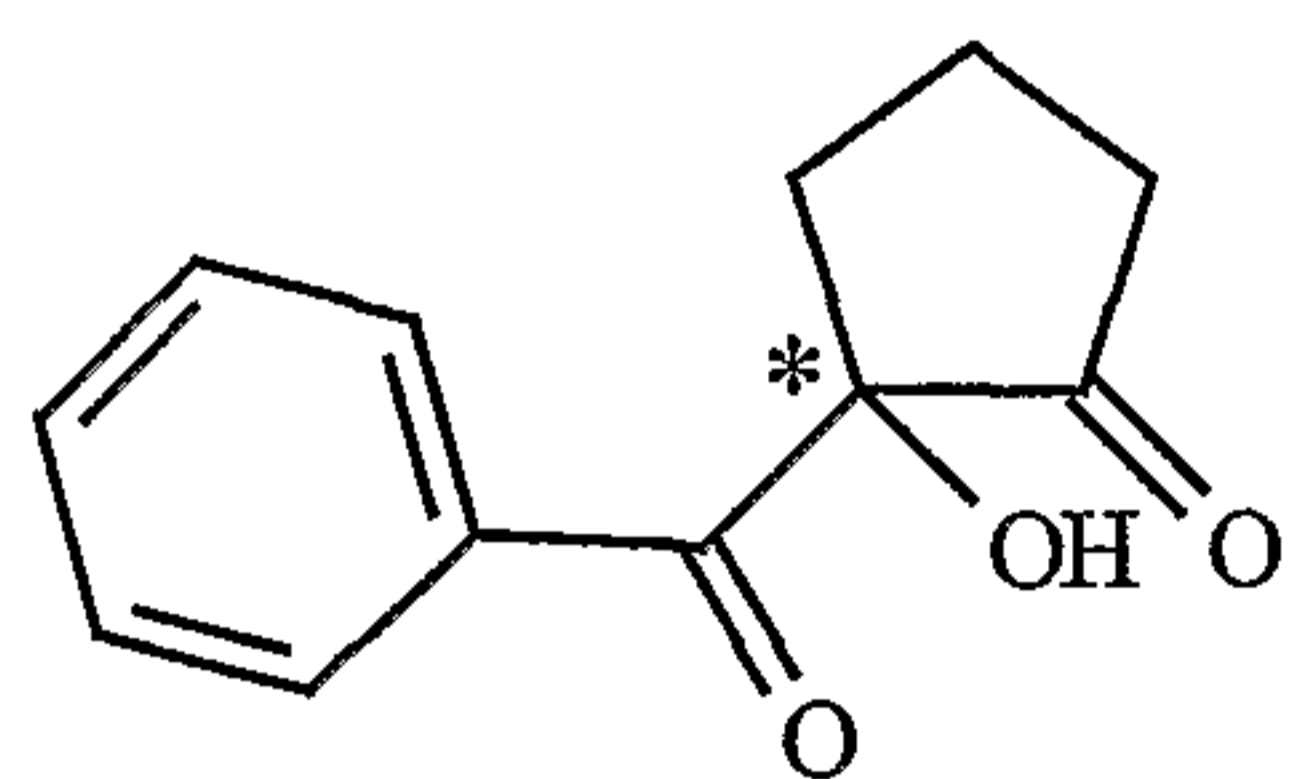
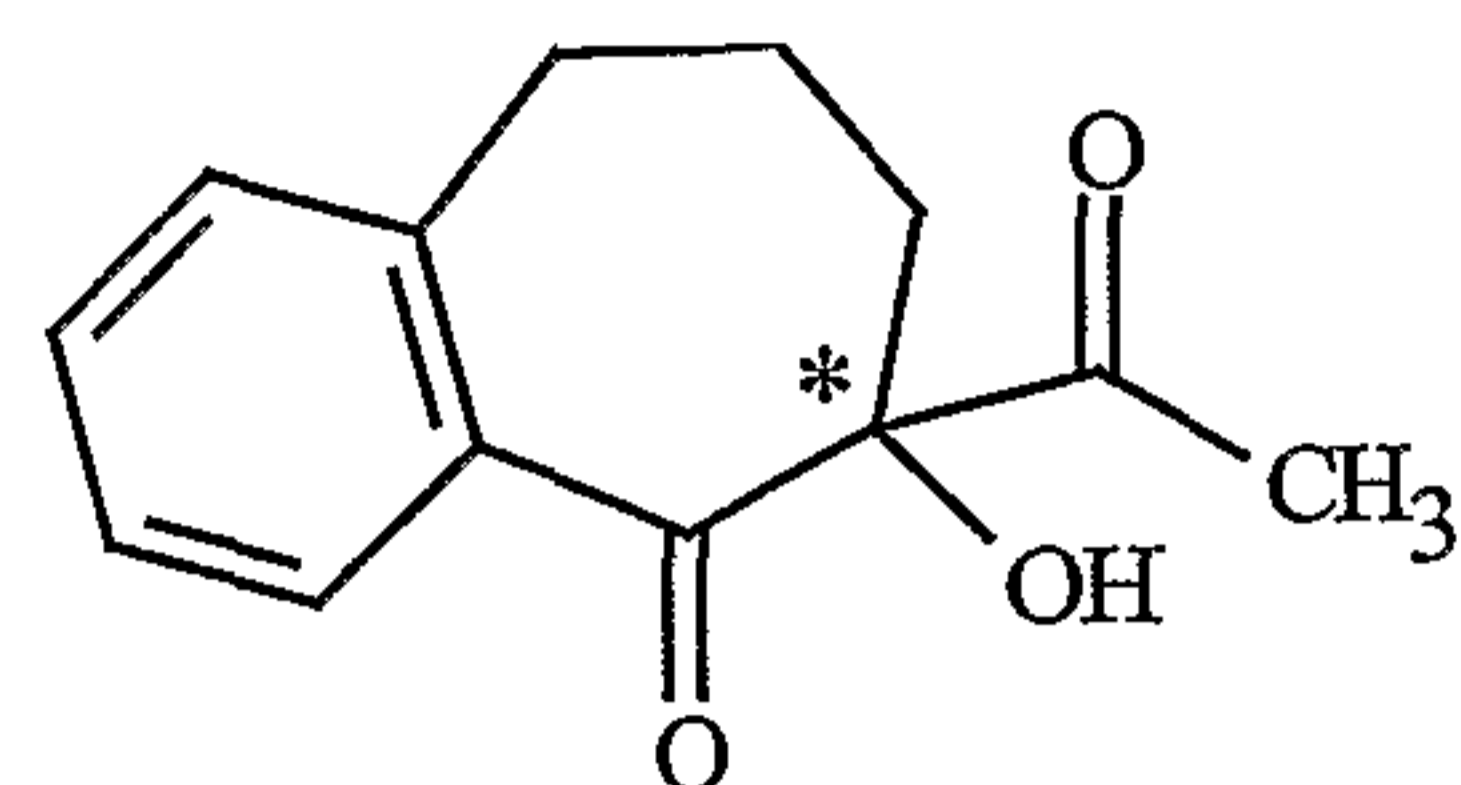
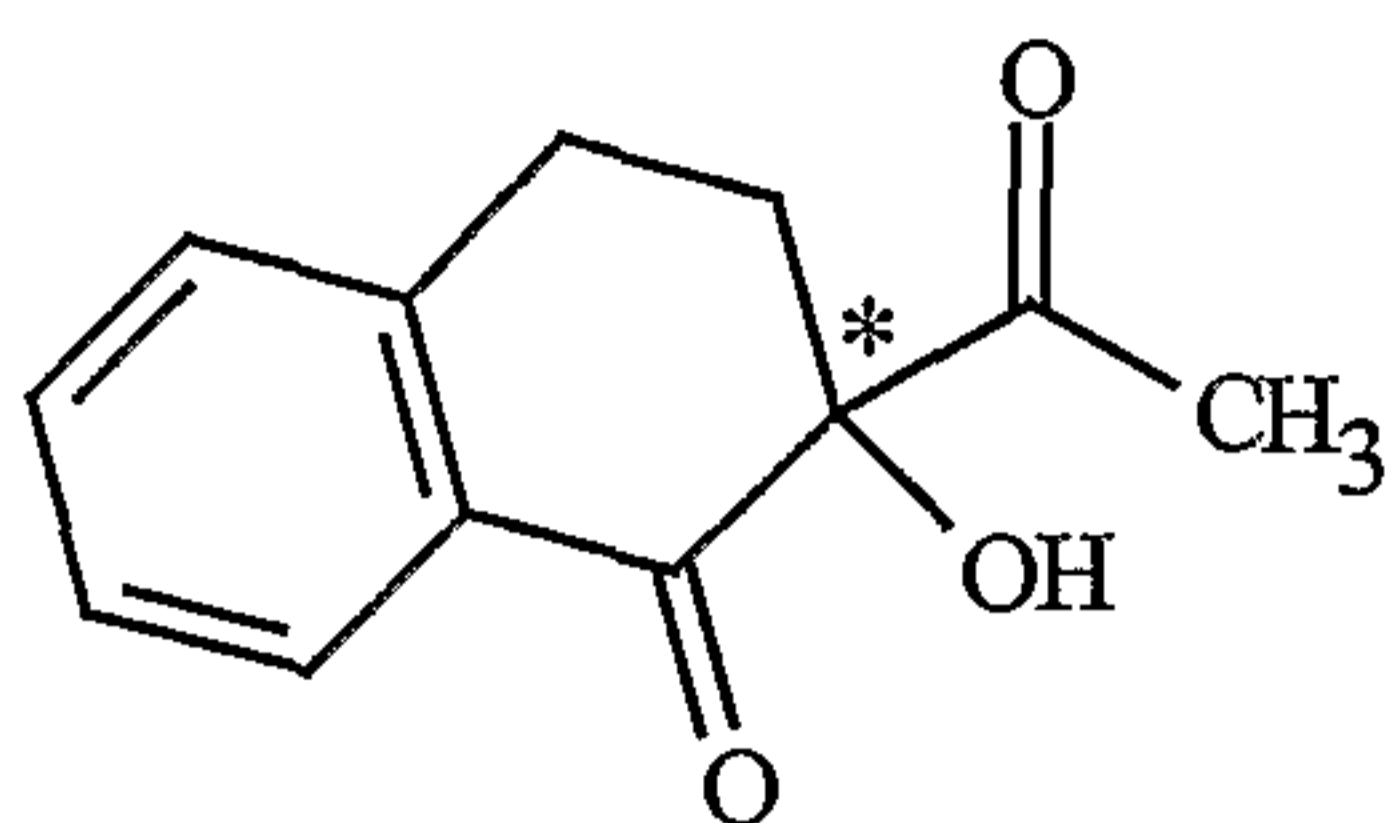
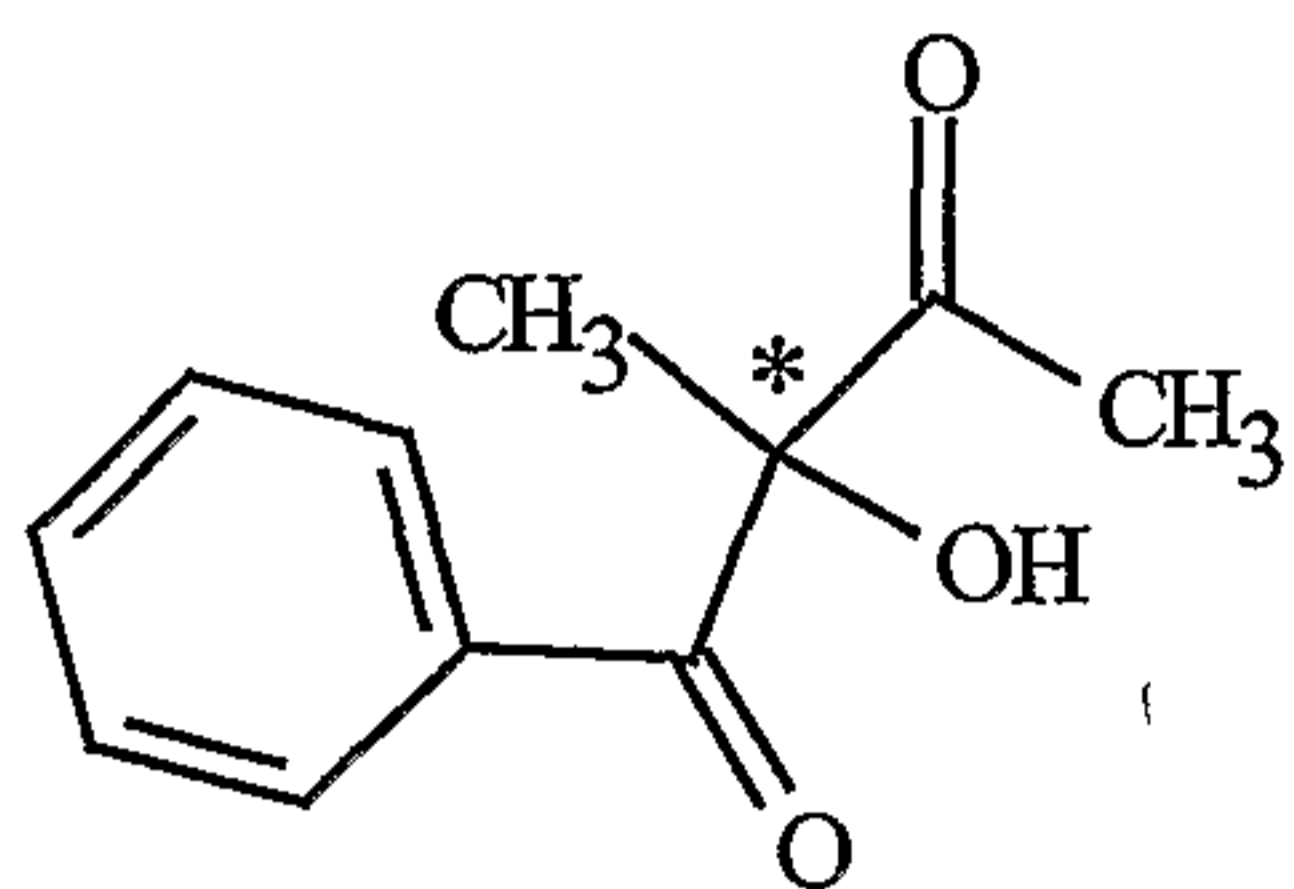
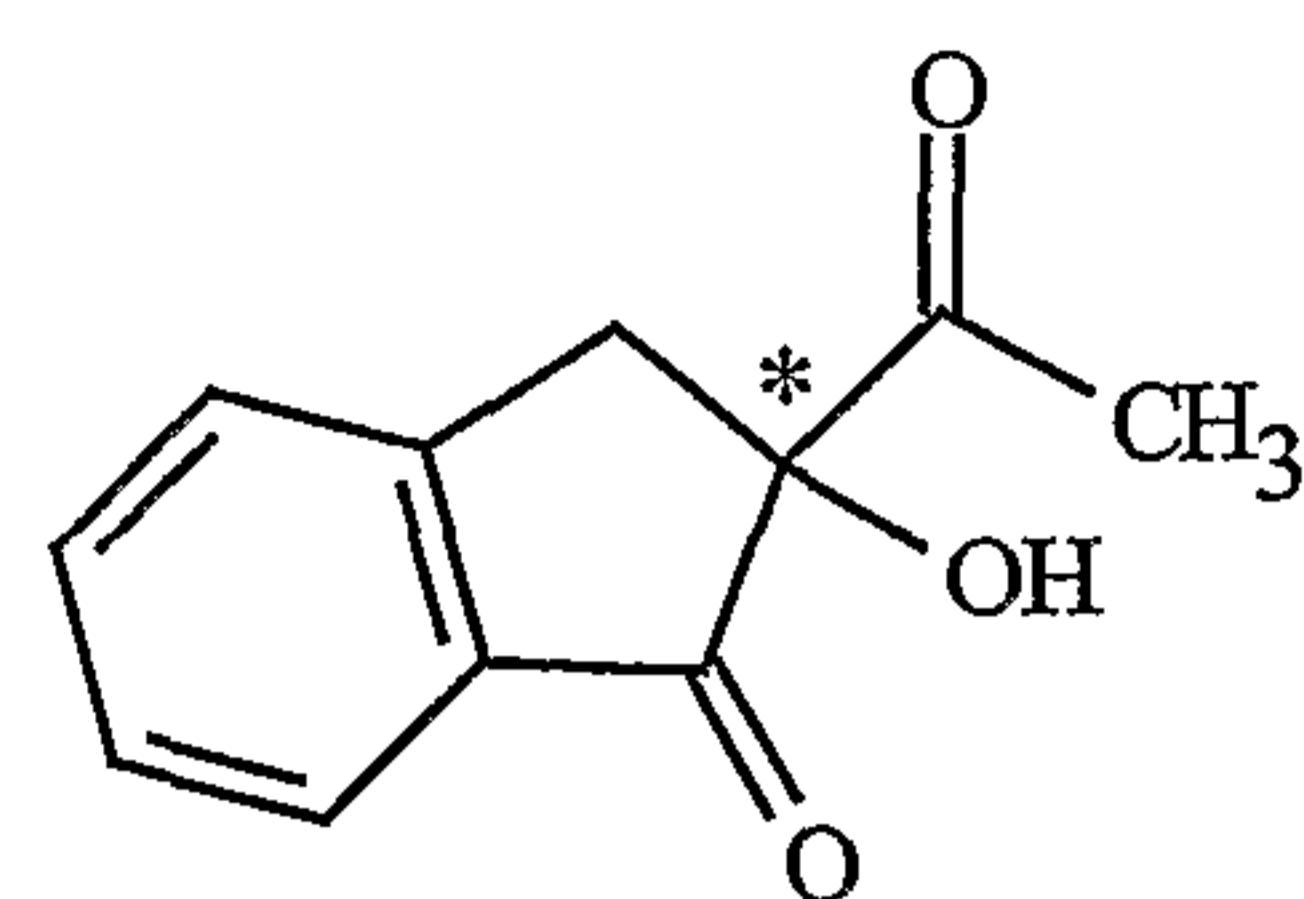
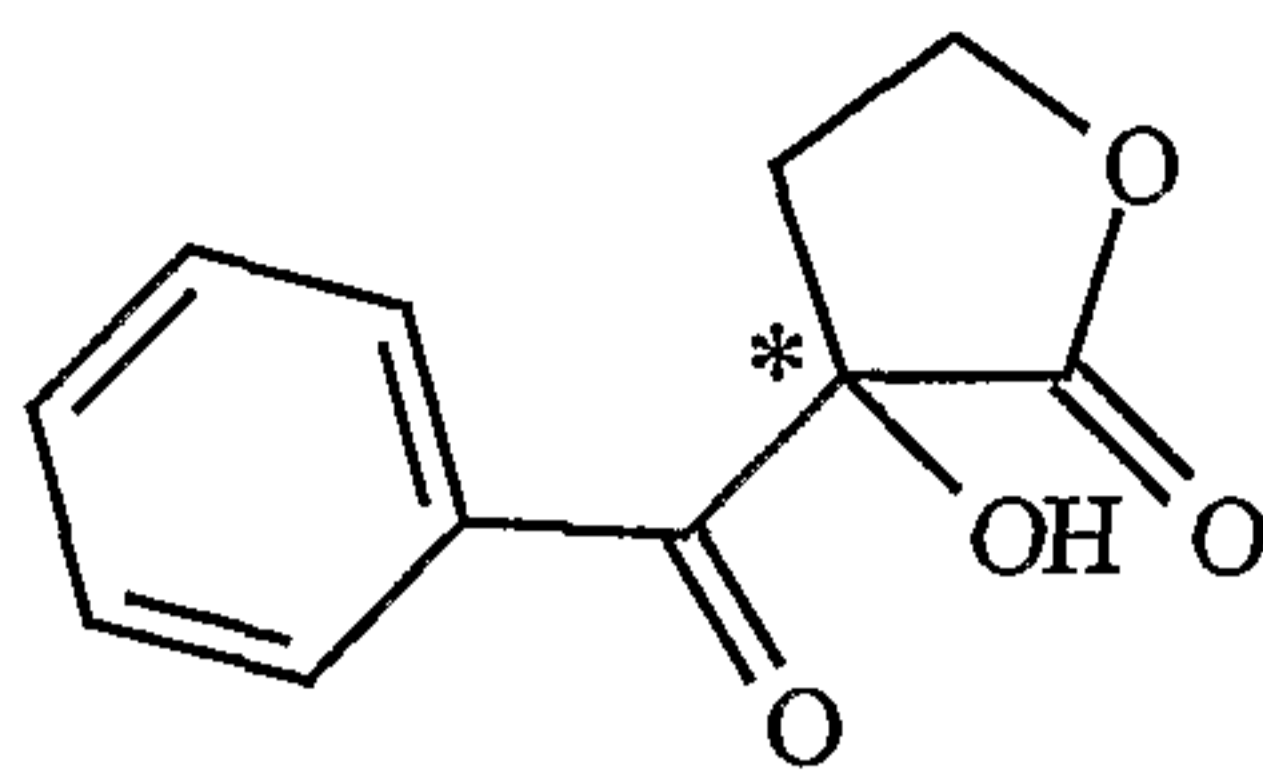
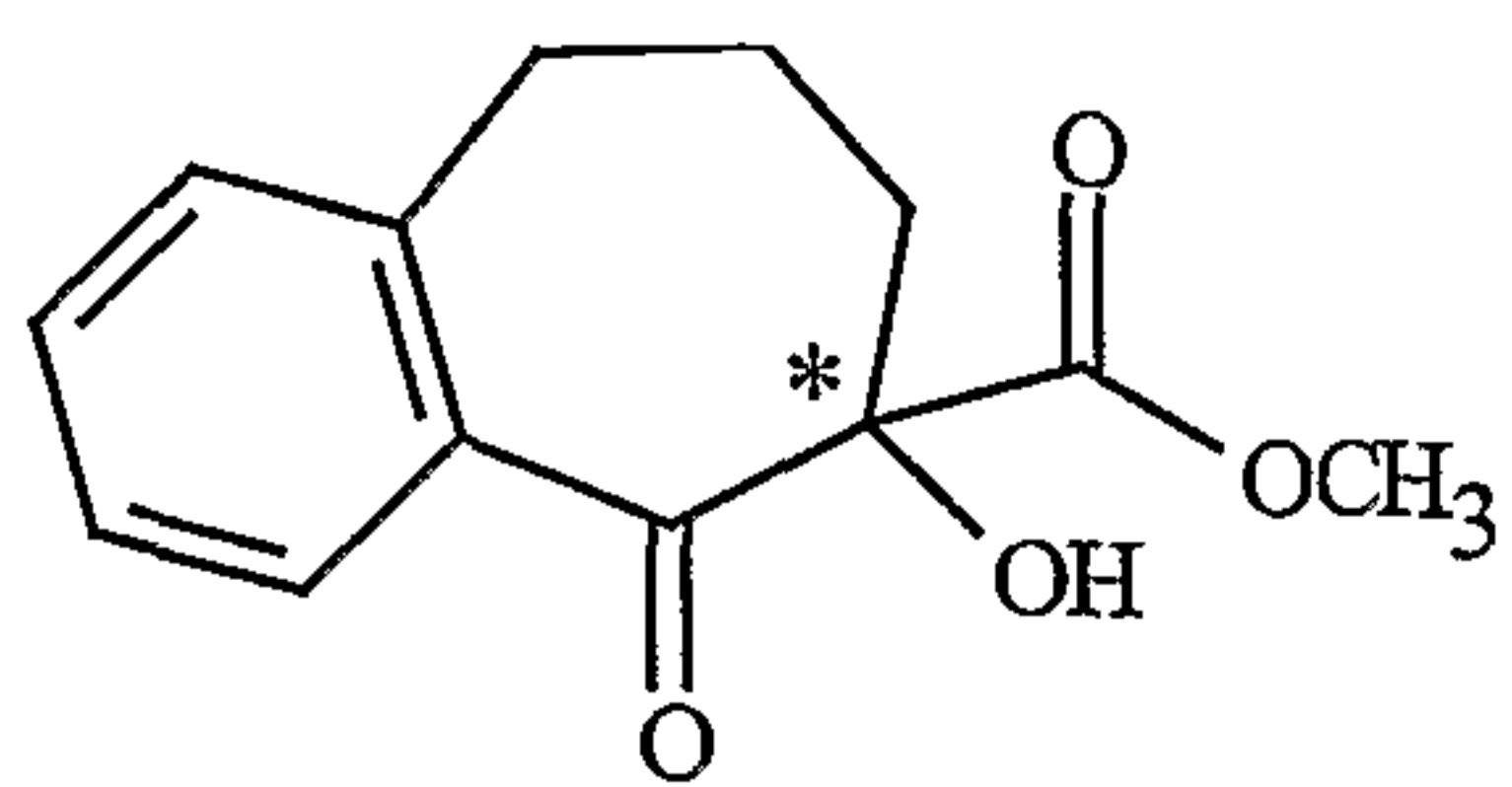


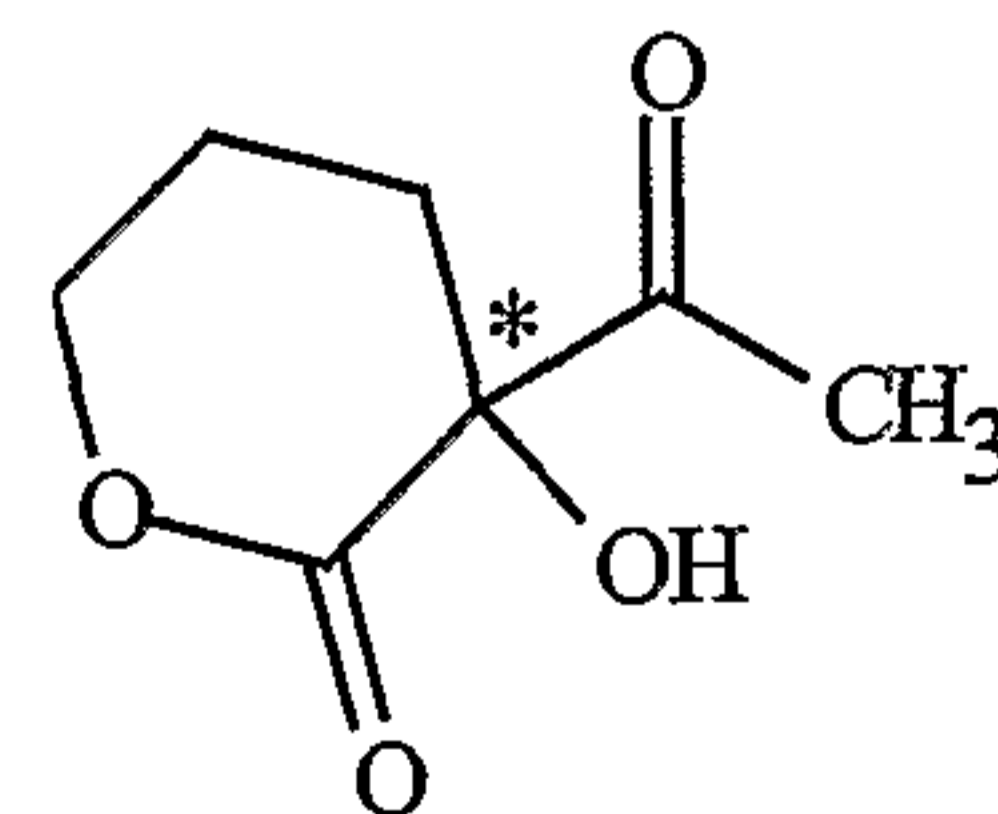
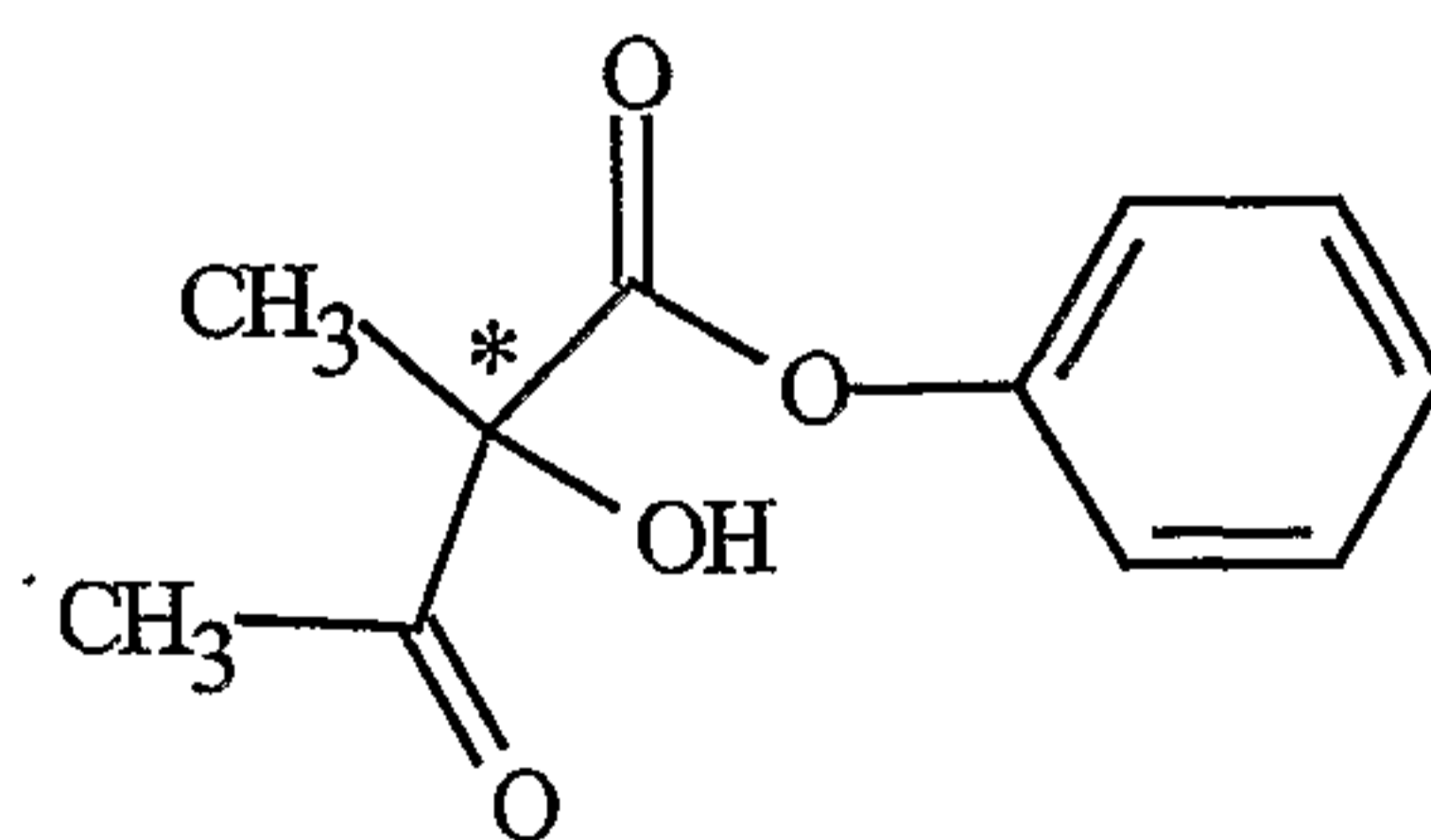
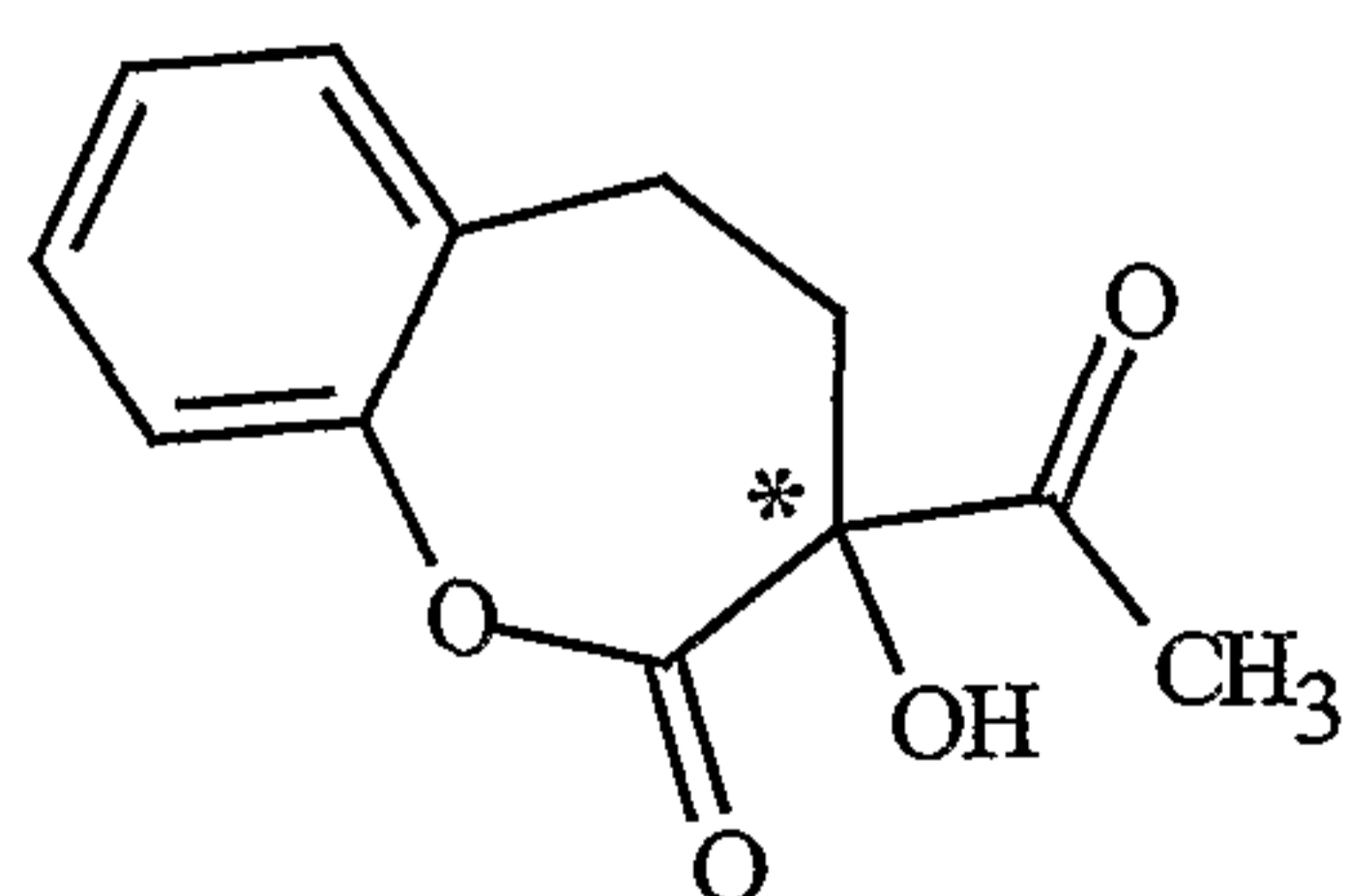
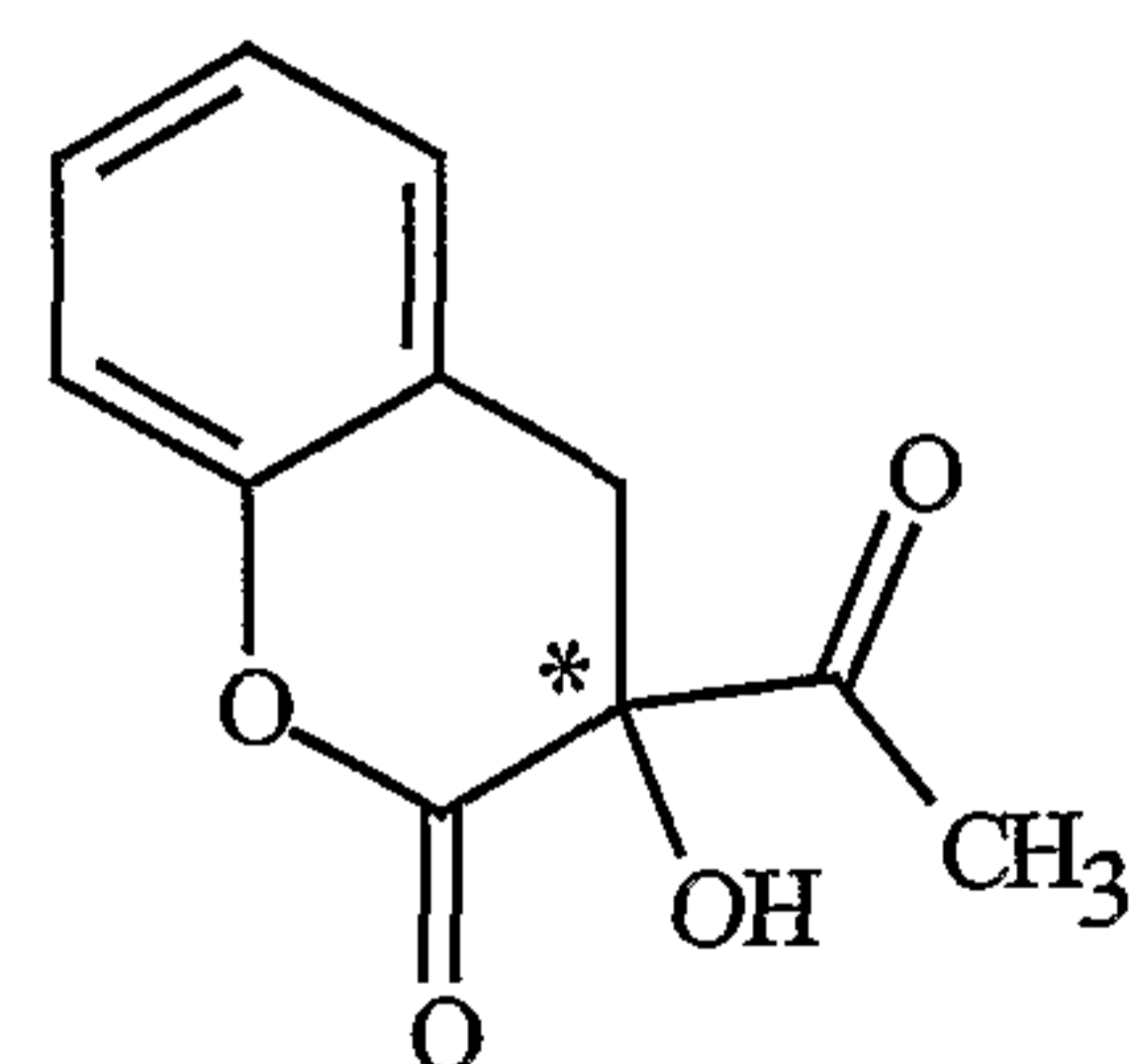
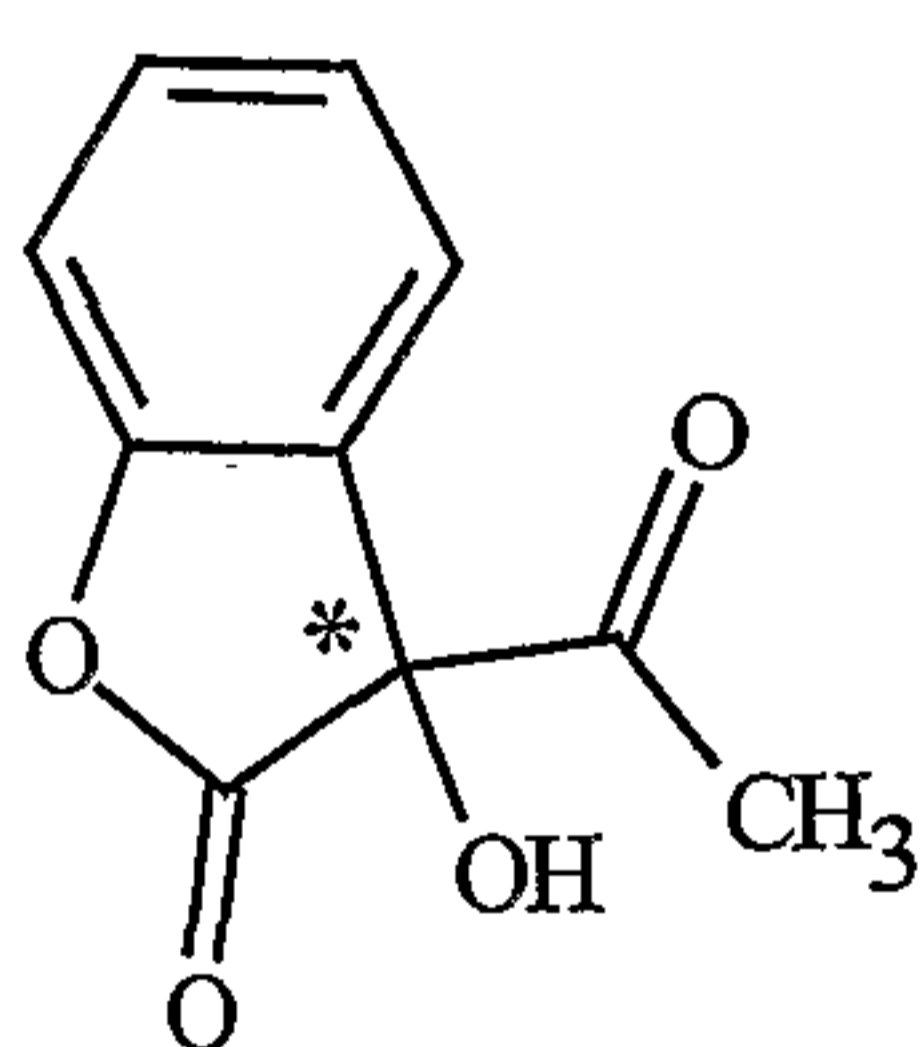
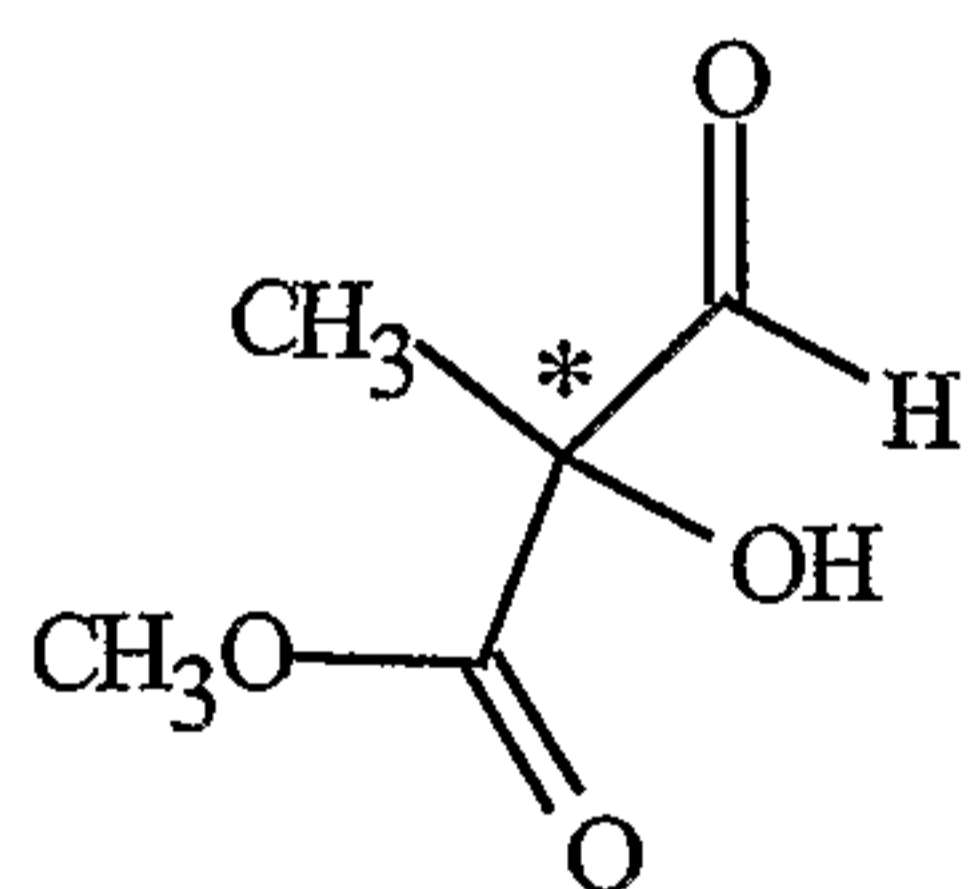
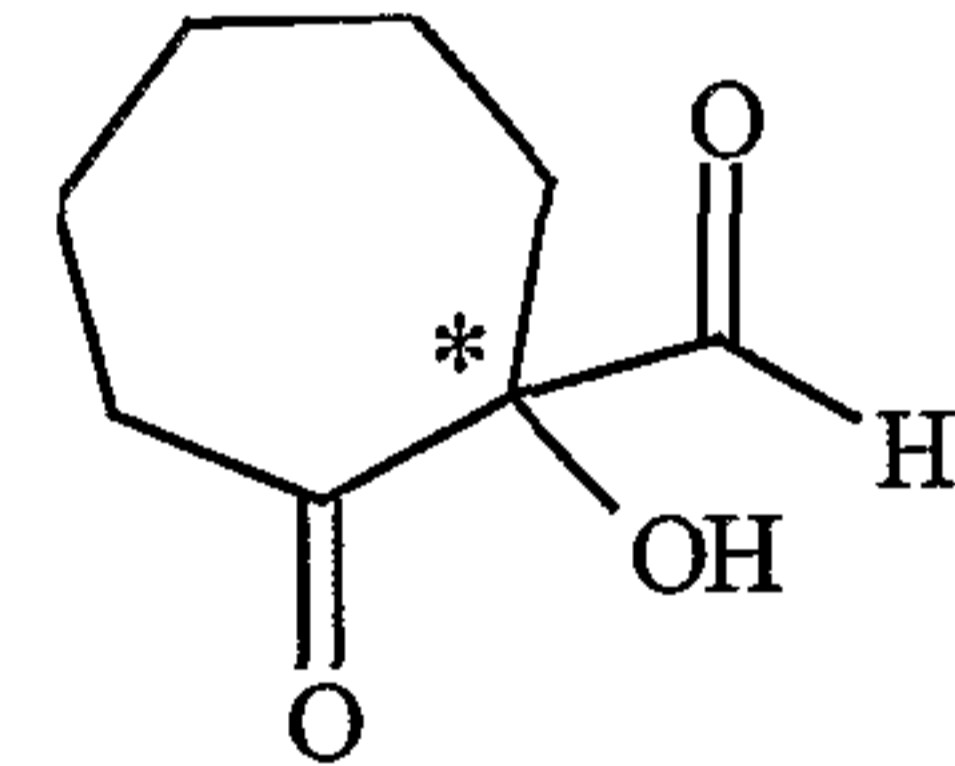
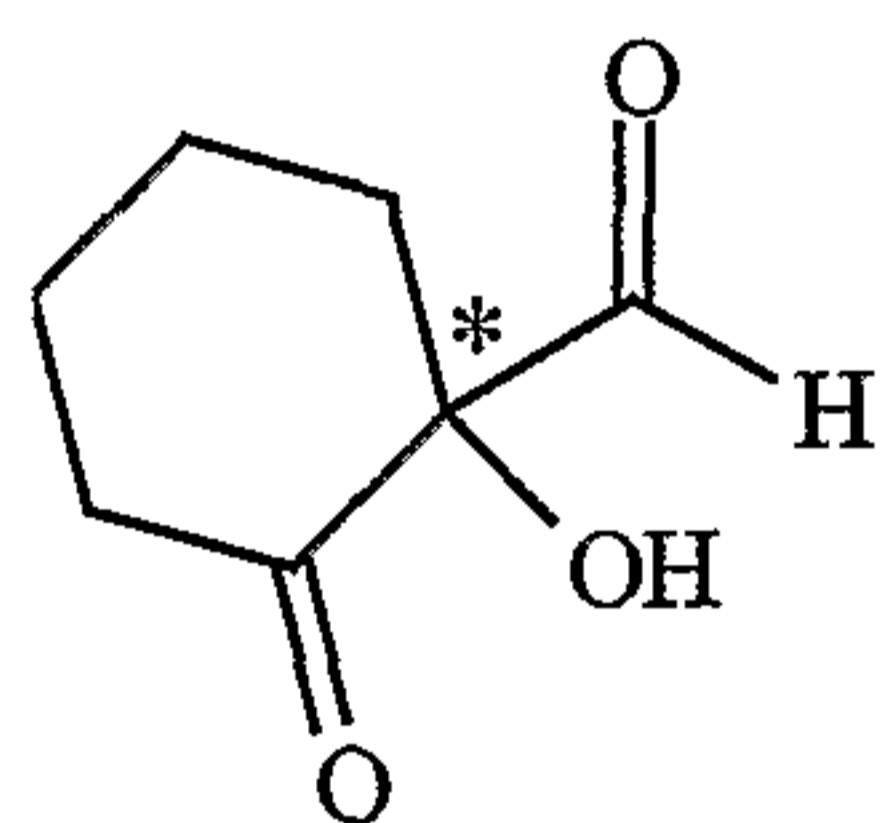
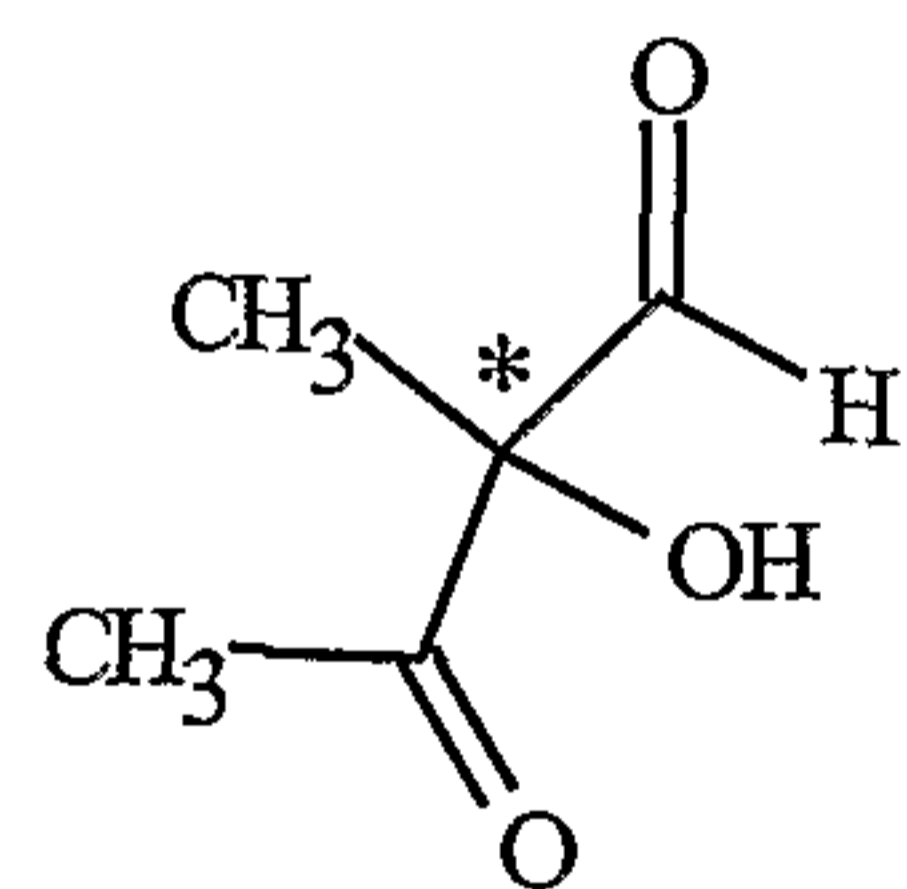
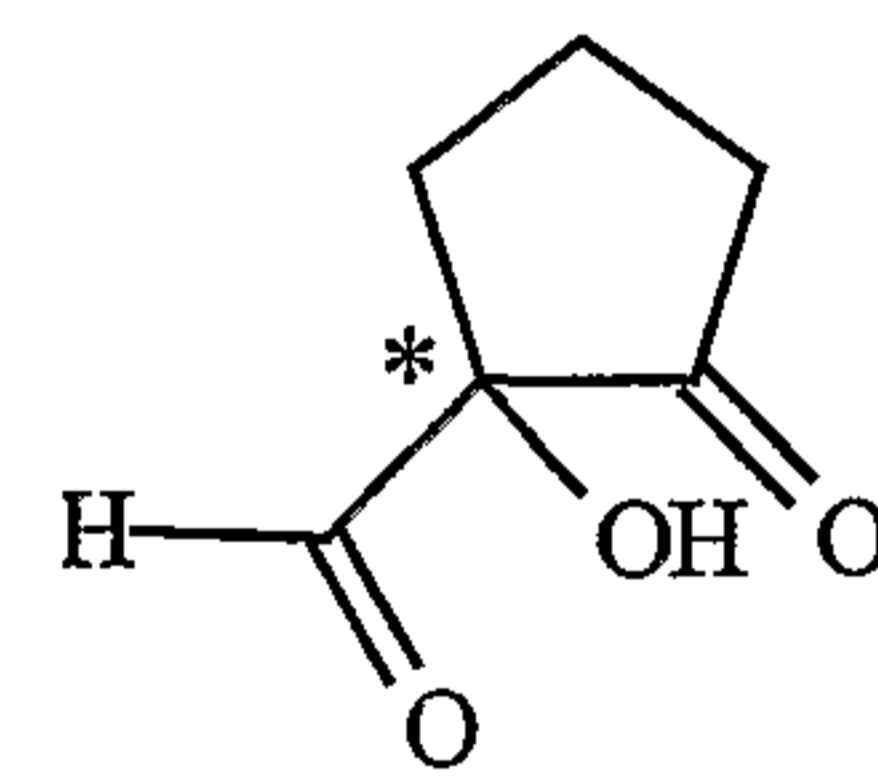
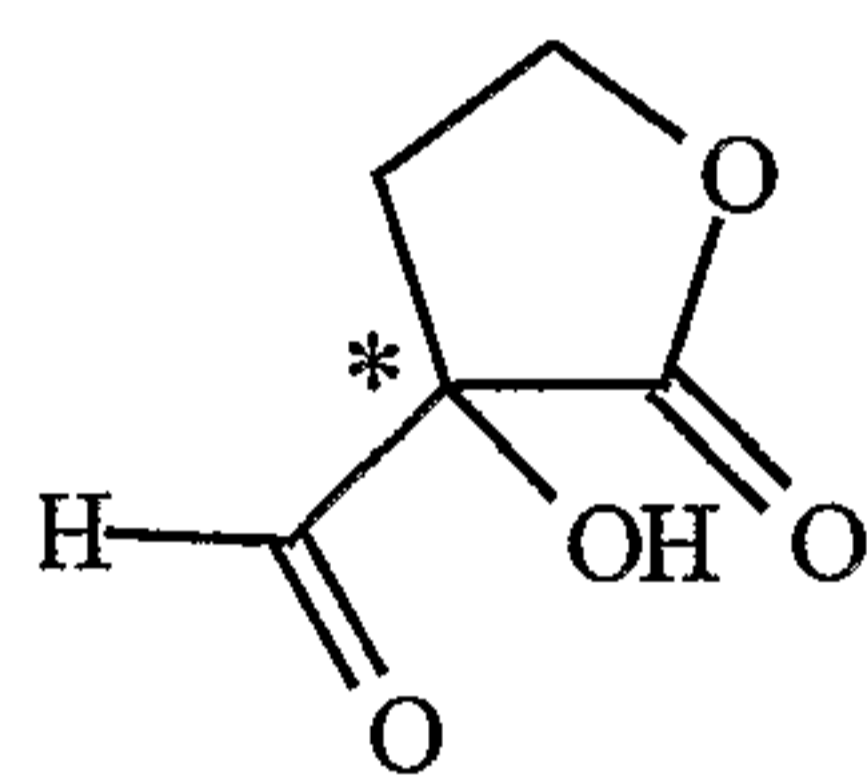
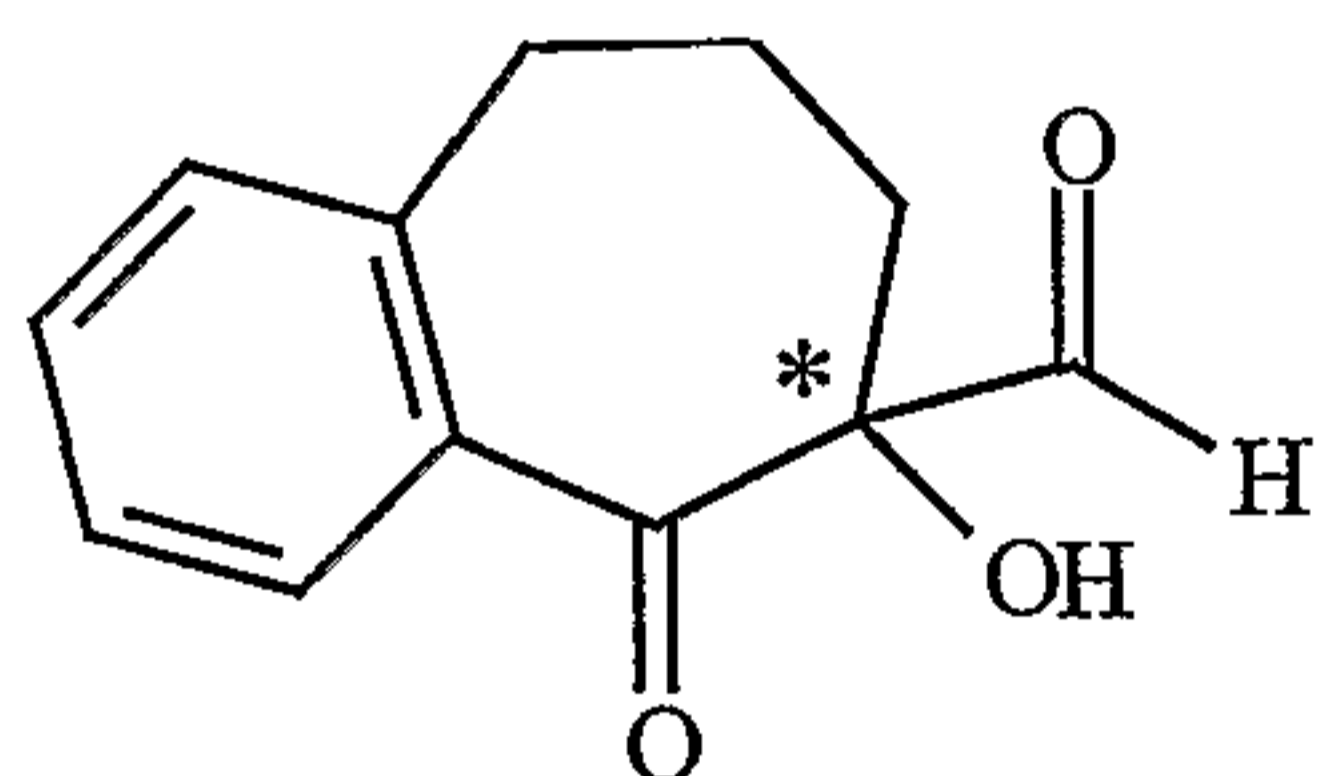
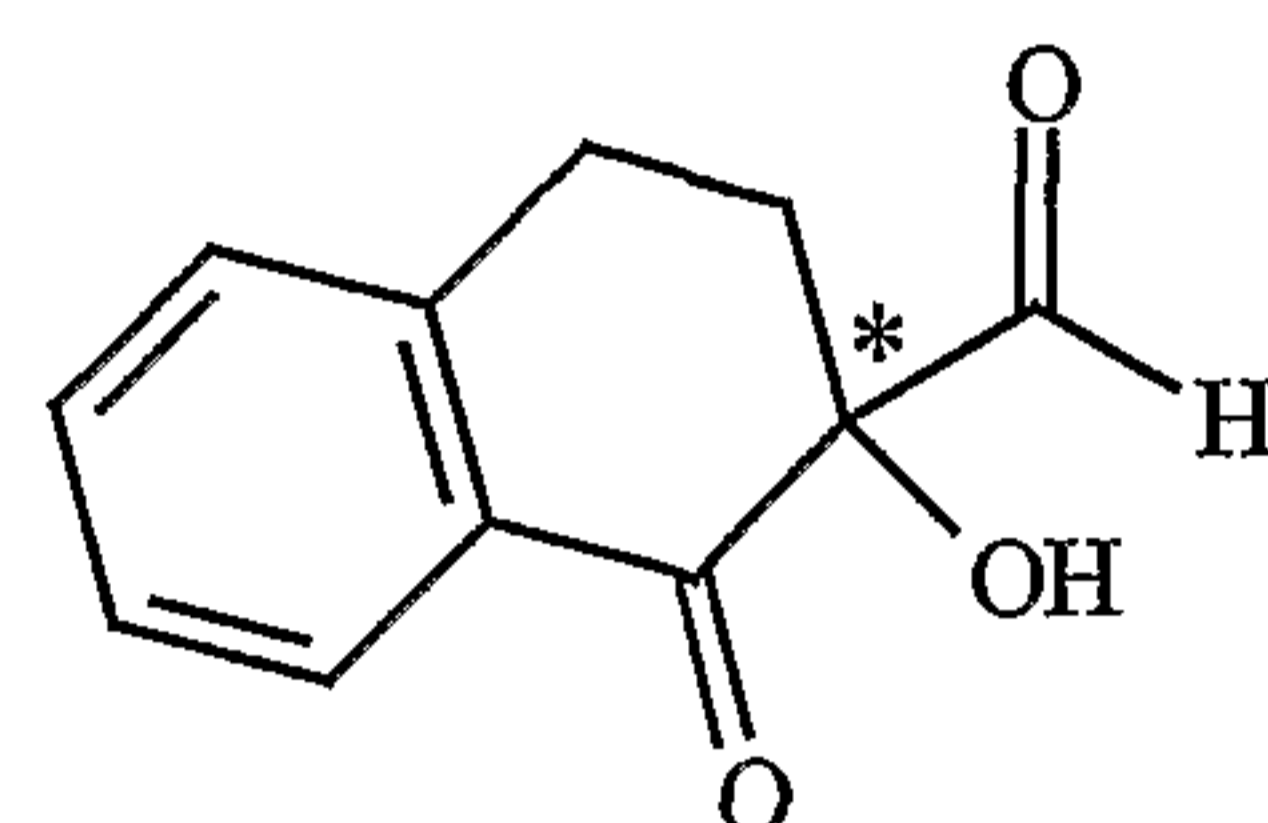
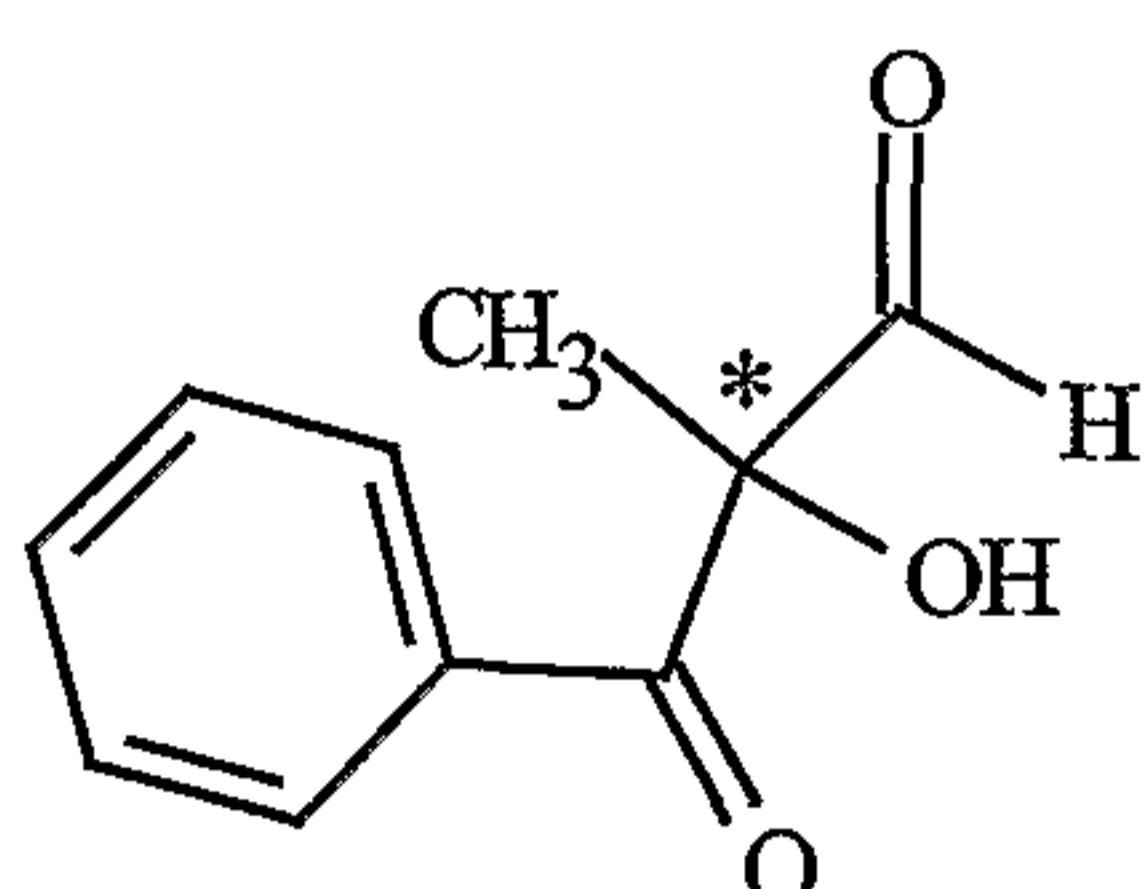
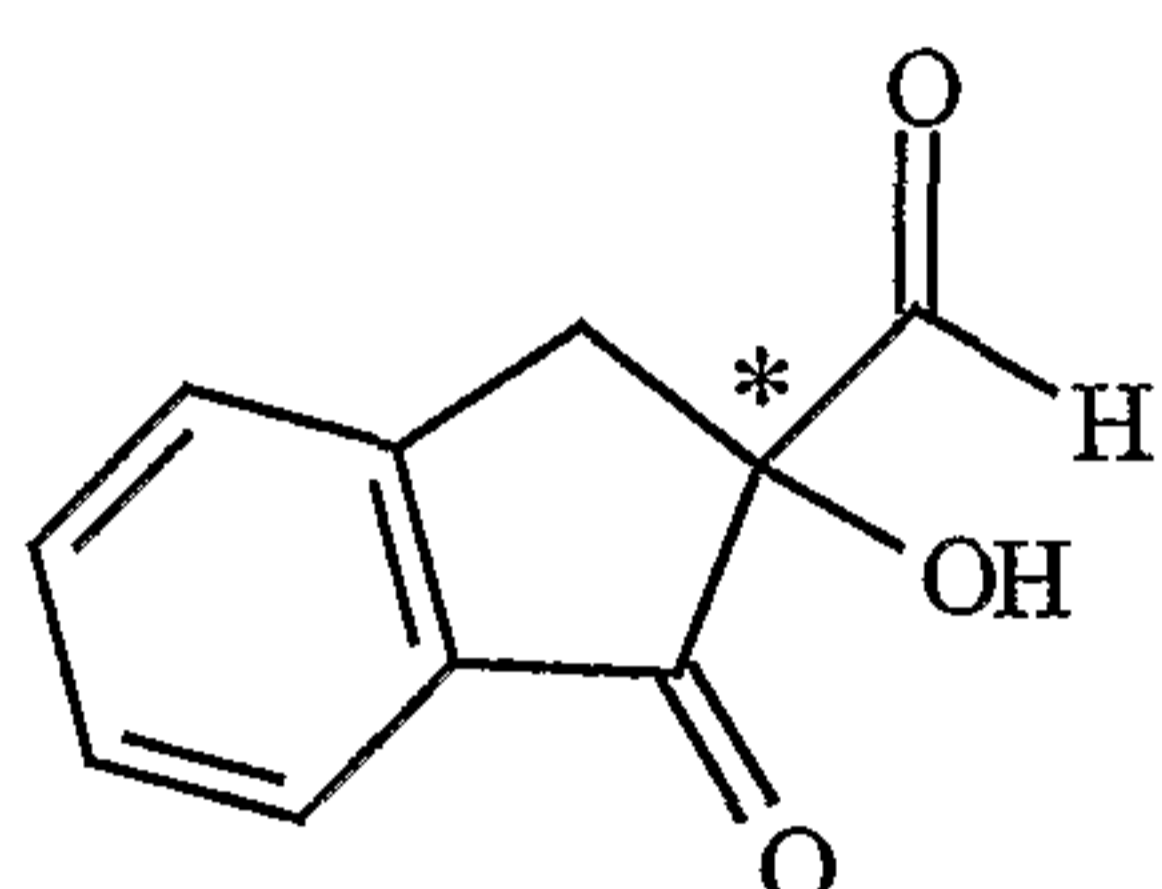
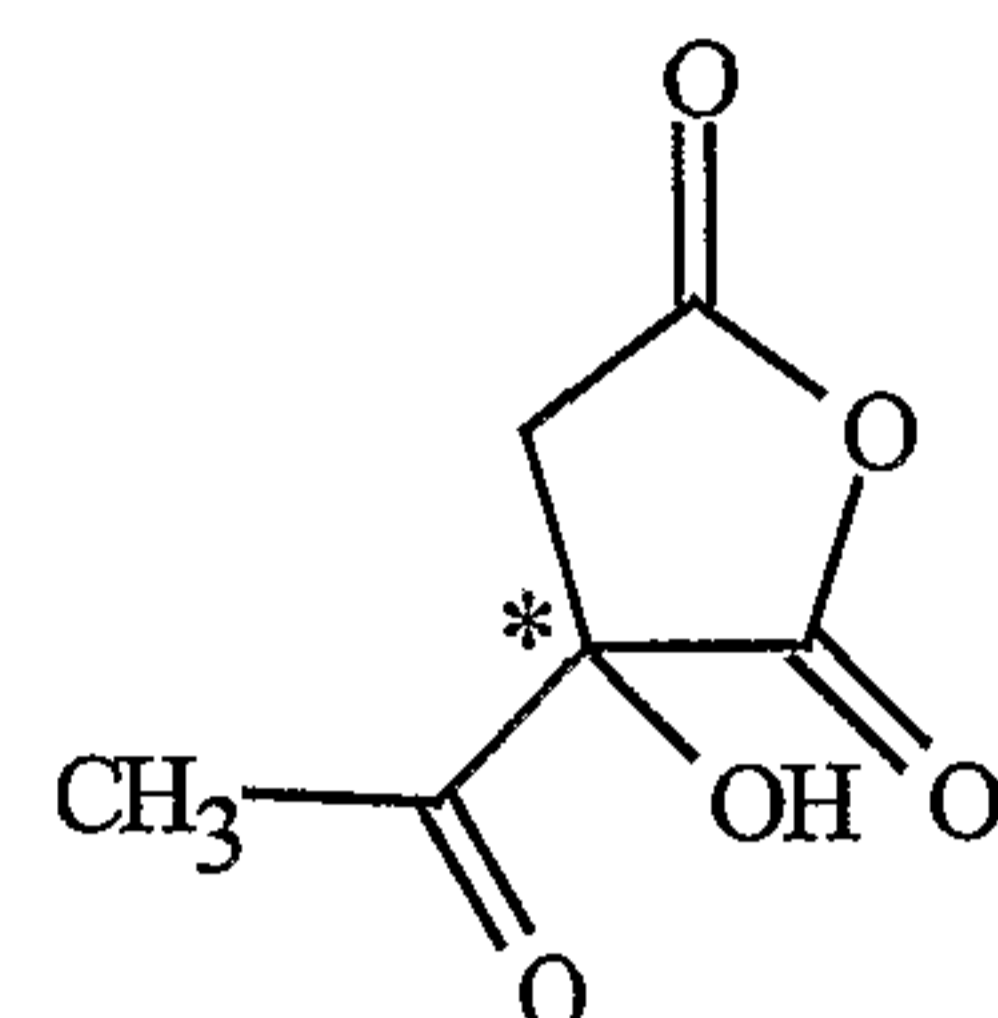
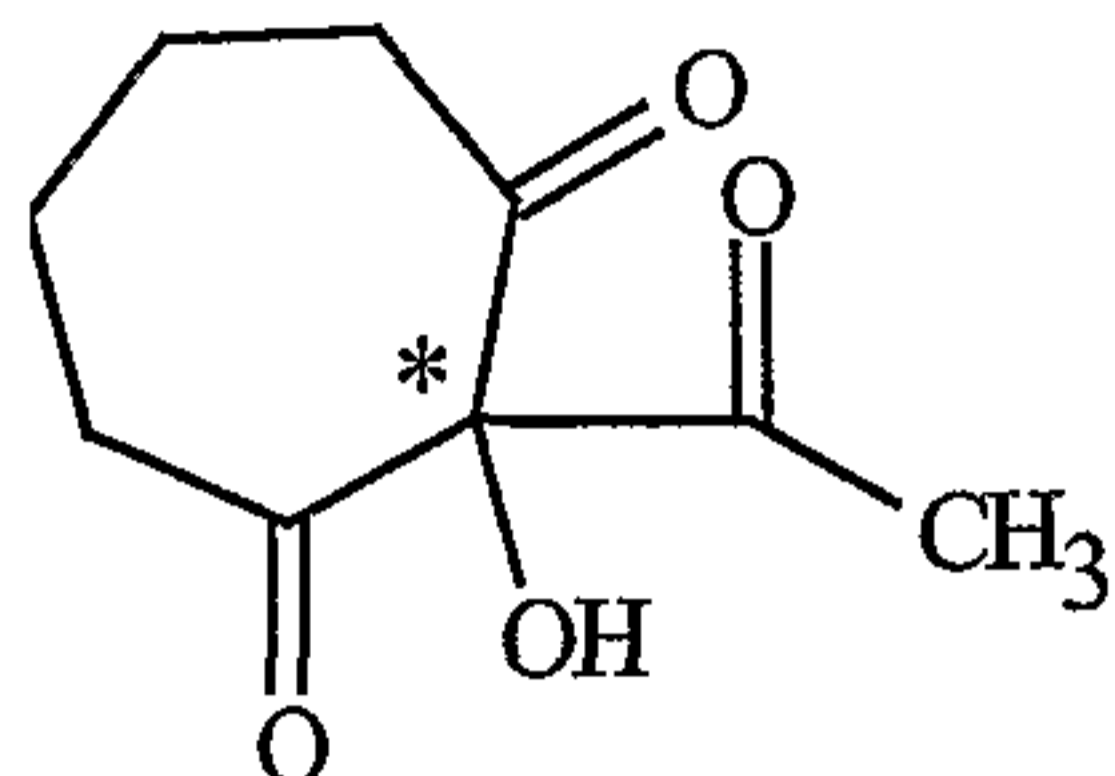
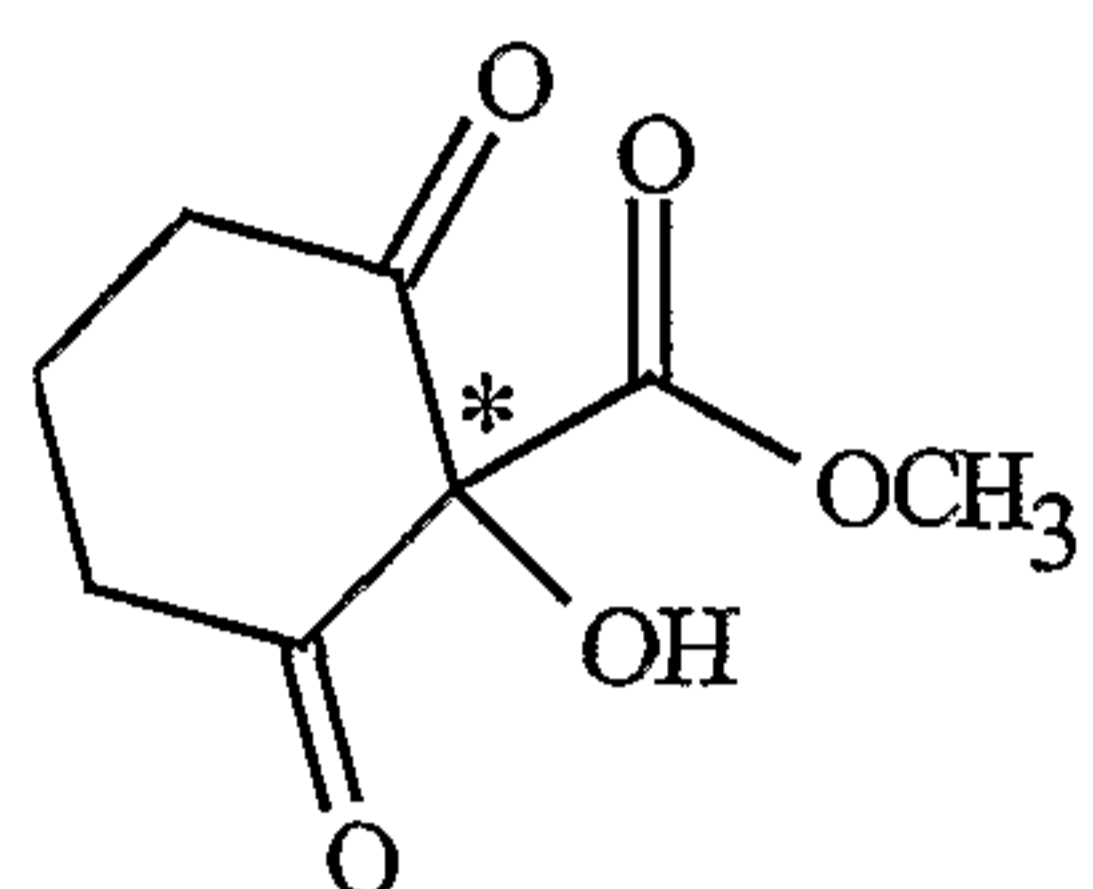
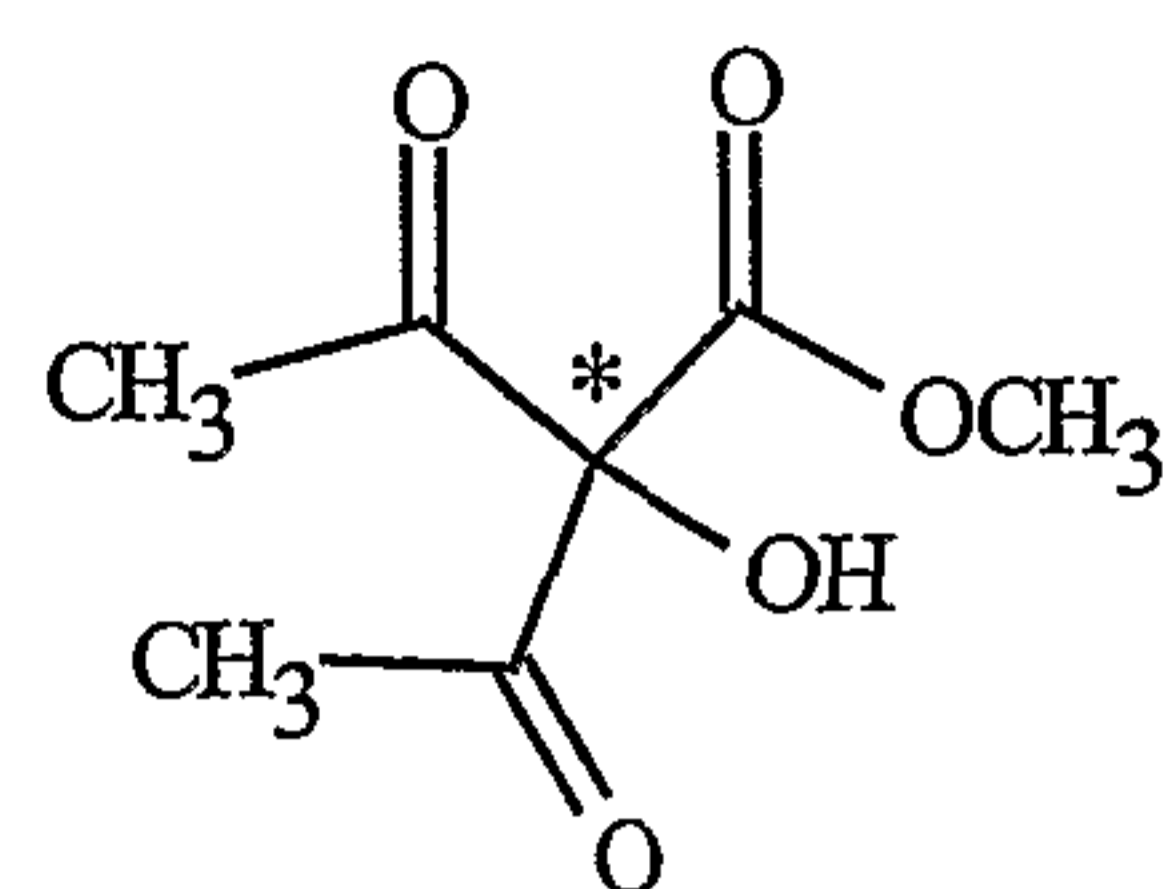
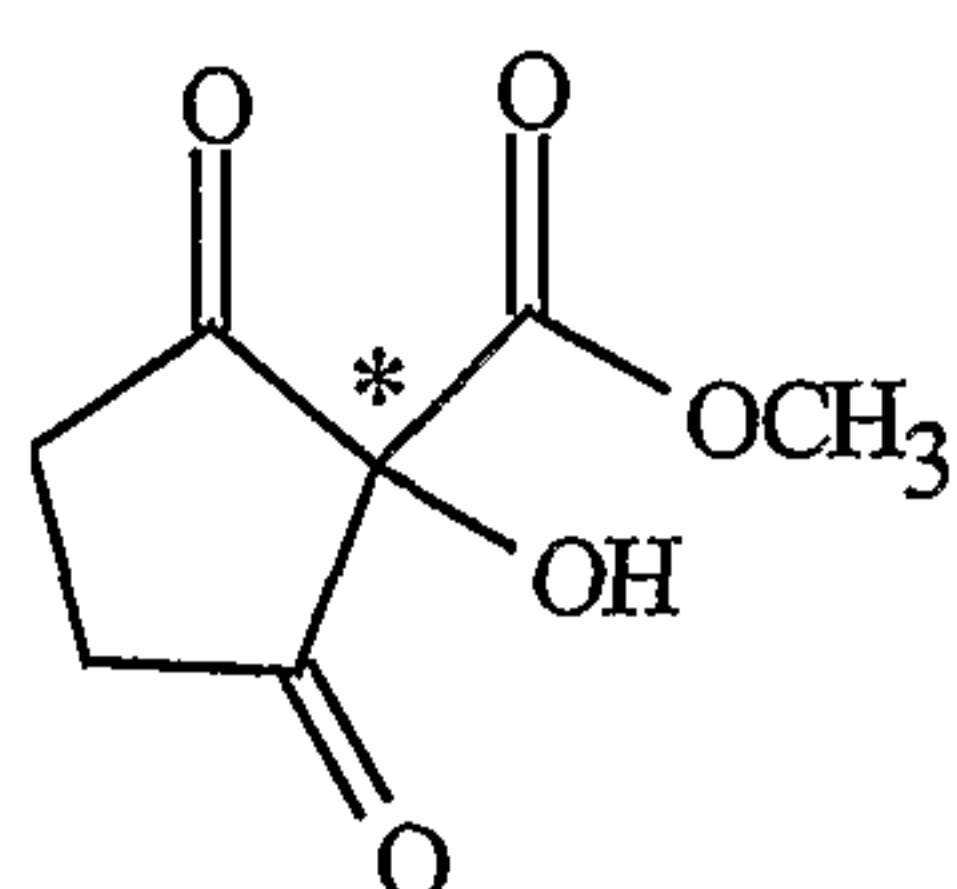
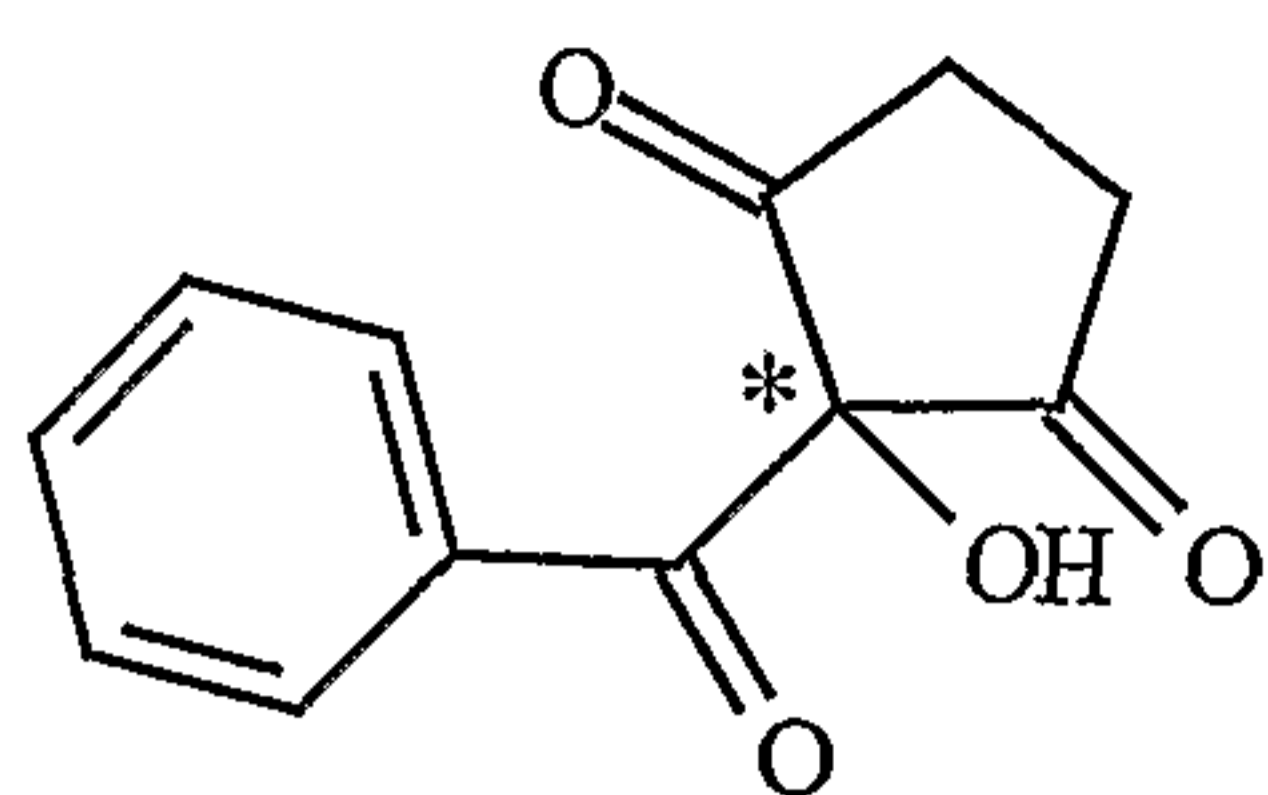
L	(R ^{6a}) _n a	(R ^{6b}) _n b	L	(R ^{6a}) _n a	(R ^{6b}) _n b
L-1	3,5-di- <i>t</i> -Bu	3- <i>t</i> -Bu	L-1	3,5-di-TMS	3- <i>t</i> -Bu
L-2	3,5-di- <i>t</i> -Bu	3- <i>t</i> -Bu	L-2	3,5-di-TMS	3- <i>t</i> -Bu
L-5	3- <i>t</i> -Bu	3,5-di- <i>t</i> -Bu	L-5	3,5-di-TMS	3- <i>t</i> -Bu
L-6	3- <i>t</i> -Bu	3,5-di- <i>t</i> -Bu	L-6	3,5-di-TMS	3- <i>t</i> -Bu

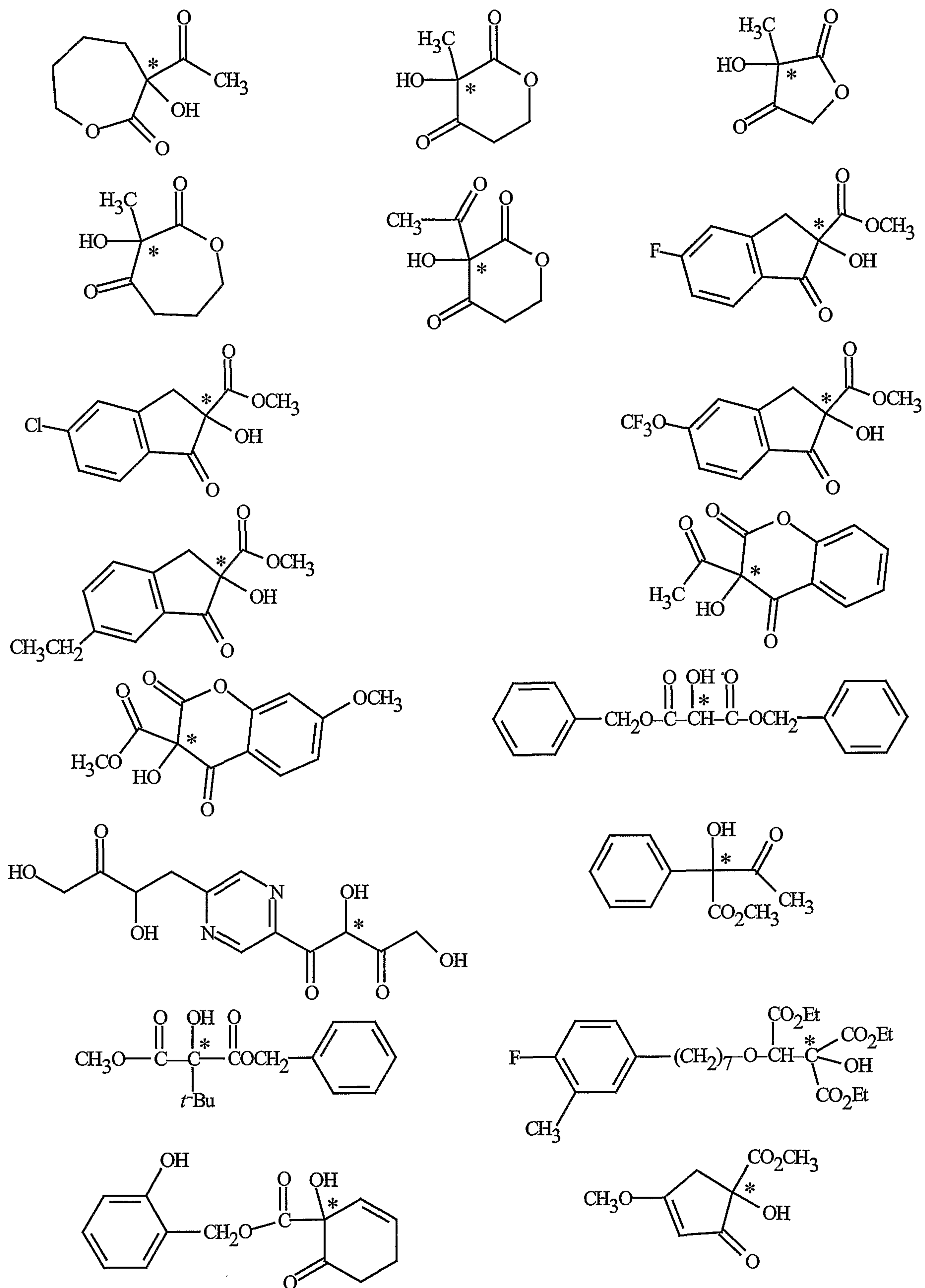
TABLE 4

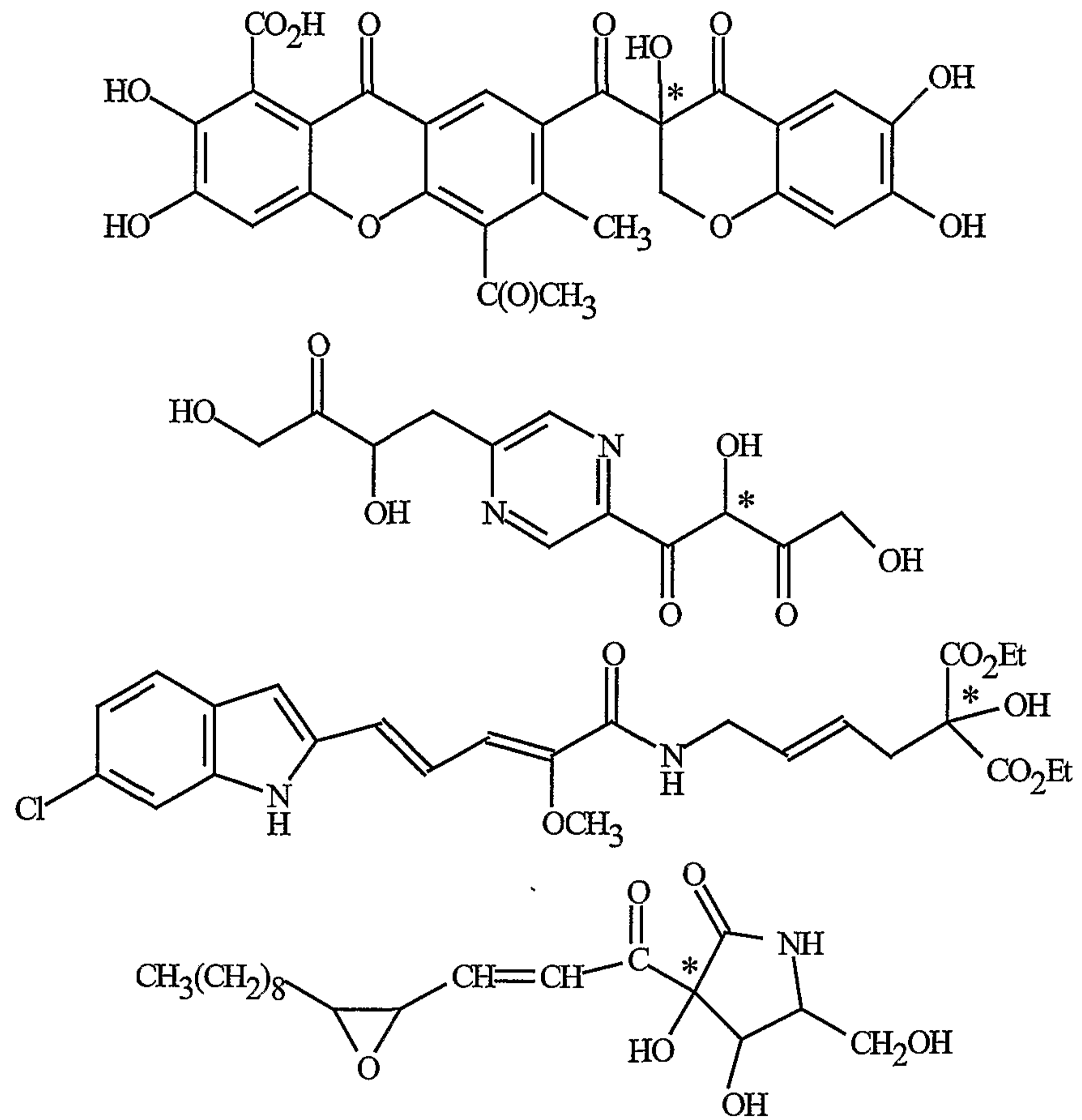
Illustrative examples of hydroxylated compounds of Formula I preparable from the corresponding β -dicarbonyl compounds of Formula II according to the process of the invention. (* indicates a hydroxylation center comprising the hydroxy group introduced by the process of the invention. When a molecule does not have a mirror plane of symmetry through the hydroxylation center, the hydroxylation center is a chiral center.)





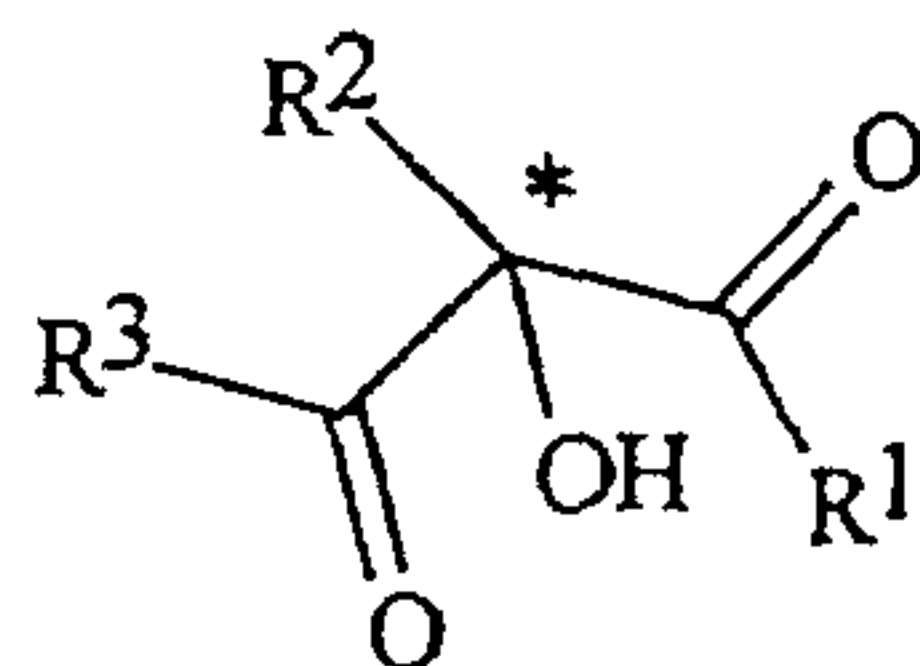






CLAIMS

1. A process for preparing a compound of Formula I that is achiral, racemic or enantiomerically enriched at the hydroxylation center indicated by *

**I**

5 wherein

R^1 is H; or alkoxy, alkyl, cycloalkyl, cycloalkoxy, a phenyl ring, a phenoxy ring or a 5- or 6-membered heteroaromatic ring, each optionally substituted;

R^2 is H; or alkyl, cycloalkyl, a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each optionally substituted;

10 R^3 is H; or alkoxy, alkyl, cycloalkyl, cycloalkoxy, a phenyl ring, a phenoxy ring or a 5- or 6-membered heteroaromatic ring, each optionally substituted; or

R^2 and R^3 can be taken together to form an optionally substituted linking chain of 3 to 6 members including at least one carbon member, optionally including no more than two carbon members as C(=O), optionally including one member selected from nitrogen and oxygen, and optionally fused to a phenyl ring or a 5- or 6-

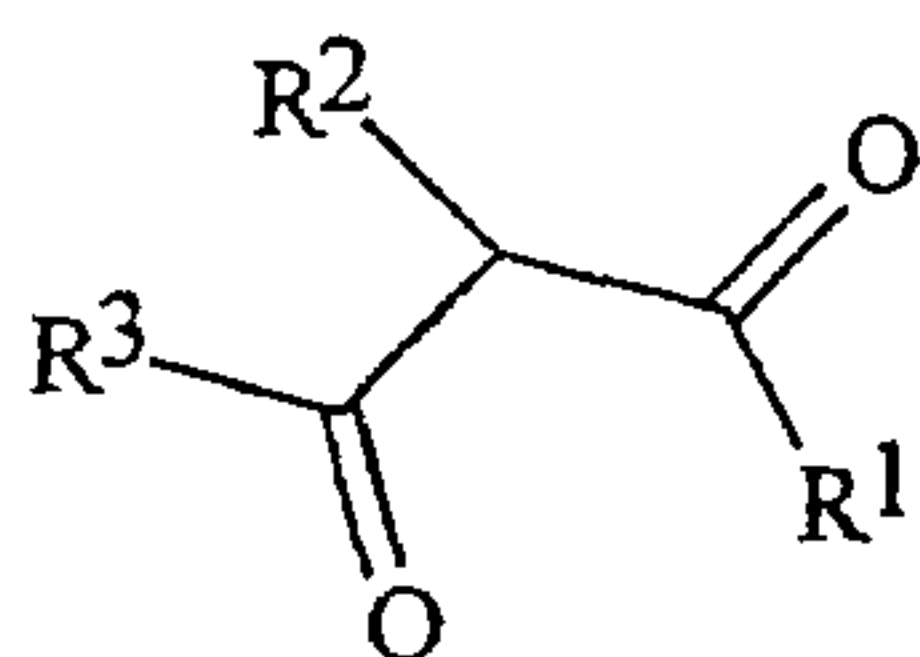
15 membered heteroaromatic ring, each ring optionally substituted; or

R^1 and R^3 can be taken together to form an optionally substituted linking chain of 2 to 5 members including at least one carbon member, optionally including no more than one carbon member as C(=O), and optionally fused to a phenyl ring or a 5- or 6-

20 membered heteroaromatic ring, each ring optionally substituted;

comprising:

contacting a compound of Formula II

**II**

25 wherein

R^1 , R^2 and R^3 are as defined above, with a zirconium complex and an oxidant.

2. The process of Claim 1 wherein, in Formulae I and II,

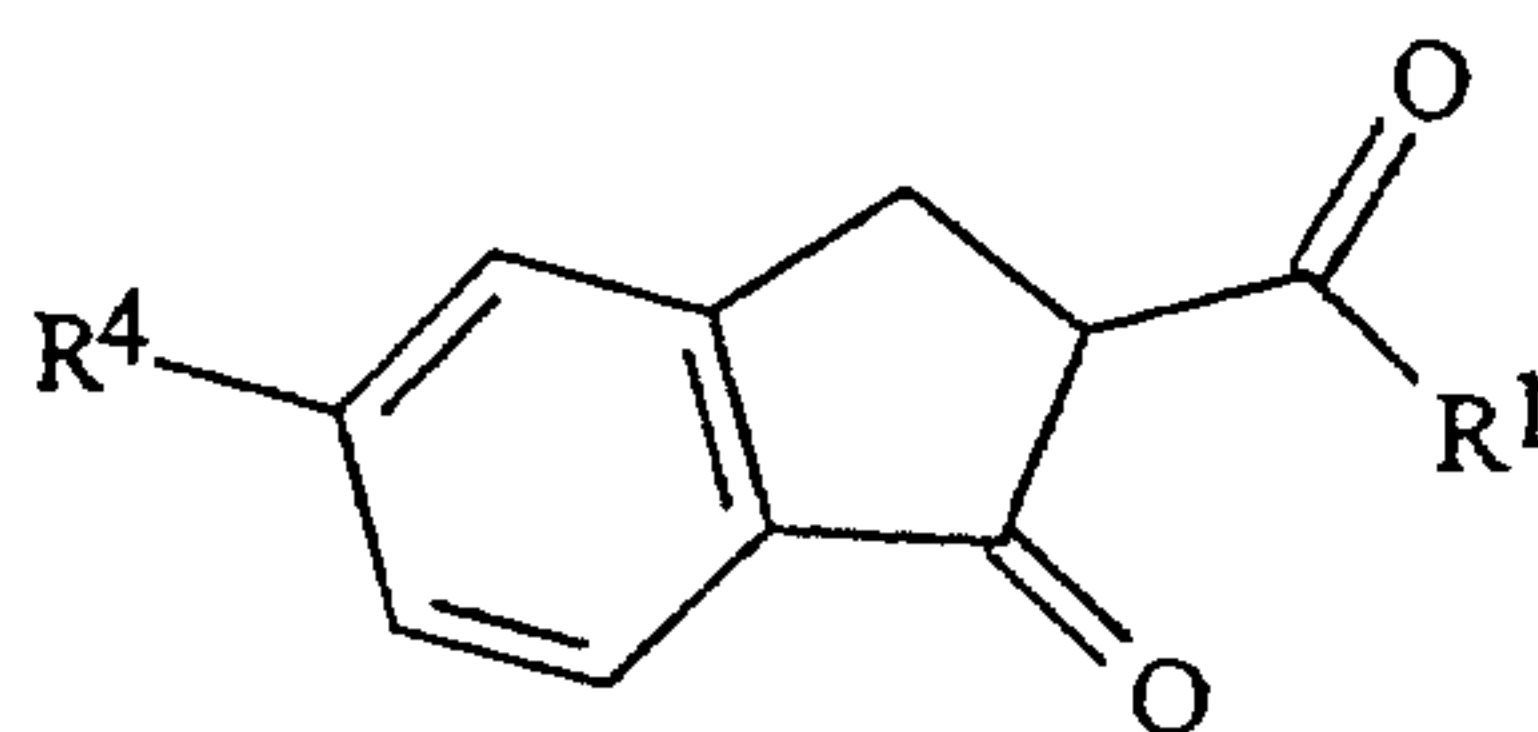
R^1 is alkoxy;

R² is alkyl;

R³ is optionally substituted phenyl, or

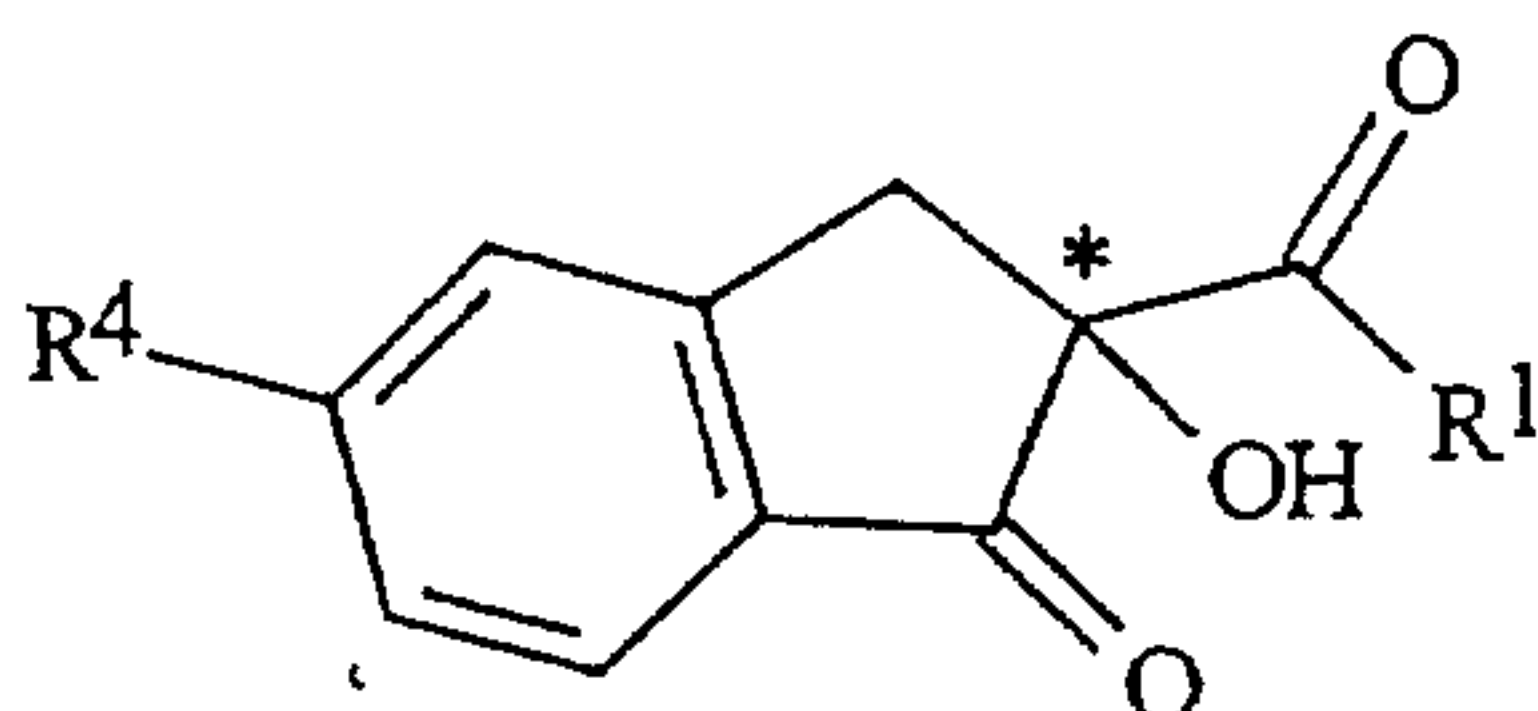
R² and R³ can be taken together to form an optionally substituted linking chain of 3 to 4 carbon members optionally fused to an optionally substituted phenyl ring.

- 5 3. The process of Claim 2 wherein the compound of Formula II is a compound of Formula IIa



IIa

wherein R¹ is C₁-C₃ alkoxy, and R⁴ is F, Cl, or C₁-C₃ fluoroalkoxy;
and the compound of Formula I is a compound of Formula Ia

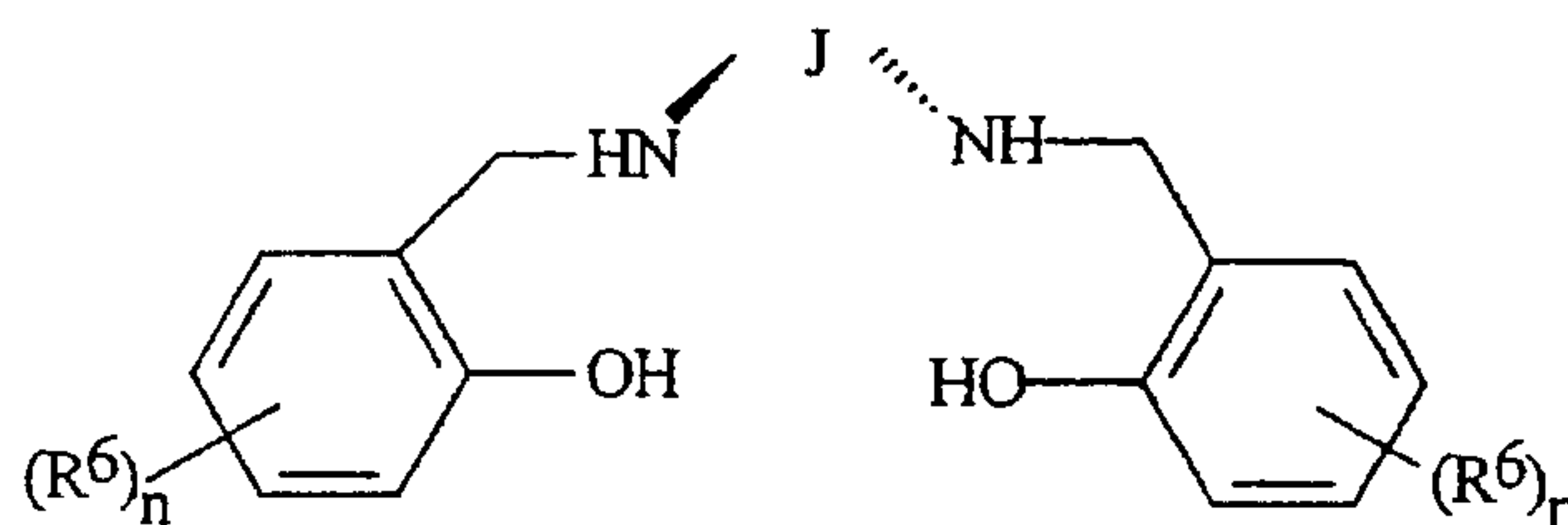


Ia

10

that is racemic or enantiomerically enriched at the hydroxylation center indicated by *.

4. The process of Claim 1 wherein the oxidant is selected from hydrogen peroxide or a mono ether of hydrogen peroxide.
5. The process of Claim 4 wherein the oxidant is *tert*-butyl hydroperoxide.
- 15 6. The process of Claim 1 wherein the zirconium complex is selected from zirconium(IV) C₁-C₄ alkoxide or zirconium(IV) acetylacetonate.
7. The process of Claim 6 wherein the zirconium complex is zirconium(IV) acetylacetonate.
8. The process of Claim 1 wherein the zirconium complex comprises zirconium and
20 a chiral ligand of Formula III



III

50

wherein

J is an optionally substituted linking chain of 2 to 4 members consisting of at least one carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as C(=O); the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a C₃-C₈ cycloalkyl ring, a C₃-C₈ nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

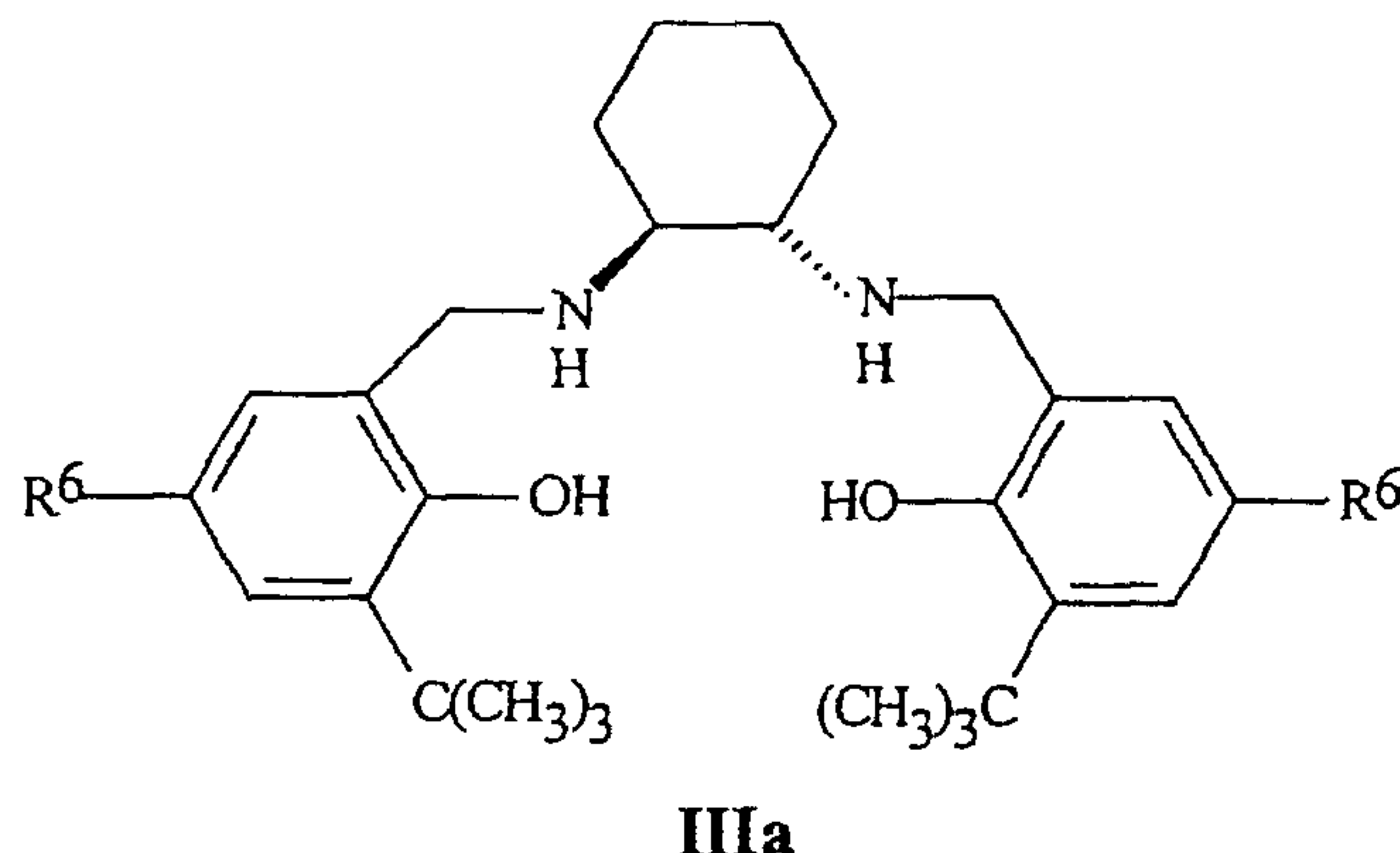
each R⁶ is independently selected from the group consisting of halogen; NO₂; cyano; C₂-C₅ alkoxy carbonyl; N(C₁-C₄ alkyl)₂; CON(C₁-C₄ alkyl)₂; C₁-C₄ alkoxy; C₂-C₅ alkyl carbonyloxy; C₂-C₅ alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; (C₁-C₄ alkyl)silyl; tri(C₁-C₄ alkyl)siloxy; C₁-C₄ alkyl optionally substituted with 1-3 phenyl rings; C₃-C₆ cycloalkyl optionally substituted with C₁-C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and

when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and

each n is independently an integer from 0 to 4.

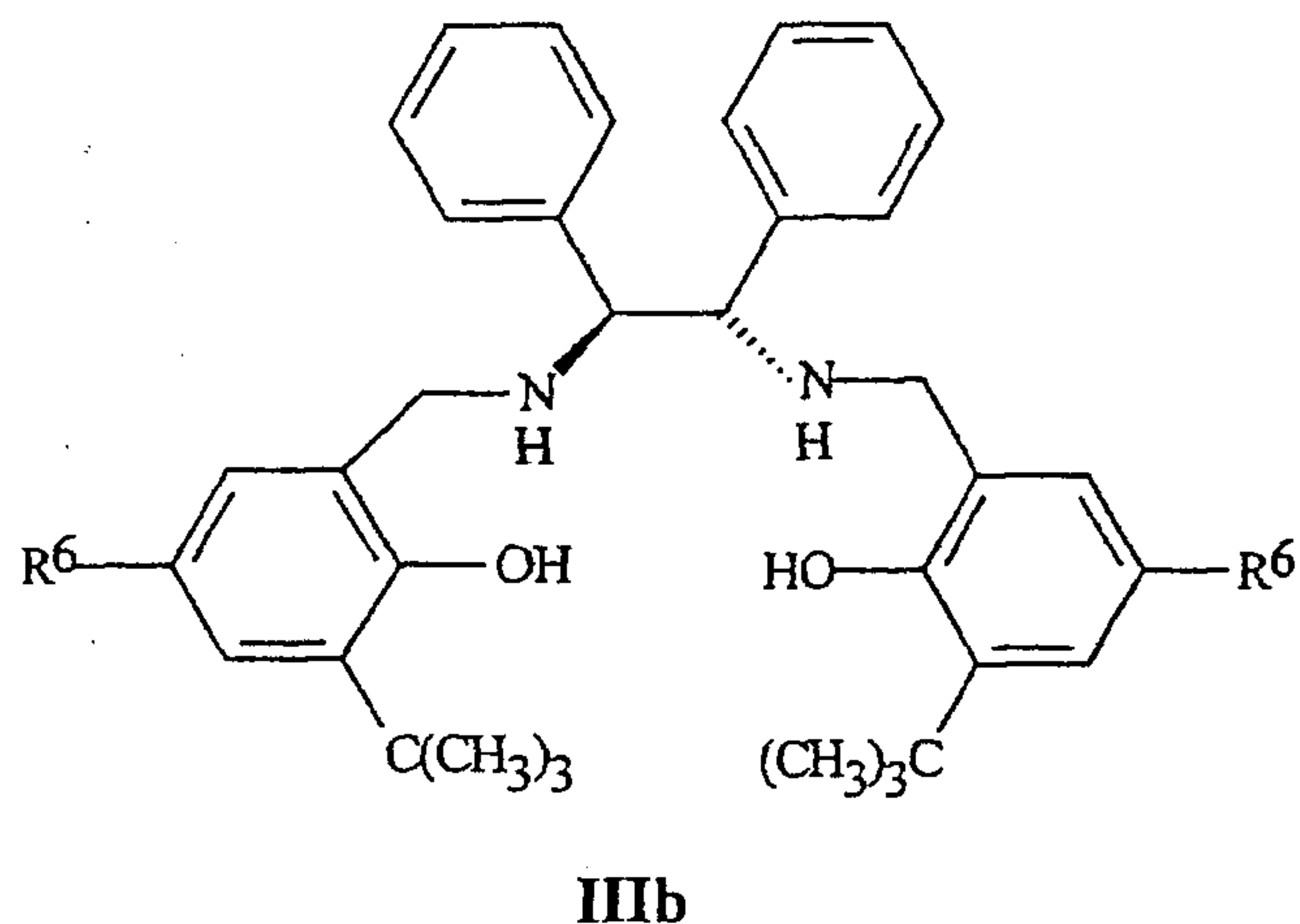
9. The process of Claim 8 wherein each phenyl ring in Formula III has an R⁶ substituent ortho to the -OH function.

10. The process of Claim 9 wherein the chiral ligand of Formula III is a ligand of Formula IIIa



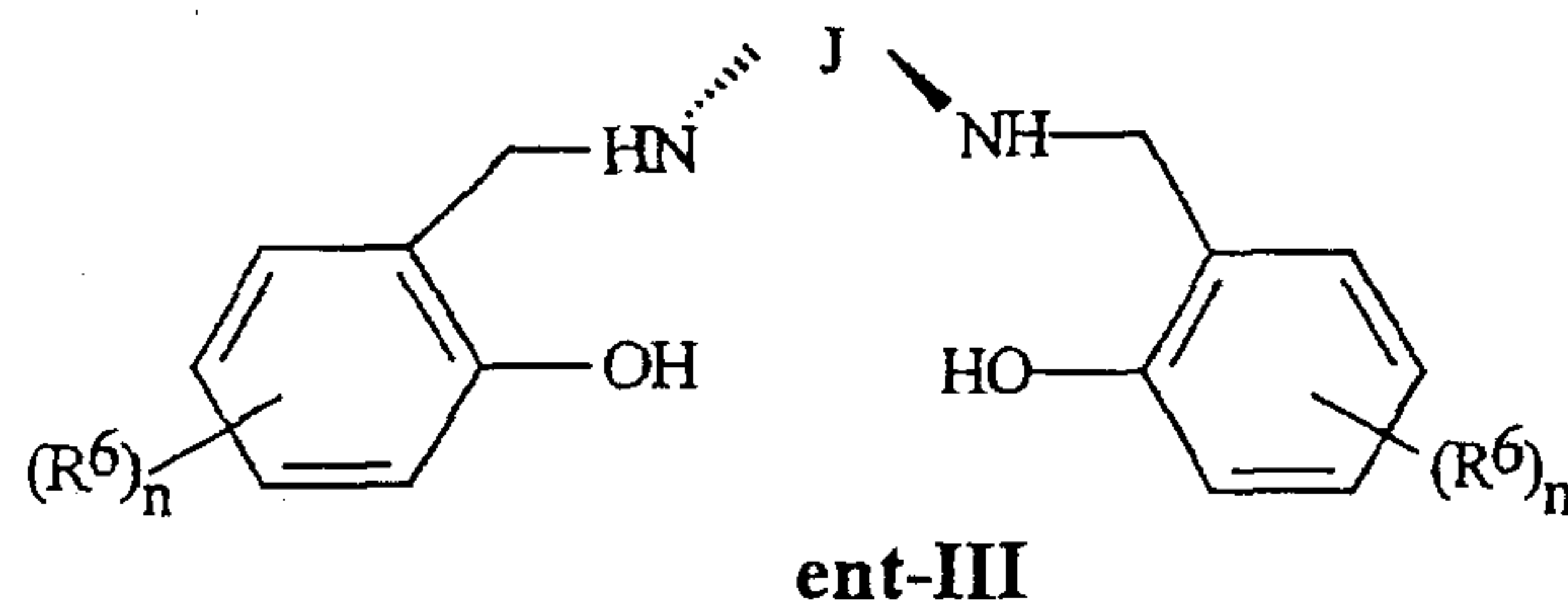
wherein each R⁶ is the same and is selected from H and C(CH₃)₃.

11. The process of Claim 9 wherein the chiral ligand of Formula **III** is a ligand of Formula **IIIb**



wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

5 12. The process of Claim 1 wherein the zirconium complex comprises zirconium and a chiral ligand of Formula **ent-III**



wherein

J is an optionally substituted linking chain of 2 to 4 members consisting of at least one
 10 carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as $C(=O)$; the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a C_3-C_8 cycloalkyl ring, a C_3-C_8 nonaromatic heterocyclic ring, a phenyl ring or a
 15 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

each R^6 is independently selected from the group consisting of halogen; NO_2 ; cyano; C_2-C_5 alkoxy carbonyl; $N(C_1-C_4 \text{ alkyl})_2$; $CON(C_1-C_4 \text{ alkyl})_2$; C_1-C_4 alkoxy; C_2-C_5 alkyl carbonyloxy; C_2-C_5 alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; $(C_1-C_4 \text{ alkyl})\text{silyl}$; $tri(C_1-C_4 \text{ alkyl})\text{siloxyl}$; C_1-C_4 alkyl optionally substituted with 1-3 phenyl rings; C_3-C_6 cycloalkyl optionally

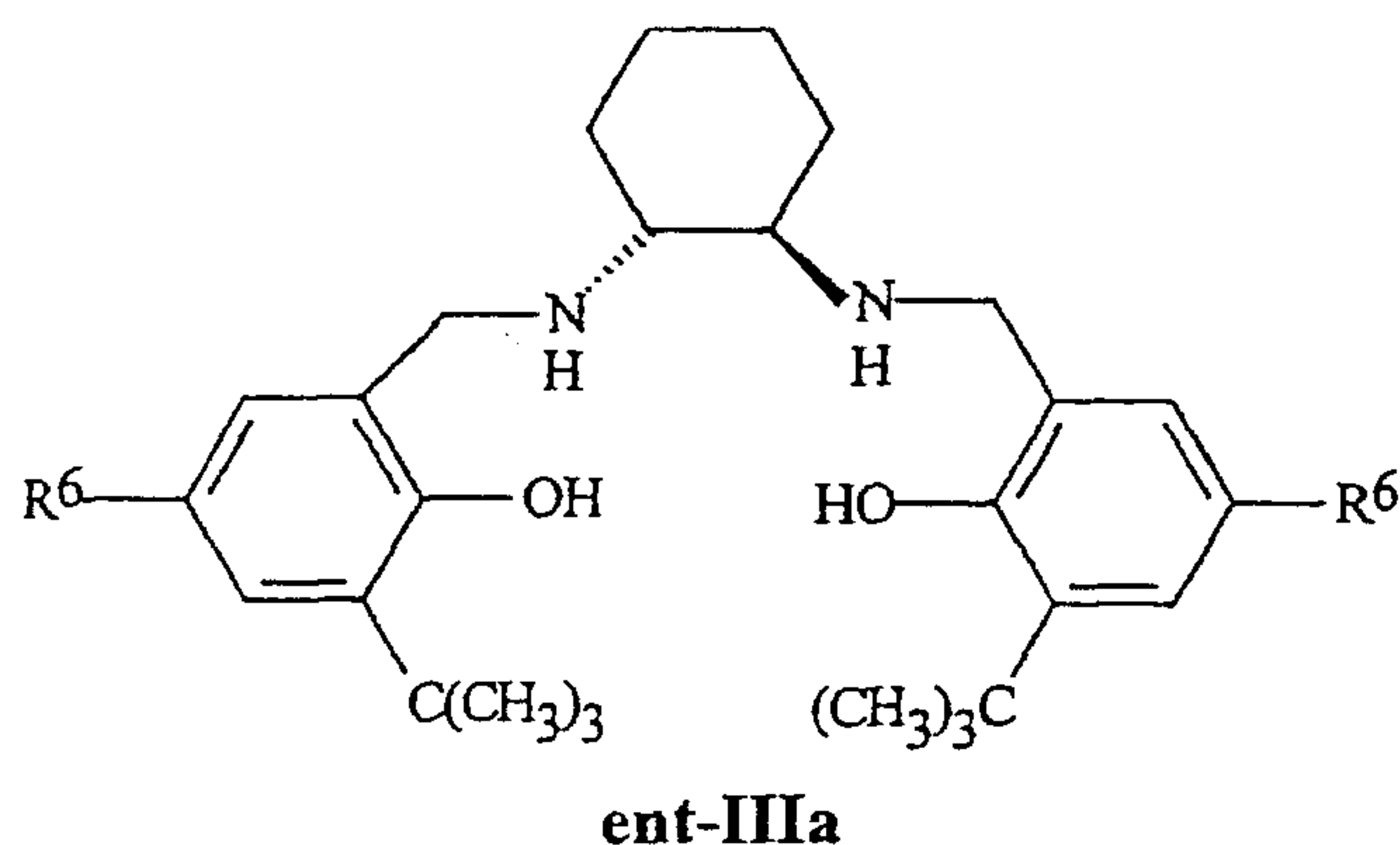
substituted with C₁-C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and

5 each n is independently an integer from 0 to 4.

13. The process of Claim 12 wherein each phenyl ring in Formula **ent-III** has an R⁶ substituent ortho to the -OH function.

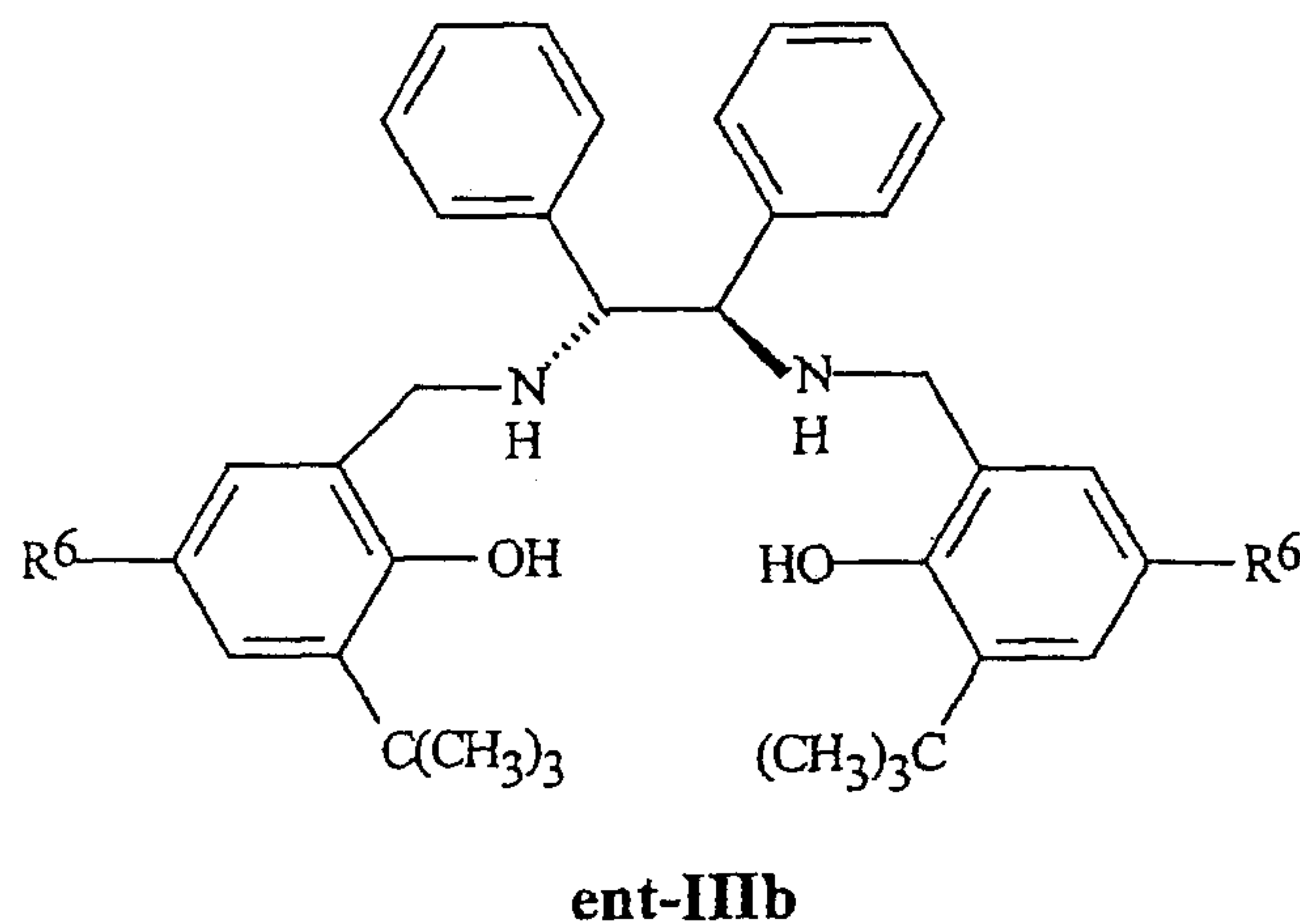
14. The process of Claim 13 wherein the chiral ligand of Formula **ent-III** is a ligand

10 of Formula **ent-IIIa**



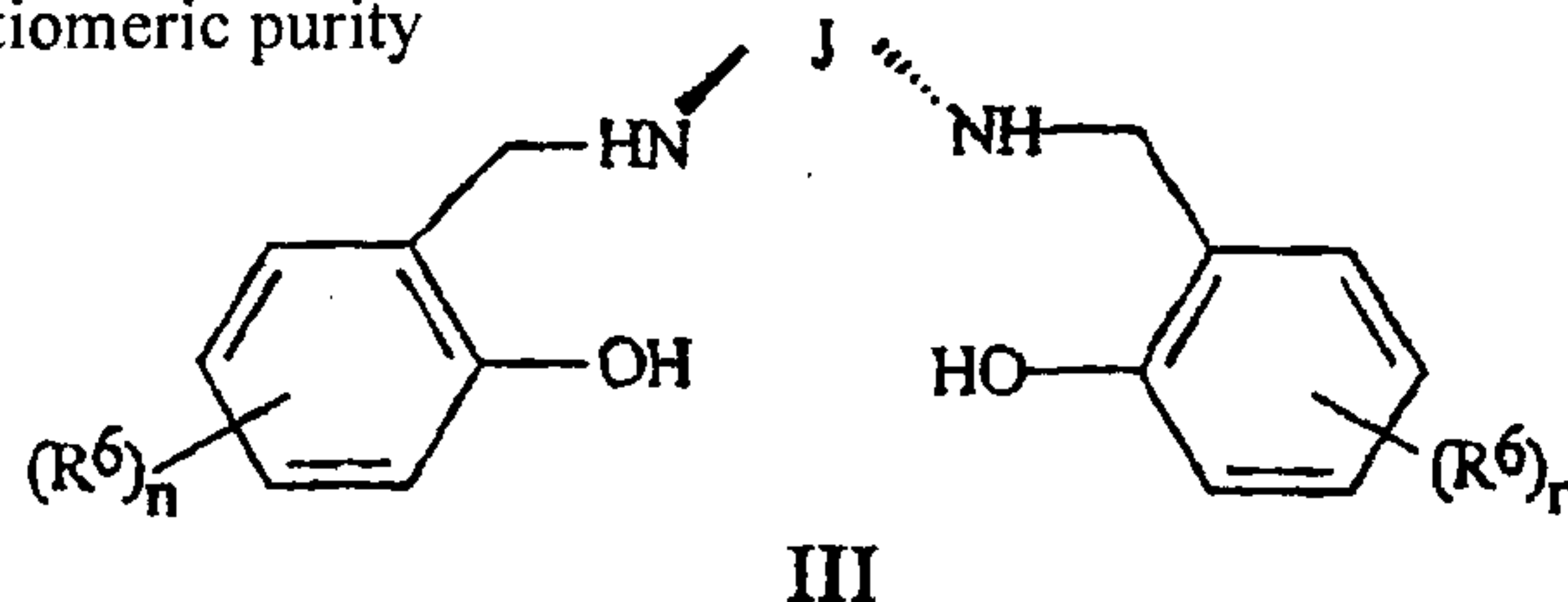
wherein each R⁶ is the same and is selected from H and C(CH₃)₃.

15. The process of Claim 13 wherein the chiral ligand of Formula **ent-III** is a ligand of Formula **ent-IIIb**



wherein each R⁶ is the same and is selected from H and C(CH₃)₃.

16. A zirconium complex comprising zirconium and a chiral ligand of Formula III of at least about 50% enantiomeric purity



wherein

J is an optionally substituted linking chain of 2 to 4 members consisting of at least one carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as C(=O); the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a C₃-C₈ cycloalkyl ring, a C₃-C₈ nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

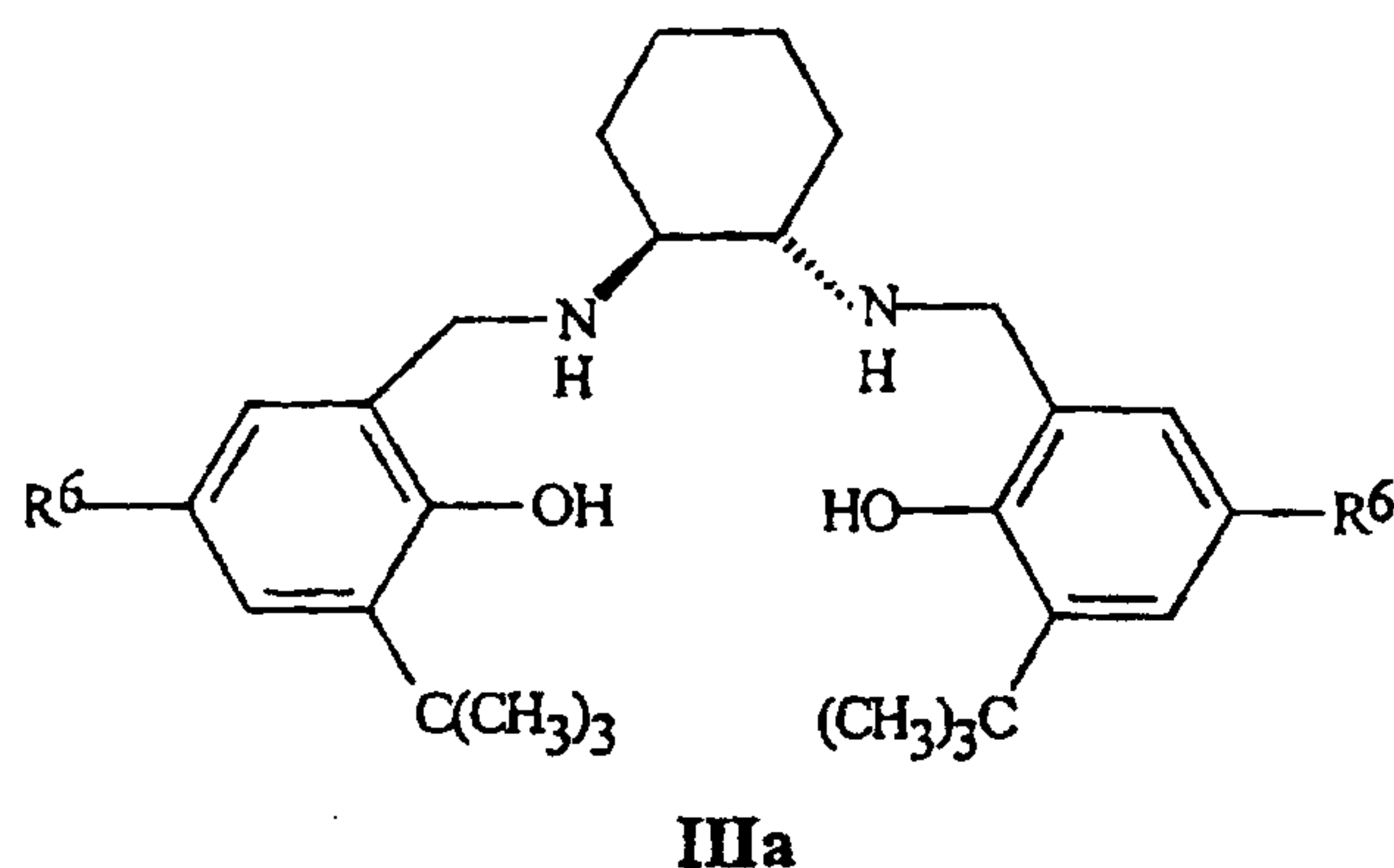
each R⁶ is independently selected from the group consisting of halogen; NO₂; cyano; C₂-C₅ alkoxy carbonyl; N(C₁-C₄ alkyl)₂; CON(C₁-C₄ alkyl)₂; C₁-C₄ alkoxy; C₂-C₅ alkyl carbonyloxy; C₂-C₅ alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; (C₁-C₄ alkyl)silyl; tri(C₁-C₄ alkyl)siloxy; C₁-C₄ alkyl optionally substituted with 1-3 phenyl rings; C₃-C₆ cycloalkyl optionally substituted with C₁-C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and

when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and

each n is independently an integer from 0 to 4.

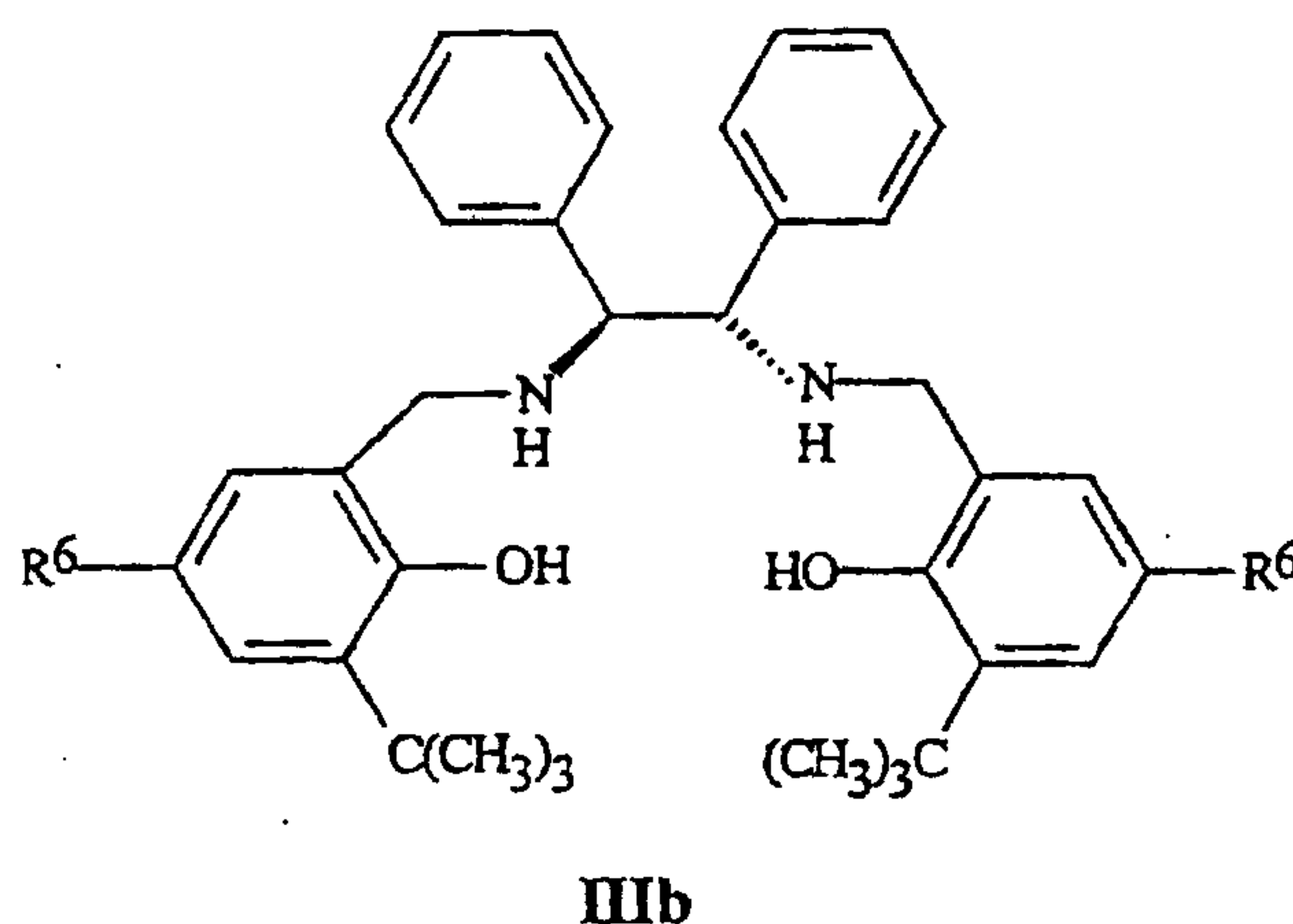
17. The zirconium complex of Claim 16 wherein each phenyl ring in Formula III has an R⁶ substituent ortho to the -OH function.

18. The zirconium complex of Claim 17 wherein the chiral ligand of Formula III is a ligand of Formula IIIa



wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

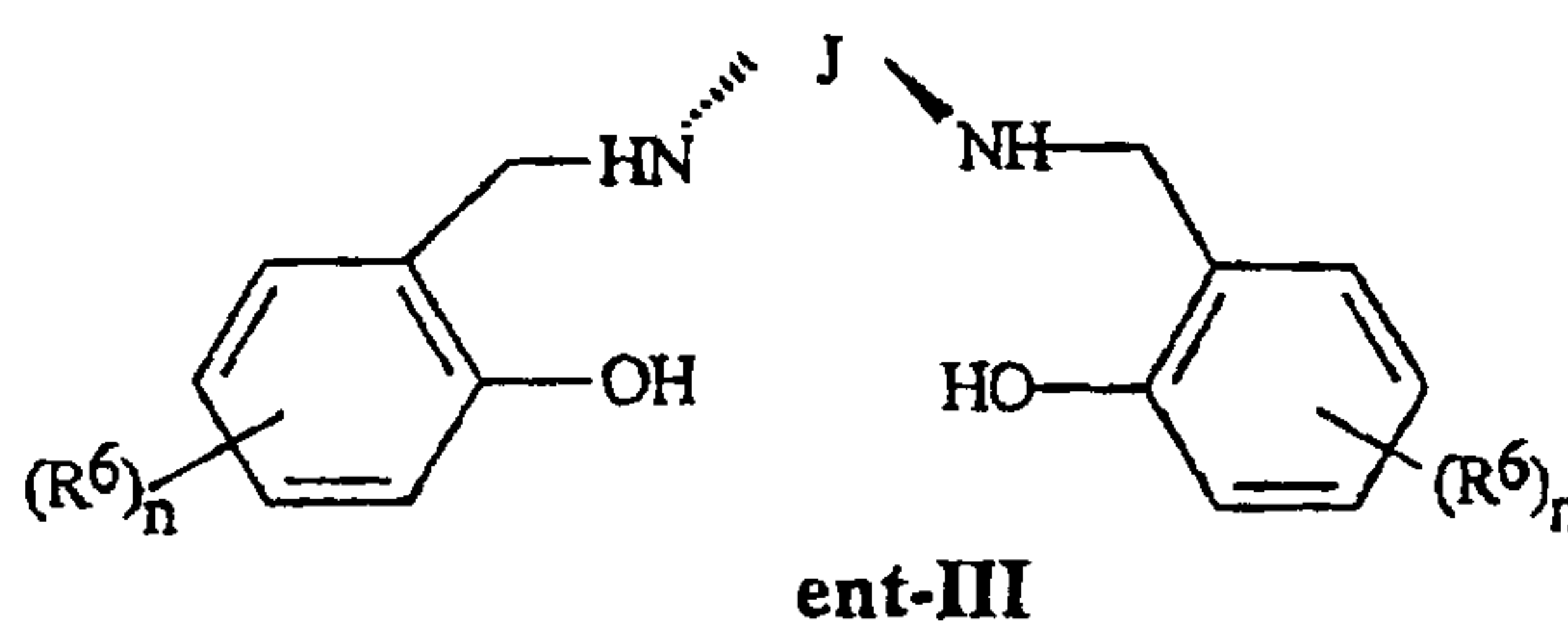
19. The zirconium complex of Claim 17 wherein the chiral ligand of Formula III is a ligand of Formula IIIb



5

wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

20. A zirconium complex comprising zirconium and a chiral ligand of Formula **ent-III** of at least about 50% enantiomeric purity



10 wherein

J is an optionally substituted linking chain of 2 to 4 members consisting of at least one carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as $C(=O)$; the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a:

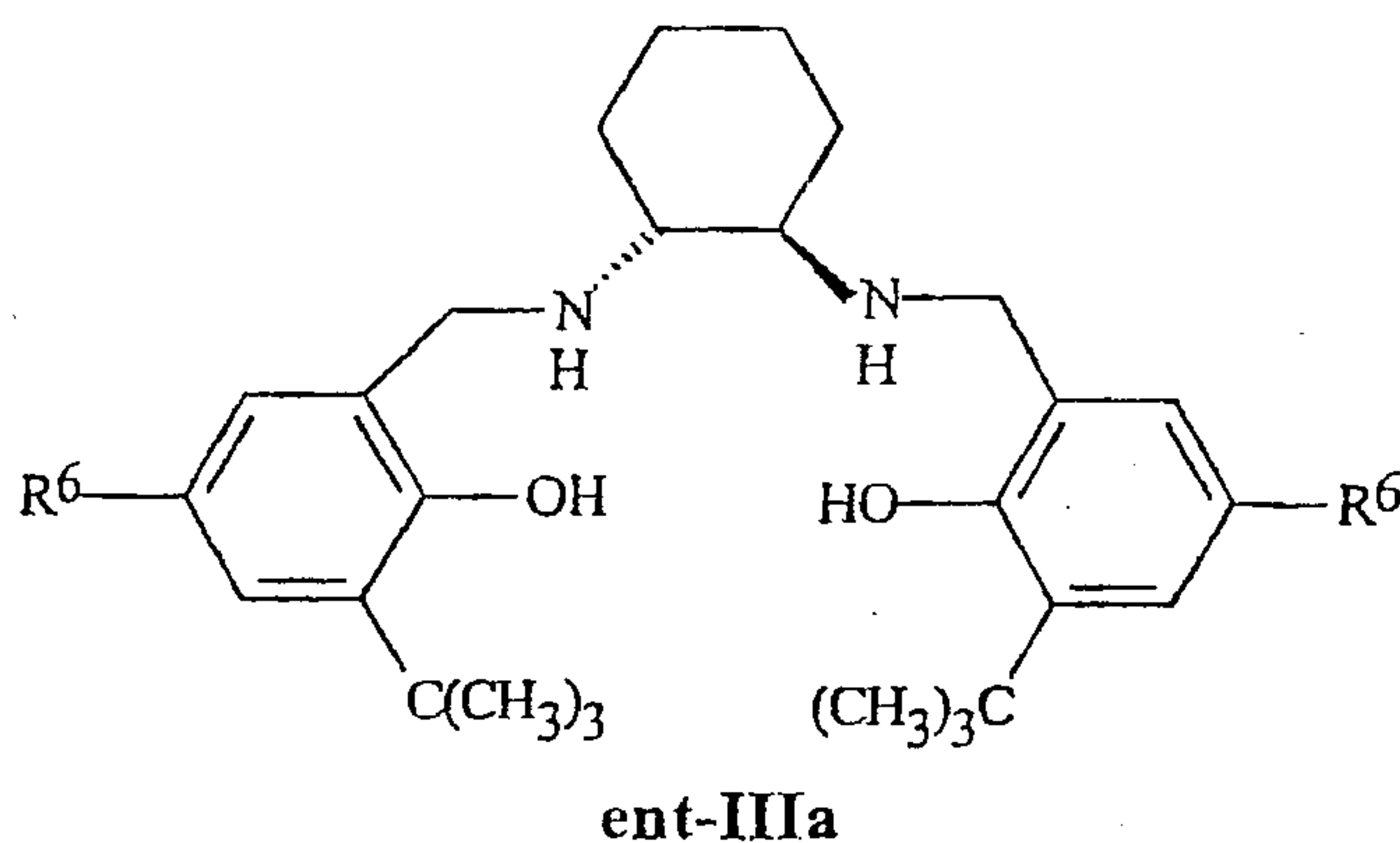
15

C₃-C₈ cycloalkyl ring, a C₃-C₈ nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

- 5 each R⁶ is independently selected from the group consisting of halogen; NO₂; cyano; C₂-C₅ alkoxycarbonyl; N(C₁-C₄ alkyl)₂; CON(C₁-C₄ alkyl)₂; C₁-C₄ alkoxy; C₂-C₅ alkylcarbonyloxy; C₂-C₅ alkoxycarbonyloxy; optionally substituted phenylcarbonyloxy; (C₁-C₄ alkyl)silyl; tri(C₁-C₄ alkyl)siloxy; C₁-C₄ alkyl optionally substituted with 1-3 phenyl rings; C₃-C₆ cycloalkyl optionally substituted with C₁-C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and
- 10 when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and
- 15 each n is independently an integer from 0 to 4.

21. The zirconium complex of Claim 20 wherein each phenyl ring in Formula **ent-III** has an R⁶ substituent ortho to the -OH function.

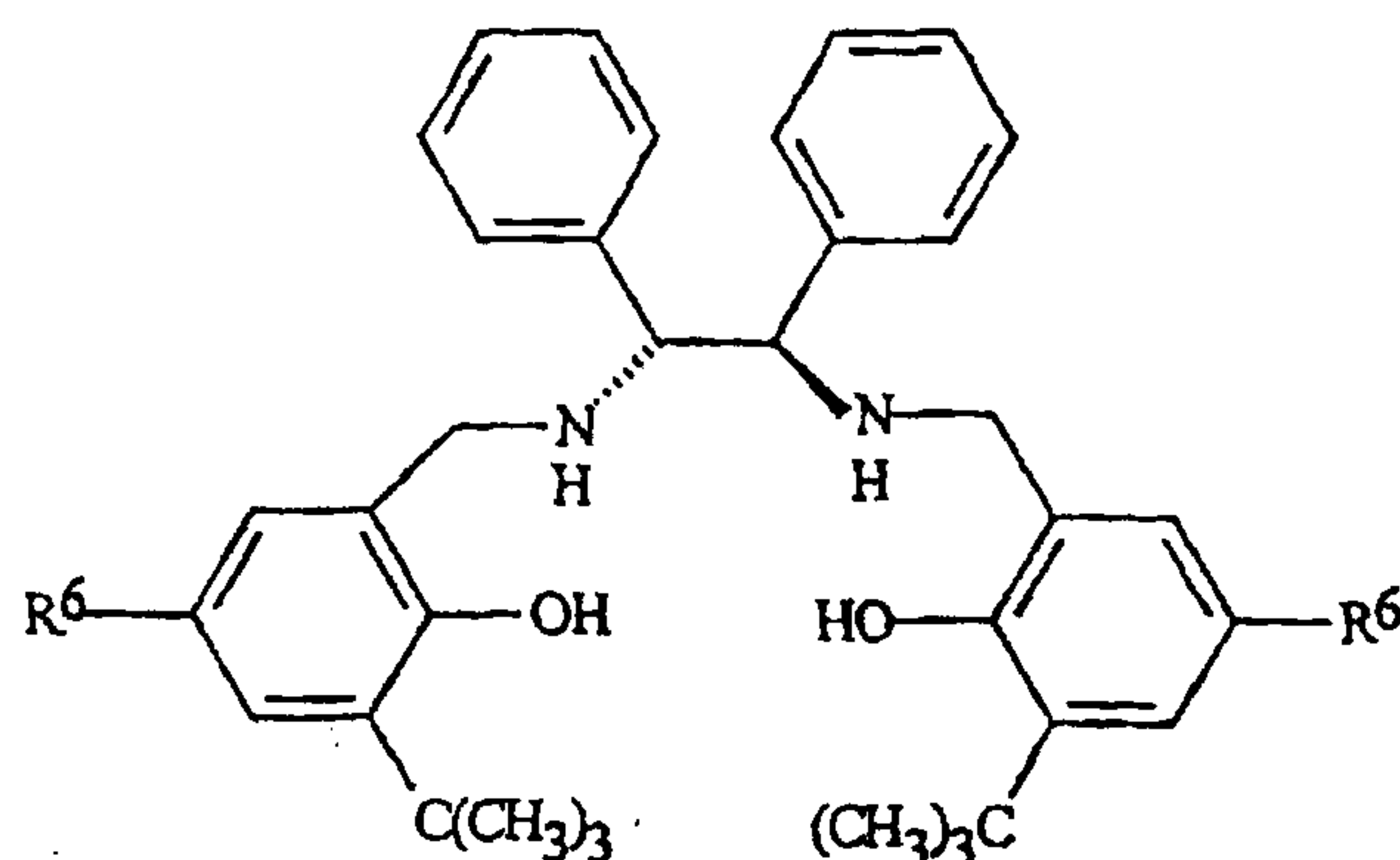
22. The zirconium complex of Claim 21 wherein the chiral ligand of Formula **ent-III** is a ligand of Formula **ent-IIIa**



20

wherein each R⁶ is the same and is selected from H and C(CH₃)₃.

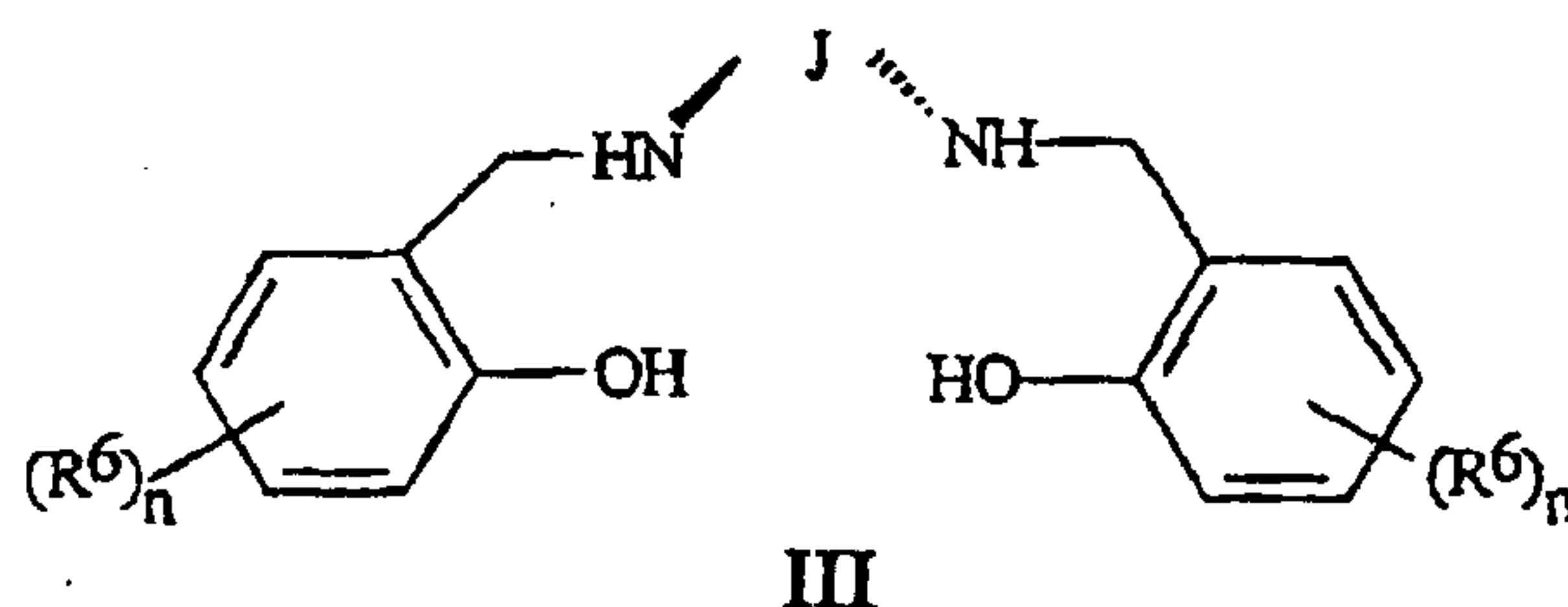
23. The zirconium complex of Claim 21 wherein the chiral ligand of Formula **ent-III** is a ligand of Formula **ent-IIIb**



ent-IIIb

wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

24. A chiral compound of Formula III of at least about 50% enantiomeric purity



III

5 wherein

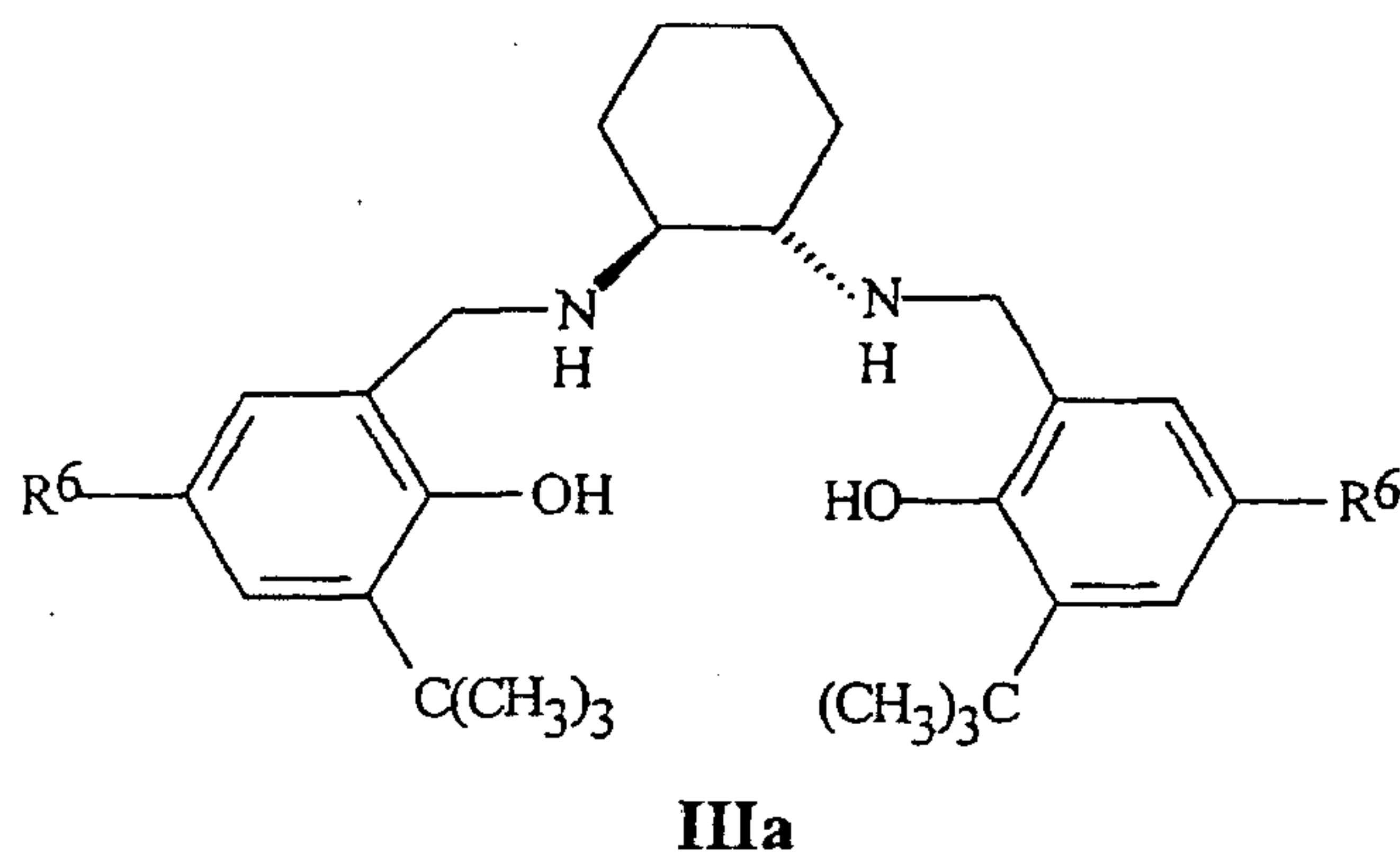
J is an optionally substituted linking chain of 2 to 4 members consisting of at least one carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as $C(=O)$; the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a C_3-C_8 cycloalkyl ring, a C_3-C_8 nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;

15 each R^6 is independently selected from the group consisting of halogen; NO_2 ; cyano; C_2-C_5 alkoxy carbonyl; $N(C_1-C_4 \text{ alkyl})_2$; $CON(C_1-C_4 \text{ alkyl})_2$; C_1-C_4 alkoxy; C_2-C_5 alkyl carbonyloxy; C_2-C_5 alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; $(C_1-C_4 \text{ alkyl})$ silyl; $tri(C_1-C_4 \text{ alkyl})$ siloxy; C_1-C_4 alkyl optionally substituted with 1-3 phenyl rings; C_3-C_6 cycloalkyl optionally substituted with C_1-C_2 alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and

when two R^6 are attached to adjacent phenyl ring carbon atoms, said two R^6 may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and each n is independently an integer from 0 to 4;

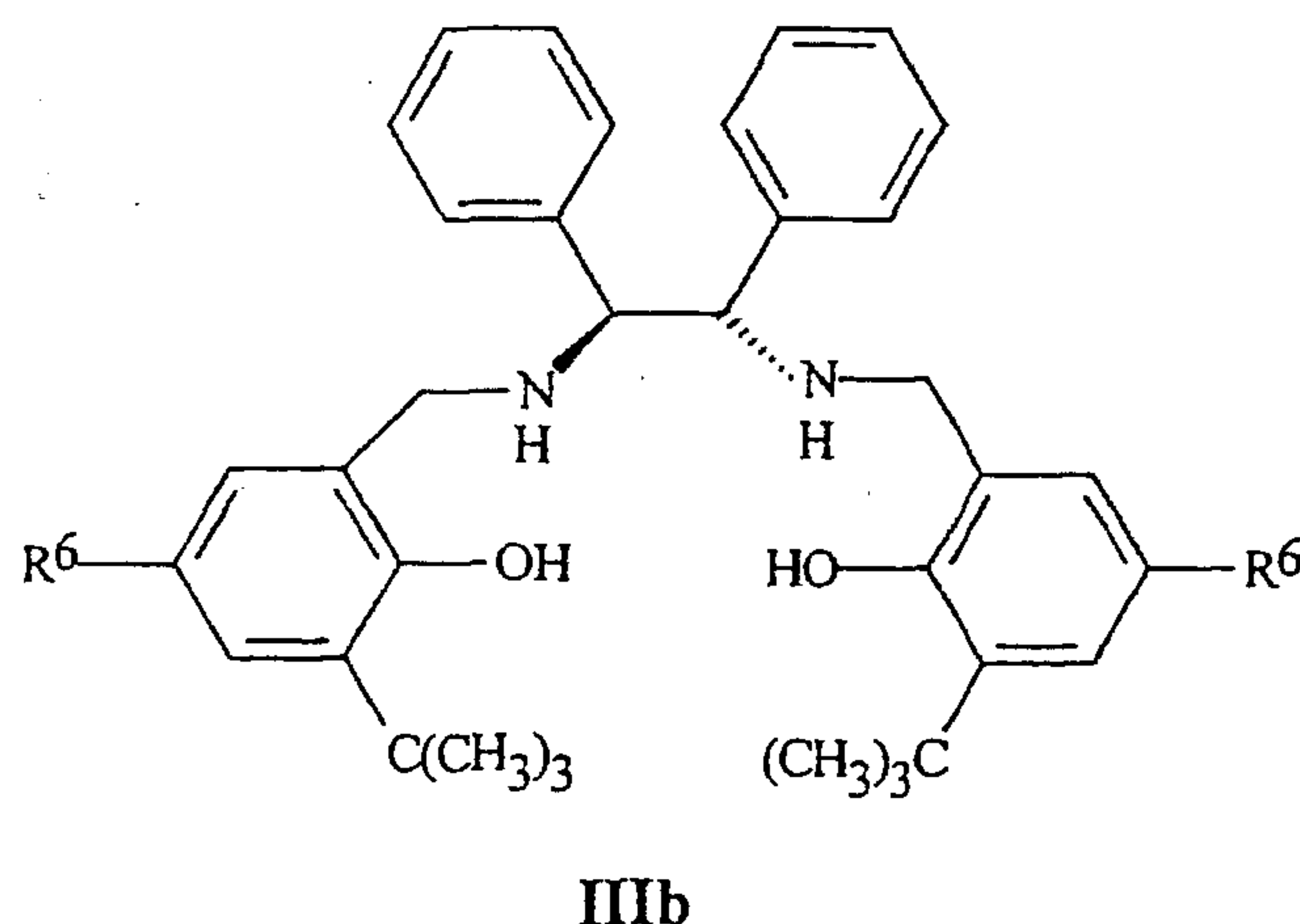
- 5 provided that (a) when J is a C_6 cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula III, then at least one n is an integer from 1 to 4; (b) when J is a C_6 cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula III, on one phenyl ring n is 2 and $(R^6)_n$ is 3-*t*-butyl-5-methyl, then $(R^6)_n$ on the other phenyl ring is other than 3-*t*-butyl-5-methyl; and
- 10 (c) when J is a 1,1'-binaphthalenyl ring system connected via the 2 and 2' positions to the remainder of Formula III, then at least one n is an integer from 1 to 4.

25. The chiral compound of Claim 24 that is Formula IIIa



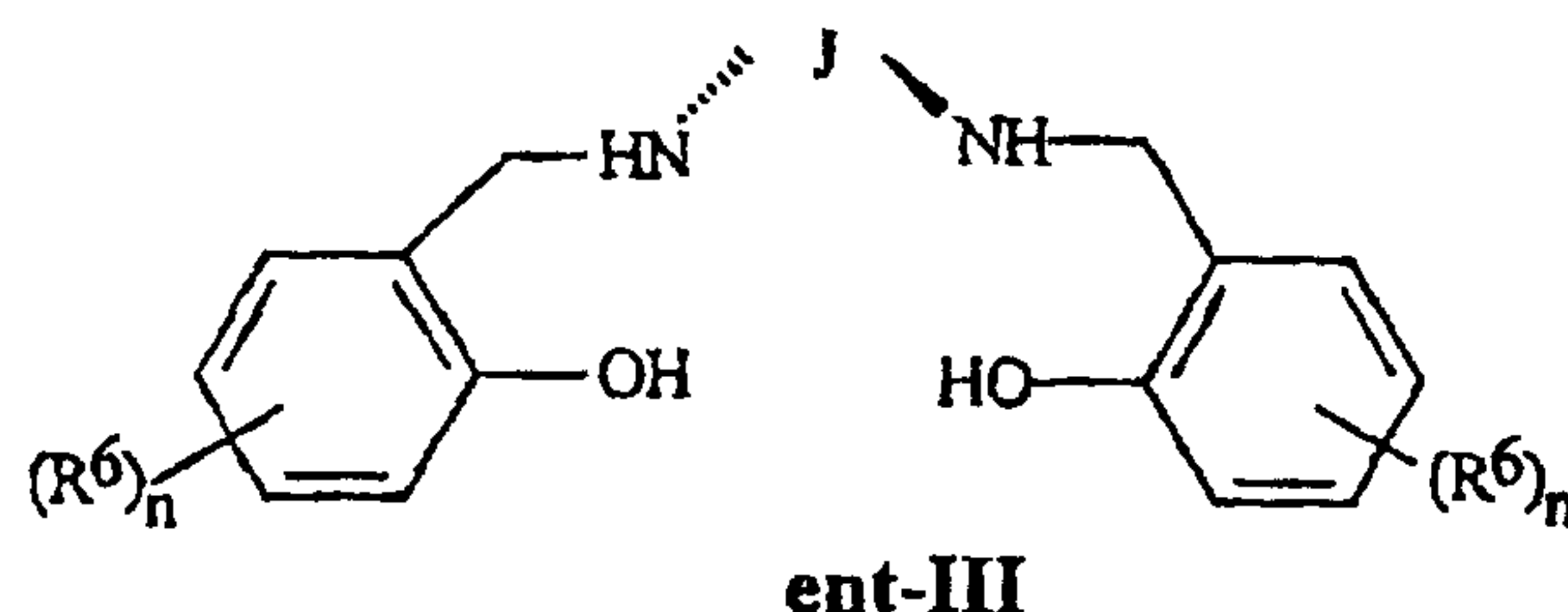
- 15 wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

26. The chiral compound of Claim 24 that is Formula IIIb



- wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

27. A chiral compound of Formula **ent-III** of at least about 50% enantiomeric purity

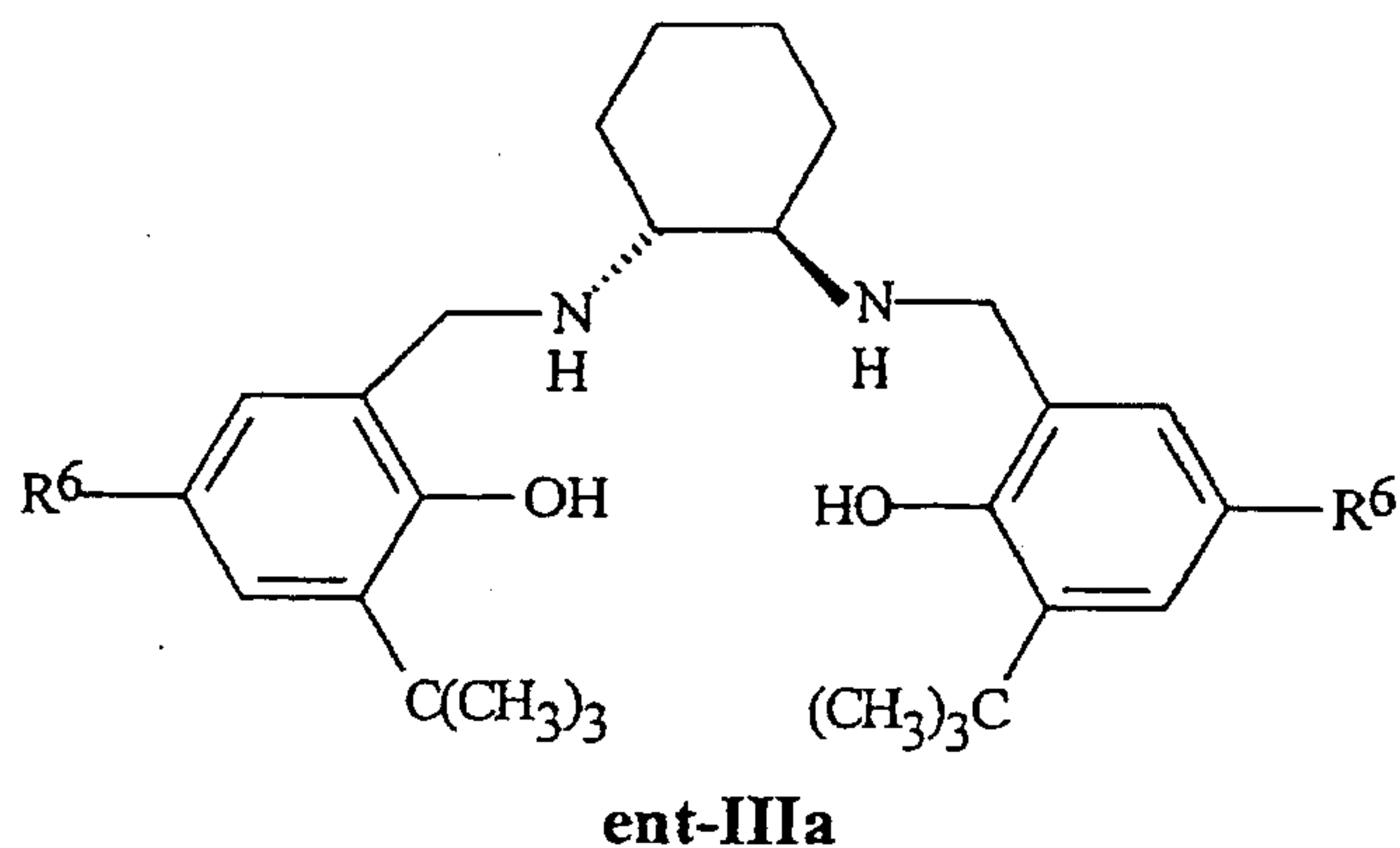


wherein

- J is an optionally substituted linking chain of 2 to 4 members consisting of at least one
 5 carbon atom member and optionally one member selected from nitrogen and oxygen, of which no more than two carbon atom members are substituted as C(=O); the linking chain optionally fused through adjacent linking chain members to 1 or 2 rings or ring systems selected from the group consisting of a
 10 C₃-C₈ cycloalkyl ring, a C₃-C₈ nonaromatic heterocyclic ring, a phenyl ring or a 1,2-naphthalenyl ring system, each ring or ring system optionally substituted; such that the attached nitrogen atoms are held in a stereospecific orientation with respect to J and each other as depicted;
- each R⁶ is independently selected from the group consisting of halogen; NO₂; cyano; C₂-C₅ alkoxy carbonyl; N(C₁-C₄ alkyl)₂; CON(C₁-C₄ alkyl)₂; C₁-C₄ alkoxy;
 15 C₂-C₅ alkyl carbonyloxy; C₂-C₅ alkoxy carbonyloxy; optionally substituted phenyl carbonyloxy; (C₁-C₄ alkyl)silyl; tri(C₁-C₄ alkyl)siloxy; C₁-C₄ alkyl optionally substituted with 1-3 phenyl rings; C₃-C₆ cycloalkyl optionally substituted with C₁-C₂ alkyl; adamantyl; a phenyl ring, or a 5- or 6-membered heteroaromatic ring, each ring optionally substituted; and
- 20 when two R⁶ are attached to adjacent phenyl ring carbon atoms, said two R⁶ may be taken together with the phenyl ring to form a naphthalene ring system optionally substituted on either ring of said naphthalene ring system; and
- each n is independently an integer from 0 to 4;
- 25 provided that (a) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **ent-III**, then at least one n is an integer from 1 to 4; (b) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the remainder of Formula **ent-III**, on one phenyl ring n is 2 and (R⁶)_n is 3-*t*-butyl-5-methyl, then (R⁶)_n on the other phenyl ring is other than 3-*t*-butyl-5-methyl; (c) when J is a C₆ cycloalkyl ring connected via adjacent carbon atoms to the
 30 remainder of Formula **ent-III**, on one phenyl ring n is 2 and (R⁶)_n is 3-*t*-butyl-5-*t*-butyl, then (R⁶)_n on the other phenyl ring is other than 3-*t*-butyl-5-*t*-butyl; and (d) when J is a 1,1'-binaphthalenyl ring system connected via the 2 and 2'

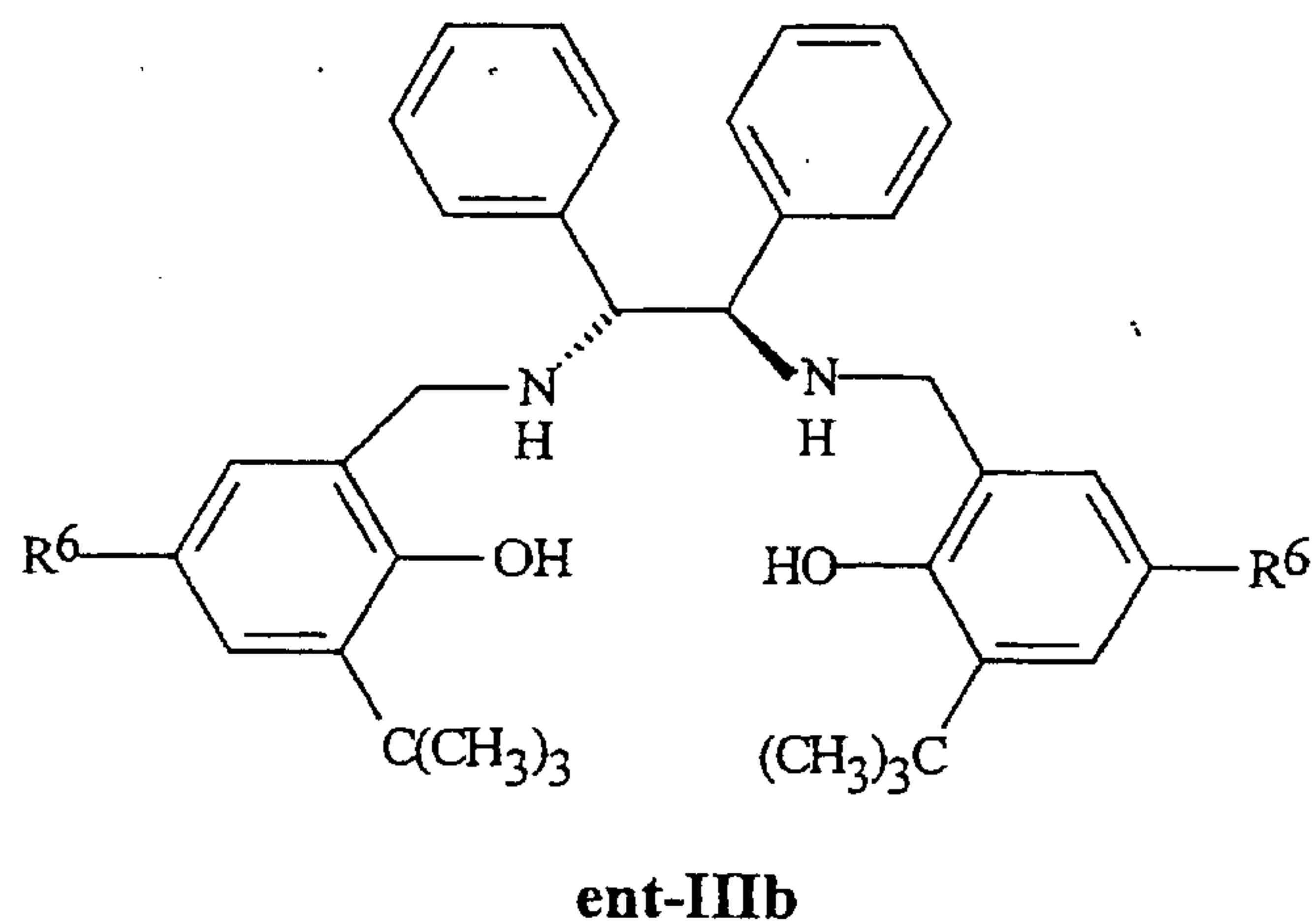
positions to the remainder of Formula **ent-III**, then at least one n is an integer from 1 to 4.

28. The chiral compound of Claim 27 that is Formula **ent-IIIa**



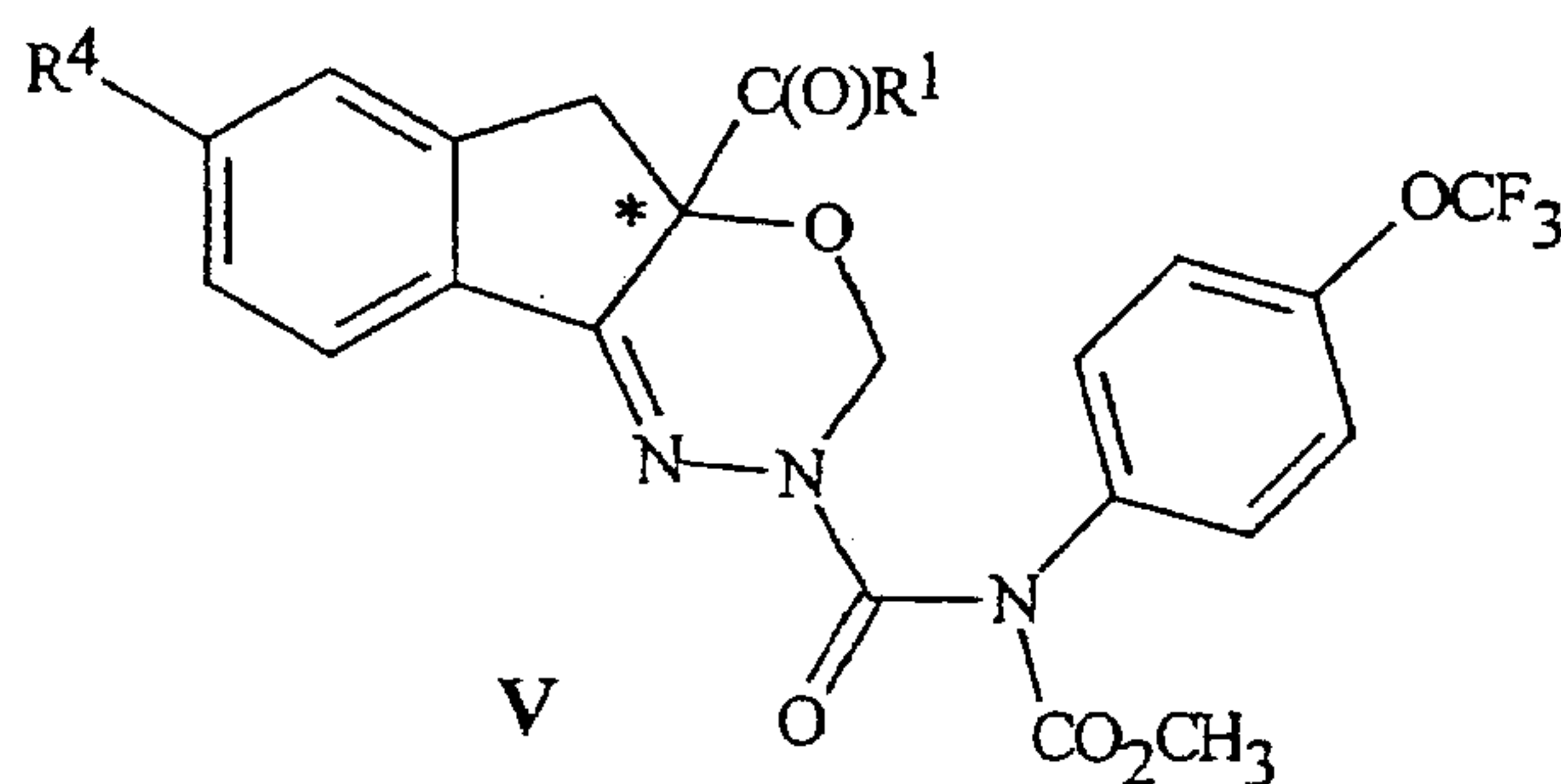
5 wherein R^6 is H.

29. The chiral compound of Claim 27 that is Formula **ent-IIIb**



wherein each R^6 is the same and is selected from H and $C(CH_3)_3$.

30. A method of preparing a compound of Formula **V**



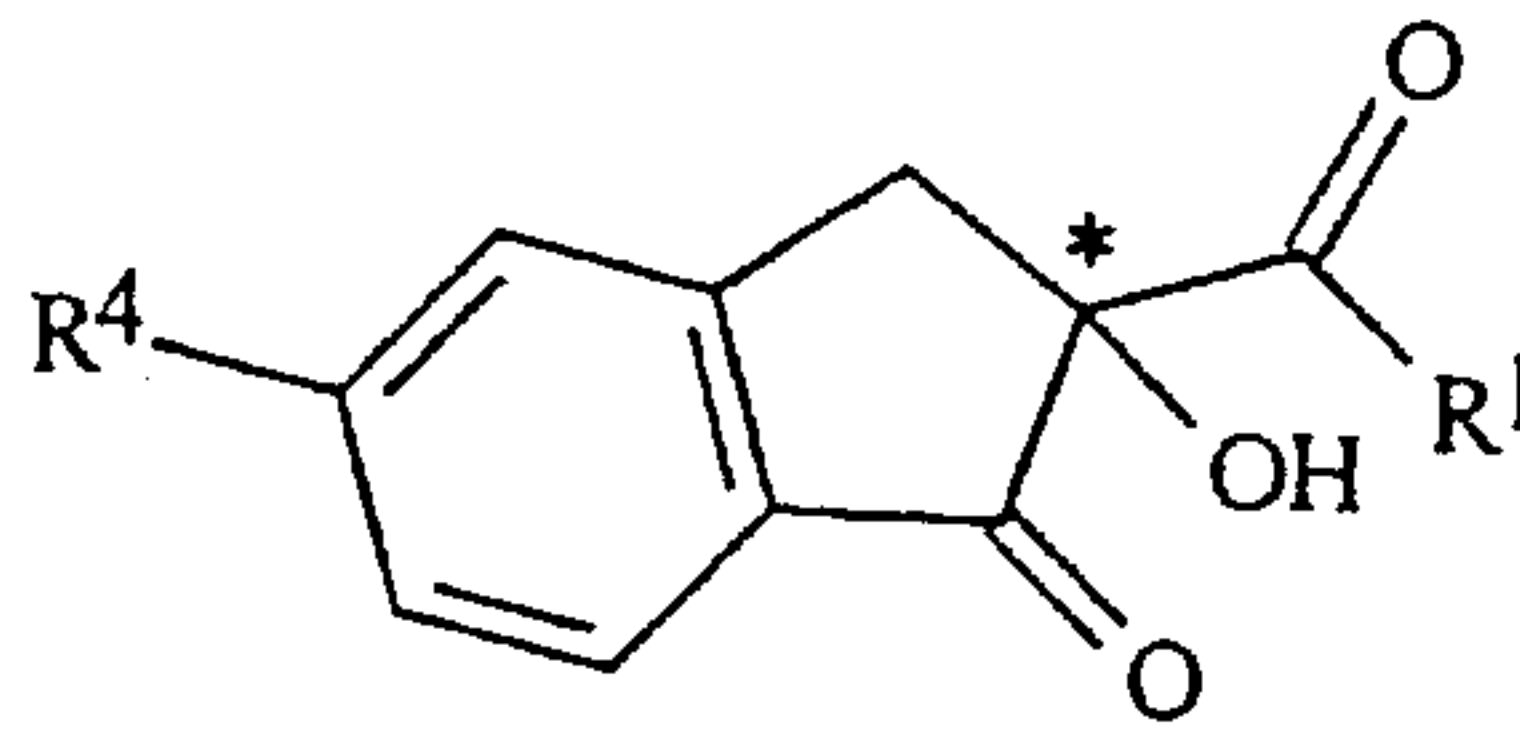
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wherein

R^1 is C_1-C_3 alkoxy; and

R^4 is F, Cl or C_1-C_3 fluoroalkoxy;

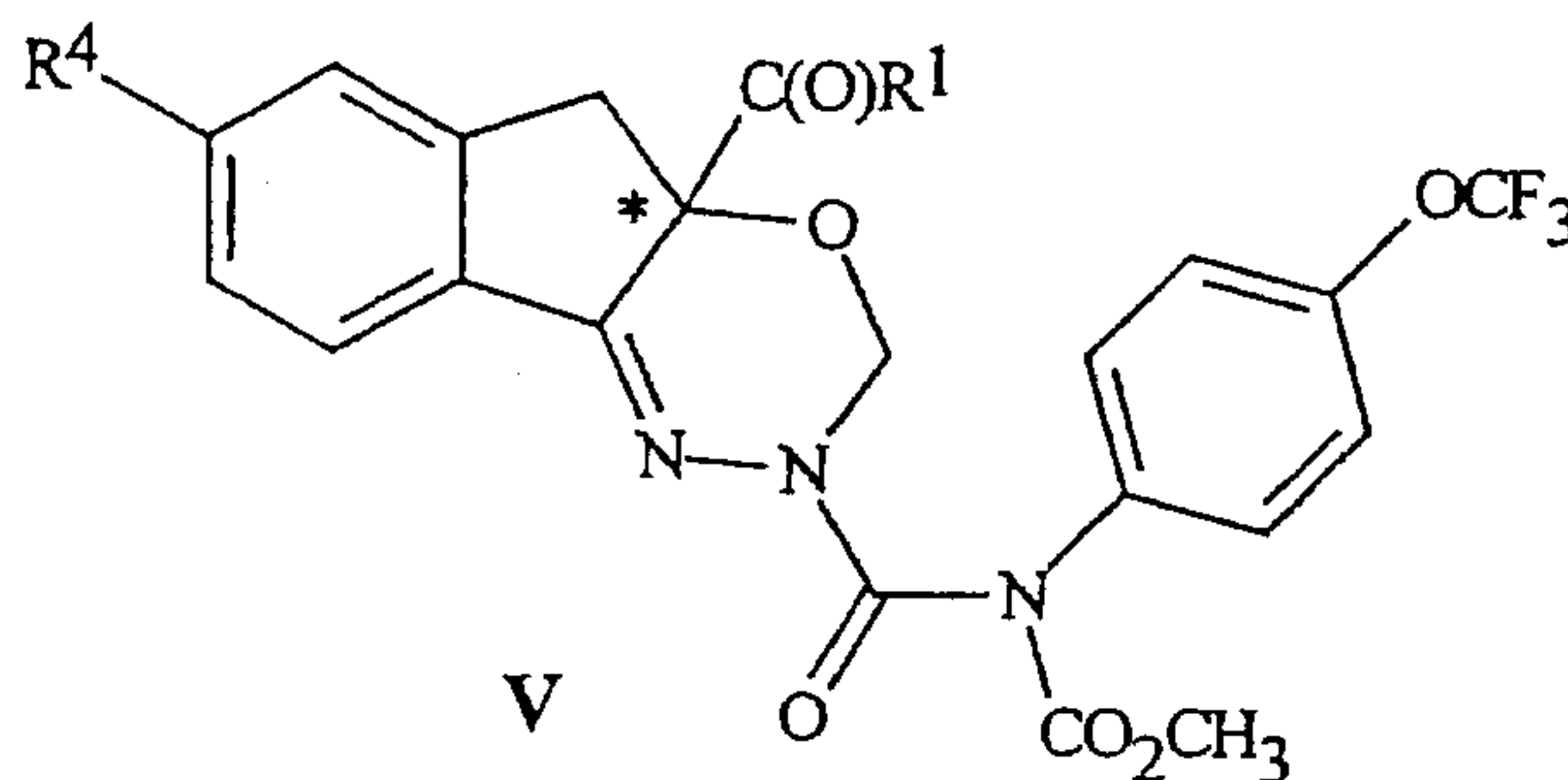
using a compound of Formula **Ia**



Ia

wherein Formulae **V** and **Ia** are racemic or enantiomerically enriched at the chiral center indicated by *; characterized by:

- 5 preparing said compound of Formula **Ia** by the method of Claim 3.
31. The method of Claim 30 wherein R^1 is OCH_3 ; and R^4 is Cl.
32. The method of Claim 30 wherein Formulae **V** and **Ia** are enantiomerically enriched with the *S* isomer.
33. A method of preparing a compound of Formula **V**



V

10

wherein

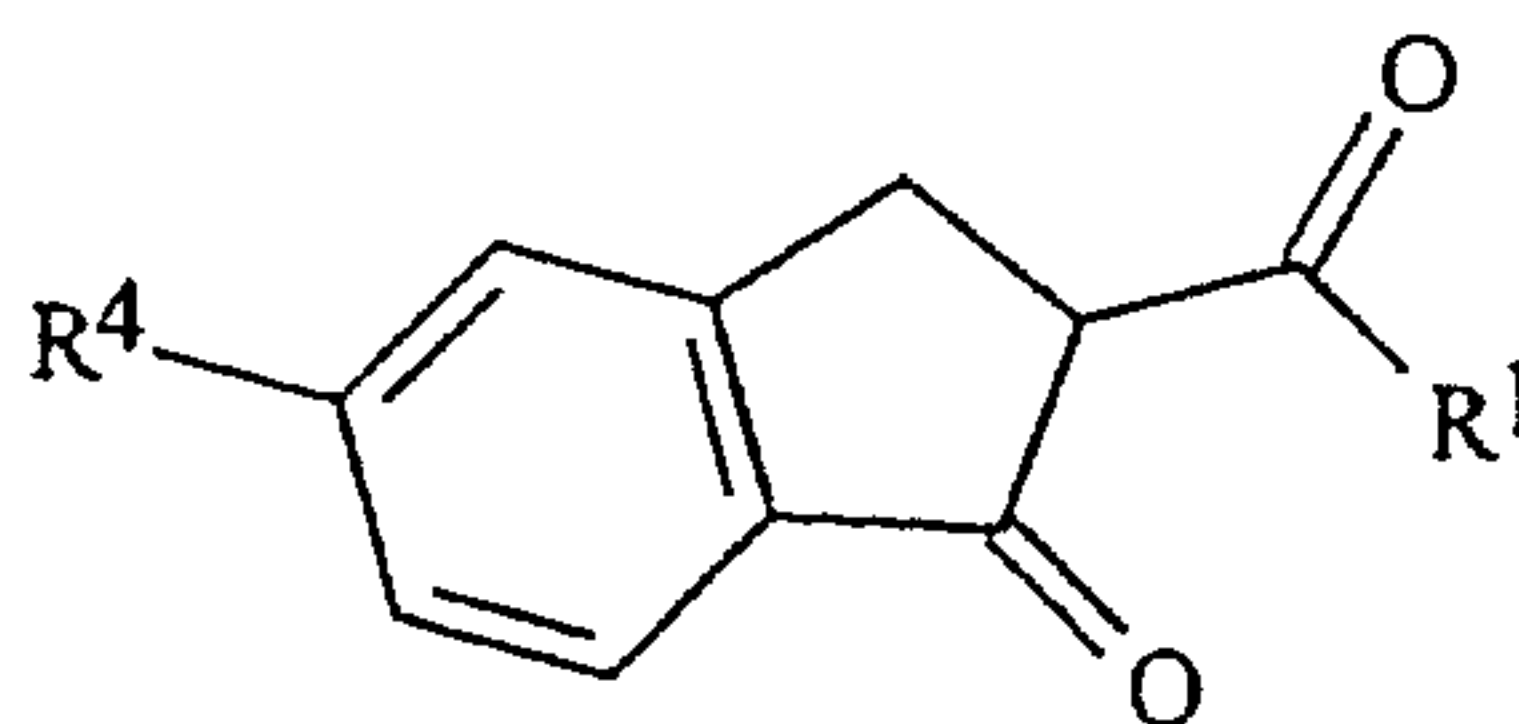
R^1 is C_1-C_3 alkoxy;

R^4 is F, Cl or C_1-C_3 fluoroalkoxy; and

Formula **V** is racemic or enantiomerically enriched at the chiral center indicated by *,

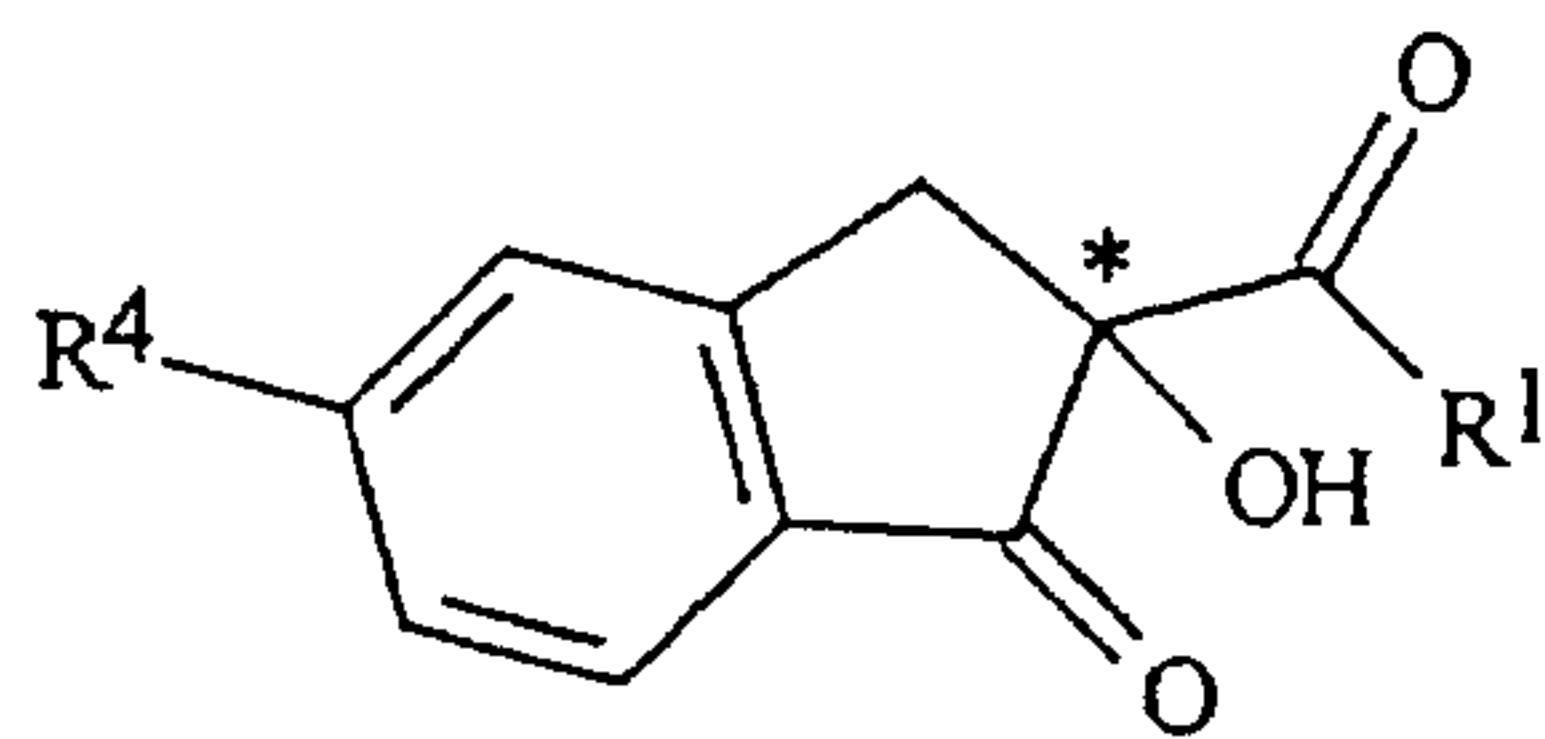
15 comprising the steps of:

(a) contacting a compound of Formula **IIa**



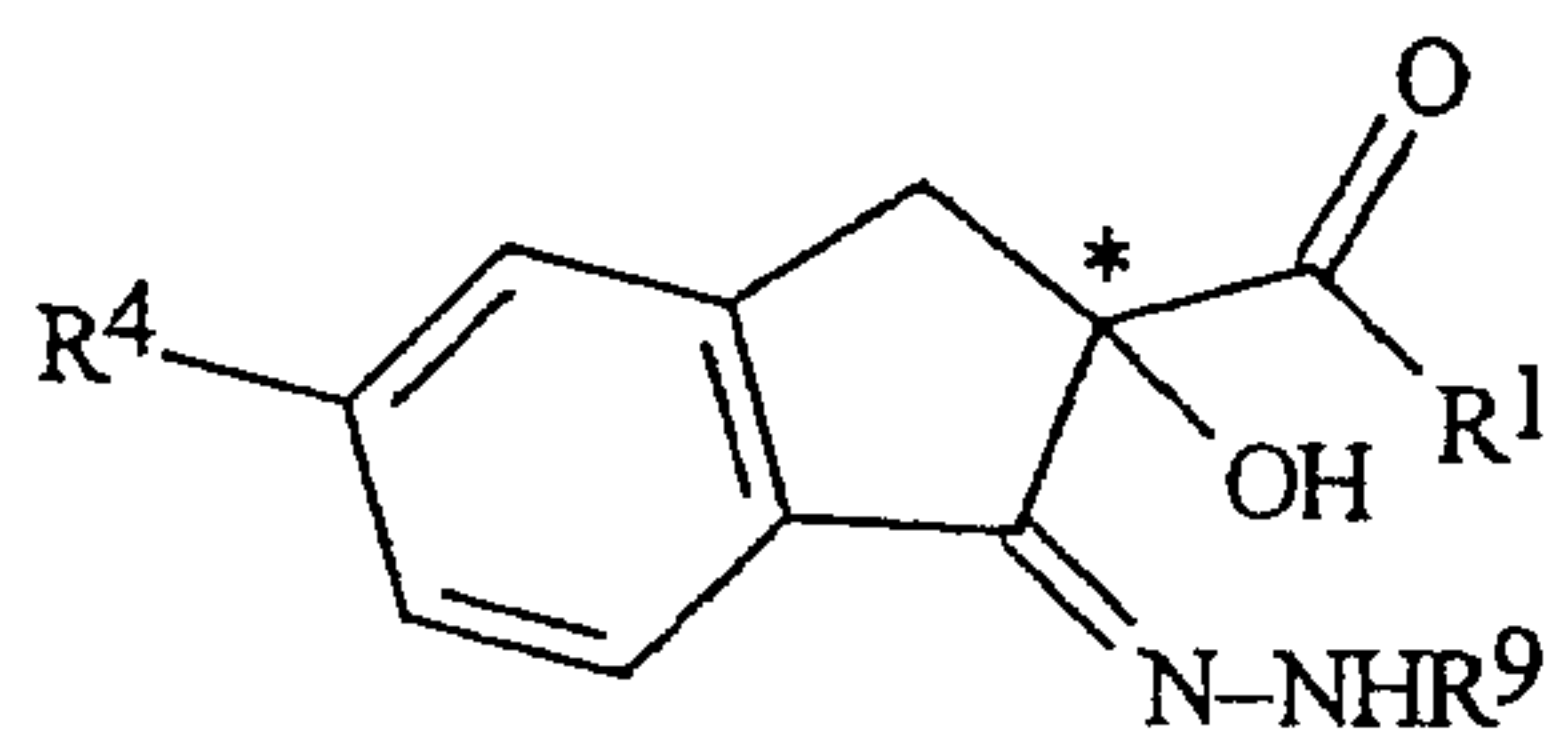
IIa

wherein R^1 is C_1-C_3 alkoxy, and R^4 is F, Cl, or C_1-C_3 fluoroalkoxy;
with a zirconium complex and an oxidant to prepare a compound of Formula **Ia**

**Ia**

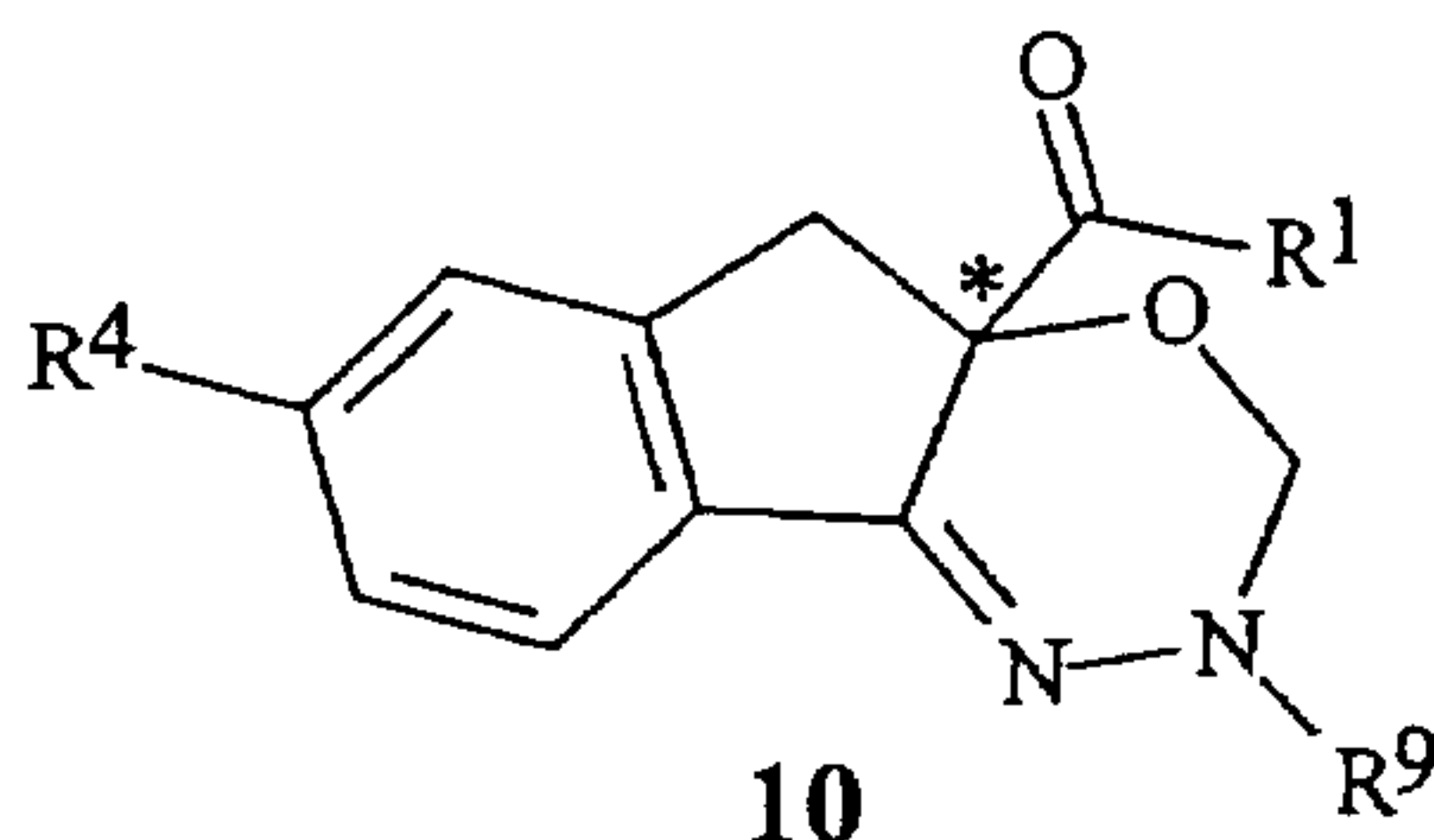
that is racemic or enantiomerically enriched at the chiral center indicated by *;

- (b) contacting the compound of Formula Ia with H_2NNHR^9 , wherein R^9 is a protecting group to form a compound of Formula 8

**8**

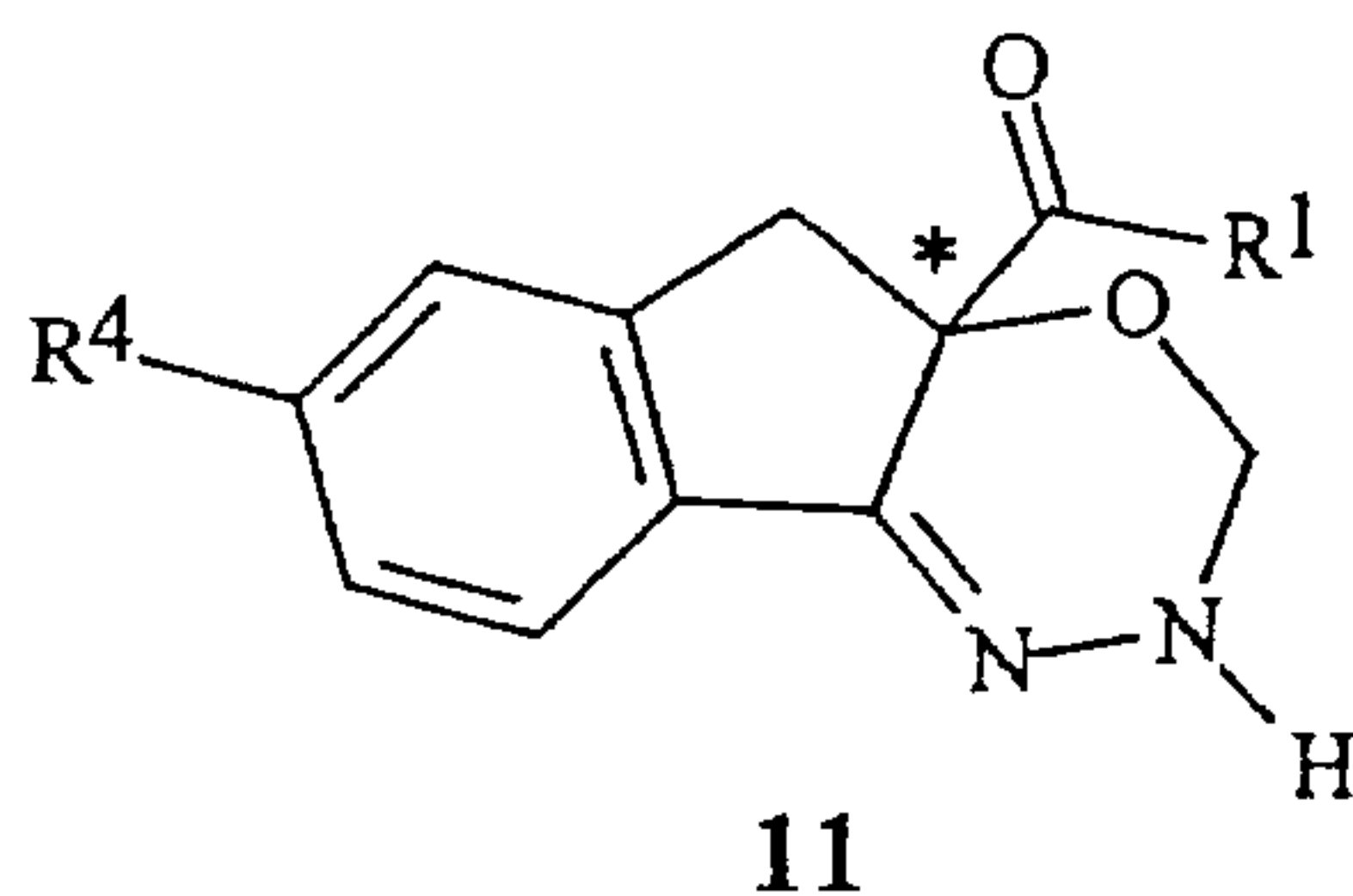
5

- (c) contacting the compound of Formula 8 with a formaldehyde equivalent to form a compound of Formula 10;

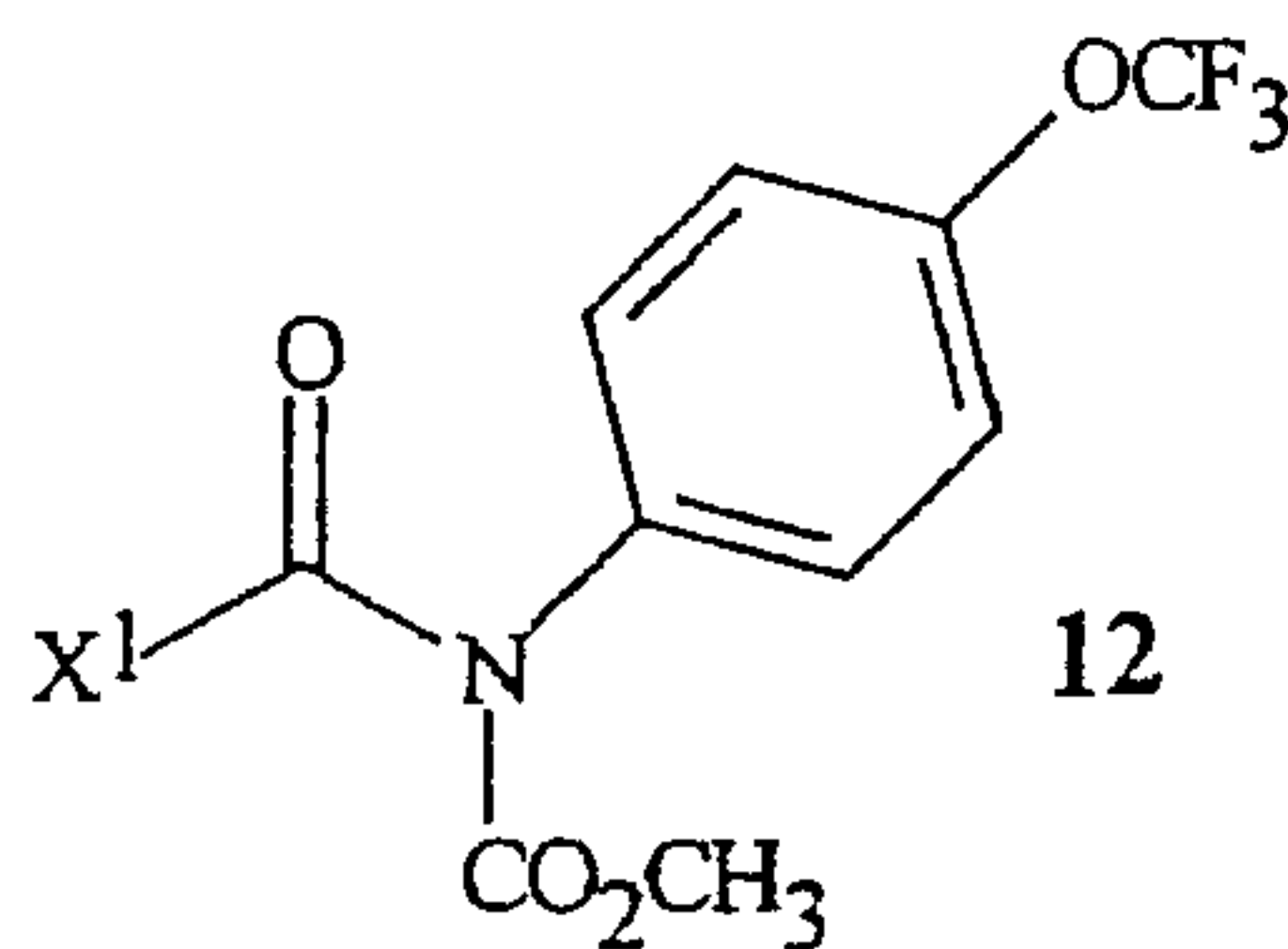
**10**

- (d) removing the protecting group from the compound of Formula 10 to form a compound of Formula 11; and

10

**11**

- (e) contacting the compound of Formula 11 with a compound of Formula 12

**12**

wherein X^1 is a leaving group;

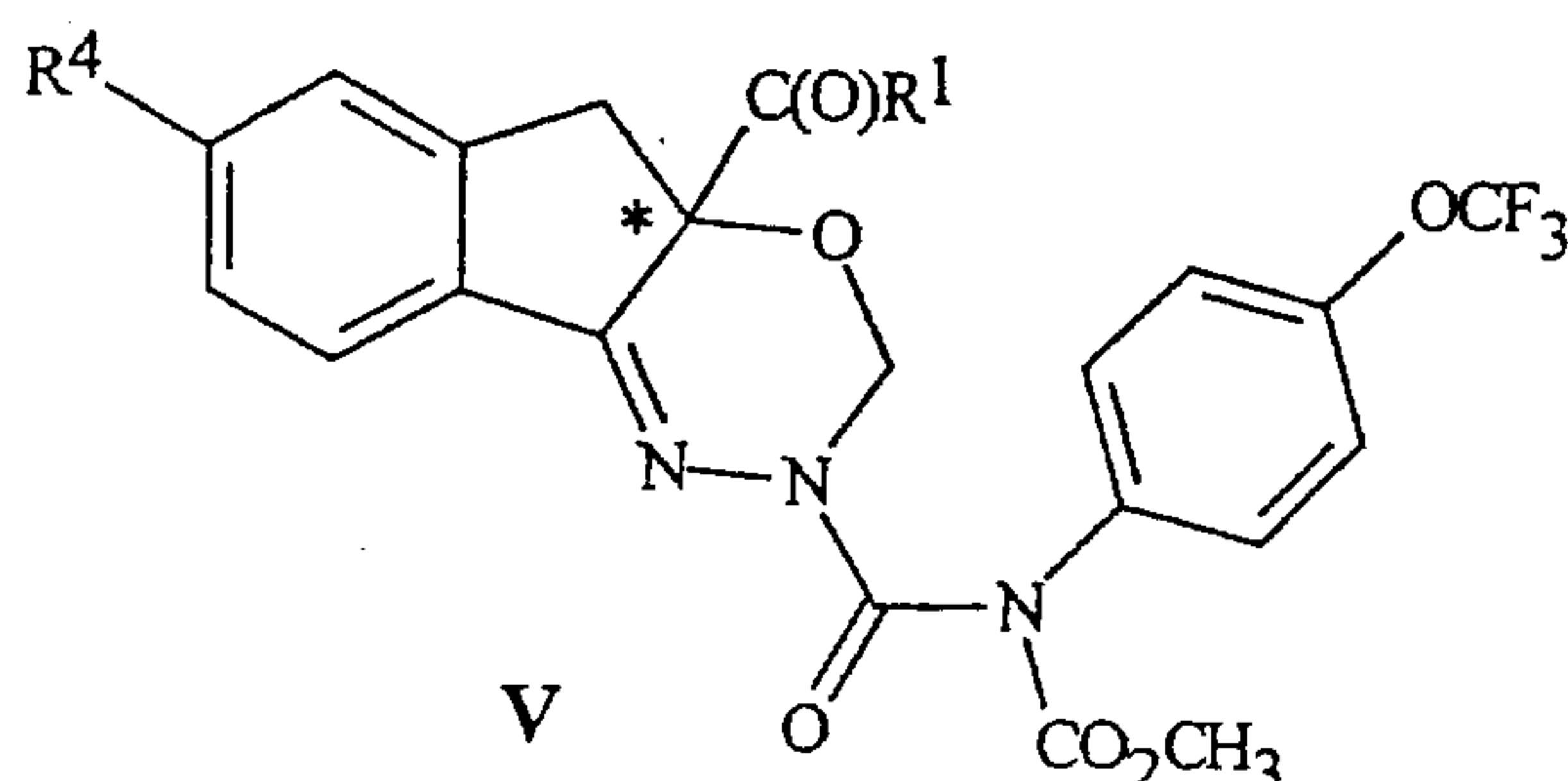
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to form the compound of Formula V.

34. The method of Claim 33 wherein R¹ is OCH₃ and R⁴ is Cl.

35. The method of Claim 33 wherein Formulae V and Ia are enantiomerically enriched with the *S* isomer.

5 36. A method of preparing a compound of Formula V



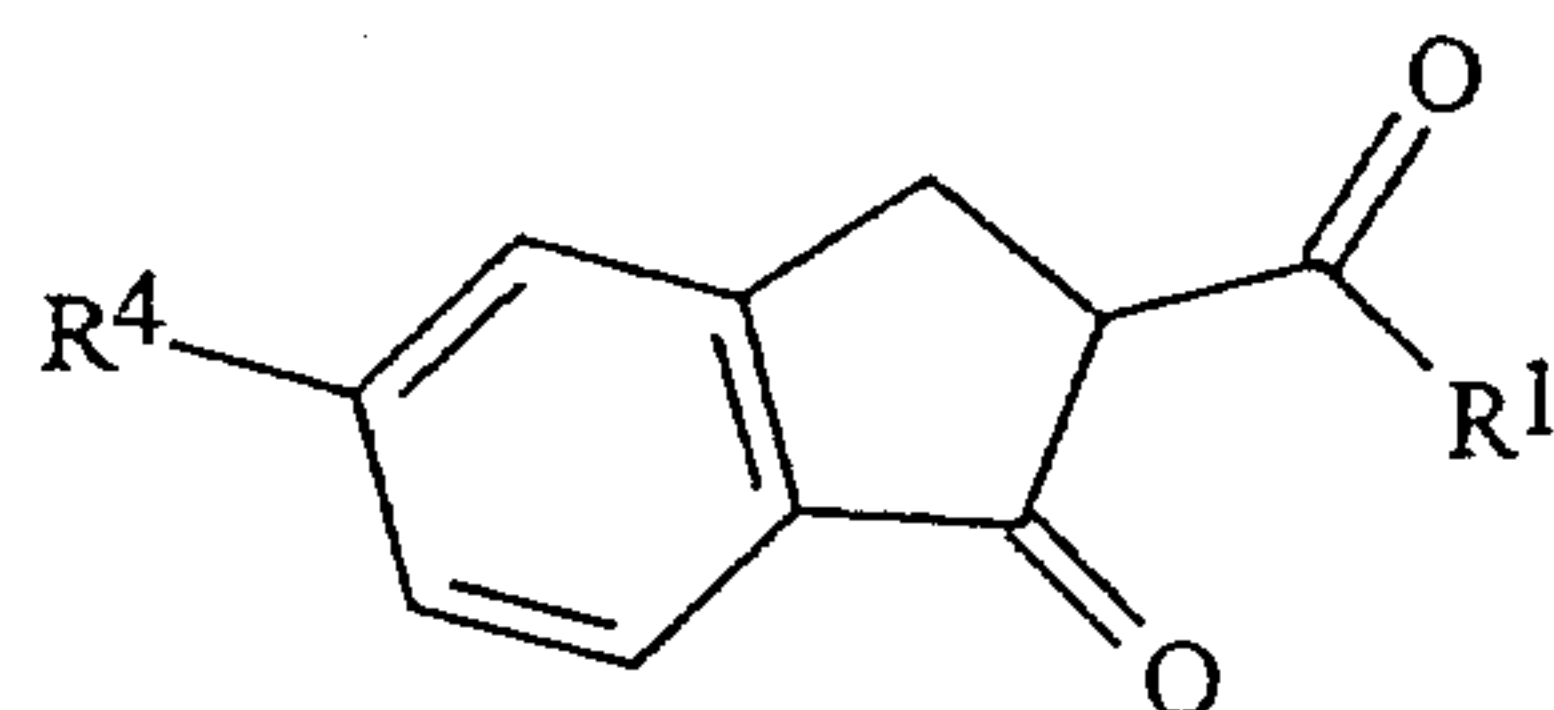
wherein

R¹ is C₁-C₃ alkoxy;

R⁴ is F, Cl or C₁-C₃ fluoroalkoxy; and

10 Formula V is racemic or enantiomerically enriched at the chiral center indicated by *, comprising the steps of:

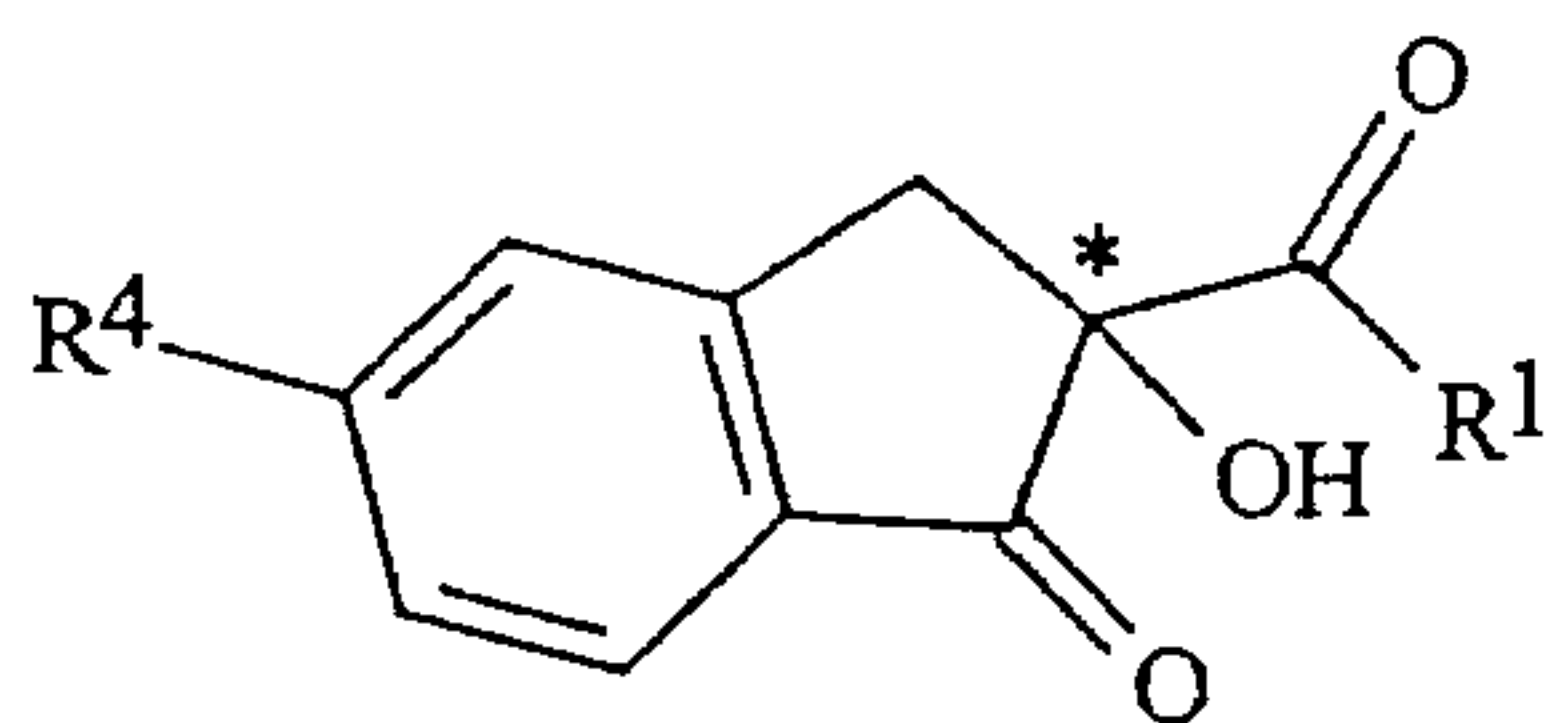
(a) contacting a compound of Formula IIa



IIa

wherein R¹ is C₁-C₃ alkoxy, and R⁴ is F, Cl, or C₁-C₃ fluoroalkoxy;

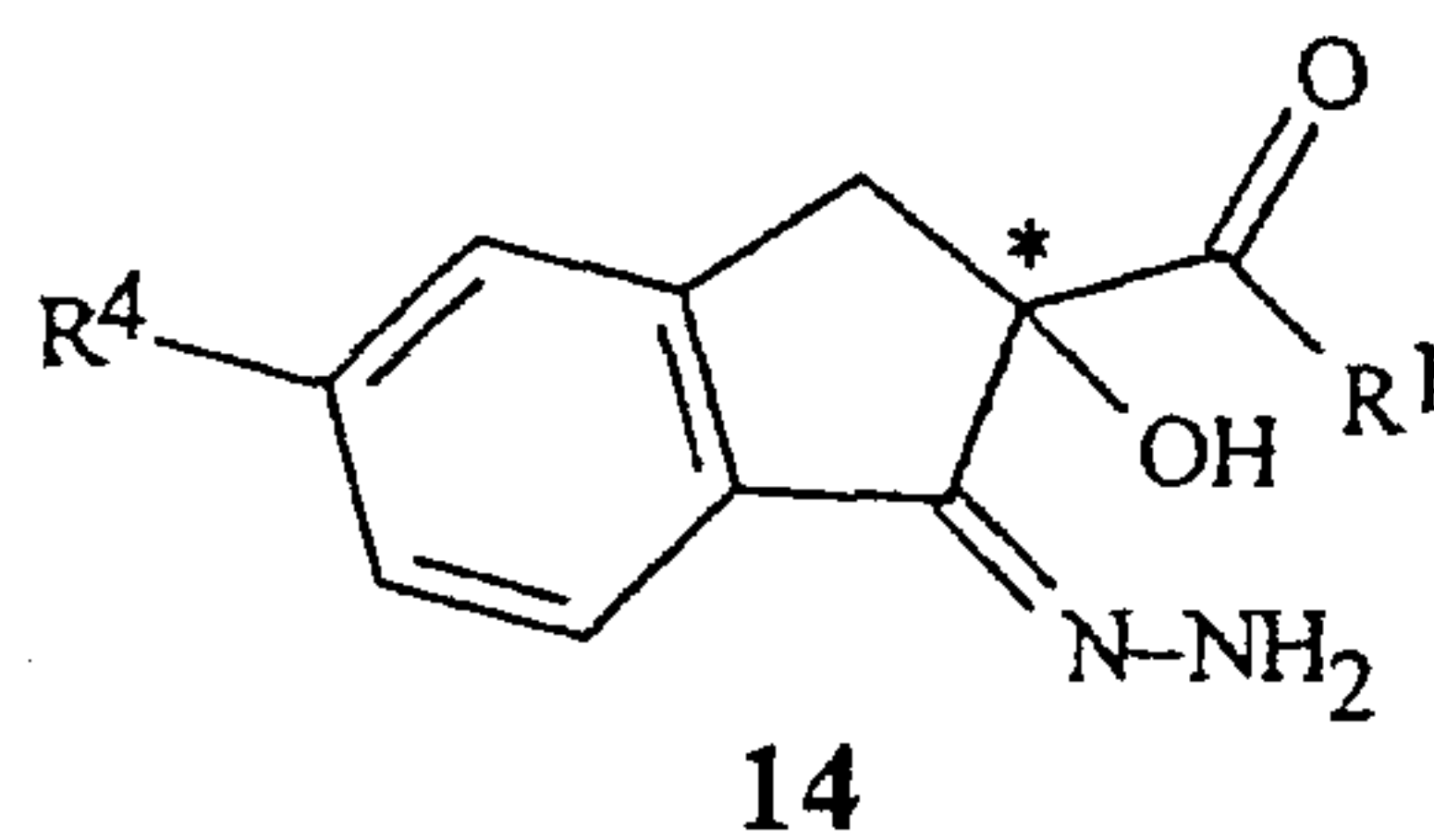
15 with a zirconium complex and an oxidant to prepare a compound of Formula Ia



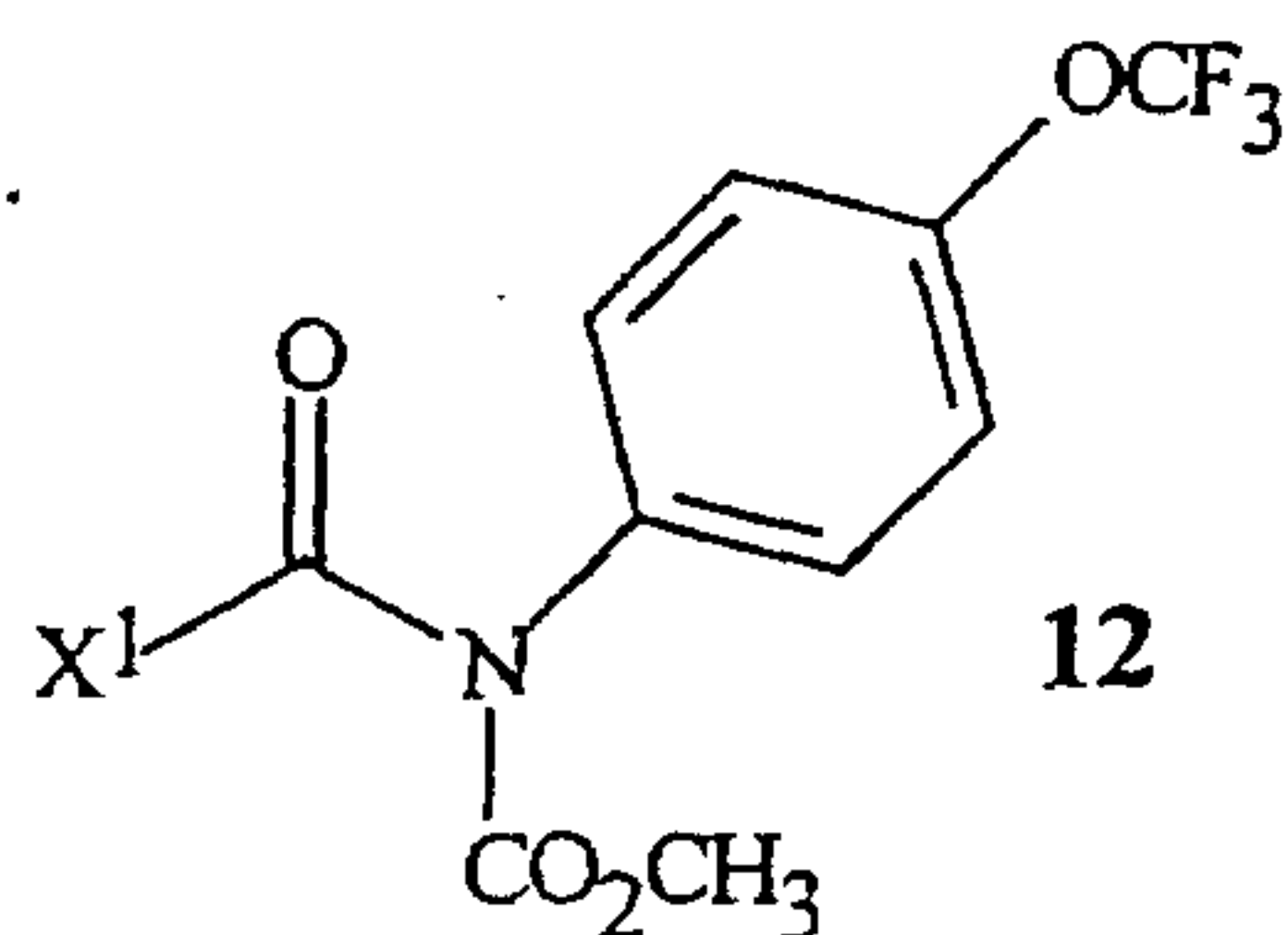
Ia

that is racemic or enantiomerically enriched at the chiral center indicated by *;

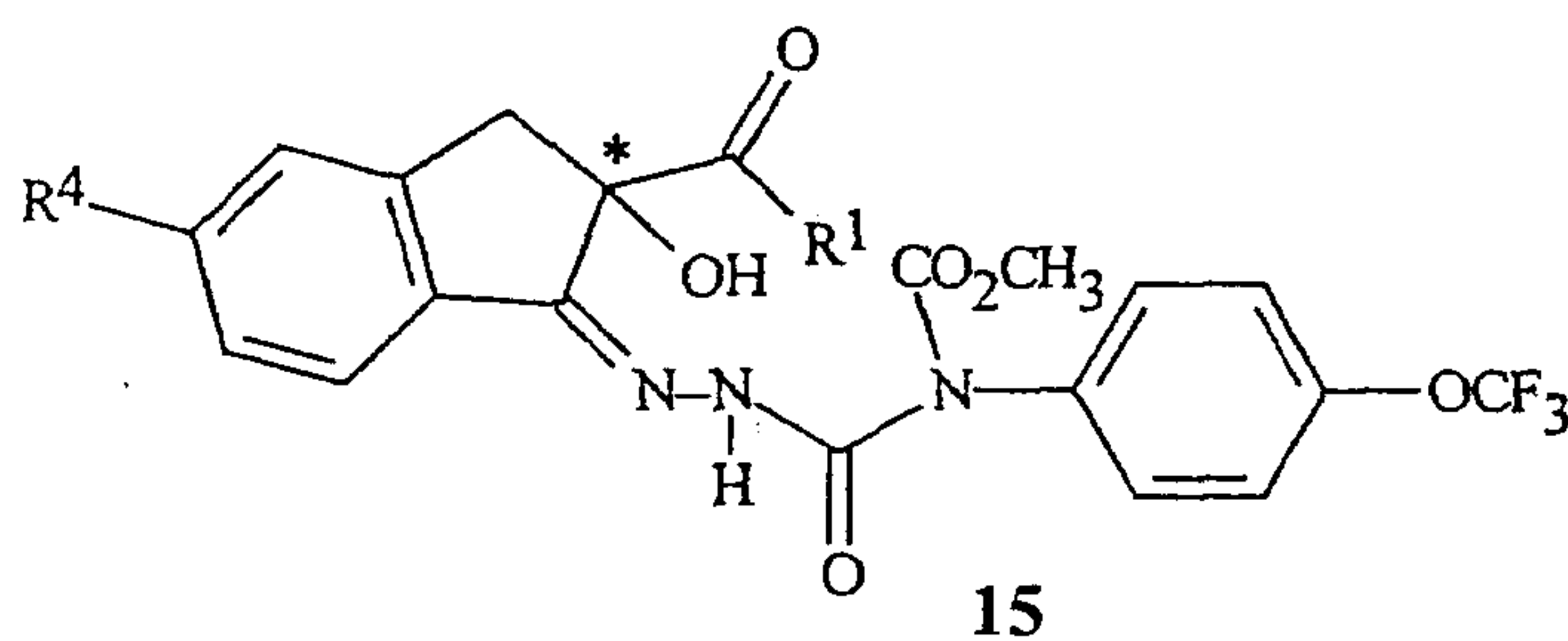
(b) contacting the compound of Formula Ia with H₂NNH₂ to form a compound of Formula 14;



(c) contacting the compound of Formula 14 with a compound of Formula 12



wherein X¹ is a leaving group to form a compound of Formula 15; and



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(d) contacting the compound of Formula 15 with a formaldehyde equivalent to form the compound of Formula V.

37. The method of Claim 36 wherein R¹ is OCH₃ and R⁴ is Cl.

38. The method of Claim 36 wherein Formulae V and Ia are enantiomerically
10 enriched with the *S* isomer.

