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MESOCYCLIQUES

(54) Title: CATALYTIC ASYMMETRIC DESYMMETRIZATION OF PROCHIRAL AND MESO CYCLIC ANHYDRIDES

(57) **Abrégé/Abstract:**

One aspect of the present invention relates to cinchona-alkaloid-based catalysts. A second aspect of the invention relates to a method of preparing a derivatized cinchona-alkaloid catalyst. Another aspect of the present invention relates to a method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of: reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a derivatized cinchona-alkaloid catalyst. Yet another aspect of the present invention relates to a method of kinetic resolution, comprising the step of: reacting a racemic cyclic anhydride with an alcohol in the presence of a derivatized cinchona-alkaloid catalyst.



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(54) Title: CATALYTIC ASYMMETRIC DESYMMETRIZATION OF PROCHIRAL AND MESO CYCLIC ANHYDRIDES

(57) Abstract: One aspect of the present invention relates to cinchona-alkaloid-based catalysts. A second aspect of the invention relates to a method of preparing a derivatized cinchona-alkaloid catalyst. Another aspect of the present invention relates to a method of preparing a chiral, nonracemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of: reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a derivatized cinchona-alkaloid catalyst. Yet another aspect of the present invention relates to a method of kinetic resolution, comprising the step of: reacting a racemic cyclic anhydride with an alcohol in the presence of a derivatized cinchona-alkaloid catalyst.



WO 2004/110609 A2

***Catalytic Asymmetric Desymmetrization
of Prochiral and Meso Cyclic Anhydrides***

Related Applications

5 This application claims the benefit of priority to United States Patent Application serial number 10/460,051, filed June 12, 2003; United States Provisional Patent Application serial number 60/477,531, filed June 11, 2003; and United States Provisional Patent Application serial number 60/484,218, filed July 1, 2003.

Government Support

10 The invention was made with support provided by the National Institutes of Health (grant number GM-61591); therefore, the government has certain rights in the invention.

Background of the Invention

 The demand for enantiomerically pure compounds has grown rapidly in recent years. One important use for such chiral, non-racemic compounds is as intermediates for synthesis in
15 the pharmaceutical industry. For instance, it has become increasingly clear that enantiomerically pure drugs have many advantages over racemic drug mixtures. These advantages include the fewer side effects and greater potency often associated with enantiomerically pure compounds.

 Traditional methods of organic synthesis were often optimized for the production of
20 racemic materials. The production of enantiomerically pure material has historically been achieved in one of two ways: use of enantiomerically pure starting materials derived from natural sources (the so-called "chiral pool"); and the resolution of racemic mixtures by classical techniques. Each of these methods has serious drawbacks, however. The chiral pool is limited to compounds found in nature, so only certain structures and configurations are readily
25 available. Resolution of racemates, which requires the use of resolving agents, may be inconvenient and time-consuming.

 One method of obtaining enantiomerically pure materials is by enantioselective alcoholysis of meso, prochiral, and racemic cyclic anhydrides (EACA). These reactions appear to be broadly applicable to both research-scale and industrial-scale asymmetric synthesis of a

wide variety of important chiral building blocks, such as hemiester, α -amino acids and α -hydroxy acids.

Summary of the Invention

One aspect of the present invention relates generally to cinchona-alkaloid-based catalysts. In certain embodiments, the quinidine-based catalyst contains a ketone, ester, amide, cyano, or alkynyl group. In preferred embodiments, the catalyst is QD-IP, QD-(-)-MN, or QD-AD. In other embodiments, the cinchona-alkaloid-based catalyst is Q-AD.

Another aspect of the invention relates to a method of preparing a derivatized cinchona alkaloid catalyst by reacting a cinchona-alkaloid with base and a compound that has a suitable leaving group. In certain embodiments, the leaving group is Cl, Br, I, OSO_2CH_3 , or OSO_2CF_3 . In a preferred embodiment, the leaving group is Cl. In a preferred embodiment, the base is a metal hydride. In a preferred embodiment, the hydroxyl group of the cinchona alkaloid undergoes reaction with an alkyl chloride to form the catalyst.

One aspect of the present invention relates to a method of preparing a chiral, non-racemic compound from a prochiral substituted cyclic anhydride or a meso substituted cyclic anhydride, comprising the step of: reacting a prochiral substituted cyclic anhydride or a meso substituted cyclic anhydride with a nucleophile in the presence of a chiral, non-racemic tertiary amine catalyst; wherein said prochiral substituted cyclic anhydride or said meso substituted cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; wherein said meso substituted cyclic anhydride comprises at least two chiral centers; and wherein said nucleophile is an alcohol, thiol or amine; thereby producing a chiral, non-racemic compound.

In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride.

In certain embodiments of the aforementioned method said nucleophile is an alcohol.

In certain embodiments of the aforementioned method said nucleophile is a primary alcohol.

In certain embodiments of the aforementioned method said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

5 In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

10 In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is QD-PP.

In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

20 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

25 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

5 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

10 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

15 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

20 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

25 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

30 In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or

substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

In certain embodiments of the aforementioned method said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is present in less than about 30 mol% relative to said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride.

In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is present in less than about 20 mol% relative to said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride.

In certain embodiments of the aforementioned method said chiral, non-racemic tertiary amine catalyst is present in less than about 10 mol% relative to said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride.

Another aspect of the present invention relates to a method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of: reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a catalyst; wherein said prochiral cyclic anhydride or meso cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; thereby producing a chiral, non-racemic compound; wherein said catalyst is a derivatized cinchona-alkaloid. In preferred embodiments, the catalyst is QD-IP, QD-(-)-MN, or QD-AD. In certain embodiments, the nucleophile is a primary alcohol.

In a preferred embodiment, the nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$. In certain embodiments, the prochiral cyclic anhydride or meso cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride. In certain embodiments, the catalyst is present in less than about 70 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride. In a preferred embodiment, the catalyst is present in less than about 10 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride. In certain embodiment, the chiral, non-

racemic compound has an enantiomeric excess greater than about 90%. In certain, embodiments, said catalyst is Q-IP, Q-PC, Q-AD, or Q-(-)-MN.

Another aspect of the present invention relates to a method of kinetic resolution, comprising the step of: reacting a racemic cyclic anhydride with an alcohol in the presence of a derivatized cinchona-alkaloid catalyst. In preferred embodiments, the catalyst is QD-IP, QD-(-)-MN, or QD-AD. In a preferred embodiment, the alcohol is a primary alcohol. In certain embodiments, the catalyst is Q-IP, Q-PC, Q-AD, or Q-(-)-MN.

In certain embodiments of the aforementioned method said chiral, non-racemic compound has an enantiomeric excess greater than about 50%.

10 In certain embodiments of the aforementioned method said chiral, non-racemic compound has an enantiomeric excess greater than about 70%.

In certain embodiments of the aforementioned method said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

15 In certain embodiments of the aforementioned method said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

Brief Description of the Drawings

Figure 1 presents the enantiomeric excess of the product obtained from the asymmetric desymmetrization of *cis*-2,3-dimethylsuccinic anhydride, as a function of the solvent and the catalyst used.

20 **Figure 2** presents the enantiomeric excesses of the products obtained from the asymmetric desymmetrization of various *meso* cyclic anhydrides, as a function of the reaction conditions used. The absolute configuration of each product was determined by comparison to an authentic sample. Enantiomeric excesses were determined using chiral GC or literature methods. In Entries 1-3, the enantiomeric excesses in parentheses pertain to products of the opposite absolute configuration obtained using (DHQ)₂AQN as the catalyst. In Entry 4, (DHQD)₂PHAL was used as the catalyst.

Figure 3 presents the enantiomeric excesses of the products obtained from the asymmetric desymmetrization of various *meso* cyclic anhydrides, as a function of the reaction conditions used. The absolute configuration of each product was determined by comparison to

an authentic sample. Enantiomeric excesses were determined using chiral GC or literature methods. In Entries 7 and 8, (DHQD)₂PHAL was used as the catalyst.

Figure 4 presents the enantiomeric excesses of the products obtained from the asymmetric desymmetrization of various *meso* cyclic anhydrides, as a function of the reaction conditions used. The absolute configuration of each product was determined by comparison to an authentic sample. Enantiomeric excesses were determined using chiral GC or literature methods. In Entries 9 and 11, (DHQD)₂PHAL was used as the catalyst.

Figure 5 depicts the structures of certain catalysts used in the methods of the present invention, and the abbreviations used herein for them.

Figure 6 depicts the structures of certain catalysts used in the methods of the present invention, and the abbreviations used herein for them.

Figure 7 depicts the structures of certain catalysts used in the methods of the present invention, and the abbreviations used herein for them.

Figure 8 depicts the enantiomeric excesses of the products obtained from the asymmetric desymmetrization of various *meso* cyclic anhydrides, as a function of the reaction conditions used.

Figure 9 depicts the enantiomeric excesses of the products obtained from the asymmetric desymmetrization of various *meso* cyclic anhydrides, as a function of the reaction conditions used. The absolute configuration of each product was determined by comparison to an authentic sample. Enantiomeric excesses were determined using chiral GC or literature methods.

Figure 10 depicts the results from desymmetrization of a number of prochiral cyclic anhydrides. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.2 M; 110 mol% catalyst was used relative to the substrate; the amount of alcohol was 1.5 equiv; the solvent was toluene; and the reaction temperature was -43 C.

Figure 11 depicts the results from desymmetrization of a number of *meso* cyclic anhydrides. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.02 M; and the solvent was ether.

Figure 12 depicts the results from desymmetrization of a number of *meso* cyclic anhydrides. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.02 M; and the solvent was ether.

Figure 13 depicts the results from desymmetrization of *cis*-2,3-dimethyl succinic anhydride. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.02 M; the catalyst was QD-PP; 20 mol% catalyst was used relative to the substrate; the amount of alcohol was 10 equiv; and the reaction was run at ambient temperature.

Figure 14 depicts the results from desymmetrization of *cis*-2,3-dimethyl succinic anhydride. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.2 M; the catalyst was QD-PP; the alcohol was methanol; and the reaction was run at ambient temperature.

Figure 15 depicts the results from desymmetrization of *cis*-2,3-dimethyl succinic anhydride. In each case: the amount of substrate was 0.1 mmol; the concentration of the substrate was 0.2 M; the catalyst was QD-PP; the alcohol was methanol; and the reaction was run at -25 C.

Figure 16 depicts the results from desymmetrization of *cis*-2,3-dimethyl succinic anhydride. In each case: the amount of substrate was 0.2 mmol; the concentration of the substrate was 0.4 M; the catalyst was QD-PP; the alcohol was methanol; the reaction was run at -25 C; and the reaction time was 6 hours.

Figure 17 depicts the results from desymmetrization of *cis*-2,3-dimethyl succinic anhydride. In each case: the concentration of the substrate was 0.02 M; 20 mol% catalyst was used relative to the substrate; the amount of alcohol was 10 equiv; and the reaction was run at ambient temperature.

Figure 18 depicts the structures of QD-PH, QD-AN, QD-NT, QD-AC and QD-CH.

Figure 19 presents a comparison of catalysts' efficiency for methanolysis of 2,3-dimethylsuccinic anhydride in Et₂O at 0.02 M concentration.

Figure 20 presents a comparison of catalysts' efficiency for methanolysis of 2,3-dimethylsuccinic anhydride in Et₂O at 0.02 M concentration.

Figure 21 presents a comparison of catalysts' efficiency for trifluoroethanolysis of 2,3-dimethylsuccinic anhydride in Et₂O at 0.02 M concentration.

Figure 22 presents reaction conditions optimization for methanolysis of 3-methylglutaric anhydride in Et₂O and 0.02 M concentration.

5 **Figure 23** presents screening of reaction conditions for alcoholysis of 3-methyl-glutaric anhydride at 0.2 M concentration.

Figure 24 presents a comparison of catalysts' efficiency for methanolysis of 3-methyl glutaric anhydride in toluene at 0.2 M concentration.

10 **Figure 25** presents a comparison of catalysts' efficiency for trifluoroethanolysis of 3-methyl glutaric anhydride in toluene at 0.2 M concentration.

Figure 26 presents a comparison of catalysts' efficiency for methanolysis of 3-phenyl glutaric anhydride in toluene at 0.2 M concentration.

Figure 27 presents a comparison of catalysts' efficiency for trifluoroethanolysis of 3-phenyl glutaric anhydride in toluene at 0.2 M concentration.

15 **Figure 28** presents a comparison of catalysts' efficiency for methanolysis of 3-isopropyl glutaric anhydride in toluene at 0.2 M concentration.

Figure 29 presents a comparison of catalysts' efficiency for trifluoroethanolysis of 3-isopropyl glutaric anhydride in toluene at 0.2 M concentration.

20 **Figure 30** presents a comparison of catalysts' efficiency for methanolysis of 3-TBSO glutaric anhydride in toluene at 0.2 M concentration.

Figure 31 presents a comparison of catalysts' efficiency for trifluoroethanolysis of 3-TBSO glutaric anhydride in toluene at 0.2 M concentration.

Figure 32 presents Q-AD catalyzed methanolysis of 3-substituted glutaric anhydride in toluene at 0.2 M concentration.

25 **Figure 33** presents Q-AD catalyzed trifluoromethanolysis of 3-substituted glutaric anhydride in toluene at 0.2 M concentration.

Figure 34 presents a comparison of catalysts' efficiency for the alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride with methanol in Et₂O at 0.02 M concentration.

30 **Figure 35** presents a comparison of catalysts' efficiency for the alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride with trifluoroethanol in Et₂O at 0.02 M concentration.

Figure 36 presents QD-AD catalyzed alcoholysis of 1,2-cyclohexanedicarboxylic anhydride with methanol in Et₂O at 0.02 M concentration.

Figure 37 presents a comparison of catalysts' efficiency for the alcoholysis of 1,2-cyclohexanedicarboxylic anhydride with trifluoroethanol in Et₂O at 0.02 M concentration.

5 **Figure 38** presents a comparison of catalysts' efficiency for the alcoholysis of *cis*-norbornene-endo-2,3-dicarboxylic anhydride in Et₂O at 0.02 M concentration.

Figure 39 presents a comparison of catalysts' efficiency for the alcoholysis of *exo*-3,6-epoxy-1,2,3,6-tetrahydrophthalic anhydride in Et₂O at 0.02 M concentration.

10 **Figure 40** presents reaction conditions optimization for the alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride in Et₂O at 0.02 M.

Figure 41 presents reaction conditions optimization for the alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride in toluene at 0.2 M.

Figure 42 presents reaction conditions optimization for the alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride in toluene at 0.5 M.

15 **Figure 43** presents alcoholysis of succinic anhydrides with Q-AD.

Figure 44 presents a comparison of catalysts' efficiency for methanolysis of 2,3-dimethylsuccinic anhydride in Et₂O at 0.02 M concentration.

Figure 45 presents a comparison of catalysts' efficiency for trifluoroethanolysis of 3-isopropyl glutaric anhydride in toluene at 0.2 M concentration.

20 ***Detailed Description of the Invention***

The invention will now be described more fully with reference to the accompanying examples, in which certain preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

25 The ability to transform selectively a prochiral or *meso* compound to a enantiomerically enriched or enantiomerically pure chiral compound has broad application, especially in the agricultural and pharmaceutical industries, as well as in the polymer industry. As described
30 herein, the present invention relates to methods and catalysts for the catalytic asymmetric

desymmetrization of prochiral and *meso* compounds and the like. The primary constituents of the methods, which are set forth in detail below, are: a non-racemic chiral tertiary-amine-containing catalyst; a prochiral or *meso* substrate, typically a heterocycle comprising a pair of electrophilic atoms related by an internal plane or point of symmetry; and a nucleophile, typically the solvent, which under the reaction conditions selectively attacks one of the two
5 aforementioned electrophilic atoms, generating an enantiomerically enriched chiral product. Additionally, the catalysts and methods of the present invention can be exploited to effect kinetic resolutions of racemic mixtures and the like.

Definitions

10 For convenience, certain terms employed in the specification, examples, and appended claims are collected here.

The term "nucleophile" is recognized in the art, and as used herein means a chemical moiety having a reactive pair of electrons. Examples of nucleophiles include uncharged compounds such as water, amines, mercaptans and alcohols, and charged moieties such as
15 alkoxides, thiolates, carbanions, and a variety of organic and inorganic anions. Illustrative anionic nucleophiles include simple anions such as hydroxide, azide, cyanide, thiocyanate, acetate, formate or chloroformate, and bisulfite. Organometallic reagents such as organocuprates, organozincs, organolithiums, Grignard reagents, enolates, acetylides, and the like may, under appropriate reaction conditions, be suitable nucleophiles. Hydride may also be
20 a suitable nucleophile when reduction of the substrate is desired.

The term "electrophile" is art-recognized and refers to chemical moieties which can accept a pair of electrons from a nucleophile as defined above. Electrophiles useful in the method of the present invention include cyclic compounds such as epoxides, aziridines, episulfides, cyclic sulfates, carbonates, lactones, lactams and the like. Non-cyclic electrophiles
25 include sulfates, sulfonates (e.g. tosylates), chlorides, bromides, iodides, and the like

The terms "electrophilic atom", "electrophilic center" and "reactive center" as used herein refer to the atom of the substrate which is attacked by, and forms a new bond to, the nucleophile. In most (but not all) cases, this will also be the atom from which the leaving group departs.

The term "electron-withdrawing group" is recognized in the art and as used herein means a functionality which draws electrons to itself more than a hydrogen atom would at the same position. Exemplary electron-withdrawing groups include nitro, ketone, aldehyde, sulfonyl, trifluoromethyl, -CN, chloride, and the like. The term "electron-donating group", as
5 used herein, means a functionality which draws electrons to itself less than a hydrogen atom would at the same position. Exemplary electron-donating groups include amino, methoxy, and the like.

The terms "Lewis base" and "Lewis basic" are recognized in the art, and refer to a chemical moiety capable of donating a pair of electrons under certain reaction conditions.
10 Examples of Lewis basic moieties include uncharged compounds such as alcohols, thiols, olefins, and amines, and charged moieties such as alkoxides, thiolates, carbanions, and a variety of other organic anions.

The terms "Lewis acid" and "Lewis acidic" are art-recognized and refer to chemical moieties which can accept a pair of electrons from a Lewis base.

15 The term "meso compound" is recognized in the art and means a chemical compound which has at least two chiral centers but is achiral due to an internal plane or point of symmetry.

The term "chiral" refers to molecules which have the property of non-superimposability on their mirror image partner, while the term "achiral" refers to molecules which are
20 superimposable on their mirror image partner. A "prochiral molecule" is an achiral molecule which has the potential to be converted to a chiral molecule in a particular process.

The term "stereoisomers" refers to compounds which have identical chemical constitution, but differ with regard to the arrangement of their atoms or groups in space. In particular, the term "enantiomers" refers to two stereoisomers of a compound which are non-
25 superimposable mirror images of one another. The term "diastereomers", on the other hand, refers to the relationship between a pair of stereoisomers that comprise two or more asymmetric centers and are not mirror images of one another.

Furthermore, a "stereoselective process" is one which produces a particular stereoisomer of a reaction product in preference to other possible stereoisomers of that product.
30 An "enantioselective process" is one which favors production of one of the two possible

enantiomers of a reaction product. The subject method is said to produce a "stereoselectively-enriched" product (e.g., enantioselectively-enriched or diastereoselectively-enriched) when the yield of a particular stereoisomer of the product is greater by a statistically significant amount relative to the yield of that stereoisomer resulting from the same reaction run in the absence of a chiral catalyst. For example, an enantioselective reaction catalyzed by one of the subject chiral catalysts will yield an e.e. for a particular enantiomer that is larger than the e.e. of the reaction lacking the chiral catalyst.

The term "regioisomers" refers to compounds which have the same molecular formula but differ in the connectivity of the atoms. Accordingly, a "regioselective process" is one which favors the production of a particular regioisomer over others, e.g., the reaction produces a statistically significant preponderance of a certain regioisomer.

The term "reaction product" means a compound which results from the reaction of a nucleophile and a substrate. In general, the term "reaction product" will be used herein to refer to a stable, isolable compound, and not to unstable intermediates or transition states.

The term "substrate" is intended to mean a chemical compound which can react with a nucleophile, or with a ring-expansion reagent, according to the present invention, to yield at least one product having a stereogenic center.

The term "catalytic amount" is recognized in the art and means a substoichiometric amount relative to a reactant. As used herein, a catalytic amount means from 0.0001 to 90 mole percent relative to a reactant, more preferably from 0.001 to 50 mole percent, still more preferably from 0.01 to 10 mole percent, and even more preferably from 0.1 to 5 mole percent relative to a reactant.

As discussed more fully below, the reactions contemplated in the present invention include reactions which are enantioselective, diastereoselective, and/or regioselective. An enantioselective reaction is a reaction which converts an achiral reactant to a chiral product enriched in one enantiomer. Enantioselectivity is generally quantified as "enantiomeric excess" (ee) defined as follows:

$$\% \text{ Enantiomeric Excess A (ee)} = (\% \text{ Enantiomer A}) - (\% \text{ Enantiomer B})$$

where A and B are the enantiomers formed. Additional terms that are used in conjunction with enantioselectivity include "optical purity" or "optical activity". An enantioselective reaction

yields a product with an e.e. greater than zero. Preferred enantioselective reactions yield a product with an e.e. greater than 20%, more preferably greater than 50%, even more preferably greater than 70%, and most preferably greater than 80%.

5 A diastereoselective reaction converts a chiral reactant (which may be racemic or enantiomerically pure) to a product enriched in one diastereomer. If the chiral reactant is racemic, in the presence of a chiral non-racemic reagent or catalyst, one reactant enantiomer may react more slowly than the other. This class of reaction is termed a kinetic resolution, wherein the reactant enantiomers are resolved by differential reaction rate to yield both enantiomerically-enriched product and enantiomerically-enriched unreacted substrate. Kinetic
10 resolution is usually achieved by the use of sufficient reagent to react with only one reactant enantiomer (i.e. one-half mole of reagent per mole of racemic substrate). Examples of catalytic reactions which have been used for kinetic resolution of racemic reactants include the Sharpless epoxidation and the Noyori hydrogenation.

A regioselective reaction is a reaction which occurs preferentially at one reactive center
15 rather than another non-identical reactive center. For example, a regioselective reaction of an unsymmetrically substituted epoxide substrate would involve preferential reaction at one of the two epoxide ring carbons.

The term "non-racemic" with respect to the chiral catalyst, means a preparation of catalyst having greater than 50% of a given enantiomer, more preferably at least 75%.
20 "Substantially non-racemic" refers to preparations of the catalyst which have greater than 90% ee for a given enantiomer of the catalyst, more preferably greater than 95% ee.

The term "alkyl" refers to the radical of saturated aliphatic groups, including straight-chain alkyl groups, branched-chain alkyl groups, cycloalkyl (alicyclic) groups, alkyl substituted cycloalkyl groups, and cycloalkyl substituted alkyl groups. In preferred embodiments, a
25 straight chain or branched chain alkyl has 30 or fewer carbon atoms in its backbone (e.g., C₁-C₃₀ for straight chain, C₃-C₃₀ for branched chain), and more preferably 20 or fewer. Likewise, preferred cycloalkyls have from 4-10 carbon atoms in their ring structure, and more preferably have 5, 6 or 7 carbons in the ring structure.

Unless the number of carbons is otherwise specified, "lower alkyl" as used herein
30 means an alkyl group, as defined above, but having from one to ten carbons, more preferably

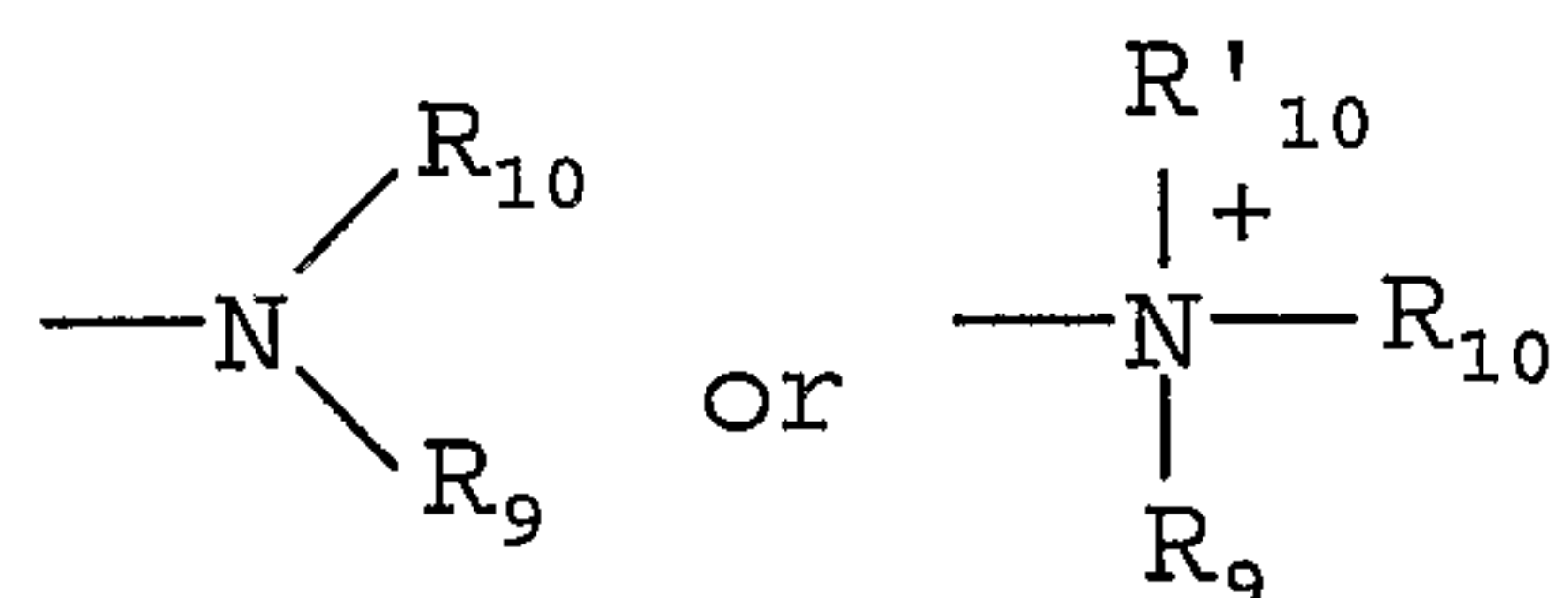
from one to six carbon atoms in its backbone structure. Likewise, "lower alkenyl" and "lower alkynyl" have similar chain lengths.

The terms "alkenyl" and "alkynyl" refer to unsaturated aliphatic groups analogous in length and possible substitution to the alkyls described above, but which contain at least one double or triple carbon-carbon bond, respectively.

The terms "alkoxyl" or "alkoxy" as used herein refers to an alkyl group, as defined above, having an oxygen radical attached thereto. Representative alkoxyl groups include methoxy, ethoxy, propyloxy, tert-butoxy and the like. An "ether" is two hydrocarbons covalently linked by an oxygen. Accordingly, the substituent of an alkyl that renders that alkyl an ether is or resembles an alkoxyl, such as can be represented by one of -O-alkyl, -O-alkenyl, -O-alkynyl, -O-(CH₂)_m-R₈, where m and R₈ are described above.

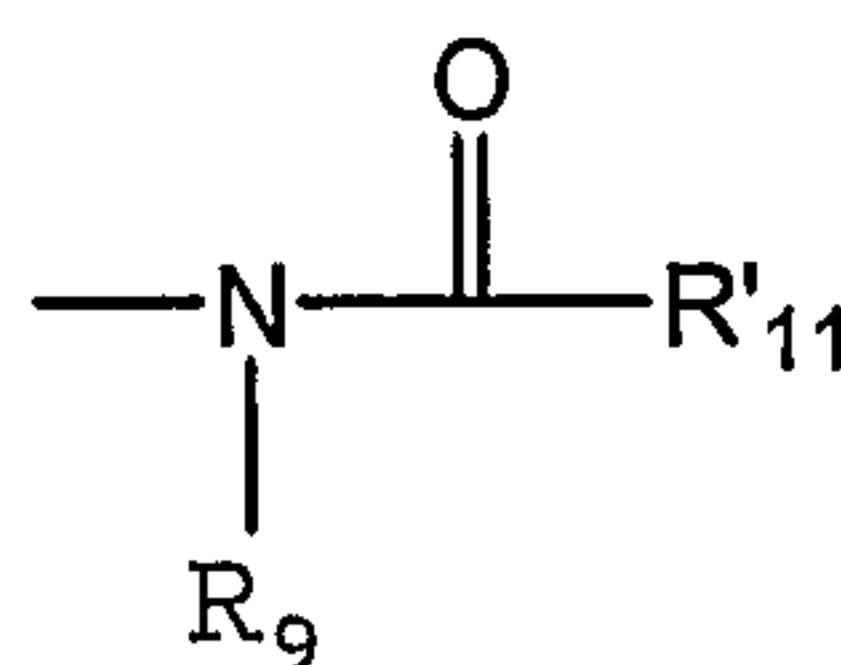
As used herein, the term "amino" means -NH₂; the term "nitro" means -NO₂; the term "halogen" designates -F, -Cl, -Br or -I; the term "thiol" means -SH; the term "hydroxyl" means -OH; the term "sulfonyl" means -SO₂-; and the term "organometallic" refers to a metallic atom (such as mercury, zinc, lead, magnesium or lithium) or a metalloid (such as silicon, arsenic or selenium) which is bonded directly to a carbon atom, such as a diphenylmethylsilyl group.

The terms "amine" and "amino" are art-recognized and refer to both unsubstituted and substituted amines, e.g., a moiety that can be represented by the general formula:



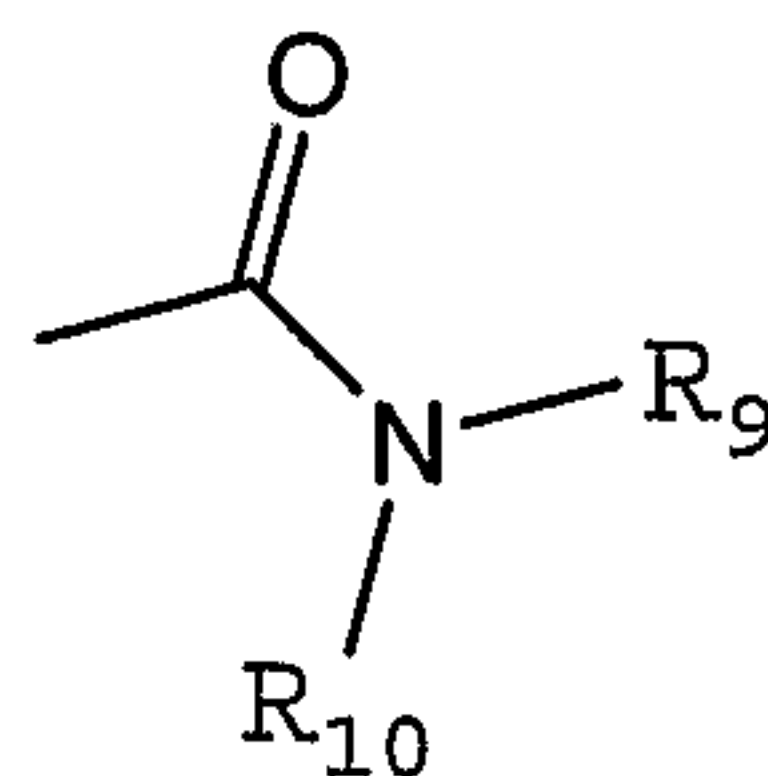
wherein R₉, R₁₀ and R'₁₀ each independently represent a group permitted by the rules of valence.

The term "acylamino" is art-recognized and refers to a moiety that can be represented by the general formula:



wherein R₉ is as defined above, and R'₁₁ represents a hydrogen, an alkyl, an alkenyl or -(CH₂)_m-R₈, where m and R₈ are as defined above.

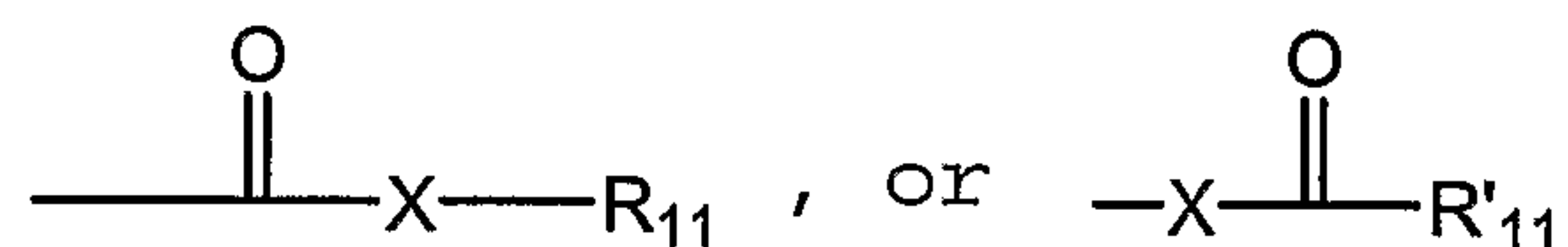
The term "amido" is art recognized as an amino-substituted carbonyl and includes a moiety that can be represented by the general formula:



wherein R₉, R₁₀ are as defined above. Preferred embodiments of the amide will not include imides which may be unstable.

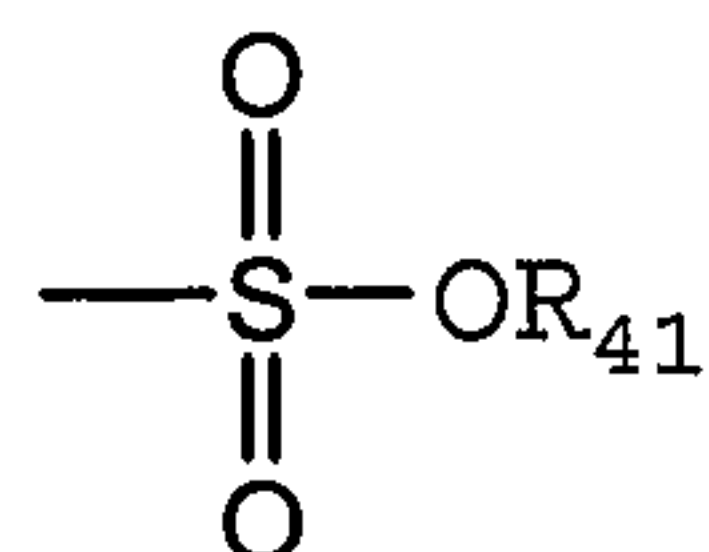
The term "alkylthio" refers to an alkyl group, as defined above, having a sulfur radical attached thereto. In preferred embodiments, the "alkylthio" moiety is represented by one of -S-alkyl, -S-alkenyl, -S-alkynyl, and -S-(CH₂)_m-R₈, wherein m and R₈ are defined above. Representative alkylthio groups include methylthio, ethyl thio, and the like.

The term "carbonyl" is art recognized and includes such moieties as can be represented by the general formula:



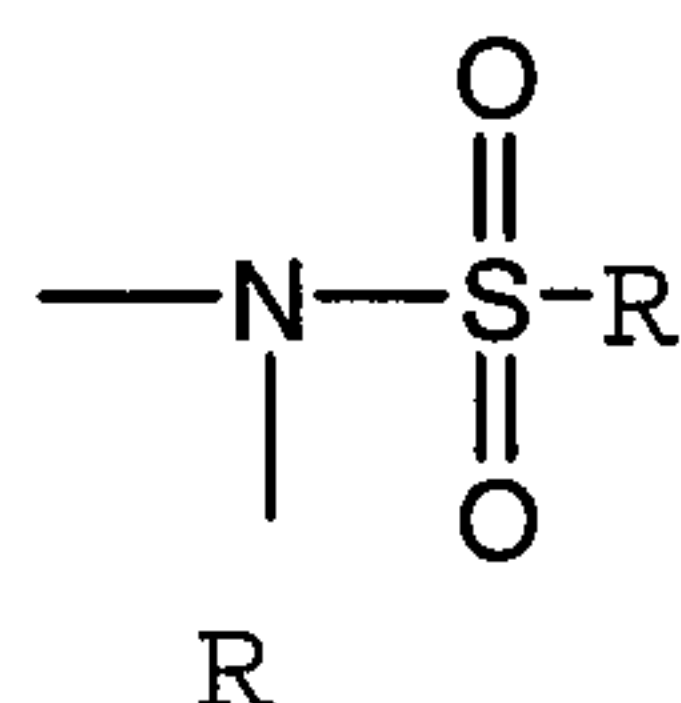
wherein X is a bond or represents an oxygen or a sulfur, and R₁₁ represents a hydrogen, an alkyl, an alkenyl, -(CH₂)_m-R₈ or a pharmaceutically acceptable salt, R'₁₁ represents a hydrogen, an alkyl, an alkenyl or -(CH₂)_m-R₈, where m and R₈ are as defined above. Where X is an oxygen and R₁₁ or R'₁₁ is not hydrogen, the formula represents an "ester". Where X is an oxygen, and R₁₁ is as defined above, the moiety is referred to herein as a carboxyl group, and particularly when R₁₁ is a hydrogen, the formula represents a "carboxylic acid". Where X is an oxygen, and R'₁₁ is hydrogen, the formula represents a "formate". In general, where the oxygen atom of the above formula is replaced by sulfur, the formula represents a "thiolcarbonyl" group. Where X is a sulfur and R₁₁ or R'₁₁ is not hydrogen, the formula represents a "thiolester." Where X is a sulfur and R₁₁ is hydrogen, the formula represents a "thiolcarboxylic acid." Where X is a sulfur and R'₁₁ is hydrogen, the formula represents a "thiolformate." On the other hand, where X is a bond, and R₁₁ is not hydrogen, the above formula represents a "ketone" group. Where X is a bond, and R₁₁ is hydrogen, the above formula represents an "aldehyde" group.

The term "sulfonate" is art recognized and includes a moiety that can be represented by the general formula:

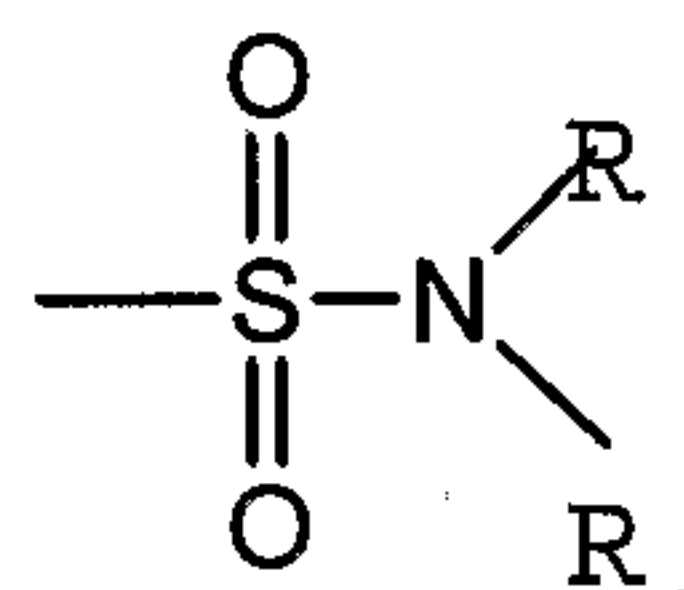


in which R₄₁ is an electron pair, hydrogen, alkyl, cycloalkyl, or aryl.

5 The term "sulfonylamino" is art recognized and includes a moiety that can be represented by the general formula:

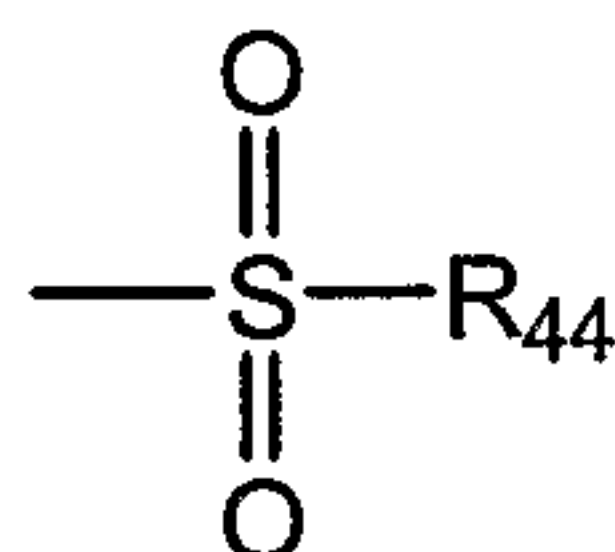


The term "sulfamoyl" is art-recognized and includes a moiety that can be represented by the general formula:



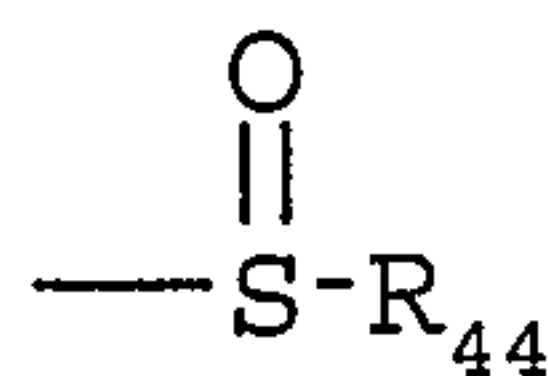
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The term "sulfonyl", as used herein, refers to a moiety that can be represented by the general formula:



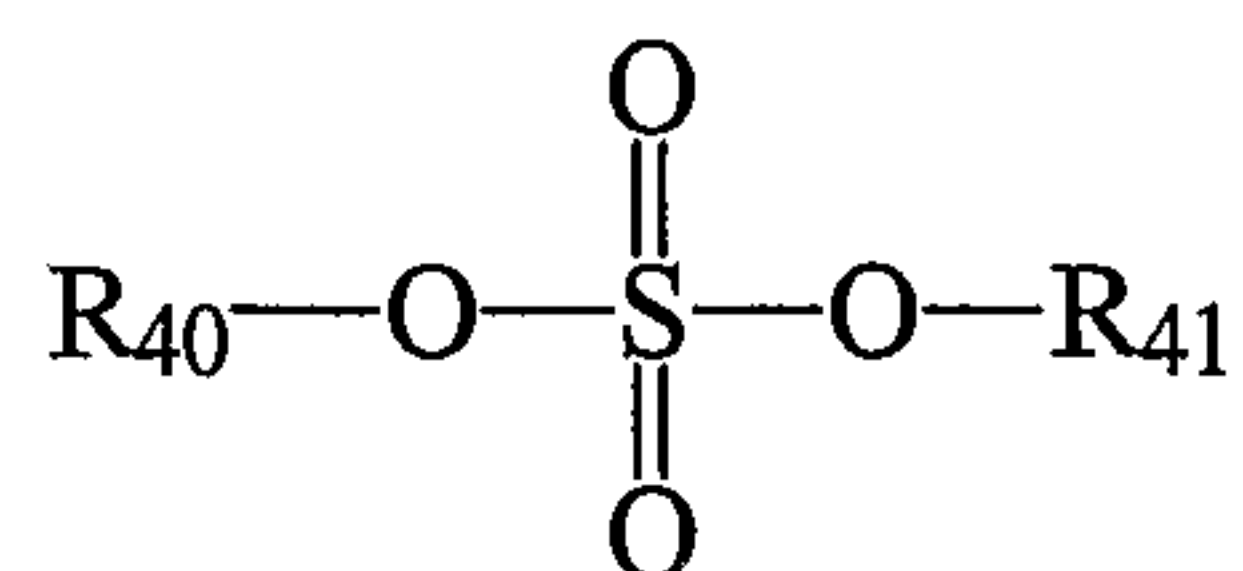
15 in which R₄₄ is selected from the group consisting of hydrogen, alkyl, alkenyl, alkynyl, cycloalkyl, heterocyclyl, aryl, or heteroaryl.

The term "sulfoxido" as used herein, refers to a moiety that can be represented by the general formula:



20 in which R₄₄ is selected from the group consisting of hydrogen, alkyl, alkenyl, alkynyl, cycloalkyl, heterocyclyl, aralkyl, or aryl.

The term "sulfate", as used herein, means a sulfonyl group, as defined above, attached to two hydroxy or alkoxy groups. Thus, in a preferred embodiment, a sulfate has the structure:



in which R₄₀ and R₄₁ are independently absent, a hydrogen, an alkyl, or an aryl. Furthermore,
 5 R₄₀ and R₄₁, taken together with the sulfonyl group and the oxygen atoms to which they are attached, may form a ring structure having from 5 to 10 members.

Analogous substitutions can be made to alkenyl and alkynyl groups to produce, for example, alkenylamines, alkynylamines, alkenylamides, alkynylamides, alkenylimines, alkynylimines, thioalkenyls, thioalkynyls, carbonyl-substituted alkenyls or alkynyls, alkenoxyls,
 10 alkynoxyls, metalloalkenyls and metalloalkynyls.

The term "aryl" as used herein includes 4-, 5-, 6- and 7-membered single-ring aromatic groups which may include from zero to four heteroatoms, for example, benzene, naphthalene, anthracene, pyrene, pyrrole, furan, thiophene, imidazole, oxazole, thiazole, triazole, pyrazole, pyridine, pyrazine, pyridazine and pyrimidine, and the like. Those aryl groups having
 15 heteroatoms in the ring structure may also be referred to as "aryl heterocycle". The aromatic ring can be substituted at one or more ring positions with such substituents as described above, as for example, halogens, alkyls, alkenyls, alkynyls, hydroxyl, amino, nitro, thiol amines, imines, amides, phosphonates, phosphines, carbonyls, carboxyls, silyls, ethers, thioethers, sulfonyls, selenoethers, ketones, aldehydes, esters, or -(CH₂)_m-R₇, -CF₃, -CN, or the like.

20 The terms "heterocycle" or "heterocyclic group" refer to 4 to 10-membered ring structures, more preferably 5 to 7 membered rings, which ring structures include one to four heteroatoms. Heterocyclic groups include pyrrolidine, oxolane, thiolane, imidazole, oxazole, piperidine, piperazine, morpholine. The heterocyclic ring can be substituted at one or more positions with such substituents as described above, as for example, halogens, alkyls, alkenyls,
 25 alkynyls, hydroxyl, amino, nitro, thiol, amines, imines, amides, phosphonates, phosphines, carbonyls, carboxyls, silyls, ethers, thioethers, sulfonyls, selenoethers, ketones, aldehydes, esters, or -(CH₂)_m-R₇, -CF₃, -CN, or the like.

The terms "polycycle" or "polycyclic group" refer to two or more cyclic rings (e.g., cycloalkyls, cycloalkenyls, cycloalkynyls, aryls and/or heterocycles) in which two or more carbons are common to two adjoining rings, e.g., the rings are "fused rings". Rings that are joined through non-adjacent atoms are termed "bridged" rings. Each of the rings of the polycycle can be substituted with such substituents as described above, as for example, halogens, alkyls, alkenyls, alkynyls, hydroxyl, amino, nitro, thiol, amines, imines, amides, phosphonates, phosphines, carbonyls, carboxyls, silyls, ethers, thioethers, sulfonyls, selenoethers, ketones, aldehydes, esters, or $-(CH_2)_m-R_7$, $-CF_3$, $-CN$, or the like.

The term "heteroatom" as used herein means an atom of any element other than carbon or hydrogen. Preferred heteroatoms are nitrogen, oxygen, sulfur, phosphorus and selenium.

For purposes of this invention, the chemical elements are identified in accordance with the Periodic Table of the Elements, CAS version, Handbook of Chemistry and Physics, 67th Ed., 1986-87, inside cover.

The terms *ortho*, *meta* and *para* apply to 1,2-, 1,3- and 1,4-disubstituted benzenes, respectively. For example, the names 1,2-dimethylbenzene and *ortho*-dimethylbenzene are synonymous.

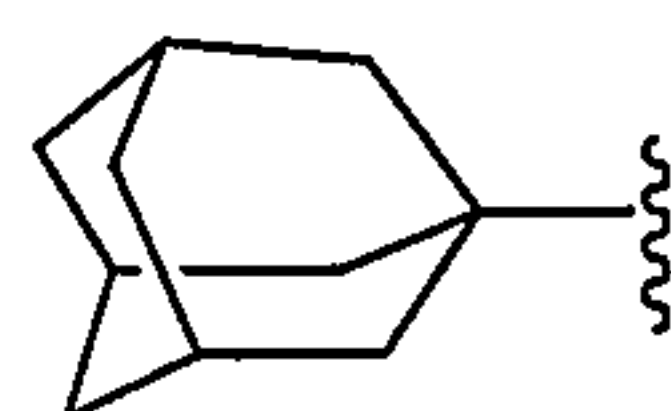
The terms triflyl, tosyl, mesyl, and nonafllyl are art-recognized and refer to trifluoromethanesulfonyl, *p*-toluenesulfonyl, methanesulfonyl, and nonafluorobutanesulfonyl groups, respectively. The terms triflate, tosylate, mesylate, and nonaflate are art-recognized and refer to trifluoromethanesulfonate ester, *p*-toluenesulfonate ester, methanesulfonate ester, and nonafluorobutanesulfonate ester functional groups and molecules that contain said groups, respectively.

The abbreviations Me, Et, Ph, Tf, Nf, Ts, and Ms, represent methyl, ethyl, phenyl, trifluoromethanesulfonyl, nonafluorobutanesulfonyl, *p*-toluenesulfonyl and methanesulfonyl, respectively. A more comprehensive list of the abbreviations utilized by organic chemists of ordinary skill in the art appears in the first issue of each volume of the *Journal of Organic Chemistry*; this list is typically presented in a table entitled Standard List of Abbreviations. The abbreviations contained in said list, and all abbreviations utilized by organic chemists of ordinary skill in the art are hereby incorporated by reference.

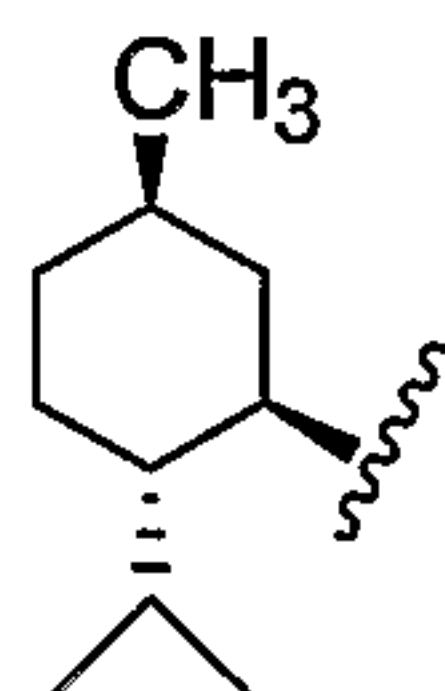
The phrase "protecting group" as used herein means temporary substituents which protect a potentially reactive functional group from undesired chemical transformations. Examples of such protecting groups include esters of carboxylic acids, silyl ethers of alcohols, and acetals and ketals of aldehydes and ketones, respectively. The field of protecting group chemistry has been reviewed (Greene, T.W.; Wuts, P.G.M. *Protective Groups in Organic*
5 *Synthesis*, 2nd ed.; Wiley: New York, 1991).

As used herein, the term "substituted" is contemplated to include all permissible substituents of organic compounds. In a broad aspect, the permissible substituents include acyclic and cyclic, branched and unbranched, carbocyclic and heterocyclic, aromatic and
10 nonaromatic substituents of organic compounds. Illustrative substituents include, for example, those described hereinabove. The permissible substituents can be one or more and the same or different for appropriate organic compounds. For purposes of this invention, the heteroatoms such as nitrogen may have hydrogen substituents and/or any permissible substituents of organic compounds described herein which satisfy the valencies of the heteroatoms. This invention is
15 not intended to be limited in any manner by the permissible substituents of organic compounds.

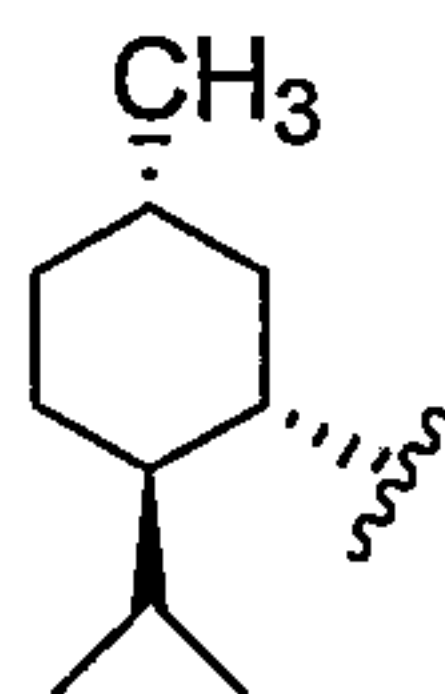
The term "1-adamantyl" is art-recognized and includes a moiety represented by the formula:



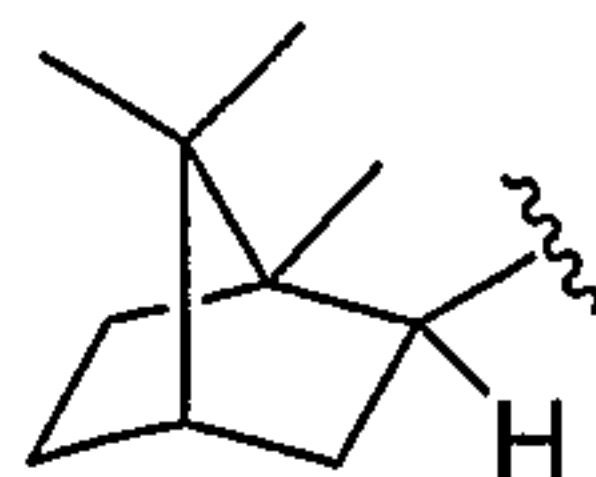
The term "(-)-menthyl" is art-recognized and includes a moiety represented by the
20 formula:



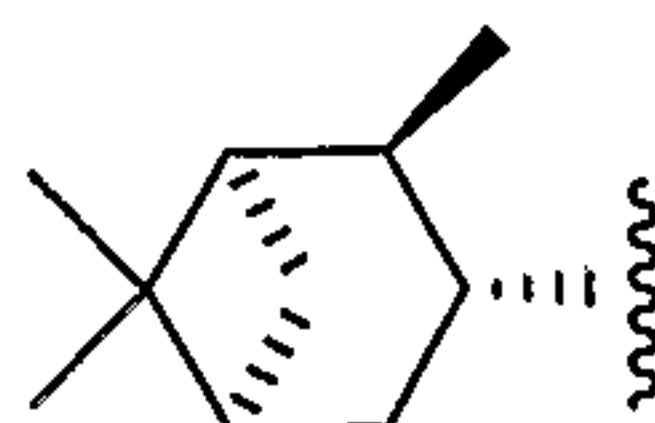
The term "(+)-menthyl" is art-recognized and includes a moiety represented by the formula:



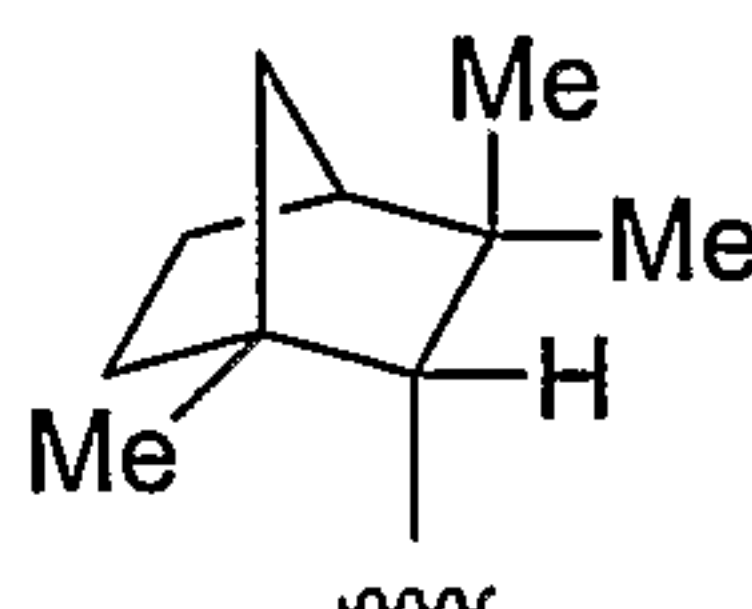
The term “isobornyl” is art-recognized and includes a moiety represented by the formula:



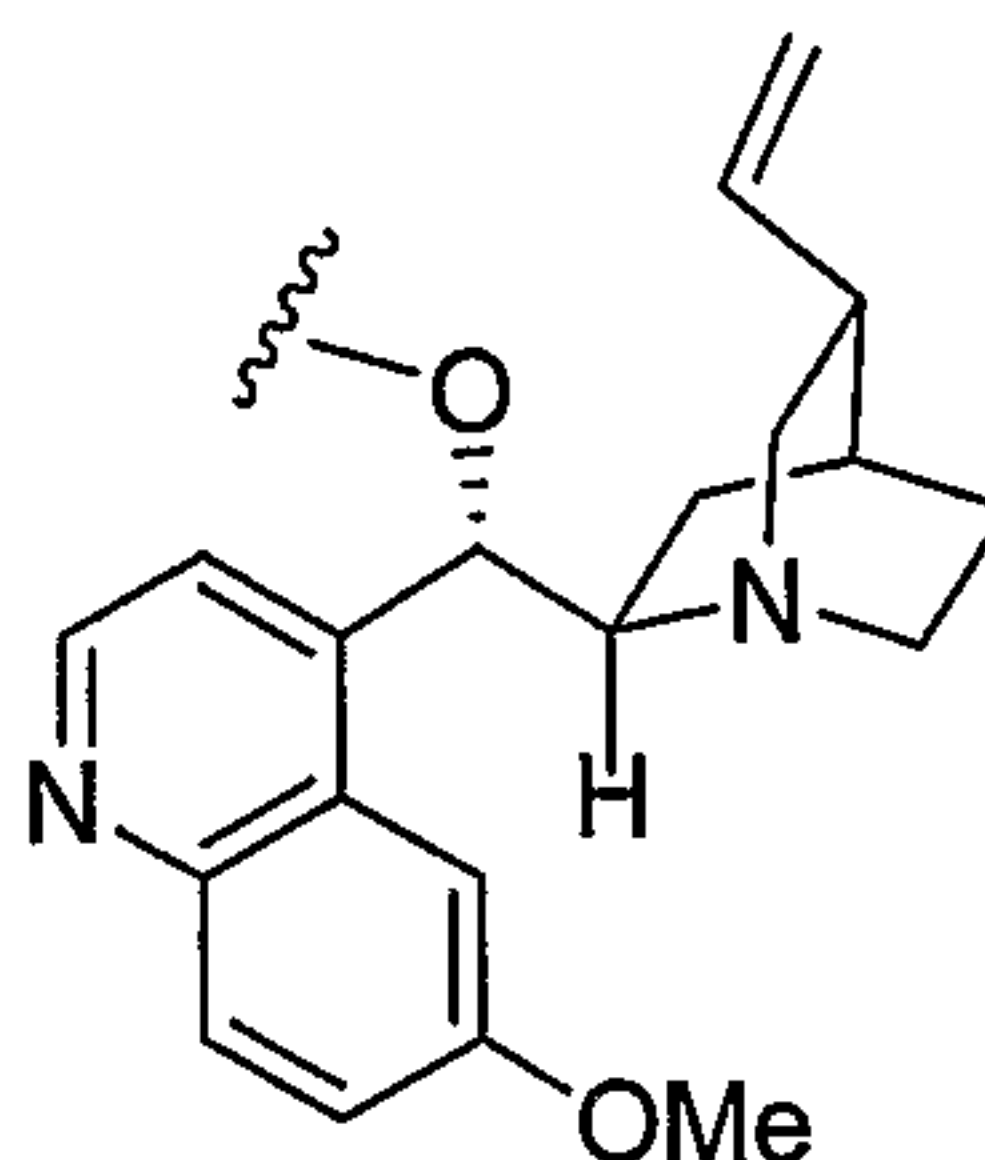
5 The term “isopinocamphyl” is art-recognized and includes a moiety represented by the formula:



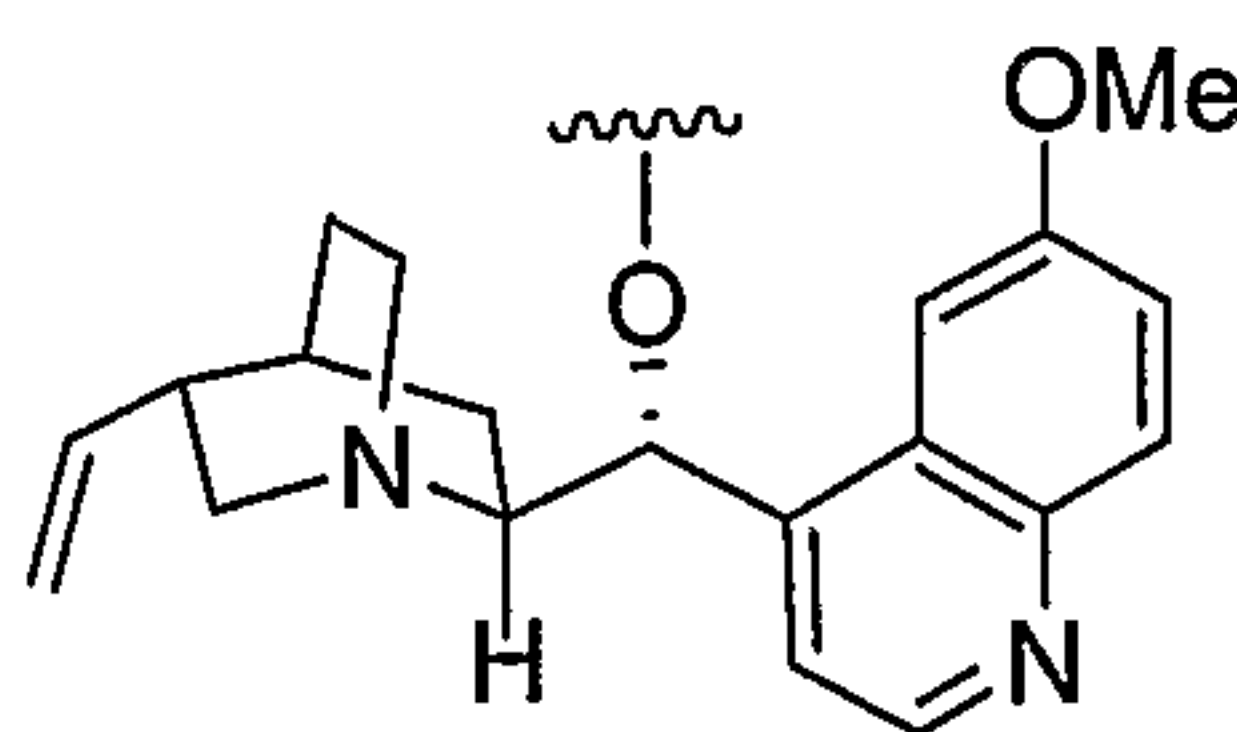
The term “(+)-fenchyl” is art-recognized and includes a moiety represented by the formula:



10 The term “QD” is represented by the formula:



The term “Q” is represented by the formula:



Catalysts of the Invention

15 The catalysts employed in the subject methods are non-racemic chiral amines which present an asymmetric environment, causing differentiation between two or more moieties related by symmetry in a prochiral or *meso* molecule, i.e., a molecule comprising at least two chiral centers, and an internal plane or point of symmetry or both. In general, catalysts intended by the present invention can be characterized in terms of a number of features. For instance, a
20 salient aspect of each of the catalysts contemplated by the instant invention concerns the use of

asymmetric bicyclic or polycyclic scaffolds incorporating the tertiary amine moiety which provide a rigid or semi-rigid environment near the amine nitrogen. This feature, through imposition of structural rigidity on the amine nitrogen in proximity to one or more asymmetric centers present in the scaffold, contributes to the creation of a meaningful difference in the energies of the corresponding diastereomeric transitions states for the overall transformation. Furthermore, the choice of substituents may also effect catalyst reactivity. For example, bulkier substituents on the catalyst are generally found to provide higher catalyst turnover numbers.

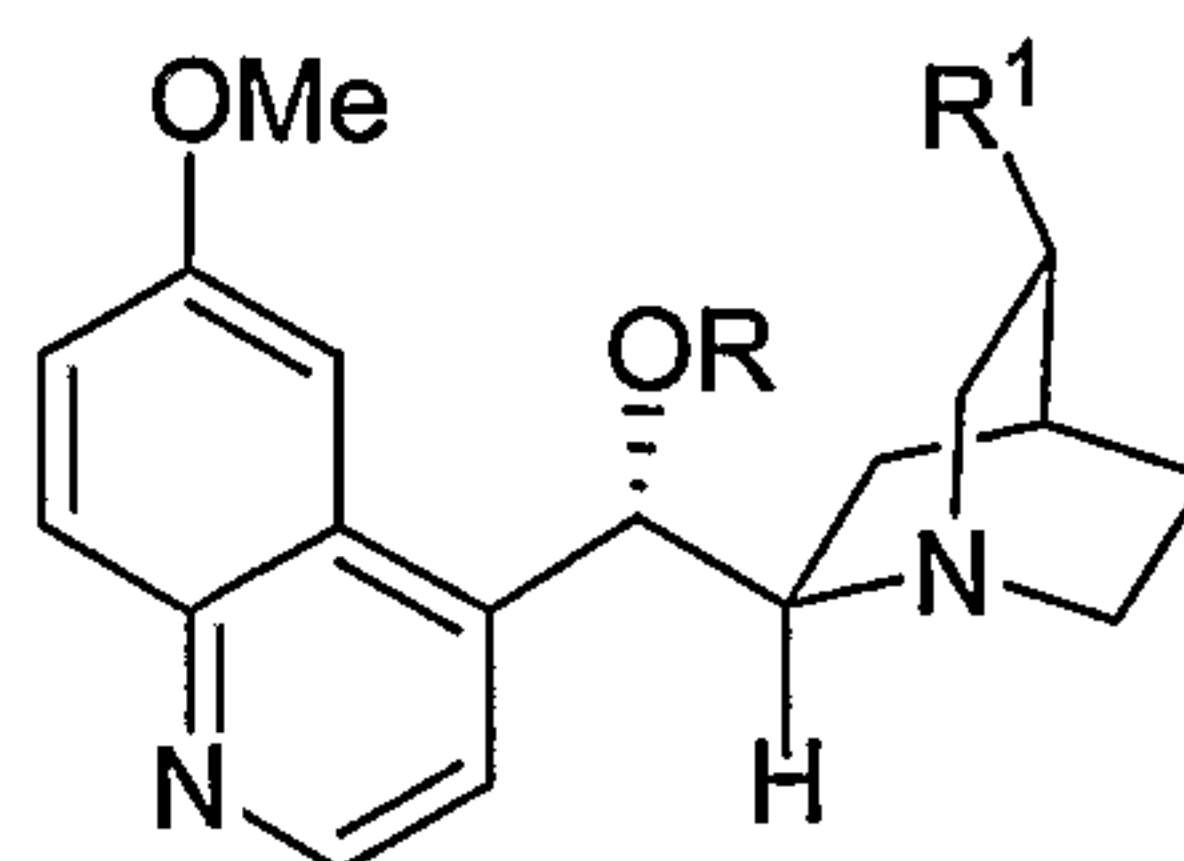
A preferred embodiment for each of the embodiments described above provides a catalyst having a molecular weight less than 2,000 g/mol, more preferably less than 1,000 g/mol, and even more preferably less than 500 g/mol. Additionally, the substituents on the catalyst can be selected to influence the solubility of the catalyst in a particular solvent system.

In certain embodiments, the chiral, non-racemic tertiary amine catalyst comprises a 1-azabicyclo[2.2.2]octane moiety or a 1,4-diazabicyclo[2.2.2]octane moiety. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is a cinchona alkaloid, Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is QD-PP.

As mentioned briefly above, the choice of catalyst substituents can also effect the electronic properties of the catalyst. Substitution of the catalyst with electron-rich (electron-donating) moieties (including, for example, alkoxy or amino groups) may increase the electron density of the catalyst at the tertiary amine nitrogen, rendering it a stronger nucleophile and/or Bronsted base and/or Lewis base. Conversely, substitution of the catalyst with electron-poor moieties (for example, chloro or trifluoromethyl groups) can result in lower electron density of the catalyst at the tertiary amine nitrogen, rendering it a weaker nucleophile and/or Bronsted base and/or Lewis base. To summarize this consideration, the electron density of the catalyst can be important because the electron density at the tertiary amine nitrogen will influence the

Lewis basicity of the nitrogen and its nucleophilicity. Choice of appropriate substituents thus makes possible the "tuning" of the reaction rate and the stereoselectivity of the reaction.

One aspect of the present invention relates to a compound represented by formula I:



I

5

wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$, $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

10 R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

15

R^4 represents cycloalkyl, $-CH(R^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

20 n is 1-10.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, or $-C(C(R^3)_2)_nC\equiv CR^6$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R^1 is ethyl.

25

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R^1 is $-CH=CH_2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{C}(\text{O})\text{R}^2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{C}(\text{O})\text{R}^2$ and R^2 is alkyl.

5 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is $-\text{CH}(\text{R}^3)_2$.

10 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, R^4 is $-\text{CH}(\text{R}^3)_2$, n is 1.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

15 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.

20 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{N}(\text{R}^5)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.

25 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{NH}$ -1-adamantyl and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CN}$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-\text{CH}_2\text{CN}$ and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-(C(R^3)_2)_nCOR^5$.

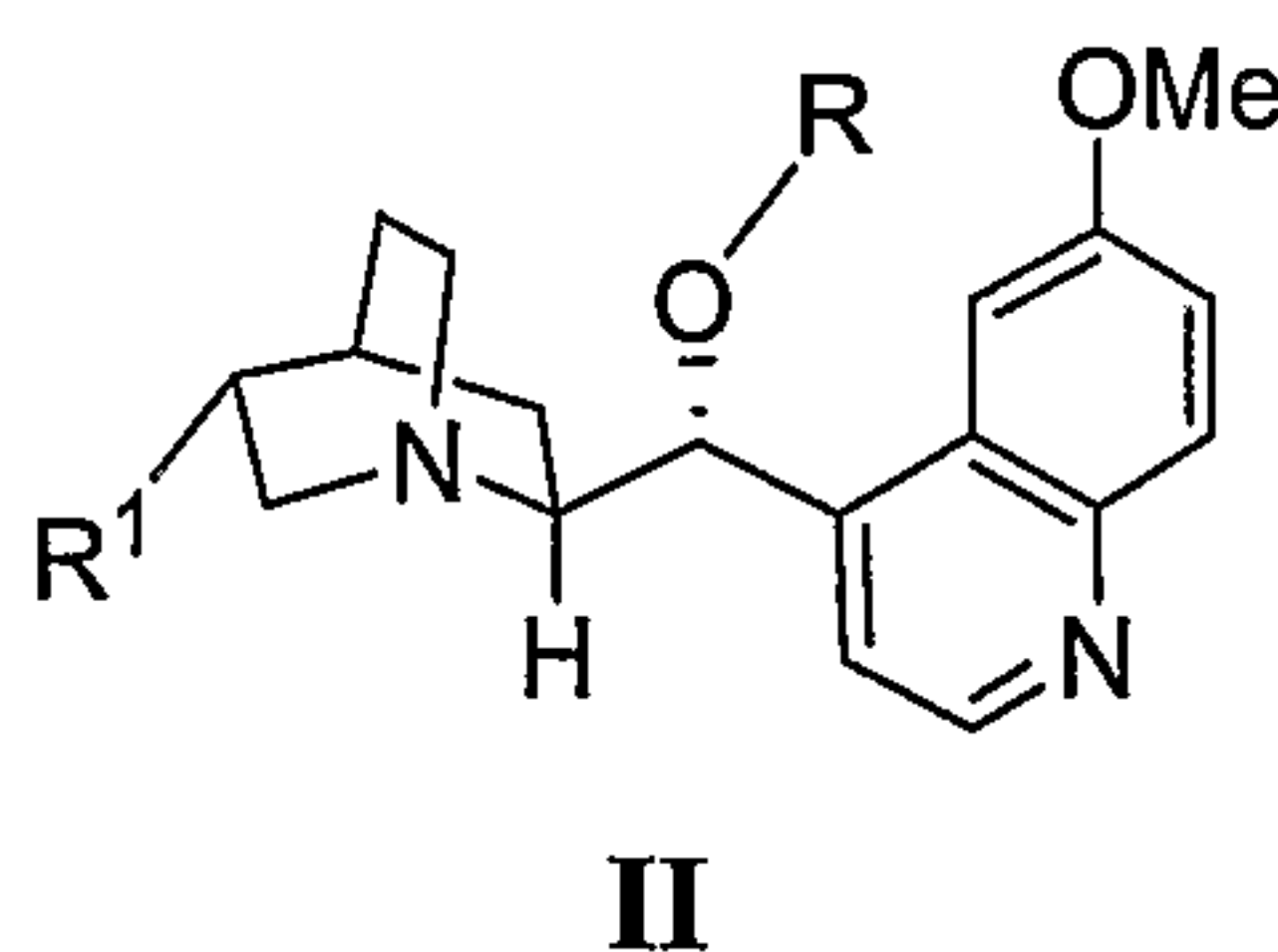
In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-CH_2C(O)R^5$ and R^5 is alkyl.

5 In certain embodiments, the compounds of the present invention are represented by formula I, wherein R is $-CH_2C(O)C(CH_3)_3$ and R^1 is $-CH=CH_2$.

In certain embodiments, said compound is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF, QD-AA, QD-MP, or QD-IPC.

10 In certain embodiments, said compound is QD-IP, QD-(-)-MN, or QD-AD.

Another aspect of the present invention relates to a compound represented by formula II:



wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$,
 20 $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine,
 25 imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-CH(R^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

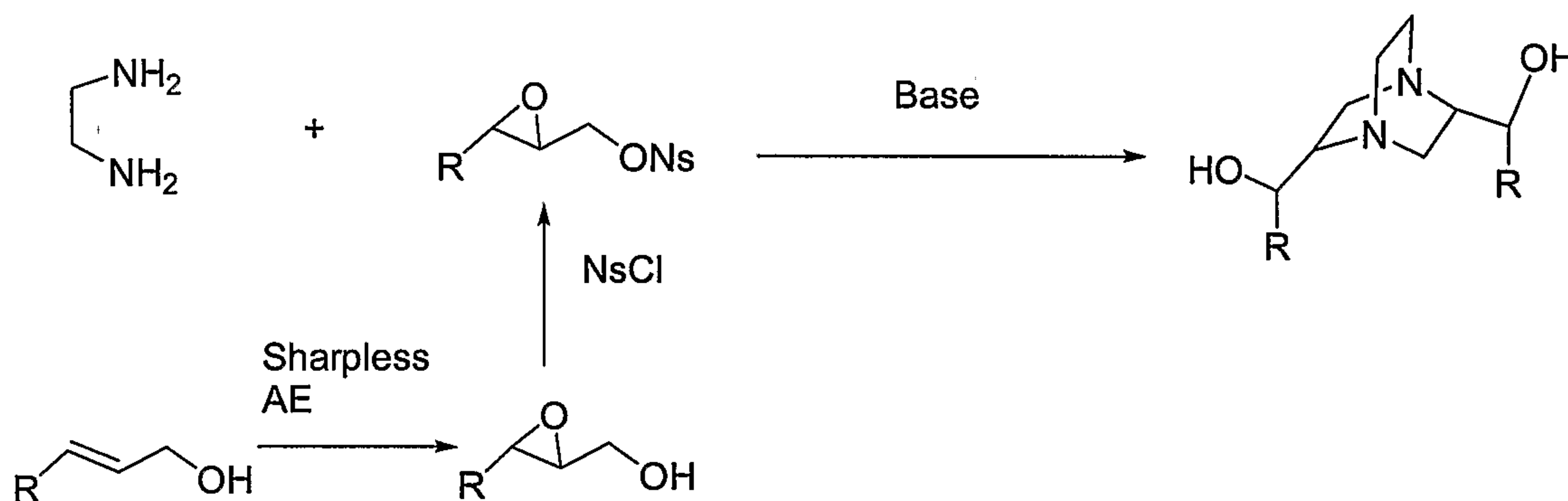
R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10.

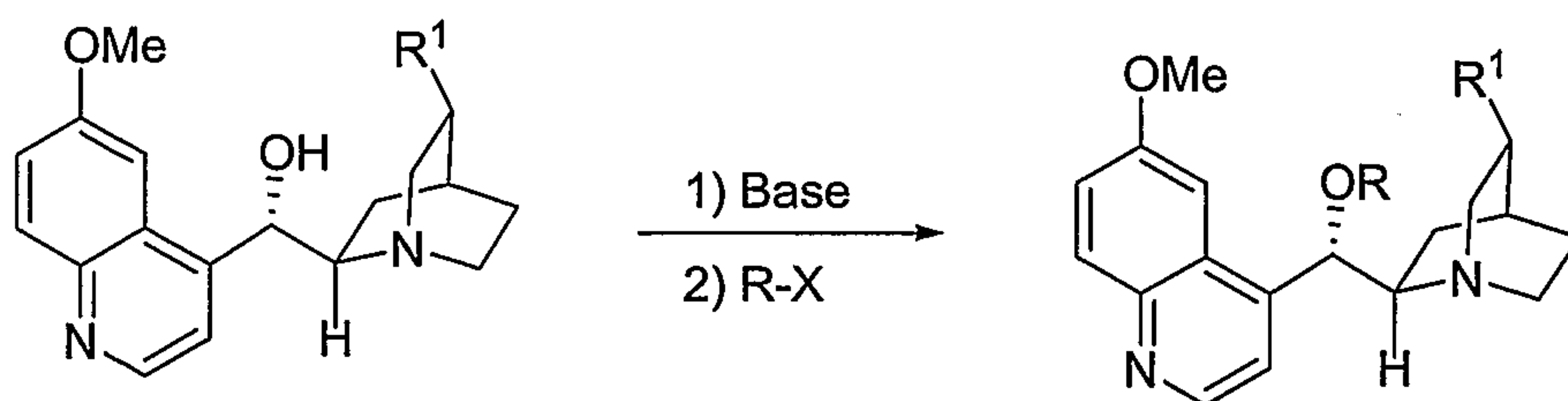
- 5 In certain embodiments, said compound is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

Methods of the Invention -- Preparation of Asymmetric Tertiary-Amine-Containing Catalysts

Certain aspects of the present invention relate to methods for preparing tertiary amines, which tertiary amine will be useful in the desymmetrization methods of the present invention. In certain embodiments, the tertiary amines are synthesized according to a general procedure, wherein a diamine is reacted with two equivalents of a chiral, non-racemic glycidyl sulfonate or halide. For example, the scheme below depicts an embodiment of these methods, wherein ethylene diamine and two equivalents of a chiral, non-racemic glycidyl nosylate react to give a chiral, non-racemic bis-tertiary amine. See also Example 2.



One aspect of the invention relates to a method of preparing a derivatized cinchona alkaloid catalyst as depicted in Scheme 1:



Scheme 1

wherein,

X represents Cl, Br, I, OSO_2CH_3 , or OSO_2CF_3 ;

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl;

n is 1-10; and

base is a Bronsted base.

In certain embodiments, the present invention relates to the aforementioned method, wherein X is Cl or Br.

In certain embodiments, the present invention relates to the aforementioned method, wherein said base is a metal hydride, alkoxide, or amide, or carbanion.

In certain embodiments, the present invention relates to the aforementioned method, wherein said base is NaH, CaH_2 , KH, or Na.

In certain embodiments, the present invention relates to the aforementioned method, wherein R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, or $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is ethyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$.

5 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$ and R^2 is alkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{C}(\text{CH}_3)_3$ and R^1 is $-\text{CH}=\text{CH}_2$.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is $-\text{CH}(\text{R}^3)_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, R^4 is $-\text{CH}(\text{R}^3)_2$, n is 1.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{CH}(\text{CH}_3)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{CH}_2\text{CH}(\text{CH}_3)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.

25 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(C(R^3)_2)_n C(O)N(R^5)_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-CH_2C(O)N(R^5)_2$ and R^1 is $-CH=CH_2$.

5 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-CH_2C(O)NH$ -1-adamantyl and R^1 is $-CH=CH_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(C(R^3)_2)_n CN$.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-CH_2CN$ and R^1 is $-CH=CH_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(C(R^3)_2)_n C(O)R^5$.

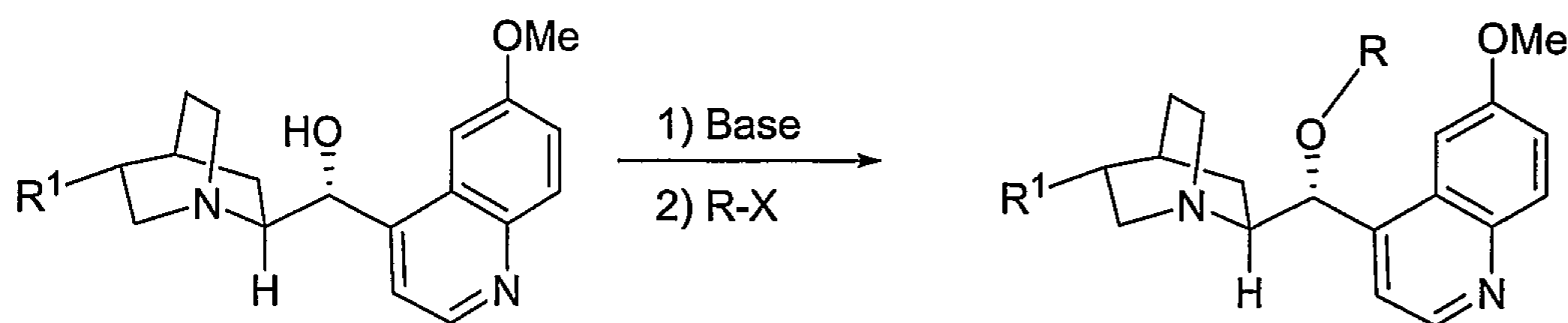
In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-CH_2C(O)R^5$ and R^5 is alkyl.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-CH_2C(O)C(CH_3)_3$ and R^1 is $-CH=CH_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF, QD-AA, QD-MP, or QD-IPC.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-(-)-MN, or QD-AD.

Another aspect of the invention relates to a method of preparing a derivatized cinchona alkaloid catalyst as depicted in Scheme 2:



Scheme 2

wherein,

X represents Cl, Br, I, OSO_2CH_3 , or OSO_2CF_3 ;

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

5 R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl;

15 n is 1-10; and

base is a Bronsted base.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

20

Methods of the Invention -- Catalyzed Reactions

In one aspect of the present invention, there is provided a method for stereoselectively producing compounds with at least one stereogenic center from prochiral or *meso* starting materials. An advantage of this invention is that enantiomerically enriched products can be synthesized from prochiral or racemic reactants. Another advantage is that yield losses associated with the production of an undesired enantiomer can be substantially reduced or eliminated altogether.

In general, the invention features a stereoselective ring opening process which comprises combining a nucleophilic reactant, a prochiral or chiral cyclic substrate, and at least a catalytic amount of non-racemic chiral catalyst of particular characteristics (as described

30

below). The cyclic substrate of the reaction will include a carbocycle or heterocycle which has an electrophilic atom susceptible to attack by the nucleophile. The combination is maintained under conditions appropriate for the chiral catalyst to catalyze stereoselective opening of the cyclic substrate at the electrophilic atom by reaction with the nucleophilic reactant. This reaction can be applied to enantioselective processes as well as diastereoselective processes. It may also be adapted for regioselective reactions. Examples of enantioselective reactions, kinetic resolutions, and regioselective reactions which may be catalyzed according to the present invention follow.

In another aspect of the present invention, kinetic resolution of enantiomers occurs by catalysis, using a subject chiral catalyst, of the transformation of a racemic substrate. In the subject kinetic resolution processes for a racemic substrate, one enantiomer can be recovered as unreacted substrate while the other is transformed to the desired product. Of course, it will be appreciated that the kinetic resolution can be performed by removing the undesired enantiomer by reaction with a nucleophile, and recovering the desired enantiomer unchanged from the reaction mixture. One significant advantage of this approach is the ability to use inexpensive racemic starting materials rather than the expensive, enantiomerically pure starting materials. In certain embodiments, the subject catalysts may be used in kinetic resolutions of racemic cyclic substrates wherein the nucleophile is a co-solvent. Suitable nucleophiles of this type include water, alcohols, and thiols.

The methods of this invention can provide optically active products with very high stereoselectivity (e.g., enantioselectivity or diastereoselectivity) or regioselectivity. In preferred embodiments of the subject desymmetrization reactions, products with enantiomeric excesses of greater than about 50%, greater than about 70%, greater than about 90%, and most preferably greater than about 95% can be obtained. The methods of the invention may also be carried out under reaction conditions suitable for commercial use, and, typically, proceed at reaction rates suitable for large scale operations.

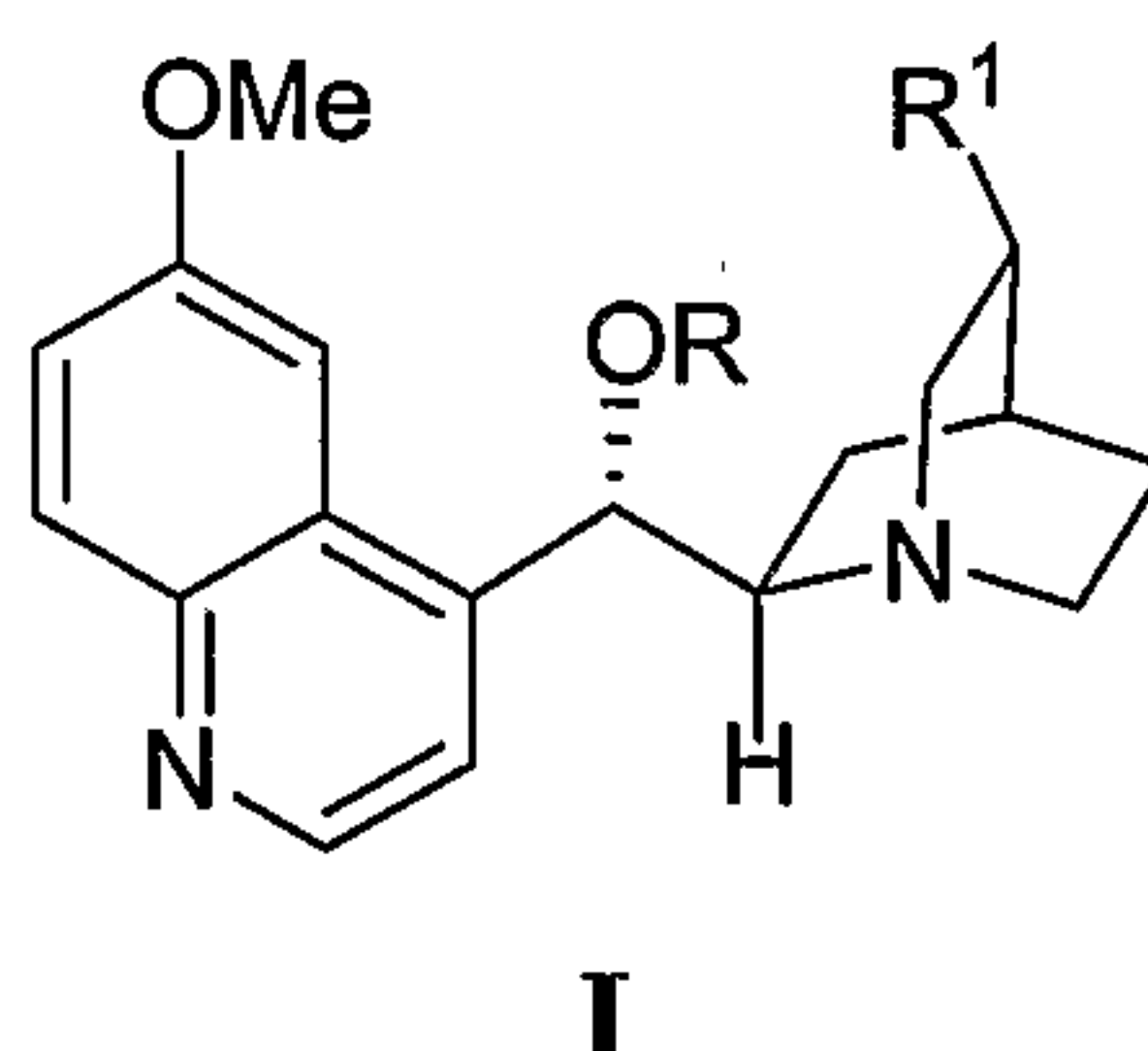
In certain embodiments, the chiral, non-racemic tertiary amine catalyst is present in less than about 30 mol% relative to the prochiral starting material. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is present in less than about 20 mol% relative to the prochiral starting material. In certain embodiments, the chiral, non-racemic tertiary amine

catalyst is present in less than about 10 mol% relative to the prochiral starting material. In certain embodiments, the chiral, non-racemic tertiary amine catalyst is present in less than about 5 mol% relative to the prochiral starting material.

As is clear from the above discussion, the chiral products produced by the asymmetric synthesis methods of this invention can undergo further reaction(s) to afford desired derivatives thereof. Such permissible derivatization reactions can be carried out in accordance with conventional procedures known in the art. For example, potential derivatization reactions include esterification, N-alkylation of amides, and the like. The invention expressly contemplates the preparation of end-products and synthetic intermediates which are useful for the preparation or development or both of cardiovascular drugs, non-steroidal anti-inflammatory drugs, central nervous system agents, and antihistaminics.

One aspect of the present invention relates to a method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of:

reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a catalyst; wherein said prochiral cyclic anhydride or meso cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; thereby producing a chiral, non-racemic compound; wherein said catalyst is represented by formula I:



wherein

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

5 R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, or $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is ethyl.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$ and R^2 is alkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is $-\text{CH}(\text{R}^3)_2$.

25 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, R^4 is $-\text{CH}(\text{R}^3)_2$, n is 1.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

30 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or
5 (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{N}(\text{R}^5)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{NH}$ -1-adamantyl and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CN}$.

In certain embodiments, the present invention relates to the aforementioned method,
15 wherein R is $-\text{CH}_2\text{CN}$ and R^1 is $\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{R}^5$ and R^5 is alkyl.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{C}(\text{CH}_3)_3$ and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF, QD-AA, QD-MP, or QD-IPC.

25 In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-(-)-MN, or QD-AD.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is an alcohol.

In certain embodiments, the present invention relates to the aforementioned method,
30 wherein said nucleophile is a primary alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is a methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

In certain embodiments, the present invention relates to the aforementioned method, wherein said prochiral cyclic anhydride or meso cyclic anhydride is a substituted succinic
5 anhydride or a substituted glutaric anhydride.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is present in less than about 70 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

In certain embodiments, the present invention relates to the aforementioned method,
10 wherein said catalyst is present in less than about 40 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is present in less than about 10 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 50%.

In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about
20 70%.

In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

In certain embodiments, the present invention relates to the aforementioned method,
25 wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

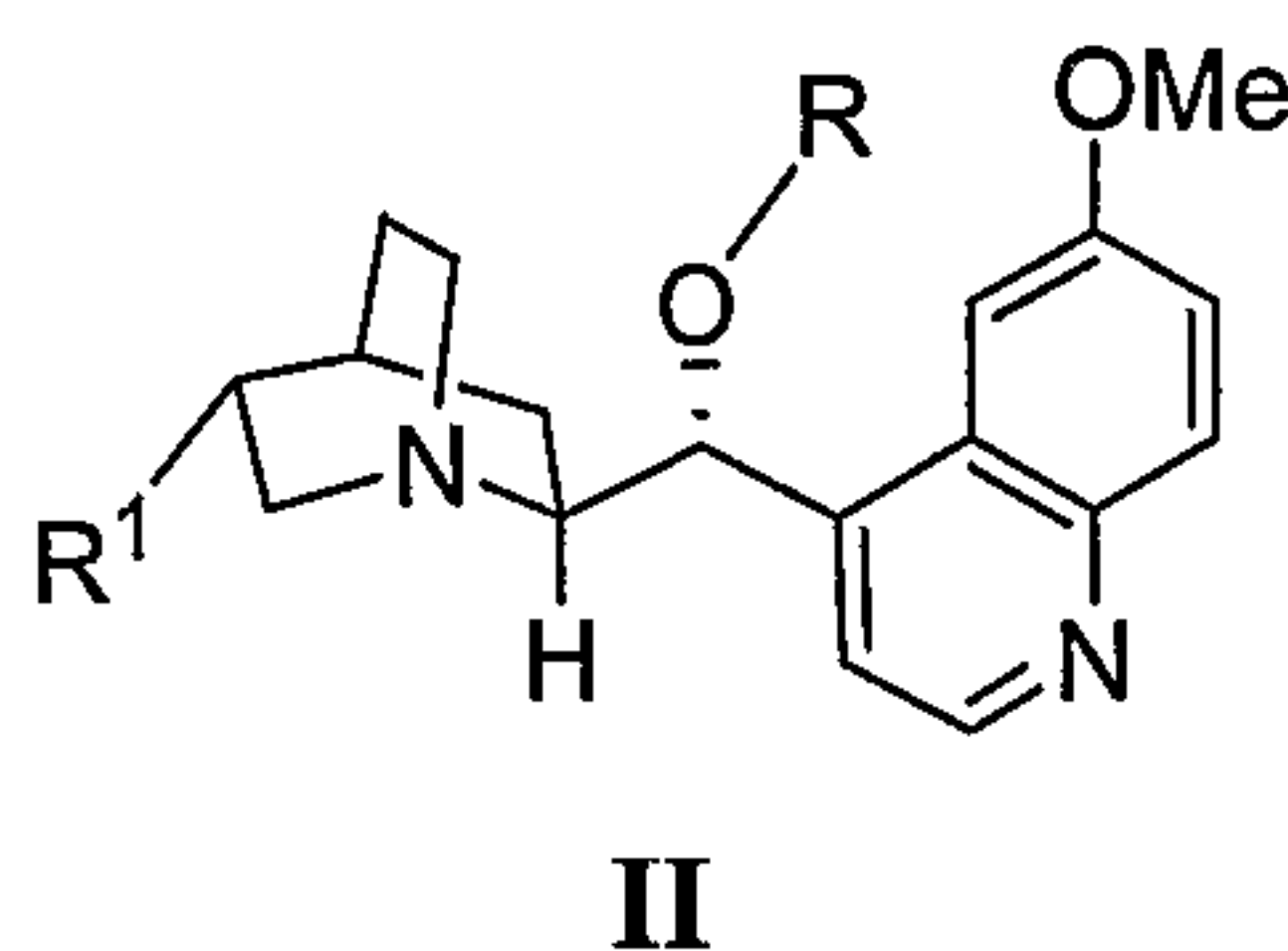
In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

Another aspect of the present invention relates to a method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of:

reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a catalyst; wherein said prochiral cyclic anhydride or meso cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; thereby producing a chiral, non-racemic compound; wherein said catalyst is represented by formula II:



wherein

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R⁵ represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R⁶ represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and
n is 1-10.

5 In certain embodiments, said catalyst is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is an alcohol.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is a primary alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is methanol or CF₃CH₂OH.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein said prochiral cyclic anhydride or meso cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is present in less than about 70 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is present in less than about 40 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is present in less than about 10 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

25 In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 50%.

30 In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 70%.

In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

5 In certain embodiments, the present invention relates to the aforementioned method, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

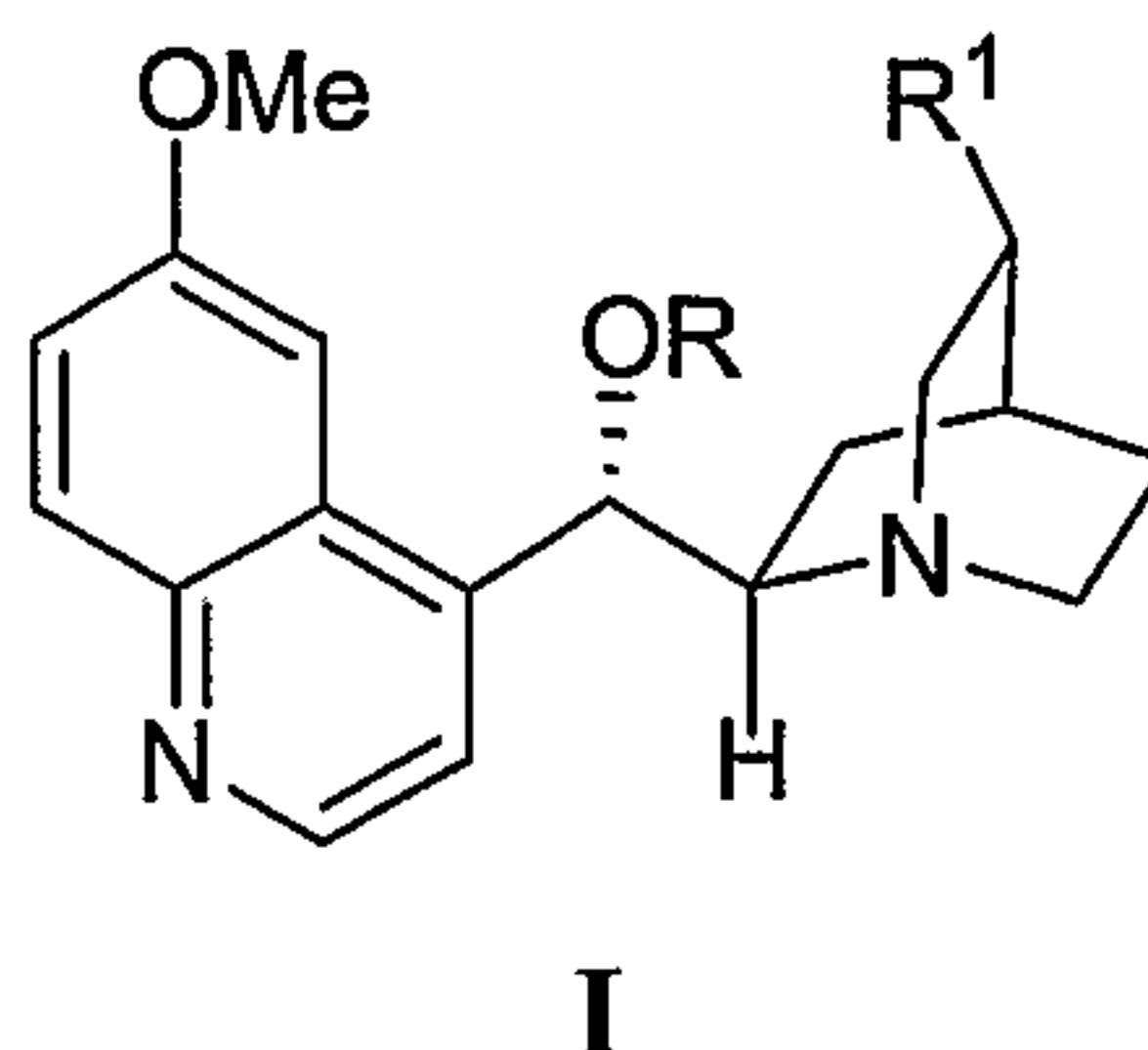
In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said
15 nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

Methods of Invention -- Kinetic Resolution

In another aspect of the present invention, kinetic resolution of enantiomers occurs by catalysis, using a subject chiral catalyst, of the transformation of a racemic substrate. In the
20 subject kinetic resolution processes for a racemic substrate, one enantiomer can be recovered as unreacted substrate while the other is transformed to the desired product. Of course, it will be appreciated that the kinetic resolution can be performed by removing the undesired enantiomer by reaction with a nucleophile, and recovering the desired enantiomer unchanged from the reaction mixture. One significant advantage of this approach is the ability to use inexpensive
25 racemic starting materials rather than the expensive, enantiomerically pure starting compounds. In certain embodiments, the subject catalysts may be used in kinetic resolutions of racemic cyclic substrates wherein the nucleophile is a co-solvent. Suitable nucleophiles of this type include water, alcohols, and thiols.

One aspect of the present invention relates to a method of kinetic resolution, comprising
30 the step of:

reacting a racemic cyclic anhydride with an alcohol in the presence of a catalyst represented by formula I:



5 wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$, $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

R^1 represents alkyl or alkenyl;

10 R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

15 R^4 represents cycloalkyl, $-CH(R^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl;

n is 1-10; and

20 when said method of kinetic resolution is completed or interrupted any unreacted cyclic anhydride has an enantiomeric excess greater than zero and the enantiomeric excess of the product is greater than zero.

In certain embodiments, the present invention relates to the aforementioned method, wherein R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, or $-C(C(R^3)_2)_nC\equiv CR^6$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is ethyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$.

5 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{C}(\text{O})\text{R}^2$ and R^2 is alkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is $-\text{CH}(\text{R}^3)_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, R^4 is $-\text{CH}(\text{R}^3)_2$, n is 1.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.

20 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$.

25 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{N}(\text{R}^5)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{NH}$ -1-adamantyl and R^1 is $-\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CN}$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{CN}$ and R^1 is $\text{CH}=\text{CH}_2$.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{COR}^5$.

5 In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{R}^5$ and R^5 is alkyl.

In certain embodiments, the present invention relates to the aforementioned method, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{C}(\text{CH}_3)_3$ and R^1 is $-\text{CH}=\text{CH}_2$.

10 In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF, QD-AA, QD-MP, or QD-IPC.

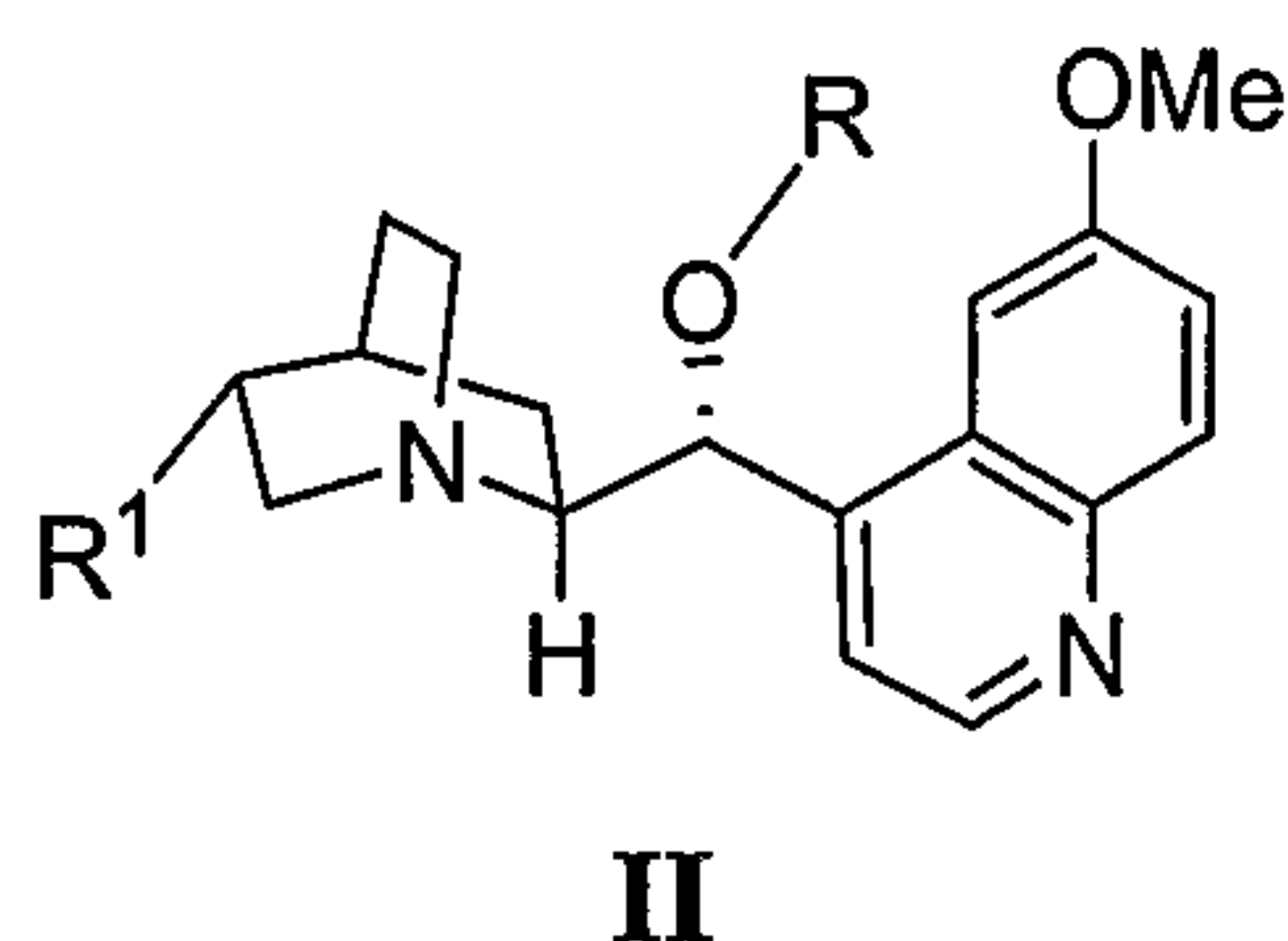
In certain embodiments, the present invention relates to the aforementioned method, wherein said catalyst is QD-IP, QD-(-)-MN, or QD-AD.

15 In certain embodiments, the present invention relates to the aforementioned method, wherein said alcohol is a primary alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

20 Another aspect of the present invention relates to a method of kinetic resolution, comprising the step of:

reacting a racemic cyclic anhydride with an alcohol in the presence of a catalyst represented by formula II:



25 wherein

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R¹ represents alkyl or alkenyl;

R² represents alkyl, cycloalkyl, or alkenyl;

R³ represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxy, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R⁴ represents cycloalkyl, -CH(R³)₂, alkenyl, alkynyl, aryl, or aralkyl;

R⁵ represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R⁶ represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10; and

when said method of kinetic resolution is completed or interrupted any unreacted cyclic anhydride has an enantiomeric excess greater than zero and the enantiomeric excess of the product is greater than zero.

In certain embodiments, said catalyst is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

In certain embodiments, the present invention relates to the aforementioned method, wherein said alcohol is a primary alcohol.

In certain embodiments, the present invention relates to the aforementioned method, wherein said nucleophile is methanol or CF₃CH₂OH.

Nucleophiles

Nucleophiles which are useful in the present invention may be determined by the skilled artisan according to several criteria. In general, a suitable nucleophile will have one or more of the following properties: 1) It will be capable of reaction with the substrate at the desired electrophilic site; 2) It will yield a useful product upon reaction with the substrate; 3) It will not react with the substrate at functionalities other than the desired electrophilic site; 4) It will react with the substrate at least partly through a mechanism catalyzed by the chiral catalyst; 5) It will not undergo substantial undesired reaction after reacting with the substrate in the desired sense; and 6) It will not substantially react with or degrade the catalyst. It will be understood that while undesirable side reactions (such as catalyst degradation) may occur, the rates of such

reactions can be rendered slow -- through the selection of reactants and conditions -- relative to the rate(s) of the desired reaction(s).

Nucleophiles which satisfy the above criteria can be chosen for each substrate and will vary according to the substrate structure and the desired product. Routine experimentation may be necessary to determine the preferred nucleophile for a given transformation. If a nitrogen-containing nucleophile is desired, for example, it may be selected from ammonia, phthalimide, hydrazine, an amine or the like. Similarly, oxygen nucleophiles such as water, hydroxide, alcohols, alkoxides, siloxanes, carboxylates, or peroxides may be used to introduce oxygen; and mercaptans, thiolates, bisulfite, thiocyanate and the like may be used to introduce a sulfur-containing moiety. Additional nucleophiles will be apparent to those of ordinary skill in the art of organic chemistry.

For nucleophiles which exist as anions, the counterion can be any of a variety of conventional cations, including alkali and alkaline earth metal cations and ammonium cations.

In certain embodiments, the nucleophile may be part of the substrate, resulting in an intramolecular reaction.

Substrates

As discussed above, a wide variety of substrates are useful in the methods of the present invention. The choice of substrate will depend on a number of factors, such as the nucleophile to be employed and the desired product, and an appropriate substrate will be apparent to the skilled artisan. It will be understood that the substrate preferably will not contain any interfering functionalities. In general, an appropriate substrate, e.g., a prochiral or *meso* compound, will contain at least a pair of reactive electrophilic centers or moieties related by an internal plane or point of symmetry at which a nucleophile attacks with the assistance of the catalyst. The catalyzed, stereoselective attack of the nucleophile at one of these electrophilic centers will produce a chiral, non-racemic product.

Most of the substrates contemplated for use in the methods of the present invention contain at least one ring having three to seven atoms. Small rings are frequently strained, enhancing their reactivity. However, in some embodiments a cyclic substrate may not be strained, i.e., it may comprise a larger ring with electrophilic centers. Examples of suitable

cyclic substrates which can be opened in the subject method include cyclic anhydrides, cyclic imides, and the like.

In preferred embodiments, the cyclic substrate is a prochiral or *meso* compound. In other embodiments, for example, kinetic resolutions, the cyclic substrate will be a chiral compound. In certain embodiments, the substrate will be a racemic mixture. In certain
5 embodiments, the substrate will be a mixture of diastereomers.

In preferred embodiments, the electrophilic atom is carbon, e.g., the carbon of a carbonyl moiety comprised by an anhydride or imide. However, in certain embodiments, the electrophilic atom may be a heteroatom.

10 Reaction Conditions

The asymmetric reactions of the present invention may be performed under a wide range of conditions, although it will be understood that the solvents and temperature ranges recited herein are not limitative and only correspond to a preferred mode of the methods of the invention.

15 In general, it will be desirable that reactions are run using mild conditions which will not adversely effect the substrate, the catalyst, or the product. For example, the reaction temperature influences the speed of the reaction, as well as the stability of the reactants, products, and catalyst. The reactions will usually be run at temperatures in the range of -78 °C to 100 °C, more preferably in the range -30 °C to 30 °C and still more preferably in the range -
20 30 °C to 0 °C.

In general, the asymmetric synthesis reactions of the present invention are carried out in a liquid reaction medium. However, the reactions may be run without addition of solvent. Alternatively, the reactions may be run in an inert solvent, preferably one in which the reaction ingredients, including the catalyst, are substantially soluble. Suitable solvents include ethers
25 such as diethyl ether, 1,2-dimethoxyethane, diglyme, t-butyl methyl ether, tetrahydrofuran and the like; halogenated solvents such as chloroform, dichloromethane, dichloroethane, chlorobenzene, and the like; aliphatic or aromatic hydrocarbon solvents such as benzene, toluene, hexane, pentane and the like; esters and ketones such as ethyl acetate, acetone, and 2-butanone; polar aprotic solvents such as acetonitrile, dimethylsulfoxide, dimethylformamide
30 and the like; or combinations of two or more solvents. Furthermore, in certain embodiments, it

may be advantageous to employ a solvent which is not inert to the substrate under the conditions employed, e.g., use of ethanol as a solvent when ethanol is the desired nucleophile. In embodiments where water or hydroxide are not preferred nucleophiles, the reactions can be conducted under anhydrous conditions. In certain embodiments, ethereal or aromatic hydrocarbon solvents are preferred. In certain preferred embodiments, the solvent is diethyl ether or toluene. In embodiments where water or hydroxide are preferred nucleophiles, the reactions may be run in solvent mixtures comprising an appropriate amount of water and/or hydroxide.

The invention also contemplates reaction in a biphasic mixture of solvents, in an emulsion or suspension, or reaction in a lipid vesicle or bilayer. In certain embodiments, it may be preferred to perform the catalyzed reactions on the solid phase. Further, in some preferred embodiments, the reaction may be carried out under an atmosphere of a reactive gas. For example, desymmetrization with cyanide as nucleophile may be performed under an atmosphere of HCN gas. The partial pressure of the reactive gas may be from 0.1 to 1000 atmospheres, more preferably from 0.5 to 100 atm, and most preferably from about 1 to about 10 atm. On the other hand, in certain embodiments it is preferable to perform the reactions under an inert atmosphere of a gas such as nitrogen or argon.

The asymmetric synthesis methods of the present invention can be conducted in continuous, semi-continuous or batch fashion and may involve a liquid recycle and/or gas recycle operation as desired. However, the methods of this invention are preferably conducted in batch fashion. Likewise, the manner or order of addition of the reaction ingredients, catalyst and solvent are also not critical and may be accomplished in any conventional fashion.

The reaction can be conducted in a single reaction zone or in a plurality of reaction zones, in series or in parallel or it may be conducted batchwise or continuously in an elongated tubular zone or series of such zones. The materials of construction employed should be inert to the starting materials during the reaction and the fabrication of the equipment should be able to withstand the reaction temperatures and pressures. Means to introduce and/or adjust the quantity of starting materials or ingredients introduced batchwise or continuously into the reaction zone during the course of the reaction can be conveniently utilized in the processes especially to maintain the desired molar ratio of the starting materials. The reaction steps may

be effected by the incremental addition of one of the starting materials to the other. Also, the reaction steps can be combined by the joint addition of the starting materials to the optically active metal-ligand complex catalyst. When complete conversion is not desired or not obtainable, the starting materials can be separated from the product and then recycled back into the reaction zone.

The methods may be conducted in either glass lined, stainless steel or similar type reaction equipment. The reaction zone may be fitted with one or more internal and/or external heat exchanger(s) in order to control undue temperature fluctuations, or to prevent any possible "runaway" reaction temperatures.

Furthermore, the chiral catalyst may be immobilized or incorporated into a polymer or other insoluble matrix by, for example, covalently linking it to the polymer or solid support through one or more of its substituents. An immobilized catalyst may be easily recovered after the reaction, for instance, by filtration or centrifugation. Further, the substrate or nucleophile may be immobilized or incorporated into a polymer or other insoluble matrix by, for example, covalently linking it to the polymer or solid support through one or more of its substituents. Such an approach may form the basis for the preparation of a combinatorial library of compounds tethered to a solid support.

Enantioselective Alcoholysis

A wide variety of catalysts derived from modified cinchona alkaloids were examined with substituted succinic anhydrides and substituted glutaric anhydrides and the results are summarized in Figures 19-45. The application of catalyst QD-(-)-MN for the desymmetrization of *cis*-1,3-dibenzyl-tetrahydro-2H-furo[3,4-d]imidazole-2,4,6-trione is also demonstrated, which could be important for the synthesis of biotin. The catalyst is also shown to be easily recyclable in greater than 95% yield using an extraction procedure.

Summarized in Figures 19 and 20 are the results of a study on the comparison of the efficiency of various catalysts for methanolysis of 2,3-dimethylsuccinic anhydride in Et₂O at 0.02 M concentration at room temperature. Modified monomeric cinchona alkaloids bearing alkylacetate side chains, including QD-AD, QD-(+)-MN, QD-(-)-MN, QD-IP, QD-TB, QD-IB, and QD-EF show overall efficiency (activity plus selectivity) comparable or superior to (DHQD)₂AQN. However, it is important to remember that QD-AD, QD-(+)-MN, QD-(-)-MN

can be prepared in reasonable yield and at a cost significantly less than (<0.5% based on Aldrich price for starting material) that of (DHQD)₂AQN. In addition, as described in more detail later, the QD-(-)-MN catalyst has been shown to be sufficiently stable toward acid to be readily recyclable in high yield using a simple extraction procedure. On the other hand, initial
5 experiments indicate that QD-TB may be too acid-sensitive to be recycled via a similar extraction procedure.

The efficiency of a variety of modified monomeric cinchona alkaloids in trifluoroethanolysis reactions was examined. Summarized in Figure 21 are the results of a comparison of the efficiency of various catalysts for trifluoroethanolysis of 2,3-
10 dimethylsuccinic anhydride in Et₂O at 0.02 M concentration at room temperature. The data indicate that QD-AD, QD-(+)-MN, and QD-(-)-MN have a higher efficiency than (DHQD)₂AQN when trifluoroethanol is used for the asymmetric alcoholysis. Interestingly, the enantioselectivity demonstrated by these three catalysts in combination with trifluoroethanol is equal to or better than that demonstrated by the combination of (DHQD)₂AQN and methanol.

15 In order to evaluate substrate scope, a study was conducted on the alcoholysis of 3-methyl glutaric anhydride. The results of the alcoholysis of 3-methyl-glutaric anhydride at 0.02 and 0.2 M is summarized in Figures 22 and 23, respectively. 3-Substituted glutaric anhydrides are among the most readily accessible cyclic anhydrides. The corresponding ring opening products, 3-substituted hemiesters, are among the most useful chiral building blocks in organic
20 synthesis. However, this class of anhydrides are the most challenging for alcoholysis due to low activity and more severe product inhibition of the catalysts. While (DHQD)₂AQN-catalyzed methanolysis of prochiral glutaric anhydrides afforded the hemiester in greater than 90% ee, the reaction has to be performed with high loading of catalyst (30 mol%) at low concentration (0.02 M); moreover, the transformation does not go to completion, rendering the
25 procedure difficult to apply on a large scale. It is therefore highly significant that QD-AD can catalyze alcoholic ring opening of glutaric anhydrides at relatively high concentration (0.2 M) providing the hemiester in high ee. Although the catalyst loading is 100-110 mol%, this procedure remains practical given that QD-AD can be prepared from inexpensive starting material and it can be recycled efficiently. Notably, unmodified quinidine is ineffective in
30 transformations using 3-substituted glutaric anhydrides.

In order to evaluate the effect of solvent, a study was conducted in which toluene was used as the solvent. Displayed in Figure 24 are the results of the methanolysis of 3-methyl gluratic anhydride in toluene at 0.2 M with different catalysts. Compared with (DHQD)₂AQN under these conditions, QD-AD and QD-MN showed comparable enantioselectivity and slightly lower activity. On the other hand, QD-PP demonstrated significantly lower enantioselectivity and activity. QD-AD and QD-MN are clearly superior in consideration of both the cost and catalytic properties of these catalysts.

Shown in Figure 25 are the results of the trifluoroethanolysis of 3-methyl gluratic anhydride in toluene at 0.2 M with various catalysts. Compared with either (DHQD)₂AQN or QD-PP under these conditions, QD-AD and QD-MN showed better enantioselectivity and activity. The efficiency demonstrated by the combination of QD-(-)-MN with trifluoroethanol matched that by the combination of (DHQD)₂AQN with methanol. Again, considering both the cost and catalytic properties, QD-AD and QD-MN are clearly superior to the dimeric catalysts.

Summarized in Figure 26 are results on the methanolysis of 3-phenyl glutaric anhydride in toluene at 0.2 M with different catalysts. The results indicate that QD-AD and QD-(-)-MN are effective for 3-alkyl glutaric anhydrides and 3-aryl glutaric anhydrides. Compared with (DHQD)₂AQN under these conditions, QD-AD and QD-MN showed slightly lower enantioselectivity and slightly lower activity. On the other hand, the QD-PP demonstrated significantly lower enantioselectivity and activity. Considering both the cost and catalytic properties, QD-AD and QD-MN are superior to the dimeric catalysts.

Summarized in Figure 27 are results on the trifluoroethanolysis of 3-phenyl gluratic anhydride in toluene at 0.2 M with different catalysts. Compared with either (DHQD)₂AQN or QD-PP under these conditions, QD-AD and QD-MN showed better enantioselectivity and activity. The efficiency demonstrated by the combination of QD-(-)-MN with trifluoroethanol matched that by the combination of (DHQD)₂AQN with methanol. Again, considering both the cost and catalytic properties, QD-AD and QD-MN are superior to the dimeric catalysts.

Summarized in Figure 28 are results on the methanolysis of 3-isopropyl glutaric anhydride in toluene at 0.2 M with different catalysts. First of all the results here indicate that QD-AD and QD-(-)-MN is effective for 3-alkyl glutaric anhydrides bearing branched substituent. Compared with (DHQD)₂AQN under these conditions, QD-AD and QD-MN

showed similar enantioselectivity and activity. On the other hand, the QD-PP demonstrated significantly lower enantioselectivity and activity. Consider both the cost and catalytic properties, QD-AD and QD-MN are clearly superior to the dimeric catalysts.

Summarized in Figure 29 are results on the trifluoroethanolysis of 3-isopropyl gluratic anhydride in toluene at 0.2 M with different catalysts. Compared with either (DHQD)₂AQN or QD-PP under these conditions, QD-AD and QD-MN showed better enantioselectivity and activity. The efficiency demonstrated by the combination of QD-(-)-MN with trifluoroethanol matched that of the combination of (DHQD)₂AQN with methanol. Again, considering both the cost and catalytic properties, QD-AD and especially QD-MN are clearly superior to the dimeric catalysts.

Summarized in Figure 30 are results on the methanolysis of 3-OTBS gluratic anhydride in toluene at 0.2 M with different catalysts. Compared with either (DHQD)₂AQN under these conditions, QD-AD and QD-MN showed similar enantioselectivity and slightly lower activity. On the other hand, QD-PP demonstrated significantly inferior catalyst properties. Again, considering both the cost and catalytic properties, QD-AD and especially QD-MN are clearly superior to the dimeric catalysts.

Summarized in Figure 31 are results on the trifluoroethanolysis of 3-OTBS gluratic anhydride in toluene at 0.2 M with different catalysts. Compared with either (DHQD)₂AQN or QD-PP under these conditions, QD-AD and QD-MN showed better enantioselectivity and activity. Again, considering both the cost and catalytic properties, QD-AD and especially QD-MN are clearly superior to the dimeric catalysts.

Summarized in Figures 32 and 33 are results on the methanolysis and trifluoroethanolysis of 3-substituted glutaric anhydrides with monomeric catalysts (Q-AD) derived from quinine. The products are the antipodes of those obtained with monomeric catalysts derived from quinidine.

In order to further evaluate the range of substrates amenable to this procedure, alcoholysis of 1,2,3,6-tetrahydrophthalic anhydrides was examined. The results on the methanolysis and trifluoroethanolysis of cis-1,2,3,6-tetrahydrophthalic anhydrides, a succinic anhydride, are summarized in Figures 34 and 35. With methanol as the nucleophile, QD-AD is comparable with (DHQD)₂AQN in terms of activity and selectivity. With trifluoroethanol as

the nucleophile, QD-AD and QD-MN demonstrate better activity than and comparable selectivity to those demonstrated by (DHQD)₂AQN. However, the selectivity of QD-PP is slightly worse.

The results of the alcoholysis of a variety of structurally unique anhydrides is shown in Figures 36-43. Summarized in Figures 36 and 37 are results on the methanolysis and tricyclic succinic anhydrides. QD-AD and QD-MN demonstrate better activity and selectivity than those demonstrated by (DHQD)₂AQN and QD-PP. Summarized in Figures 38 and 39 are results on the methanolysis and trifluoroethanolysis of cis-1,2-cyclohexanedicarboxylic anhydrides. With trifluoroethanol as the nucleophile, QD-AD and QD-MN demonstrate comparable activity and selectivity to those demonstrated by (DHQD)₂AQN and better catalyst properties than that of QD-PP. Summarized in Figures 40 and 41 are results on the trifluoroethanolysis of cis-1,2-cyclohexanedicarboxylic anhydrides at 0.2 M in toluene and ether, respectively. In toluene, the amount of the alcohol used impacts the enantioselectivity of the reaction. Summarized in Figure 42 are results on the trifluoroethanolysis of cis-1,2-cyclohexanedicarboxylic anhydrides at 0.5 M in toluene. The use of molecular sieves was beneficial for the reaction. Summarized in Figure 43 are results on the alcoholysis of various succinic anhydrides with Q-AD.

Exemplification

The invention now being generally described, it will be more readily understood by reference to the following examples which are included merely for purposes of illustration of certain aspects and embodiments of the present invention, and are not intended to limit the invention.

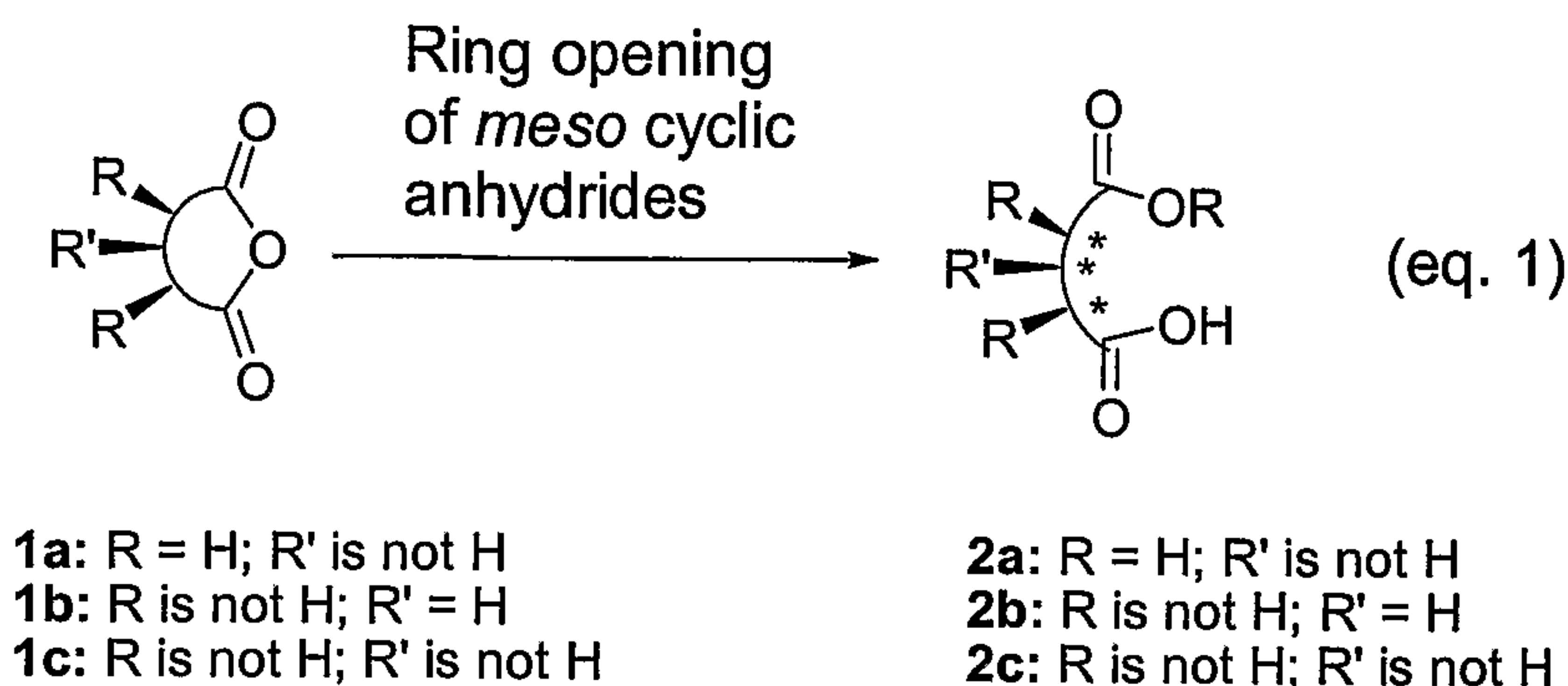
Example 1

Highly Enantioselective Catalytic Desymmetrization of Cyclic *meso* Anhydrides

Enantioselective opening of the readily accessible *meso*-cyclic anhydrides generates enantiomerically enriched chiral hemiesters containing one or multiple stereogenic centers and two chemically differentiated carbonyl functionalities (eq. 1). These optically active bifunctional hemiesters are versatile chiral building blocks in asymmetric synthesis.^{1,2,3,4,5,6,7,8,9} Due to its great significance for organic synthesis, the development of highly enantioselective desymmetrization of *meso*-cyclic anhydrides has been a topic of intense research.^{10,11,12,13,14,15}

Synthetically useful selectivity has been obtained in desymmetrizations assisted by a stoichiometric amount of chiral auxiliaries or chiral mediators.^{10,11} Despite considerable efforts,¹¹⁻¹⁵ the development of a general and effective catalytic desymmetrization of *meso*-cyclic anhydrides has not yet been achieved and therefore remains a desirable and highly

5 challenging goal.



Our general interests in asymmetric catalysis of chiral Lewis bases lead our attention to amine-catalyzed alcoholysis of cyclic anhydride. Oda first reported that *cinchona* alkaloids catalyze asymmetric methanolysis of various mono and bicyclic anhydrides.¹² Atkin later

10 extended this reaction to desymmetrize certain tricyclic anhydrides.¹³ Although the reactions proceeded in good yield, the hemiesters were obtained in low to modest enantiomeric excess. We suspect that the unsatisfactory enantioselectivity may partially arise from the existence of a non-selective catalysis by the quinoline nitrogen since the monohydrochloride quinine is reported by Atkin to catalyze the methanolysis of the cyclic anhydride with no

15 enantioselectivity.^{13a} This quinoline nitrogen-catalyzed racemic pathway should become increasingly competitive as the reaction proceeds to high conversion when the rate of the quinuclidine nitrogen-catalyzed enantioselective reaction is expected to reduce significantly as a result of deactivation of the catalyst caused by protonation of the quinuclidine nitrogen by the acidic hemiester. In principle the racemic pathway could be suppressed by using analogs of

20 *cinchona* alkaloids devoid of the quinoline nitrogen as the catalyst. The implementation of such an approach is, however, experimentally difficult due to the considerable synthetic effort required for the preparation of such analogs.¹⁶ Furthermore, a large, if not stoichiometric, amount of the quinuclidine catalysts may be required to promote the reaction to go to completion. We are interested in exploring an alternative strategy of decreasing the basicity of

25 the quinuclidine nitrogen, thereby shifting the equilibrium of the acid-base reaction towards the

formation of the free amine catalyst. Such a strategy could lead to significant improvements in both the efficiency and the selectivity of the asymmetric catalysis through minimizing the deactivation of the free base amine catalyst by the acidic hemiester. Furthermore this approach could be easily implemented experimentally by changing the environment around the quinuclidine nitrogen via a simple modification of the cinchona alkaloid. We envisaged that a straightforward derivatizations of the C-9 alcohol with bulky alkyl or aryl groups could generate ethers of cinchona alkaloids with a decreased basicity of the quinuclidine nitrogen by destabilizing the ammonium ion x via the creation of a steric barrier for ion solvation. To this end, following the condition reported by Oda,¹² a variety of commercially available aryl ethers and esters of cinchona alkaloids are screened for their ability to catalyze enantioselective methanolysis of 2,3-dimethyl succinic anhydride (**3**). The results of our screening study are described in Figure 1.

We were pleased to find that very good enantioselectivity is obtained with reactions mediated by aryl ethers of both a monocinchona (DHQD.PHN) and a biscinchona alkaloids [(DHQD)₂AQN].¹⁷ While both alkaloids are effective catalyst, the latter in general gives higher enantioselectivity. When one equivalent of anhydride **3** was treated with 10 equivalent of methanol in dry toluene in the presence of 5 mol% of either DHQD.PHN or (DHQD)₂AQN as catalyst, the reaction went to completion in 2-4 hours to give the corresponding hemiester in 81% and 85% ee respectively. The structure of the aryl group of the modified cinchona alkaloids has a dramatic impact on the selectivity of the catalyst. While catalysts bearing bulky aromatic groups such as PHN and AQN afford high enantioselectivities, a dramatic deterioration in enantioselectivity was observed with catalysts bearing relatively small heterocyclic rings as substituents at *O*-9 position (entries 2, 3, 6, 7 in Figure 1). The reaction can be further optimized to give the product in excellent ee (93% ee) at room temperature by using ether as the solvent.

Encouraged by these promising results, we investigated the catalytic desymmetrization of a wide variety of cyclic anhydrides. The results are summarized in Figures 2-4. The scope of the reaction is very general in giving excellent enantioselectivity and yield for the desymmetrization of a wide range of *meso*-cyclic anhydrides. Extraordinarily high enantioselectivity was observed for anhydride **3** as well as each of the bicyclic anhydrides

employed in our investigation (entries 1, 5, 6 and 7 in Figures 2-4). Excellent enantioselectivities are obtained with monocyclic and tricyclic anhydrides (entries 2, 3, 8, 9, 10, and 11 in Figures 2-4) to give acyclic and bicyclic chiral hemiesters respectively in highly enantiomerically enriched form. Substrates containing heterocyclic rings other than the cyclic anhydride are also converted into the desired product in very high enantioselectivity (entries 10 and 11 in Figures 2-4). It is remarkable that even a monocyclic anhydride with a β -methyl substituent is transformed in 89% ee although a relatively high catalyst loading is required. The high enantioselectivity in the ring opening of 1,2-cyclopentyl anhydride (entry 5 in Figures 2-4) is particularly noteworthy considering that it is significantly higher than that obtained by reactions using stoichiometric amount of chiral promoters.¹¹ Furthermore, synthetic routes based on hydrolytic enzymes can only provide the cyclopentyl hemiester in low ee. It is significant to note that when (DHQ)₂AQN was employed to catalyze the ring opening of 2,3-dimethylsuccinic anhydride (**3**) the opposite enantiomer of the corresponding hemiester was obtained in 96% ee, thus proving that either enantiomers of the hemiesters can be prepared in a straightforward and highly enantioselective fashion via the reaction described here. We are surprised to find that (DHQD)₂ AQN-mediated ring opening of 2,4-dimethylglutaric anhydride gives the desired hemiester in good yield but in very low ee (30% ee). The enantioselectivity can, however, be improved significantly when the reaction is promoted by (DHQD)₂PHAL (entry 4 in Figures 2-4).

We have performed a preparative scale reaction to demonstrate the practicality of this catalytic desymmetrization. Anhydride **3** was transformed on a 5 mmol scale to the corresponding hemiester in larger than 98% ee with a catalyst loading of 5 mol%. When the starting material was consumed (24 hour), a simple extraction of the reaction mixture with aqueous HCl (1 N) separates the catalyst from the product. Evaporation of the organic solvent provides the desired product in high purity (pure by NMR) and excellent yield (95%). The catalyst can be easily recovered quantitatively. Basifying the aqueous phase with KOH followed by extraction of the alkaline aqueous solution with EtOAc and removal of the organic solvent furnished the recovered catalyst in high purity (pure by NMR). The recovered catalyst is used without further treatment for another preparative scale reaction to give a new batch of product without deterioration in ee and yield.

We have demonstrated that the newly uncovered catalytic desymmetrization of *meso*-cyclic anhydrides mediated by the commercially available aryl ethers of chinchona alkaloids is a general, highly selective and practical catalytic asymmetric transformation. The reaction described here represents the first catalytic reaction that provides straightforward accesses toward both enantiomers of a broad range of valuable chiral hemiesters in high optical purity. It is important to note that most of these chiral hemiesters have been employed in the syntheses of various natural products and biologically important compounds.¹⁻⁸ The availability of the catalyst, the simple experimental procedure and the easy yet quantitative recovery of the catalyst renders this reaction a highly attractive synthetic method. Studies aiming to expand the synthetic utility of the reaction and to gain mechanistic insights into the origin of highly selective catalysis are in progress.

References and Notes for Example 1

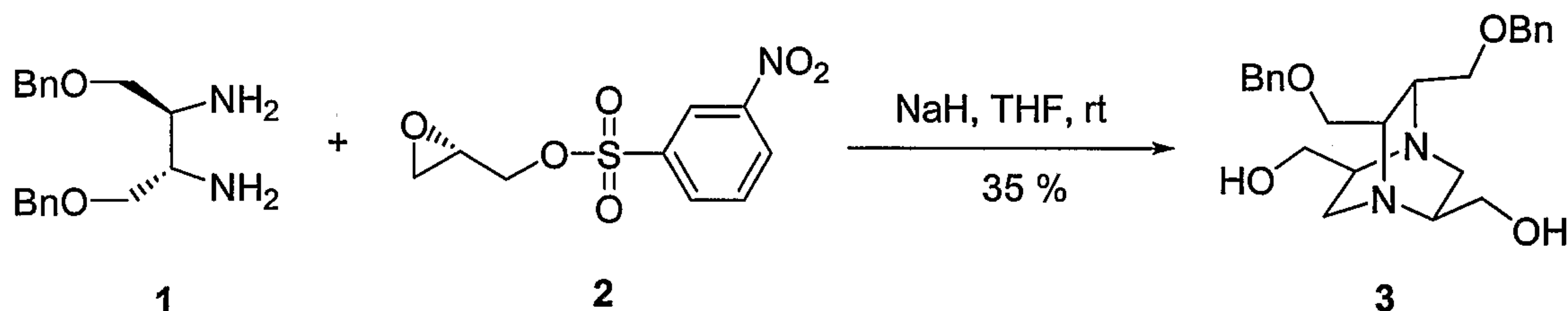
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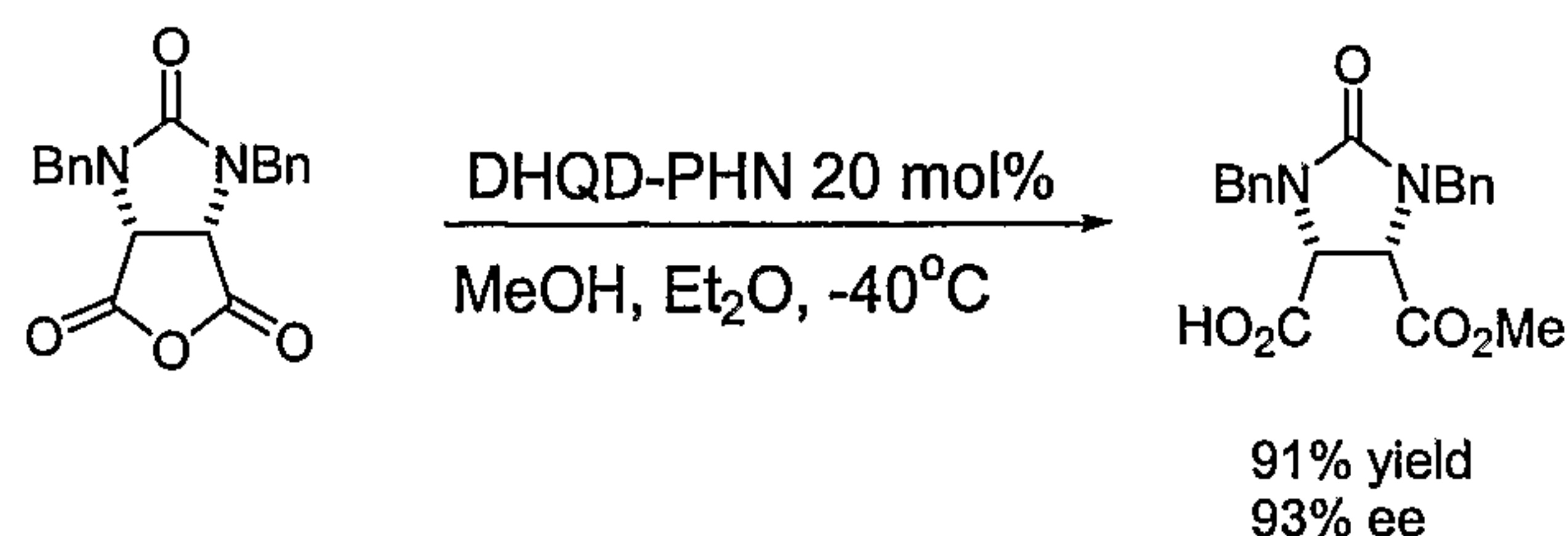
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Example 2

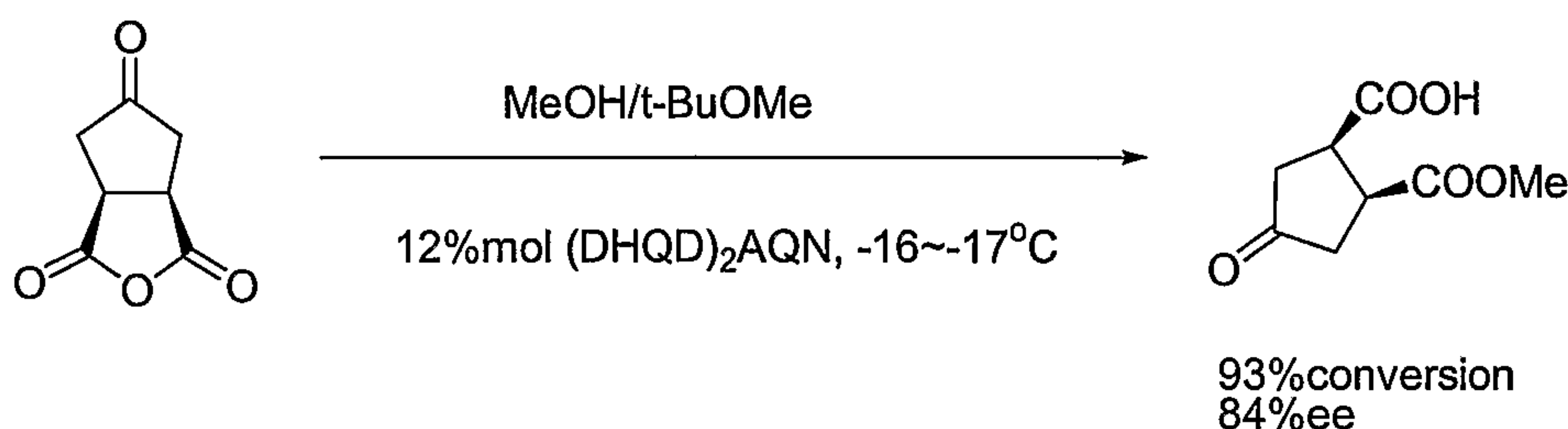
General Method for Synthesizing Tertiary Amine Catalysts



To a solution of diamine **1** (1.40 g, 4.67 mmol) in dry tetrahydrofuran (93 mL) under nitrogen at room temperature was added sodium hydride (60 % suspension in mineral oil, 1.87 g, 46.7 mmol). The mixture was stirred for 10 minutes, and then glycidol nosylate **2** was added. After being stirred for 88 hours, the mixture was filtered, and the filtrate was concentrated under reduced pressure. The resulting residue was purified by chromatography [basic aluminum oxide, CH₃OH:CH₂Cl₂ (1:100 to 1:20)] to give the chiral tertiary amine **3** (667 mg, 35 %) as a white solid.

Example 3**Catalytic Desymmetrization of a *Meso* Bicyclic Succinic Anhydride Comprising a Urea**

To a mixture of anhydride (16.8 mg, 0.05 mmol) and DHQD-PHN (20 mol%, 5 mg) in Et₂O (2.5 mL) at -40 °C, anhydrous MeOH (0.5 mmol, 20.2 ul) cooled at -20 °C was added in one portion. The resulting mixture was stirred until the reaction was complete (~30 hrs) as monitored by TLC (20% MeOH in CH₂Cl₂). The reaction was quenched with aqueous HCl (1 N, 3 mL). The aqueous layer was extracted with EtOAc (2 x 10 mL). The combined organic layer was dried over MgSO₄ and concentrated. The residue was purified by flash chromatography (100% CH₂Cl₂ to 10 % MeOH in CH₂Cl₂) to afford the hemiester (16.7 mg, 91% yield). The ee of the hemiester was determined to be 93% by converting the hemiester into the corresponding ester amide (*J. Chem.. Soc. Perkin. Trans I* **1987**, 1053) via a reaction of the hemiester with (*R*)-1-(1-naphthyl) ethyl amine. The ester amide was analyzed by chiral HPLC (Chiralpak, OD, 280 nm, 0.6 mL/min; retention times for the relevant diastereomers are 20.030 and 25.312 minutes, respectively).

Example 4**Catalytic Desymmetrization of a *Meso* Bicyclic Succinic Anhydride Comprising a Ketone**

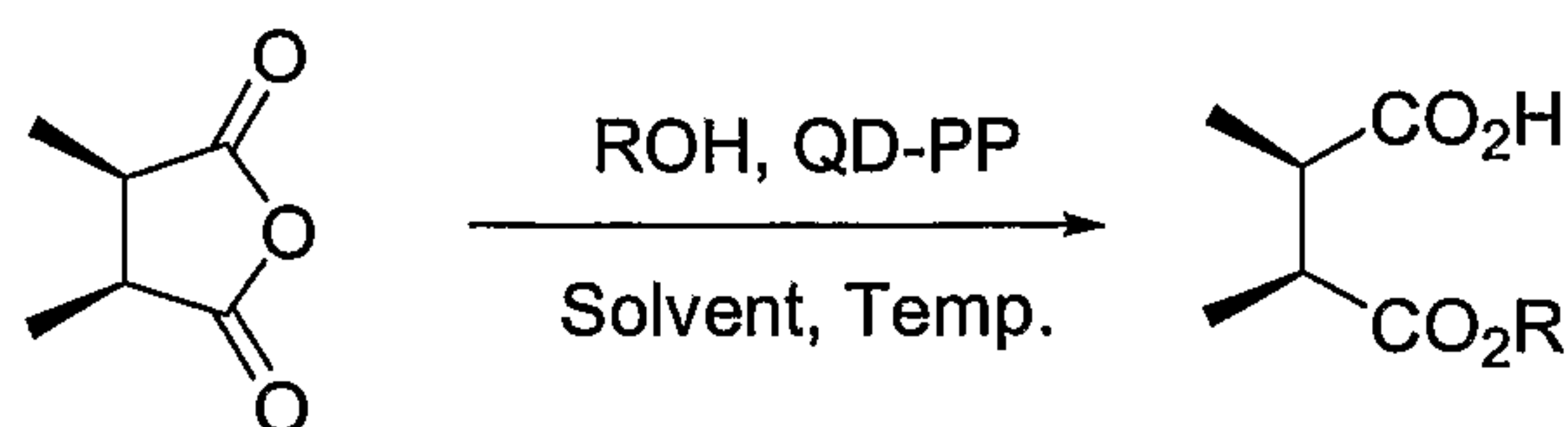
Dry methanol (32 mg, 1.0 mmol) was added dropwise to a stirred solution of the anhydride (0.1 mol, 15.4 mg) and (DHQD)₂AQN (12 %mol, 10.3 mg) in *t*-butyl methyl ether at -16~-17°C. The reaction mixture was stirred at that temperature for 80 hrs. The reaction was then quenched with HCl (1 N, 3 mL). The aqueous phase was extracted with EtOAc (2 x 15 mL). The organic phase was combined, dried over Na₂SO₄, and the solvent was removed under reduced pressure. The ee of the hemiester was determined to be 84% by converting the

hemiester into the corresponding ester amide (*J. Chem. Soc. Perkin. Trans I* **1987**, 1053) via a reaction of the hemiester with (*R*)-1-(1-naphthyl) ethyl amine. It was analyzed by HPLC (Hypersil SI 4.6×200 mm, 280 nm, 0.5 mL/min, Hexanes: *i*-Propanol=9:1; retention times for the relevant diastereomers are 28.040 and 33.479 minutes, respectively).

5

Example 5

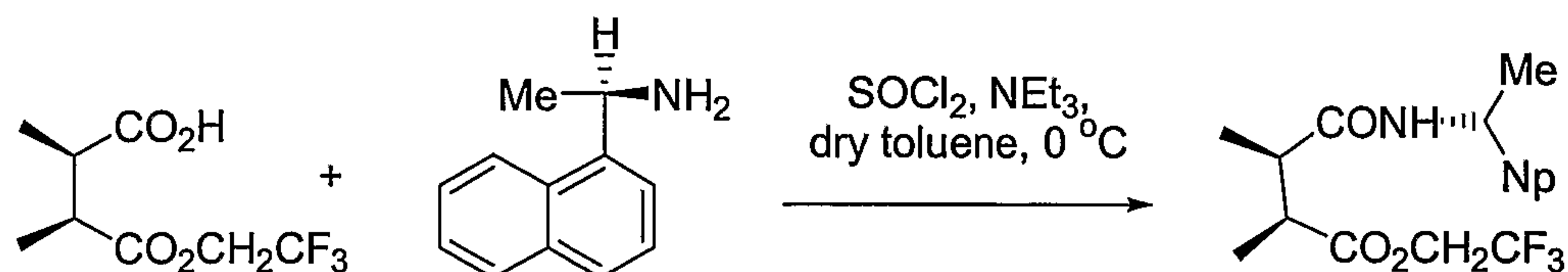
General Procedure for the Alcoholysis of 2,3-Dimethyl succinic Anhydride Using QD-PP as Catalyst



Alcohol (0.1-1.0 mmol) was added to a solution of anhydride (0.1–0.2 mmol) and QD-PP (20-100 mol%) in ether (0.5-5.0 mL) at the reaction temperatures indicated in the Figures. The reaction mixture was initially stirred and then allowed to sit at that temperature until the starting material was consumed as indicated by TLC analysis (43 h) or Chiral GC (β -CD) analysis (0.5-101 h). The reaction was quenched by adding HCl (1 N, 5 mL) in one portion. The aqueous phase was extracted with ether (2 x 20 mL). The organic phase was combined, dried over Na₂SO₄, and concentrated to provide the desired product without further purification. The enantiomeric excess (ee) of each product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the hemiester according to a modified literature procedure below or chiral GC analysis.

Modified Literature Procedure for Determining the Enantiomeric Excess of Products

(*J. Hiratake, M. Inagaki, Y Yamamoto, J. Oda, J. Chem. Soc., Perkin Trans. 1* **1987**, 1053.)



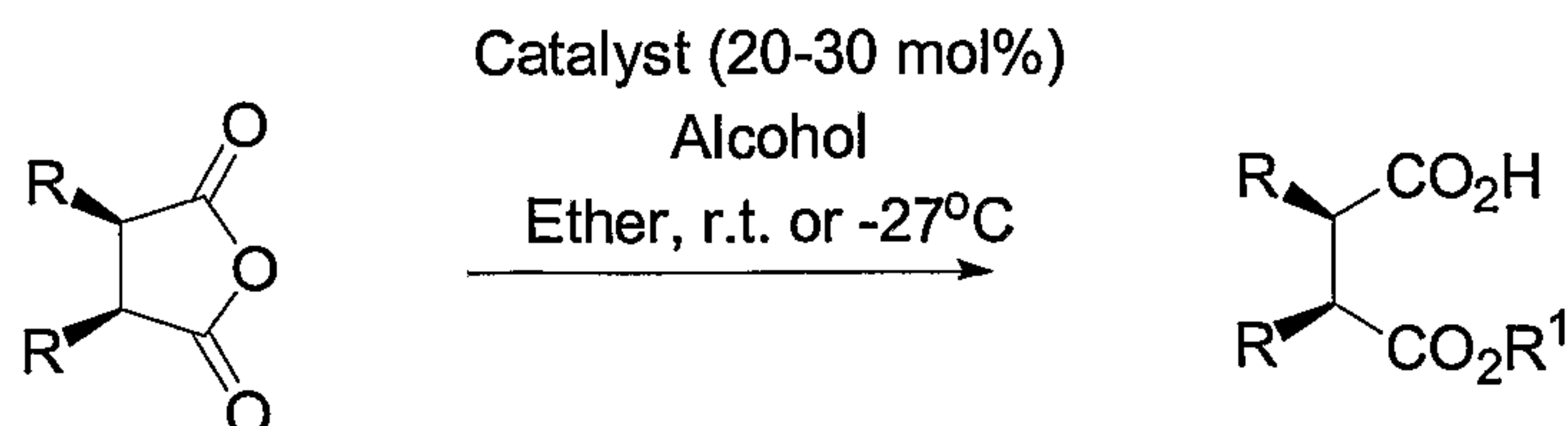
To a solution of hemiester (0.1 mmol) in dry toluene (3 mL) at 0 °C was added thionyl chloride (14.3 mg, 0.12 mmol). The mixture was allowed to stir at 0 °C for 10 min followed by the addition of (*R*)-1-(1-naphthyl)ethylamine (18.8 mg, 0.11 mmol) and triethylamine (33.4 mg, 0.33 mmol), respectively. The resulting mixture was allowed to stir for 30 minutes at 0 °C followed by another 30 minutes at room temperature. The reaction was then quenched with

HCl (1 N, 5 mL), diluted with EtOAc (20 mL), and washed with saturated NaHCO₃ (5 mL) and saturated brine (5 mL), respectively. The organic layer was dried with Na₂SO₄.

Example 6

General Procedure for the Alcoholysis of *Meso* Substituted Succinic Anhydrides Using QD-PP

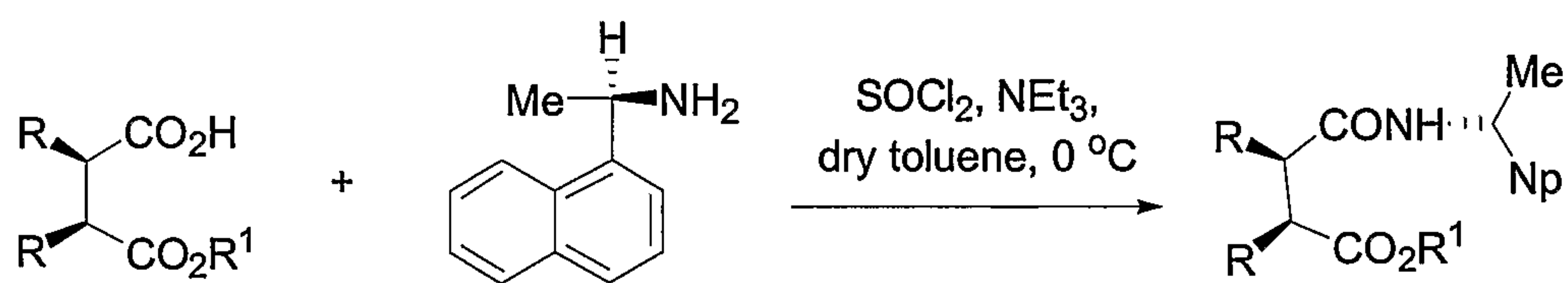
5 in Ether



Alcohol (1.0 mmol) was added to a solution of anhydride (0.1 mmol) and QD-PP (20-100 mol %) in ether (5.0 mL) at the reaction temperature indicated in the Figures. *See, e.g.,* Figures 11 and 12. The reaction mixture was initially stirred and then allowed to sit at that temperature until the starting material is consumed as indicated by TLC analysis (2-72 h). The reaction was quenched by adding HCl (1 N, 3 mL) in one portion. The aqueous phase was extracted with ether (2 x 10 mL). The organic phase was combined, dried over Na₂SO₄, and concentrated to provide the desired product without further purification. The product was determined pure as indicated by NMR). The enantiomeric excess (ee) of each product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the hemiester according to the modified literature procedure below.

Modified Literature Procedure for Determining the Enantiomeric Excess of Products

(*J. Hiratake, M. Inagaki, Y Yamamoto, J. Oda, J. Chem. Soc., Perkin Trans. 1 1987, 1053.*)

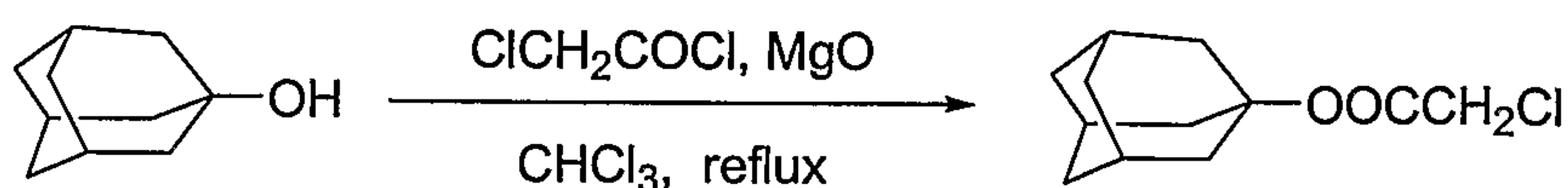


To a solution of hemiester (0.1 mmol) in dry toluene (3 mL) at 0 °C was added thionyl chloride (14.3 mg, 0.12 mmol). The mixture was allowed to stir at 0 °C for 10 min followed by the addition of (R)-1-(1-naphthyl)ethan-1-amine (18.8 mg, 0.11 mmol) and triethylamine (33.4 mg, 0.33 mmol), respectively. The resulting mixture was allowed to stir for 30 minutes at 0 °C followed by another 30 minutes at room temperature. The reaction was then diluted with

EtOAc (20 mL) and washed successively with HCl (1 N, 10 mL), saturated NaHCO₃ (10 mL) and saturated brine (10 mL). The organic layer was dried with Na₂SO₄.

Example 7

Preparation of adamantyl chloroacetate (2)



5

1-Adamantanol (1)

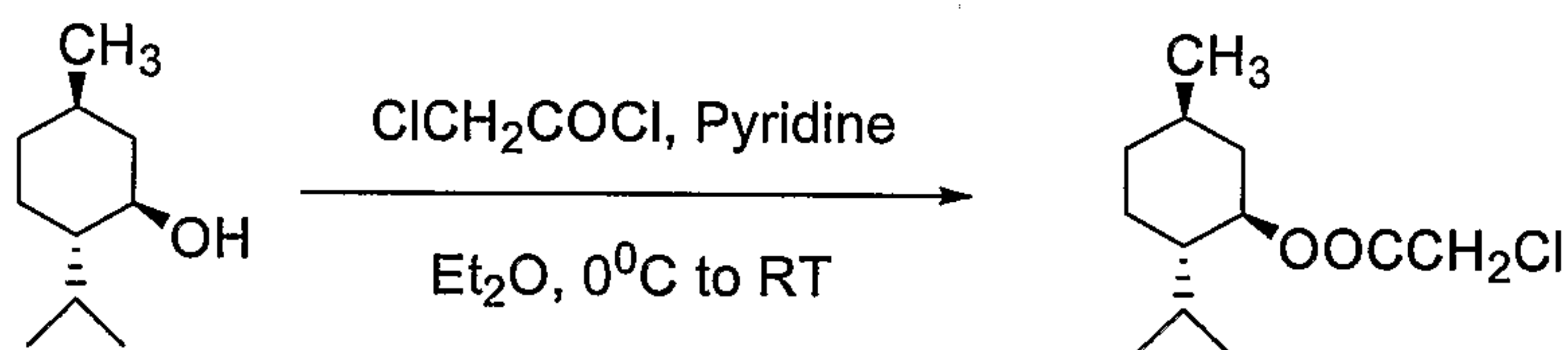
1-Adamantyl chloroacetate (2)

At 10 °C and under N₂, chloroacetyl chloride (9 mL, 113 mmol) was added slowly to a suspension of 1-adamantanol (11.4 g, 75 mmol) and MgO (4.5 g, 113 mmol) in CHCl₃ (150 mmol). The mixture was heated to slight reflux for 43 h and cooled to RT. The insoluble material was removed by filtration and the solvent was evaporated. The residue was crystallized in hexanes to afford **2** as a white solid (6.324 g, 37%). US 4,456,611; Helv. Chim. Acta 1988, 71, 1553.

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Example 8

Preparation of (-)-menthyl chloroacetate (4a)



(-)-Menthol (3a)

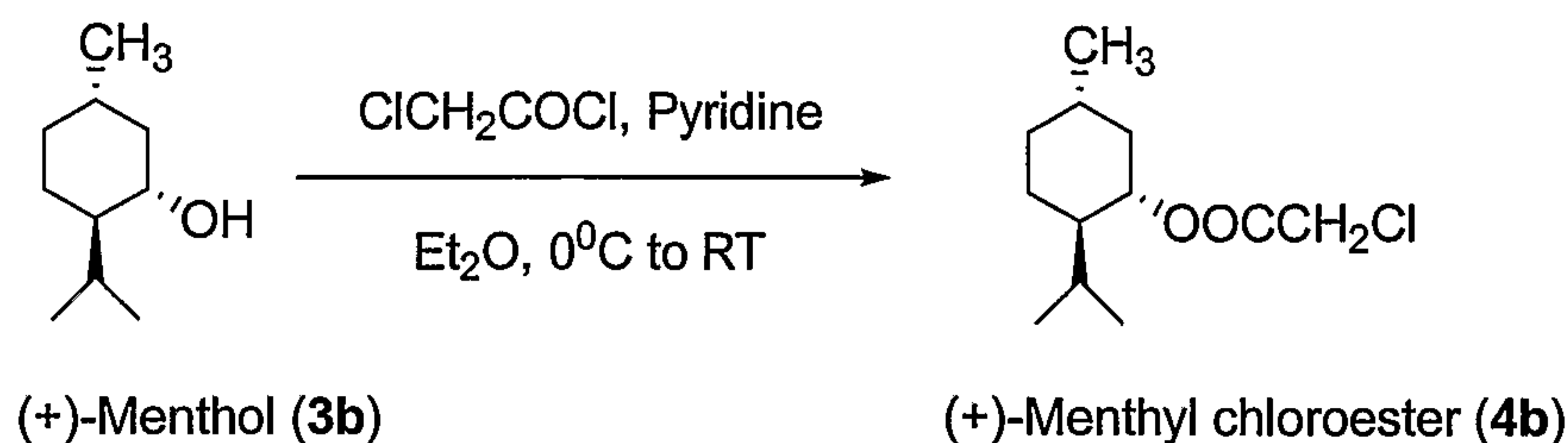
(-)-Menthyl chloroester (4a)

15

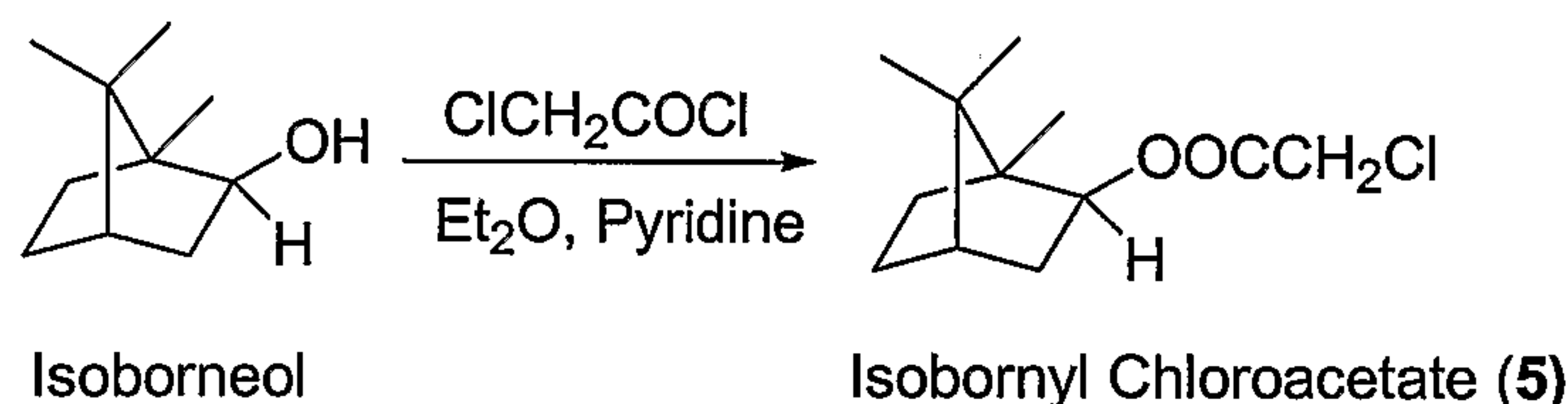
A solution of chloroacetyl chloride (6.4 mL, 80 mmol) in 40 mL anhydrous diethyl ether was added dropwise within 2 h to a solution of (-)-menthol (**3a**) (12.5 g, 80 mmol) and pyridine (6.5 mL, 80 mmol) in anhydrous diethyl ether (160 mL) at 0 °C. After warming to RT, the white suspension was stirred for 2 h and the resulting mixture was then filtered. The filtrate was washed with HCl (60 mL, 2 N), saturated. NaHCO₃ (60 mL), brine and dried with Na₂SO₄. Removal of the solvent and drying under vacuum afford (-)-menthyl chloroacetate (**4a**) (17.64 g, 94%), which was used without further purification. US 4,456,611; Helv. Chim. Acta 1988, 71, 1553.

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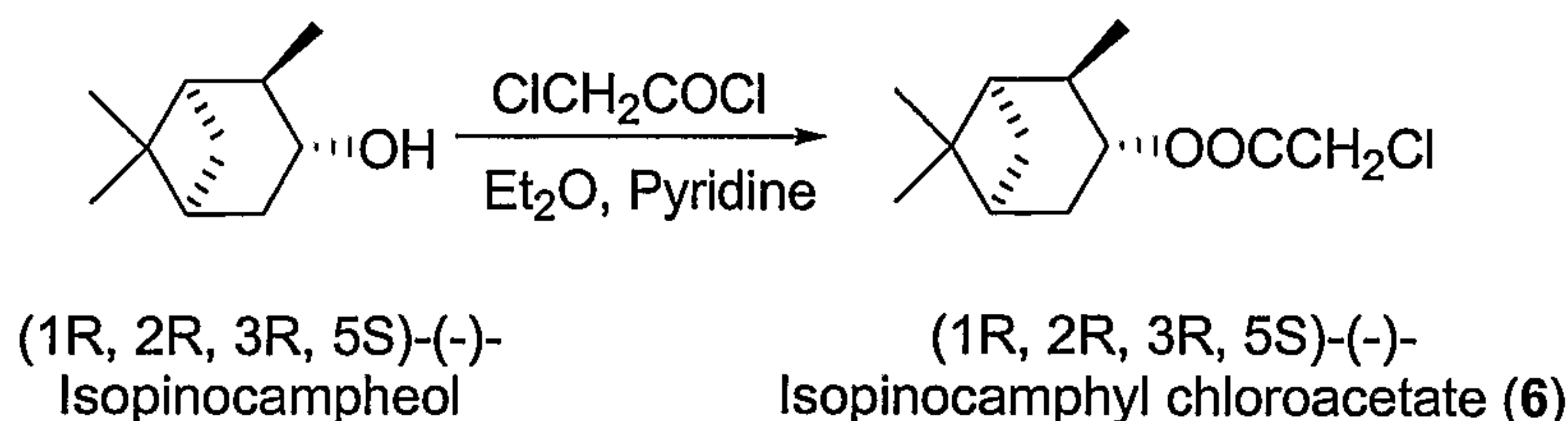
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Example 9**Preparation of (+)-menthyl chloroacetate (4b)**

The procedure described in the preceding Example was carried out on 40 mmol scale to synthesis (+)-menthyl chloroester (4b) in 95% yield from (+)-menthol (3b). US 4,456,611; Helv. Chim. Acta **1988**, 71, 1553.

Example 10**Synthesis of Chloroacetate Ester 5**

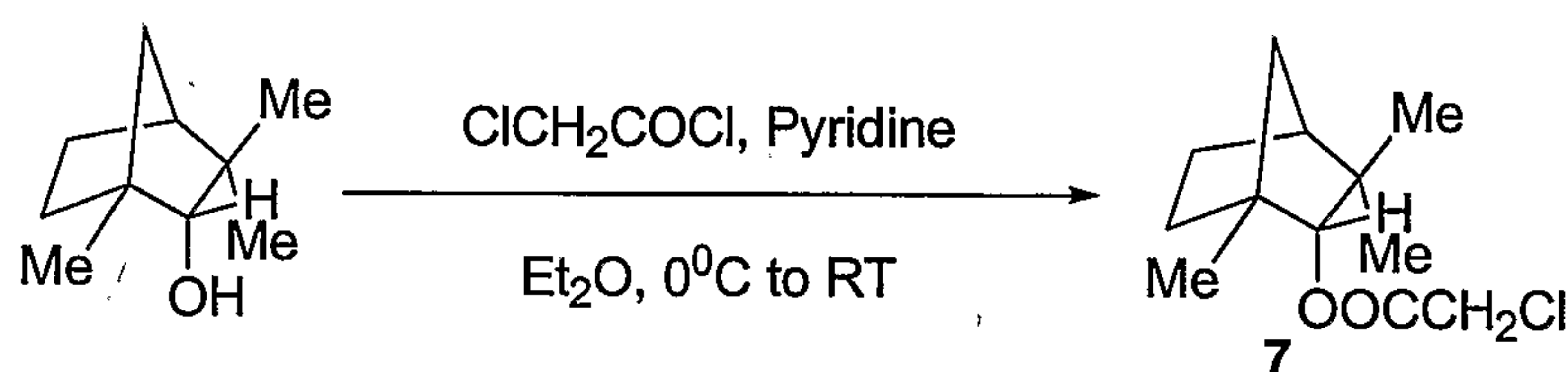
To a solution of isoborneol (9.255 g, 0.06 mol), pyridine (4.9 mL, 0.06 mol) in anhydrous diethyl ether (120 mL) at 0 °C, chloroacetyl chloride (4.78 mL, 0.06 mol) in anhydrous diethyl ether (30 mL) was added dropwise during a period of 2 h. Then the reaction mixture was allowed to warm to room temperature and stirred for another 3 h. The resulting mixture was filtrated with the aid of Celite, washed with diethyl ether (30 mL). The combined organic layer was washed with aqueous HCl (2 N, 45 mL), followed by saturated aqueous NaHCO₃ (45 mL), then saturated brine (45 mL), dried over Na₂SO₄, concentrated to give yellow greenish oil (13.10 g, 95% yield) in NMR-pure form and was used without further purification.

Example 11**Synthesis of (1R, 2R, 3R, 5S)-(-)-Isopinocampyl chloroacetate (6)**

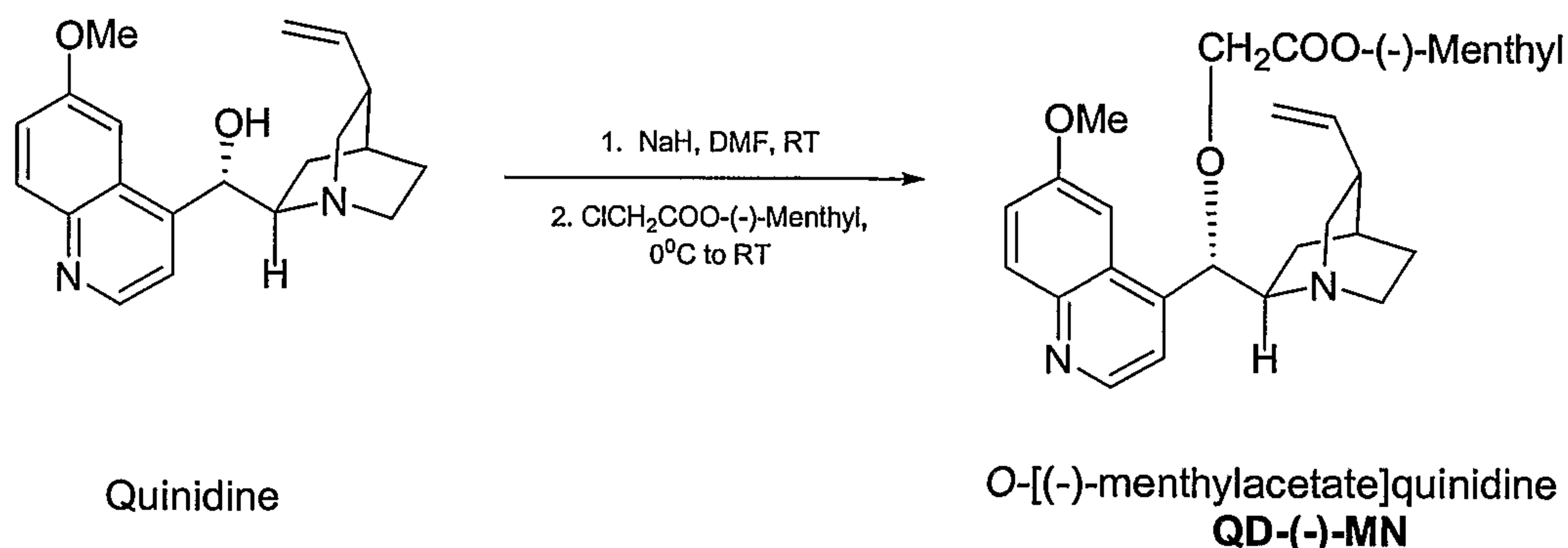
To a solution of (1R, 2R, 3R, 5S)-(-)-Isopinocampheol (9.255 g, 0.06 mol), pyridine (4.9 mL, 0.06 mol) in anhydrous diethyl ether (120 mL) at 0 °C, chloroacetyl chloride (4.78 mL, 0.06mol) in anhydrous diethyl ether (30 mL) was added dropwise during a period of 2 h. Then the reaction mixture was allowed to warm to room temperature and stirred for another 3 h. The resulting mixture was filtrated with the aid of Celite, washed with diethyl ether (30 mL). The combined organic layer was washed with aqueous HCl (2 N, 45 mL), followed by saturated aqueous NaHCO₃ (45 mL), then saturated brine (45 mL), dried over Na₂SO₄, concentrated to give yellow greenish oil (13.13 g, 95% yield) in NMR-pure form and was used without further purification.

Example 12

Synthesis of (1R)-Endo-(+)-Fenchyl Chloroacetate (QD-EF, 7)



A solution of chloroacetyl chloride (6.4 mL, 80 mmol) in 40 mL anhydrous diethyl ether was added dropwise within 2 h to a solution of (1R)-Endo-(+)-Fenchyl Alcohol (12.25 g, 79.5 mmol) and pyridine (6.5 mL, 80 mmol) in 160 mL of anhydrous diethyl ether at 0°C. After warming to RT, the white suspension was stirred for 2.5 h. The precipitate was removed by filtration and washed by diethyl ether (30 mL). The combined organic solution was washed with HCl (2 N, 60 mL), followed by sat. NaHCO₃ (60 mL), sat. NaCl (60 mL) solutions and dried with Na₂SO₄. Removal of the solvent and drying at vacuum afford (1R)-Endo-(+)-Fenchyl Chloroacetate (17.33 g, 94.5%) which was used without further purification.

Example 13**Synthesis of *O*-[(-)-menthylacetate]quinidine and *O*-[(+)-menthylacetate]quinidine (QD-(-)-MN)****5 Procedure A (using chromatography purification)**

Under a nitrogen atmosphere, NaH (60 mg, 1.5 mmol, 60 % in mineral oil) was washed with hexanes (2×3 mL) and suspended in DMF (5 mL). Quinidine (0.324 g, 1.0 mmol) was added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 3 h). It was then cooled to 0 °C. (-)-Menthyl chloroacetate (**4a**) (0.349 g, 1.5 mmol) was added dropwise over one minute to the cooled reaction mixture. The reaction mixture was stirred for 0.5 h at 0 °C, then warmed to room temperature and kept at that temperature for 1.5 h. It is then carefully quenched with H₂O (10 mL) the mixture is mixed with ethyl acetate (15 mL). The organic and aqueous layers were separated. The aqueous phase was extracted with ethyl acetate (15 mL). The organic phases were combined, washed with sat. NaHCO₃ (10 mL), water (3×10 mL), brine (10 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash chromatography (ethyl acetate : methanol = 10 : 1) to afford *O*-((-)-menthylacetate)quinidine (0.2752 g, 53%) as a white foam. ¹H NMR (CDCl₃): δ 0.73 (d, J = 6.8 Hz, 3H), 0.76-1.10 (m, 9H), 1.22-1.40 (m, 2H), 1.40-1.60 (m, 3H), 1.60-1.72 (m, 2H), 1.72-1.84 (m, 2H), 1.93-2.20 (m, 1H), 2.14-2.32 (m, 2H), 2.70-2.90 (m, 3H), 3.04-3.16 (m, 1H), 3.28-3.44 (br, 1H), 3.89 (d, J = 16.4 Hz, 1H), 3.93 (s, 3H), 4.06 (d, J = 16.0 Hz, 1H), 4.77 (td, J = 11.2, 4.4, 1H), 5.08-5.15 (m, 2H), 5.20-5.45 (br, 1H), 6.12-6.21 (m, 1H), 7.20-7.50 (m, 3H), 8.04 (d, J = 8.8 Hz, 1H), 8.76 (d, J = 4.4 Hz, 1H)

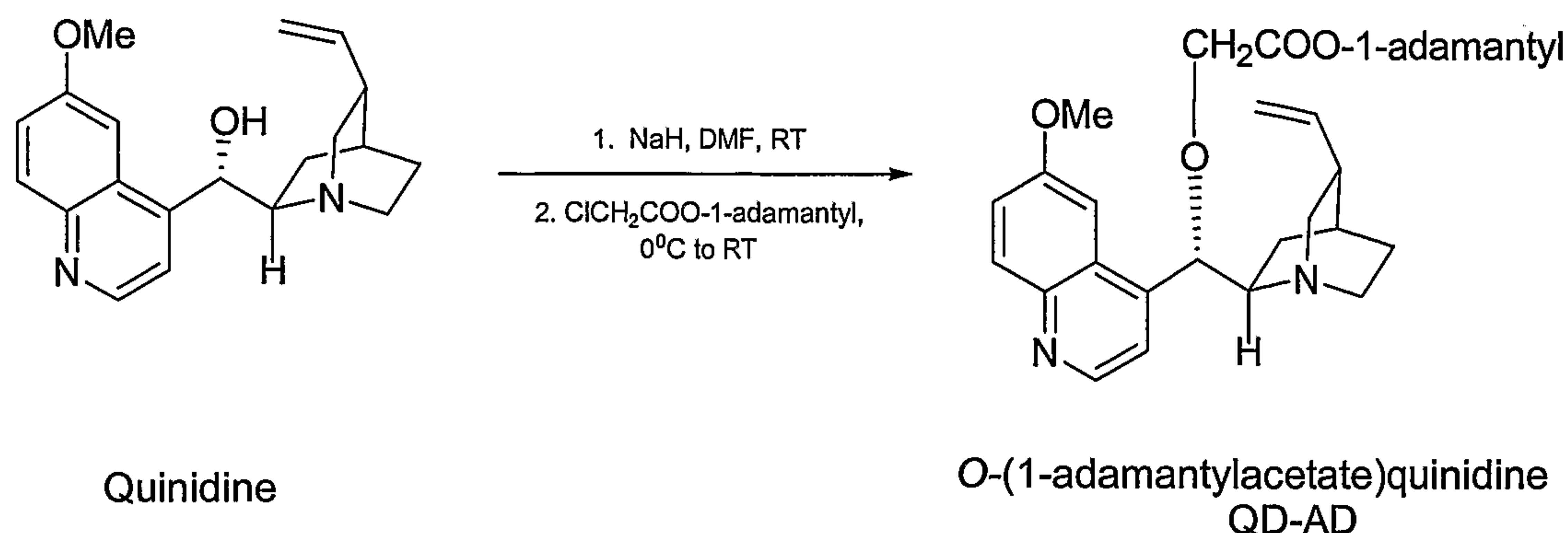
Synthesis of *O*-[(+)-menthylacetate]quinidine (QD-(+)-MN)

The procedure described above was used to prepare *O*-[(+)-menthylacetate]quinidine as a white foam in 43% yield. ¹H NMR (CDCl₃): 0.75 (d, J = 7.2 Hz, 3H), 0.85 (d, J = 7.6 Hz,

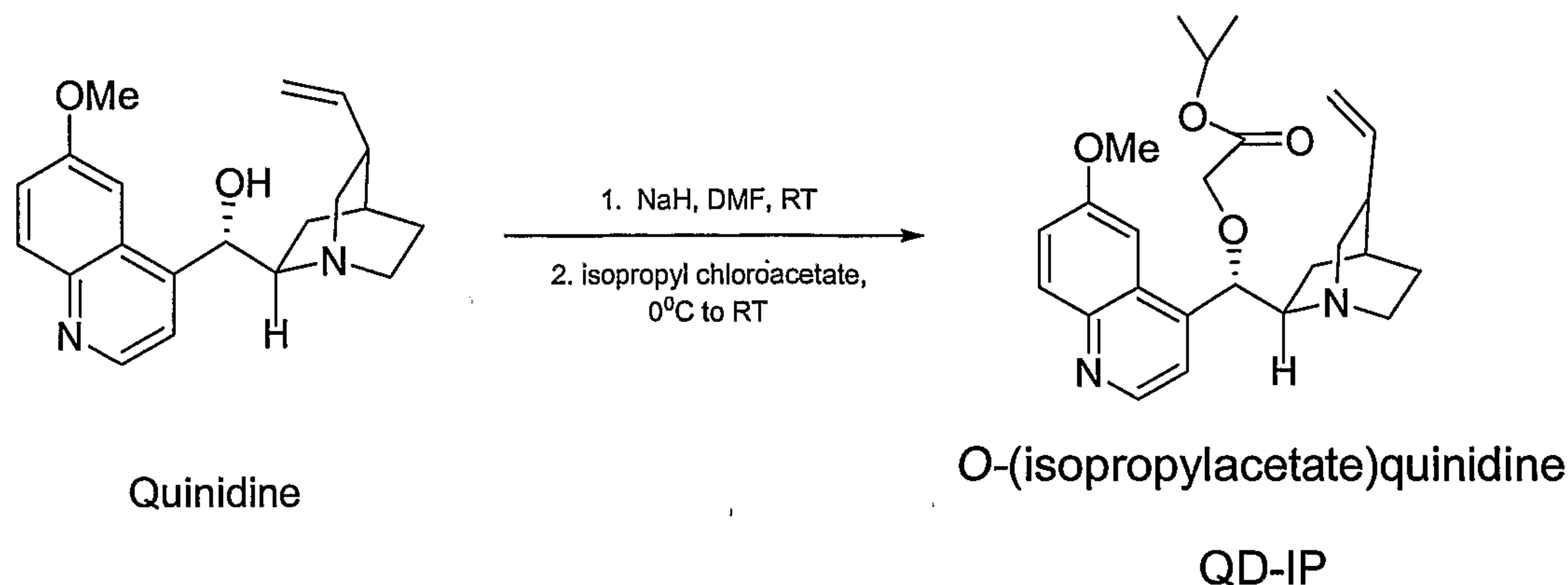
3H), 0.90 (d, $J = 6.8$ Hz, 3H), 0.78-1.12 (m, 3H), 1.20-1.40 (m, 2H), 1.42-1.94 (m, 7H), 1.97-2.06 (m, 1H), 2.26-2.48 (m, 2H), 2.80-3.30 (m, 4H), 3.46-3.90 (br, 1H), 3.99 (d, $J = 16$ Hz, 1H), 4.00 (s, 3H), 4.08 (d, $J = 16.0$ Hz, 1H), 4.79 (td, $J = 10.8, 4.8$, 1H), 5.10-5.30 (m, 2H), 5.46-6.10 (br, 1H), 6.10-6.24 (m, 1H), 7.36-7.56 (m, 3H), 8.04 (d, $J = 9.2$ Hz, 1H), 8.76 (d, $J = 4.4$ Hz, 1H)

Procedure B (purification without chromatographic separation) for preparation of QD-(-)-MN

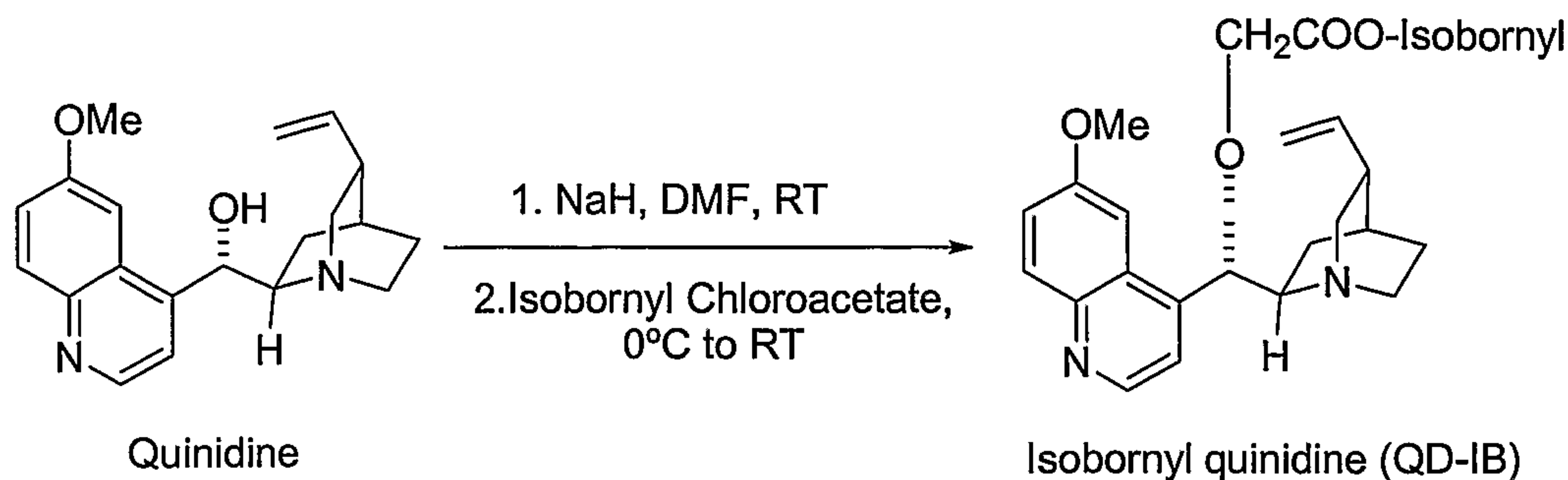
Under a nitrogen atmosphere, NaH (0.52 g, 12.9 mmol, 60 % in mineral oil) was washed with hexanes (2×9 mL) and suspended in DMF (43 mL). Quinidine (2.786 g, 8.6 mmol) was added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 2.5 h). It was then cooled to 0 °C. (-)-menthyl chloroacetate (3.0 g, 12.9 mmol) was added dropwise over a 1 min period to the cooled reaction mixture. The reaction mixture was stirred for 1 h at 0 °C, 1.5 h at RT. The mixture was cooled to 0 °C again, carefully quenched with H₂O (60 mL) and then ethyl acetate (60 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with ethyl acetate (30 mL). The organic phases were combined, washed with sat. NaHCO₃ (30 mL), water (3×30 mL), sat. NaCl (30 mL), and then extracted by 3×40 mL 5%w/w HCl. The combined acidic aqueous phase was extracted by 2×50 mL CH₂Cl₂. The combined organic phase was washed by 25 mL 5%w/w HCl and concentrated under reduced pressure. The brown residue was dissolved in 100 mL 0.1 N HCl. The aqueous phase was extracted by 50 mL Et₂O to remove trace impurities, basified to pH = 11 by KOH and extracted by 2×50 mL ether. The combined organic phase was dried over Na₂SO₄ and concentrated under reduced pressure to afford crude *O*-((-)-menthylacetate)quinidine as a yellowish foam. This crude produce was dissolved in 40 mL of anhydrous diethyl ether and treated dropwise with 0.95 equiv of 1.0 M solution of hydrogen chloride in diethyl ether (Aldrich) to precipitate the *O*-((-)-menthylacetate)quinidine hydrochloride. The seperated precipitate was washed by 2×10 mL diethyl ether, dried in air and suspended in 50 mL H₂O. KOH was used to adjusted the solution's pH = 11 and the resulted mixture was extracted by 3×50 mL diethyl ether. The combined organic phase was dried with Na₂SO₄ and concentrated under reduced pressure to afford *O*-((-)-menthylacetate)quinidine (1.783 g, 40%) as an off white crystalline foam.

Example 14**Synthesis of *O*-(1-adamantylacetate)quinidine (QD-AD)**

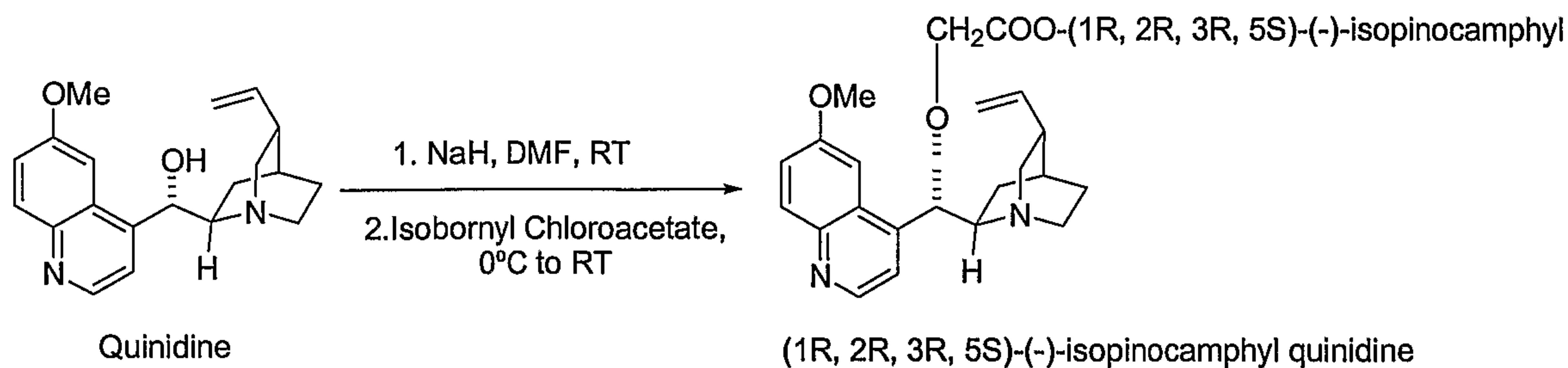
Under a nitrogen atmosphere, NaH (80 mg, 2 mmol, 60 % in mineral oil) was washed
 5 with hexanes (2×3 mL) and suspended in DMF (3 mL). Quinidine (0.1944 g, 0.6 mmol) was
 added to the mixture in small portions. The reaction mixture was stirred until the solution
 turned a yellow color (about 2h). It was then cooled to 0 °C. 1-Adamantyl chloroacetate
 (0.2285 g, 1 mmol) was added in small portions to the cooled reaction mixture. The reaction
 mixture was stirred for 3 h at RT, cooled to 0 °C, carefully quenched with H₂O (5 mL) and
 10 then was extracted with toluene (4×10 mL). The organic phases were combined, washed with
 water (5×5 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown
 residue was purified by flash chromatography (ethyl acetate : methanol = 9 : 1) to afford *O*-(1-
 adamantylacetate)quinidine (0.1640 g, 53%) as a white foam. ¹H NMR (CDCl₃): δ 1.22-1.38
 (m, 1H), 1.44-1.59 (m, 2H), 1.59-1.69 (m, 6H), 1.74-1.80 (m, 1H), 2.04-2.12 (m, 6H), 2.12-
 15 2.18 (m, 3H), 2.18-2.31 (m, 2H), 2.70-3.15 (m, 4H), 2.30-3.48 (m, 1H), 3.78 (d, J = 16 Hz,
 1H), 3.94 (s, 3H), 3.95 (d, J = 16 Hz, 1H), 5.08-5.15 (m, 2H), 5.20-5.50 (br, 1H), 6.11-6.22 (m,
 1H), 7.27-7.50 (m, 3H), 8.04 (d, J = 9.2 Hz, 1H), 8.76 (d, J = 4 Hz, 1H).

Example 15**Synthesis of *O*-(isopropylacetate)quinidine (QD-IP)**

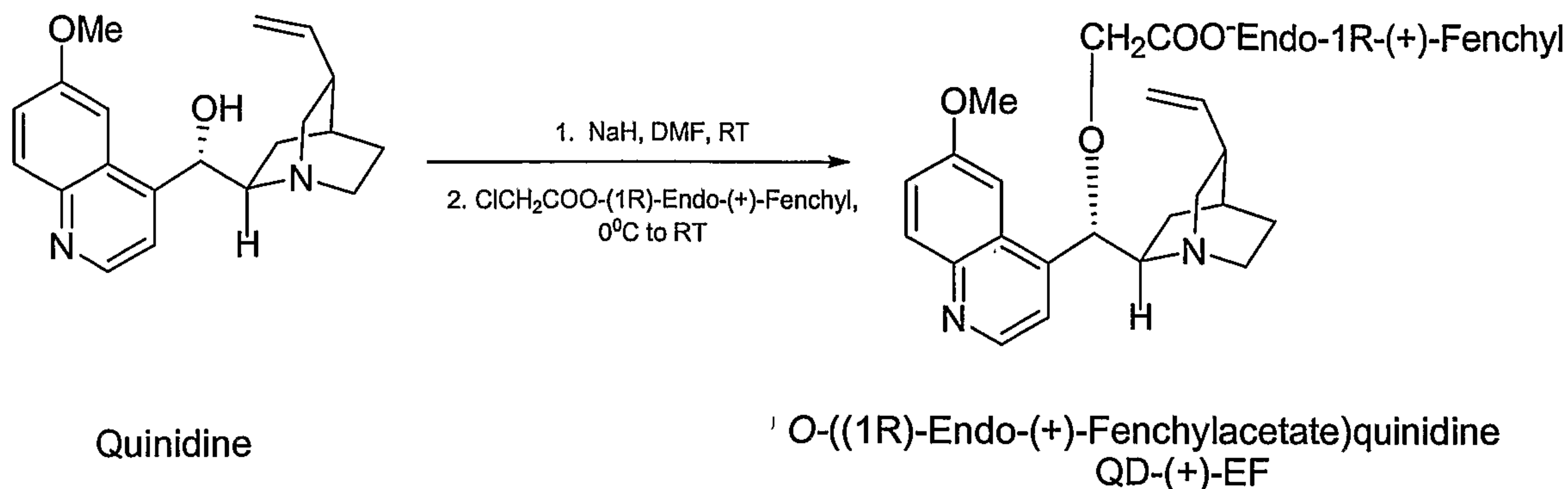
Under a nitrogen atmosphere, NaH (160 mg, 4 mmol, 60 % in mineral oil) was washed
 5 with hexanes (2×5 mL) and suspended in DMF (15 mL). Quinidine (0.972 g, 3 mmol) was
 added to the mixture in small portions. The reaction mixture was stirred until the solution
 turned a yellow color (about 2h). It was then cooled to 0 °C. Isopropyl chloroacetate (0.683 g,
 5 mmol) was added in one portion to the cooled reaction mixture. The reaction mixture was
 stirred for 3 h at 0 °C, 25 h at RT. Then another portion of Isopropyl chloroacetate (0.342 g,
 10 2.5 mmol) was added in one portion. The mixture was stirred at RT for 13h and carefully
 quenched with H₂O (20 mL) and then toluene (20 mL) was added. The organic and aqueous
 layers were separated. The aqueous phase was extracted with toluene (3×10 mL). The organic
 phases were combined, washed with water (5×10 mL), dried over Na₂SO₄, and concentrated
 under reduced pressure. The brown residue was purified by flash chromatography (ethyl
 15 acetate : methanol = 10 : 1) to afford *O*-(isopropylacetate)quinidine (0.1884 g, 15%) as a light
 yellow oil. ¹H NMR (CDCl₃): δ 1.23 (d, J = 6.0 Hz, 6H), 1.20-1.38 (m, 1H), 1.42-1.60 (m,
 2H), 1.75-1.84 (m, 1H), 2.16-2.32 (m, 2H), 2.71-3.02 (m, 3H), 3.05-3.18 (m, 1H), 3.30-3.50
 (m, 1H), 3.86 (d, J = 16.8 Hz, 1H), 3.94 (s, 3H), 4.04 (d, J = 16.4 Hz, 1H), 5.02-5.20 (m, 3H),
 5.26-5.44 (br, 1H), 6.11-6.24 (m, 1H), 7.24-7.54 (m, 3H), 8.04 (d, J = 9.2 Hz, 1H), 8.76 (d, J =
 20 4.4 Hz, 1H).

Example 16**Synthesis of isobornyl quinidine and (1R, 2R, 3R, 5S)-(-)-isopinocampyl quinidine (QD-IB)**

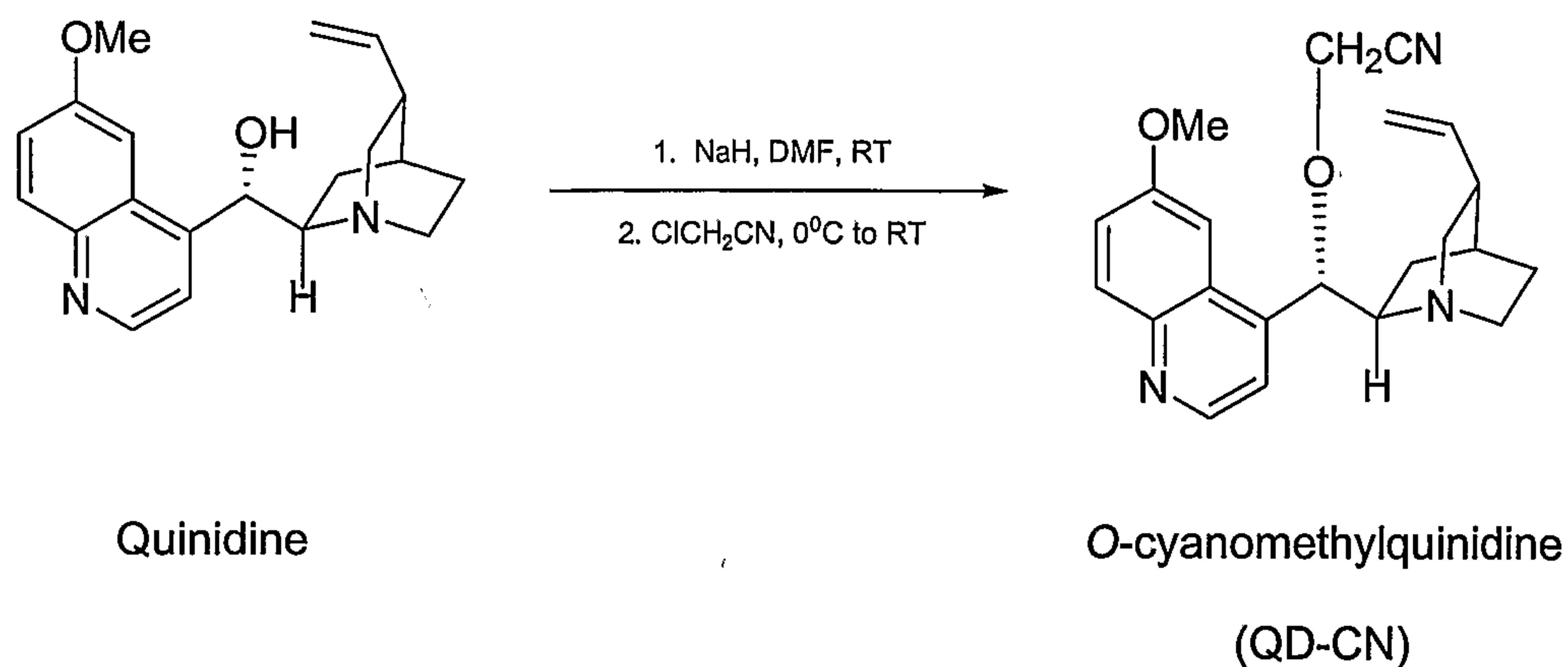
Under a nitrogen atmosphere, NaH (300 mg, 7.5 mmol, 60 % in mineral oil) was washed with hexanes (2×5 mL) and suspended in DMF (25 mL). Quinidine (1.62 g, 5.0 mmol) was added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 2h). It was then cooled to 0 °C. Isobornyl chloroacetate (1.728 g, 7.5 mmol) was added dropwise over a 2 min period to the cooled reaction mixture. The reaction mixture was stirred for 1 h at 0 °C, 1 h at RT, and carefully quenched with H₂O (35 mL) and then ethyl acetate (35 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with ethyl acetate (35 mL). The organic phases were combined, washed with sat. NaHCO₃ (17 mL), water (3 × 17 mL), sat. NaCl (17 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash chromatography (ethyl acetate : methanol = 20 : 1) to afford isobornylacetate)quinidine (1.218 g, 47%) as a white foam.

Example 17**Synthesis of (1R, 2R, 3R, 5S)-(-)-isopinocampyl quinidine [QD-(-)-IPC]**

The procedure described in the preceding Example afforded (1R, 2R, 3R, 5S)-(-)-isopinocampyl chloroacetate) quinidine (QD-(-)-IPC) as a white foam in 45% yield.

Example 18**Synthesis of *O*-((1*R*)-Endo-(+) Fenchylacetate)quinidine**

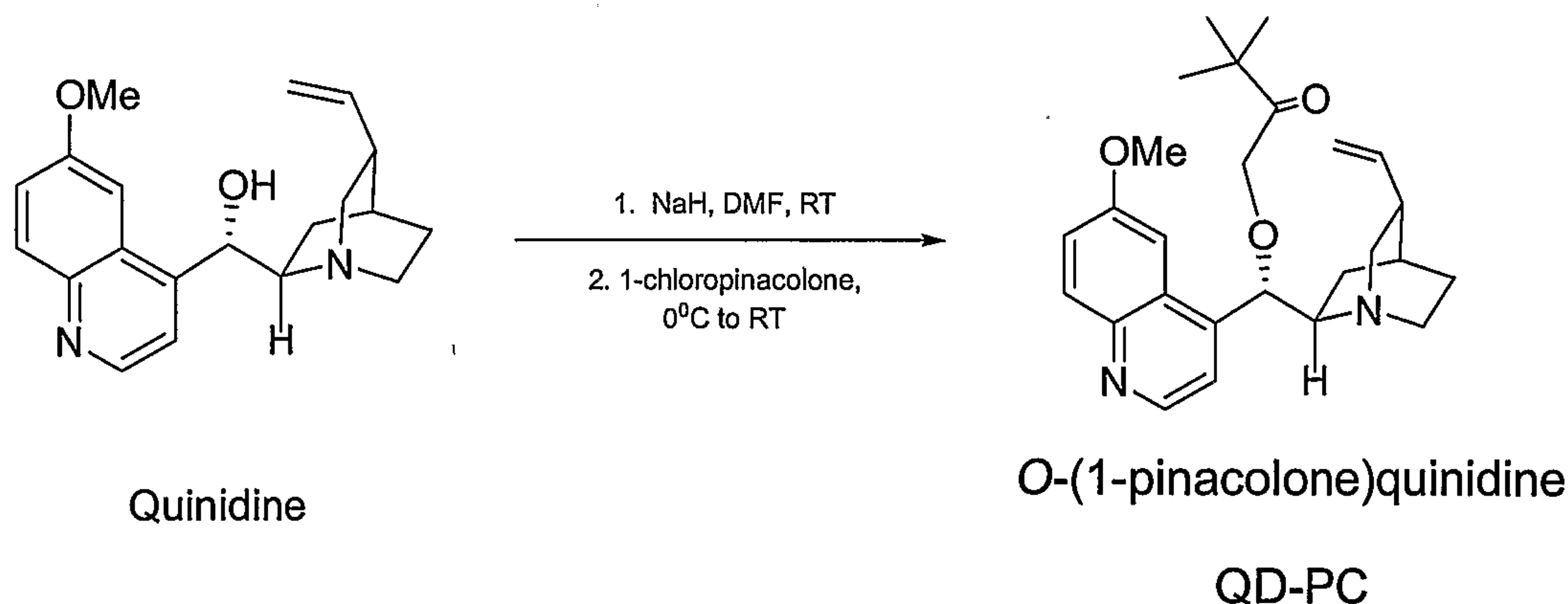
Under a nitrogen atmosphere, NaH (0.3 g, 7.5 mmol, 60 % in mineral oil) was washed
 5 with hexanes (2×5 mL) and suspended in DMF (25 mL). Quinidine (1.620 g, 5 mmol) was
 added to the mixture in small portions. The reaction mixture was stirred until the solution
 turned a yellow color (about 2.5 h). It was then cooled to 0 °C. (1*R*)-Endo-(+)-Fenchyl
 Chloroacetate (1.728 g, 7.5 mmol) was added dropwise over a 1 min period to the cooled
 reaction mixture. The reaction mixture was stirred for 1 h at 0 °C, 1.5 h at RT, and carefully
 10 quenched with H₂O (35 mL) and then ethyl acetate (35 mL) was added. The organic and
 aqueous layers were separated. The aqueous phase was extracted with ethyl acetate (35 mL).
 The organic phases were combined, washed with sat. NaHCO₃ (17 mL), water (3 × 17 mL), sat.
 NaCl (17 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown
 residue was purified by flash chromatography (ethyl acetate : methanol = 9:1) to afford *O*-
 15 ((1*R*)-Endo-(+)-Fenchylacetate)quinidine (1.0119 g, 39%) as a light yellowish foam.

Example 19**Synthesis of *O*-cyanomethylquinidine (QD-CN)**

Under a nitrogen atmosphere, NaH (0.266 g, 6.66 mmol, 60 % in mineral oil) was washed with hexanes (2×10 mL) and suspended in DMF (10 mL). Quinidine (0.648 g, 2 mmol) was added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 2 h). It was then cooled to 0 °C. Chloroacetonitrile (0.227 g, 3 mmol) was added dropwise over a 5 min period to the cooled reaction mixture. The reaction mixture was stirred for 1.5 h at 0 °C and then 1.5 h at room temperature (TLC check, conversion 40%, ethyl acetate : methanol = 5 : 2). The mixture was again cooled to 0 °C, chloroacetonitrile (0.227 g, 3 mmol) was added dropwise over a 5 min period and the reaction mixture was allowed to stir overnight at room temperature (TLC check, no enhancement of conversion, ethyl acetate : methanol = 5 : 2). The mixture was cooled to 0 °C and carefully quenched with H₂O (13 mL) and then toluene (13 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with toluene (3×7 mL). The organic phases were combined, washed with sat. NaHCO₃ (7 mL), sat. NaCl (7 mL), water (5×7 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The black residue was purified by flash chromatography (ethyl acetate : methanol = 5:2) to afford *O*-cyanomethylquinidine (85.4 mg, 12%) as a light brown viscous oil. ¹H NMR (CDCl₃): 1.32-1.88 (m, 4H), 1.95-2.10 (m, 1H), 2.25-2.36 (m, 1H), 2.70-2.89 (m, 2H), 2.91-3.03 (m, 1H), 3.05-3.22 (m, 2H), 3.97 (s, 3H), 4.03 (d, J = 16.0 Hz, 1H), 4.31 (d, J = 16.0 Hz, 1H), 5.09-5.18 (m, 2H), 5.33-5.56 (br, 1H), 5.99-6.11 (m, 1H), 7.30-7.46 (m, 3H), 8.05 (d, J = 9.2 Hz, 1H), 8.77 (d, J = 4.8 Hz, 1H).

Example 20

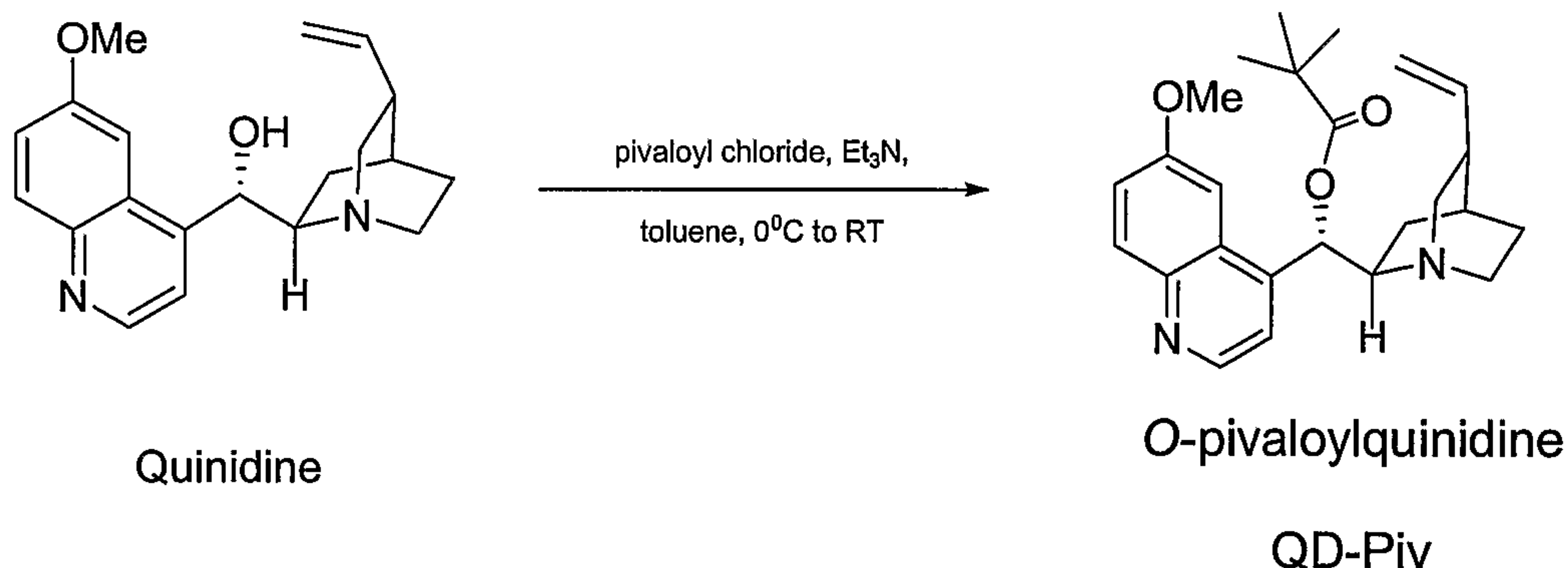
Synthesis of *O*-(1-pinacolone)quinidine (QD-PC)



Under a nitrogen atmosphere, NaH (160 mg, 4 mmol, 60 % in mineral oil) was washed with hexanes (2×5 mL) and suspended in DMF (15 mL). Quinidine (0.972 g, 3 mmol) was

added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 2 h). It was then cooled to 0 °C. 1-chloropinacolone (0.670 g, 5 mmol) was added in one portion to the cooled reaction mixture. The reaction mixture was stirred for 0.5 h at 0 °C, 3.5 h at RT. Then another portion of 1-chloropinacolone (0.670 g, 5 mmol) was added in one portion. The mixture was stirred at RT for 36 h and carefully quenched with H₂O (20 mL) and then toluene (20 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with toluene (2×20 mL). The organic phases were combined, washed with water (5×10 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash chromatography (ethyl acetate : methanol = 5 : 1) to afford *O*-(1-pinacolone)quinidine (0.3296 g, 26%) as a colorless oil. ¹H NMR (CDCl₃): δ 1.06 (s, 9H), 1.23-1.38 (m, 1H), 1.45-1.63 (m, 2H), 1.76-1.84 (m, 1H), 2.22-2.38 (m, 2H), 2.72-3.20 (m, 4H), 3.32-3.54 (m, 1H), 3.95 (s, 3H), 4.20 (d, J = 18.0 Hz, 1H), 4.29 (d, J = 17.2 Hz, 1H), 5.10-5.20 (m, 2H), 5.26-5.48 (m, 1H), 6.16-6.26 (m, 1H), 7.30-7.48 (m, 3H), 8.04 (d, J = 9.2 Hz, 1H), 8.75 (d, J = 4.4 Hz, 1H).

15

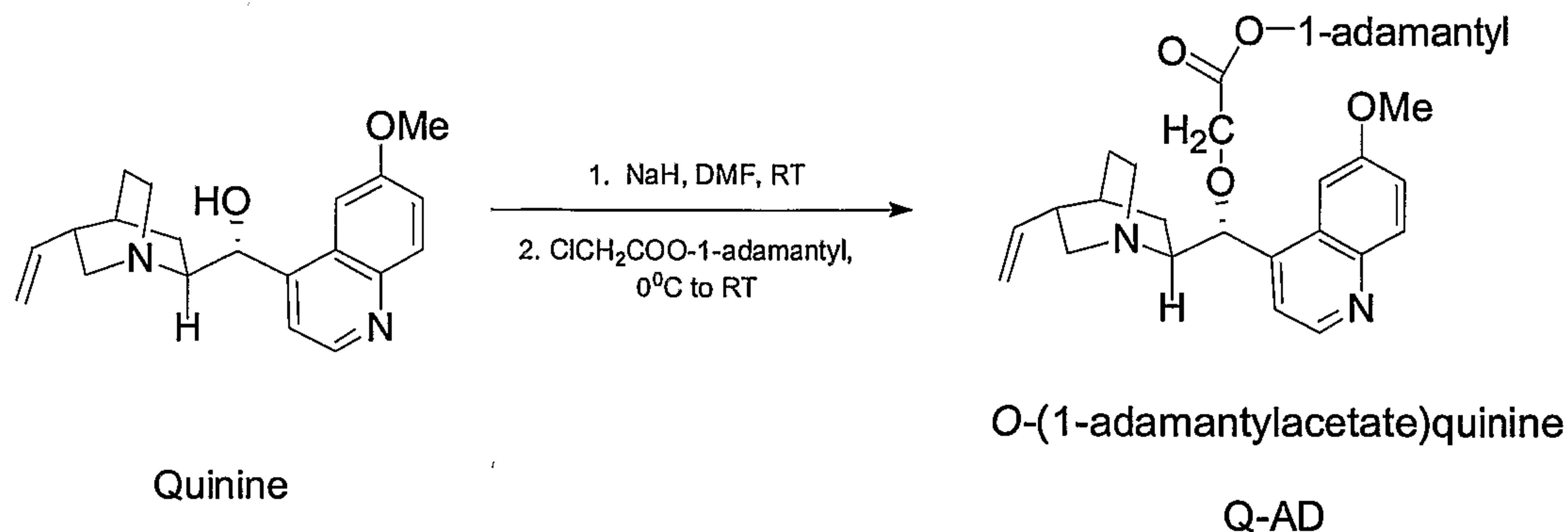
Example 21**Synthesis of *O*-pivaloylquinidine (QD-Piv)**

To a stirred suspension of Quinidine (0.972 g, 3 mmol) in toluene at 0 °C, pivaloyl chloride (0.362 g, 3 mmol) was added dropwise, followed by adding triethyl amine (1 mL). The reaction mixture was stirred at RT for 9.5 h. Then another portion of pivaloyl chloride (0.362 g, 3 mmol) was added in one portion. The mixture was stirred at RT for 13h and carefully quenched with H₂O (20 mL) and then toluene (20 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with toluene (20 mL). The organic phases were combined, washed with sat. NaHCO₃ (10 mL), sat. NaCl (2×10 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash

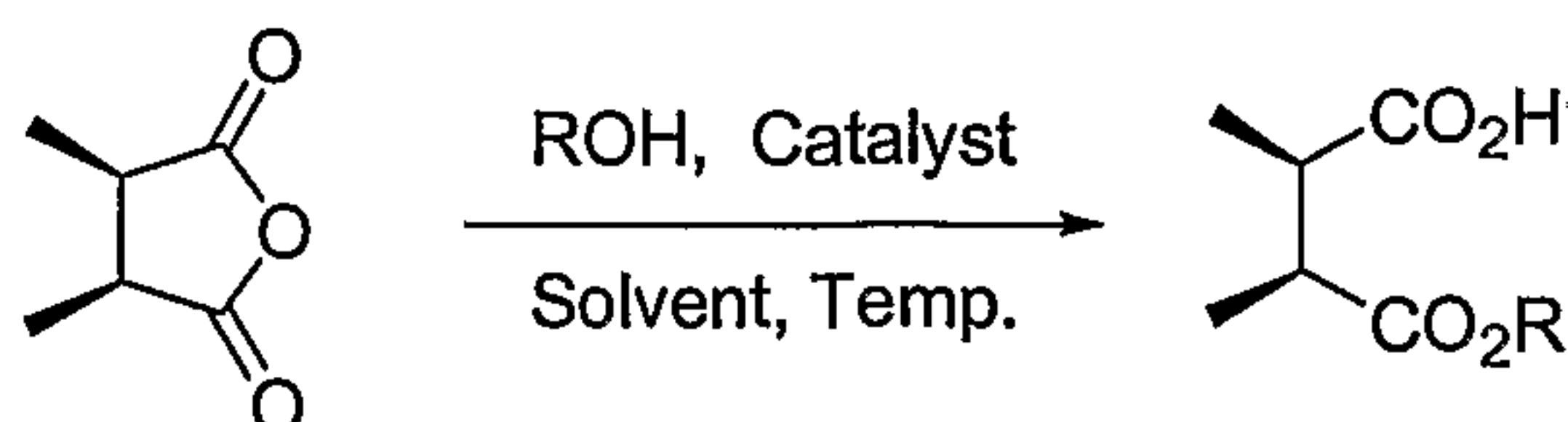
chromatography (ethyl acetate : methanol = 10 : 1) to afford O-pivaloylquinidine (0.5582 g, 46%) as a colorless oil. ¹H NMR (CDCl₃): δ 1.22 (s, 9H), 1.48-1.66 (m, 3H), 1.74-1.86 (m, 2H), 2.30-2.52 (m, 1H), 2.65-2.82 (m, 2H), 2.92 (d, J = 8.8Hz, 2H), 3.26-3.38 (m, 1H), 3.96 (s, 3H), 5.06-5.15 (m, 2H), 5.97-6.08 (m, 1H), 6.44 (d, J = 8.0Hz, 1H), 7.31-7.45 (m, 3H), 8.00 (d, J = 9.2 Hz, 1H), 8.73 (d, J = 4.4 Hz, 1H).

Example 22

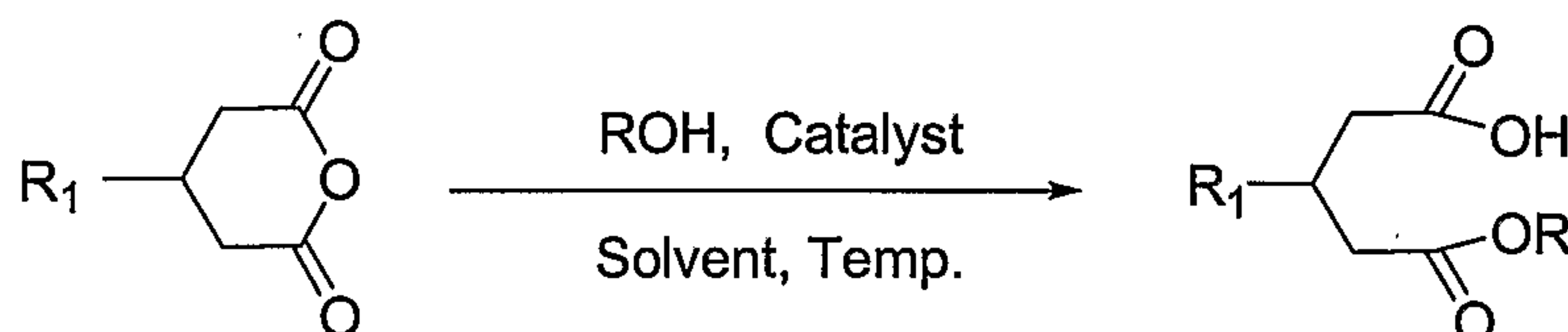
Synthesis of O-(1-adamantylacetate)quinine (Q-AD)



Under a nitrogen atmosphere, NaH (180 mg, 4.5 mmol, 60 % in mineral oil) was washed with hexanes (2×5 mL) and suspended in DMF (15 mL). Quinine (0.972 g, 3 mmol) was added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 4.5 h). It was then cooled to 0 °C. 1-adamantyl chloroacetate (1.028 g, 4.5 mmol) was added in small portions to the cooled reaction mixture. The reaction mixture was stirred for 1 h at 0 °C, 1 h at RT, cooled to 0 °C, carefully quenched with H₂O (20 mL) and then was extracted with ethyl acetate (20 mL, 10 mL). The organic phases were combined, washed with sat. NaHCO₃ (10 mL), water (3×10 mL), sat. NaCl (10 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash chromatography (ethyl acetate : methanol = 10 : 1) to afford O-(1-adamantylacetate)quinine (0.4222 g, 27%) as a white foam. ¹H NMR (CDCl₃): δ 1.48-1.76 (m, 8H), 1.78-2.01 (m, 3H), 2.04-2.12 (m, 6H), 2.12-2.20 (m, 3H), 2.24-2.39 (m, 1H), 2.56-2.80 (m, 2H), 3.03-3.27 (m, 2H), 3.44-3.72 (m, 1H), 3.76 (d, J = 16 Hz, 1H), 3.96 (s, 3H), 3.97 (d, J = 16 Hz, 1H), 4.90-5.01 (m, 2H), 5.20-5.56 (br, 1H), 5.70-5.80 (m, 1H), 7.30-7.50 (m, 3H), 8.04 (d, J = 9.2 Hz, 1H), 8.76 (d, J = 4.4 Hz, 1H).

Example 23**General Procedure for the Alcoholysis of 2,3-dimethyl succinic Anhydride**

Alcohol (0.1-1.0 mmol) was added to a solution of anhydride (0.05–0.2 mmol) and catalyst (5-110 mol %) in solvent (0.5-5.0 mL) at the reaction temperature indicated in the table. The reaction mixture was initially stirred and then allowed to sit at that temperature until the starting material was consumed as indicated by TLC analysis* or Chiral GC (β -CD, 130 °C/20 min)** analysis (0.5 h-37 d). The reaction was quenched by adding HCl (1 N, 5mL) in one portion. The aqueous phase was extracted with ether (2 x 20 mL). The organic phase was combined, dried over Na₂SO₄, and concentrated to provide the desired product. The enantiomeric excess (ee) of the product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the product according to a modified literature procedure (for trifluoroethyl ester) or chiral GC analysis (β -CD, 130 °C/20 min) (for methyl ester).

Example 24**General Procedure for the Alcoholysis of Prochiral Cyclic Anhydrides**

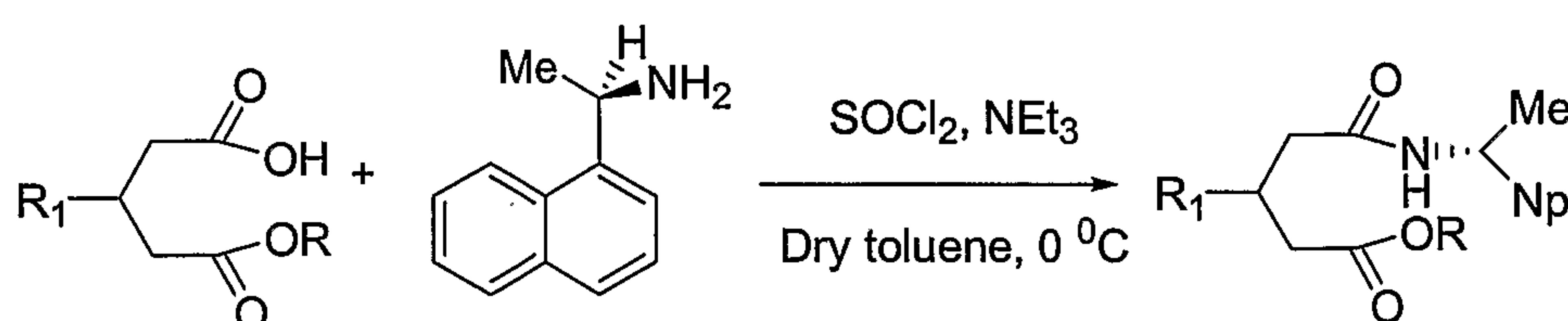
Alcohol (0.15-1.0 mmol) was added to a solution of anhydride (0.1 mmol) and catalyst (20-110 mol %) in solvent (0.5-5.0 mL) at the reaction temperature indicated in the table. The reaction mixture was stirred at that temperature until the starting material is consumed as indicated by GC (β -CD) analysis (19- 141 h). The reaction was quenched by adding HCl (1 N, 4 mL) in one portion (when an acid-sensitive substrate, such as 3-*tert*-butyldimethylsilyl glutaric anhydride was used, H₃PO₄ (1.0 M) was used to quench the reaction). The aqueous phase was extracted with ether (40 mL). The organic phase was washed by another portion of

HCl (1 N, 4 mL)*, dried over Na₂SO₄, and concentrated to provide the desired product with or without further purification by flash chromatography. The enantiomeric excess (ee) of each product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the hemiester according to a modified literature procedure or chiral GC analysis.

Example 25

Preparation of amide-ester for ee analysis

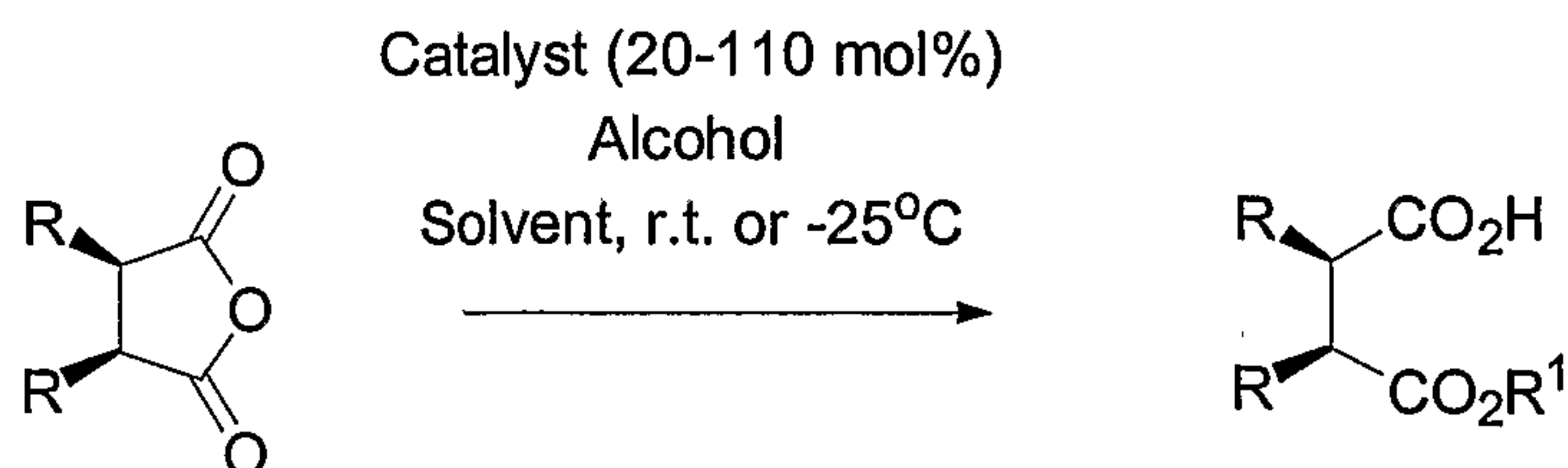
(See J. Hiratake, M. Inagaki, Y. Yamamoto, J. Oda, *J. Chem. Soc., Perkin Trans. 1*, 1987, 1053)



A mixture of the hemiester (0.1 mmol) and SOCl₂ (14.3 mg, 0.12 mmol) in toluene (3 mmol) was allowed to cool to 0 °C and kept at that temperature for 10 minutes. To the resulting solution, (*R*)-1-(1-naphthyl)ethyl-amine (18.8 mg, 0.11 mmol) and triethyl amine (33.4 mg, 0.33 mmol) were then added. The resulting mixture was allowed to stir for 30 minutes at 0 °C followed by another 30 minutes at room temperature. The reaction was then quenched with HCl (1 N, 5 mL), diluted with EtOAc (20 mL), and washed with saturated NaHCO₃ (5 mL) and brine (5 mL). The organic layer was dried with Na₂SO₄.

Example 26

General Procedure for the Alcoholysis of Prochiral Cyclic Anhydrides

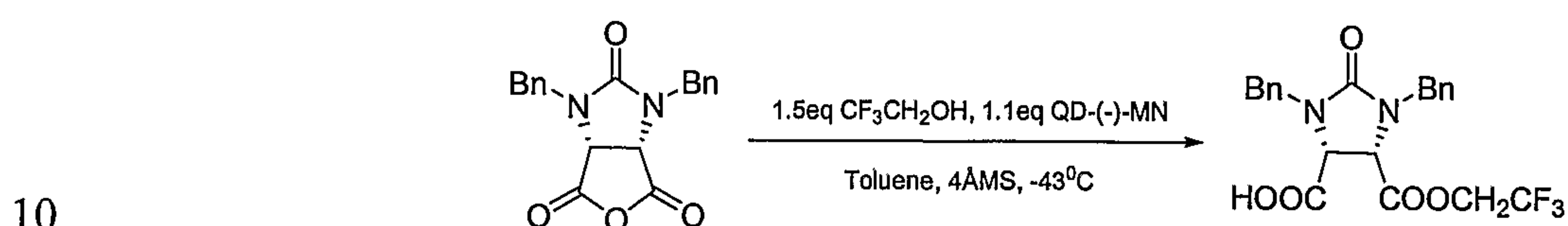


Alcohol (0.15-1.0 mmol) was added to a solution of anhydride (0.1 mmol) and catalyst (20-110 mol %) in the respective solvent (0.5-5.0 mL) at the reaction temperature indicated in the table. The reaction mixture was initially stirred and then allowed to sit at that temperature until the starting material is consumed as indicated by TLC analysis (2-186 h). The reaction was quenched by adding HCl (1 N, 3 mL) in one portion. The aqueous phase was extracted

with ether (2 x 10 mL). The organic phase was combined, washed with HCl (1 N, 2 x 3 mL), dried over Na₂SO₄, and concentrated to provide the desired product without further purification. The product was determined pure as indicated by NMR. The enantiomeric excess (ee) of each product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the hemiester according to a modified literature procedure.

Example 27

Procedure for trifluoroethanolysis of *cis*-1,3-Dibenzyl-tetrahydro-2H-furo[3,4-d]imidazole-2,4,6-trione



A mixture of QD-(-)-MN (57.2 mg, 0.11 mmol) and 4Å molecular sieves (22 mg) in anhydrous toluene was stirred at RT for 5 minutes, then *cis*-1,3-Dibenzyl -tetrahydro-2H-furo[3,4-d]imidazole-2,4,6-trione (33.6 mg, 0.10 mmol) was added, after which the mixture was cooled to -43 °C and stirred for another 10 minutes. CF₃CH₂OH was added in one portion.

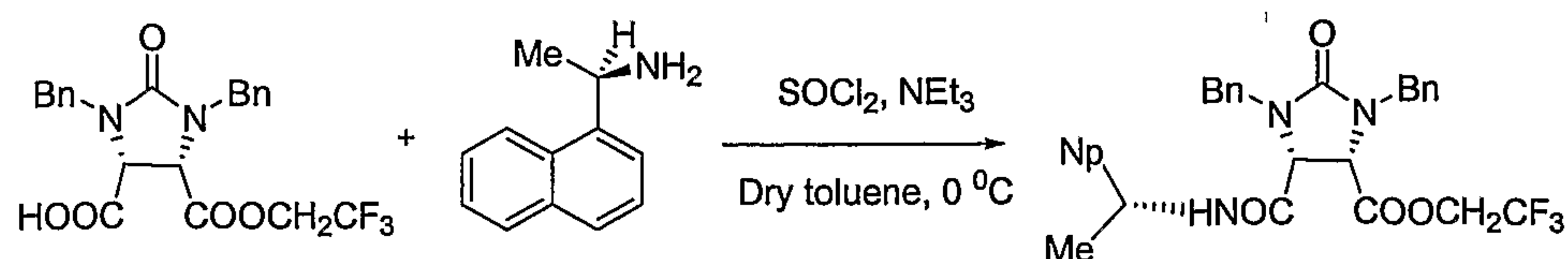
15 The mixture was stirred at that temperature until the starting material was consumed as indicated by TLC (20% methanol in methylene chloride) analysis (9 h). Aq. HCl (1.0 N, 4.0 mL) was added to quench the reaction. The aqueous phase was extracted by 40 mL diethyl ether. The combined organic phase was washed by another portion of aq. HCl (1 N, 4 mL), dried with NaSO₄ and concentrated to afford the hemiester as a white solid (38.8 mg, 89%,

20 94%ee) which is pure by NMR. The enantiomeric excess (ee) of the product was determined by HPLC analysis of a diastereoisomeric mixture of the corresponding amide-ester prepared from the hemiester according to a modified literature procedure.

Example 28

Procedure for ee analysis

25 (See J. Hiratake, M. Inagaki, Y Yamamoto, J. Oda, *J. Chem. Soc., Perkin Trans. 1*, 1987, 1053)

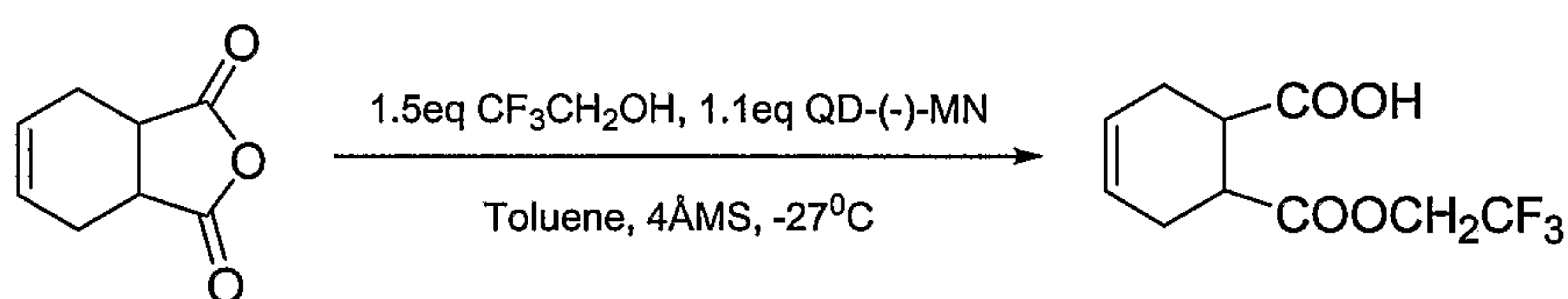


To a solution of hemiester (0.1 mmol) in dry toluene (6 mL) and methylene chloride (6 mL) at 0 °C was added thionyl chloride (14.3 mg, 0.12 mmol). The mixture was allowed to stir at 0 °C for 15 min followed by the addition of (R)-1-(1-naphthyl)ethylamine (18.8 mg, 0.11 mmol) and triethylamine (33.4 mg, 0.33 mmol), respectively. The resulting mixture was allowed to stir for 1 h at 0 °C followed by another 1 h at room temperature. The reaction was then quenched with HCl (1 N, 5 mL), diluted with EtOAc (40 mL), and washed with saturated NaHCO₃ (5 mL) and saturated brine (5 mL), respectively. The organic layer was dried with Na₂SO₄ and concentrated to half of its original volume.

10

Example 29

Procedure for Alcoholysis of Cis-1,2,3,6-Tetrahydrophthalic Anhydride at 1.0 mmol scale and Catalyst Recovery



A mixture of QD-(-)-MN (purified by hydrochloride salt) (572 mg, 1.1 mmol) and 4Å molecular sieves (220 mg) in anhydrous toluene was stirred at RT for 10 minutes, then *cis*-1,2,3,6-tetrahydrophthalic anhydride (152 mg, 1.0 mmol) was added, after which the mixture was cooled to -27 °C and stirred for another 15 minutes. Trifluoroethanol was added dropwise within 1 minute. The mixture was stirred at that temperature until the starting material was consumed as indicated by TLC (ethyl acetate : hexanes = 1:1) analysis (4 h). Aq. HCl (1 N, 10 mL) was added to quench the reaction. The aqueous phase was extracted by 50 mL diethyl ether. The organic phase was washed by aq. HCl (1 N, 2×10 mL), dried with NaSO₄ and concentrated to afford the hemiester as a colorless oil (239.7 mg, 95%, 98% ee) without further purification.

Catalyst Recovery

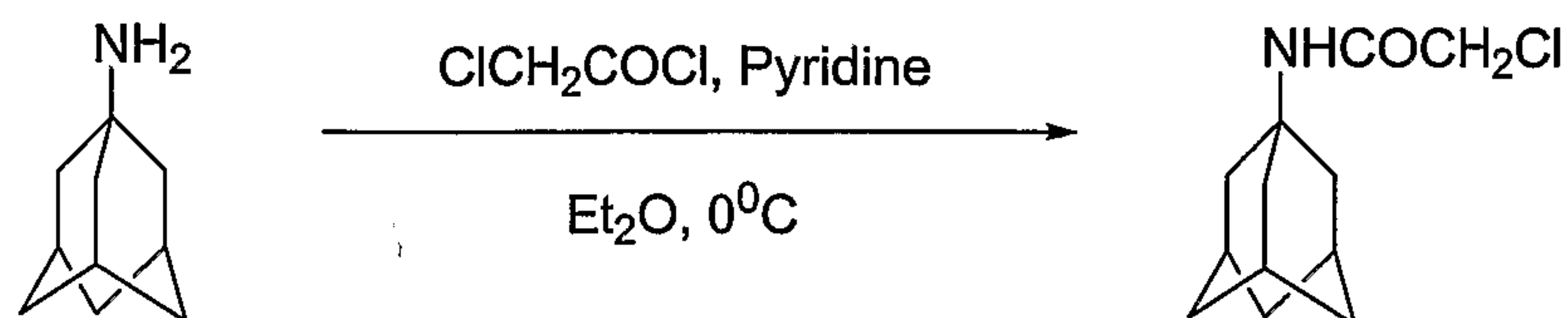
To recover the catalyst QD-(-)-MN, KOH was added to the aqueous layer to adjust the pH value of the solution to 11. The resulting mixture was extracted with ethyl acetate (3×15

mL). The combined organic layer was dried over Na_2SO_4 and concentrated to afford the catalyst (Quantity, recovery >95%). The recovered catalyst was used for a new batch of alcoholysis of *cis*-1,2,3,6-tetrahydrophthalic anhydride (1.0 mmol) to give the hemiester in 99% ee and 95% yield.

5

Example 30

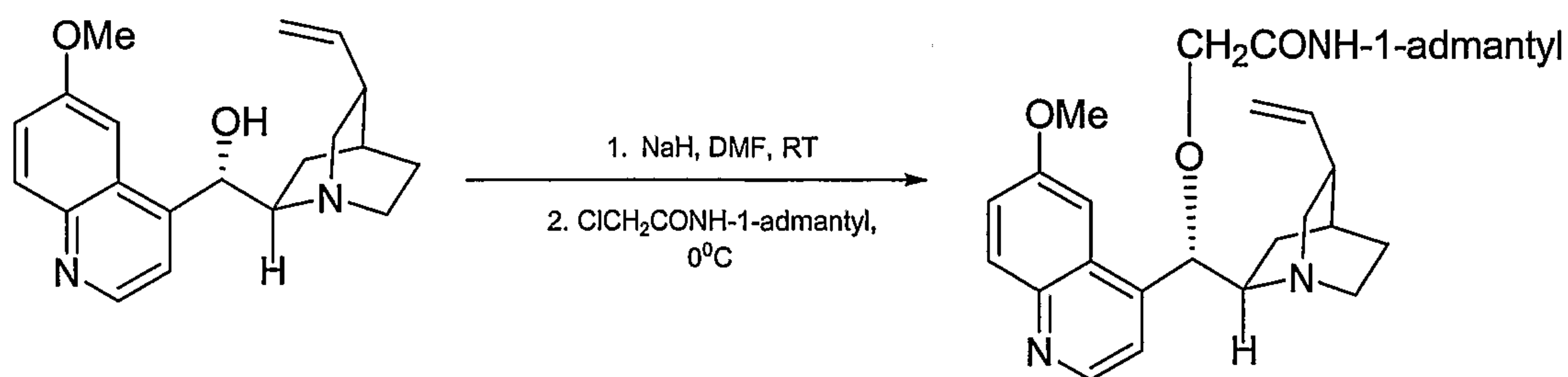
Synthesis of N-(1-Adamantyl)chloroacetamide using a procedure similar to that described in *Helv. Chim. Acta* **1988**, 71, 1553



A solution of chloroacetyl chloride (1.6 mL, 20 mmol) in anhydrous diethyl ether (10 mL) was added dropwise within 5 min to a solution of 1-adamantanamine (3.0 g, 20 mmol) and pyridine (1.63 mL, 20 mmol) in anhydrous diethyl ether (40 mL) at 0°C . The yellow suspension was stirred for 1 h at that temperature. The precipitate was removed by filtration and washed by diethyl ether (10 mL). The combined organic solution was washed with HCl (2 N, 2×15 mL), followed by sat. NaHCO_3 (15 mL), sat. NaCl (15 mL) solutions and dried with Na_2SO_4 . The solvent was removed at reduced pressure and the residue was recrystallized from diethyl ether-hexanes to afford N-(1-adamantyl)chloroacetamide (1.551 g, 34%) as a yellow solid.

Example 31

Synthesis of O-(1-adamantylacetamide)quinidine (Purified by Chromatography)



Quinidine

O-(1-adamantylacetamide)quinidine

20

QD-AA

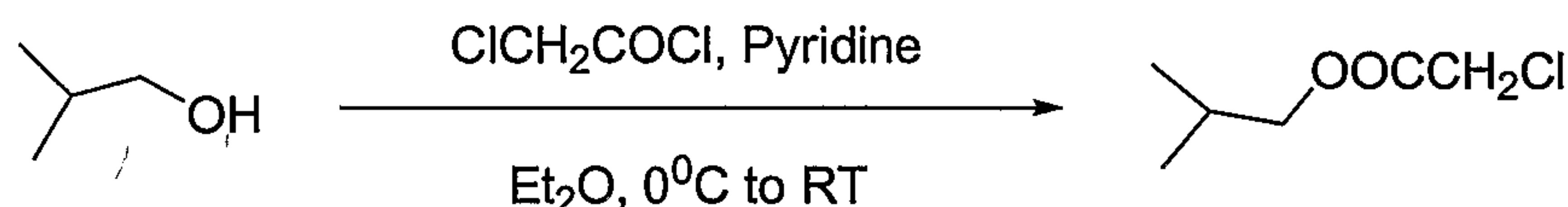
Under a nitrogen atmosphere, NaH (0.12 g, 3.0 mmol, 60% in mineral oil) was washed with hexanes (2×3 mL) and suspended in DMF (10 mL). Quinidine (0.652 g, 2.0 mmol) was

added to the mixture in small portions. The reaction mixture was stirred until the solution turned a yellow color (about 2 h). It was then cooled to 0 °C. N-(1-adamantyl)chloroacetamide (0.683 g, 3.0 mmol) was added in small portions to the cooled reaction mixture. The reaction mixture was stirred for 2 h at 0 °C and carefully quenched with H₂O (14 mL) and then ethyl acetate (14 mL) was added. The organic and aqueous layers were separated. The aqueous phase was extracted with ethyl acetate (2×14 mL). The organic phases were combined, washed with sat. NaHCO₃ (14 mL), water (3×14 mL), sat. NaCl (14 mL), dried over Na₂SO₄, and concentrated under reduced pressure. The brown residue was purified by flash chromatography (ethyl acetate : methanol = 9 : 1) to afford O-(1-adamantylacetamide)quinidine (0.8383 g, 81%) as a white crystalline foam. ¹H NMR (CDCl₃): δ 1.27-1.39 (m, 1H), 1.48-1.64 (m, 2H), 1.65-1.76 (br, 6H), 1.85 (s, 1H), 1.91-2.07 (m, 1H), 2.02 (s, 6H), 2.07-2.14 (br, 3H), 2.26-2.38 (m, 1H), 2.71-3.27 (m, 5H), 3.81 (s, 2H), 3.96 (s, 3H), 5.05-5.20 (m, 2H), 5.20-5.50 (br, 1H), 5.96-6.07 (m, 1H), 6.30-6.50 (br, 1H), 7.20-7.43 (m, 3H), 8.05 (d, J = 9.2 Hz, 1H), 8.77 (d, J = 4.8 Hz, 1H).

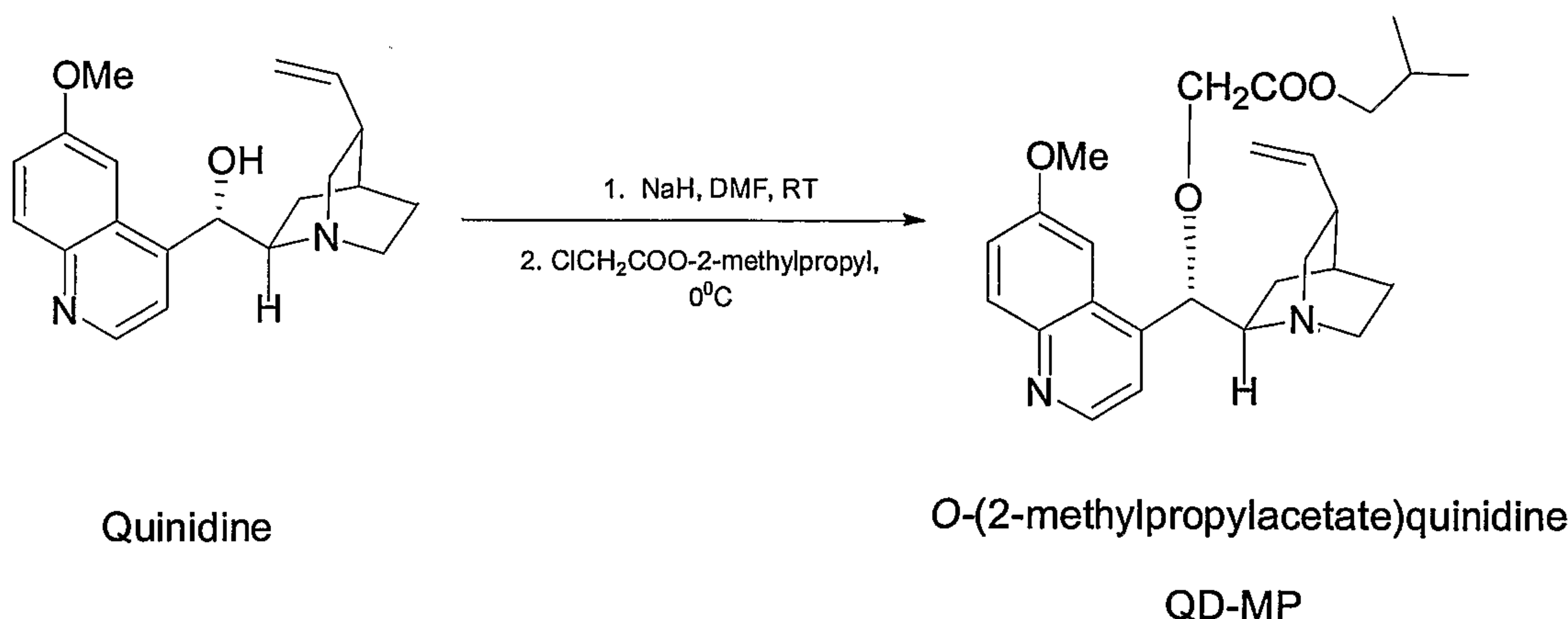
Example 32

Synthesis of 2-Methylpropyl Chloroacetate

(See *Helv. Chim. Acta* **1988**, 71, 1553)



A solution of chloroacetyl chloride (3.2 mL, 40 mmol) in anhydrous diethyl ether (20 mL) was added dropwise within 1 h to a solution of 2-methylpropanol (2.96 g, 40 mmol) and pyridine (3.25 mL, 40 mmol) in anhydrous diethyl ether (80 mL) at 0 °C. After warming to RT, the white suspension was stirred for 3 h. The precipitate was removed by filtration and washed by diethyl ether (15 mL). The combined organic solution was washed with HCl (2 N, 30 mL), followed by sat. NaHCO₃ (30 mL), sat. NaCl (30 mL) solutions and dried with Na₂SO₄. Removal of the solvent at about 60 mmHg/30 °C afford 2-Methylpropyl Chloroacetate (5.65 g, 94%) which was used without further purification.

Example 33**Synthesis of O-(2-Methylpropylacetate)quinidine (Purified by Chromatography)**

Under a nitrogen atmosphere, NaH (0.12 g, 3 mmol, 60% in mineral oil) was washed
 5 with hexanes (2×3 mL) and suspended in DMF (10 mL). Quinidine (0.648 g, 2 mmol) was
 added to the mixture in small portions. The reaction mixture was stirred until the solution
 turned a yellow color (about 2 h). It was then cooled to 0 °C. 2-Methylpropyl Chloroacetate
 (0.452 g, 3 mmol) was added dropwise over a 1 min period to the cooled reaction mixture. The
 reaction mixture was stirred for 4 h at 0 °C and carefully quenched with H₂O (14 mL) and then
 10 ethyl acetate (14 mL) was added. The organic and aqueous layers were separated. The aqueous
 phase was extracted with ethyl acetate (2 × 14 mL). The organic phases were combined,
 washed with sat. NaHCO₃ (14 mL), water (3 × 14 mL), sat. NaCl (14 mL), dried over Na₂SO₄,
 and concentrated under reduced pressure. The brown residue was purified by flash
 chromatography (ethyl acetate : methanol = 9 : 1) to afford O-(2-methylpropylacetate)quinidine
 15 (0.278 g, 32%) as a light brown oil. ¹H NMR (CDCl₃): δ 0.90 (d, J = 6.8 Hz, 6H), 1.22-1.39
 (m, 1H), 1.48-1.69 (m, 2H), 1.79-1.86 (br, 1H), 1.86-1.98 (m, 1H), 2.21-2.39 (m, 2H), 2.75-
 3.22 (m, 4H), 3.44-3.67 (br, 1H), 3.88-4.04 (m, 6H), 4.12 (d, J = 16.4 Hz, 1H), 5.08-5.23 (m,
 2H), 5.44-5.60 (br, 1H), 6.10-6.24 (m, 1H), 7.32-7.54 (m, 3H), 8.04 (d, J = 9.2 Hz, 1H), 8.76
 (d, J = 4.4 Hz, 1H).

20

Incorporation by Reference

All of the U.S. patents and U.S. published patent applications cited herein are hereby
 incorporated by reference.

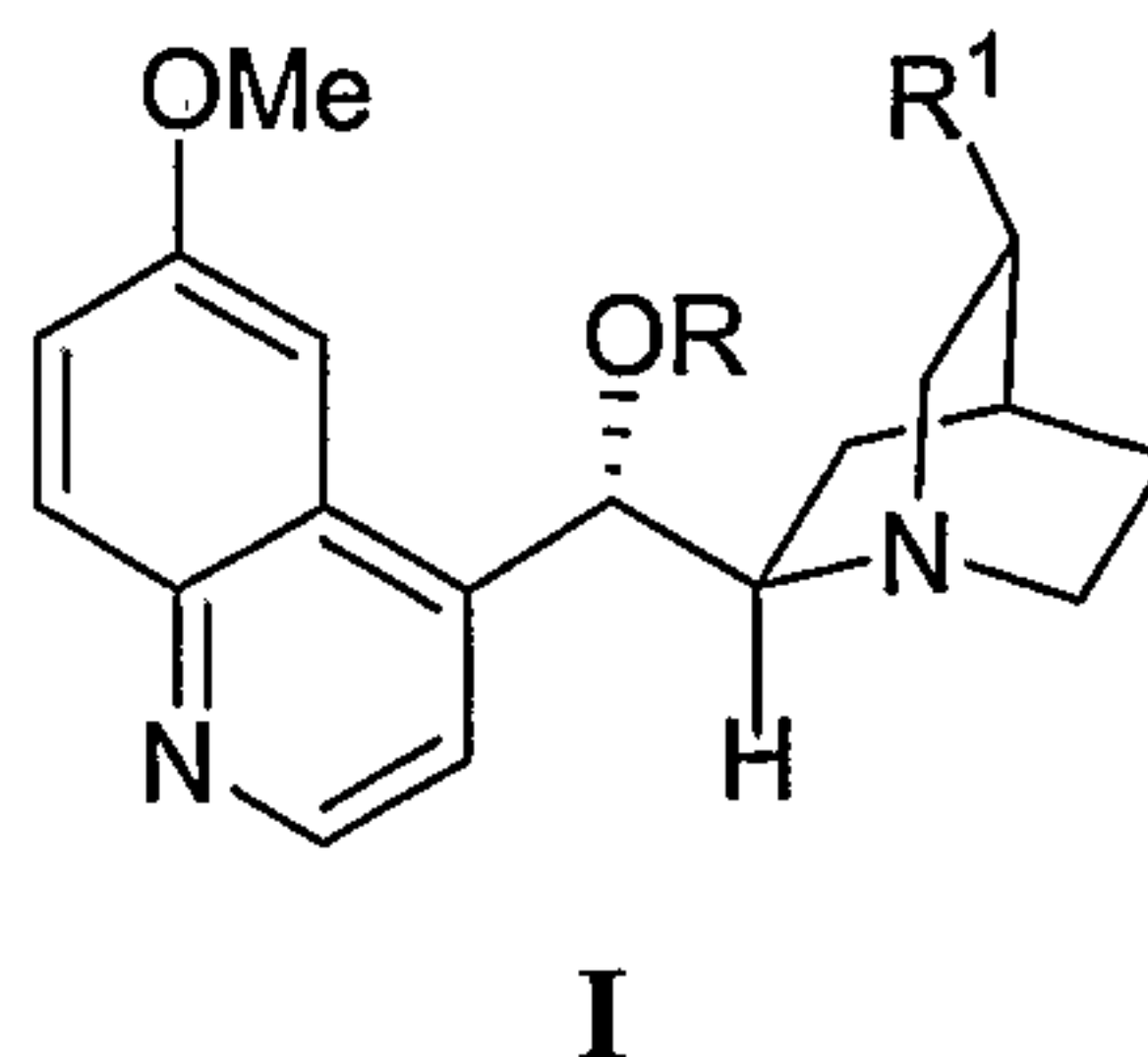
Equivalents

Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. Such equivalents are intended to be encompassed by the following claims.

5

We Claim:

1. A compound represented by formula I:



5 wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$, $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

R^1 represents alkyl or alkenyl;

10 R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

15 R^4 represents cycloalkyl, $-CH(R^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10.

20 2. The compound of claim 1, wherein R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, or $-C(C(R^3)_2)_nC\equiv CR^6$.

3. The compound of claim 1, wherein R^1 is ethyl.

4. The compound of claim 1, wherein R^1 is $-CH=CH_2$.

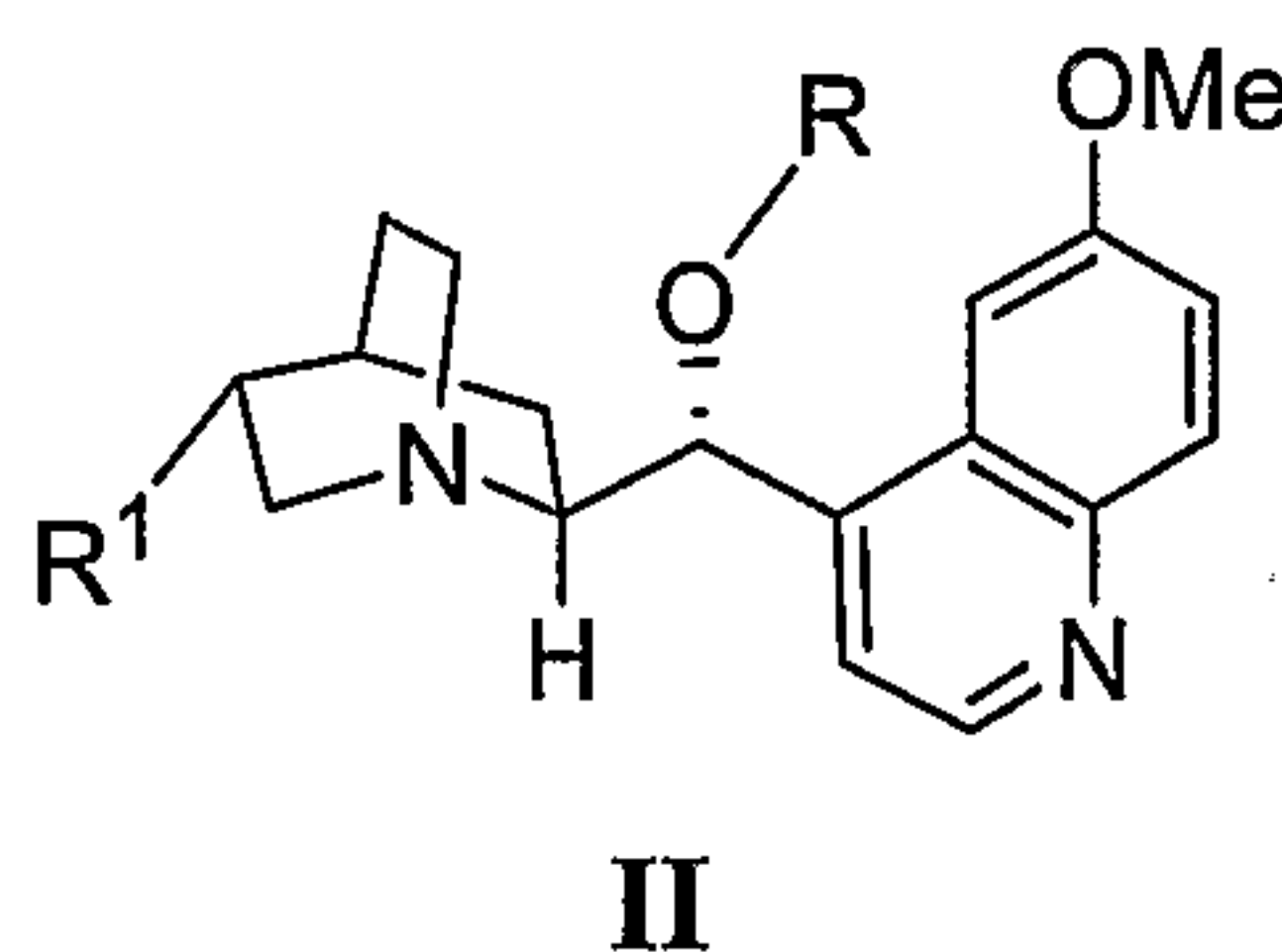
5. The compound of claim 1, wherein R is $-C(O)R^2$.

25 6. The compound of claim 1, wherein R is $-C(O)R^2$ and R^2 is alkyl.

7. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCO_2R^4$.

8. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCO_2R^4$ and R^4 is $-CH(R^3)_2$.

9. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCO_2R^4$, R^4 is $-CH(R^3)_2$, n is 1.
10. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCO_2R^4$ and R^4 is cycloalkyl.
11. The compound of claim 1, wherein R is $-CH_2CO_2R^4$ and R^4 is cycloalkyl.
12. The compound of claim 1, wherein R is $-CH_2CO_2R^4$, R^4 is cyclohexyl; and R^1 is -
5 $CH=CH_2$.
13. The compound of claim 1, wherein R is $-CH_2CO_2R^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-CH=CH_2$.
14. The compound of claim 1, wherein R is $-(C(R^3)_2)_nC(O)N(R^5)_2$.
15. The compound of claim 1, wherein R is $-CH_2C(O)N(R^5)_2$ and R^1 is $-CH=CH_2$.
- 10 16. The compound of claim 1, wherein R is $-CH_2C(O)NH$ -1-adamantyl and R^1 is -
 $CH=CH_2$.
17. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCN$.
18. The compound of claim 1, wherein R is $-CH_2CN$ and R^1 is $-CH=CH_2$.
19. The compound of claim 1, wherein R is $-(C(R^3)_2)_nCOR^5$.
- 15 20. The compound of claim 1, wherein R is $-CH_2C(O)R^5$ and R^5 is alkyl.
21. The compound of claim 1, wherein R is $-CH_2C(O)C(CH_3)_3$ and R^1 is $-CH=CH_2$.
22. The compound of claim 1, wherein said compound is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF, QD-AA, QD-MP, or QD-IPC.
- 20 23. The compound of claim 1, wherein said compound is QD-IP, QD-(-)-MN, or QD-AD.
24. A compound represented by formula II:



25 wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$, $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

R¹ represents alkyl or alkenyl;

R² represents alkyl, cycloalkyl, or alkenyl;

R³ represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R⁴ represents cycloalkyl, -CH(R³)₂, alkenyl, alkynyl, aryl, or aralkyl;

R⁵ represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R⁶ represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and
n is 1-10.

25. The compound of claim 24, wherein said compound represented by formula **II** is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

26. A method of preparing a chiral, non-racemic compound from a prochiral substituted cyclic anhydride or a meso substituted cyclic anhydride, comprising the step of:

reacting a prochiral substituted cyclic anhydride or a meso substituted cyclic anhydride with a nucleophile in the presence of a chiral, non-racemic tertiary amine catalyst; wherein said prochiral substituted cyclic anhydride or said meso substituted cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; wherein said meso substituted cyclic anhydride comprises at least two chiral centers; and wherein said nucleophile is an alcohol, thiol or amine; thereby producing a chiral, non-racemic compound.

27. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride.

28. The method of claim 26, wherein said nucleophile is an alcohol.

29. The method of claim 26, wherein said nucleophile is a primary alcohol.

30. The method of claim 26, wherein said nucleophile is methanol or CF₃CH₂OH.

31. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

5 32. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

33. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

10 34. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is QD-PP.

35. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, 15 (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

36. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine 20 catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

37. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric 25 anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP, QD-TB, (DHQ)₂PHAL, (DHQD)₂PHAL, (DHQ)₂PYR, (DHQD)₂PYR, (DHQ)₂AQN, (DHQD)₂AQN, DHQ-CLB, DHQD-CLB, DHQ-MEQ, DHQD-MEQ, DHQ-AQN, DHQD-AQN, DHQ-PHN, or DHQD-PHN.

38. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso 30 substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric

anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

39. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

40. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is DHQD-PHN or (DHQD)₂AQN.

41. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

42. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

43. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or CF₃CH₂OH; and said chiral, non-racemic tertiary amine catalyst is Q-PP, Q-TB, QD-PP or QD-TB.

44. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is an alcohol; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

45. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is a primary alcohol; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

46. The method of claim 26, wherein said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride is a substituted succinic anhydride or substituted glutaric anhydride; said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$; and said chiral, non-racemic tertiary amine catalyst is QD-PP.

5 47. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is present in less than about 30 mol% relative to said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride.

48. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is present in less than about 20 mol% relative to said prochiral substituted cyclic anhydride or
10 meso substituted cyclic anhydride.

49. The method of claim 26, wherein said chiral, non-racemic tertiary amine catalyst is present in less than about 10 mol% relative to said prochiral substituted cyclic anhydride or meso substituted cyclic anhydride.

50. The method of claim 26, wherein said chiral, non-racemic compound has an
15 enantiomeric excess greater than about 50%.

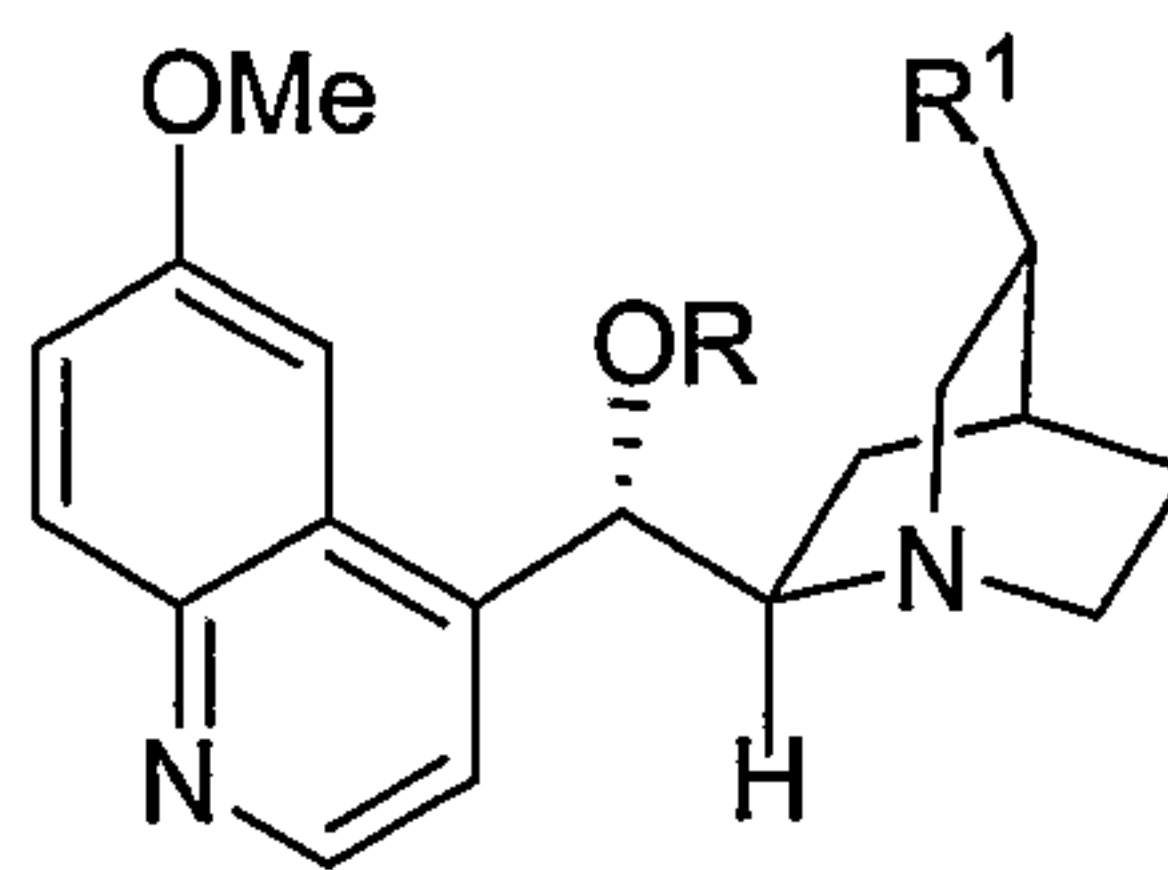
51. The method of claim 26, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 70%.

52. The method of claim 26, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

20 53. The method of claim 26, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

54. A method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of:

25 reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a catalyst; wherein said prochiral cyclic anhydride or meso cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; thereby producing a chiral, non-racemic compound; wherein said catalyst is represented by formula I:

**I**

wherein

R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, $-C(C(R^3)_2)_nC\equiv CR^6$, $-(C(R^3)_2)_nOPO(OR^5)_2$, $-(C(R^3)_2)_nOR^5$, $-(C(R^3)_2)_nN(R^5)_2$, $-(C(R^3)_2)_nSR^5$, or $-(C(R^3)_2)_nNO_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-CH(R^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10.

55. The method of claim 54, wherein R represents $-C(O)R^2$, $-(C(R^3)_2)_nCO_2R^4$, $-(C(R^3)_2)_nC(O)N(R^5)_2$, $-(C(R^3)_2)_nCN$, $-(C(R^3)_2)_nC(O)R^5$, or $-C(C(R^3)_2)_nC\equiv CR^6$.

56. The method of claim 54, wherein R^1 is ethyl.

57. The method of claim 54, wherein R^1 is $-CH=CH_2$.

58. The method of claim 54, wherein R is $-C(O)R^2$.

59. The method of claim 54, wherein R is $-C(O)R^2$ and R^2 is alkyl.

60. The method of claim 54, wherein R is $-(C(R^3)_2)_nCO_2R^4$.

61. The method of claim 54, wherein R is $-(C(R^3)_2)_nCO_2R^4$ and R^4 is $-CH(R^3)_2$.

62. The method of claim 54, wherein R is $-(C(R^3)_2)_nCO_2R^4$, R^4 is $-CH(R^3)_2$, n is 1.

63. The method of claim 54, wherein R is $-(C(R^3)_2)_nCO_2R^4$ and R^4 is cycloalkyl.

64. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.
65. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.
66. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl,
5 isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.
67. The method of claim 54, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$.
68. The method of claim 54, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{N}(\text{R}^5)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.
69. The method of claim 54, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{NH}$ -1-adamantyl and R^1 is $-\text{CH}=\text{CH}_2$.
70. The method of claim 54, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CN}$.
- 10 71. The method of claim 54, wherein R is $-\text{CH}_2\text{CN}$ and R^1 is $\text{CH}=\text{CH}_2$.
72. The method of claim 54, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$.
73. The method of claim 54, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{R}^5$ and R^5 is alkyl.
74. The method of claim 54, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{C}(\text{CH}_3)_3$ and R^1 is $-\text{CH}=\text{CH}_2$.
75. The method of claim 54, wherein said catalyst is QD-IP, QD-PC, QD-AD, QD-(-)-MN,
15 QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-EF,
QD-AA, QD-MP, or QD-IPC.
76. The method of claim 54, wherein said catalyst is QD-IP, QD-(-)-MN, or QD-AD.
77. The method of claim 54, wherein said nucleophile is an alcohol.
78. The method of claim 54, wherein said nucleophile is a primary alcohol.
- 20 79. The method of claim 54, wherein said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.
80. The method of claim 54, wherein said prochiral cyclic anhydride or meso cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride.
81. The method of claim 54, wherein said catalyst is present in less than about 70 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.
- 25 82. The method of claim 54, wherein said catalyst is present in less than about 40 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.
83. The method of claim 54, wherein said catalyst is present in less than about 10 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.
84. The method of claim 54, wherein said chiral, non-racemic compound has an
30 enantiomeric excess greater than about 50%.

85. The method of claim 54, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 70%.

86. The method of claim 54, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

5 87. The method of claim 54, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

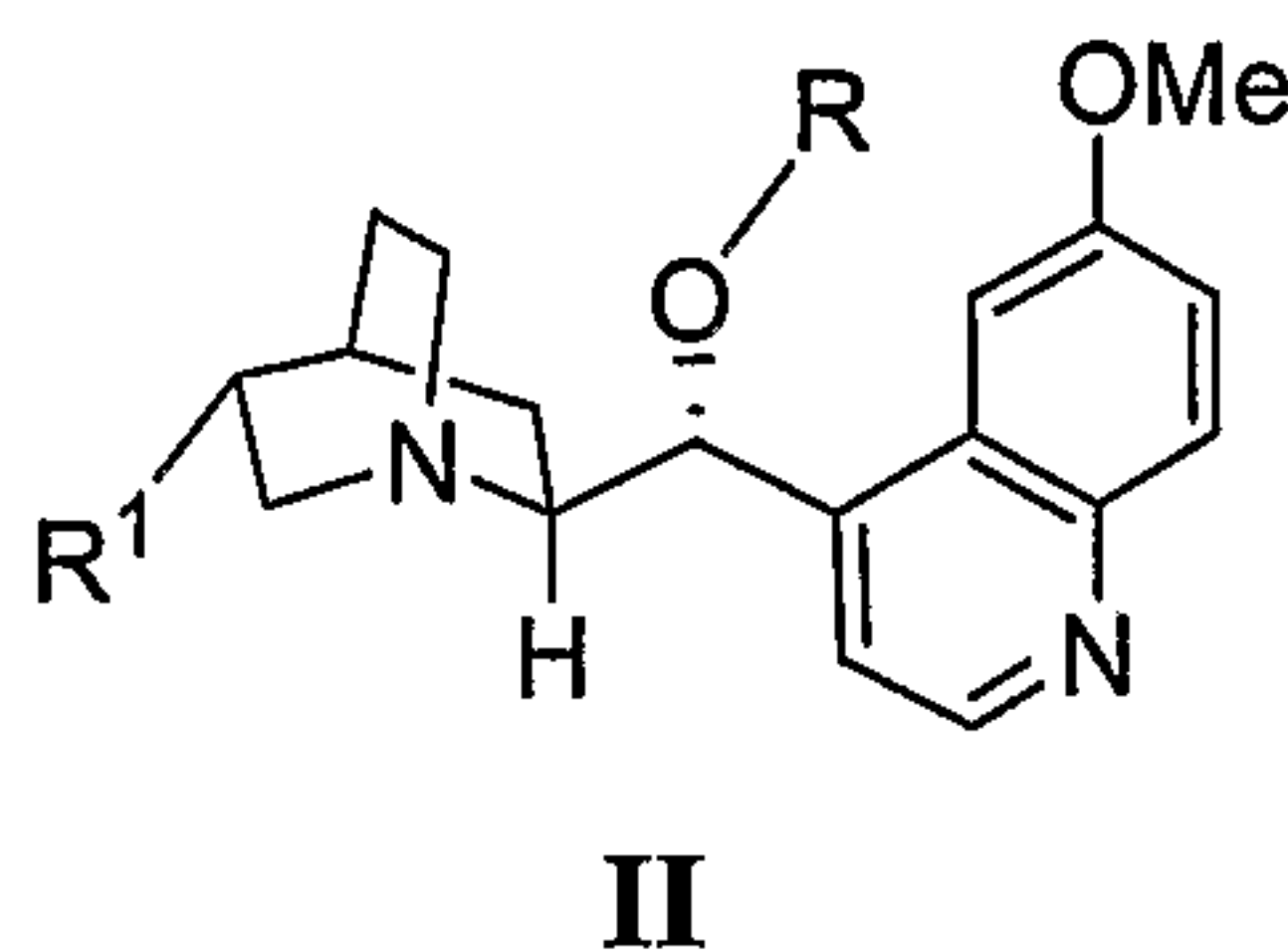
88. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

10 89. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

90. The method of claim 54, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is a methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

15 91. A method of preparing a chiral, non-racemic compound from a prochiral cyclic anhydride or a meso cyclic anhydride, comprising the step of:

reacting a prochiral cyclic anhydride or a meso cyclic anhydride with a nucleophile in the presence of a catalyst; wherein said prochiral cyclic anhydride or meso cyclic anhydride comprises an internal plane of symmetry or point of symmetry or both; thereby producing a chiral, non-racemic compound; wherein said catalyst is represented by formula II:



wherein

25 R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxy, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

5 R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10.

10 92. The method of claim 91, wherein said catalyst is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.

93. The method of claim 91, wherein said nucleophile is an alcohol.

94. The method of claim 91, wherein said nucleophile is a primary alcohol.

95. The method of claim 91, wherein said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

15 96. The method of claim 91, wherein said prochiral cyclic anhydride or meso cyclic anhydride is a substituted succinic anhydride or a substituted glutaric anhydride.

97. The method of claim 91, wherein said catalyst is present in less than about 70 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

20 98. The method of claim 91, wherein said catalyst is present in less than about 40 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

99. The method of claim 91, wherein said catalyst is present in less than about 10 mol% relative to said prochiral cyclic anhydride or meso cyclic anhydride.

100. The method of claim 91, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 50%.

25 101. The method of claim 91, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 70%.

102. The method of claim 91, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 90%.

30 103. The method of claim 91, wherein said chiral, non-racemic compound has an enantiomeric excess greater than about 95%.

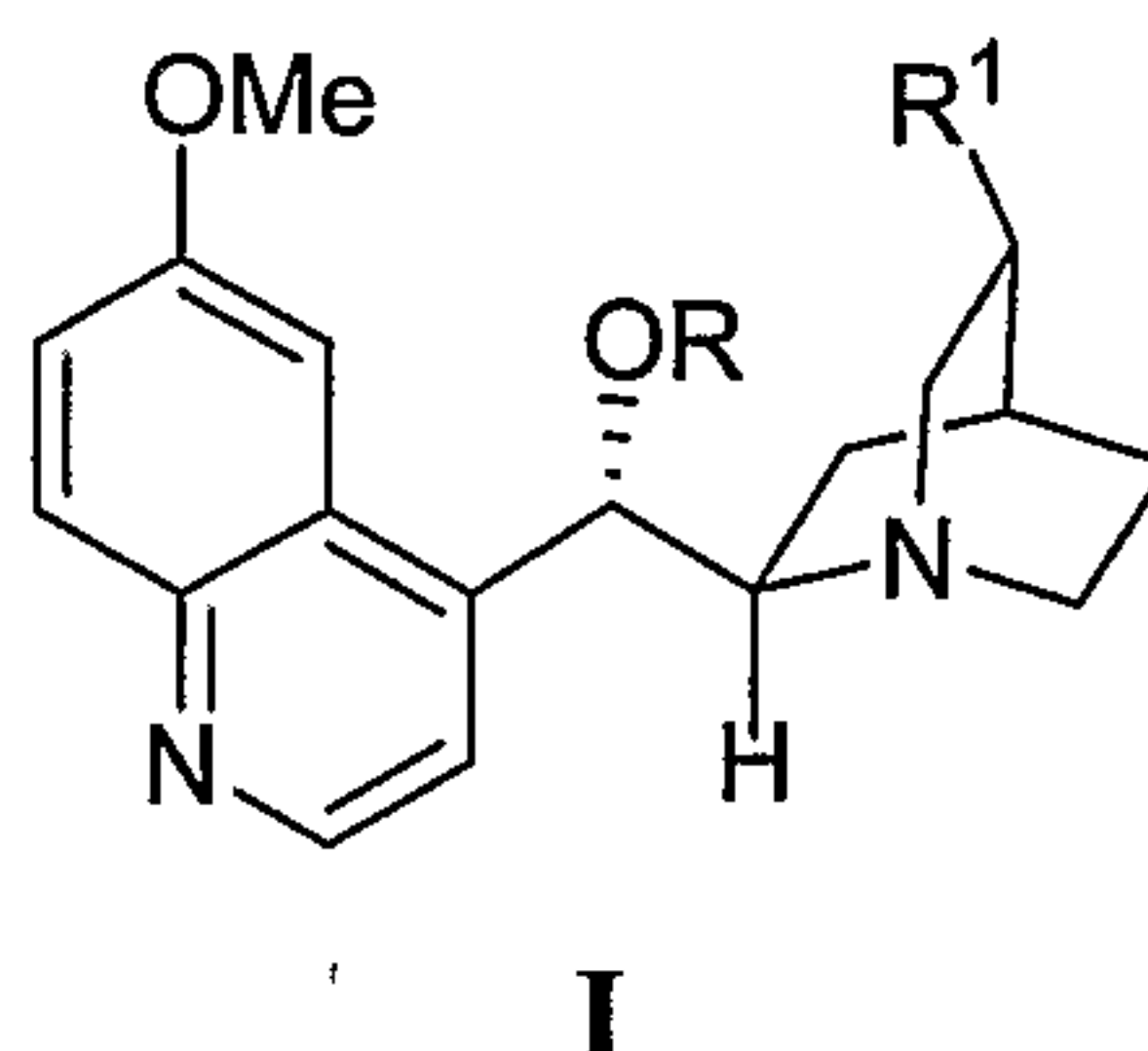
104. The method of claim 91, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

105. The method of claim 91, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is an alcohol.

106. The method of claim 91, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl or 1-adamantyl; R^1 is $-\text{CH}=\text{CH}_2$; and said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

107. A method of kinetic resolution, comprising the step of:

reacting a racemic cyclic anhydride with an alcohol in the presence of a catalyst represented by formula I:



wherein

R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10; and

when said method of kinetic resolution is completed or interrupted any unreacted cyclic anhydride has an enantiomeric excess greater than zero and the enantiomeric excess of the product is greater than zero.

108. The method of claim 107, wherein R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, or $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$.
109. The method of claim 107, wherein R^1 is ethyl.
110. The method of claim 107, wherein R^1 is $-\text{CH}=\text{CH}_2$.
111. The method of claim 107, wherein R is $-\text{C}(\text{O})\text{R}^2$.
112. The method of claim 107, wherein R is $-\text{C}(\text{O})\text{R}^2$ and R^2 is alkyl.
- 10 113. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$.
114. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is $-\text{CH}(\text{R}^3)_2$.
115. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, R^4 is $-\text{CH}(\text{R}^3)_2$, n is 1.
116. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.
117. The method of claim 107, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$ and R^4 is cycloalkyl.
- 15 118. The method of claim 107, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$, R^4 is cyclohexyl; and R^1 is $-\text{CH}=\text{CH}_2$.
119. The method of claim 107, wherein R is $-\text{CH}_2\text{CO}_2\text{R}^4$; R^4 is (-)-menthyl, 1-adamantyl, isobornyl, (-)-isopinocampyl, or (+)-fenchyl; and R^1 is $-\text{CH}=\text{CH}_2$.
120. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$.
- 20 121. The method of claim 107, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{N}(\text{R}^5)_2$ and R^1 is $-\text{CH}=\text{CH}_2$.
122. The method of claim 107, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{NH}$ -1-adamantyl and R^1 is $-\text{CH}=\text{CH}_2$.
123. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{CN}$.
124. The method of claim 107, wherein R is $-\text{CH}_2\text{CN}$ and R^1 is $\text{CH}=\text{CH}_2$.
- 25 125. The method of claim 107, wherein R is $-(\text{C}(\text{R}^3)_2)_n\text{COR}^5$.
126. The method of claim 107, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{R}^5$ and R^5 is alkyl.
127. The method of claim 107, wherein R is $-\text{CH}_2\text{C}(\text{O})\text{C}(\text{CH}_3)_3$ and R^1 is $-\text{CH}=\text{CH}_2$.
128. The method of claim 107, wherein said catalyst is QD-IP, QD-PC, QD-AD, QD-(-)-MN, QD-(+)-MN, QD-AC, QD-Piv, QD-PH, QD-AN, QD-NT, QD-CN, QD-CH, QD-IB, QD-30 EF, QD-AA, QD-MP, or QD-IPC.

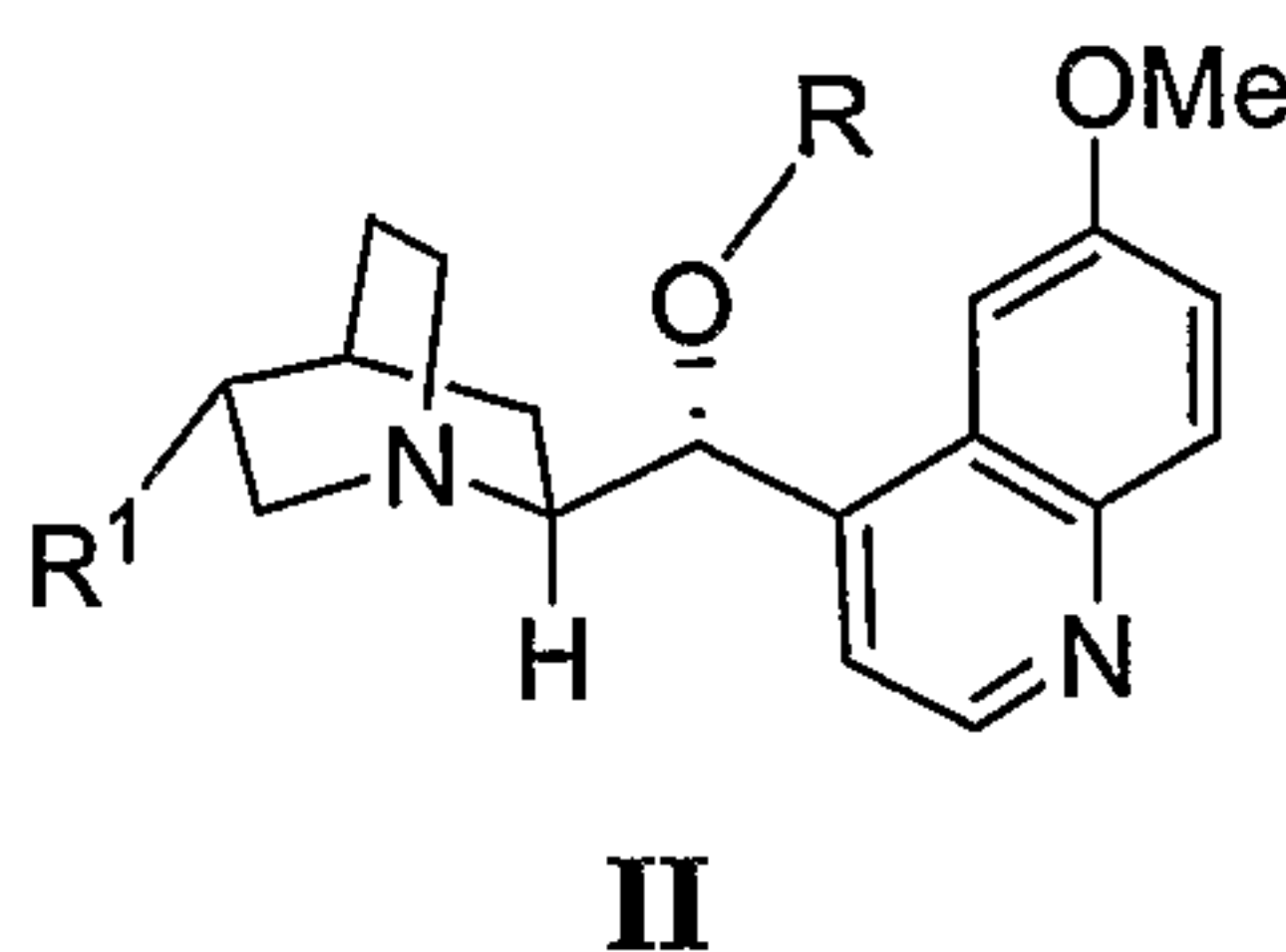
129. The method of claim 107, wherein said catalyst is QD-IP, QD-(-)-MN, or QD-AD.

130. The method of claim 107, wherein said alcohol is a primary alcohol.

131. The method of claim 107, wherein said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

132. A method of kinetic resolution, comprising the step of:

5 reacting a racemic cyclic anhydride with an alcohol in the presence of a catalyst represented by formula II:



wherein

10 R represents $-\text{C}(\text{O})\text{R}^2$, $-(\text{C}(\text{R}^3)_2)_n\text{CO}_2\text{R}^4$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{CN}$, $-(\text{C}(\text{R}^3)_2)_n\text{C}(\text{O})\text{R}^5$, $-\text{C}(\text{C}(\text{R}^3)_2)_n\text{C}\equiv\text{CR}^6$, $-(\text{C}(\text{R}^3)_2)_n\text{OPO}(\text{OR}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{OR}^5$, $-(\text{C}(\text{R}^3)_2)_n\text{N}(\text{R}^5)_2$, $-(\text{C}(\text{R}^3)_2)_n\text{SR}^5$, or $-(\text{C}(\text{R}^3)_2)_n\text{NO}_2$;

R^1 represents alkyl or alkenyl;

R^2 represents alkyl, cycloalkyl, or alkenyl;

15 R^3 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, aralkyl, heteroalkyl, halogen, cyano, amino, acyl, alkoxyl, silyloxy, amino, nitro, thiol, amine, imine, amide, phosphonate, phosphine, carbonyl, carboxyl, silyl, ether, thioether, sulfonyl, selenoether, ketone, aldehyde, or ester;

R^4 represents cycloalkyl, $-\text{CH}(\text{R}^3)_2$, alkenyl, alkynyl, aryl, or aralkyl;

20 R^5 represents independently for each occurrence H, alkyl, alkenyl, aryl, cycloalkyl, or aralkyl;

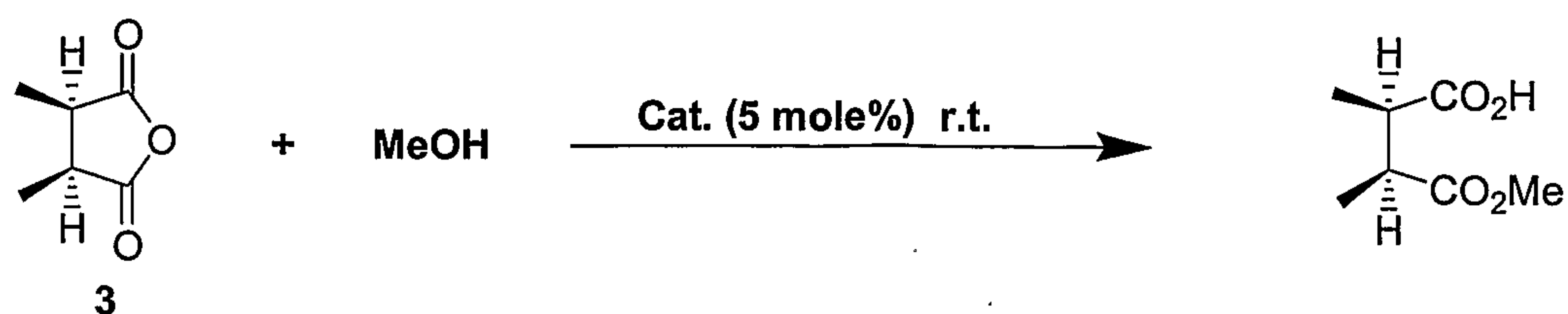
R^6 represents optionally substituted alkyl, alkenyl, aryl, or aralkyl; and

n is 1-10; and

25 when said method of kinetic resolution is completed or interrupted any unreacted cyclic anhydride has an enantiomeric excess greater than zero and the enantiomeric excess of the product is greater than zero.

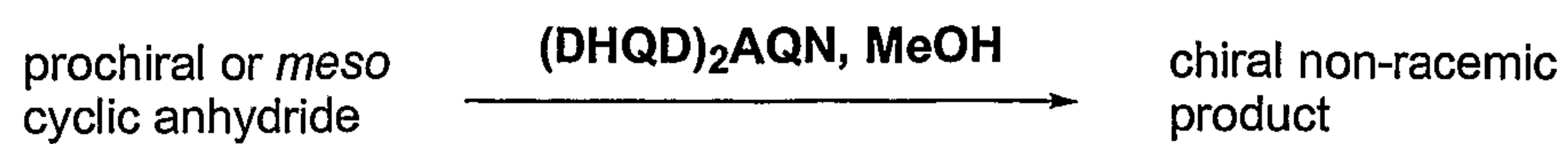
133. The method of claim 132, wherein said catalyst is Q-IP, Q-PC, Q-AD, Q-(-)-MN, Q-(+)-MN, Q-AC, Q-Piv, Q-PH, Q-AN, Q-NT, Q-CN, Q-CH, Q-IB, Q-EF, Q-AA, Q-MP, or Q-IPC.
134. The method of claim 132, wherein said alcohol is a primary alcohol.
- 5 135. The method of claim 132, wherein said nucleophile is methanol or $\text{CF}_3\text{CH}_2\text{OH}$.

Figure 1



Entry	Catalyst	Solvent	ee (%) of Product
1	Quinidine	Toluene	64
2	(DHQD) ₂ PYR	Toluene	13
3	(DHQD) ₂ PHAL	Toluene	18
4	(DHQD) ₂ AQN	Toluene	85
5	DHQD-PHN	Toluene	81
6	DHQD-CLB	Toluene	32
7	DHQD-MEQ	Toluene	31
8	(DHQD) ₂ AQN	CCl ₄	88
9	(DHQD) ₂ AQN	Et ₂ O	93
10	(DHQD) ₂ AQN	CHCl ₃	82
11	(DHQD) ₂ AQN	Hexane	54
12	(DHQD) ₂ AQN	THF	89
13	(DHQD) ₂ AQN	^t BuOMe	92
14	(DHQD) ₂ AQN	MeCN	71
15	(DHQD) ₂ AQN	CH ₂ Cl ₂	73

Figure 2



60-95% yield

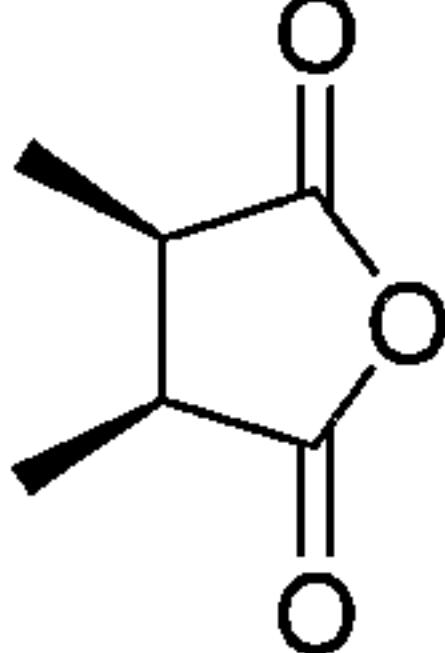
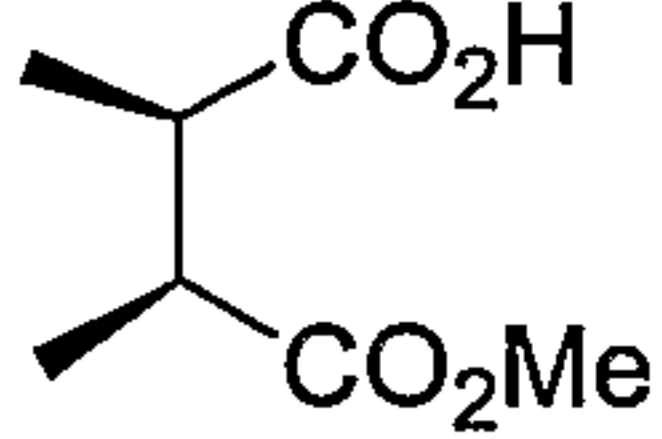
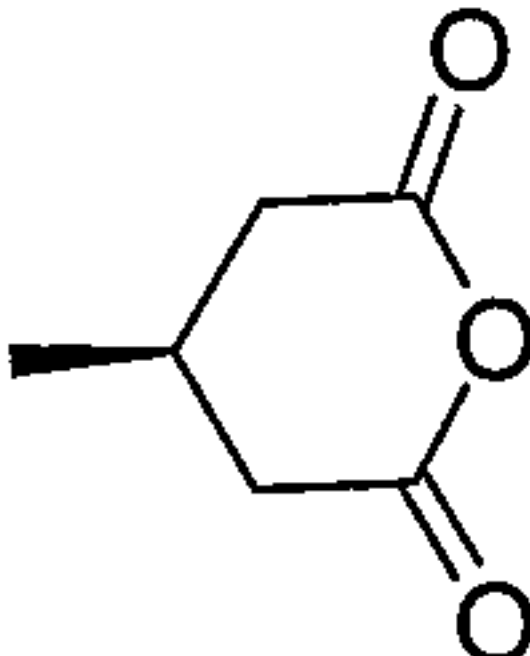
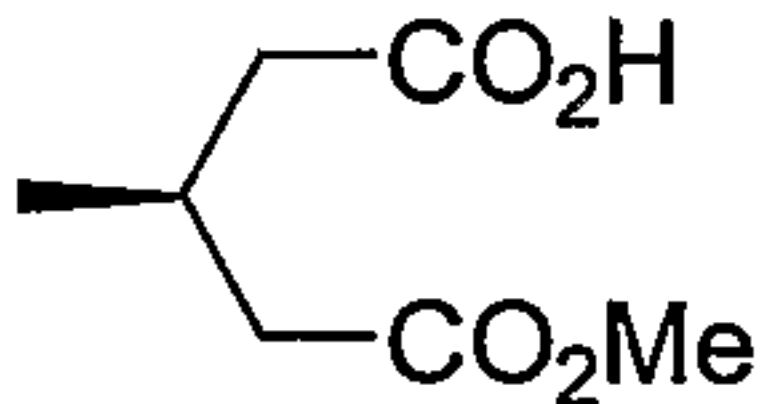
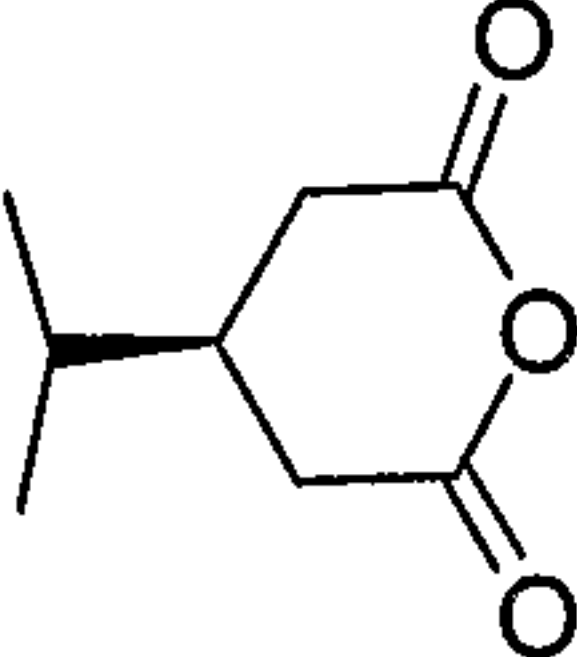
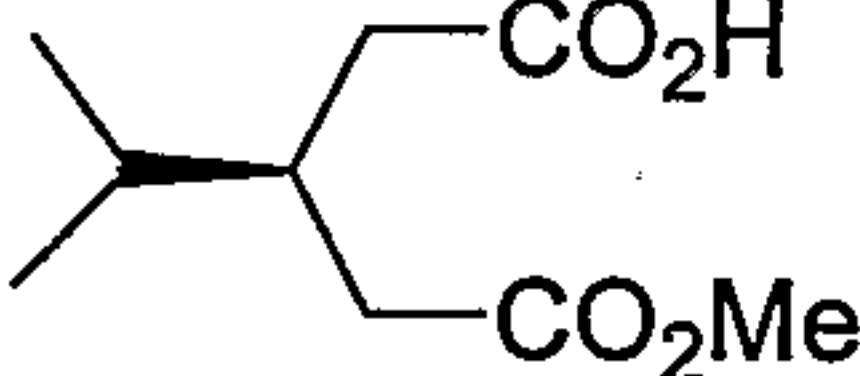
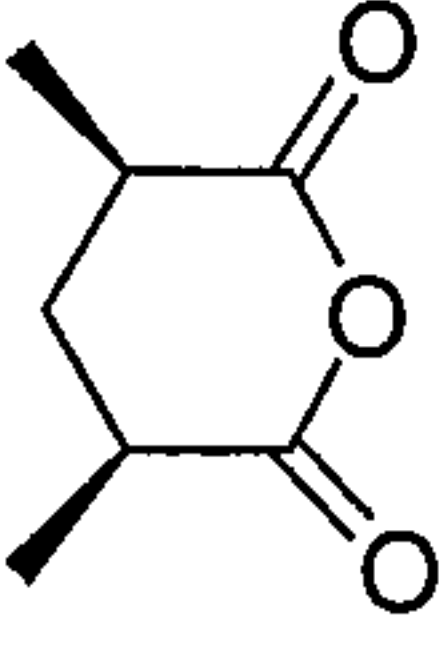
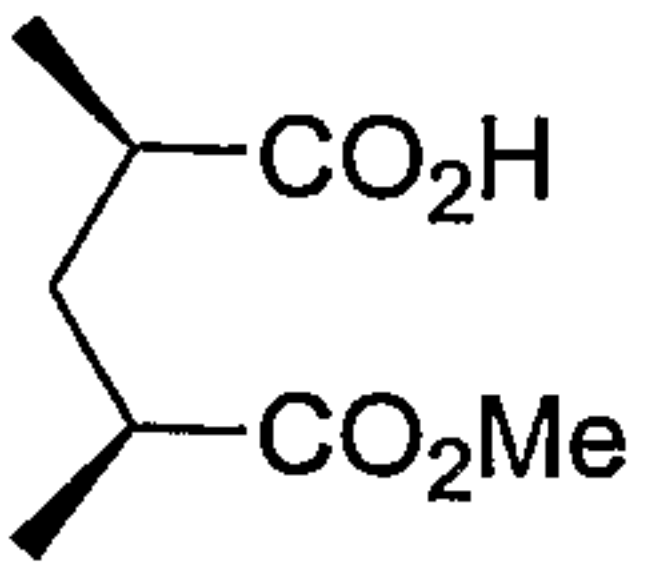
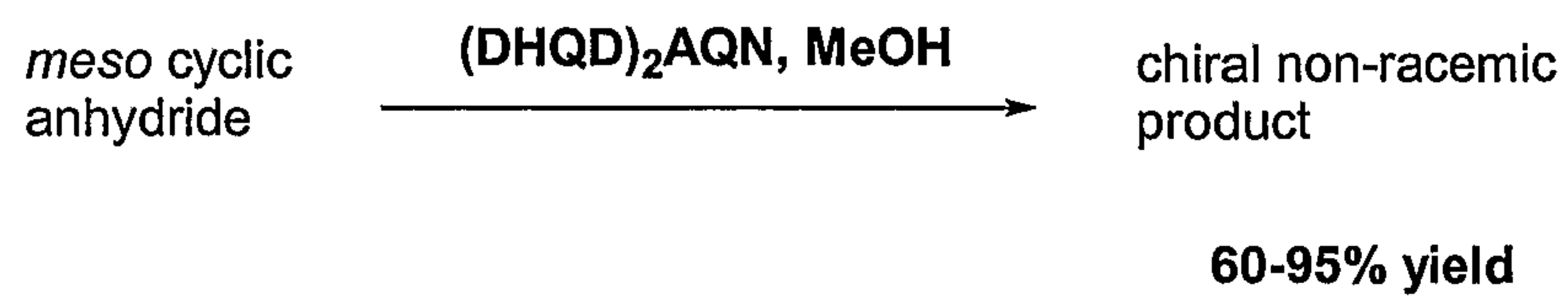
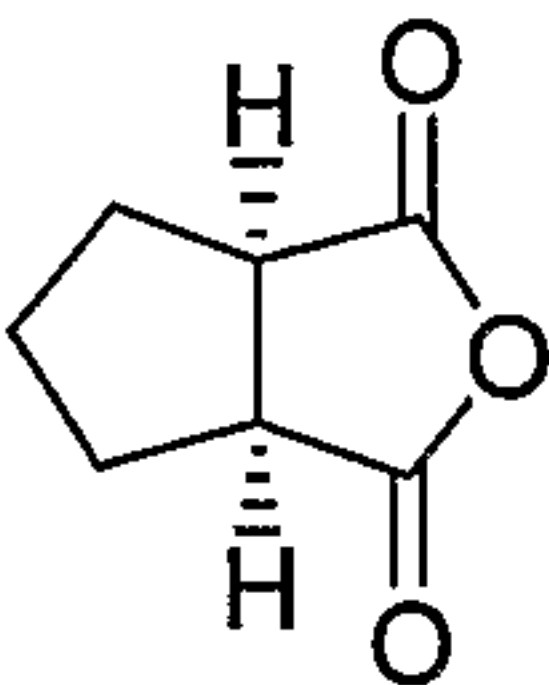
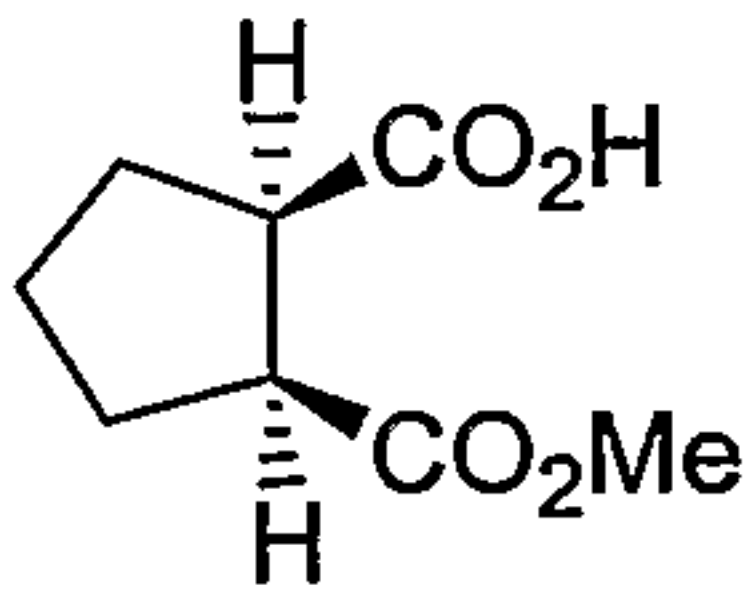
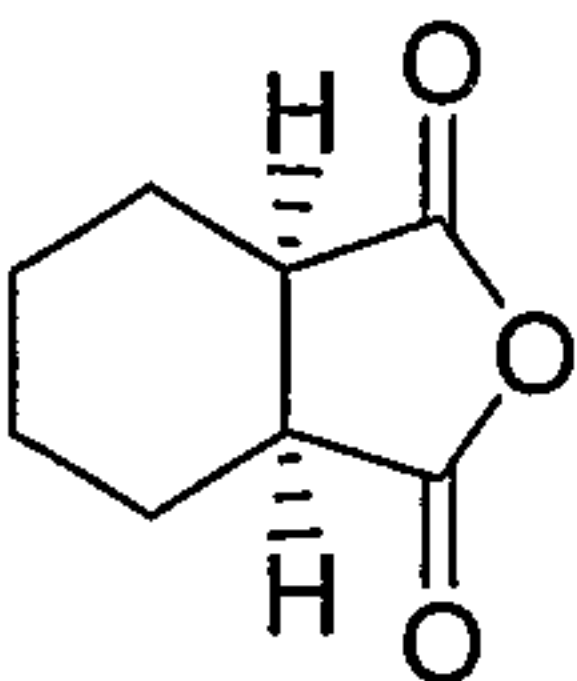
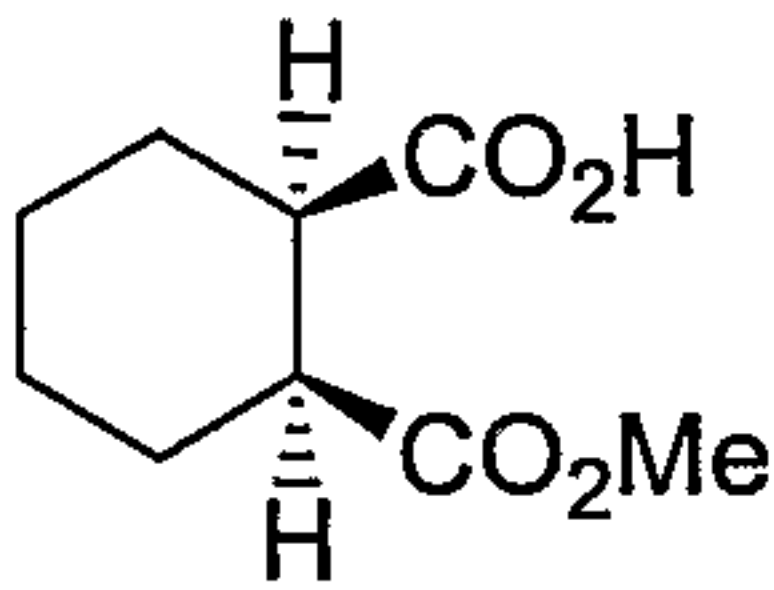
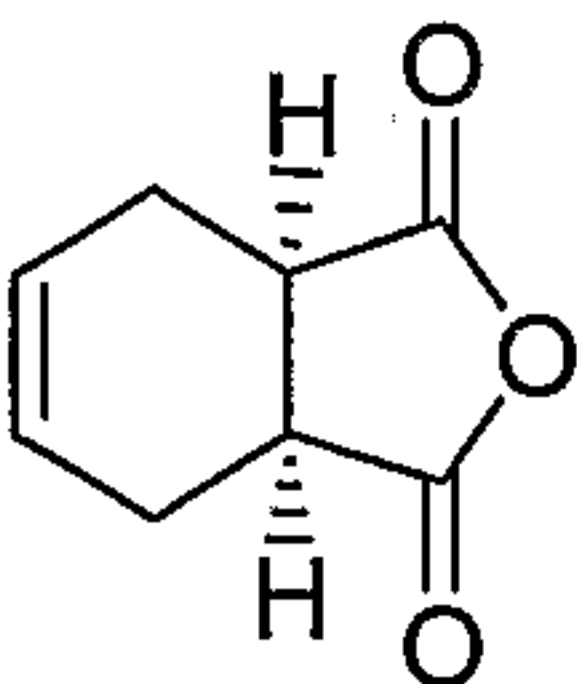
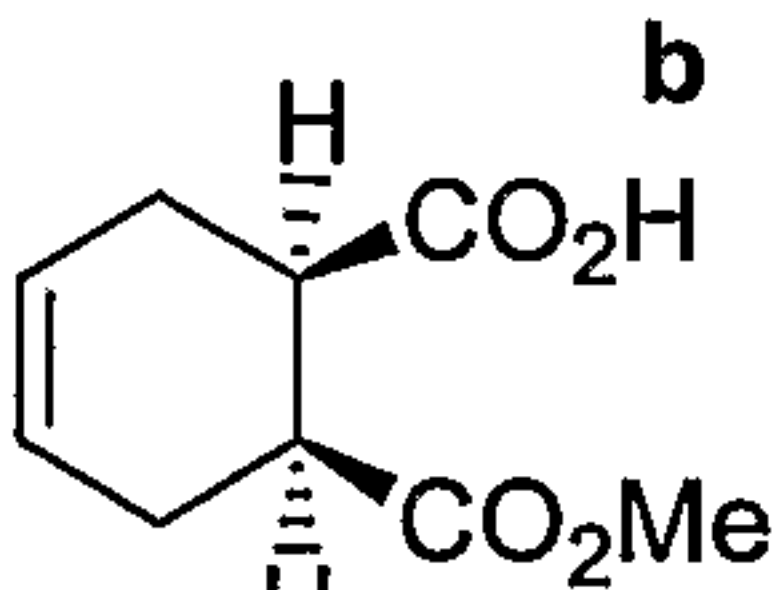
Entry	Anhydride	Catalyst Loading (mole %)	Solvent	Temp. (°C)	ee (%) ^c	Product ^b
1		5	Ether	-20	98 (98)	
2		30	Ether	-35	91 (82)	
3		30	Ether	-35	90 (83)	
4		10	Toluene	r.t.	76 ^a	

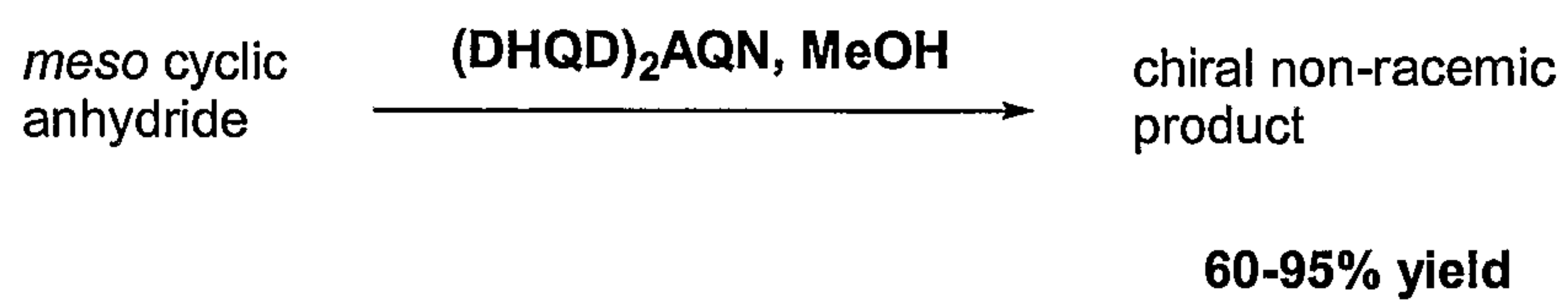
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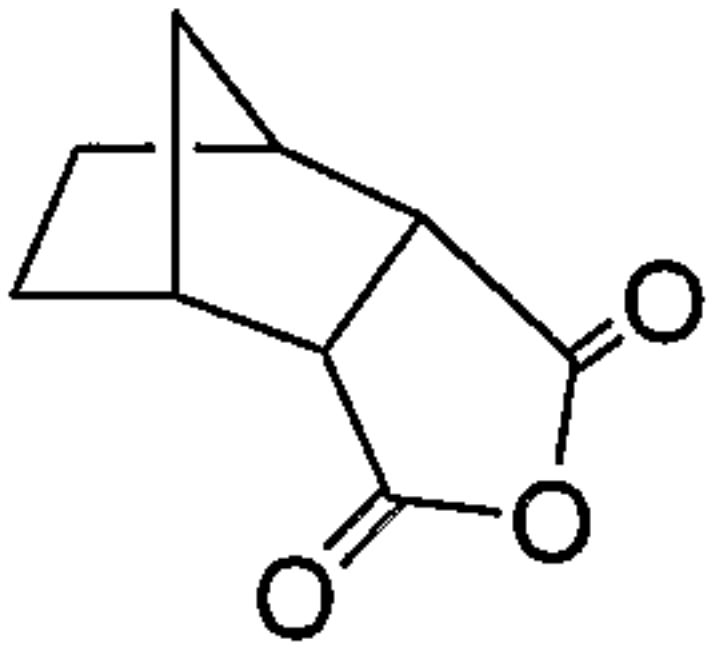
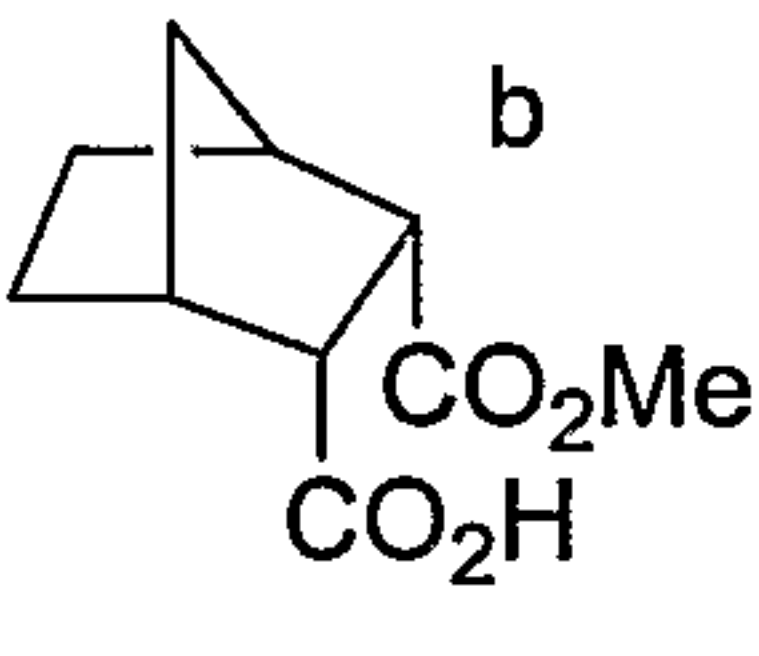
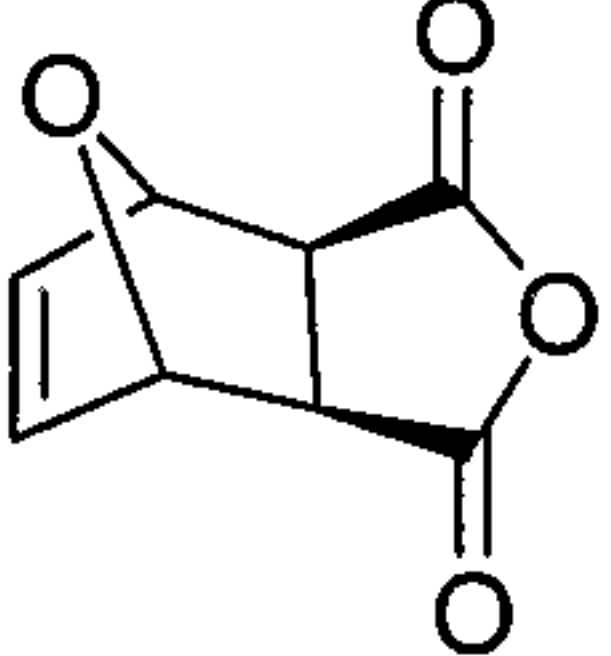
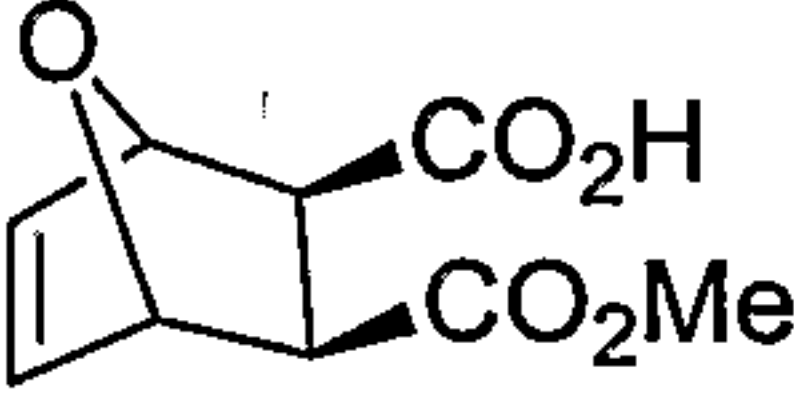
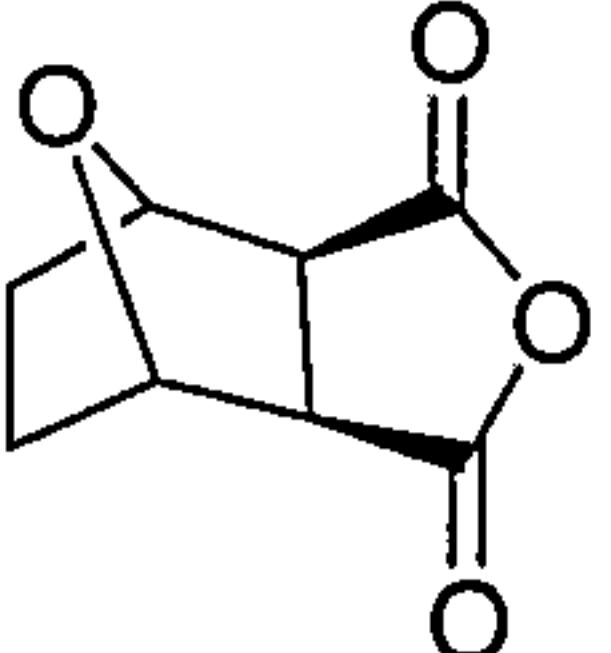
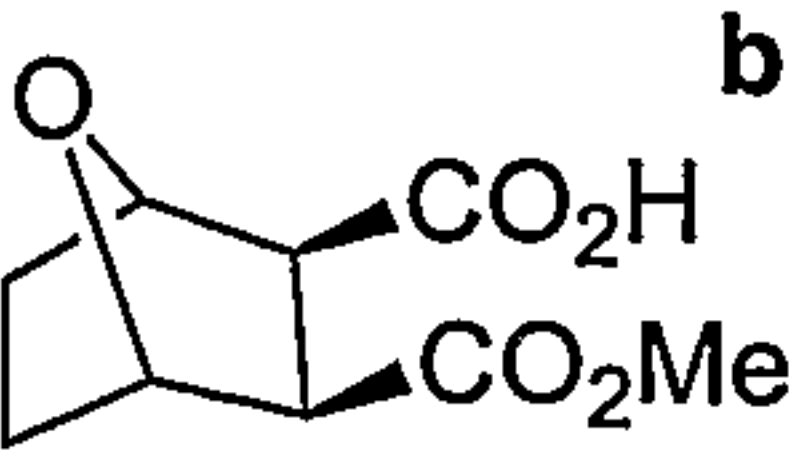


Entry	Anhydride	Catalyst Loading (mole %)	Solvent	Temp. (°C)	ee (%) ^c	Product ^b
5		10	Ether	-30	96	
6		5	Ether	-20	97	
7		7	Ether	-20	98	

4/45

Figure 4



Entry	Anhydride	Catalyst Loading (mole %)	Solvent	Temp. (°C)	ee (%) ^c	Product ^b
9		15	Ether	-30	90	
10		20	Ether	-20	95	
11		15	Ether	-20	92	

5/45

Figure 5

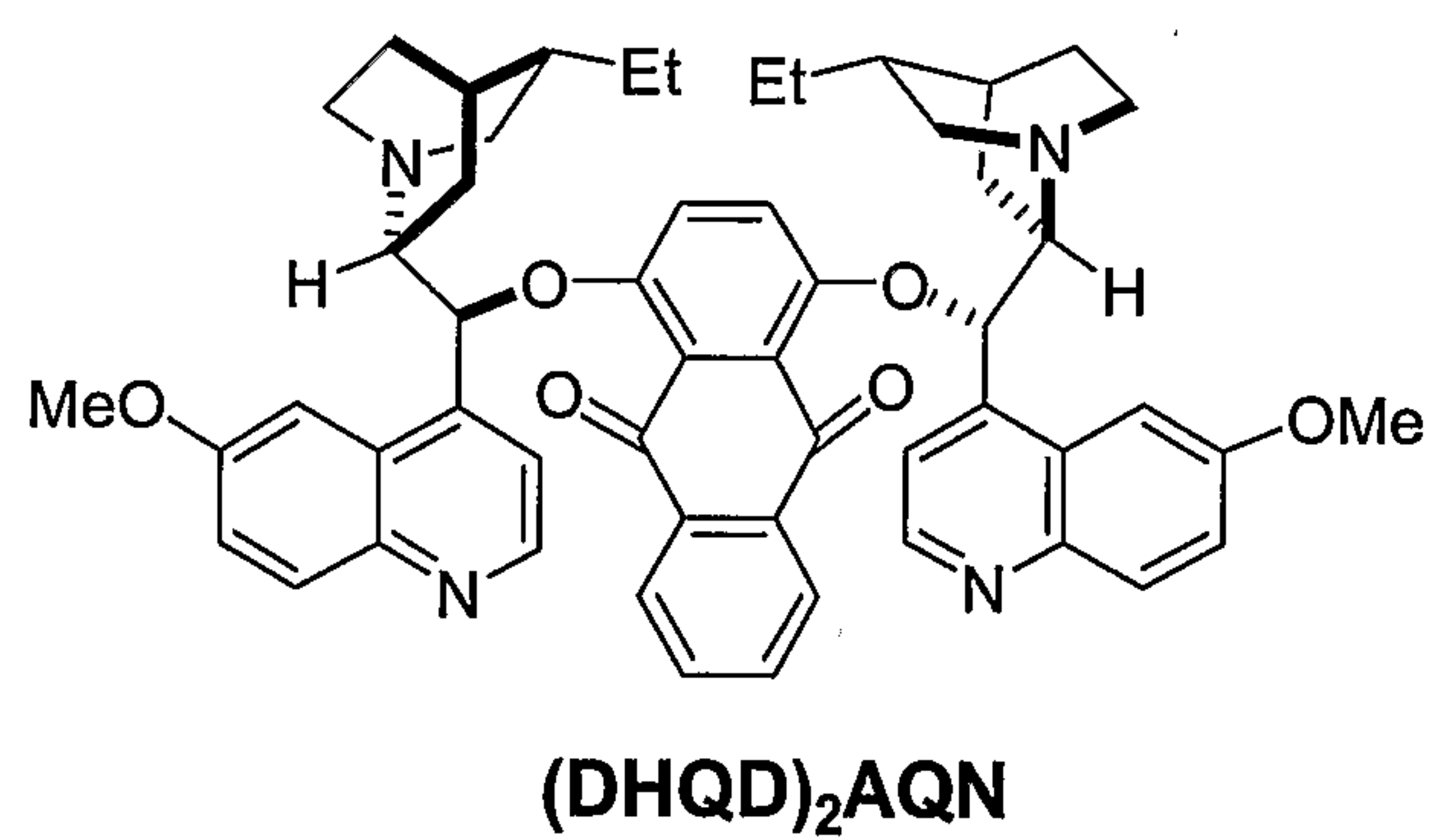
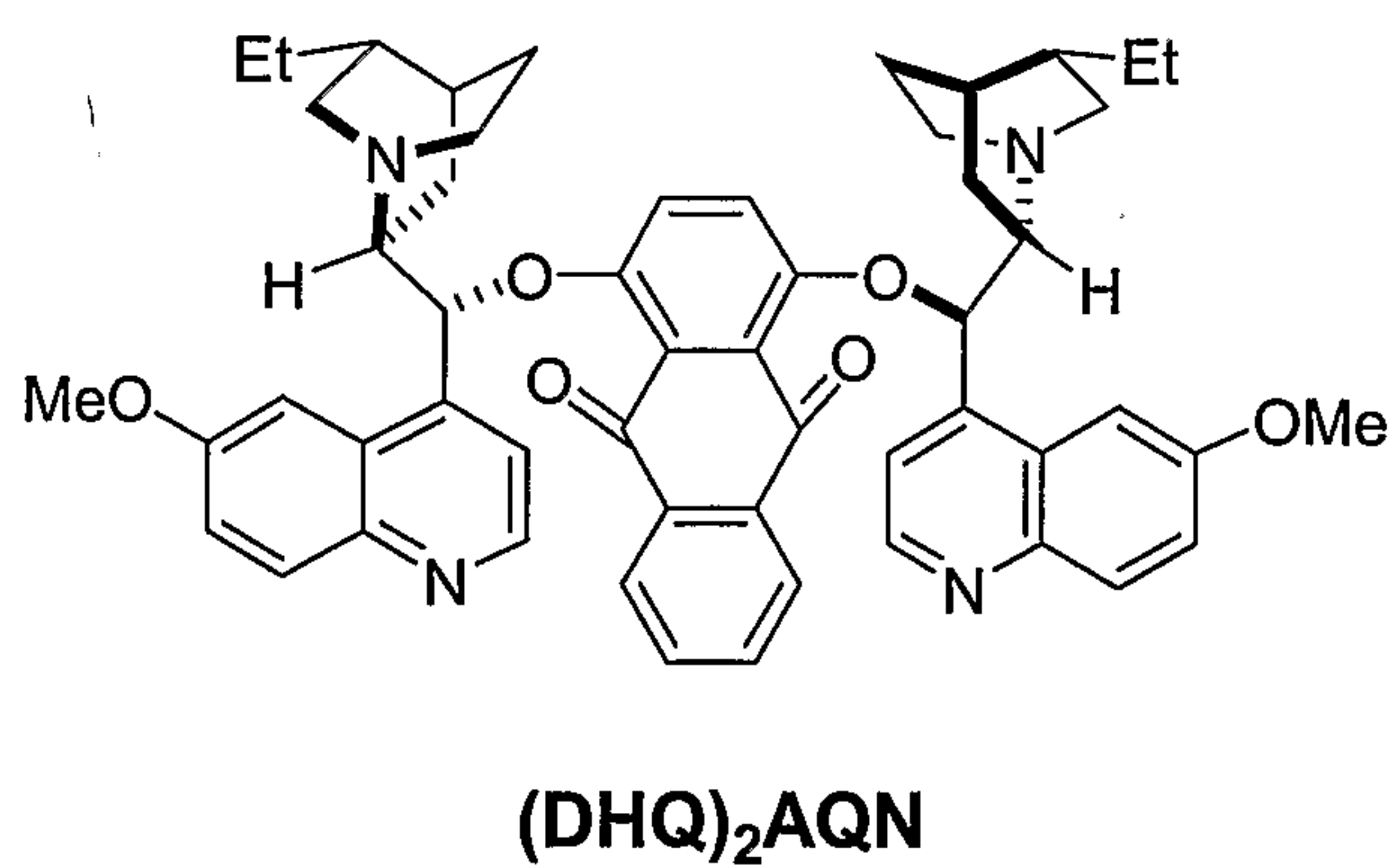
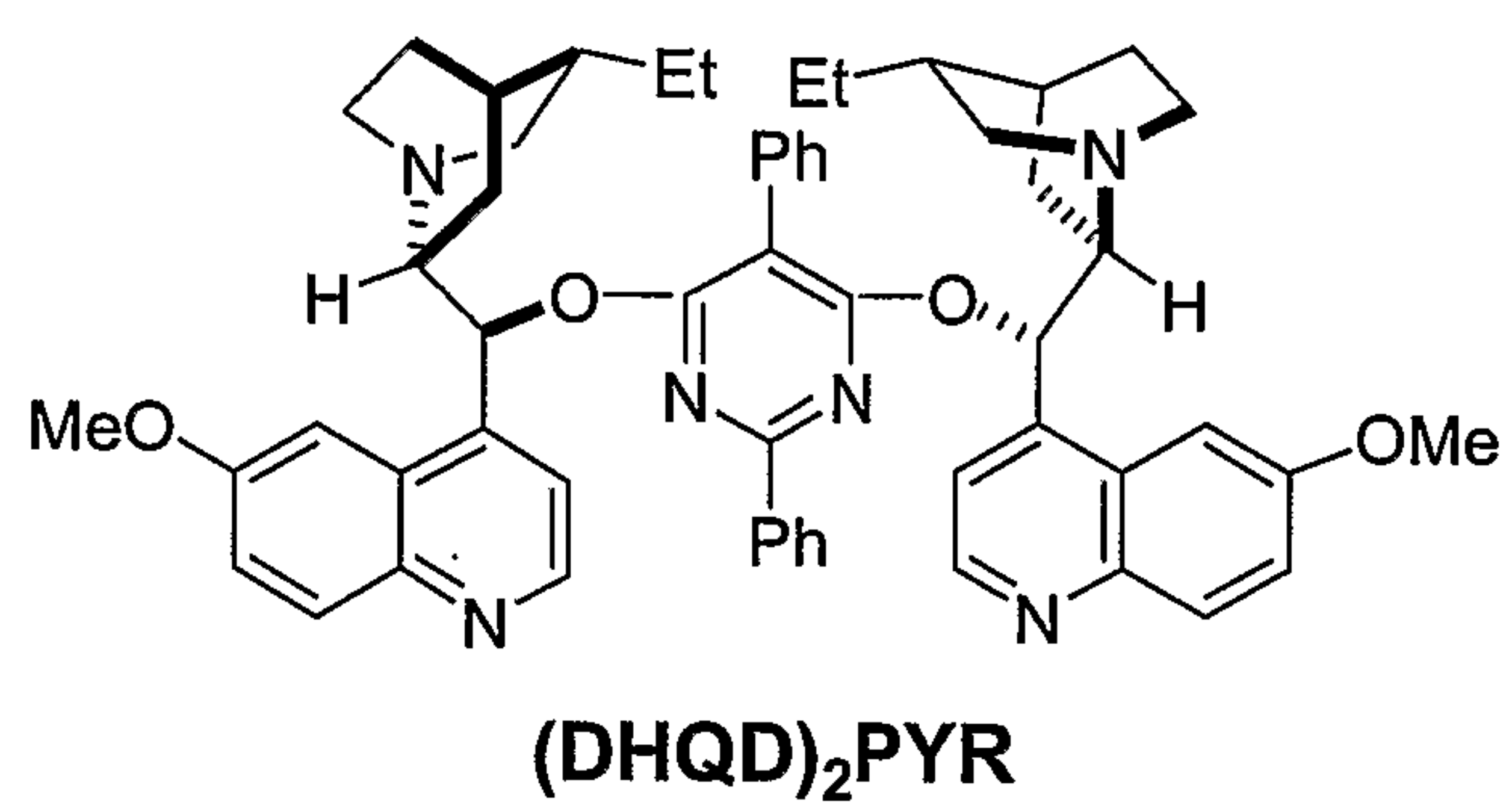
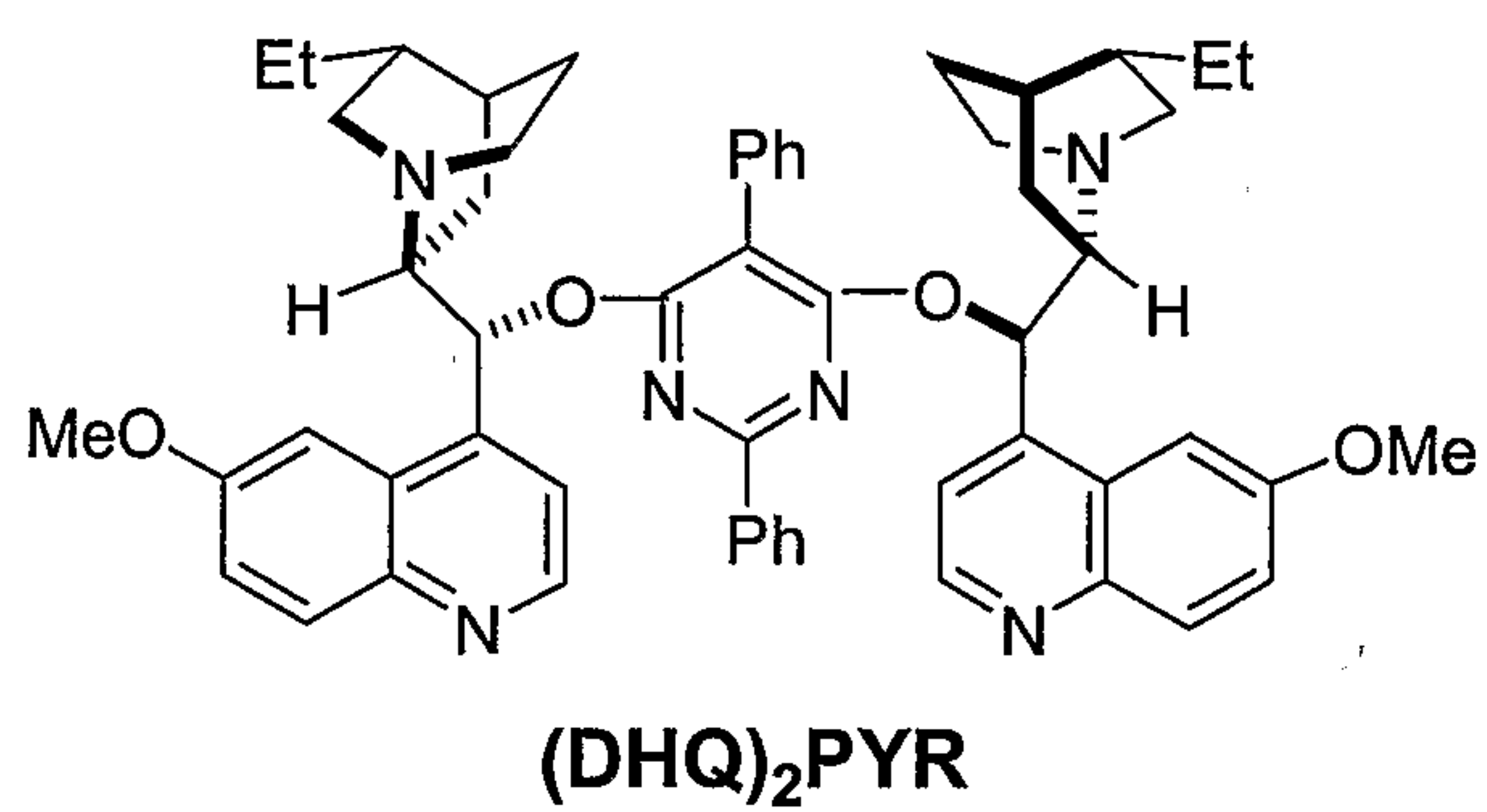
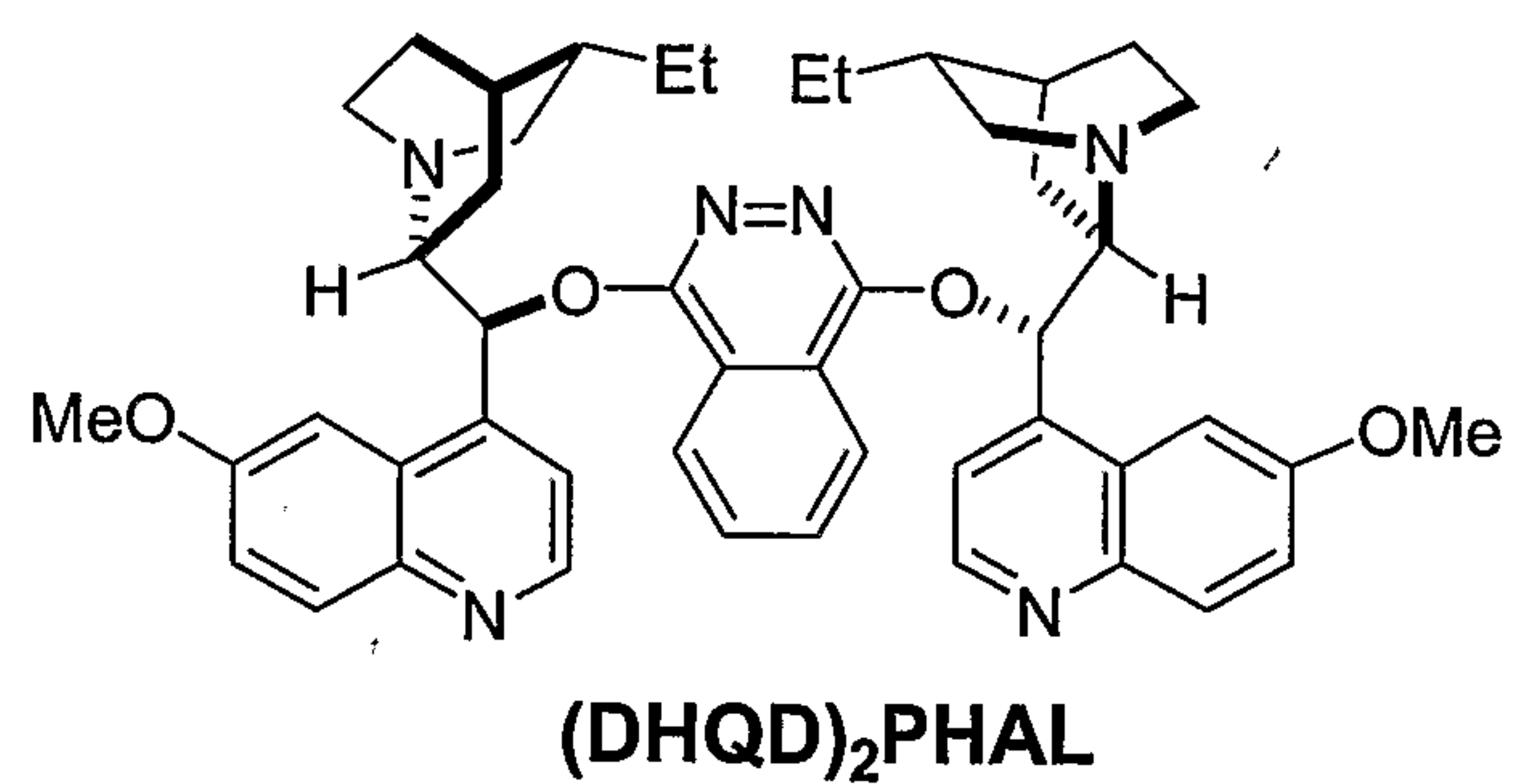
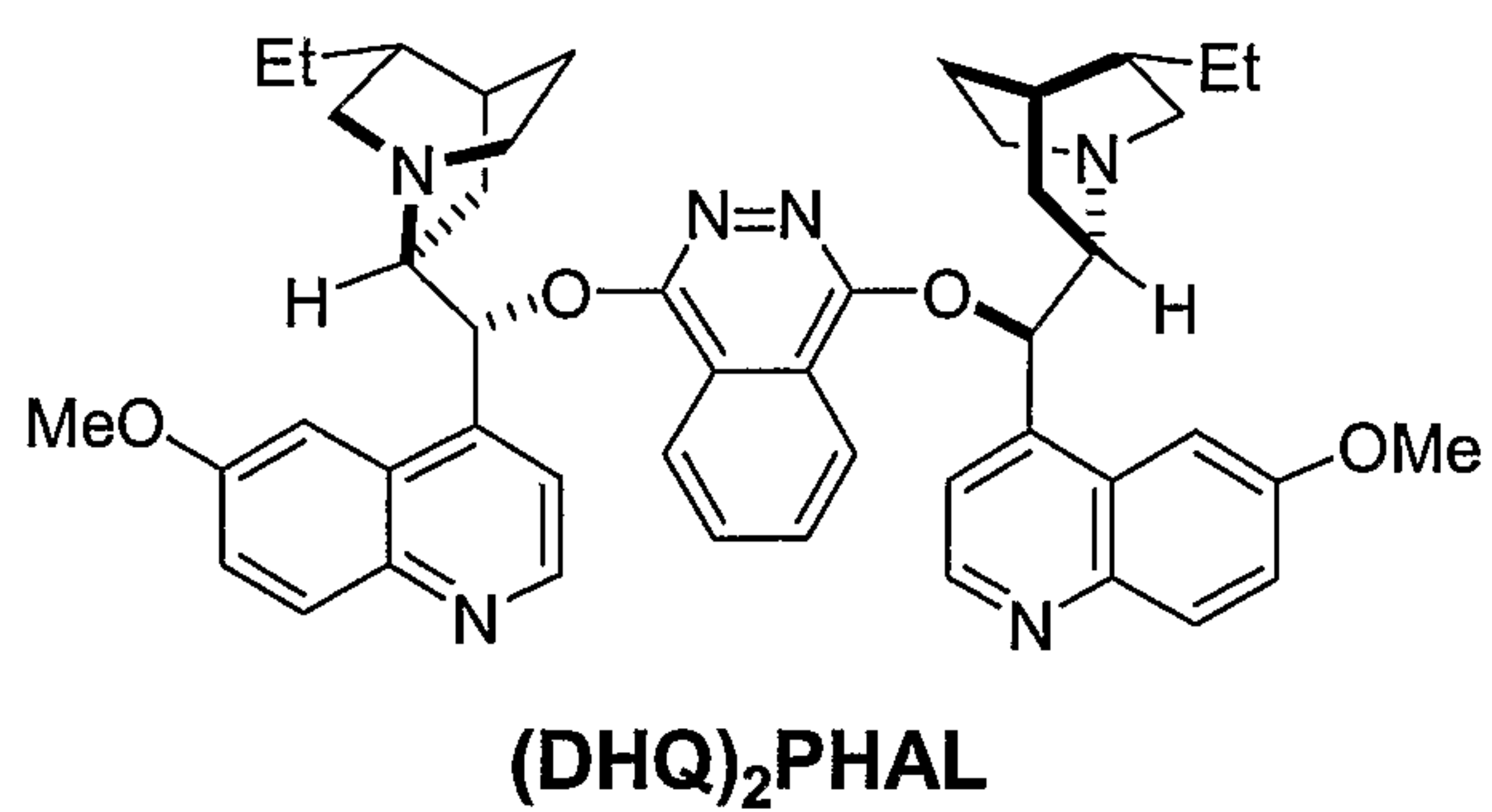
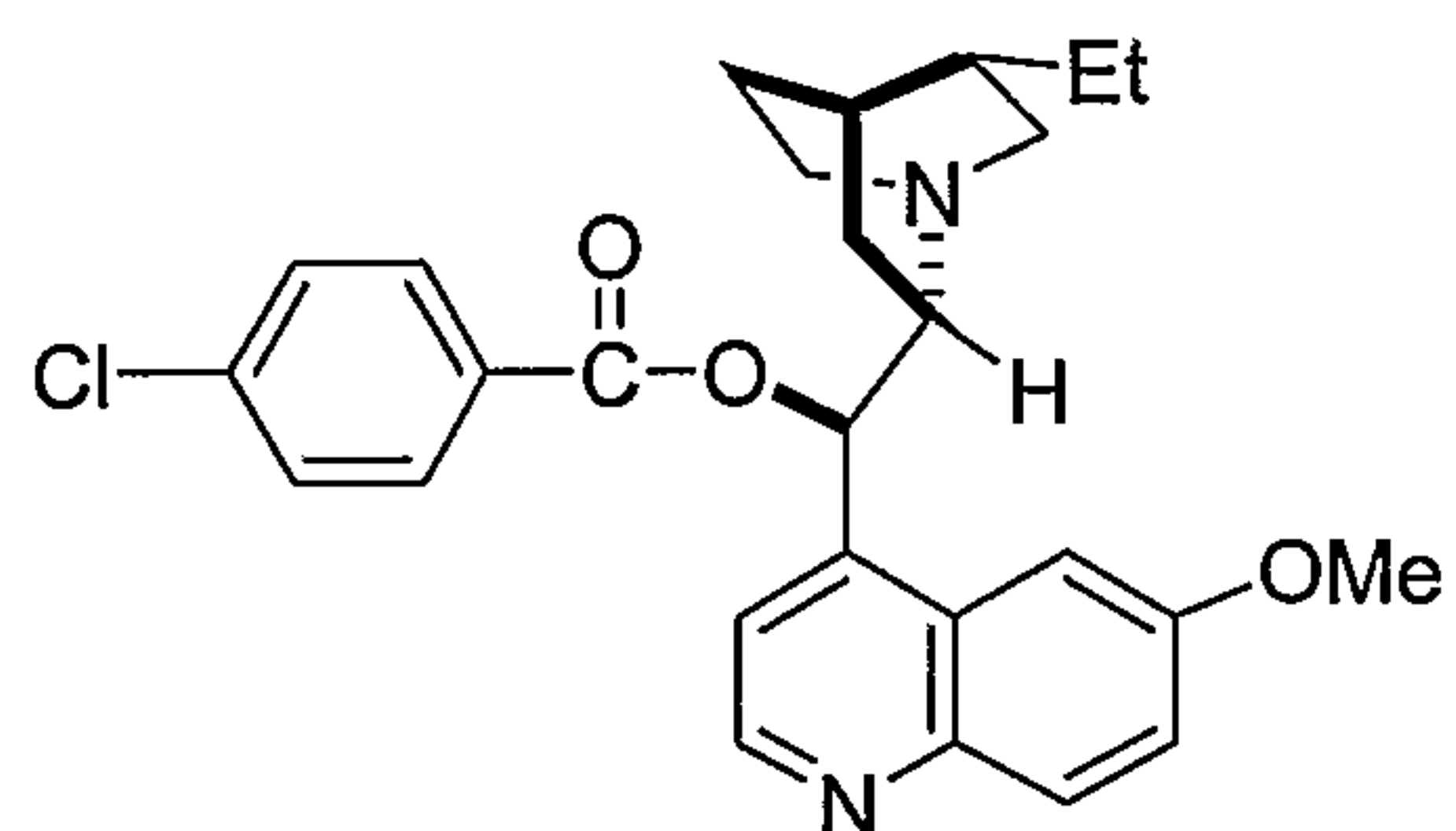
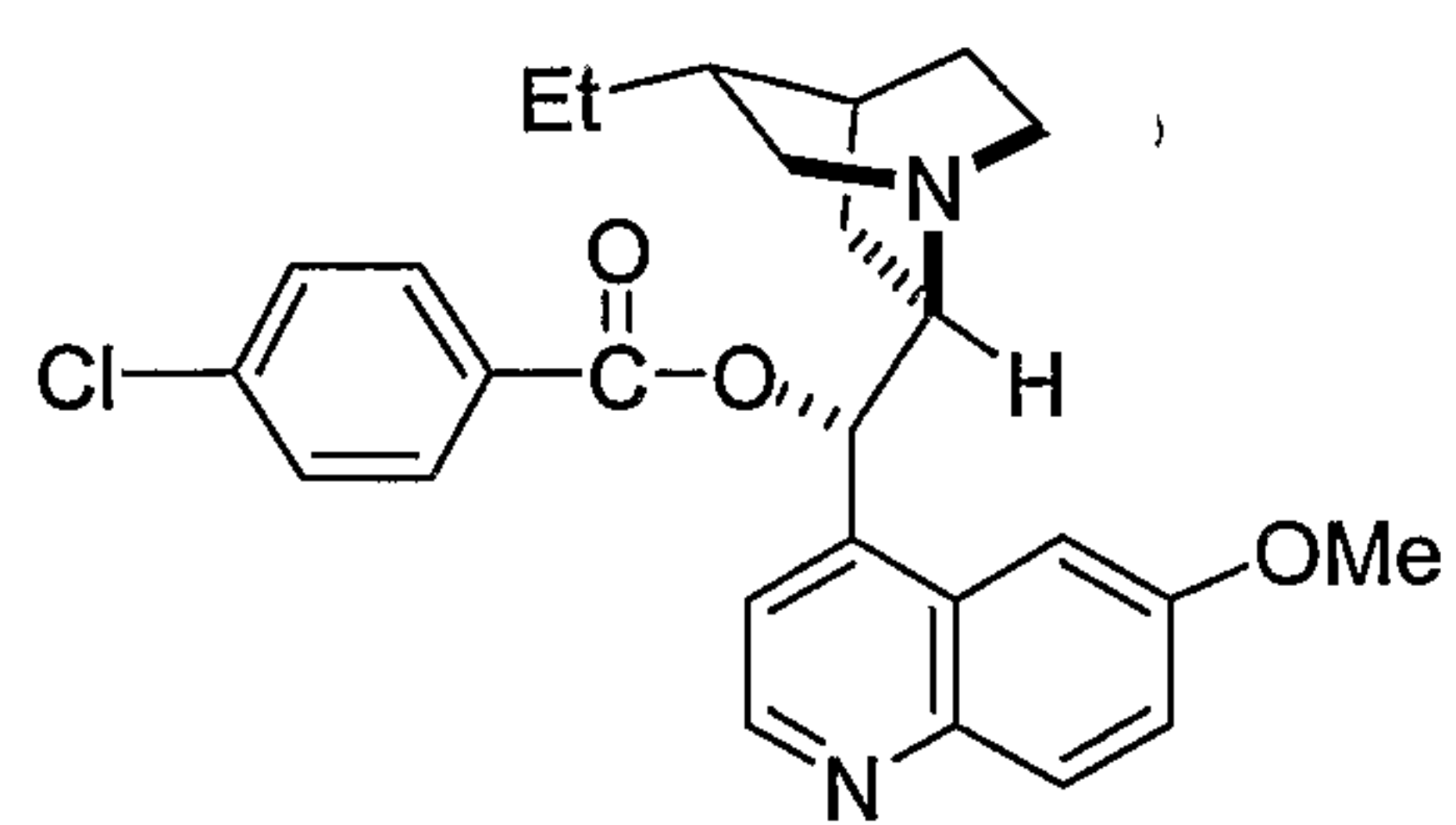


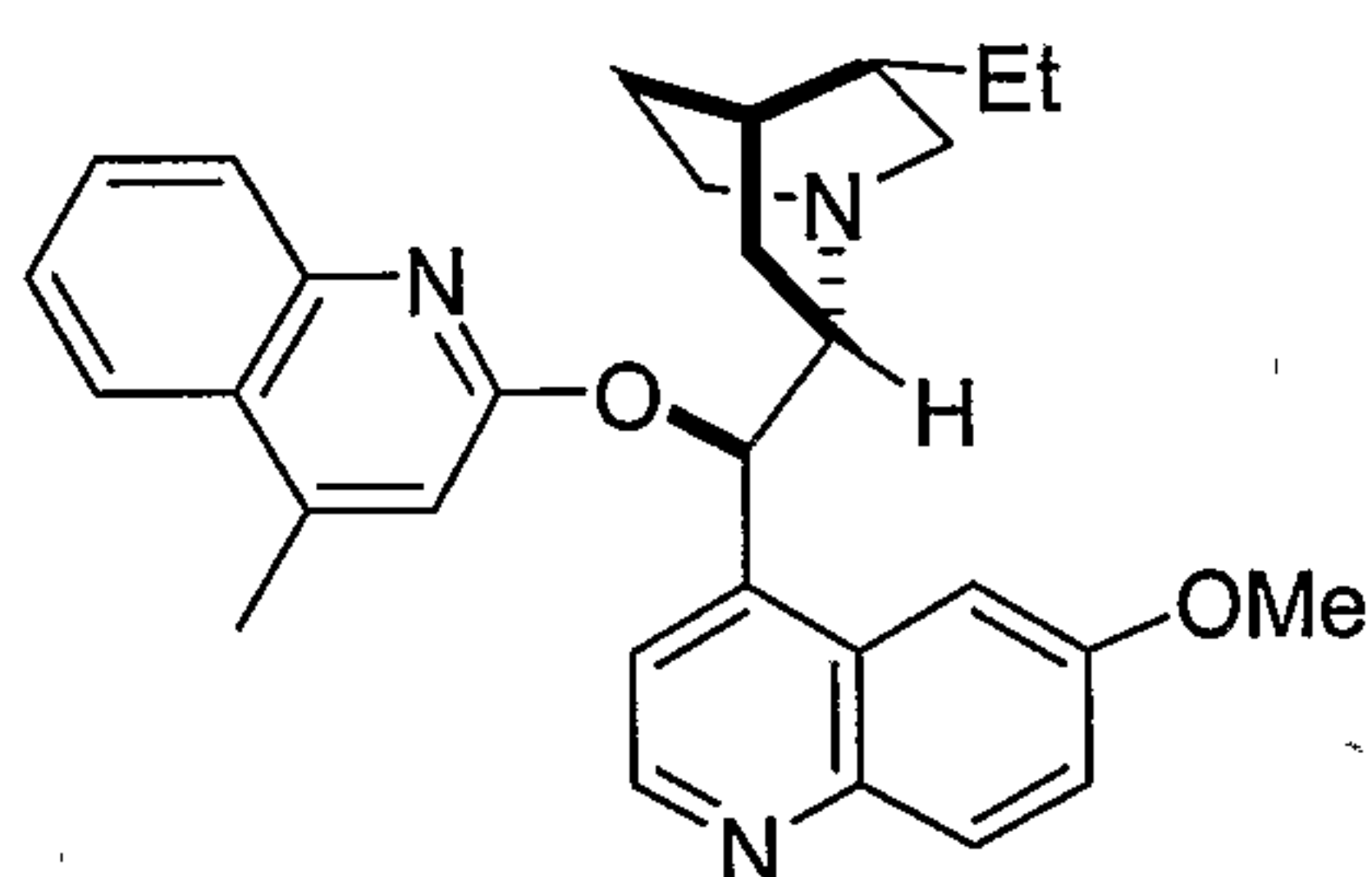
Figure 6



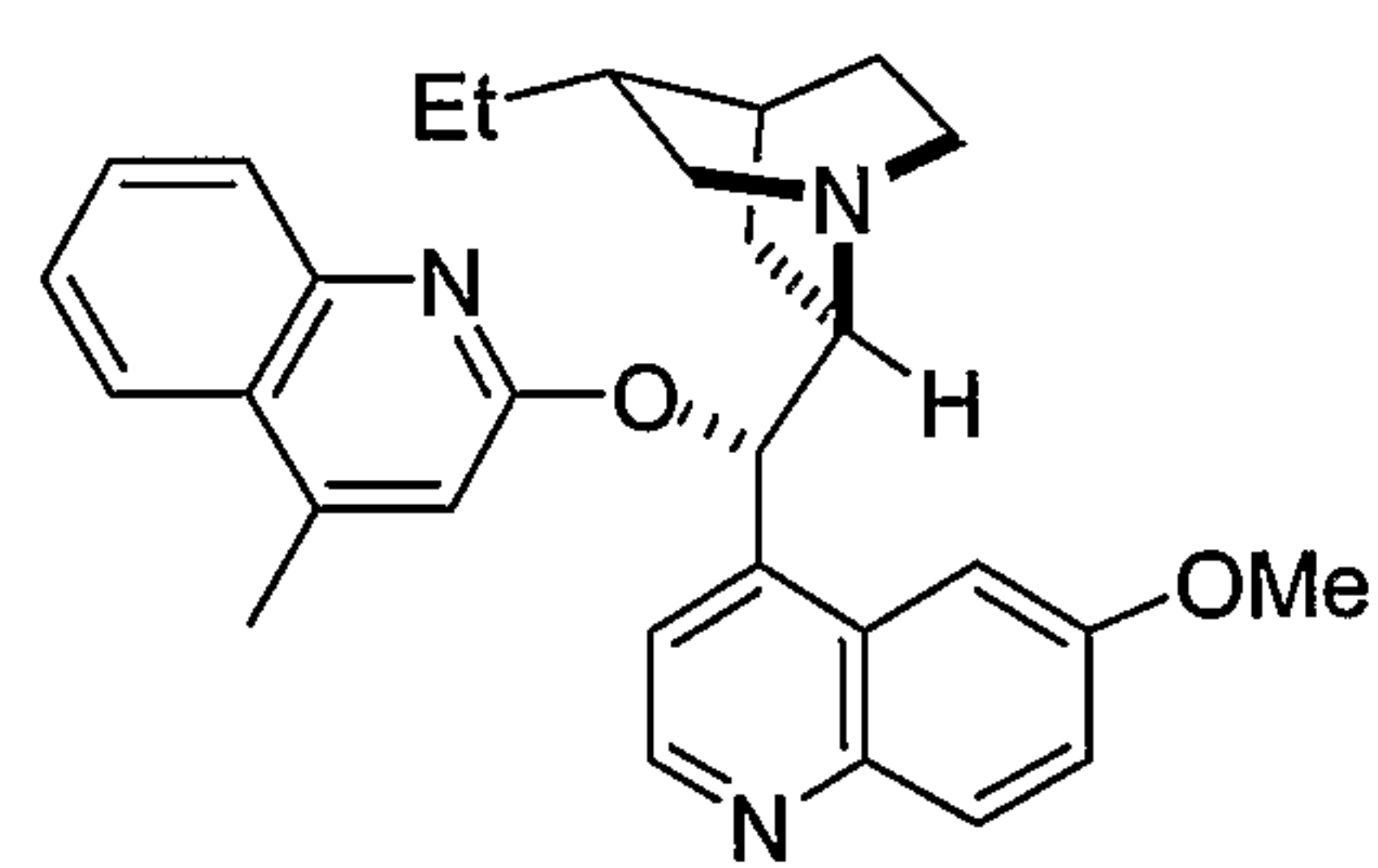
DHQ-CLB



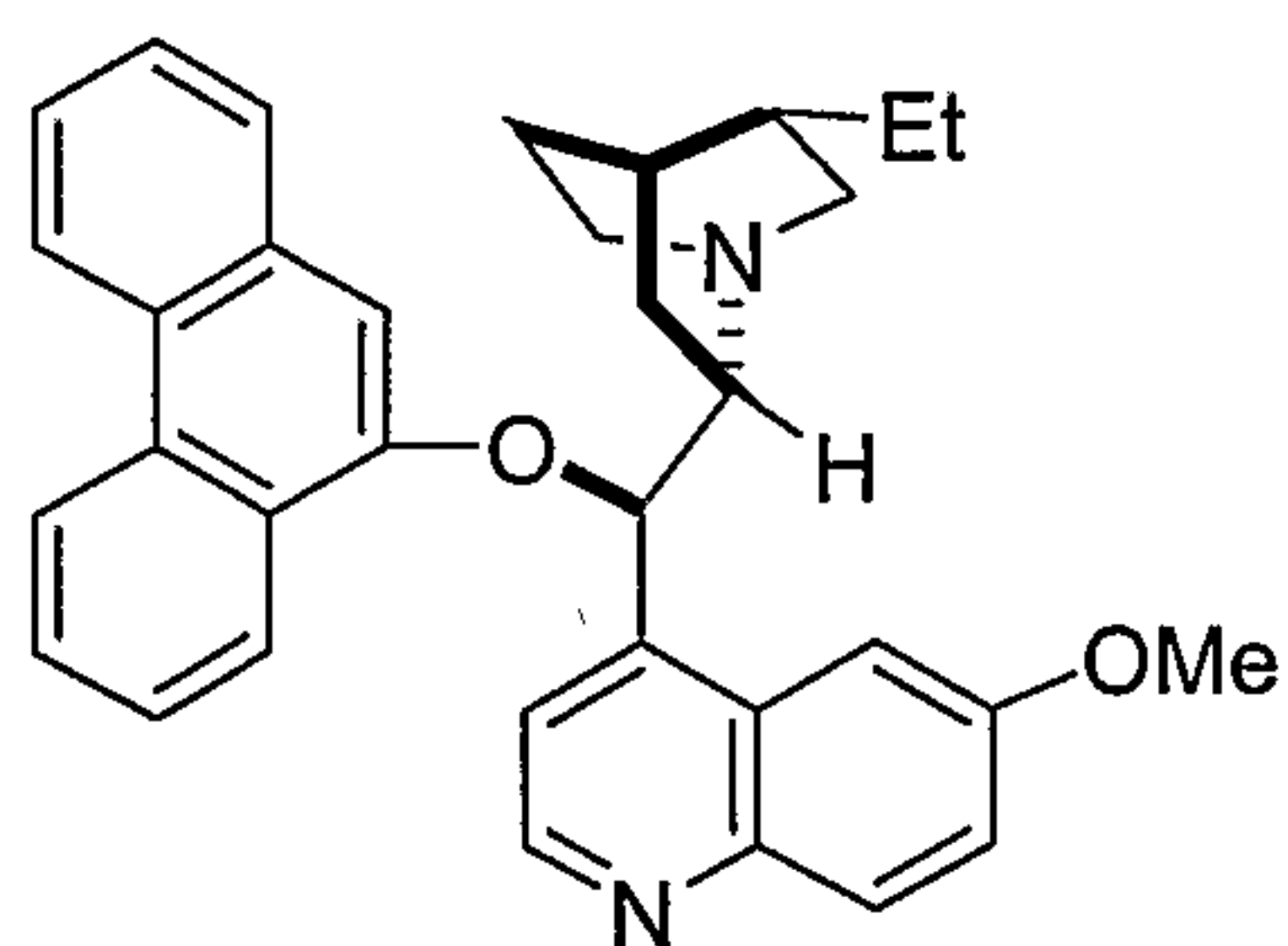
DHQD-CLB



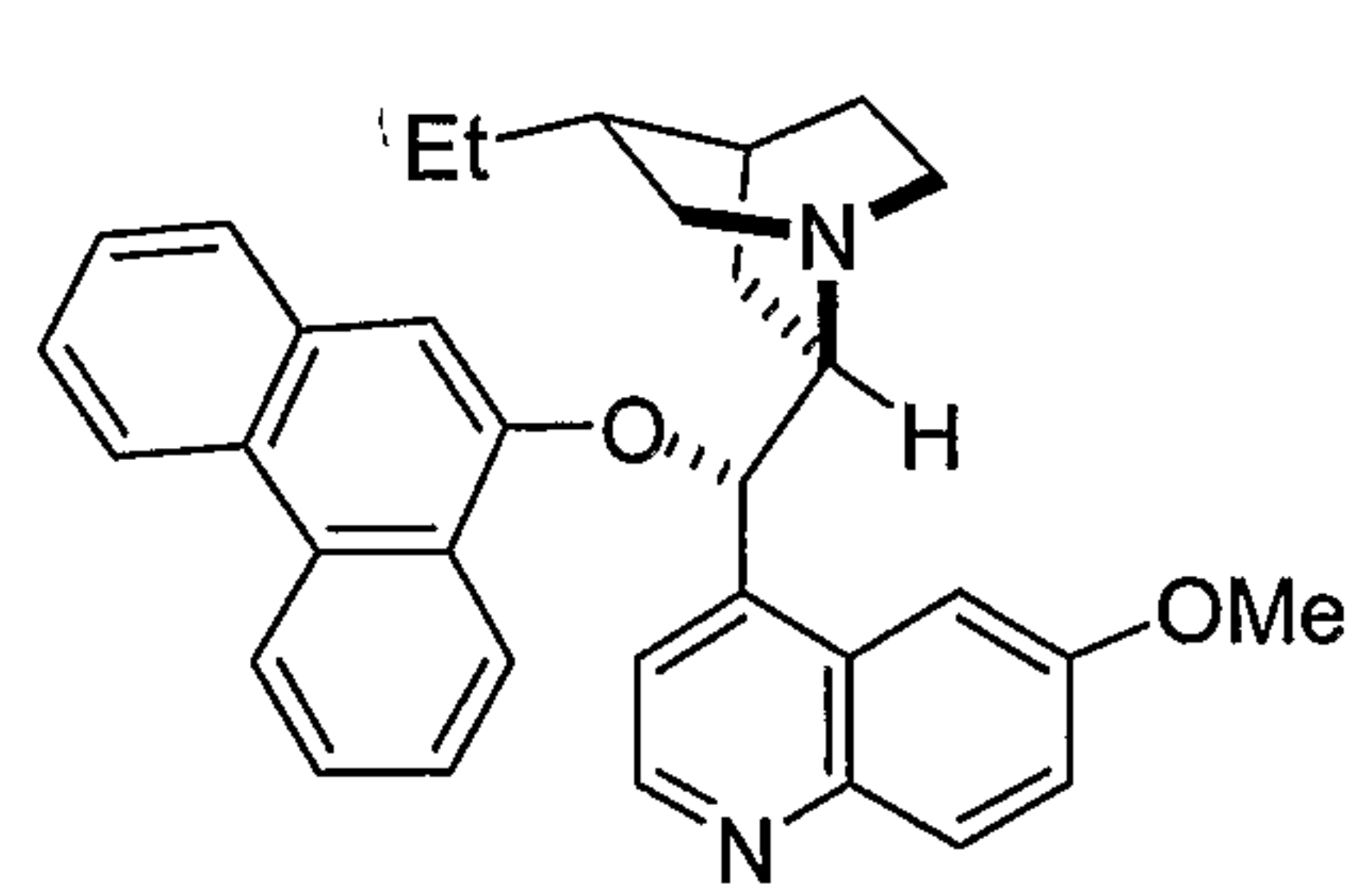
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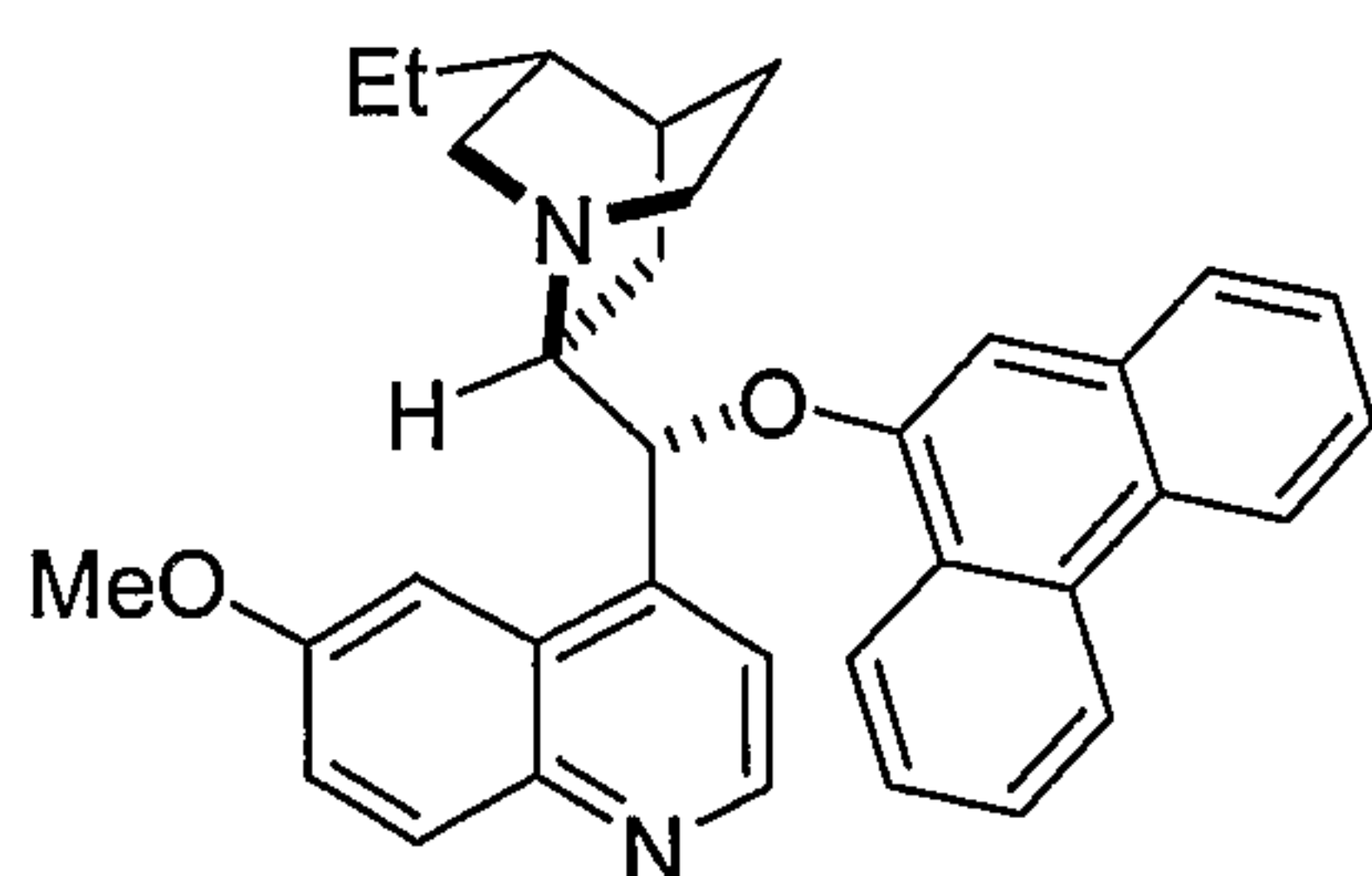
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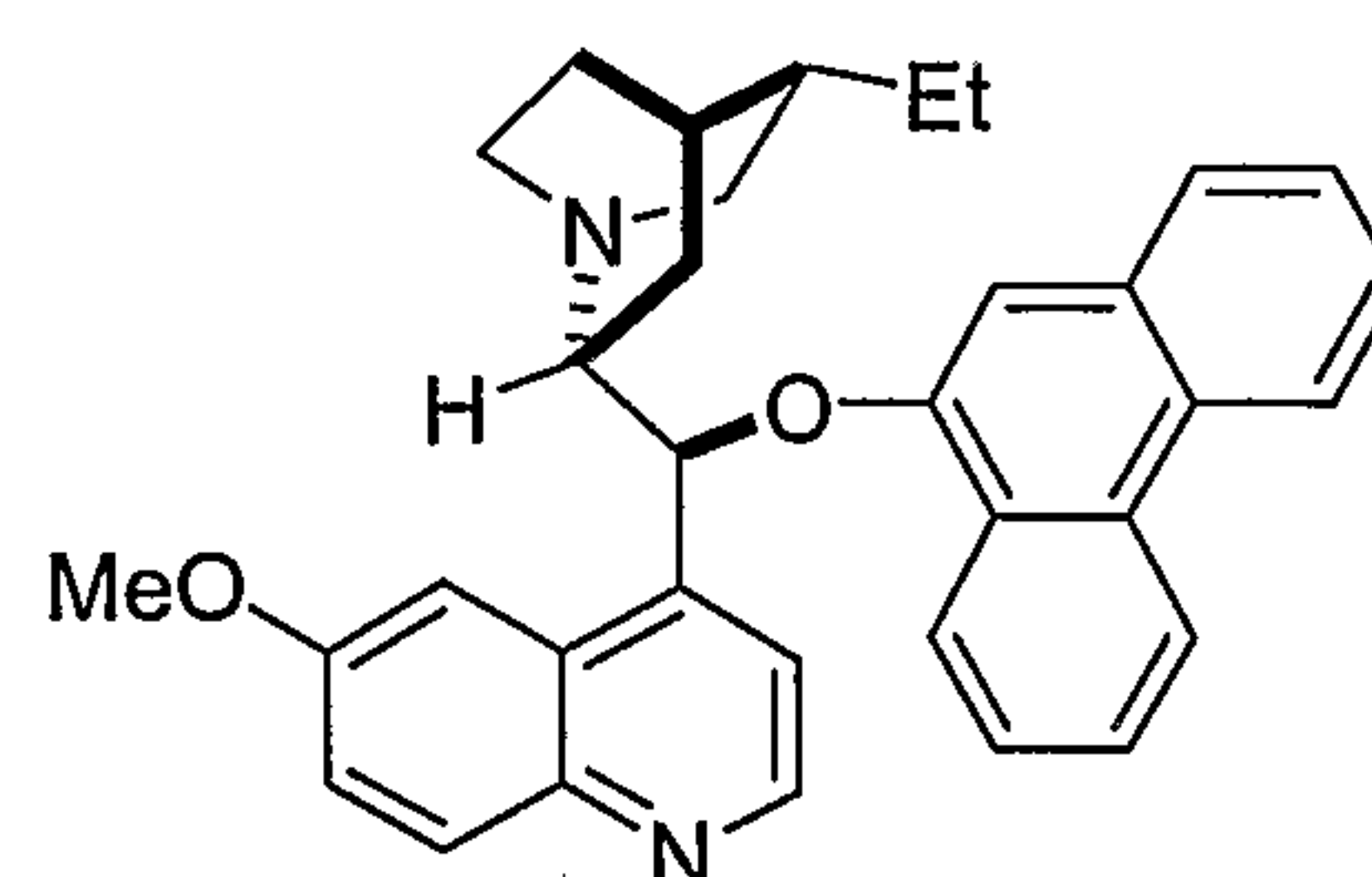
DHQ-AQN



DHQD-AQN

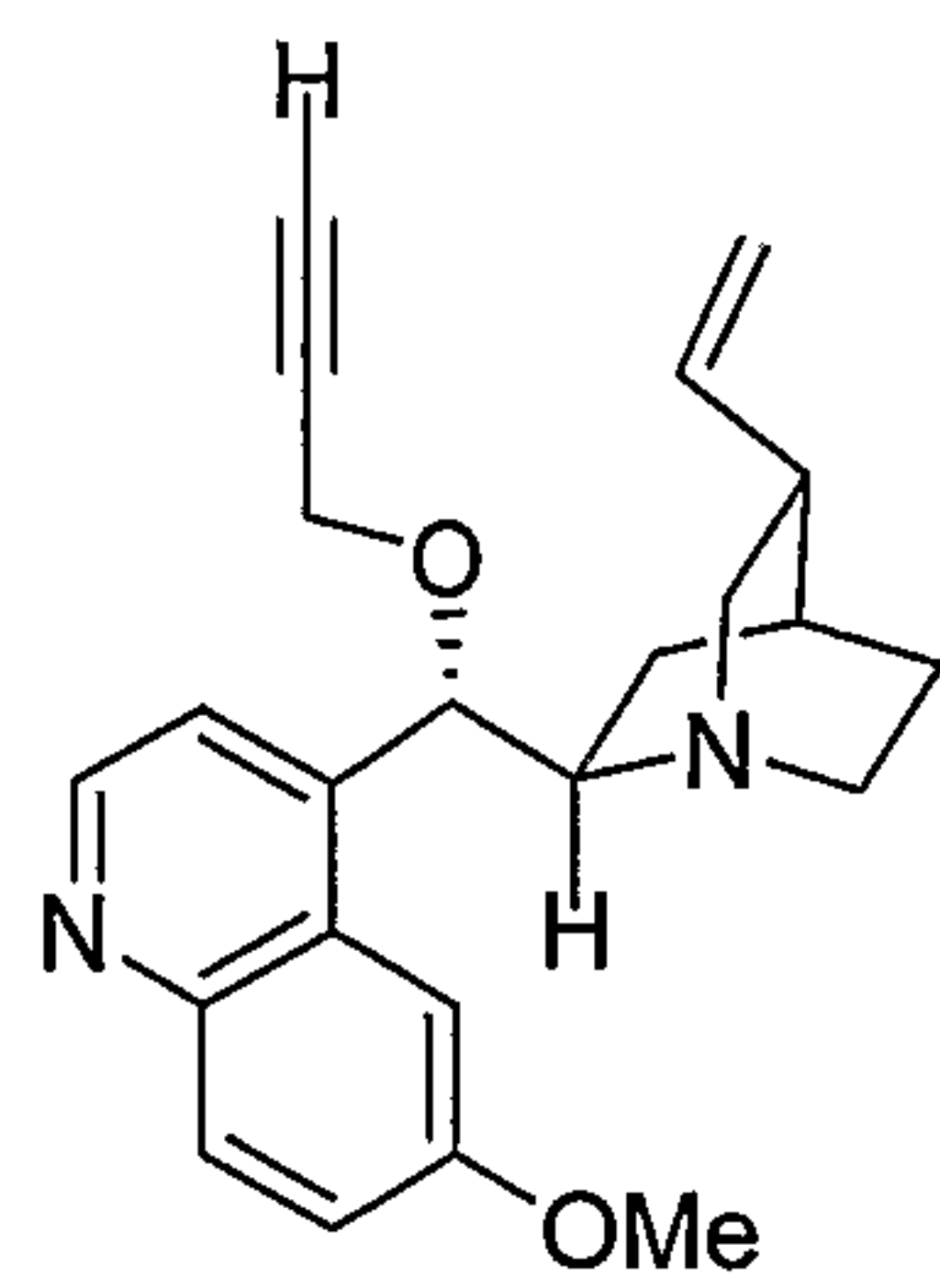


DHQ-PHN

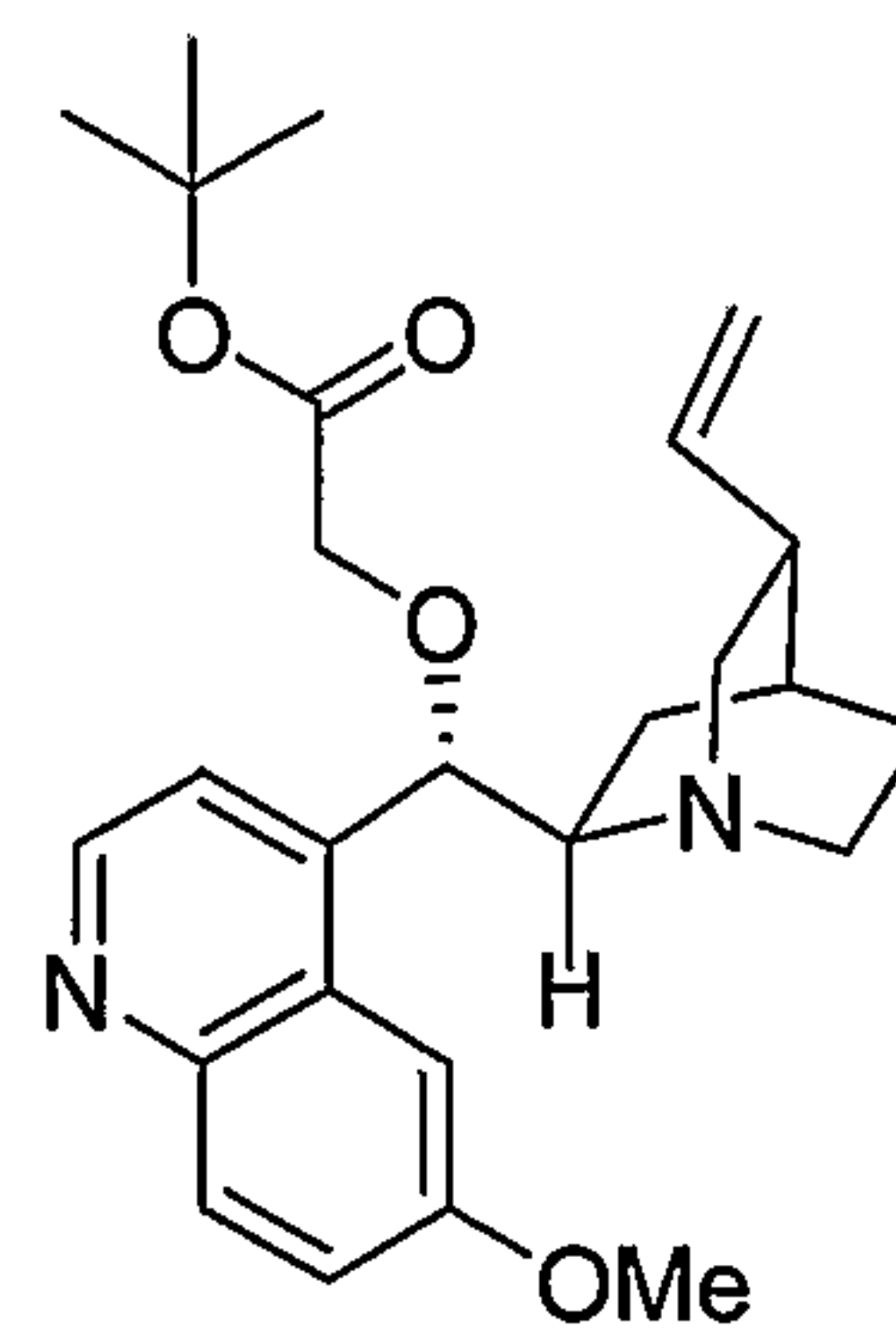


DHQD-PHN

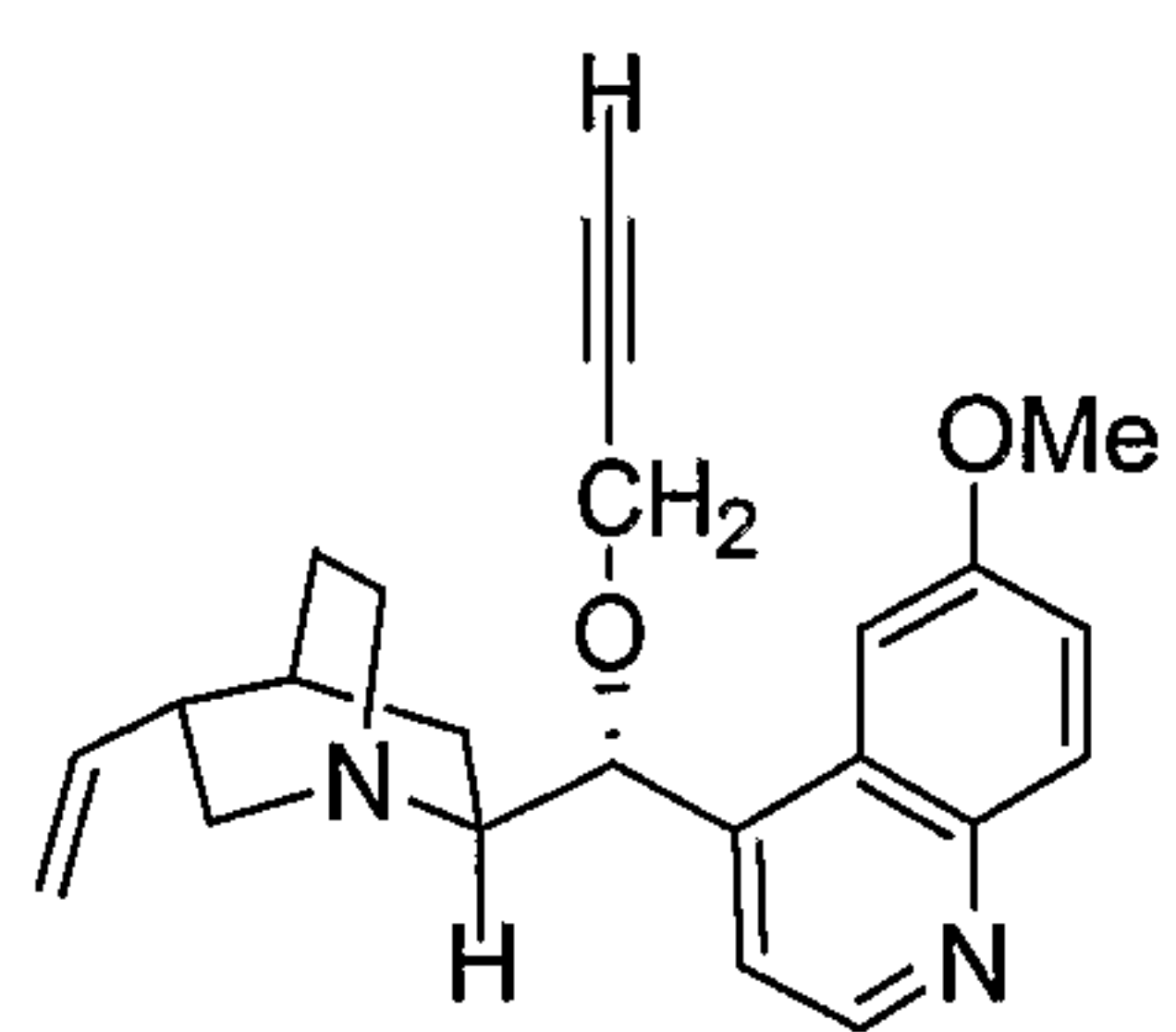
7/45

Figure 7

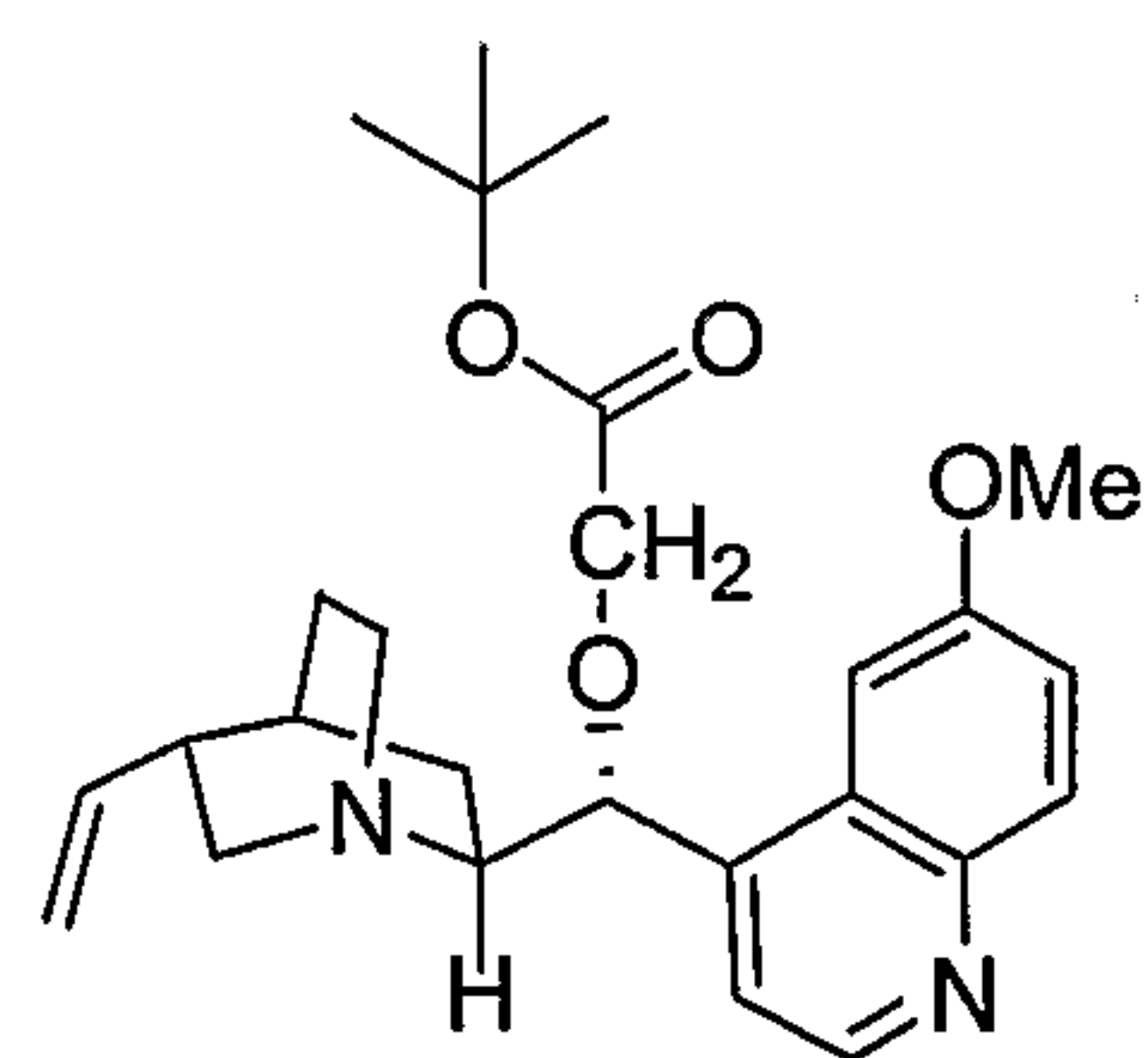
QD-PP



QD-TB



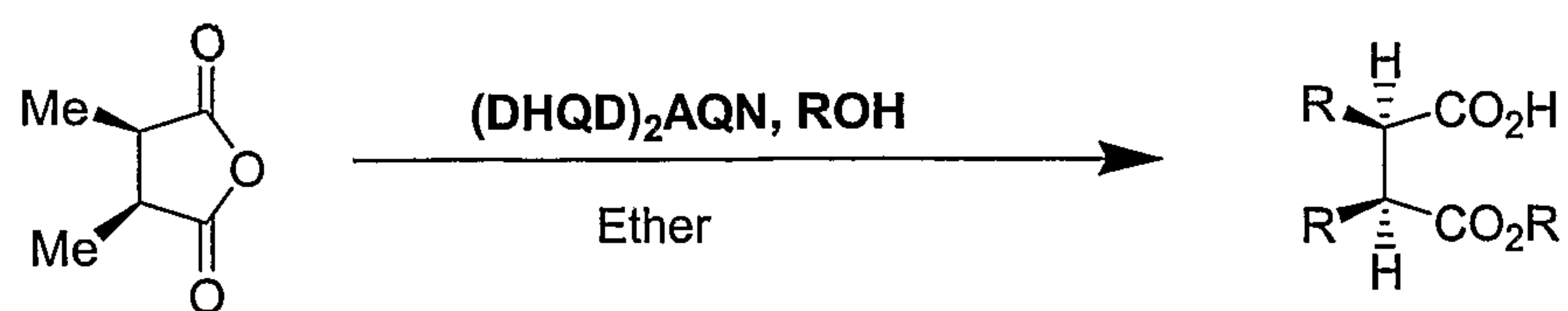
Q-PP



Q-TB

8/45

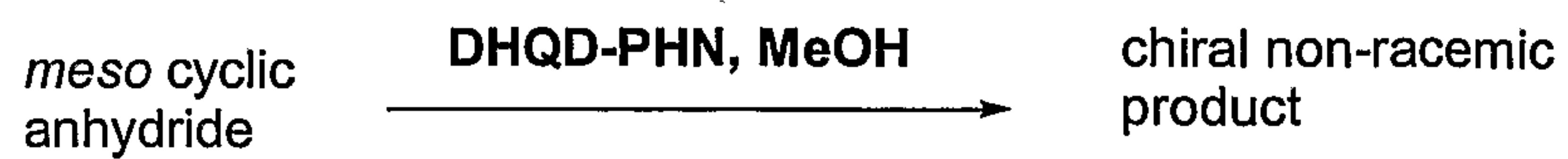
Figure 8



Entry	ROH	Catalyst Loading (mole %)	Solvent	Temp. ($^{\circ}\text{C}$)	ee (%)	Product
1	MeOH	5	Ether	r.t.	93	
2	EtOH	5	Ether	r.t.	95	
3	EtOH	10	Ether	r.t.	97	
4	iPrOH	10	Ether	r.t.		No Reaction

9/45

Figure 9



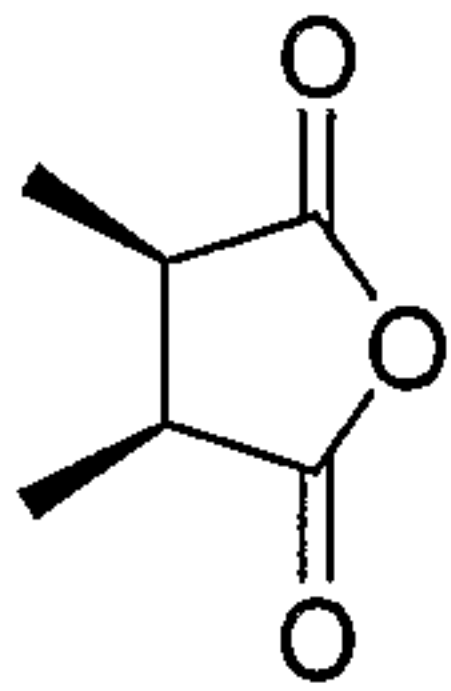
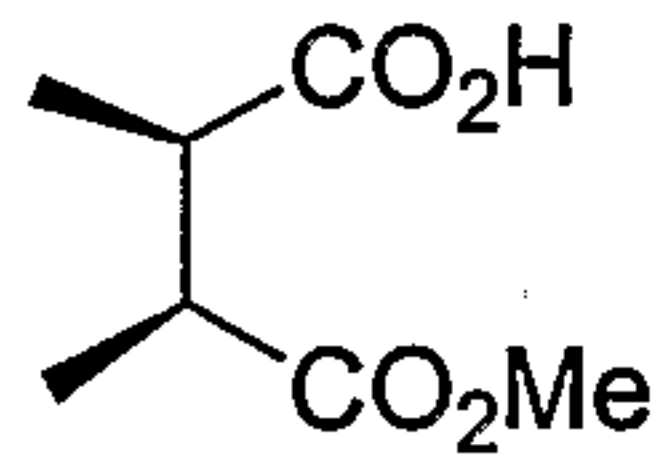
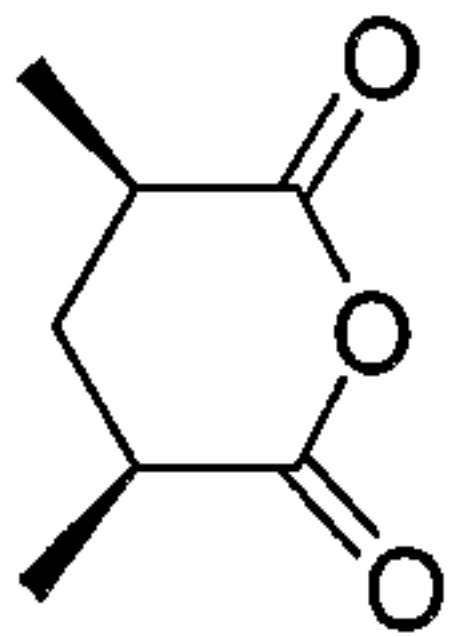
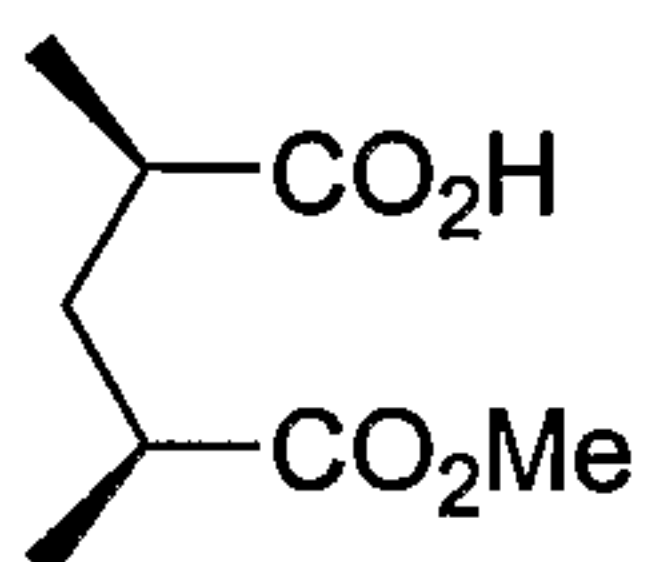
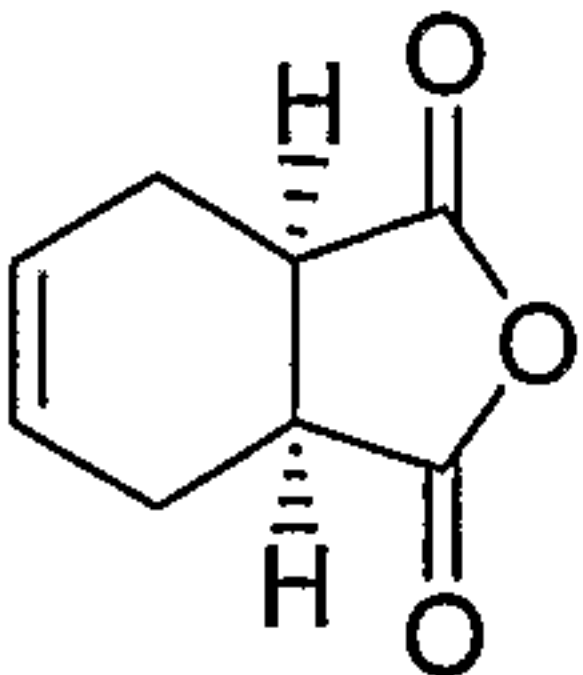
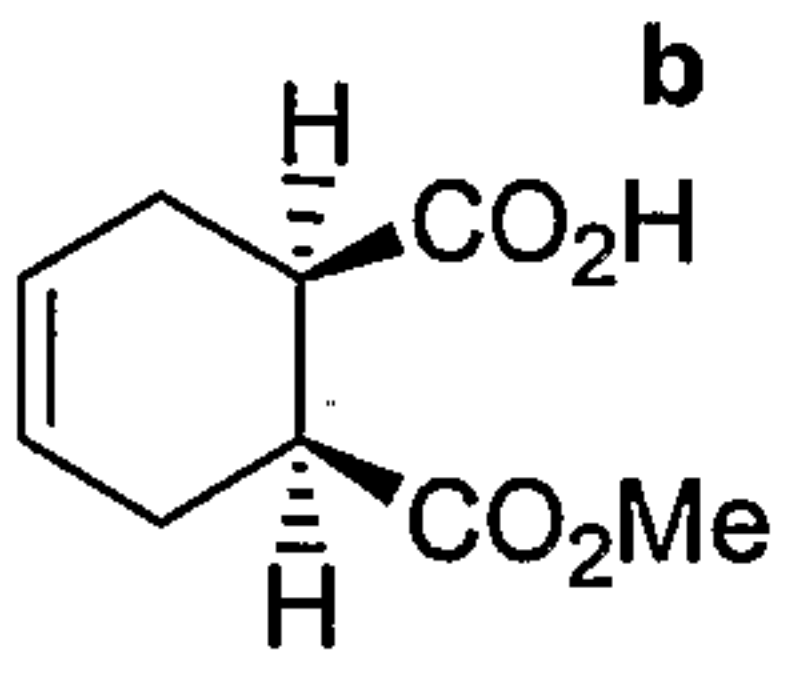
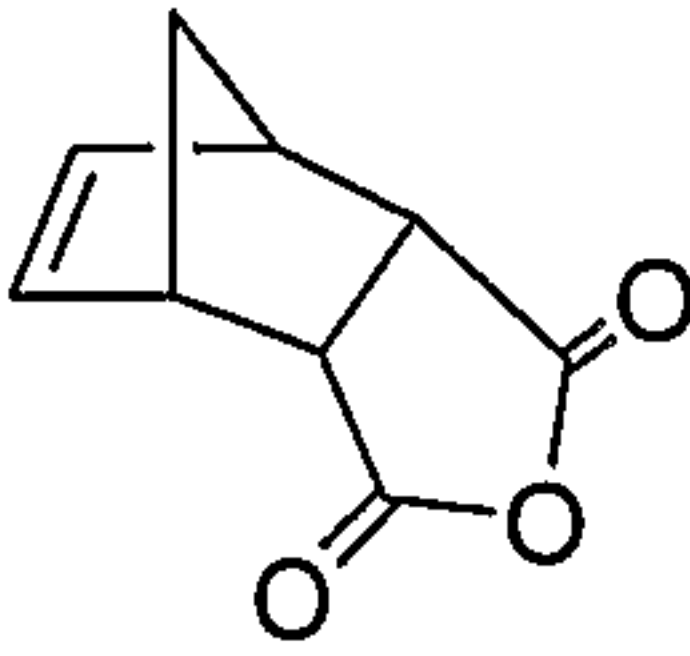
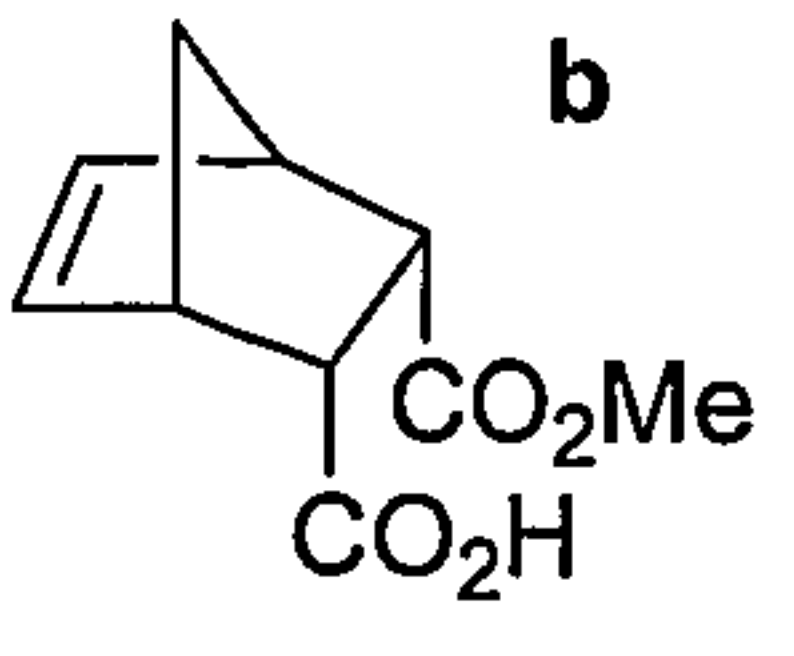
Entry	Anhydride	Catalyst Loading (mole %)	Solvent	Temp. (°C)	ee (%) ^a	Product ^b
1		5	Toluene	r.t.	81	
		15	Toluene	-30	95	
		30	Toluene	-30	96	
2		10	Toluene	r.t.	19	
3		5	Ether	r.t.	88	
4		3	CCl ₄	r.t.	78	

Figure 10

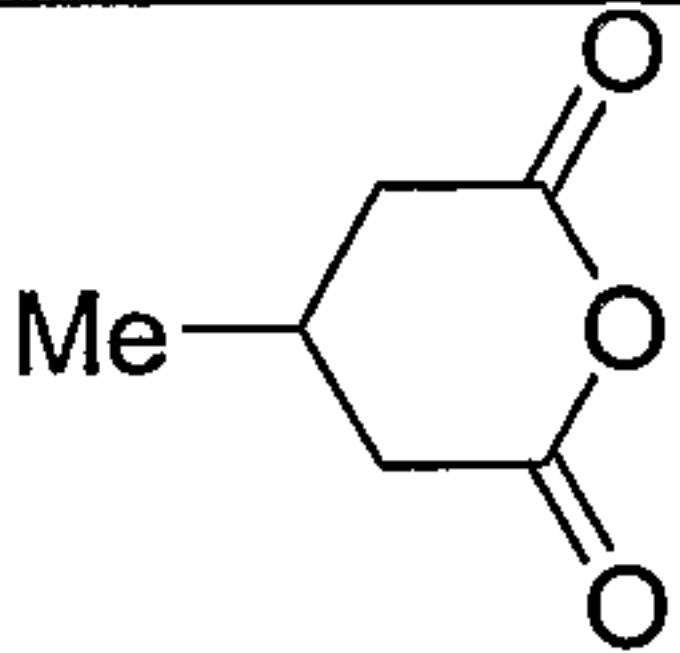
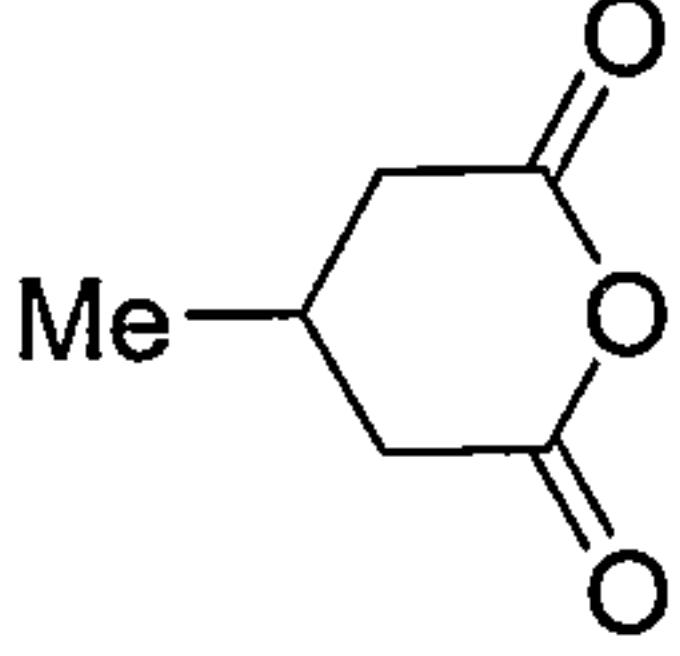
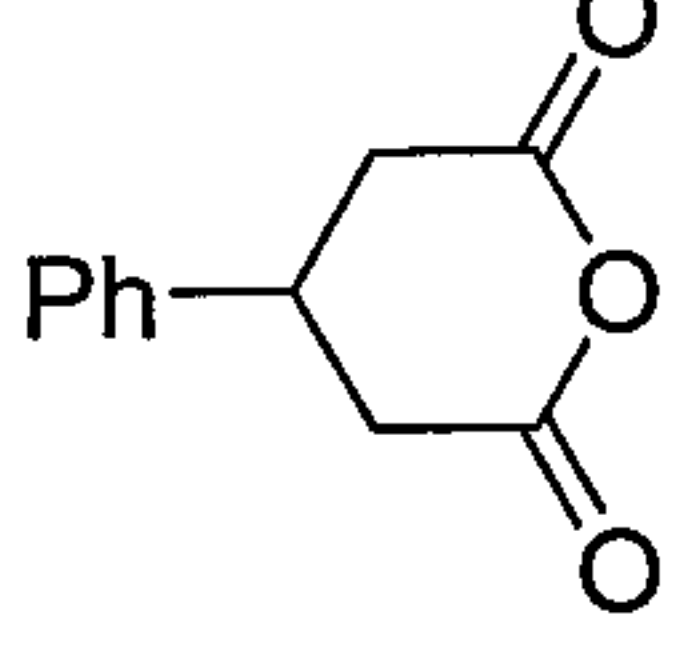
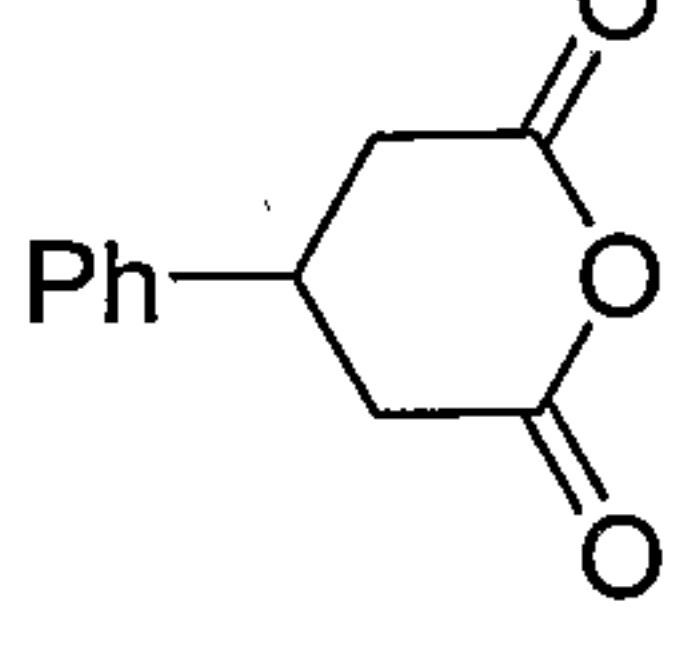
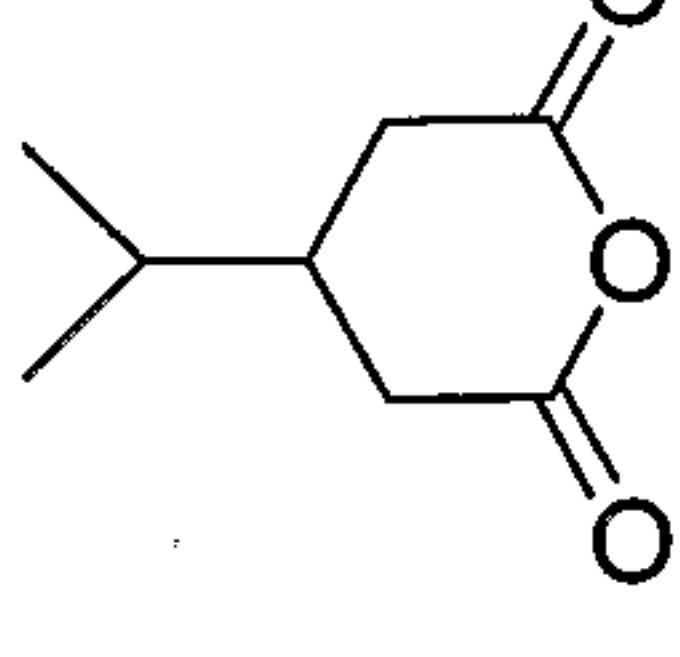
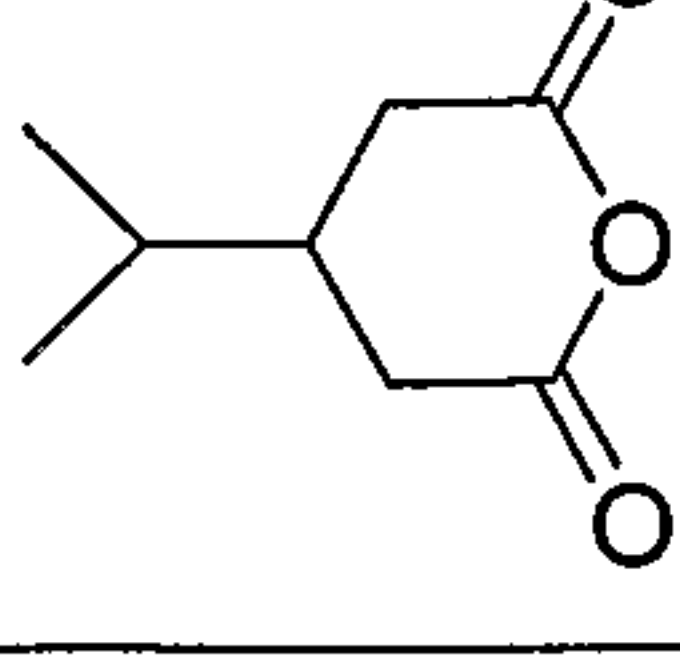
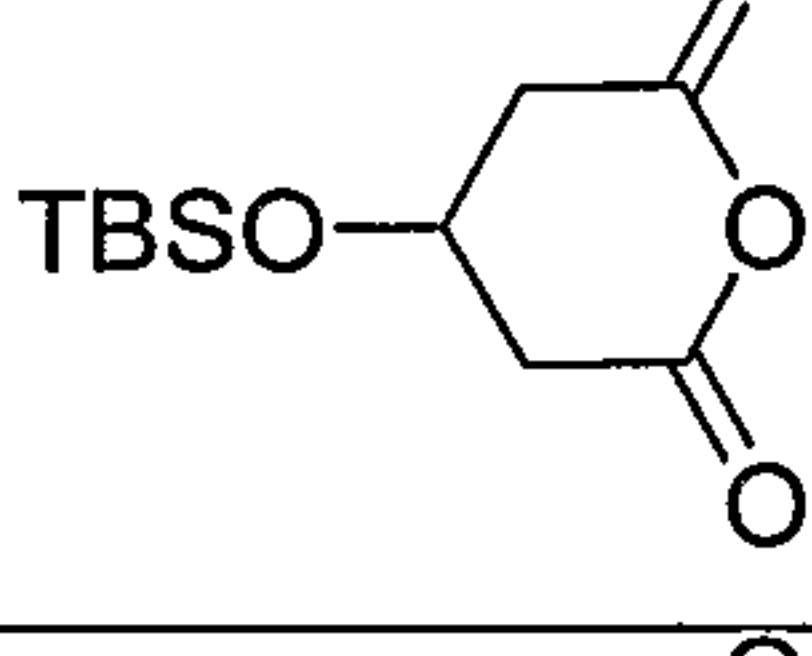
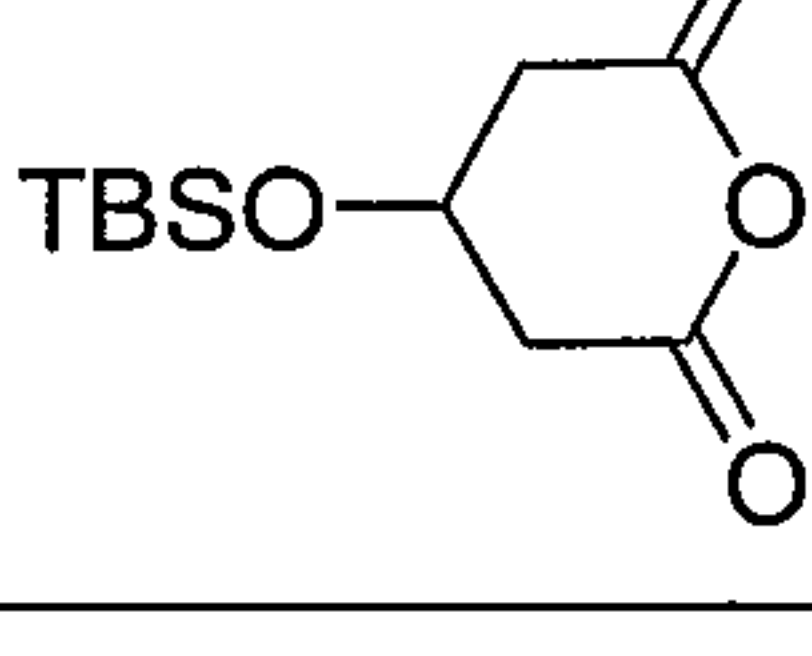
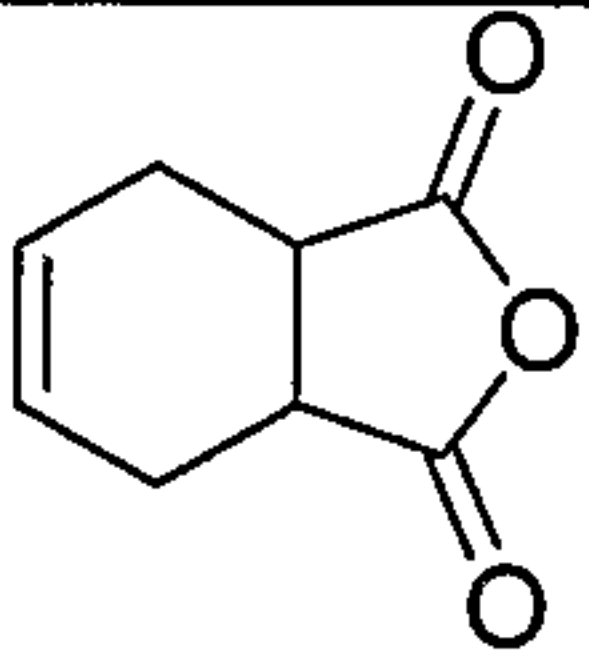
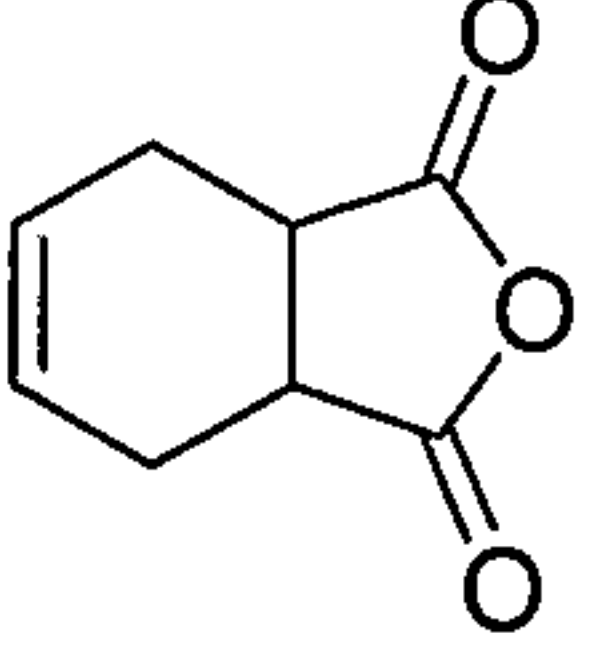
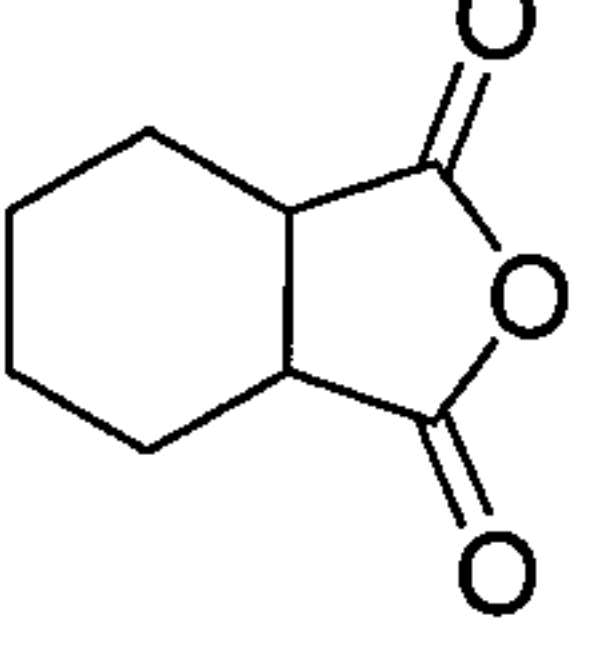
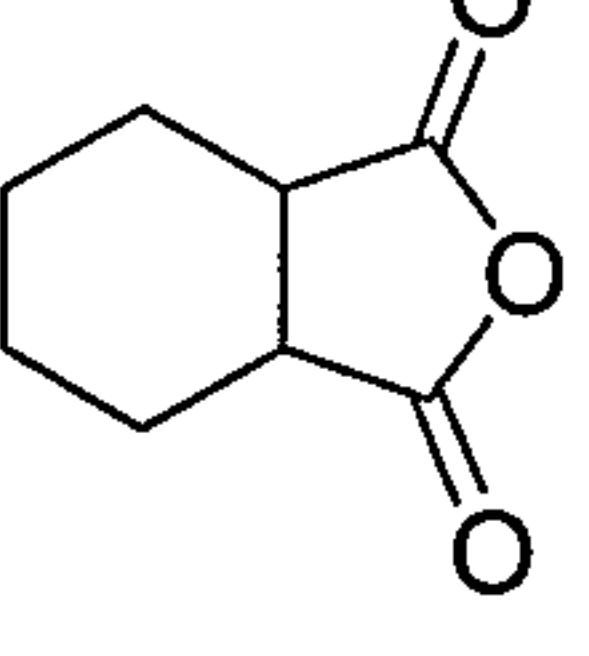
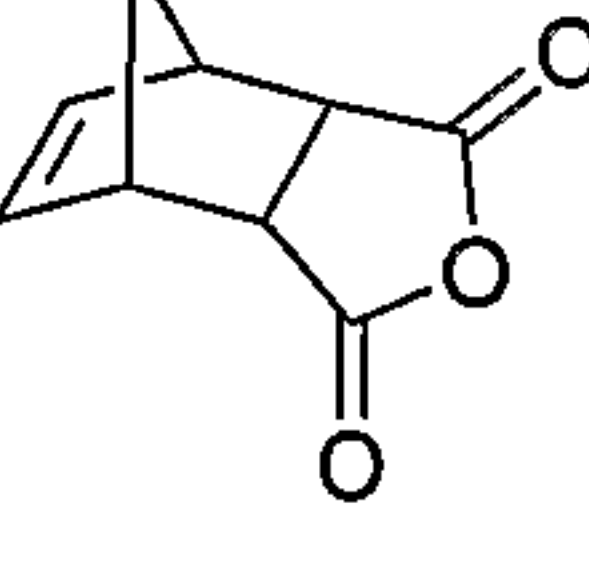
Substrate	Catalyst	Alcohol	Reaction Time (h)	Conversion % (% Yield)	Ee (%)
	QD-PP	MeOH	77.5	92% (69%)	77%
	QD-PP	CF ₃ CH ₂ OH	70.5	93% (65%)	77%
	QD-PP	MeOH	52	91.5% (73%)	79%
	QD-PP	CF ₃ CH ₂ OH	71.5	97% (89%)	81%
	QD-PP	MeOH	91	90.3% (72%)	80%
	QD-PP	CF ₃ CH ₂ OH	91	90.9% (70%)	55%
	QD-PP	MeOH	105	91.5% (45.7%)	78%
	QD-PP	CF ₃ CH ₂ OH	105	87.4% (68.3%)	48%

Figure 11

Substrate	Catalyst	Catalyst (mol%)	Alcohol	Alcohol (equiv)	Temp. (C)	Reaction Time (h)	Conversion % (% yield)	Ee (%)
	QD-PP	20	CF ₃ CH ₂ OH	10	RT	2	100 (99)	90
	QD-PP	20	CF ₃ CH ₂ OH	10	-27	48	100 (92)	94
	QD-PP	20	CF ₃ CH ₂ OH	10	RT	5	100 (75)	89
	QD-PP	20	CF ₃ CH ₂ OH	10	-27	16	100 (87)	91
	QD-PP	20	CH ₃ OH	10	-27	192	65 (93)	96

12/45

Figure 12

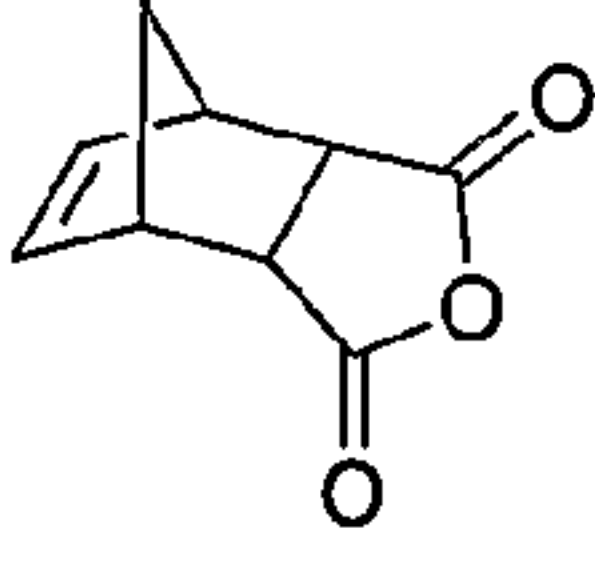
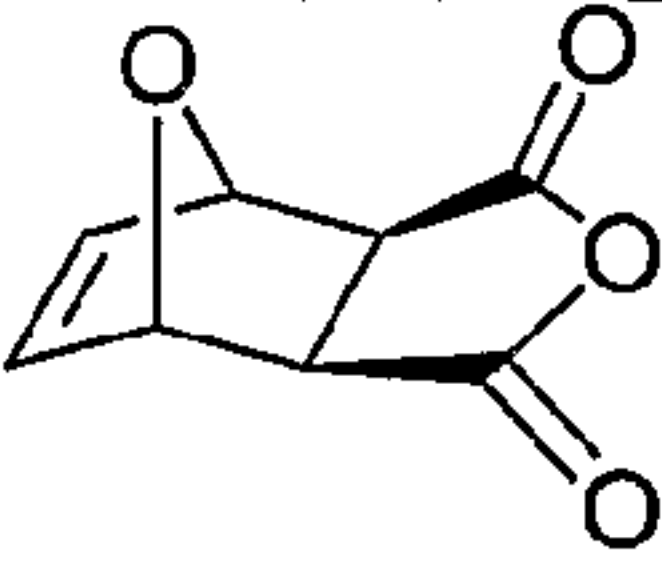
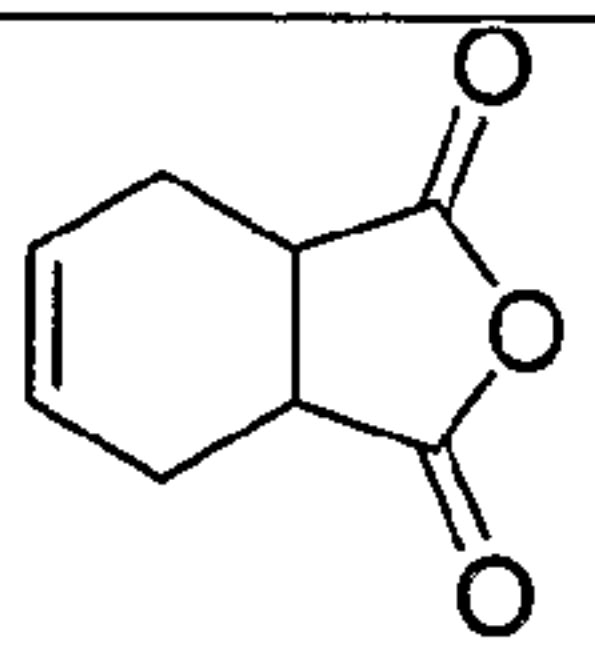
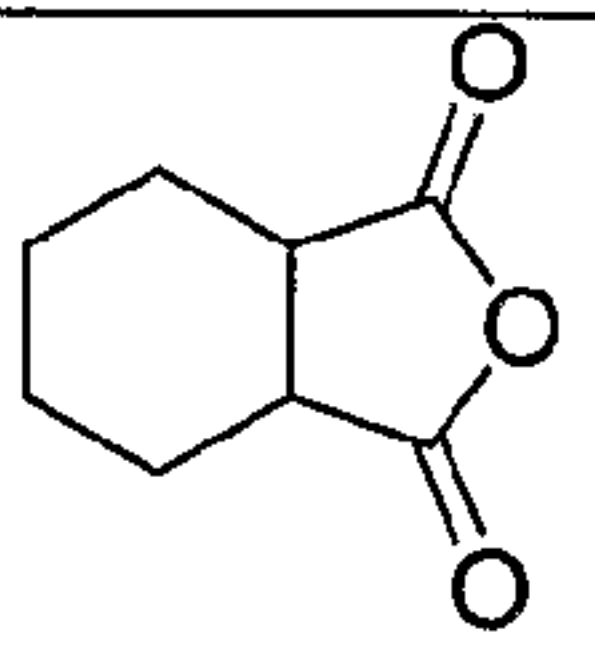
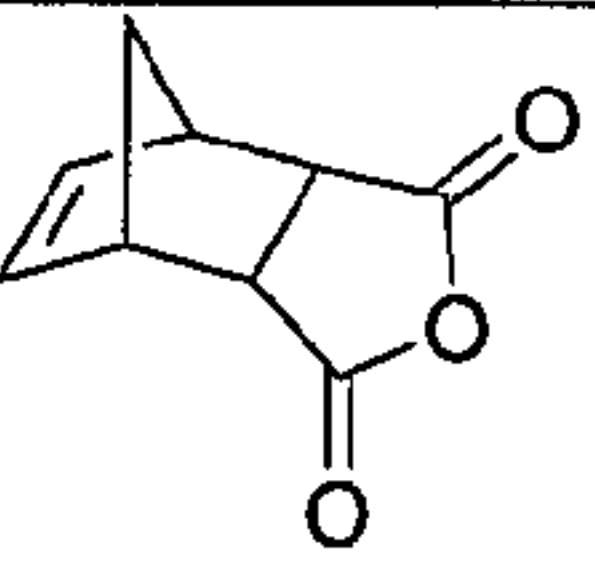
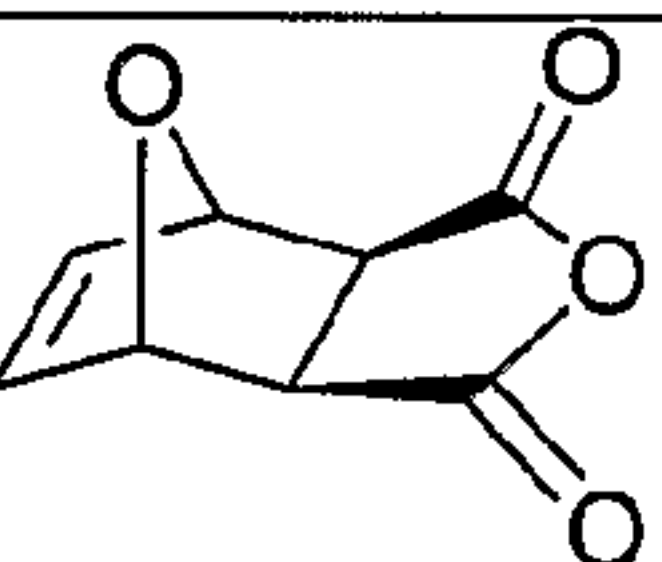
Substrate	Catalyst	Catalyst (mol%)	Alcohol	Alcohol (equiv)	Temp. (C)	Reaction Time (h)	Conversion % (% yield)	Ee (%)
	QD-PP	30	CH ₃ OH	10	-27	72	100 (81)	79
	QD-PP	30	CH ₃ OH	10	-27	72	100 (78)	85
	QD-PP	100	CF ₃ CH ₂ OH	10	-27	12	100 (96)	88
	QD-PP	100	CF ₃ CH ₂ OH	10	-27	12	100 (83)	76
	QD-PP	100	CH ₃ OH	10	-27	12	100 (94)	75
	QD-PP	100	CH ₃ OH	10	-27	36	100 (85)	84

Figure 13

Alcohol	Solvent	Reaction Time (h)	Conversion % (% Yield)	Ee (%)
CF ₃ CH ₂ OH	Ether	53	100 (98)	89
CH ₃ OH	Ether	13	82	86
CH ₃ OH	Toluene	11	81	69

Figure 14

Catalyst (mol%)	Alcohol (equiv)	Solvent	Reaction Time (min)	Conversion % (% Yield)	Ee (%)
20	10	Toluene	40	87	56
100	10	Toluene	30	98	72
100	1	Toluene	90	93	82
100	1	Ether	90	92	83

Figure 15

Catalyst (mol%)	Alcohol (equiv)	Solvent	Reaction Time (h)	Conversion % (% Yield)	Ee (%)
100	10	Toluene	2	93	82
100	10	Ether	2	87	86
100	1	Toluene	20	96	91
100	1	Ether	20	96	91
50	1	Ether	101	89	85

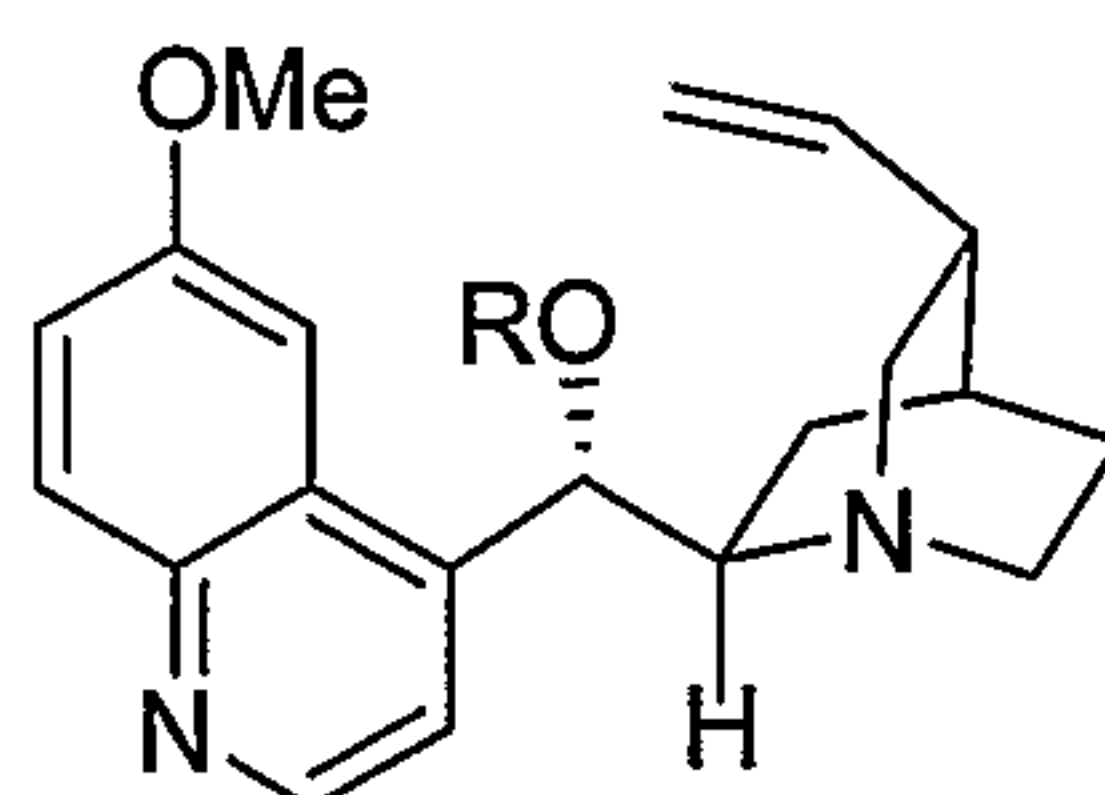
Figure 16

Catalyst (mol%)	Alcohol (equiv)	Solvent	Conversion % (% Yield)	Ee (%)
100	1	Ether	93	90
100	1	Toluene	95	89

Figure 17

Substrate (mmol)	Catalyst	Alcohol	Solvent	Reaction Time (h)	Conversion % (% Yield)	Ee (%)
0.1	QD-TB	MeOH	Ether	49	95	88
0.05	QD-TB	MeOH	Toluene	11	82	78
0.1	QD-TB	CF ₃ CH ₂ OH	Ether	13	100 (94)	92
0.05	Q-PP	MeOH	Ether	75	91	75
0.05	Q-PP	MeOH	Toluene	49	96	50

Figure 18

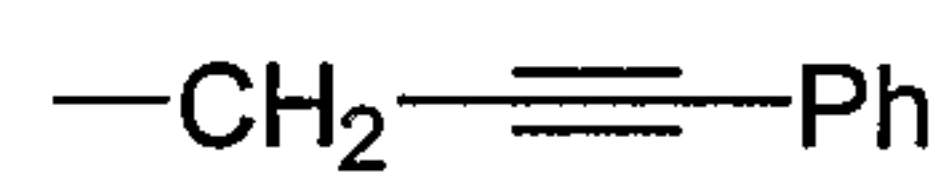


quinidine-based catalysts

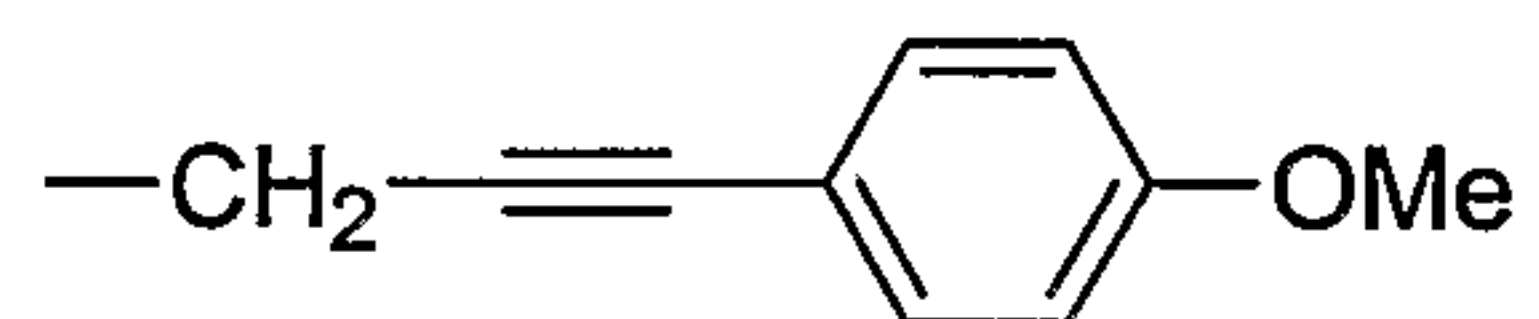
Catalyst

R

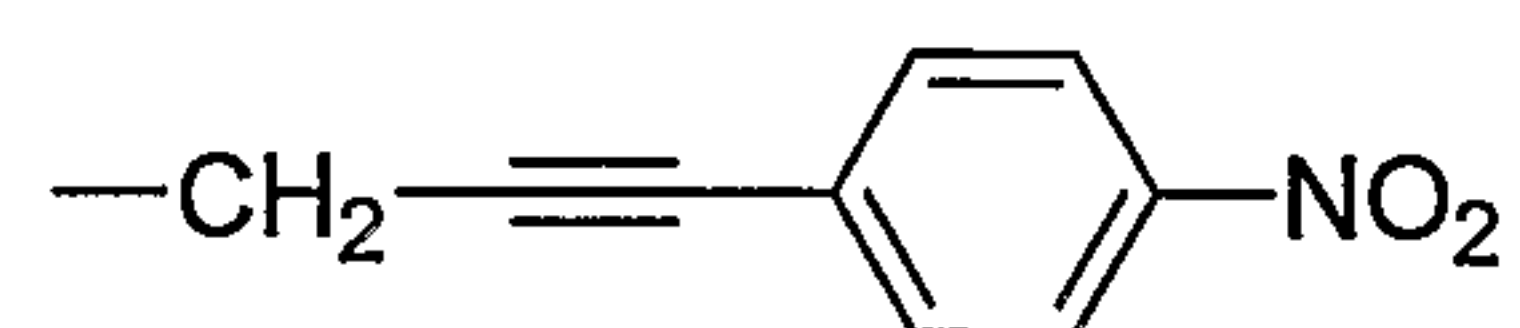
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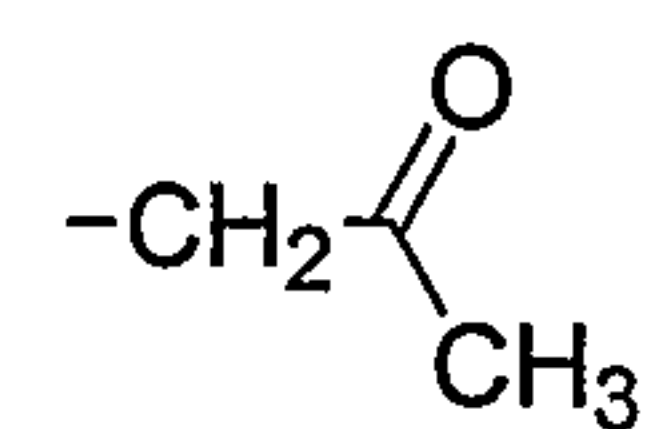
QD-AN



QD-NT



QD-AC



QD-CH

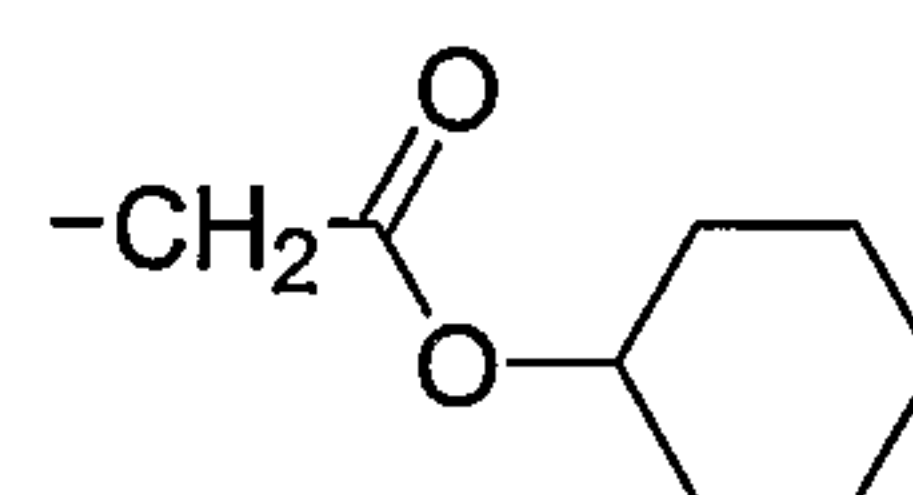


Figure 19

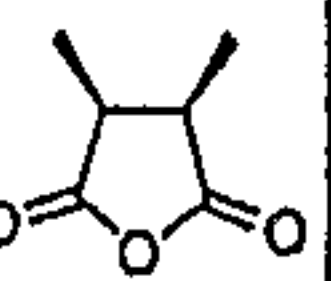
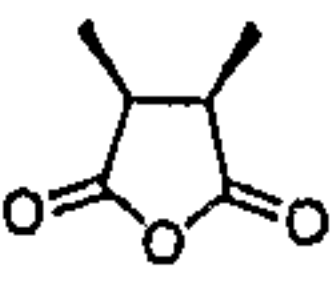
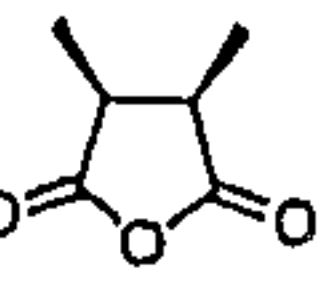
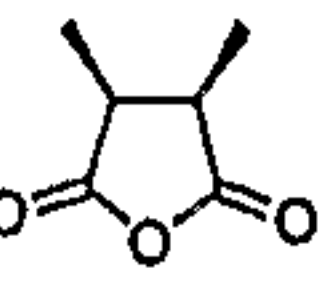
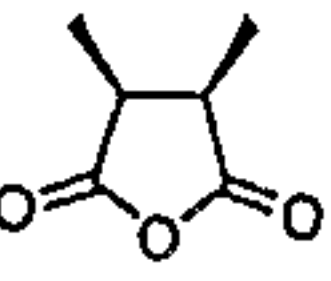
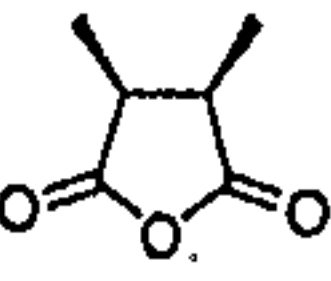
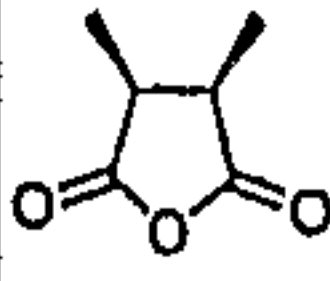
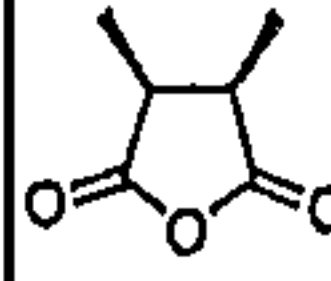
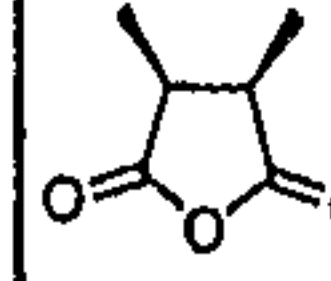
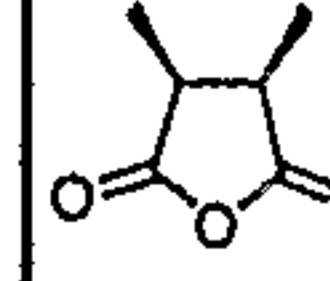
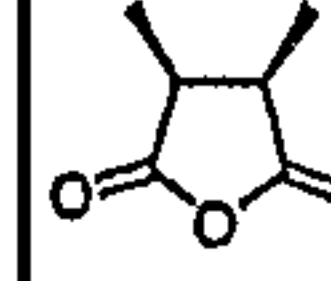
Table 1. Comparison of Catalysts' efficiency for methanolysis of 2,3-dimethylsuccinic anhydride in Et ₂ O at 0.02M concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (%Yield)	ee %
1		0.1	0.02M	(DHQD) ₂ AQN	5%	MeOH	10eq	Et ₂ O	RT	13h	86	92%
2		0.05	0.02M	QD-PP	20%	MeOH	10eq	Et ₂ O	RT	48h	93	87%
3		0.1	0.02M	QD-TB	20%	MeOH	10eq	Et ₂ O	RT	49h	95	88%
4		0.05	0.02M	QD-IP	20%	MeOH	10eq	Et ₂ O	RT	25h	99	86%
5		0.05	0.02M	QD-PC	20%	MeOH	10eq	Et ₂ O	RT	27.5h	92	86%
6		0.05	0.02M	QD-AD	20%	MeOH	10eq	Et ₂ O	RT	2.5h/25h	81/99	90%
7		0.05	0.02M	QD-(-)-MN	20%	MeOH	10eq	Et ₂ O	RT	7h	99	89%
8		0.05	0.02M	QD-(+)-MN	20%	MeOH	10eq	Et ₂ O	19	9h	96	89%
9		0.05	0.02M	QD-AC	20%	MeOH	10eq	Et ₂ O	RT	17h	98	82%
10		0.05	0.02M	QD-PIV	20%	MeOH	10eq	Et ₂ O	RT	37d	98	54%
11		0.05	0.02M	QD-PH	20%	MeOH	10eq	Et ₂ O	RT	75h	97	85%

Figure 20

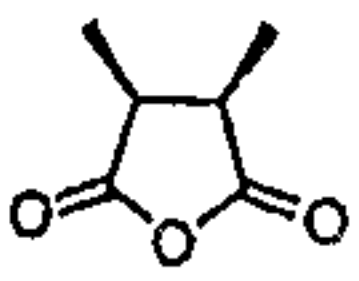
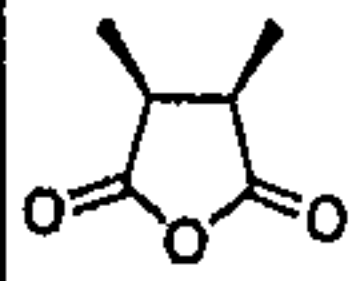
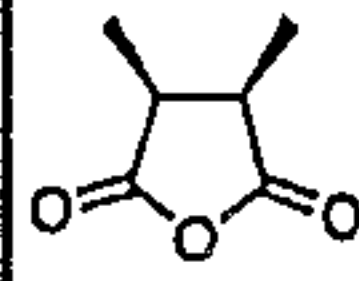
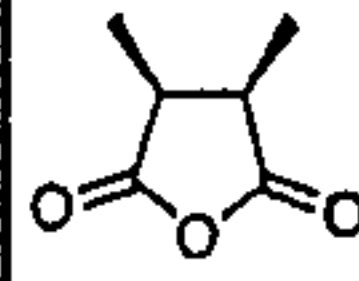
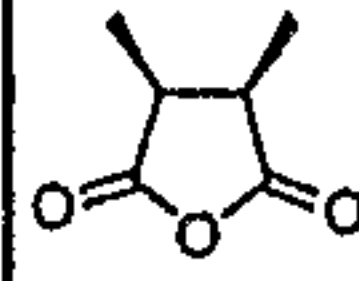
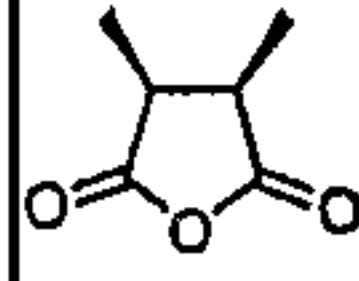
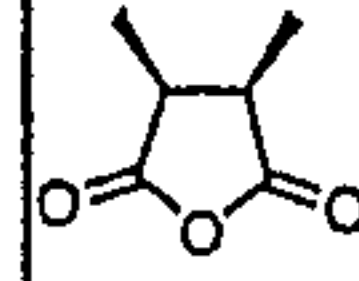
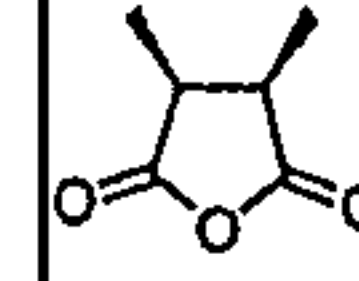
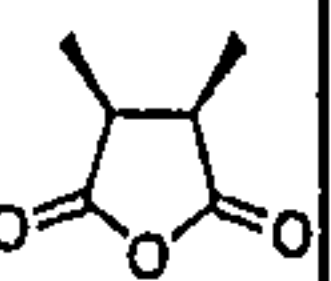
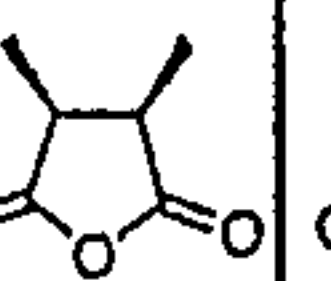
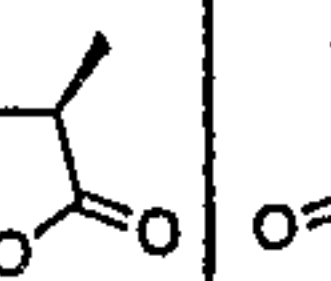
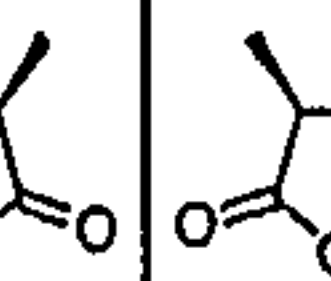
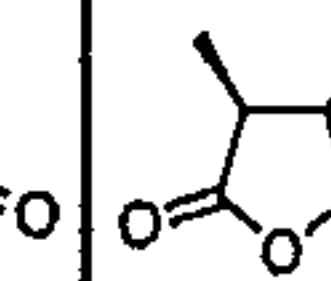
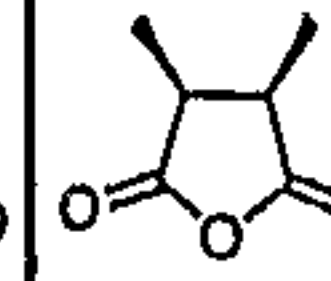
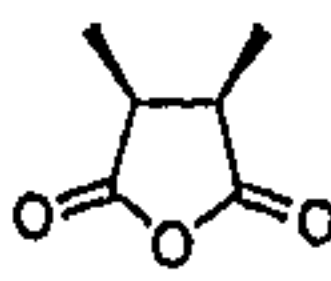
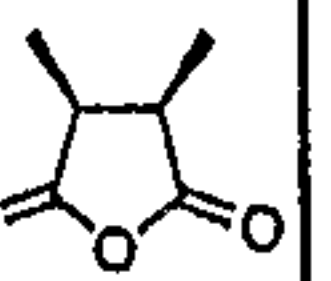
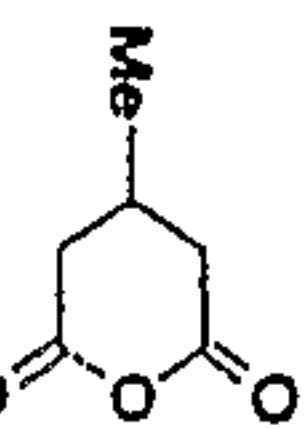
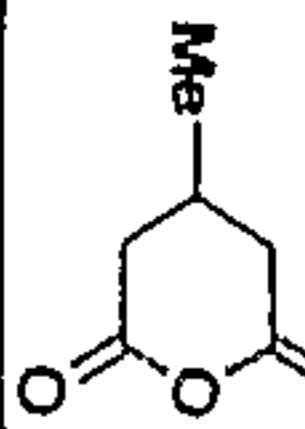
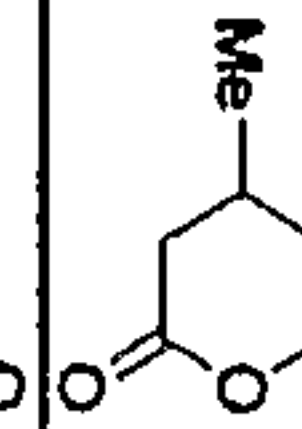
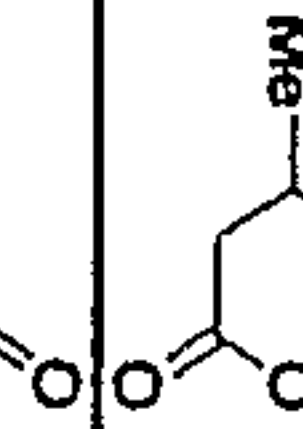
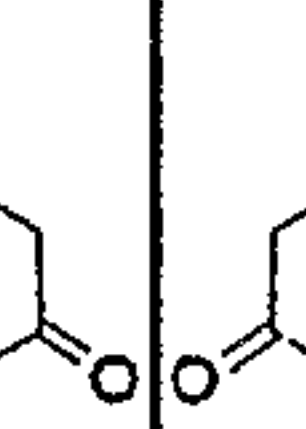
12		0.05	0.02M	QD-AN	20%	MeOH	10eq	Et ₂ O	RT	25h	90	86%
13		0.05	0.02M	QD-NT	20%	MeOH	10eq	Et ₂ O	RT	48h	94	78%
14		0.05	0.02M	QD-CN	20%	MeOH	10eq	Et ₂ O	RT	258h	96	81%
15		0.05	0.02M	Quinidine	20%	MeOH	10eq	Et ₂ O	RT	2.5h	94	70%
16		0.05	0.02M	Quinidine	110%	MeOH	10eq	Et ₂ O	RT	2.5h	100	74%
17		0.05	0.02M	QD-(+)-EF	20%	MeOH	10eq	Et ₂ O	RT	14.5h	99	88.5%
18		0.05	0.02M	QD-IB	20%	MeOH	10eq	Et ₂ O	RT	16h	96	87.5%
19		0.05	0.02M	QD-CH	20%	MeOH	10eq	Et ₂ O	RT	13h	97.7	88.5%

Figure 21

Table2. Comparison of Catalysts' efficiency for Trifluoroethanolysis of 2,3-dimethylsuccinic anhydride in Et ₂ O at 0.02M concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (Yield ^a)	ee %
1		0.1	0.02M	(DHQD) ₂ ACN	5%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	53h	100	87%
2		0.1	0.02M	QD-PP	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	53h	100	89%
3		0.1	0.02M	QD-TB	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	13h	100 (94)	92%
4		0.1	0.02M	QD-IP	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	25h	100 (98)	90%
5		0.1	0.02M	QD-PC	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	13h	100 (81)	91%
6		0.1	0.02M	QD-AD	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	24h	100	95%
7		0.1	0.02M	QD-(+)-MN	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	RT	26h	100 (99)	92%
8		0.1	0.02M	QD-(-)-MN	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	19	21h	100 (76)	94%

a. The Purity of Crude Product was larger than 98% (NMR)

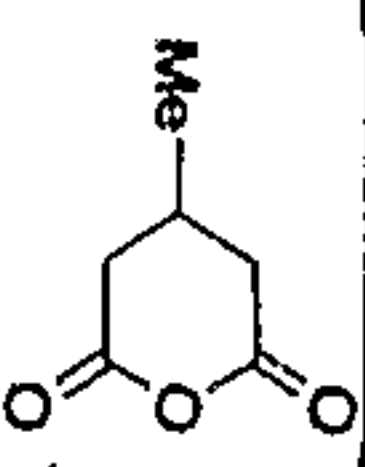
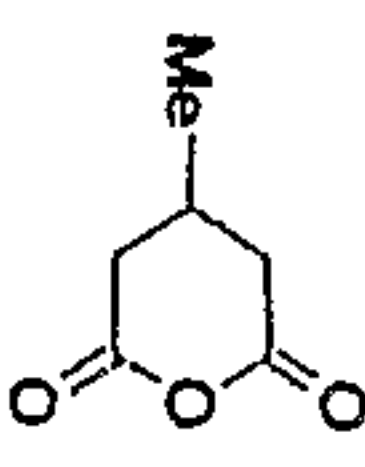
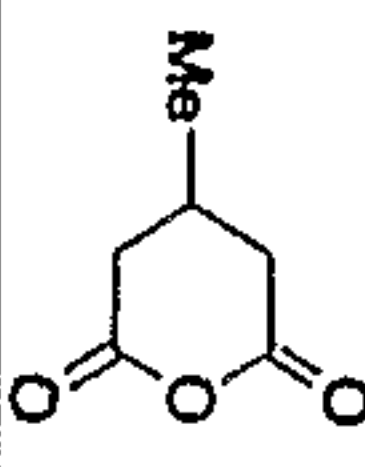
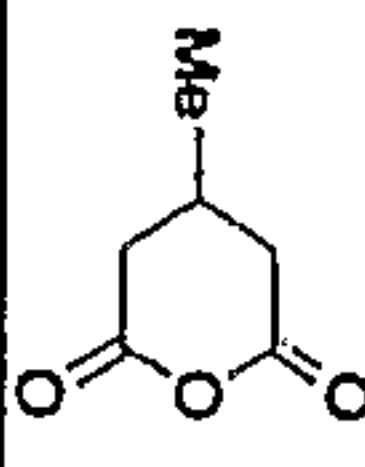
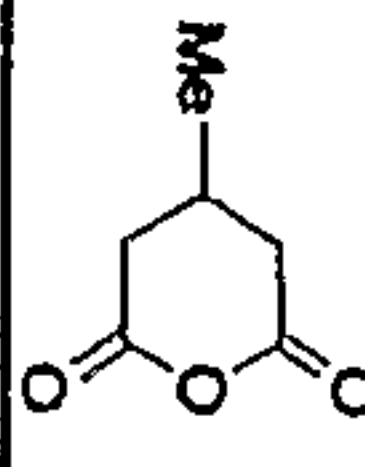
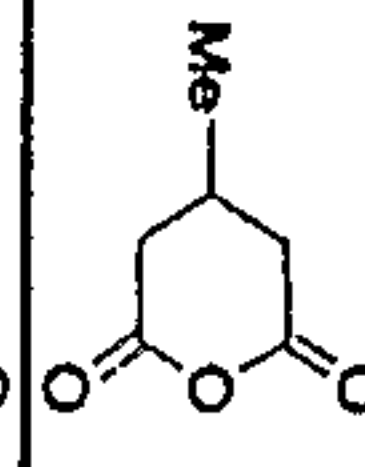
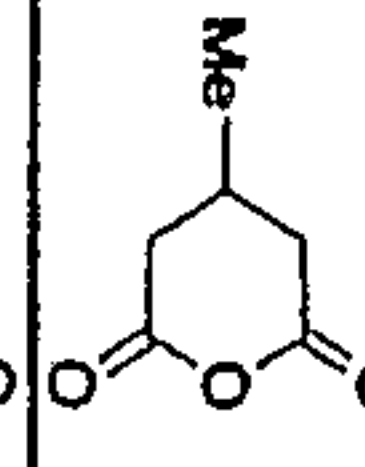
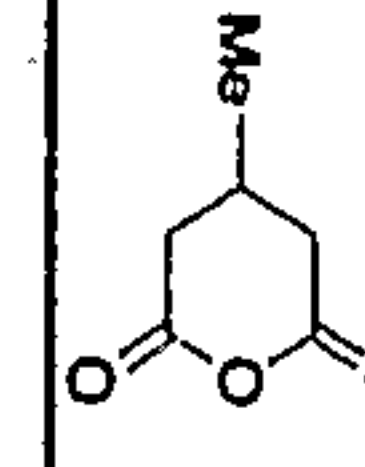
Figure 22

Table3. Reaction Conditions Optimization for Methanolysis of 3-Methylglutaric Anhydride in Et ₂ O at 0.02M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.02M	QD-AD	50%	MeOH	10eq	Et ₂ O	-27	96h	98.6% (94% ^a)	82%
2		0.1	0.02M	QD-AD	100%	MeOH	10eq	Et ₂ O	-27	50h	99% (91% ^a)	82%
3		0.1	0.02M	QD-AD	50%	MeOH	10eq	Et ₂ O	-40	79h	63.5% (46% ^b)	88%
4		0.1	0.02M	QD-AD	100%	MeOH	10eq	Et ₂ O	-40	96h	89.1%	89%
5		0.1	0.02M	QD-PP	100%	MeOH	10eq	Et ₂ O	-40	84.5h	41%	84%
6		0.1	0.02M	Quinidine	110%	MeOH	10eq	Et ₂ O	-40	84.5h	26% (25% ^b)	34%

- a. The Purity of Crude Product was larger than 98% (by NMR)
b. Isolated yield with purity larger than 98% (by NMR)

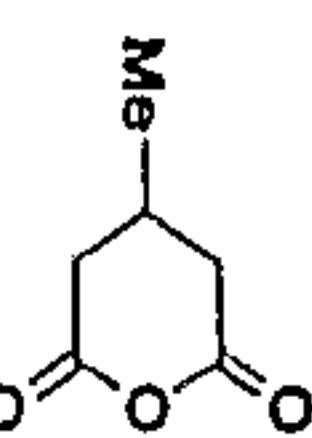
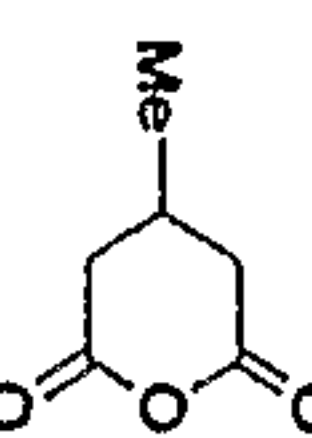
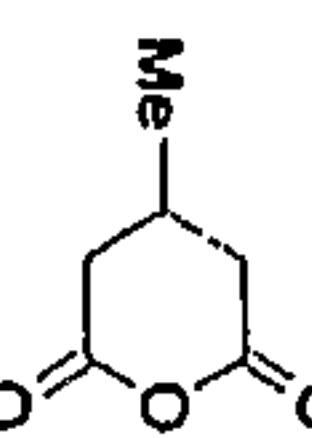
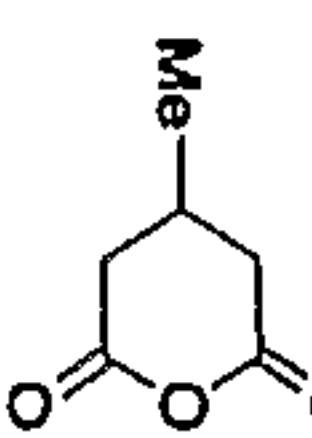
Figure 23

Table 4. Screening of Reaction Conditions for Alcoholysis of 3-methyl-glutaric anhydride at 0.2M concentration

Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-43	37.5h	99% (95% ^a)	70%
2		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	1.5eq	Et ₂ O	-43	72h	93%	88%
3		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	10eq	Toluene	-43	19h	99% (87% ^a)	16%
4		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	36.5h	97%	87%
5		0.1	0.2M	QD-AD	110%	MeOH	1.5eq	Et ₂ O	-53	141h	86% (58% ^b)	90%
6		0.1	0.2M	QD-AD	110%	MeOH	1.5eq	Toluene	-53	86h	98.4% (93% ^a)	87%
7		0.1	0.2M	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Et ₂ O	-53	94h	87.6% (70% ^b)	90%
8		0.1	0.2M	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-53	49.5h	98.5% (91% ^a)	88%

- a. The Purity of Crude Product was larger than 98% (by NMR)
b. Isolated yield with purity larger than 98% (by NMR)

Figure 24

Table5. Comparison of Catalysts' Efficiency for Methanolysis of 3-Methyl Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (%Yield)	ee %
1		0.1	0.2	QD-AD	110%	MeOH	1.5eq	Toluene	-43	40h	90%	86%
2		0.1	0.2	QD-(-)-MN	110%	MeOH	1.5eq	Toluene	-43	42h	91.5%	85%
3		0.1	0.2	QD-PP	110%	MeOH	1.5eq	Toluene	-43	77.5h	92% (69% ^a)	77%
4		0.1	0.2	(DHQD) ₂ AQN	55%	MeOH	1.5eq	Toluene	-43	17h	96.2%	88%

a. Isolated yield with purity larger than 98% (by NMR)

Figure 25

- a. The Purity of Crude Product was larger than 98% (by NMR)
b. Isolated yield with purity larger than 98% (by NMR)

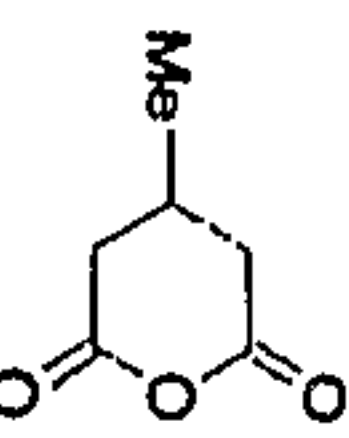
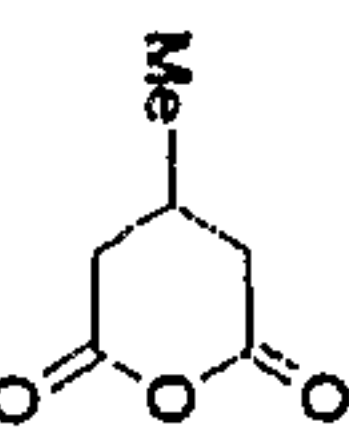
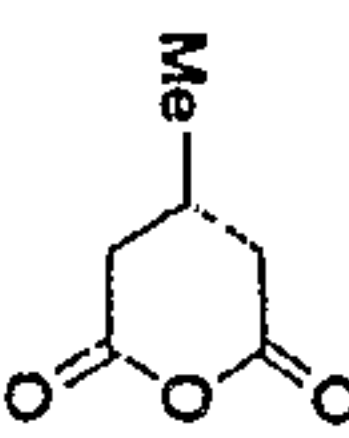
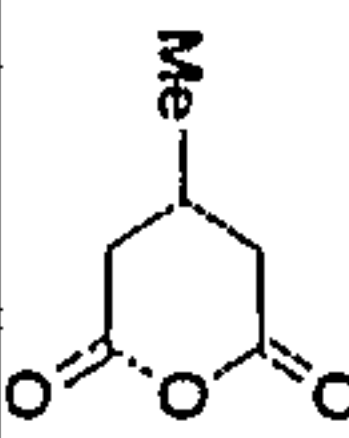
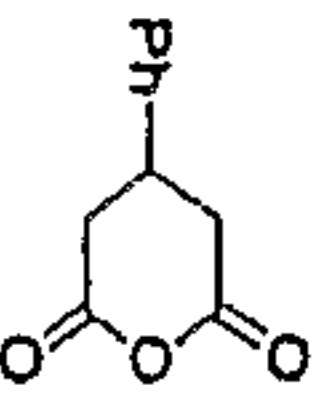
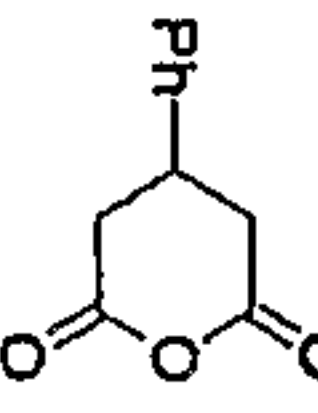
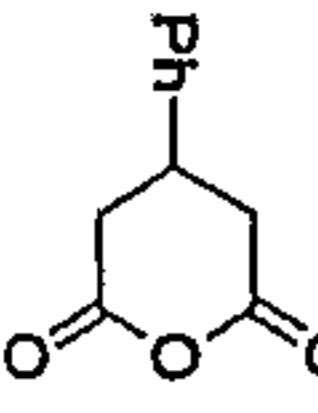
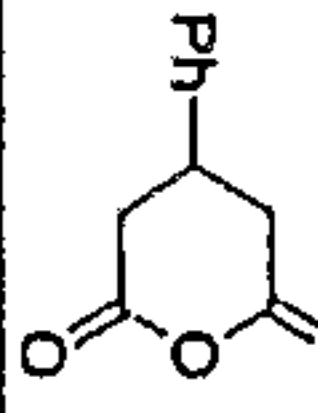
Table6. Comparison of Catalysts' Efficiency for Trifluoroethanolysis of 3-Methyl Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	23.5h	98.2%(88% ^a)	86%
2		0.1	0.2	QD-(-)-MN	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	23.5h	94.7%	88%
3		0.1	0.2	QD-PP	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	70.5h	93% (65% ^b)	77%
4		0.1	0.2	(DHQD) ₂ AQN	55%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	44h	97.5%	74%

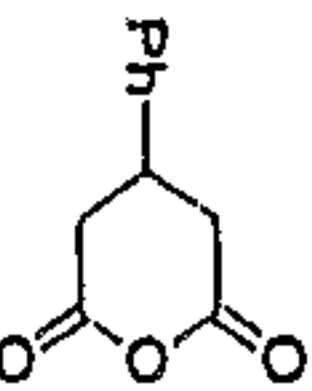
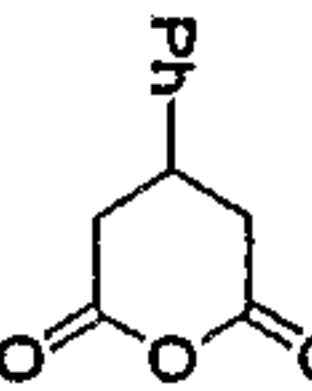
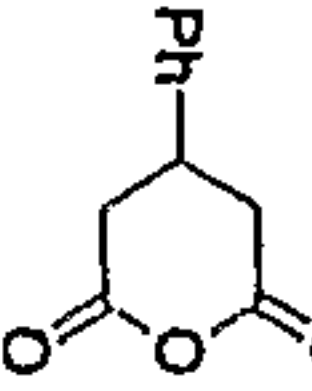
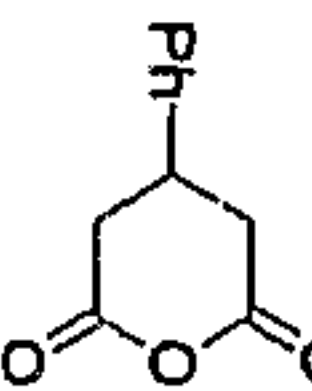
Table 7. Comparison of Catalysts' Efficiency for Methanolysis of 3-Phenyl Glutaric Anhydride in Toluene at 0.2M Concentration

Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	MeOH	1.5eq	Toluene	-43	24.5h	98.7% (92% ^a)	86%
2		0.1	0.2	QD-(+)-MN	110%	MeOH	1.5eq	Toluene	-43	29h	100%(100% ^a)	84%
3		0.1	0.2	QD-PP	110%	MeOH	1.5eq	Toluene	-43	52h	91.5% (73% ^b)	79%
4		0.1	0.2	(DHQD) ₂ AQN	55%	MeOH	1.5eq	Toluene	-43	18h	100% (98% ^a)	90%

a. The Purity of Crude Product was larger than 98% (by NMR)

b. Isolated yield with purity larger than 98% (by NMR)

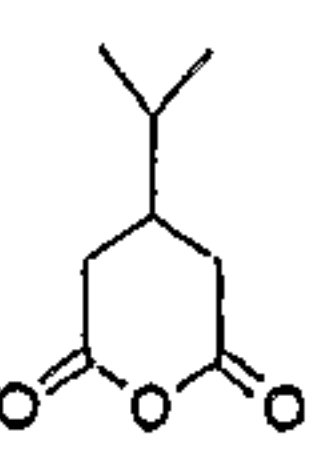
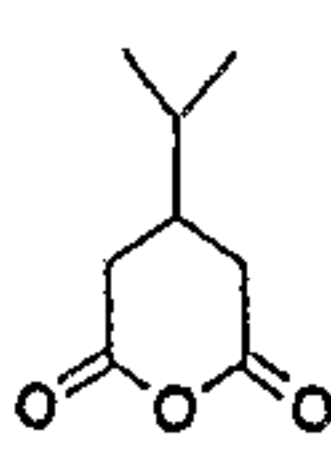
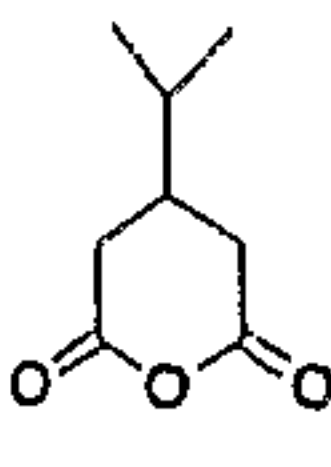
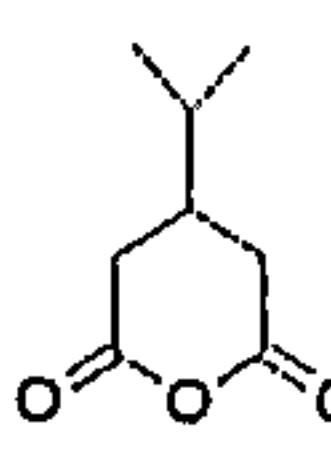
Figure 26

Table 8. Comparison of Catalysts' Efficiency for Trifluoroethanolysis of 3-Phenyl Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	35.5h	100% (91% ^a)	91%
2		0.1	0.2	QD-(-)-MN	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	23.5h	97.7%	90%
3		0.1	0.2	QD-PP	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	71.5h	97%	81%
4		0.1	0.2	(DHQD) ₂ AQN	55%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	44.5h	100% (84% ^a)	81%

a. The Purity of Crude Product was larger than 98% (by NMR)

Figure 27

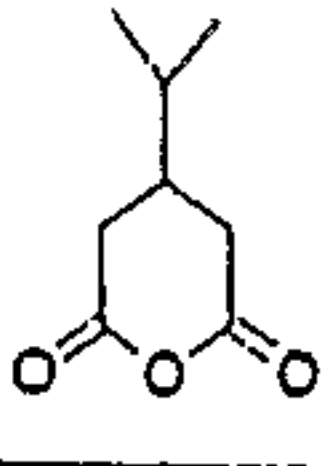
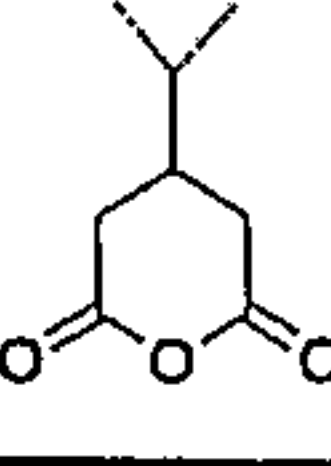
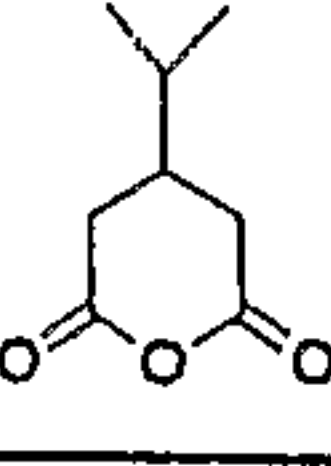
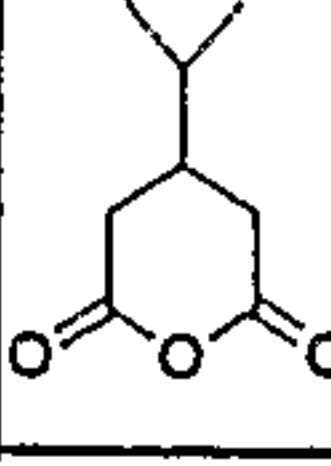
Table 9 Comparison of Catalysts' Efficiency for Methanolysis of 3-Isopropyl Glutaric Anhydride in Toluene at 0.2M Concentration

Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	MeOH	1.5eq	Toluene	-43	36.5h	96%	87%
2		0.1	0.2	QD-(-)-MN	110%	MeOH	1.5eq	Toluene	-43	42h	97%	86%
3		0.1	0.2	QD-PP	110%	MeOH	1.5eq	Toluene	-43	91h	90.3%	80%
4		0.1	0.2	(DHQD) ₂ AQN	55%	MeOH	1.5eq	Toluene	-43	36.5h	99% (86% ^a)	88%

a. The Purity of Crude Product was larger than 98% (by NMR)

Figure 28

Figure 29

Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	52h	98.2% (87% ^a)	89%
2		0.1	0.2	QD-(-)-MN	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	61h	96.4%	87%
3		0.1	0.2	QD-PP	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	91h	90.9%	55%
4		0.1	0.2	(DHQD) ₂ AQN	55%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	51h	96.7%	78%

a. The Purity of Crude Product was larger than 98% (by NMR)

Figure 30

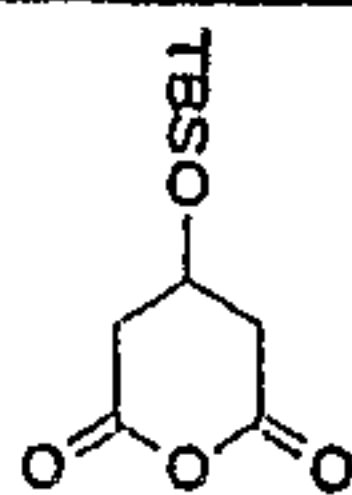
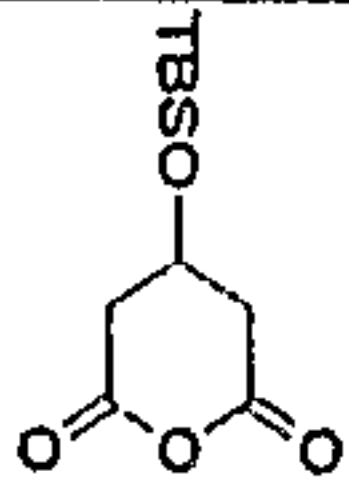
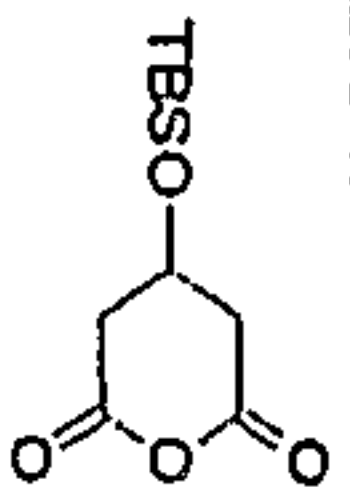
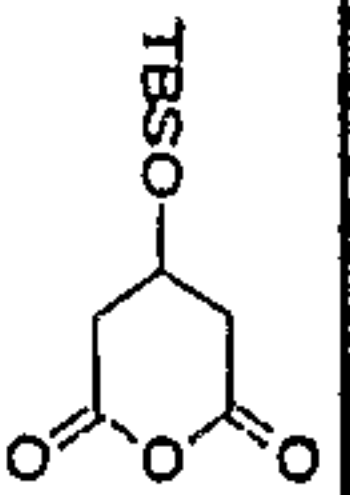
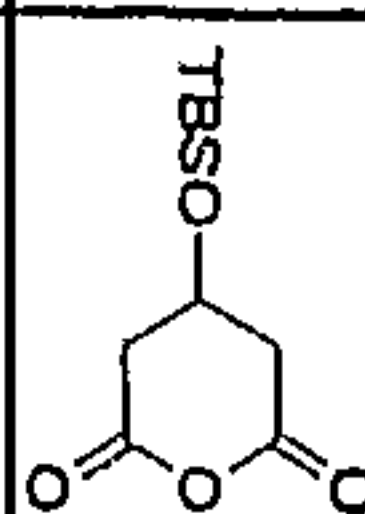
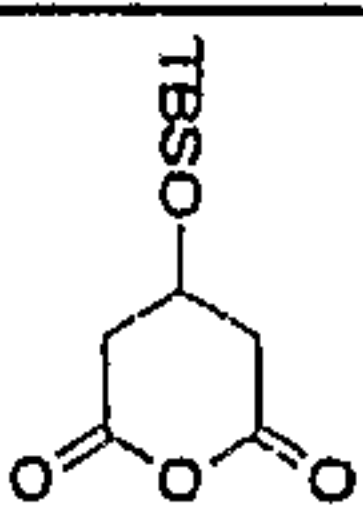
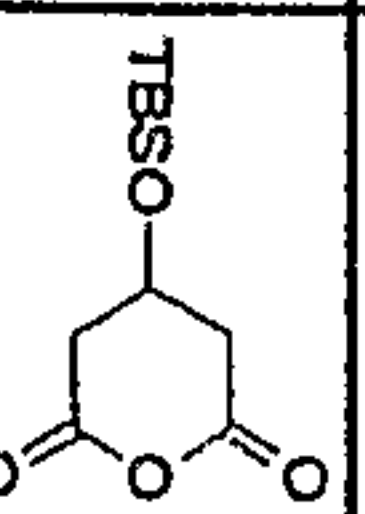
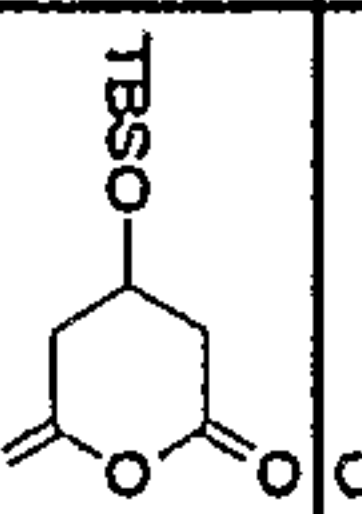
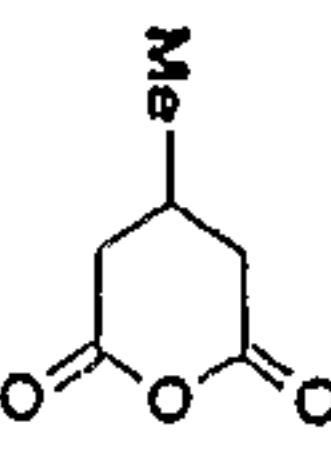
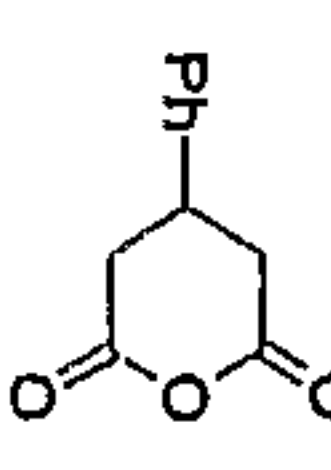
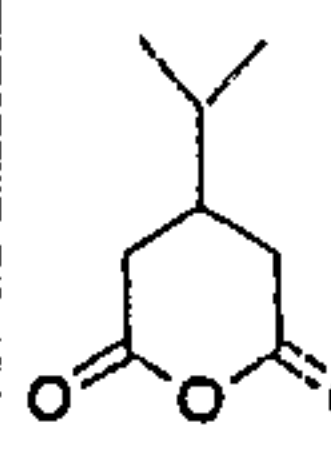
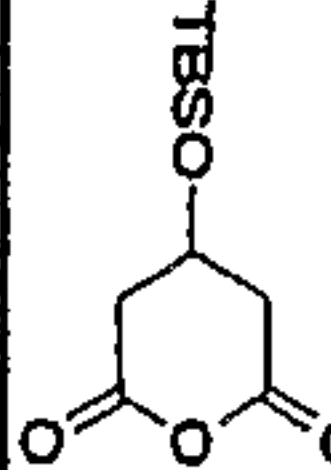
Table11 Comparison of Catalysts' Efficiency for Methanolysis of 3-TBSO Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	QD-AD	110%	MeOH	1.5eq	Toluene	-43	56h	95.7%	92%
2		0.1	0.2	QD-(-)-MN	110%	MeOH	1.5eq	Toluene	-43	42h	94%	92%
3		0.1	0.2	QD-PP	110%	MeOH	1.5eq	Toluene	-43	105h	91.5%	78%
4		0.1	0.2	(DHQD) ₂ AQN	55%	MeOH	1.5eq	Toluene	-43	33.5h	97.2%	95%

Figure 31

Table12. Comparison of Catalysts' Efficiency for Trifluoroethanolysis of 3-TBSO Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (Yield)	ee %
1		0.1	0.2	QD-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	71h	97.8%	85%
2		0.1	0.2	QD-(-)-MN	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	91h	97.1%	89%
3		0.1	0.2	QD-PP	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	105h	87% (68% ^a)	48%
4		0.1	0.2	(DHQD) ₂ AQN	55%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	81h	94.2%	79%

a. Isolated yield with purity larger than 98% (by NMR)

Table 13 Q-AD Catalyzed Methanolysis of 3-Substitutedglutaric Anhydride in Toluene at 0.2M Concentration

Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2	Q-AD	110%	MeOH	1.5eq	Toluene	-43	88h	80.4% (64% ^a)	69%
2		0.1	0.2	Q-AD	110%	MeOH	1.5eq	Toluene	-43	78h	97%	68%
3		0.1	0.2	Q-AD	110%	MeOH	1.5eq	Toluene	-43	68h	86%	78%
4		0.1	0.2	Q-AD	110%	MeOH	1.5eq	Toluene	-43	105h	87%	75%

a. Isolated yield with purity larger than 98% (NMR)

Figure 32

Figure 33

a. The Purity of Crude Product was larger than 98% (by NMR)

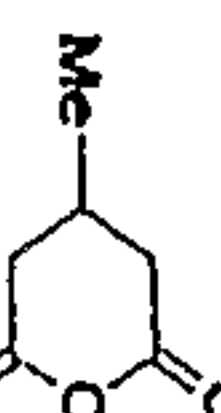
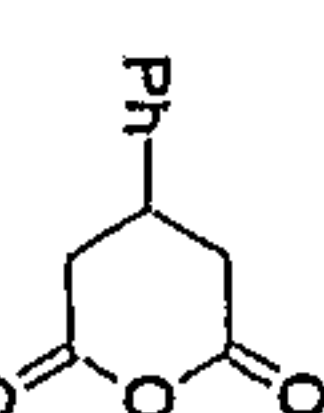
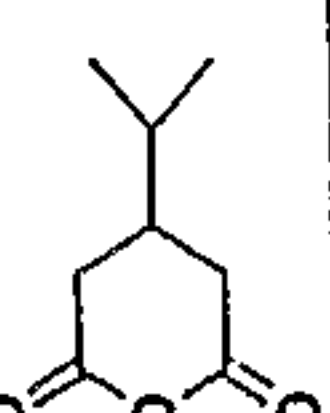
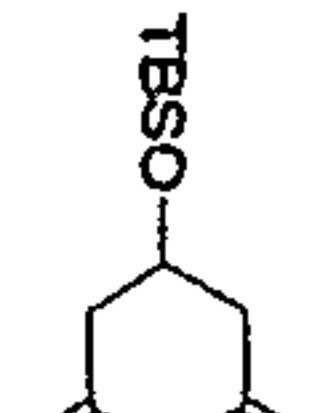
Table 14 Q-AD Catalyzed Trifluoroethanolysis of 3-Substitutedglutaric anhydride in Toluene at 0.2M concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (Yield)	ee %
1		0.1	0.2	Q-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	88h	96%	76%
2		0.1	0.2	Q-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	78h	98.1% (96% ^a)	80%
3		0.1	0.2	Q-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	68h	89%	80%
4		0.1	0.2	Q-AD	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	105h	88%	69%

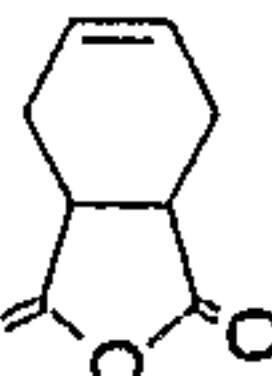
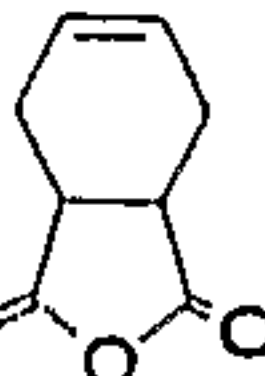
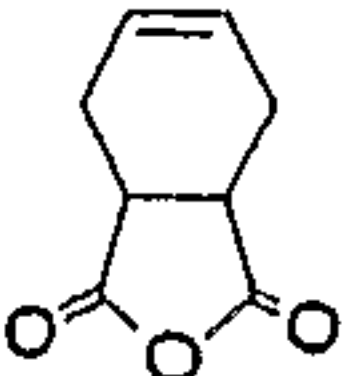
Table 15. Comparison of Catalysts' Efficiency for the Alcoholysis of <i>cis</i> -1, 2, 3, 6-Tetrahydrophthalic Anhydride with Methanol in Et ₂ O at 0.02M concentration.												
Entry	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
#												
1		0.1	0.02M	QD-AD	20%	MeOH	10eq	Et ₂ O	r.t.	2 h	100%	92%
2		0.1	0.02M	QD-AD	20%	MeOH	10eq	Et ₂ O	-25	48 h	100%	96%
3		0.1	0.02M	(DHQD)2AQN	7%	MeOH	10eq	Et ₂ O	-20	60 h	100	98%

Figure 34

Figure 35

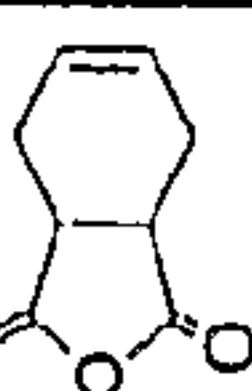
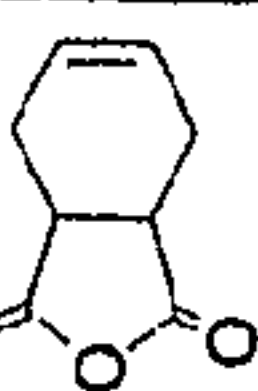
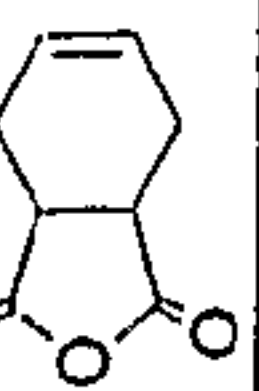
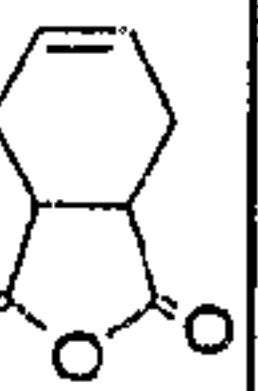
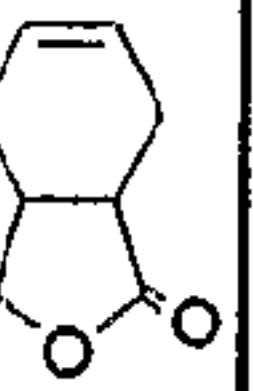
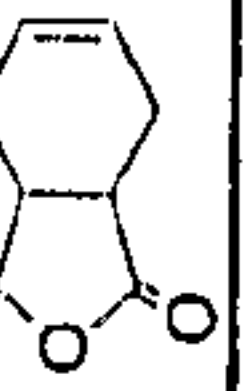
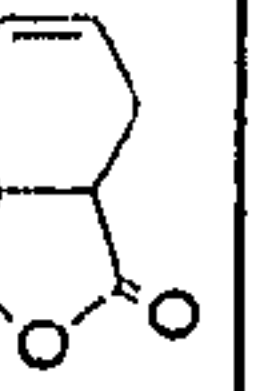
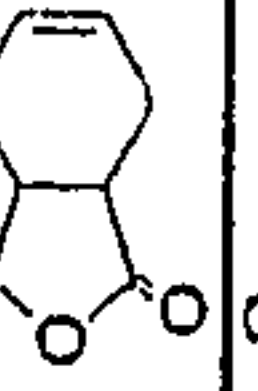
Table 16. Comparison of Catalysts' Efficiency for the Alcoholysis of <i>cis</i> -1, 2, 3, 6-Tetrahydrophthalic Anhydride with Trifluoroethanol in Et ₂ O at 0.02M concentration.												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.02M	QD-AD	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	4 h	100%	94%
2		0.1	0.02M	QD-AD	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	18 h	100%	98%
3		0.1	0.02M	(DHQD) ₂ AQN	10%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	2 h	100%	94%
4		0.1	0.02M	(DHQD) ₂ AQN	10%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	48 h	100%	96%
5		0.1	0.02M	QD-PP	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	2 h	100%	90%
6		0.1	0.02M	QD-PP	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	48 h	100%	94%
7		0.1	0.02M	QD-MN	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-27	24 h	100	96%
8		0.1	0.02M	QD-PP	100%	CF ₃ CH ₂ OH	10eq	Et ₂ O	-27	12 h	100	87%

Figure 36

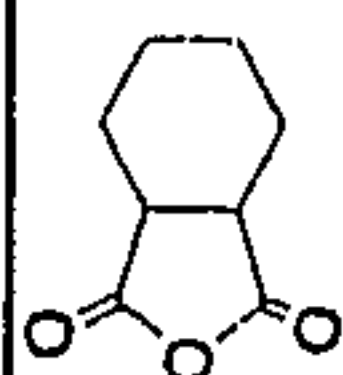
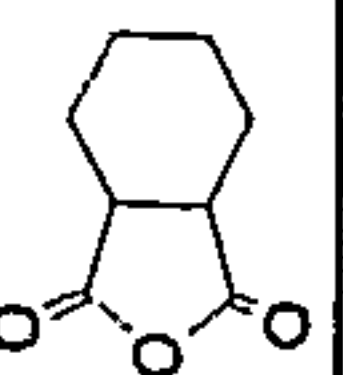
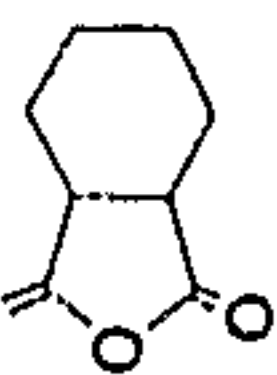
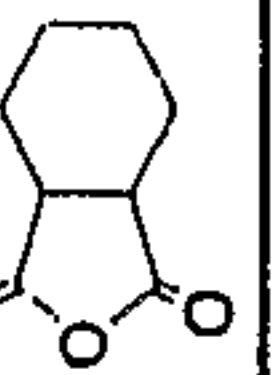
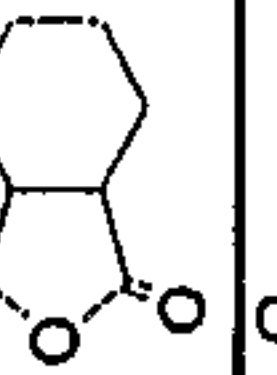
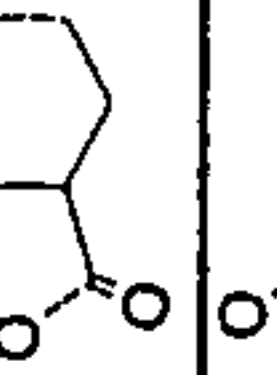
Table 17. QD-AD-Catalyzed Alcoholysis of 1,2-Cyclohexanedicarboxylic Anhydride with Methanol in Et ₂ O at 0.02M concentration.												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.02M	QD-AD	20%	MeOH	10eq	Et ₂ O	r.t.	4h	100	91%
2		0.1	0.02M	QD-AD	50%	MeOH	10eq	Et ₂ O	r.t.	4h	100	91%
3		0.1	0.02M	QD-AD	100%	MeOH	10eq	Et ₂ O	r.t.	4h	100	91%
4		0.1	0.02M	QD-AD	20%	MeOH	10eq	Et ₂ O	-25	37h	100	92%
5		0.1	0.02M	QD-AD	50%	MeOH	10eq	Et ₂ O	-25	37h	100	94%
6		0.1	0.02M	QD-AD	100%	MeOH	10eq	Et ₂ O	-25	37h	100	91%

Figure 37

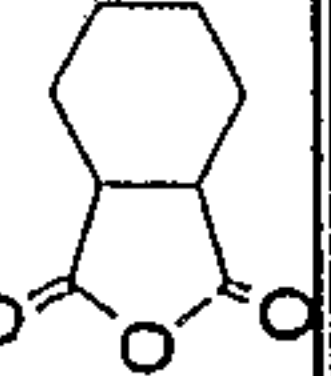
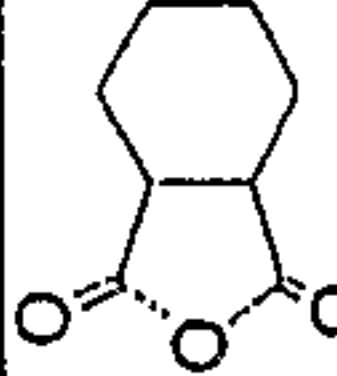
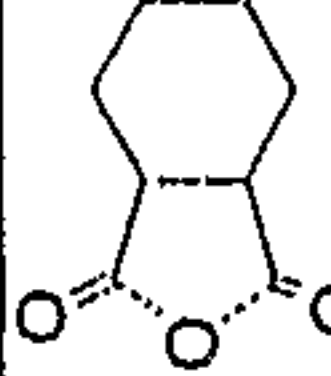
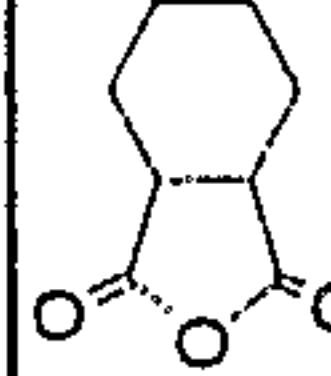
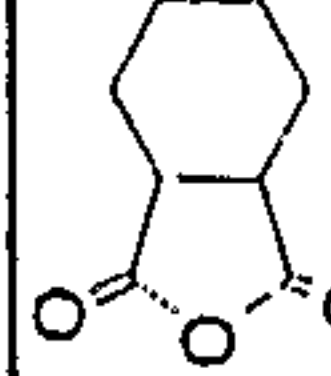
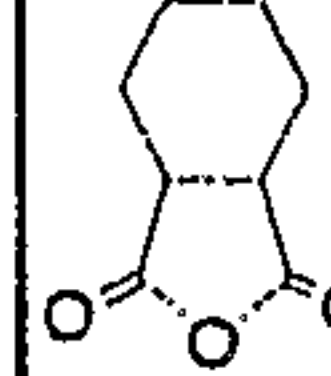
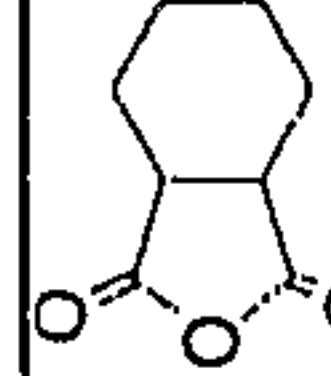
Table 18. Comparison of Catalysts' Efficiency for the Alcoholysis of 1,2-Cyclohexanedicarboxylic Anhydride with Trifluoroethanol in Et ₂ O at 0.02M concentration.												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.02M	QD-AD	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	2h	100	94%
2		0.1	0.02M	QD-PP	20%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	5h	100	89%
3		0.1	0.02M	(DHQD) ₂ AQN	10%	CF ₃ CH ₂ OH	10eq	Et ₂ O	r.t.	2h	100	90%
4		0.1	0.02M	QD-AD	20	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	16h	100	96%
5		0.1	0.02M	QD-PP	20	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	16h	100	91%
6		0.1	0.02M	(DHQD) ₂ AQN	10	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	16h	100	90%
7		0.1	0.02M	QD-MN	20	CF ₃ CH ₂ OH	10eq	Et ₂ O	-25	24h	100	95%

Figure 38

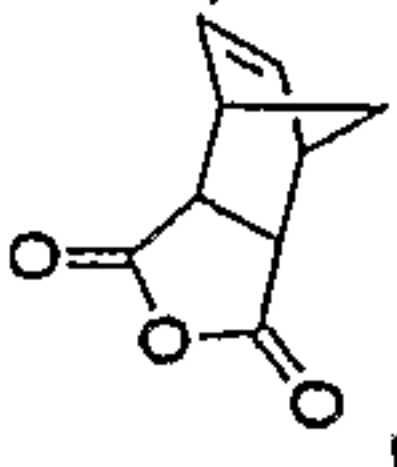
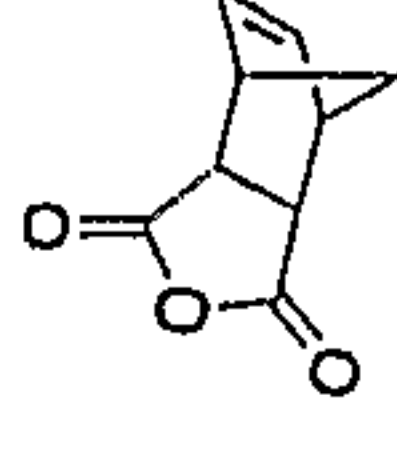
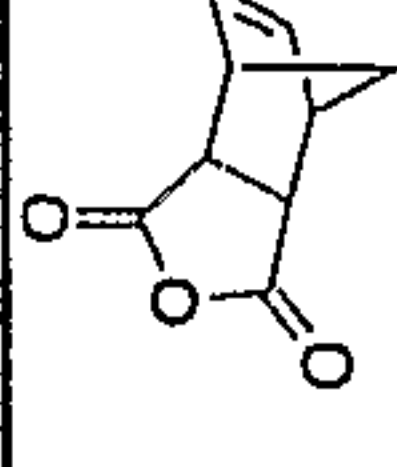
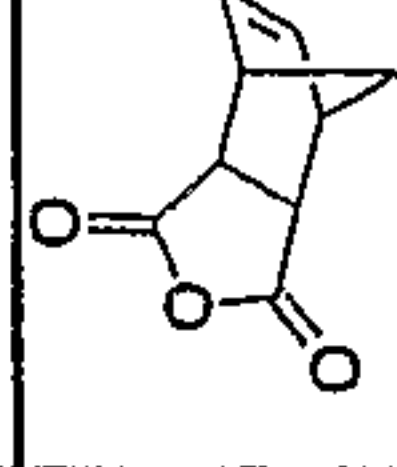
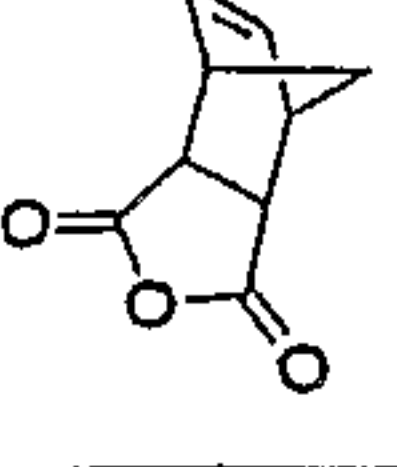
Table 19. Comparison of Catalysts' efficiency for the alcoholysis of <i>cis</i> -5-norbornene- <i>endo</i> -2,3-dicarboxylic anhydride in Et ₂ O at 0.02M Concentration.												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.02M	QD-AD	30	MeOH	10eq	Et ₂ O	-27	3d	100(98)	96%
2		0.1	0.02M	QD-MN	30	MeOH	10eq	Et ₂ O	-27	7d	100(96)	97%
3		0.1	0.02M	(DHQD) ₂ AQN	15	MeOH	10eq	Et ₂ O	-27	3d	100(97)	95%
4		0.1	0.02M	QD-PP	30	MeOH	10eq	Et ₂ O	-27	3d	100(81)	79%
5		0.1	0.02M	QD-PP	100	MeOH	10eq	Et ₂ O	-27	4.5d	100(96)	84%

Figure 39

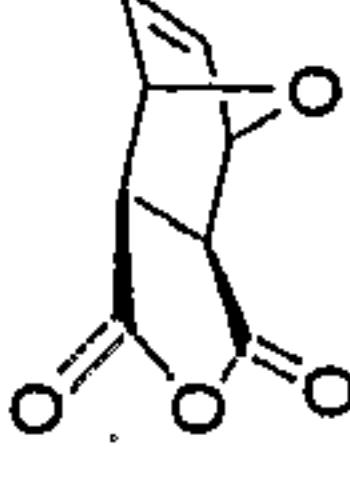
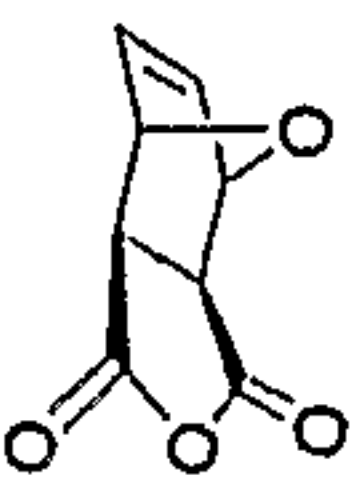
Table 20. Comparison of Catalysts' Efficiency for the Alcoholysis of exo-3,6-epoxy-1,2,3,6-tetrahydrophthalic Anhydride in Et ₂ O at 0.02M.												
Entry #	Substrate	Substrate Loading	Substrate Concentration	Catalyst		Alcohol	Alcohol Loading	Solvent	Temp. (°C)	Reaction Time	Conversion % (%Yield)	ee %
					(mol%)							
1		0.1	0.02M	QD-AD	40%	MeOH	10eq	Et ₂ O	-27	36 h	100(97)	98%
2		0.1	0.02M	QD-MN	40%	MeOH	10eq	Et ₂ O	-27	3 d	100(77)	97%
3		0.1	0.02M	QD-PP	30%	MeOH	10eq	Et ₂ O	-27	3 d	100(78)	85%
4		0.1	0.02M	QD-PP	100%	MeOH	10eq	Et ₂ O	-27	36 h	100(85)	84%
5		0.1	0.02M	(DHQD)2AQN	20%	MeOH	10eq	Et ₂ O	-20	4d	100(74)	92%

Figure 40

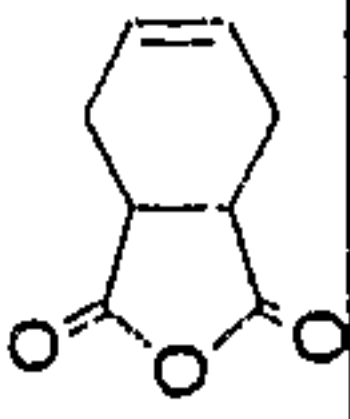
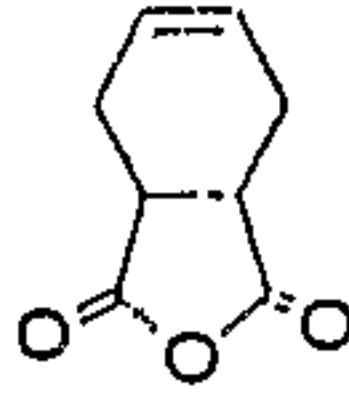
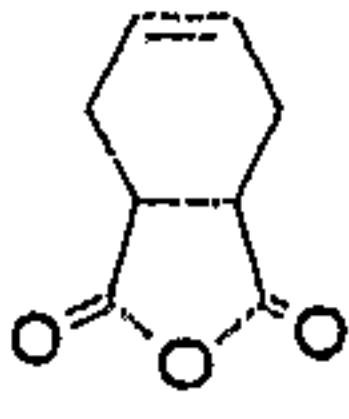
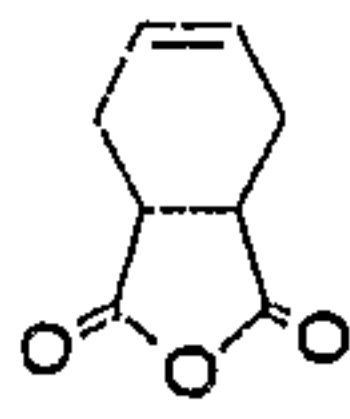
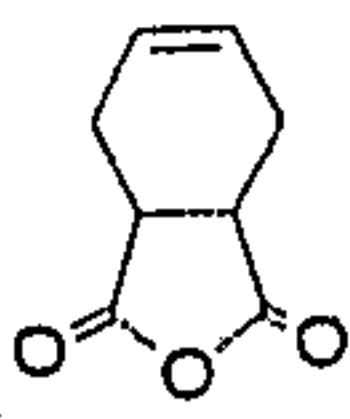
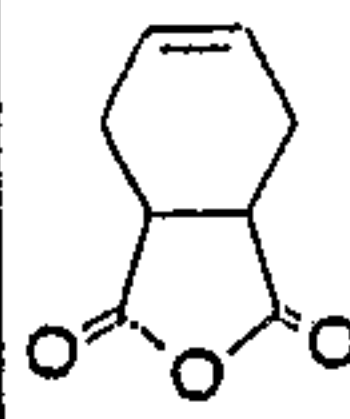
Table 21. Reaction Conditions Optimization for the Alcoholysis of <i>cis</i> -1,2,3,6-Tetrahydrophthalic Anhydride in Et ₂ O at 0.2M												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2M	QD-AD	20%	CF ₃ CH ₂ OH	10	Et ₂ O	-25	12 h	100	92%
2		0.1	0.2M	QD-MN	20%	CF ₃ CH ₂ OH	10	Et ₂ O	-25	12 h	100	92%
3		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	10	Et ₂ O	-25	4 h	100	98%
4		0.1	0.2M	QD-MN	100%	CF ₃ CH ₂ OH	10	Et ₂ O	-25	4 h	100	98%
5		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	1.5	Et ₂ O	-25	3 d	100	98%
6		0.1	0.2M	QD-MN	100%	CF ₃ CH ₂ OH	1.5	Et ₂ O	-25	3 d	100	99%

Figure 41

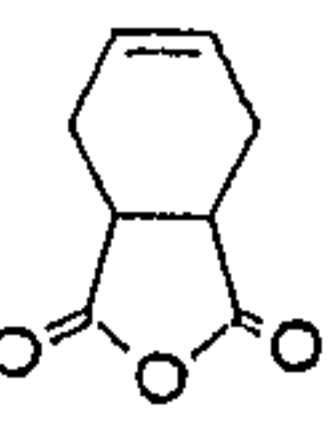
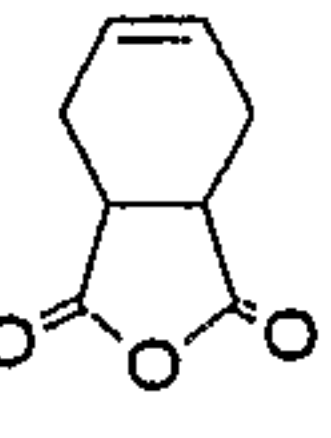
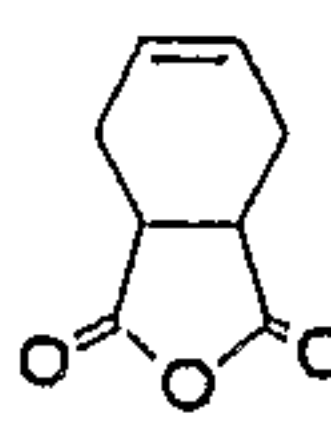
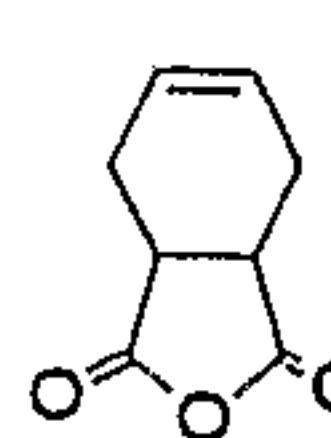
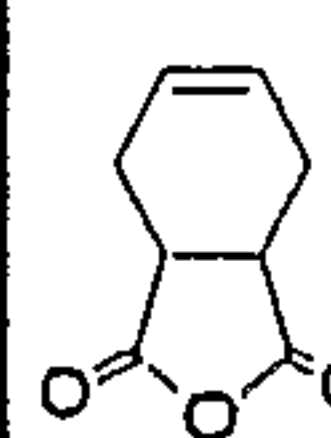
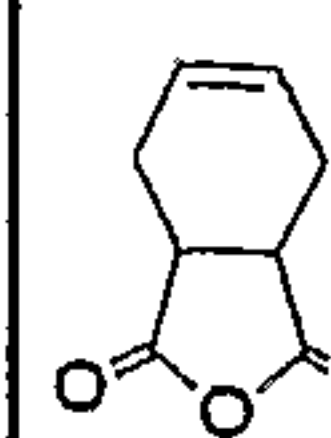
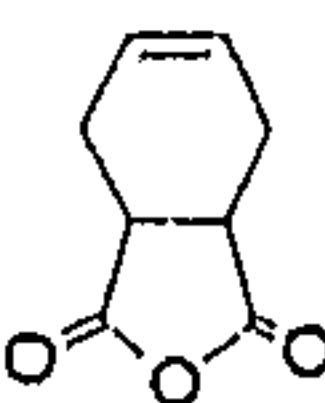
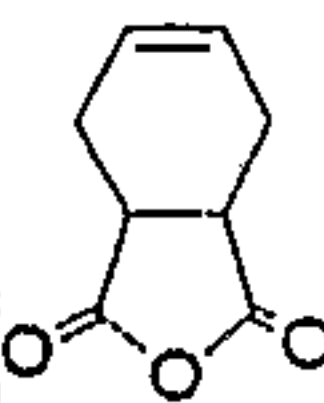
Table 22. Reaction Conditions Optimization for the Alcoholysis of <i>cis</i> -1,2,3,6-Tetrahydrophthalic Anhydride in Toluene at 0.2M												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
1		0.1	0.2M	QD-AD	20%	CF ₃ CH ₂ OH	10	toluene	-25	12 h	100	51%
2		0.1	0.2M	QD-MN	20%	CF ₃ CH ₂ OH	10	toluene	-25	12 h	100	48%
3		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	10	toluene	-25	4 h	100	80%
4		0.1	0.2M	QD-MN	100%	CF ₃ CH ₂ OH	10	toluene	-25	4 h	100	76%
5		0.1	0.2M	QD-AD	100%	CF ₃ CH ₂ OH	1.5	toluene	-25	3 d	100(99)	>99%
6		0.1	0.2M	QD-MN	100%	CF ₃ CH ₂ OH	1.5	toluene	-25	3 d	100(99)	99%

Table 23. Reaction Conditions Optimization for the Alcoholysis of cis-1,2,3,6-Tetrahydrophthalic Anhydride in Toluene at 0.5M												
Entry	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
#												
1		0.1	0.5M	QD-AD	100%	CF ₃ CH ₂ OH	1.5	toluene	-25	7 d	94	NA
2 ^a		0.1	0.5M	QD-MN	110%	CF ₃ CH ₂ OH	1.5	toluene	-25	3 d	100	>99%

^aWith 4Å molecular sieves.

^aWith 4Å molecular sieves.

Figure 42

Table 24. Alcoholysis of Succinic Anhydrides with Q-AD

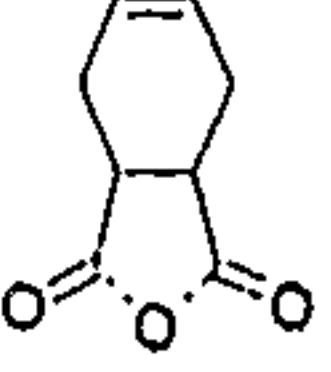
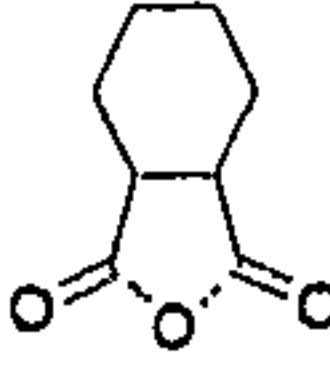
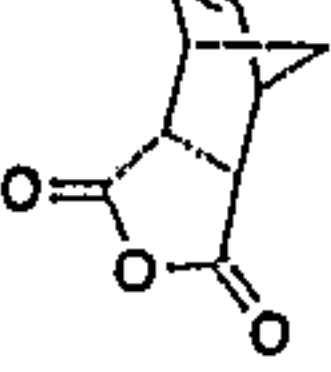
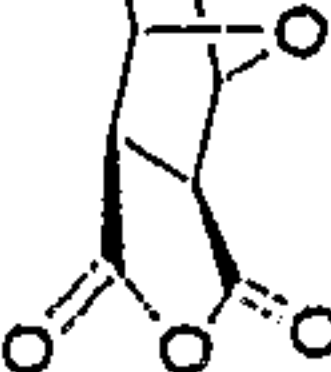
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (Yield)	ee %
1		0.1 mmol	0.02 M	Q-AD	20%	CF ₃ CH ₂ OH	10 equiv	Ether	-27	48 h	100(91%)	94%
2		0.1 mmol	0.02M	Q-AD	20%	CF ₃ CH ₂ OH	10 equiv	Ether	-27	48 h	100(99)	90%
3		0.1 mmol	0.02M	Q-AD	30%	CH ₃ OH	10 equiv	Ether	-27	5 days	100(92)	76%
4		0.1 mmol	0.02 M	Q-AD	30%	CH ₃ OH	10 equiv	Ether	-27	3 days	100(70)	82%

Figure 43

Figure 44

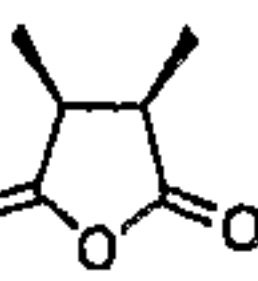
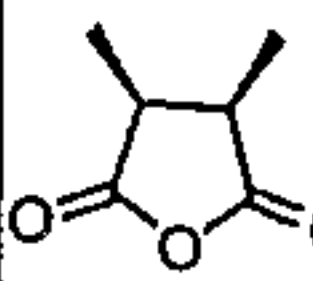
Table 25. Comparison of Catalysts' efficiency for methanolysis of 2,3-dimethylsuccinic anhydride in Et ₂ O at 0.02M concentration												
Entry #	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion % (Yield)	ee %
1		0.05	0.02M	QD-AA	20%	MeOH	10eq	Et ₂ O	RT	23.5h	97.4	79.0%
2		0.05	0.02M	QD-MP	20%	MeOH	10eq	Et ₂ O	RT	19.5h	98.6	87.0%

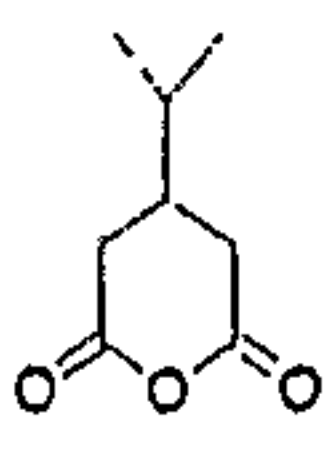
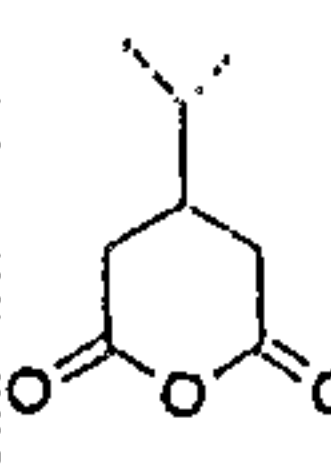
Table 26. Comparison of Catalysts' Efficiency for Trifluoroethanolysis of 3-Isopropyl Glutaric Anhydride in Toluene at 0.2M Concentration												
Entry	Substrate	Substrate Loading (mmol)	Substrate Concentration	Catalyst	Catalyst Loading (mol%)	Alcohol	Alcohol Loading (eq.)	Solvent	Temp. (°C)	Reaction Time	Conversion %	ee %
#												
1		0.13	0.2	QD-CH	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	107h	97.2%	76%
2		0.113	0.2	QD-MP	110%	CF ₃ CH ₂ OH	1.5eq	Toluene	-43	22h	70.9%	79%

Figure 45