

## SYNTHESIS OF CYCLIC CARBONATES IN THE PRESENCE OF DIMERIC ALUMINIUM (SALEN) CATALYSTS

The present invention relates to a process for synthesising cyclic carbonates from epoxides and carbon dioxide using aluminium(salen) complexes as catalysts. The invention also provides a method for manufacturing aluminium(salen) complexes and further provides novel aluminium(salen) complexes.

Cyclic carbonates are commercially important products currently manufactured on a multi-tonne scale for use as polar aprotic solvents, additives, antifoam agents for anti-freeze, plasticisers, and monomers for polymer synthesis (see Darensbourg, *et al.*, *Coord. Chem. Rev.*, **153** (1996), 155-174; Coates, *et al.*, *Angew. Chem. Int. Ed.*, **43** (2004), 6618-6639).

The synthesis of cyclic carbonates generally involves the reaction of epoxides with carbon dioxide, and hence could be used to sequestrate carbon dioxide, thus reducing the level of greenhouse gases in the atmosphere.

Catalysts for the synthesis of cyclic carbonates from epoxides and carbon dioxide are known in the art (see Darensbourg, *et al.*, *Coord. Chem. Rev.*, **153** (1996), 155-174; Yoshida, *et al.*, *Chem. Eur. J.*, **10** (2004), 2886-2893; Sun, *et al.*, *J. Organomet. Chem.*, **690** (2005), 3490-3497) although these require elevated reaction temperatures and / or high pressures of carbon dioxide, the reaction often being conducted in supercritical carbon dioxide (see Lu, *et al.*, *App. Cat. A*, **234** (2002), 25-33).

Ratzenhofer, *et al.*, (*Angew. Chemie Int. Ed. Engl.*, **19** (1980), 317-318) succeeded in carrying out the reaction between 2-methyloxirane and carbon dioxide at room temperature and atmospheric pressure using catalysts consisting of a mixture of a metal halide and a Lewis base. However, a long reaction time of 7 days was required. Kisch, *et al.*, (*Chem. Ber.*, **119** (1986), 1090-1094), carrying out the same reaction under the same conditions and also using catalysts of this type, reports a reaction time of 3.5 to 93 hours using upto 4 mol% of a  $ZnCl_2$  catalyst and upto 16 mol% of a  $(n\text{Butyl})_4\text{NI}$  catalyst.

Lu, *et al.*, (*J. Mol. Cat. A*, **210** (2004), 31-34; *J. Cat.*, **227** (2004), 537-541) describe the use of tetradentate Schiff-base aluminium complexes in conjunction with a

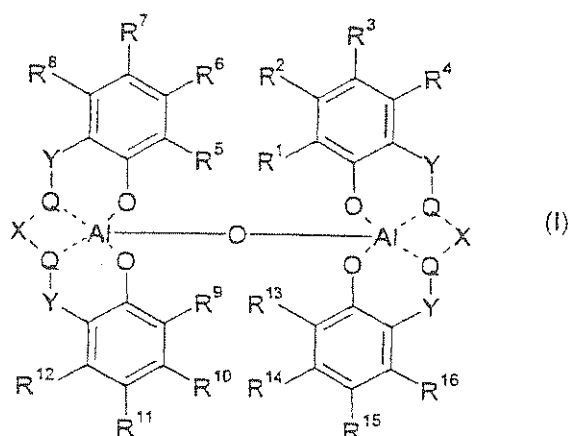
quaternary ammonium salt or polyether-KY complexes as catalyst systems for the reaction of various epoxides with carbon dioxide at room temperature and about 6 atmospheres.

- 5 Metal(salen) complexes, including aluminium(salen) complexes, are well-known in the art for their use as catalysts. Lu, et al., *App. Cat. A*, **234** (2002), 25-33, describes the use of a monomeric aluminium(salen) catalyst.

Also known in the art is the method of synthesising aluminium(salen) catalysts by  
 10 treating a salen ligand with  $\text{Me}_3\text{Al}$ ,  $\text{Et}_3\text{Al}$ ,  $\text{Me}_2\text{AlCl}$ ,  $\text{Me}_2\text{AlOTf}$ ,  $\text{Et}_2\text{AlBr}$  or  $\text{Et}_2\text{AlCl}$  in a two-stage process (reviewed in Atwood and Harvey, *Chem. Rev.*, 2001, **101**, 37-52).

It has been found by the inventor that dimeric aluminium(salen) complexes are highly  
 15 active catalysts for the reaction of epoxides with carbon dioxide to produce cyclic carbonates, and allow the reaction to be carried out at room temperature and atmospheric pressure, using short reaction times and commercially viable amounts of catalyst.

Accordingly, in a first aspect, there is provided a process for the production of  
 20 cyclic carbonates comprising contacting an epoxide with carbon dioxide in the presence of a dimeric aluminium(salen) catalyst and a co-catalyst capable of supplying  $\text{Y}^-$ , where Y is selected from Cl, Br and I. The dimeric aluminium(salen) catalysts are of formula I:



25 wherein:

$\text{Y-Q}$  is  $\text{CR}^{\text{C1}}=\text{N}$  or  $\text{CR}^{\text{C1}}\text{R}^{\text{C2}}-\text{NR}^{\text{N1}}$ , where  $\text{R}^{\text{C1}}$ ,  $\text{R}^{\text{C2}}$  and  $\text{R}^{\text{N1}}$  are independently selected from H, halo, optionally substituted  $\text{C}_{1-20}$  alkyl, optionally substituted  $\text{C}_{5-20}$  aryl, ether and nitro;

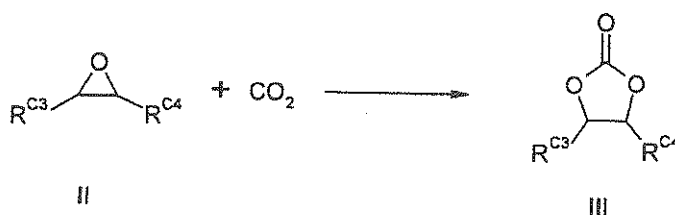
each of the substituents  $R^1, R^2, R^3, R^4, R^5, R^6, R^7, R^8, R^9, R^{10}, R^{11}, R^{12}, R^{13}, R^{14}, R^{15}$ , and  $R^{16}$ , is independently selected from H, halo, optionally substituted  $C_{1-20}$  alkyl (including  $CAr_3$ , where Ar is a  $C_{5-20}$  aryl group), optionally substituted  $C_{5-20}$  aryl, optionally substituted  $C_{3-20}$  heterocyclyl, ether, ammonium and nitro;

- 5 X is either of the formula  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3, or represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted.

- If the catalyst of formula I includes one or more chiral centres, then it may be a  
 10 (wholly or partially) racemic mixture or other mixture thereof, for example, a mixture enriched in one enantiomer or diastereoisomer, a single enantiomer or diastereoisomer, or a mixture of the stereoisomers. Methods for the preparation (e.g., asymmetric synthesis) and separation (e.g., fractional crystallisation and chromatographic means) of such isomeric forms are either known in the art or are  
 15 readily obtained by adapting the methods taught herein, or known methods, in a known manner. Preferably the catalyst of formula I is a single enantiomer, if a chiral centre is present.

- The cocatalyst is preferably soluble in the reaction mixture. Suitable sources of  $Y^-$  are MY, where M is a suitable cation, such as onium halides, which include, but are not limited to,  $R_4NY$ ,  $R_3SY$ ,  $R_4PY$  and  $R_4SbY$ , where each R is independently selected from optionally substituted  $C_{1-10}$  alkyl,  $C_{3-20}$  heterocyclyl and  $C_{5-20}$  aryl groups and one R can be an acyl group, and simple halides, e.g. NaCl, KI.

- 25 The reaction of the first aspect may be defined as follows:



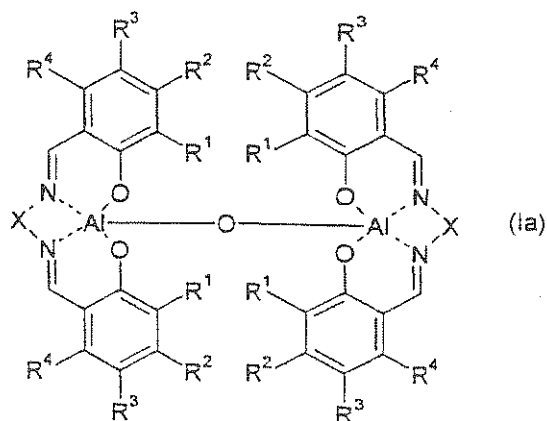
- wherein  $R^{C3}$  and  $R^{C4}$  are independently selected from H, optionally substituted  $C_{1-10}$  alkyl, optionally substituted  $C_{3-20}$  heterocyclyl and optionally substituted  $C_{5-20}$  aryl, or  $R^{C3}$  and  $R^{C4}$  form an optionally substituted linking group between the two carbon  
 30 atoms to which they are respectively attached. The linking group, together with the carbon atoms to which it is attached, may form an optionally substituted  $C_{5-20}$  cycloalkyl or  $C_{5-20}$  heterocyclyl group. The  $C_{5-20}$  cycloalkyl or  $C_{5-20}$  heterocyclyl group may be substituted only in a single position on the ring, for example, adjacent the

epoxide. Suitable substituents, include optionally substituted  $C_{1-10}$  alkyl, optionally substituted  $C_{3-20}$  heterocyclyl and optionally substituted  $C_{5-20}$  aryl.

A possible substituent for the  $C_{1-10}$  alkyl group is a  $C_{5-20}$  aryl group. A further possible group of substituents includes, but is not limited to, a  $C_{5-20}$  aryl group (e.g. phenyl, 4-methoxy phenyl), a hydroxy group, a halo group (e.g. Cl), a acetyl group, an ester group, or a  $C_{5-20}$  aryloxy group (e.g. phenoxy).

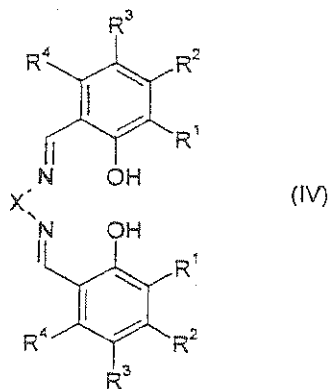
The first aspect of the invention also provides the use of a dimeric aluminium(salen) catalyst of formula I and a co-catalyst capable of supplying Y as a catalyst system for the production of cyclic carbonates from epoxides.

The dimeric aluminium(salen) catalysts of the first aspect may be of formula Ia:



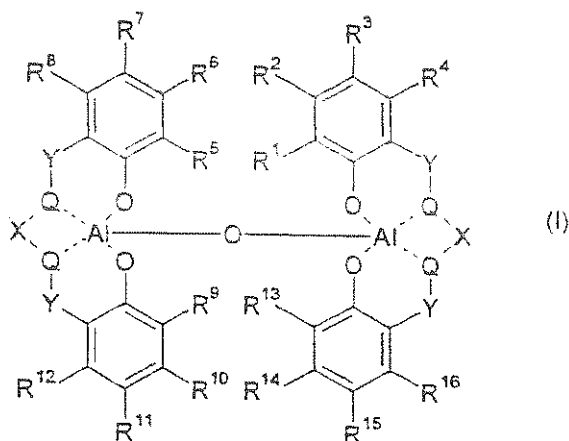
where  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^4$  and X are as defined above.

In a second aspect, there is provided a process for the synthesis of a dimeric aluminium(salen) catalyst of formula Ia comprising treating a salen ligand of formula IV:



where  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^4$  and  $X$  are as defined above, with  $Al(OR^0)_3$  in an organic solvent, wherein  $R^0$  is selected from  $C_{1-4}$  alkyl and  $C_{5-7}$  aryl.

In a third aspect, there is provided a dimeric aluminium(salen) catalyst of formula I:



wherein:

$Y-Q$  is  $CR^{C1}=N$  or  $CR^{C1}R^{C2}-NR^{N1}$ , where  $R^{C1}$ ,  $R^{C2}$  and  $R^{N1}$  are independently selected from H, halo, optionally substituted  $C_{1-20}$  alkyl, optionally substituted  $C_{5-20}$  aryl, ether and nitro;

each of the substituents  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^4$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^8$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{12}$ ,  $R^{13}$ ,  $R^{14}$ ,  $R^{15}$ , and  $R^{16}$ , is independently selected from H, halo, optionally substituted  $C_{1-20}$  alkyl, optionally substituted  $C_{5-20}$  aryl, optionally substituted  $C_{3-20}$  heterocyclyl, ether, ammonium and nitro;

$X$  is either of the formula  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where  $n$  is 2, 3, 4, or 5 and  $p$  is 1, 2, or 3, or represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted, wherein:

- (a) at least one of  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^4$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^8$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{12}$ ,  $R^{13}$ ,  $R^{14}$ ,  $R^{15}$ , or  $R^{16}$  is nitro; or
- (b) at least one of  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^4$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^8$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{12}$ ,  $R^{13}$ ,  $R^{14}$ ,  $R^{15}$ , or  $R^{16}$  is ether.

The catalysts of the present invention may be immobilized on a solid support.

### Detailed description of the invention

#### Definitions

Epoxide: The term "epoxide", as used herein, may pertain to a compound of the formula:



wherein  $R^{C3}$  and  $R^{C4}$  are independently selected from H, optionally substituted  $C_{1-10}$  alkyl, optionally substituted  $C_{3-20}$  heterocyclyl and optionally substituted  $C_{5-20}$  aryl, or  $R^{C3}$  and  $R^{C4}$  form an optionally substituted linking group between the two carbon atoms to which they are respectively attached. The linking group, together with the carbon atoms to which it is attached, may form an optionally substituted  $C_{5-20}$  cycloalkyl or  $C_{5-20}$  heterocyclyl group. The  $C_{5-20}$  cycloalkyl or  $C_{5-20}$  heterocyclyl group may be substituted only in a single position on the ring, for example, adjacent the epoxide. Suitable substituents, include optionally substituted  $C_{1-10}$  alkyl, optionally substituted  $C_{3-20}$  heterocyclyl and optionally substituted  $C_{5-20}$  aryl.

The optional substituents may be selected from:  $C_{1-10}$  alkyl,  $C_{3-20}$  heterocyclyl,  $C_{5-20}$  aryl, halo, hydroxy, ether, cyano, nitro, carboxy, ester, amido, amino, acylamido, ureido, acyloxy, thiol, thioether, sulfoxide, sulfonyl, thioamido and sulfonamino.

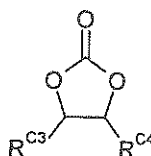
In some embodiments, the  $C_{1-10}$  alkyl group is substituted by a  $C_{5-20}$  aryl group. In other embodiments, the  $C_{1-10}$  alkyl group may be substituted by a  $C_{5-20}$  aryl group (e.g. phenyl, 4-methoxy phenyl), a hydroxy group, a halo group (e.g. Cl), an acetyl group, an ester group, or a  $C_{5-20}$  aryloxy group (e.g. phenoxy).

Preferably, the epoxide is a terminal epoxide, i.e.  $R^{C4} = H$ .

In some embodiments,  $R^{C3}$  is selected from optionally substituted  $C_{1-4}$  alkyl and optionally substituted  $C_{5-7}$  aryl. In some of these embodiments  $R^{C3}$  is unsubstituted.

- Preferred epoxides are ethylene oxide ( $R^{C3} = R^{C4} = H$ ), propylene oxide ( $R^{C3} =$  methyl,  $R^{C4} = H$ ), butylene oxide ( $R^{C3} =$  ethyl,  $R^{C4} = H$ ), and styrene oxide ( $R^{C3} =$  phenyl,  $R^{C4} = H$ ). Other epoxides of interest include hydroxypropyl oxide ( $R^{C3} =$  CH<sub>2</sub>OH,  $R^{C4} = H$ ), chloropropyl oxide ( $R^{C3} =$  CH<sub>2</sub>Cl,  $R^{C4} = H$ ), acetyloxypropyl oxide ( $R^{C3} =$  CH<sub>2</sub>OAc,  $R^{C4} = H$ ), phenylcarbonyloxypropyl oxide ( $R^{C3} =$  CH<sub>2</sub>OCOPh,  $R^{C4} =$  H), phenoxypropyl oxide ( $R^{C3} =$  CH<sub>2</sub>OPh,  $R^{C4} = H$ ) and 4-methoxyphenylethyl oxide ( $R^{C3} =$  4-MeOC<sub>6</sub>H<sub>4</sub>,  $R^{C4} = H$ ).

- 10 Cyclic carbonate: the term "cyclic carbonate", as used herein, may pertain to a compound of the formula:



wherein  $R^{C3}$  and  $R^{C4}$  are as defined above.

- 15 Alkyl: The term "alkyl", as used herein, pertains to a monovalent moiety obtained by removing a hydrogen atom from a carbon atom of a hydrocarbon having from 1 to 20 carbon atoms (unless otherwise specified), which may be aliphatic or alicyclic and which may be saturated or unsaturated (e.g. partially saturated, fully unsaturated). Thus, the term "alkyl" includes the sub-classes alkenyl, alkynyl, cycloalkyl, 20 cycloalkenyl, cycloalkynyl, etc., as discussed below.

- In the context of alkyl groups, the prefixes (e.g. C<sub>1-4</sub>, C<sub>1-7</sub>, C<sub>1-20</sub>, C<sub>2-7</sub>, C<sub>3-7</sub>, etc.) denote the number of carbon atoms, or the range of number of carbon atoms. For example, the term "C<sub>1-4</sub> alkyl", as used herein, pertains to an alkyl group having from 1 to 4 25 carbon atoms. Examples of groups of alkyl groups include C<sub>1-4</sub> alkyl ("lower alkyl"), C<sub>1-7</sub> alkyl and C<sub>1-20</sub> alkyl. Note that the first prefix may vary according to other limitations; for example, for unsaturated alkyl groups, the first prefix must be at least 2; for cyclic alkyl groups, the first prefix must be at least 3; etc.

- 30 Examples of (unsubstituted) saturated alkyl groups include, but are not limited to, methyl (C<sub>1</sub>), ethyl (C<sub>2</sub>), propyl (C<sub>3</sub>), butyl (C<sub>4</sub>), pentyl (C<sub>5</sub>), hexyl (C<sub>6</sub>), and heptyl (C<sub>7</sub>).

Examples of (unsubstituted) saturated linear alkyl groups include, but are not limited to, methyl ( $C_1$ ), ethyl ( $C_2$ ), n-propyl ( $C_3$ ), n-butyl ( $C_4$ ), n-pentyl (amyl) ( $C_5$ ), n-hexyl ( $C_6$ ), and n-heptyl ( $C_7$ ).

- 5 Examples of (unsubstituted) saturated branched alkyl groups include iso-propyl ( $C_3$ ), iso-butyl ( $C_4$ ), sec-butyl ( $C_4$ ), tert-butyl ( $C_4$ ), iso-pentyl ( $C_5$ ), and neo-pentyl ( $C_5$ ).

- Alkenyl: The term "alkenyl", as used herein, pertains to an alkyl group having one or more carbon-carbon double bonds. Examples of groups of alkenyl groups include
- 10  $C_{2-4}$  alkenyl,  $C_{2-7}$  alkenyl,  $C_{2-20}$  alkenyl.

- Examples of (unsubstituted) unsaturated alkenyl groups include, but are not limited to, ethenyl (vinyl,  $-CH=CH_2$ ), 1-propenyl ( $-CH=CH-CH_3$ ), 2-propenyl (allyl,  $-CH_2-CH=CH_2$ ), isopropenyl (1-methylvinyl,  $-C(CH_3)=CH_2$ ), butenyl ( $C_4$ ), pentenyl ( $C_5$ ), and
- 15 hexenyl ( $C_6$ ).

- Alkynyl: The term "alkynyl", as used herein, pertains to an alkyl group having one or more carbon-carbon triple bonds. Examples of groups of alkynyl groups include  $C_{2-4}$  alkynyl,  $C_{2-7}$  alkynyl,  $C_{2-20}$  alkynyl.
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Examples of (unsubstituted) unsaturated alkynyl groups include, but are not limited to, ethynyl (ethinyl,  $-C\equiv CH$ ) and 2-propynyl (propargyl,  $-CH_2-C\equiv CH$ ).

- Cycloalkyl: the term "cycloalkyl", as used herein, pertains to an alkyl group which is
- 25 also a cyclyl group; that is, a monovalent moiety obtained by removing a hydrogen atom from an alicyclic ring atom of a carbocyclic ring of a carbocyclic compound, which carbocyclic ring may be saturated or unsaturated (e.g. partially unsaturated, fully unsaturated), which moiety has from 3-20 carbon atoms (unless otherwise specified), including from 3 to 20 ring atoms. Thus, the term "cycloalkyl" includes the
- 30 sub-classes cycloalkenyl and cycloalkynyl. Preferably, each ring has from 3 to 7 ring atoms. Examples of groups of cycloalkyl groups include  $C_{3-20}$  cycloalkyl,  $C_{3-15}$  cycloalkyl,  $C_{3-10}$  cycloalkyl,  $C_{3-7}$  cycloalkyl.

- Cyclic alkylene: The term "cyclic alkylene" as used herein pertains to a divalent
- 35 moiety obtained by removing a hydrogen atom from each of two adjacent alicyclic ring atoms of a carbocyclic ring of a carbocyclic compound, which carbocyclic ring

- may be saturated or unsaturated (e.g. partially saturated, fully unsaturated), which moiety has from 3 to 20 carbon atoms (unless otherwise specified), including from 3 to 20 ring atoms. Preferably each ring has from 5 to 7 ring atoms. Examples of groups of cyclic alkylene groups include C<sub>3-20</sub> cyclic alkenes, C<sub>3-15</sub> cyclic alkenes,
- 5 C<sub>3-10</sub> cyclic alkenes, C<sub>3-7</sub> cyclic alkenes.

Examples of cycloalkyl groups and cyclic alkylene groups include, but are not limited to, those derived from:

saturated monocyclic hydrocarbon compounds:

- 10 cyclopropane (C<sub>3</sub>), cyclobutane (C<sub>4</sub>), cyclopentane (C<sub>5</sub>), cyclohexane (C<sub>6</sub>), cycloheptane (C<sub>7</sub>), methylcyclopropane (C<sub>4</sub>), dimethylcyclopropane (C<sub>5</sub>), methylcyclobutane (C<sub>5</sub>), dimethylcyclobutane (C<sub>6</sub>), methylcyclopentane (C<sub>6</sub>), dimethylcyclopentane (C<sub>7</sub>), methylcyclohexane (C<sub>7</sub>), dimethylcyclohexane (C<sub>8</sub>), menthane (C<sub>10</sub>);

- 15 unsaturated monocyclic hydrocarbon compounds:

cyclopropene (C<sub>3</sub>), cyclobutene (C<sub>4</sub>), cyclopentene (C<sub>5</sub>), cyclohexene (C<sub>6</sub>), methylcyclopropene (C<sub>4</sub>), dimethylcyclopropene (C<sub>5</sub>), methylcyclobutene (C<sub>5</sub>), dimethylcyclobutene (C<sub>6</sub>), methylcyclopentene (C<sub>6</sub>), dimethylcyclopentene (C<sub>7</sub>), methylcyclohexene (C<sub>7</sub>), dimethylcyclohexene (C<sub>8</sub>);

- 20 saturated polycyclic hydrocarbon compounds:

thujane (C<sub>10</sub>), carane (C<sub>10</sub>), pinane (C<sub>10</sub>), bornane (C<sub>10</sub>), norcarane (C<sub>7</sub>), norpinane (C<sub>7</sub>), norbornane (C<sub>7</sub>), adamantane (C<sub>10</sub>), decalin (decahydronaphthalene) (C<sub>10</sub>);

unsaturated polycyclic hydrocarbon compounds:

camphene (C<sub>10</sub>), limonene (C<sub>10</sub>), pinene (C<sub>10</sub>);

- 25 polycyclic hydrocarbon compounds having an aromatic ring:

indene (C<sub>9</sub>), indane (e.g., 2,3-dihydro-1H-indene) (C<sub>9</sub>), tetraline (1,2,3,4-tetrahydronaphthalene) (C<sub>10</sub>), acenaphthene (C<sub>12</sub>), fluorene (C<sub>13</sub>), phenalene (C<sub>13</sub>), acephenanthrene (C<sub>15</sub>), aceanthrene (C<sub>16</sub>), cholanthrene (C<sub>20</sub>).

- 30 Heterocyclyl: The term "heterocyclyl", as used herein, pertains to a monovalent moiety obtained by removing a hydrogen atom from a ring atom of a heterocyclic compound, which moiety has from 3 to 20 ring atoms (unless otherwise specified), of which from 1 to 10 are ring heteroatoms. Preferably, each ring has from 3 to 7 ring atoms, of which from 1 to 4 are ring heteroatoms.

Heterocyclylene: The term "heterocyclylene", as used herein, pertains to a divalent moiety obtained by removing a hydrogen atom from each of two adjacent ring atoms of a heterocyclic compound, which moiety has from 3 to 20 ring atoms (unless otherwise specified), of which from 1 to 10 are ring heteroatoms. Preferably, each  
5 ring has from 3 to 7 ring atoms, of which from 1 to 4 are ring heteroatoms.

The heterocyclyl or heterocyclylene group may be bonded via carbon or hetero ring atoms. Preferably, the heterocyclylene group is bonded via two carbon atoms.

10 When referring to heterocyclyl or heterocyclylene groups, the prefixes (e.g. C<sub>3-20</sub>, C<sub>3-7</sub>, C<sub>5-6</sub>, etc.) denote the number of ring atoms, or range of number of ring atoms, whether carbon atoms or heteroatoms. For example, the term "C<sub>5-6</sub> heterocyclyl", as used herein, pertains to a heterocyclyl group having 5 or 6 ring atoms. Examples of groups of heterocyclyl groups include C<sub>3-20</sub> heterocyclyl, C<sub>5-20</sub> heterocyclyl, C<sub>3-15</sub>  
15 heterocyclyl, C<sub>5-15</sub> heterocyclyl, C<sub>3-12</sub> heterocyclyl, C<sub>5-12</sub> heterocyclyl, C<sub>3-10</sub> heterocyclyl, C<sub>5-10</sub> heterocyclyl, C<sub>3-7</sub> heterocyclyl, C<sub>5-7</sub> heterocyclyl, and C<sub>5-6</sub> heterocyclyl.

Similarly, the term "C<sub>5-6</sub> heterocyclylene", as used herein, pertains to a heterocyclylene group having 5 or 6 ring atoms. Examples of groups of  
20 heterocyclylene groups include C<sub>3-20</sub> heterocyclylene, C<sub>5-20</sub> heterocyclylene, C<sub>3-15</sub> heterocyclylene, C<sub>5-15</sub> heterocyclylene, C<sub>3-12</sub> heterocyclylene, C<sub>5-12</sub> heterocyclylene, C<sub>3-10</sub> heterocyclylene, C<sub>5-10</sub> heterocyclylene, C<sub>3-7</sub> heterocyclylene, C<sub>5-7</sub> heterocyclylene, and C<sub>5-6</sub> heterocyclylene.

25 Examples of monocyclic heterocyclyl and heterocyclylene groups include, but are not limited to, those derived from:

N<sub>1</sub>: aziridine (C<sub>3</sub>), azetidine (C<sub>4</sub>), pyrrolidine (tetrahydropyrrole) (C<sub>5</sub>), pyrroline (e.g., 3-pyrroline, 2,5-dihydropyrrole) (C<sub>5</sub>), 2H-pyrrole or 3H-pyrrole (isopyrrole, isoazole)  
30 (C<sub>5</sub>), piperidine (C<sub>6</sub>), dihydropyridine (C<sub>6</sub>), tetrahydropyridine (C<sub>6</sub>), azepine (C<sub>7</sub>);

O<sub>1</sub>: oxirane (C<sub>3</sub>), oxetane (C<sub>4</sub>), oxolane (tetrahydrofuran) (C<sub>5</sub>), oxole (dihydrofuran) (C<sub>5</sub>), oxane (tetrahydropyran) (C<sub>6</sub>), dihydropyran (C<sub>6</sub>), pyran (C<sub>6</sub>), oxepin (C<sub>7</sub>);

35 S<sub>1</sub>: thiirane (C<sub>3</sub>), thietane (C<sub>4</sub>), thiolane (tetrahydrothiophene) (C<sub>5</sub>), thiane (tetrahydrothiopyran) (C<sub>6</sub>), thiepane (C<sub>7</sub>);

O<sub>2</sub>: dioxolane (C<sub>5</sub>), dioxane (C<sub>6</sub>), and dioxepane (C<sub>7</sub>);

O<sub>3</sub>: trioxane (C<sub>6</sub>);

5

N<sub>2</sub>: imidazolidine (C<sub>5</sub>), pyrazolidine (diazolidine) (C<sub>5</sub>), imidazoline (C<sub>5</sub>), pyrazoline (dihydropyrazole) (C<sub>5</sub>), piperazine (C<sub>6</sub>);

10 N<sub>1</sub>O<sub>1</sub>: tetrahydrooxazole (C<sub>5</sub>), dihydrooxazole (C<sub>5</sub>), tetrahydroisoxazole (C<sub>5</sub>), dihydroisoxazole (C<sub>5</sub>), morpholine (C<sub>6</sub>), tetrahydrooxazine (C<sub>6</sub>), dihydrooxazine (C<sub>6</sub>), oxazine (C<sub>6</sub>);

N<sub>1</sub>S<sub>1</sub>: thiazoline (C<sub>5</sub>), thiazolidine (C<sub>5</sub>), thiomorpholine (C<sub>6</sub>);

15 N<sub>2</sub>O<sub>1</sub>: oxadiazine (C<sub>6</sub>);

O<sub>1</sub>S<sub>1</sub>: oxathiole (C<sub>5</sub>) and oxathiane (thioxane) (C<sub>6</sub>); and,

N<sub>1</sub>O<sub>1</sub>S<sub>1</sub>: oxathiazine (C<sub>6</sub>).

20

Examples of substituted (non-aromatic) monocyclic heterocyclyl and heterocyclylene groups include those derived from saccharides, in cyclic form, for example, furanoses (C<sub>5</sub>), such as arabinofuranose, lyxofuranose, ribofuranose, and xylofuranse, and pyranoses (C<sub>6</sub>), such as allopripyranose, altropyranose, glucopyranose, mannopyranose, gulopyranose, idopyranose, galactopyranose, and talopyranose.

25

C<sub>5-20</sub> aryl: The term "C<sub>5-20</sub> aryl", as used herein, pertains to a monovalent moiety obtained by removing a hydrogen atom from an aromatic ring atom of a C<sub>5-20</sub> aromatic compound, said compound having one ring, or two or more rings (e.g., fused), and having from 5 to 20 ring atoms, and wherein at least one of said ring(s) is an aromatic ring. Preferably, each ring has from 5 to 7 carbon atoms.

30

The ring atoms may be all carbon atoms, as in "carboaryl groups" in which case the group may conveniently be referred to as a "C<sub>5-20</sub> carboaryl" group.

35

$C_{5-20}$  arylene: The term " $C_{5-20}$  arylene", as used herein, pertains to a divalent moiety obtained by removing a hydrogen atom from each of two adjacent ring atoms of a  $C_{5-20}$  aromatic compound, said compound having one ring, or two or more rings (e.g., fused), and having from 5 to 20 ring atoms, and wherein at least one of said ring(s) is an aromatic ring. Preferably, each ring has from 5 to 7 carbon atoms.

The ring atoms may be all carbon atoms, as in "carboarylene groups" in which case the group may conveniently be referred to as a " $C_{5-20}$  carboarylene" group.

Examples of  $C_{5-20}$  aryl and  $C_{5-20}$  arylene groups which do not have ring heteroatoms (i.e.  $C_{5-20}$  carboaryl and  $C_{5-20}$  carboarylene groups) include, but are not limited to, those derived from benzene (i.e. phenyl) ( $C_6$ ), naphthalene ( $C_{10}$ ), anthracene ( $C_{14}$ ), phenanthrene ( $C_{14}$ ), and pyrene ( $C_{16}$ ).

Alternatively, the ring atoms may include one or more heteroatoms, including but not limited to oxygen, nitrogen, and sulfur, as in "heteroaryl groups" or "heteroarylene groups". In this case, the group may conveniently be referred to as a " $C_{5-20}$  heteroaryl" or " $C_{5-20}$  heteroarylene" group, wherein " $C_{5-20}$ " denotes ring atoms, whether carbon atoms or heteroatoms. Preferably, each ring has from 5 to 7 ring atoms, of which from 0 to 4 are ring heteroatoms.

The heteroaryl or heteroarylene group may be bonded via carbon or hetero ring atoms. Preferably, the heteroarylene group is bonded via two carbon atoms.

Examples of  $C_{5-20}$  heteroaryl and  $C_{5-20}$  heteroarylene groups include, but are not limited to,  $C_5$  heteroaryl and  $C_5$  heteroarylene groups derived from furan (oxole), thiophene (thiole), pyrrole (azole), imidazole (1,3-diazole), pyrazole (1,2-diazole), triazole, oxazole, isoxazole, thiazole, isothiazole, oxadiazole, tetrazole and oxatriazole; and  $C_6$  heteroaryl groups derived from isoxazine, pyridine (azine), pyridazine (1,2-diazine), pyrimidine (1,3-diazine; e.g., cytosine, thymine, uracil), pyrazine (1,4-diazine) and triazine.

Examples of  $C_{5-20}$  heteroaryl and  $C_{5-20}$  heteroarylene groups which comprise fused rings, include, but are not limited to,  $C_9$  heteroaryl and  $C_9$  heteroarylene groups derived from benzofuran, isobenzofuran, benzothiophene, indole, isoindole;  $C_{10}$  heteroaryl and  $C_{10}$  heteroarylene groups derived from quinoline, isoquinoline,

benzodiazine, pyridopyridine; C<sub>14</sub> heteroaryl and C<sub>14</sub> heteroarylene groups derived from acridine and xanthene.

5 The above alkyl, cyclic alkylene, heterocyclyl, heterocyclylene, aryl, and arylene groups, whether alone or part of another substituent, may themselves optionally be substituted with one or more groups selected from themselves and the additional substituents listed below.

10 Halo: -F, -Cl, -Br, and -I.

Hydroxy: -OH.

15 Ether: -OR, wherein R is an ether substituent, for example, a C<sub>1-7</sub> alkyl group (also referred to as a C<sub>1-7</sub> alkoxy group), a C<sub>3-20</sub> heterocyclyl group (also referred to as a C<sub>3-20</sub> heterocycliloxy group), or a C<sub>5-20</sub> aryl group (also referred to as a C<sub>5-20</sub> aryloxy group), preferably a C<sub>1-7</sub> alkyl group.

Nitro: -NO<sub>2</sub>.

20 Cyano (nitrile, carbonitrile): -CN.

25 Acyl (keto): -C(=O)R, wherein R is an acyl substituent, for example, H, a C<sub>1-7</sub> alkyl group (also referred to as C<sub>1-7</sub> alkylacyl or C<sub>1-7</sub> alkanoyl), a C<sub>3-20</sub> heterocyclyl group (also referred to as C<sub>3-20</sub> heterocyclylacyl), or a C<sub>5-20</sub> aryl group (also referred to as C<sub>5-20</sub> arylacyl), preferably a C<sub>1-7</sub> alkyl group. Examples of acyl groups include, but are not limited to, -C(=O)CH<sub>3</sub> (acetyl), -C(=O)CH<sub>2</sub>CH<sub>3</sub> (propionyl), -C(=O)C(CH<sub>3</sub>)<sub>3</sub> (pivaloyl), and -C(=O)Ph (benzoyl, phenone).

30 Carboxy (carboxylic acid): -COOH.

Ester (carboxylate, carboxylic acid ester, oxycarbonyl): -C(=O)OR, wherein R is an ester substituent, for example, a C<sub>1-7</sub> alkyl group, a C<sub>3-20</sub> heterocyclyl group, or a C<sub>5-20</sub> aryl group, preferably a C<sub>1-7</sub> alkyl group. Examples of ester groups include, but are not limited to, -C(=O)OCH<sub>3</sub>, -C(=O)OCH<sub>2</sub>CH<sub>3</sub>, -C(=O)OC(CH<sub>3</sub>)<sub>3</sub>, and -C(=O)OPh.

35

Amido (carbamoyl, carbamyl, aminocarbonyl, carboxamide):  $-C(=O)NR^1R^2$ , wherein  $R^1$  and  $R^2$  are independently amino substituents, as defined for amino groups.

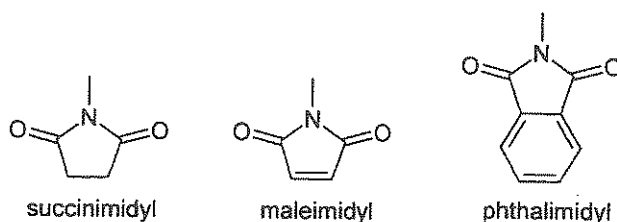
Examples of amido groups include, but are not limited to,  $-C(=O)NH_2$ ,  $-C(=O)NHCH_3$ ,  $-C(=O)N(CH_3)_2$ ,  $-C(=O)NHCH_2CH_3$ , and  $-C(=O)N(CH_2CH_3)_2$ , as well as amido groups  
 5 in which  $R^1$  and  $R^2$ , together with the nitrogen atom to which they are attached, form a heterocyclic structure as in, for example, piperidinocarbonyl, morpholinocarbonyl, thiomorpholinocarbonyl, and piperazinylcarbonyl.

Amino:  $-NR^1R^2$ , wherein  $R^1$  and  $R^2$  are independently amino substituents, for  
 10 example, hydrogen, a  $C_{1-7}$  alkyl group (also referred to as  $C_{1-7}$  alkylamino or di- $C_{1-7}$  alkylamino), a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably H or a  $C_{1-7}$  alkyl group, or, in the case of a "cyclic" amino group,  $R^1$  and  $R^2$ , taken together with the nitrogen atom to which they are attached, form a heterocyclic ring having from 4 to 8  
 ring atoms. Examples of amino groups include, but are not limited to,  $-NH_2$ ,  $-NHCH_3$ ,  
 15  $-NHCH(CH_3)_2$ ,  $-N(CH_3)_2$ ,  $-N(CH_2CH_3)_2$ , and  $-NHPh$ . Examples of cyclic amino groups include, but are not limited to, aziridinyl, azetidiny, pyrrolidinyl, piperidino, piperazinyl, perhydrodiazepinyl, morpholino, and thiomorpholino. In particular, the cyclic amino groups may be substituted on their ring by any of the substituents defined here, for example carboxy, carboxylate and amido.

20

Ammonium:  $-NH_4^+Z^-$ , wherein  $Z^-$  is an appropriate counterion, such as halide (e.g.  $Cl^-$ ,  $Br^-$ ), nitrate, perchlorate.

Acylamido (acylamino):  $-NR^1C(=O)R^2$ , wherein  $R^1$  is an amide substituent, for  
 25 example, hydrogen, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably H or a  $C_{1-7}$  alkyl group, most preferably H, and  $R^2$  is an acyl substituent, for example, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of acylamide groups include, but are not limited to,  $-NHC(=O)CH_3$ ,  $-NHC(=O)CH_2CH_3$ , and  $-NHC(=O)Ph$ .  $R^1$  and  $R^2$  may together form  
 30 a cyclic structure, as in, for example, succinimidyl, maleimidyl, and phthalimidyl:



Ureido:  $-N(R^1)CONR^2R^3$  wherein  $R^2$  and  $R^3$  are independently amino substituents, as defined for amino groups, and  $R^1$  is a ureido substituent, for example, hydrogen, a  $C_{1-7}$ alkyl group, a  $C_{3-20}$ heterocyclyl group, or a  $C_{5-20}$ aryl group, preferably hydrogen or a  $C_{1-7}$ alkyl group. Examples of ureido groups include, but are not limited to, -

- 5  $NHCONH_2$ ,  $-NHCONHMe$ ,  $-NHCONHEt$ ,  $-NHCONMe_2$ ,  $-NHCONEt_2$ ,  $-NMeCONH_2$ ,  $-NMeCONHMe$ ,  $-NMeCONHEt$ ,  $-NMeCONMe_2$ ,  $-NMeCONEt_2$  and  $-NHCONHPh$ .

- Acyloxy (reverse ester):  $-OC(=O)R$ , wherein R is an acyloxy substituent, for example, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of acyloxy groups include, but are not limited to,  $-OC(=O)CH_3$  (acetoxyl),  $-OC(=O)CH_2CH_3$ ,  $-OC(=O)C(CH_3)_3$ ,  $-OC(=O)Ph$ ,  $-OC(=O)C_6H_4F$ , and  $-OC(=O)CH_2Ph$ .
- 10

Thiol :  $-SH$ .

15

Thioether (sulfide):  $-SR$ , wherein R is a thioether substituent, for example, a  $C_{1-7}$  alkyl group (also referred to as a  $C_{1-7}$  alkylthio group), a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of  $C_{1-7}$  alkylthio groups include, but are not limited to,  $-SCH_3$  and  $-SCH_2CH_3$ .

20

Sulfoxide (sulfinyl):  $-S(=O)R$ , wherein R is a sulfoxide substituent, for example, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of sulfoxide groups include, but are not limited to,  $-S(=O)CH_3$  and  $-S(=O)CH_2CH_3$ .

25

- Sulfonyl (sulfone):  $-S(=O)_2R$ , wherein R is a sulfone substituent, for example, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of sulfone groups include, but are not limited to,  $-S(=O)_2CH_3$  (methanesulfonyl, mesyl),  $-S(=O)_2CF_3$ ,  $-S(=O)_2CH_2CH_3$ , and 4-methylphenylsulfonyl (tosyl).
- 30

Thioamido (thiocarbamyl):  $-C(=S)NR^1R^2$ , wherein  $R^1$  and  $R^2$  are independently amino substituents, as defined for amino groups. Examples of amido groups include, but are not limited to,  $-C(=S)NH_2$ ,  $-C(=S)NHCH_3$ ,  $-C(=S)N(CH_3)_2$ , and  $-C(=S)NHCH_2CH_3$ .

35

Sulfonamino:  $-NR'S(=O)_2R$ , wherein  $R'$  is an amino substituent, as defined for amino groups, and  $R$  is a sulfonamino substituent, for example, a  $C_{1-7}$  alkyl group, a  $C_{3-20}$  heterocyclyl group, or a  $C_{5-20}$  aryl group, preferably a  $C_{1-7}$  alkyl group. Examples of sulfonamino groups include, but are not limited to,  $-NHS(=O)_2CH_3$ ,  $-NHS(=O)_2Ph$  and  
5  $-N(CH_3)S(=O)_2C_6H_5$ .

As mentioned above, the groups that form the above listed substituent groups, e.g.  $C_{1-7}$  alkyl,  $C_{3-20}$  heterocyclyl and  $C_{5-20}$  aryl, may themselves be substituted. Thus, the above definitions cover substituent groups which are substituted.

10

#### Chemically Protected Forms

It may be convenient or desirable to prepare, purify, handle and/or use the active compound in a chemically protected form. The term "chemically protected form" is used herein in the conventional chemical sense and pertains to a compound in which  
15 one or more reactive functional groups are protected from undesirable chemical reactions under specified conditions (e.g., pH, temperature, radiation, solvent, and the like). In practice, well known chemical methods are employed to reversibly render unreactive a functional group, which otherwise would be reactive, under specified conditions. In a chemically protected form, one or more reactive functional  
20 groups are in the form of a protected or protecting group (also known as a masked or masking group or a blocked or blocking group). By protecting a reactive functional group, reactions involving other unprotected reactive functional groups can be performed, without affecting the protected group; the protecting group may be removed, usually in a subsequent step, without substantially affecting the remainder  
25 of the molecule. See, for example, Protective Groups in Organic Synthesis (T. Green and P. Wuts; 3rd Edition; John Wiley and Sons, 1999).

30

Unless otherwise specified, a reference to a particular compound also includes chemically protected forms thereof.

A wide variety of such "protecting," "blocking," or "masking" methods are widely used and well known in organic synthesis. For example, a compound which has two nonequivalent reactive functional groups, both of which would be reactive under specified conditions, may be derivatized to render one of the functional groups  
35 "protected," and therefore unreactive, under the specified conditions; so protected, the compound may be used as a reactant which has effectively only one reactive

functional group. After the desired reaction (involving the other functional group) is complete, the protected group may be "deprotected" to return it to its original functionality.

- 5 For example, a hydroxy group may be protected as an ether (-OR) or an ester (-OC(=O)R), for example, as: a t-butyl ether; a benzyl, benzhydryl (diphenylmethyl), or trityl (triphenylmethyl) ether; a trimethylsilyl or t-butyldimethylsilyl ether; or an acetyl ester (-OC(=O)CH<sub>3</sub>, -OAc).
- 10 For example, an aldehyde or ketone group may be protected as an acetal (R-CH(OR)<sub>2</sub>) or ketal (R<sub>2</sub>C(OR)<sub>2</sub>), respectively, in which the carbonyl group (>C=O) is converted to a diether (>C(OR)<sub>2</sub>), by reaction with, for example, a primary alcohol. The aldehyde or ketone group is readily regenerated by hydrolysis using a large excess of water in the presence of acid.
- 15 For example, an amine group may be protected, for example, as an amide (-NRCO-R) or a urethane (-NRCO-OR), for example, as: a methyl amide (-NHCO-CH<sub>3</sub>); a benzyloxy amide (-NHCO-OCH<sub>2</sub>C<sub>6</sub>H<sub>5</sub>, -NH-Cbz); as a t-butoxy amide (-NHCO-OC(CH<sub>3</sub>)<sub>3</sub>, -NH-Boc); a 2-biphenyl-2-propoxy amide (-NHCO-OC(CH<sub>3</sub>)<sub>2</sub>C<sub>6</sub>H<sub>4</sub>C<sub>6</sub>H<sub>5</sub>, -NH-Bpoc), as a 9-fluorenylmethoxy amide (-NH-Fmoc), as a 6-nitroveratryloxy amide (-NH-Nvoc), as a 2-trimethylsilylethoxy amide (-NH-Teoc), as a 2,2,2-trichloroethoxy amide (-NH-Troc), as an allyloxy amide (-NH-Alloc), as a 2(-phenylsulphonyl)ethoxy amide (-NH-Psec); or, in suitable cases (e.g., cyclic amines), as a nitroxide radical (>N-O).
- 20
- 25 For example, a carboxylic acid group may be protected as an ester for example, as: an C<sub>1-7</sub>alkyl ester (e.g., a methyl ester; a t-butyl ester); a C<sub>1-7</sub>haloalkyl ester (e.g., a C<sub>1-7</sub>trihaloalkyl ester); a triC<sub>1-7</sub>alkylsilyl-C<sub>1-7</sub>alkyl ester; or a C<sub>5-20</sub>aryl-C<sub>1-7</sub>alkyl ester (e.g., a benzyl ester; a nitrobenzyl ester); or as an amide, for example, as a methyl
- 30 amide.
- For example, a thiol group may be protected as a thioether (-SR), for example, as: a benzyl thioether; an acetamidomethyl ether (-S-CH<sub>2</sub>NHC(=O)CH<sub>3</sub>).
- 35 In particular application in the present invention is the protection of hydroxy and amino groups.

### Solid Support

Catalysts of the present invention may be immobilized on a solid support by:

- (a) steric trapping; or
- 5 (b) electrostatic binding.

These methods are reviewed by Carlos Baleizão and Hermenegildo Garcia in "Chiral Salen Complexes: An Overview to Recoverable and Reusable Homogeneous and Heterogeneous Catalysts" (*Chem. Rev.* 2006, **106**, 3987-4043).

10

For steric trapping, the most suitable class of solid support is zeolites, which may be natural or modified. The pore size must be sufficiently small to trap the catalyst but sufficiently large to allow the passage of reactants and products to and from the catalyst. Suitable zeolites include zeolites X, Y and EMT as well as those which  
15 have been partially degraded to provide mesopores, that allow easier transport of reactants and products.

For the electrostatic binding of the catalyst to a solid support, typical solid supports may include silica, Indian clay, Al-pillared clay, Al-MCM-41, K10, Iaponite, bentonite,  
20 and zinc-aluminum layered double hydroxide. Of these silica and montmorillonite clay are of particular interest.

### Catalysed reactions

In one aspect of the present invention, there is provided a process for the production  
25 of cyclic carbonates comprising contacting an epoxide with carbon dioxide in the presence of a dimeric aluminium(salen) catalyst of formula I, preferably of formula Ia, and a co-catalyst which is a source of Y<sup>-</sup>.

This reaction has the advantage that it may be carried out at easily accessible  
30 temperatures of between 0 and 40°C and pressures of between 0.5 and 2 atm. Preferably, the reaction temperature lies between 20 and 30°C. Yields of over 50% may be achieved with short reaction times of 3 to 24 hours, using commercially viable amounts of catalyst, that is, from 0.1 to 10 mol%, preferably 0.1 to 2.5 mol%. In some cases, yields of over 70% or over 90% may be achieved under these  
35 conditions.

Preferably, the aluminium(salen) catalyst of formula I is symmetrical, such that  $R^1=R^{13}$ ,  $R^2=R^{14}$ ,  $R^3=R^{15}$ ,  $R^4=R^{16}$ ,  $R^5=R^9$ ,  $R^6=R^{10}$ ,  $R^7=R^{11}$ , and  $R^8=R^{12}$ . More preferably  $R^1$ ,  $R^5$ ,  $R^9$ , and  $R^{13}$  are identical,  $R^2$ ,  $R^6$ ,  $R^{10}$  and  $R^{14}$  are identical,  $R^3$ ,  $R^7$ ,  $R^{11}$ , and  $R^{15}$  are identical, and  $R^4$ ,  $R^8$ ,  $R^{12}$  and  $R^{16}$  are identical. Such catalysts are of formula Ia,

5 which may be preferred.

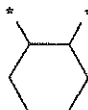
In some embodiments, X is  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3. In these embodiments, n is preferably 2 or 3 and p is preferably 1 or 2. n is more preferably 2. In some embodiments, n is preferably 3. In these

10 embodiments X is preferably  $-(CH_2)_n-$  (e.g.  $-C_2H_4-$ ,  $-C_3H_6-$ ).

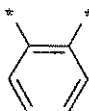
In other embodiments, X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted.

Preferably X represents  $C_{5-7}$  cyclic alkylene, and more preferably  $C_6$  cyclic alkylene.

15 This group is preferably saturated, and therefore is the group:



In other preferred embodiments, X represents  $C_{5-7}$  arylene, which is more preferably  $C_6$  arylene, and in particular, benzylene:



20

When X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, it may preferably be unsubstituted. If it is substituted, then the substituents may be selected from nitro, halo,  $C_{1-4}$  alkyl, including substituted  $C_{1-4}$  alkyl, (e.g. methyl, benzyl),  $C_{1-4}$  alkoxy (e.g. methoxy) and hydroxy.

25

Preferably Y-Q is  $CR^{C1}=N$ , wherein  $R^{C1}$  is as defined above.  $R^{C1}$  is preferably selected from H and  $C_{1-4}$  alkyl. More preferably Y-Q is  $CH=N$ .

If Y-Q is  $CR^{C1}R^{C2}-NR^{N1}$ , then in some embodiments  $R^{C1}$ ,  $R^{C2}$  and  $R^{N1}$  are H.

30

Preferably  $R^4 = R^8 = R^{12} = R^{16} = H$ . Preferably  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  are independently selected from H,  $C_{1-7}$  alkyl, ether and nitro.

If a group selected from  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  is ether, then the ether group is preferably a  $C_{1-7}$  alkoxy group and more preferably  $C_{1-4}$  alkoxy group, e.g. methoxy.

5

If a group selected from  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  is  $C_{1-7}$  alkyl, it is preferably butyl, more preferably tert-butyl. In other embodiments, the  $C_{1-7}$  alkyl is preferably optionally substituted methyl, e.g. di- $C_{1-4}$  alkylamino substituted methyl (diethylaminomethyl).

10

A particularly preferred set of embodiments of the catalyst of formula Ia have:

Y-Q is  $CH=N$ ;

X as:

(i)  $-C_2H_4-$ ;

15

(ii) 1,2  $C_6$  cyclic alkylene; or

(iii) 1,2 benzylene;

$R^4 = H$ ;

$R^1$ ,  $R^2$  and  $R^3$  selected from H, tert-butyl, methoxy and nitro, where only one of these three groups can be nitro.

20

A further particularly preferred set of embodiments of the catalyst of formula Ia have:

Y-Q is  $CH=N$ ;

X as:

(iii) 1,2 benzylene;

25

(iv)  $-C_3H_6-$

$R^4 = H$ ;

one of  $R^1$ ,  $R^2$  and  $R^3$  is di- $C_{1-4}$  alkyl amino methyl, and the others of  $R^1$ ,  $R^2$  and  $R^3$  are H.

30

The cocatalyst is a source of  $Y^-$ , and in particular MY, where M is a suitable cation, such as onium halides, which include, but are not limited to,  $R_4NY$ ,  $R_3SY$ ,  $R_4PY$  and  $R_4SbY$ , where each R is independently selected from optionally substituted  $C_{1-10}$  alkyl,  $C_{3-20}$  heterocyclyl and  $C_{5-20}$  aryl groups and one R can be an acyl group, and simple halides, e.g. NaCl, KI.

35

It is preferred that the co-catalyst for this reaction is of the form  $R_4NY$ , where each R is independently  $C_{1-10}$  alkyl and Y is selected from I, Br and Cl. R is preferably selected from  $C_{3-5}$  alkyl, and more preferably is butyl. Y is preferably Br. Therefore, a particularly preferred co-catalyst is  $Bu_4NBr$ . The amount of co-catalyst is preferably  
 5 0.1 to 10 mol%, more preferably 0.1 to 2.5 mol%.

The reaction may be carried out under solvent-free conditions, depending on the epoxides used. In some cases, the epoxides may act as a solvent for the catalyst.

#### 10 Manufacture of dimeric aluminium(salen) complexes

In a second aspect of the invention, there is provided a process for the production of dimeric aluminium(salen) catalysts of formula Ia comprising treating a salen ligand of formula IV with  $Al(OR^O)_3$  in an organic solvent, wherein  $R^O = C_{1-4}$  alkyl or  $C_{5-7}$  aryl.

15 The organic solvent can be an aprotic solvent. Preferably, the organic solvent is toluene. It is also preferred that  $R^O$  is  $C_{1-4}$  alkyl and more preferably ethyl. The reaction time preferably lies between 2 and 18 hours, more preferably between 3 and 10 hours.

20 The reaction may be heated, if required, by any conventional means. In some embodiments, the carbon dioxide may be supplied heated, and in other embodiments, the reaction may be heated by a convention or microwave system.

#### Novel dimeric aluminium(salen) complexes

25 In a third aspect of the invention there are provided novel aluminium(salen) complexes of formula I. In particular, these novel catalysts may have:

(a) at least one of  $R^1, R^2, R^3, R^4, R^5, R^6, R^7, R^8, R^9, R^{10}, R^{11}, R^{12}, R^{13}, R^{14}, R^{15}$ , or  $R^{16}$  as nitro;

(b) at least one of  $R^1, R^2, R^3, R^4, R^5, R^6, R^7, R^8, R^9, R^{10}, R^{11}, R^{12}, R^{13}, R^{14}, R^{15}$ , or  
 30  $R^{16}$  as ether.

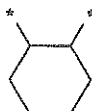
In general, the preferences expressed in regard the first aspect of the invention may apply to the third aspect, provided that they are compatible with the above statements.

Preferably, the aluminium(salen) catalyst of formula I is symmetrical, such that  $R^1=R^{13}$ ,  $R^2=R^{14}$ ,  $R^3=R^{15}$ ,  $R^4=R^{16}$ ,  $R^5=R^9$ ,  $R^6=R^{10}$ ,  $R^7=R^{11}$ , and  $R^8=R^{12}$ . More preferably  $R^1$ ,  $R^5$ ,  $R^9$ , and  $R^{13}$  are identical,  $R^2$ ,  $R^6$ ,  $R^{10}$  and  $R^{14}$  are identical,  $R^3$ ,  $R^7$ ,  $R^{11}$ , and  $R^{15}$  are identical, and  $R^4$ ,  $R^8$ ,  $R^{12}$  and  $R^{16}$  are identical. Such catalysts are of formula Ia.

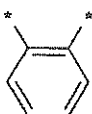
5

In some embodiments, X is  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3. In these embodiments, n is preferably 2 or 3 and p is preferably 1 or 2. n is more preferably 2. In these embodiments X is preferably  $-(CH_2)_n-$  (e.g.  $-C_2H_4-$ ).

- 10 In other embodiments, X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted. Preferably X represents  $C_{5-7}$  cyclic alkylene, and more preferably  $C_6$  cyclic alkylene. This group is preferably saturated, and therefore is the group:



- 15 In other preferred embodiments, X represents  $C_{5-7}$  arylene, which is more preferably  $C_6$  arylene, and in particular, benzylene:



- When X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, it may preferably be unsubstituted. If it is substituted, then  
20 the substituents may be selected from  $C_{1-4}$  alkyl (e.g. methyl),  $C_{1-4}$  alkoxy (e.g. methoxy) and hydroxy.

Preferably Y-Q is  $CR^{C1}=N$ , wherein  $R^{C1}$  is as defined above.  $R^{C1}$  is preferably selected from H and  $C_{1-4}$  alkyl. More preferably Y-Q is  $CH=N$ .

25

If Y-Q is  $CR^{C1}R^{C2}-NR^{N1}$ , then in some embodiments  $R^{C1}$ ,  $R^{C2}$  and  $R^{N1}$  are H.

Preferably  $R^4 = R^8 = R^{12} = R^{16} = H$ . Preferably  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  are independently selected from H,  $C_{1-7}$  alkyl, ether and nitro.

30

If a group selected from  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  is ether, then the ether group is preferably a  $C_{1-7}$  alkoxy group and more preferably  $C_{1-4}$  alkoxy group, e.g. methoxy.

- 5 If a group selected from  $R^1$ ,  $R^2$ ,  $R^3$ ,  $R^5$ ,  $R^6$ ,  $R^7$ ,  $R^9$ ,  $R^{10}$ ,  $R^{11}$ ,  $R^{13}$ ,  $R^{14}$ , and  $R^{15}$  is  $C_{1-7}$  alkyl, it is preferably butyl, more preferably tert-butyl.

More preferably, the catalyst is of formula Ia.

- 10 A particularly preferred set of embodiments of the novel catalyst of formula Ia have:

Y-Q is  $CH=N$ ;

X as 1,2  $C_6$  cyclic alkylene;

$R^4 = H$ ; and

- (i)  $R^1 = R^3 = \text{tert-butyl}$  and  $R^2 = H$ ;  
 15 (ii)  $R^1 = R^3 = H$  and  $R^2 = \text{methoxy}$ ;  
 (iii)  $R^1 = R^2 = R^3 = H$ ;  
 (iv)  $R^1 = \text{tert-butyl}$  and  $R^2 = R^3 = H$ ; or  
 (v)  $R^1 = \text{tert-butyl}$ ,  $R^2 = H$  and  $R^3 = \text{methoxy}$ .

- 20 A further particularly preferred set of embodiments of the catalyst of formula Ia have:

Y-Q is  $CH=N$ ;

X as:

(iii) 1,2 benzylene;

(iv)  $-C_3H_6-$

- 25  $R^4 = H$ ;

one of  $R^1$ ,  $R^2$  and  $R^3$  is di $C_{1-4}$  alkyl amino methyl, and the others of  $R^1$ ,  $R^2$  and  $R^3$  are H.

### Examples

- 30 *General experimental methods*

#### IR spectroscopy

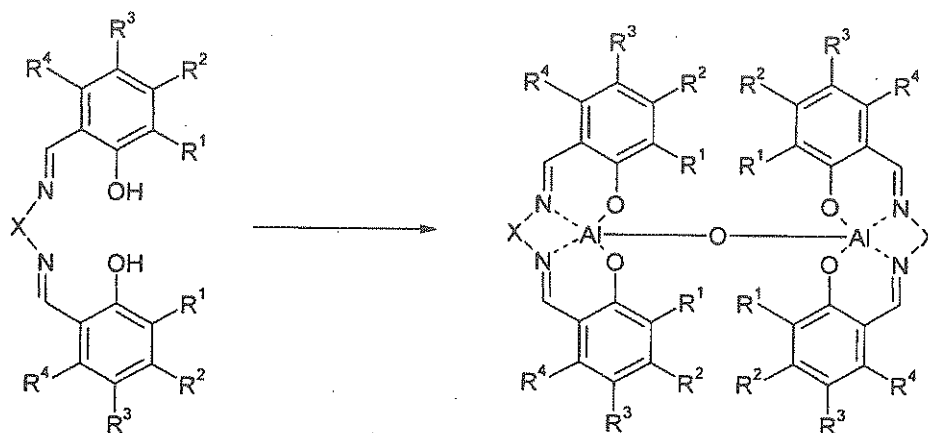
IR spectra of liquids or of solids dissolved in a solvent were recorded between NaCl plates on a PE Spectrum 1 spectrometer. IR spectra of pure solids were recorded on a Nicolet380 FTIR spectrometer fitted with a 'Smart orbit' attachment.

NMR

All NMR spectra were recorded at ambient temperature on a Bruker Avance 300 spectrometer. The sample was dissolved in  $\text{CDCl}_3$  unless specified otherwise.

5 Mass spectroscopy

low resolution EI and CI spectra were recorded on a Varian Saturn 2200 GC-mass spectrometer. Low and high resolution electrospray spectra were recorded on a Waters LCT Premier mass spectrometer.

10 **Example 1: General procedure for the synthesis of catalysts 1a-h**

**1a:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = R<sup>3</sup> = <sup>t</sup>Bu; R<sup>2</sup> = R<sup>4</sup> = H

**1b:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = <sup>t</sup>Bu; R<sup>2</sup> = R<sup>4</sup> = H; R<sup>3</sup> = NO<sub>2</sub>

**1c:** X = (CH<sub>2</sub>)<sub>2</sub>; R<sup>1</sup> = R<sup>3</sup> = <sup>t</sup>Bu; R<sup>2</sup> = R<sup>4</sup> = H

15 **1d:** X = 1,2-C<sub>6</sub>H<sub>4</sub>; R<sup>1</sup> = R<sup>3</sup> = <sup>t</sup>Bu; R<sup>2</sup> = R<sup>4</sup> = H

**1e:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = R<sup>3</sup> = R<sup>4</sup> = H; R<sup>2</sup> = OMe

**1f:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = R<sup>2</sup> = R<sup>3</sup> = R<sup>4</sup> = H

**1g:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = <sup>t</sup>Bu; R<sup>2</sup> = R<sup>3</sup> = R<sup>4</sup> = H;

**1h:** X = (1*R*,2*R*)-cyclohexyl; R<sup>1</sup> = <sup>t</sup>Bu; R<sup>2</sup> = H; R<sup>3</sup> = OMe; R<sup>4</sup> = H

20

Al(OEt)<sub>3</sub> (0.28 g, 1.72 mmol) was added to dry toluene (60 mL) and stirred under reflux for 1 hour. The appropriate salen ligand (1.68 mmol) dissolved in dry toluene (40 mL) was then added and the reaction mixture was stirred under reflux for a further 3 hours before being allowed to cool to room temperature. The solution was dried (Na<sub>2</sub>SO<sub>4</sub>) and solvents were evaporated *in vacuo* to give a solid which was purified as specified below. The analysis data are set out below.

25

Data for complex 1a: Yellow solid purified by washing with cold hexane. Yield 63%;

$[\alpha]_D^{20}$  -548 ( $c=0.11$ ,  $\text{CHCl}_3$ );  $\nu_{\text{max}}(\text{CH}_2\text{Cl}_2)$  2953 m, 1626 m, and 1474  $\text{cm}^{-1}$  m;  $\delta_{\text{H}}(\text{CDCl}_3)$  8.35 (2H, s, CH=N), 8.15 (2H, s, CH=N), 7.52 (4H, d  $J$  2.3 Hz, 4 x ArH), 7.07 (4H, d  $J$  2.3 Hz, 4 x ArH), 3.9-3.7 (2H, br m, CHN), 3.2-3.0 (2H, br m, CHN), 2.7-1.8 (16H, m, 2 x  $(\text{CH}_2)_4$ ), 1.50 (36H, s, 4 x  $(\text{CH}_3)_3$ ), 1.29 (36H, s, 4 x  $(\text{CH}_3)_3$ );  $m/z$  (ESI) 1159.7 ( $\text{MH}^+$ ), 649.4, 623.4, 603.4, 569.3; Found (ESI) 1159.7106,  $\text{C}_{72}\text{H}_{105}\text{N}_4\text{O}_5\text{Al}_2$  ( $\text{MH}^+$ ) requires 1159.7716.

Data for complex 1b: Orange solid purified by washing with  $\text{Et}_2\text{O}$ . Yield 63%;  
 $[\alpha]_D^{20}$  -575 ( $c=0.1$ , toluene);  $\nu_{\text{max}}(\text{ATR})$  2925 w, 1638 m, 1599 m, and 1573  $\text{cm}^{-1}$  m;  
 $\delta_{\text{H}}(\text{CDCl}_3)$  8.64 (4H, s, 4 x CH=N), 8.36 (4H, s, 4 x ArH), 8.02 (4H, s, 4 x ArH), 3.7-3.8 (4H, br, CHN), 3.7-2.0 (16H, m, 2 x  $(\text{CH}_2)_4$ ), 1.55 (36H, s, 4 x  $(\text{CH}_3)_3$ );  $m/z$  (ESI) 1115.4 ( $\text{MH}^+$ ); Found (ESI) 1115.4536  $\text{C}_{56}\text{H}_{69}\text{N}_6\text{O}_{13}\text{Al}_2$  ( $\text{MH}^+$ ) requires 1115.4615.

Data for complex 1c: Yellow solid purified by washing with cold  $\text{Et}_2\text{O}$ . Yield 50%;  
 $\nu_{\text{max}}(\text{ATR})$  2950 m, 2866 w, 1628 m, and 1538  $\text{cm}^{-1}$  m;  $\delta_{\text{H}}(\text{CDCl}_3)$  8.38 (4H, s, 4 x CH=N), 7.52 (4H, d  $J$  2.5 Hz, 4 x ArH), 7.04 (4H, d  $J$  2.6 Hz, 4 x ArH), 4.2-4.1 (4H, br,  $(\text{CH}_2)_2$ ), 3.8-3.7 (4H, br,  $(\text{CH}_2)_2$ ), 1.30 (36H, s, 4 x  $(\text{CH}_3)_3$ ), 1.55 (36H, s, 4 x  $(\text{CH}_3)_3$ );  $m/z$  (ESI) 1051.7 ( $\text{MH}^+$ ), 664.5, 638.5, 549.4, 517.3; Found (ESI) 1051.6721  $\text{C}_{64}\text{H}_{93}\text{N}_4\text{O}_5\text{Al}_2$  ( $\text{MH}^+$ ) requires 1051.6777.

Data for complex 1d: The reaction was heated at reflux overnight and gave an orange powder. Yield 60%;  
 $\nu_{\text{max}}(\text{CH}_2\text{Cl}_2)$  2952 m, 2868 m, 1614 s, 1583 s, and 1531  $\text{cm}^{-1}$  s;  $\delta_{\text{H}}(\text{CDCl}_3)$  8.66 (4H, s, 4 x CH=N), 7.43 (4H, d  $J$  2.3 Hz, 4 x ArH), 7.3-7.2 (4H, m, 4 x ArH), 7.2-7.0 (8H, m, 8 x ArH), 1.43 (36H, s, 4 x  $(\text{CH}_3)_3$ ), 1.32 (36H, s, 4 x  $(\text{CH}_3)_3$ );  $m/z$  (Maldi) 1147.7 ( $\text{MH}^+$ ), 582.3, 540.4; Found (ESI) 1147.6801  $\text{C}_{72}\text{H}_{93}\text{N}_4\text{O}_5\text{Al}_2$  ( $\text{MH}^+$ ) requires 1147.6777.

Data for complex 1e: The reaction was heated at reflux overnight and gave a yellow powder which was purified by dissolution in cold  $\text{Et}_2\text{O}$  followed by evaporation of solvent *in vacuo*. Yield 35%;  
 $[\alpha]_D^{20}$  -753 ( $c=0.1$ ,  $\text{CHCl}_3$ );  $\nu_{\text{max}}(\text{ATR})$  2937 m, 2838 m, 1606 s, and 1537  $\text{cm}^{-1}$  s;  
 $\delta_{\text{H}}(\text{CDCl}_3)$  9.87 (4H, s, 4 x CH=N), 7.18 (4H, dd  $J$  8.9, 3.0 Hz, 4 x ArH), 7.03 (4H, d  $J$  3.1 Hz, 4 x ArH), 6.97 (4H, d  $J$  9.0 Hz, 4 x ArH), 3.82 (12H, s, 4 x  $\text{OCH}_3$ ), 3.8-3.5 (4H, m, 4 x CHN), 1.5-1.2 (16H, m 2 x  $(\text{CH}_2)_4$ );  $m/z$  (Maldi) 831.3 ( $\text{MH}^+$ ), 789.3, 662.4, 407.1; Found (ESI) 831.3139  $\text{C}_{44}\text{H}_{49}\text{N}_4\text{O}_9\text{Al}_2$  ( $\text{MH}^+$ ) requires 831.3130.

Data for complex 1f: The reaction was heated at reflux overnight and gave a yellow powder which was purified by dissolution in cold Et<sub>2</sub>O followed by evaporation of solvent *in vacuo*. Yield 33%;

$[\alpha]_D^{20}$  -381 (*c*= 0.1, CHCl<sub>3</sub>);  $\nu_{\max}$ (ATR) 2863 w, 1628 s, 1601 m, and 1537 cm<sup>-1</sup> m;

- 5  $\delta_H$ (CDCl<sub>3</sub>) 8.27 (4H, s, CH=N), 7.5-7.4 (4H, m, ArH), 7.2-7.1 (4H, m, ArH), 7.0-6.9 (4H, m, ArH), 6.9-6.8 (4H, m, ArH), 3.4-3.3 (4H, m, CHN), 2.0-1.5 (16H, m, 2 x (CH<sub>2</sub>)<sub>4</sub>); *m/z*(ESI) (Maldi) 711.3 (MH<sup>+</sup>), 669.3, 364.1, 347.1; Found (ESI) 711.2708 C<sub>40</sub>H<sub>41</sub>N<sub>4</sub>O<sub>5</sub>Al<sub>2</sub> (MH<sup>+</sup>) requires 711.2708.

- 10 Data for complex 1g: The reaction was heated at reflux overnight and gave a yellow powder which was purified by dissolution in cold Et<sub>2</sub>O followed by evaporation of solvent *in vacuo* and chromatography on Sephadex LH50 using toluene / ethanol (1:1) as eluent. Yield 45%;

$[\alpha]_D^{20}$  -372 (*c*= 0.1, CHCl<sub>3</sub>);  $\nu_{\max}$ (ATR) 2951 m, 1633 s, and 1538 cm<sup>-1</sup> m;  $\delta_H$ (CDCl<sub>3</sub>)

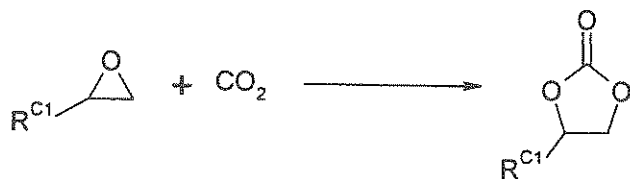
- 15 8.28 (4H, s, 4 x CH=N), 7.29 (4H, dd *J* 8.1, 2.1 Hz, 4 x ArH), 7.14 (4H, d *J* 2.7 Hz, 4 x ArH), 6.84 (4H, d *J* 8.7 Hz, 4 x ArH), 3.4-3.2 (4H, m, 4 x CHN), 2.0-1.4 (16H, m 2 x (CH<sub>2</sub>)<sub>4</sub>), 1.45 (36H, s, 4 x C(CH<sub>3</sub>)<sub>3</sub>); *m/z* (Maldi) 935.5 (MH<sup>+</sup>), 893.6, 847.5, 775.4, 573.4, 459.3; Found (ESI) 935.5223 C<sub>56</sub>H<sub>73</sub>N<sub>4</sub>O<sub>5</sub>Al<sub>2</sub> (MH<sup>+</sup>) requires 935.5212.

- 20 Data for complex 1h: The reaction was heated at reflux overnight and gave a yellow powder which was purified by dissolution in cold Et<sub>2</sub>O followed by evaporation of solvent *in vacuo* and chromatography on Sephadex LH50 using toluene / ethanol (1:1) as eluent. Yield 30%;

$[\alpha]_D^{20}$  -612 (*c*= 0.1, CHCl<sub>3</sub>);  $\nu_{\max}$ (ATR) 2949 m, 1627 s, and 1552 cm<sup>-1</sup> m;  $\delta_H$ (CDCl<sub>3</sub>)

- 25 8.26 (4H, s, 4 x CH=N), 6.91 (4H, d *J* 3.0 Hz, 4 x ArH), 6.49 (4H, d *J* 3.0 Hz, 4 x ArH), 3.70 (12H, s, 4 x OCH<sub>3</sub>), 3.4-3.2 (4H, m, 4 x CHN), 2.0-1.4 (16H, m 2 x (CH<sub>2</sub>)<sub>4</sub>), 1.41 (36H, s, 4 x C(CH<sub>3</sub>)<sub>3</sub>); *m/z* (Maldi) 1055.6 (MH<sup>+</sup>), 876.6, 848.5, 519.3, 494.3; Found (ESI) 1055.5602 C<sub>60</sub>H<sub>81</sub>N<sub>4</sub>O<sub>9</sub>Al<sub>2</sub> (MH<sup>+</sup>) requires 1055.5634.

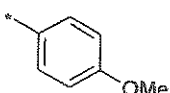
- 30 **Example 2: General procedure for the synthesis of cyclic carbonates 3a-k**



2,3a: R<sup>C1</sup> = Ph

2,3b: R<sup>C1</sup> = Me

2,3c:  $R^{C1} = CH_2Ph$ 2,3d:  $R^{C1} = Bu$ 2,3e:  $R^{C1} = C_8H_{17}$ 2,3f:  $R^{C1} = CH_2OH$ 5 2,3g:  $R^{C1} = CH_2Cl$ 2,3h:  $R^{C1} = CH_2OAc$ 2,3i:  $R^{C1} = CH_2OCOPh$ 2,3j:  $R^{C1} = CH_2OPh$ 

2,3k:  $R^{C1} =$  

10

A mixture of an epoxide 2a-k (2 mmol), tetrabutylammonium bromide (0-2.5 mol%) and the appropriate catalyst 1a-h (0-2.5 mol%) was vigorously stirred until complete dissolution occurred, then  $CO_2$  was passed through the flask at atmospheric pressure.

After being stirred at 25°C for between 3 and 48 hours, a sample of the reaction was

15 analysed by  $^1H$  NMR spectroscopy to determine the conversion, and the reaction mixture was purified by flash chromatography to give cyclic carbonate 3a-k. The results are shown below:

| Reaction | Cyclic carbonate | Catalyst (mol%) | Co-catalyst (mol%) | $CO_2$ pressure (atm.) | Temp (°C) | Time (h) | Conv (%) |
|----------|------------------|-----------------|--------------------|------------------------|-----------|----------|----------|
| 1        | 3a               | 1a (0.1)        | $Bu_4NBr$ (0.1)    | 1                      | 25        | 3        | 5        |
| 2        | 3a               | 1a (1.0)        | $Bu_4NBr$ (1.0)    | 1                      | 25        | 3        | 38       |
| 3        | 3a               | 1a (1.0)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 56       |
| 4        | 3a               | 1a (2.5)        | $Bu_4NBr$ (1.0)    | 1                      | 25        | 3        | 51       |
| 5        | 3a               | 1a (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 62       |
| 6        | 3a               | 1a (0.1)        | $Bu_4NBr$ (0.1)    | 1                      | 25        | 24       | 27       |
| 7        | 3a               | 1a (1.0)        | $Bu_4NBr$ (1.0)    | 1                      | 25        | 24       | 86       |
| 8        | 3a               | 1a (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 24       | 98       |
| 9        | 3a               | 1b (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 50       |
| 10       | 3a               | 1c (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 52       |
| 11       | 3a               | 1d (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 33       |
| 12       | 3a               | 1e (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 41       |
| 13       | 3a               | 1f (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 28       |
| 14       | 3a               | 1g (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 51       |
| 15       | 3a               | 1h (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 64       |
| 16       | 3b               | 1a (2.5)        | $Bu_4NBr$ (2.5)    | 1                      | 25        | 3        | 77       |

| Reaction               | Cyclic carbonate | Catalyst (mol%) | Co-catalyst (mol%)        | CO <sub>2</sub> pressure (atm.) | Temp (°C) | Time (h) | Conv (%) |
|------------------------|------------------|-----------------|---------------------------|---------------------------------|-----------|----------|----------|
| 17                     | 3b               | 1a (1)          | Bu <sub>4</sub> NBr (1)   | 1                               | 0         | 3        | 40       |
| 18                     | 3b               | 1a (1)          | Bu <sub>4</sub> NBr (1)   | 1                               | 0         | 24       | 63       |
| 19                     | 3c               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 0         | 3        | 44       |
| 20                     | 3c               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 24       | 99       |
| 21                     | 3d               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 87       |
| 22                     | 3e               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 64       |
| 23                     | 3f               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 43       |
| 24                     | 3g               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 90       |
| 25                     | 3h               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 50       |
| 26                     | 3h               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 24       | 75       |
| 27                     | 3i               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 72       |
| 28                     | 3i               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 24       | 62       |
| 29                     | 3j               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 55       |
| 30                     | 3k               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 3        | 30       |
| 31                     | 3k               | 1a (2.5)        | Bu <sub>4</sub> NBr (2.5) | 1                               | 25        | 24       | 84       |
| Comparative reaction 1 | 3a               | 1a (1.0)        | ---                       | 1                               | 25        | 3        | 0        |
| Comparative reaction 2 | 3a               | 1a (1.0)        | ---                       | 5                               | 50        | 24       | 0        |
| Comparative reaction 3 | 3a               | 1a (0.1)        | DMAP (1.0)                | 8                               | 50        | 24       | 0        |
| Comparative reaction 4 | 3a               | ---             | Bu <sub>4</sub> NBr (1.0) | 1                               | 25        | 3        | 4        |

## Detailed results for Example 2

The analysis data are given below for cyclic carbonates 3a-e, synthesised under the following conditions:

- 5 Temperature: 25°C  
 Pressure: atmospheric  
 Reaction time: 3 hours  
 Catalyst: 1a (2.5 mol%)  
 Co-catalyst: Bu<sub>4</sub>NBr (2.5 mol %)

10

Data for styrene carbonate 3a – Reaction 5: Conversion 62%, isolated yield 57% after purification by flash chromatography (hexane / EtOAc 2:3). Mp 49-52°C;  $\nu_{\max}$ (ATR) 3047 m, 3020 m, 2968 m, 2899 m, 1812 s, and 1592 cm<sup>-1</sup> w;  $\delta_{\text{H}}$  7.5-7.2 (5H, m, ArH),

5.68 (1H, t J 8.0 Hz, PhCHO), 4.81 (1H, t J 8.5 Hz, OCH<sub>2</sub>), 4.35 (1H, t J 8.4 Hz, OCH<sub>2</sub>).  
 $\delta_c$  154.9, 135.9, 129.8, 129.3, 126.0, 78.1, 71.3; m/z (EI) 164 (M<sup>+</sup>, 100), 119 (10), 105 (10).

- 5 Data for propylene carbonate 3b – Reaction 17: Reaction carried out at 0°C, conversion 82%, isolated yield 77% after purification by flash chromatography (hexane / EtOAc)  $\nu_{max}(\text{neat})$  2991 m, 2921 m, 1786 cm<sup>-1</sup> s;  $\delta_H$  4.9-4.8 (1H, m, CHO), 4.55 (1H, t J 8.4 Hz OCH<sub>2</sub>), 4.02 (1H, dd J 8.4, 7.3 Hz OCH<sub>2</sub>), 1.49 (3H, d J 6.3 Hz, CH<sub>3</sub>);  $\delta_c$  154.5, 73.7, 70.9, 19.7; m/z (EI) 102 (M<sup>+</sup>, 100), 100 (5).

10

- Data for allylbenzene carbonate 3c – Reaction 19: Conversion 50%, isolated yield 44% after purification by flash chromatography (hexane / EtOAc 2:3).  $\nu_{max}(\text{neat})$  3064 w, 3031 w, 2980 w, 2920 w, 1800 cm<sup>-1</sup> s;  $\delta_H$  7.2-7.0 (5H, m, ArH), 4.85 (1H, m, OCH), 4.35 (1H, t J 7.8 Hz, OCH<sub>2</sub>), 4.08 (1H, dd J 8.4, 6.9 Hz, OCH<sub>2</sub>), 3.06 (1H, dd J 14.1, 6.3 Hz, CH<sub>2</sub>Ph), 2.90 (1H, dd J 14.1, 6.3 Hz, CH<sub>2</sub>Ph);  $\delta_c$  154.5, 134.1, 129.3, 128.9, 127.5, 76.8, 68.5, 39.6; m/z (EI), 178 (M<sup>+</sup>, 20), 91 (100).

15

- Data for hex-1-ene carbonate 3d – Reaction 21: Conversion 90%, isolated yield 87% after purification by flash chromatography (hexane / EtOAc 2:3).  $\nu_{max}(\text{neat})$  2960 s, 2934 s, 2874 m, 1797 cm<sup>-1</sup> s;  $\delta_H$  4.64 (1H, qd J 7.5, 5.4 Hz, OCH), 4.46 (1H, t J 7.8 Hz, OCH<sub>2</sub>), 4.09 (1H, dd J 8.4, 7.2 Hz, OCH<sub>2</sub>), 2.0-1.6 (2H, m, CH<sub>2</sub>), 1.6-1.2 (4H, m, 2 x CH<sub>2</sub>), 0.95 (3H, t J 7.1 Hz, CH<sub>3</sub>);  $\delta_c$  155.2, 77.2, 69.5, 33.7, 26.5, 22.4, 13.9; m/z? (CI, NH<sub>3</sub>), 162 (M+NH<sub>4</sub><sup>+</sup>, 100), 161 (40), 100 (10).

20

- 25 Data for dec-1-ene carbonate 3e – Reaction 22: Conversion 70%, isolated yield 64% after purification by flash chromatography (Et<sub>2</sub>O).  $\nu_{max}(\text{neat})$  2928 s, 2857 s, 1805 cm<sup>-1</sup> s;  $\delta_H$  4.72 (1H, qd J 7.5, 5.7 Hz, OCH), 4.54 (1H, t J 8.1 Hz, OCH<sub>2</sub>), 4.09 (1H, t J 7.5 Hz, OCH<sub>2</sub>), 1.9-1.6 (2H, m, CH<sub>2</sub>), 1.6-1.2 (12H, m, 6 x CH<sub>2</sub>), 0.90 (3H, t J 6.6 Hz, CH<sub>3</sub>);  $\delta_c$  155.2, 77.1, 69.5, 34.0, 31.9, 29.4, 29.2, 29.1, 24.5, 22.7, 14.2; m/z (EI), 162 (M<sup>+</sup>, 8), 95 (38), 67 (100).

30

- Data for hydroxypropyl carbonate 3f - Reaction 23: Conversion 43%, isolated yield 36% after purification by distillation.  $\nu_{max}(\text{neat})$  3400 s, 2933 m, and 1789 cm<sup>-1</sup> s;  $\delta_H(\text{CDCl}_3)$  4.8-4.9 (1H, m, OCH), 4.4-4.5 (2H, m, CH<sub>2</sub>), 3.9-4.0 (1H, m OCH), 3.6-3.8 (2H, br, OH, OCH);  $\delta_c(\text{CDCl}_3)$  155.2, 75.0, 65.8, 61.6; m/z(CI) 119 (MH<sup>+</sup>, 100), 118(M<sup>+</sup>, 10).

35

Data for chloropropyl carbonate 3g - Reaction 24: Conversion 90%, isolated yield 60% after purification by flash chromatography (hexane / EtOAc 2:3).  $\nu_{\max}(\text{neat})$  3467 w, 1960 m, and 1799  $\text{cm}^{-1}$  s;  $\delta_{\text{H}}(\text{CDCl}_3)$  5.0-4.9 (1H, m, OCH), 4.59 (1H, dd  $J$  8.7, 8.4 Hz,  $\text{OCH}_2$ ), 4.40 (1H, dd  $J$  9.0, 8.7 Hz,  $\text{OCH}_2$ ), 3.8-3.7 (2H, m,  $\text{CH}_2\text{Cl}$ );  $\delta_{\text{C}}(\text{CDCl}_3)$  154.4, 74.6, 67.4, 43.9;  $m/z(\text{EI})$  139 ( $(^{37}\text{Cl})\text{M}^+$ , 5), 137 ( $(^{35}\text{Cl})\text{M}^+$ , 10), 86 (35), 87 (55), 49 (45), 51 (13), 43 (100), 44 (25).

Data for acetyloxypropyl carbonate 3h - Reaction 25: Conversion 50%, isolated yield 34% after purification by flash chromatography (hexane / EtOAc 2:3). Reaction 26: Conversion 75%, isolated yield 55% after purification by flash chromatography.  $\nu_{\max}(\text{neat})$  3545 m, 2960 m, 1788 s, and 1746  $\text{cm}^{-1}$  s;  $\delta_{\text{H}}(\text{CDCl}_3)$  4.93 (1H, m, OCH), 4.57 (1H, t  $J$  9.0 Hz,  $\text{OCH}_2$ ), 4.27 (3H, m,  $\text{OCH}_2$ ,  $\text{CH}_2$ ), 2.15 (3H, s,  $\text{CH}_3$ );  $\delta_{\text{C}}(\text{CDCl}_3)$  170.5, 154.8, 74.1, 66.4, 63.4, 20.1;  $m/z(\text{EI})$  161 ( $\text{MH}^+$ , 75) 160 ( $\text{M}^+$ , 8), 43 (100).

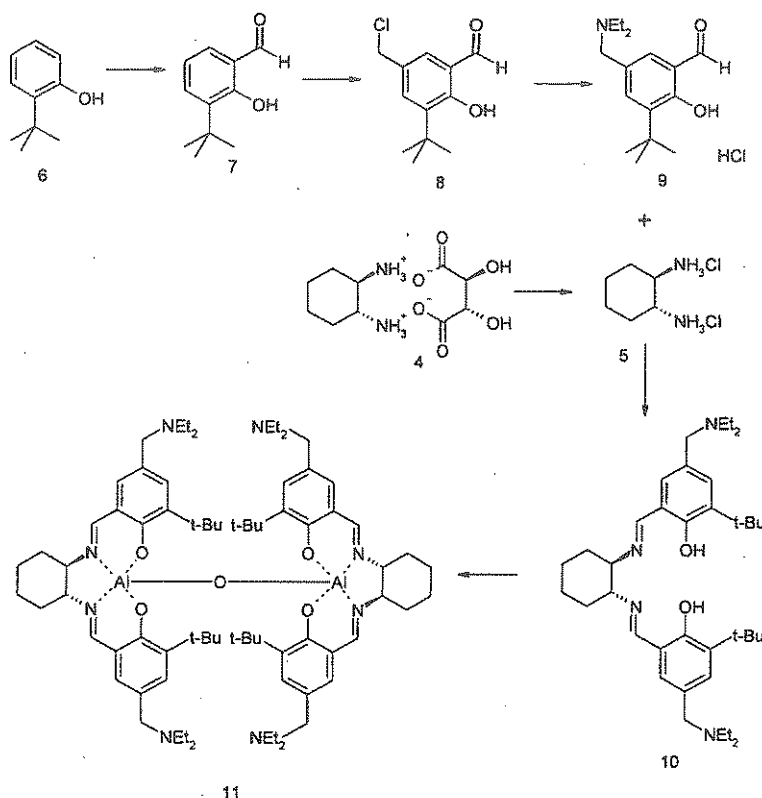
Data for phenylcarbonyloxypropyl carbonate 3i - Reaction 27: Conversion 72%, isolated yield 12% after purification by flash chromatography (hexane / EtOAc 1:3). Reaction 28: Conversion 62%; isolated yield 58% following purification by flash chromatography (hexane / EtOAc 1:3).  $\nu_{\max}(\text{neat})$  3585 m, 3055 m, 2956 m, 1799 s, and 1715  $\text{cm}^{-1}$  s;  $\delta_{\text{H}}(\text{CDCl}_3)$  8.0-8.1 (2H, m, ArH) 7.6-7.7 (1H, m, ArH), 7.4-7.5 (2H, m, ArH), 5.0-5.1 (1H, m, OCH), 4.5-4.6 (4H, m,  $\text{OCH}_2$ ,  $\text{CH}_2$ );  $\delta_{\text{C}}(\text{CDCl}_3)$  166.4, 154.8, 134.1, 130.2, 129.2, 129.1, 74.3, 66.5, 66.0;  $m/z(\text{EI})$  223 ( $\text{MH}^+$ , 3), 122 (13), 105 (100), 77 (38), 51 (15).

Data for phenoxypropylcarbonate 3j - Reaction 29: Conversion 55%, isolated yield 46% following purification by flash chromatography (hexane / EtOAc 2:3) followed by recrystallization from hexane.  $\nu_{\max}(\text{neat})$  2524 w, 2160 s, 2032 s, 1976 s, and 1783  $\text{cm}^{-1}$  s;  $\delta_{\text{H}}(\text{CDCl}_3)$  7.3-7.4 (2H, m, 2 x ArH), 7.01 (1H, t  $J$  7.4 Hz, ArH), 6.9-7.0 (2H, m, 2 x ArH), 5.1-5.0 (1H, m, OCH), 4.7-4.5 (2H, m,  $\text{OCH}_2$ ), 4.24 (1H, dd  $J$  10.5, 4.2 Hz,  $\text{OCH}_2$ ), 4.14 (1H, dd  $J$  10.8, 9.0 Hz,  $\text{OCH}_2$ );  $\delta_{\text{C}}(\text{CDCl}_3)$  158.1, 155.0, 130.1, 122.4, 155.0, 74.5, 67.3, 66.6;  $m/z(\text{EI})$  194 ( $\text{M}^+$ , 100), 133 (11), 107 (70), 94 (50), 79 (25), 66 (18).

Data for 4-methoxyphenylethylcarbonate 3k - reaction 30: Yield 30%. Reaction 31: yield 84%, isolated yield 79% following purification by flash chromatography (hexane / EtOAc 2:3).  $\nu_{\max}(\text{neat})$  2926 w, 1789 s, 1612 s, 1513 s, 1248 s, and 1163  $\text{cm}^{-1}$  s;

$\delta_{\text{H}}(\text{CDCl}_3)$  7.29 (2H, d  $J$  8.7 Hz, 2 x ArH), 6.94 (2H, d  $J$  8.7 Hz, 2 x ArH), 5.60 (1H, t  $J$  8.1 Hz, OCH), 4.74 (1H, t  $J$  8.4 Hz, OCH<sub>2</sub>), 4.33 (1H, t  $J$  9.0 Hz, OCH<sub>2</sub>), 3.81 (3H, s, OCH<sub>3</sub>);  $\delta_{\text{C}}(\text{CDCl}_3)$  160.7, 154.8, 127.7, 127.4, 114.6, 78.1, 71.0, 55.3;  $m/z(\text{EI})$  195 ( $\text{MH}^+$ , 12), 194 ( $\text{M}^+$ , 20), 150 (50), 149 (25), 135 (20), 122 (12), 121 (100), 119 (20), 91 (25).

### Example 3



### (1*R*,2*R*)-Cyclohexane-1,2-diammonium dichloride (5)

(Larrow, J. F., *et al.*, *J. Org. Chem.* **1994**, *59*, 193)

To a suspension of (1*R*,2*R*)-cyclohexane-1,2-diammonium L-tartrate (4) (13.7 g, 52 mmol) in MeOH (50 mL) was added a cooled solution (0°C) of acetyl chloride (27.4 mL, 385 mmol) in MeOH (50 mL). The solution was stirred at room temperature overnight. The resulting precipitate was filtered off, washed with Et<sub>2</sub>O (10 mL) and dried by suction to leave the desired product as a white powder. A second crop was obtained by diluting the mother liquor with Et<sub>2</sub>O (200 mL) and cooling for half an hour. The product was collected and dried to yield a white powder. Yield: 80%. Crystalline white powder.  $[\alpha]_{\text{D}}^{20} -16$  ( $c$  5.0, aq. 1 M HCl). <sup>1</sup>H-NMR  $\delta_{\text{H}}$  (DMSO-*d*<sub>6</sub>, 300 MHz): 1.05–1.25, 1.30–1.55 (4H, 2m, CH<sub>2</sub>CH<sub>2</sub>CHN), 1.60–1.75, 2.00–2.15 (4H, 2m, CH<sub>2</sub>CHN), 3.13–3.30 (2H, m, CHN), 8.70 (6H, br s, NH<sub>3</sub>).

**3-tert-Butylsalicylaldehyde (7)**

(Gisch, N.; Balzarini, J.; Meier, C. *J. Med. Chem.* 2007, 50, 1658)

To a stirred suspension of 2-tert-butylphenol (6) (4.55 g, 30 mmol), magnesium chloride (5.71 g, 60 mmol) and paraformaldehyde (2.08 g, 66 mmol) in THF (120 mL) at room temperature, was added triethylamine (8.35 mL, 60 mmol) dropwise. The reaction was heated to reflux for 3 hours to give an orange suspension. The crude was extracted using EtOAc (3×50 mL). A small amount of diluted HCl can be added if a permanent emulsion is formed. The organic layers were dried over MgSO<sub>4</sub> and the volatiles evaporated under low pressure to yield a pale yellow oil which did not need any further purification. It can become dark green on storage. Yield: 90%. Pale yellow oil. <sup>1</sup>H-NMR δ<sub>H</sub> (CDCl<sub>3</sub>, 300 MHz): 1.44 (9H, s, 3×CH<sub>3</sub>), 6.97 (1H, t, J = 7.5 Hz, H<sub>Ar</sub>), 7.41 (1H, dd, J = 1.5 Hz, J = 7.5 Hz, H<sub>Ar</sub>), 7.54 (1H, dd, J = 1.2 Hz, J = 7.5 Hz, H<sub>Ar</sub>), 9.88 (1H, s, CHO), 11.82 (1H, s, OH).

**3-tert-Butyl-5-chloromethylsalicylaldehyde (8)**

A mixture of 3-tert-butylsalicylaldehyde (7) (3.56 g, 20 mmol) and paraformaldehyde (1.20 g, 40 mmol) was stirred with concentrated HCl (15 mL) for 14 days, although with the first drops of concentrated HCl, the emulsion became red. The mixture was then treated with a saturated solution of Na<sub>2</sub>CO<sub>3</sub> until neutralisation. The mixture was extracted with EtOAc (3×30 mL). Organic layers were dried over MgSO<sub>4</sub> and the volatiles were evaporated under low pressure to give a beige solid which did not require further purification. Yield: 97%. Beige to red solid. <sup>1</sup>H-NMR δ<sub>H</sub> (CDCl<sub>3</sub>, 300 MHz): 1.43 (9H, s, 3×CH<sub>3</sub>), 4.59 (2H, s, CH<sub>2</sub>), 7.43, 7.52 (2H, 2d, J = 2.1 Hz, 2×H<sub>Ar</sub>), 9.87 (1H, s, CHO), 11.86 (1H, s, OH).

**3-tert-Butyl-5-diethylaminomethylsalicylaldehyde hydrochloride (9)**

To a solution of 3-tert-butyl-5-chloromethylsalicylaldehyde (8) (226.5 mg, 1 mmol) in acetonitrile (60 mL), diethylamine (1 mmol) was added dropwise to give a greenish solution. The reaction was stirred at 30°C overnight. After evaporation of volatiles, a green oil was obtained and it was used without any purification for the next step. Yield: 77%. Green oil. IR 3300, 2899, 1720. <sup>1</sup>H-NMR δ<sub>H</sub> (CDCl<sub>3</sub>, 300 MHz): 1.35 (9H, s, C(CH<sub>3</sub>)<sub>3</sub>), 1.45 (6H, t, J = 7.2 Hz, 2×CH<sub>2</sub>CH<sub>3</sub>), 3.43 (4H, q, J = 7.2 Hz, 2×CH<sub>2</sub>CH<sub>3</sub>), 4.90 (2H, s, CCH<sub>2</sub>N), 7.57, 8.03 (2H, 2d, J = 2.1 Hz, 2×H<sub>Ar</sub>), 9.98 (1H, s, CHO), 12.00 (1H, br s, OH). δ<sub>C</sub> (CDCl<sub>3</sub>, 75 MHz): 10.8, 28.3, 33.7, 45.8, 56.0, 119.5, 129.8, 130.3, 133.7, 137.0, 159.0, 195.9.

HRMS: Calcd. for C<sub>18</sub>H<sub>30</sub>NO<sub>2</sub><sup>+</sup> 292.2277, found 292.2243.

**(1*R*,2*R*)-*N,N'*-Bis(3-*tert*-butyl-5-diethylaminomethylsalicylidene)cyclohexane-1,2-diamine (10)**

- 5 (1*R*,2*R*)-cyclohexane-1,2-diammonium dichloride (5)(93.5 mg, 0.5 mmol) and NaOMe (55 mg, 1 mmol) were stirred in MeOH (10 mL) for 30 min. After that, a solution of 3-*tert*-butyl-5-diethylaminomethylsalicylaldehyde hydrochloride (9)(299.8 mg, 1 mmol) in MeOH (5 mL) was added and the solution, which became rapidly yellow, was stirred overnight at 30°C. Evaporation of MeOH was followed by addition
- 10 of a saturated solution of Na<sub>2</sub>CO<sub>3</sub> (20 mL). Organic compounds were extracted using dichloromethane (3×15 mL). It is important that the aqueous phase remains completely colourless and the organic layer changes from orange to green colour. Organic layers were dried over MgSO<sub>4</sub> and volatiles were removed under vacuum to give a greenish slurry oil which was used without any purification in the next step.
- 15 Yield: 55%. Yellow-green oil.  $[\alpha]^{20}_{\text{D}} -184.5$  (c 1.0, CHCl<sub>3</sub>). IR 3410, 2899, 1610, 1550, 830. <sup>1</sup>H-NMR  $\delta_{\text{H}}$  (CDCl<sub>3</sub>, 300 MHz): 0.99 (12H, t, *J* = 7.2 Hz, 4×CH<sub>2</sub>CH<sub>3</sub>), 1.40 (18H, s, 2×C(CH<sub>3</sub>)<sub>3</sub>), 1.50–2.05 (8H, m, (CH<sub>2</sub>)<sub>4</sub>), 2.44 (8H, q, *J* = 7.2 Hz, 4×CH<sub>2</sub>CH<sub>3</sub>), 3.40–3.50 (6H, m, 2×CHN, 2×CCH<sub>2</sub>N), 6.95, 7.17 (4H, 2d, *J* = 1.8 Hz, 4×H<sub>Ar</sub>), 8.28 (2H, s, 2×HC=N), 13.77 (2H, br s, 2×OH).  $\delta_{\text{C}}$  (CDCl<sub>3</sub>, 75 MHz): 11.9, 24.4, 29.6, 33.2, 34.8,
- 20 46.8, 57.3, 72.5, 118.4, 128.8, 129.8, 130.1, 136.9, 159.3, 165.7. HRMS: Calcd. for C<sub>38</sub>H<sub>61</sub>N<sub>4</sub>O<sub>2</sub><sup>+</sup> 605.4795, found 605.4783.

**Bis[(1*R*,2*R*)-*N,N'*-Bis(3-*tert*-butyl-5-diethylaminomethylsalicylidene)cyclohexane-1,2-diaminoaluminium(III)] oxide (11)**

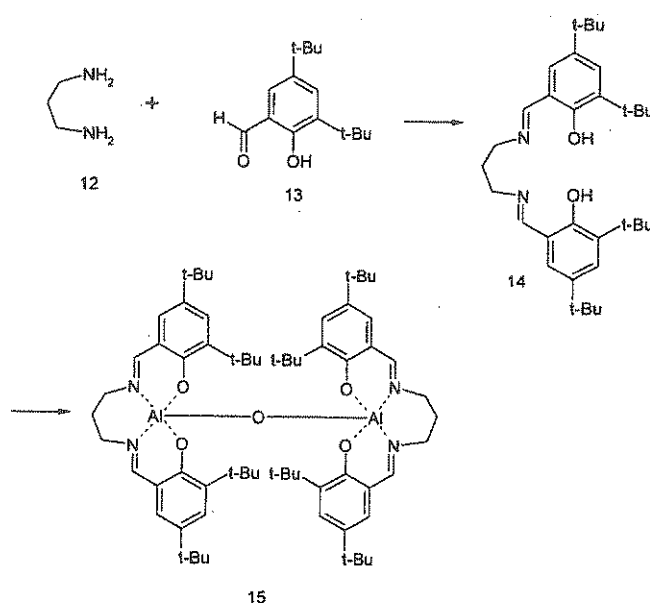
- 25 This reaction was performed under an inert atmosphere in dry conditions. The ligand (10)(1 mmol) and Al(OEt)<sub>3</sub> (324.1 mg, 2 mmol) were dissolved in toluene (10 mL). The reacting mixture was heated to reflux for 5 hours. Occasional residue of alumina could be removed by filtering through a sinter. The mother liquor was evaporated and then, H<sub>2</sub>O (30 mL) and CH<sub>2</sub>Cl<sub>2</sub>(30 mL) were added. The complex was extracted using
- 30 dichloromethane (3×20 mL) and organic layers were dried over MgSO<sub>4</sub>. Volatiles were removed under low pressure to give a pale solid, which was recrystallised using acetonitrile. Yield: 40%. Pale green solid.  $[\alpha]^{20}_{\text{D}} -522$  (c 1.0, CHCl<sub>3</sub>). IR 2865, 1626, 1548, 1440, 1027, 836, 577. <sup>1</sup>H-NMR  $\delta_{\text{H}}$  (CDCl<sub>3</sub>, 300 MHz): 1.02 (24H, t, *J* = 7.2 Hz, 8×CH<sub>2</sub>CH<sub>3</sub>), 1.46 (36H, s, 4×C(CH<sub>3</sub>)<sub>3</sub>), 1.50–2.15 (16H, m, 2×(CH<sub>2</sub>)<sub>4</sub>), 2.52 (16H, m, 8×CH<sub>2</sub>CH<sub>3</sub>), 3.10–3.15, 3.80–3.85 (4H, 2m, 4×CHN), 3.50 (8H, m, 4×CCH<sub>2</sub>N), 7.09, 7.35 (8H, 2d, *J* = 5.7 Hz, 8×H<sub>Ar</sub>), 8.19, 8.37 (4H, 2s, 4×HC=N).  $\delta_{\text{C}}$  (CDCl<sub>3</sub>, 75 MHz):
- 35 10.2, 24.7, 29.9, 30.1, 35.0, 47.1, 57.6, 73.2, 118.9, 119.2, 128.9, 135.3, 141.7,

157.2, 165.1. m/z (electrospray) 661.5 (100), 1275.9 (80), 1276.9 (72), 1277.9 (32), 1278.9 (16), 1279.9 (4)

Use of catalyst 11

- 5 Catalyst 11 was tested in the insertion of carbon dioxide into styrene oxide. The reaction was carried out with no solvent using catalyst 11 (2.5 mol %) and tetrabutylammonium bromide (2.5 mol %) under a carbon dioxide atmosphere (1 atm. Pressure). After 3 hours a conversion of 69% was obtained.

#### 10 Example 4



#### **N,N'-bis(3,5-di-tert-butylsalicylidene)propane-1,3-diamine (14)**

- 15 (Nomura, N. et al., *Chem. Eur. J.* **2007**, *13*, 4433 – 4451)
- 3,5-Di-tert-butyl salicylaldehyde (13)(1.34 mmol) and 1,3-diamino propane (12)(0.68 mmol) were mixed together and stirred at room temperature. After 1 hour, methanol (4 mL) was added forming a yellow precipitate which was allowed to stir overnight. The precipitate was extracted with CH<sub>2</sub>Cl<sub>2</sub>/water (2 x 10 mL of CH<sub>2</sub>Cl<sub>2</sub>), then the
- 20 organic layer was recovered, dried (Na<sub>2</sub>SO<sub>4</sub>) and finally evaporated under vacuum to give a yellow residue which was recrystallized from methanol to give the desired ligand (96%) as a yellow solid.  $\nu_{\text{max}}$ (ATR) 2956 s, 2530 w, 2159 s, 2031 s, 1977 s, 1630 s, and 1439 cm<sup>-1</sup> m;  $\delta_{\text{H}}$ (CDCl<sub>3</sub>) 13.82 (2H, s, 2 x OH), 8.39 (2H, s, 2 x CH=N), 7.39 (2H, d J 2.4 Hz, ArH), 7.09 (2H, d J 2.4 Hz, ArH), 3.71 (4H, t J 6.4 Hz, 2 x CH<sub>2</sub>),

2.1-2.2 (2H, m, -CH<sub>2</sub>-);  $\delta$ (CDCl<sub>3</sub>, 75 MHz): 166.5, 158.1, 140.1, 136.7, 126.7, 125.8, 56.8, 35.0, 34.1, 31.5, 29.5, 26.2; HRMS: Calcd. for C<sub>33</sub>H<sub>51</sub>N<sub>2</sub>O<sub>2</sub> (MH<sup>+</sup>) 507.3988, found 507.3951.

#### 5 Catalyst 15

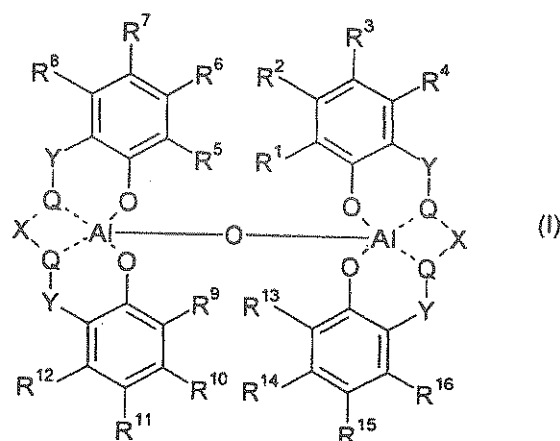
*N,N'*-bis(3,5-di-*tert*-butyl-salicylidene)propane-1,3-diamine (14)(0.19 mmol) and Al(OEt)<sub>3</sub> (0.20 mmol) were dissolved in toluene (40 mL) and heated at reflux for 4 hours. Solvents were removed under reduced pressure and H<sub>2</sub>O (20 mL) and CH<sub>2</sub>Cl<sub>2</sub> (20 mL) were added. The complex was extracted using dichloromethane (3 x 20 mL) and the organic layers were combined and dried (MgSO<sub>4</sub>). Solvents were removed under reduced pressure to give the desired complex as a yellow solid in 45% yield.  $\nu_{\text{max}}$ (ATR) 2959 m, and 1622 cm<sup>-1</sup> m;  $\delta^{\text{H}}$ (CDCl<sub>3</sub>) 1.31 (36H, s, 4 x C(CH<sub>3</sub>)<sub>3</sub>), 1.46 (36H, s, 4 x C(CH<sub>3</sub>)<sub>3</sub>), 2.1-2.2 (4H, m, 2 x CH<sub>2</sub>), 3.71 (8H, t *J* 6.9 Hz, 4 x NCH<sub>2</sub>), 7.09 (4H, d *J* 2.4 Hz, 4 x ArH), 7.39 (4H, d *J* 2.4 Hz, 4 x ArH), 8.40 (4H, s, 4 x CH=N); *m/z* found (ESI) 1079.7168 C<sub>66</sub>H<sub>97</sub>N<sub>4</sub>O<sub>5</sub>Al<sub>2</sub> (MH<sup>+</sup>) requires 1079.7090.

#### Use of catalyst 15

Catalyst 15 was tested in the insertion of carbon dioxide into styrene oxide. The reaction was carried out with no solvent using catalyst 15 (2.5 mol %) and tetrabutylammonium bromide (2.5 mol %) under a carbon dioxide atmosphere (1 atm. Pressure). After 3 hours a conversion of 14% was obtained.

## Claims

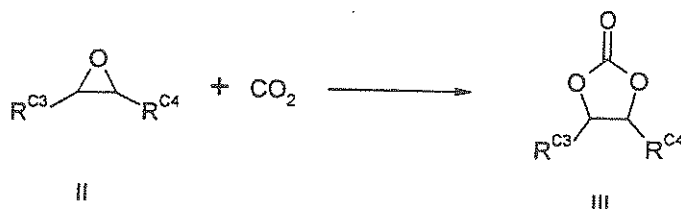
1. A process for the production of cyclic carbonates comprising contacting an epoxide with carbon dioxide in the presence of a dimeric aluminium(salen) catalyst, and a co-catalyst capable of supplying Y<sup>-</sup>, where Y is selected from Cl, Br and I, where the dimeric aluminium(salen) catalyst is of formula I:



wherein:

- Y-Q is CR<sup>C1</sup>=N or CR<sup>C1</sup>R<sup>C2</sup>-NR<sup>N1</sup>, where R<sup>C1</sup>, R<sup>C2</sup> and R<sup>N1</sup> are independently selected from H, halo, optionally substituted C<sub>1-20</sub> alkyl, optionally substituted C<sub>5-20</sub> aryl, ether and nitro;
- each of the substituents R<sup>1</sup>, R<sup>2</sup>, R<sup>3</sup>, R<sup>4</sup>, R<sup>5</sup>, R<sup>6</sup>, R<sup>7</sup>, R<sup>8</sup>, R<sup>9</sup>, R<sup>10</sup>, R<sup>11</sup>, R<sup>12</sup>, R<sup>13</sup>, R<sup>14</sup>, R<sup>15</sup>, and R<sup>16</sup>, is independently selected from H, halo, optionally substituted C<sub>1-20</sub> alkyl, optionally substituted C<sub>5-20</sub> aryl, optionally substituted C<sub>3-20</sub> heterocyclyl, ether, ammonium and nitro;
- X is either of the formula -(CH<sub>2</sub>)<sub>n</sub>- or -O-(CH<sub>2</sub>)<sub>p</sub>-O-, where n is 2, 3, 4, or 5 and p is 1, 2, or 3, or represents a divalent group selected from C<sub>5-7</sub> arylene, C<sub>5-7</sub> cyclic alkylene and C<sub>3-7</sub> heterocyclylene, which may be optionally substituted.

2. The process of claim 1, wherein the catalysed reaction is:



wherein R<sup>C3</sup> and R<sup>C4</sup> are independently selected from H, optionally substituted C<sub>1-10</sub> alkyl, optionally substituted C<sub>3-20</sub> heterocyclyl and optionally substituted C<sub>5-20</sub> aryl, or R<sup>C3</sup>

and  $R^{C4}$  form an optionally substituted linking group between the two carbon atoms to which they are respectively attached.

3. The process according to claim 2, wherein  $R^{C4}$  is H.

4. The process according to claim 2 or claim 3, wherein  $R^{C3}$  is selected from optionally substituted  $C_{1-4}$  alkyl and optionally substituted  $C_{5-7}$  aryl.

5. The process according to any one of claims 1 to 4, wherein the source of  $Y^-$  is selected from  $R_4NY$ ,  $R_3SY$ ,  $R_4PY$  and  $R_4SbY$ , where each R is independently selected from optionally substituted  $C_{1-10}$  alkyl,  $C_{3-20}$  heterocyclyl and  $C_{5-20}$  aryl groups and one R can be an acyl group.

6. The process according to claim 5, wherein the source of  $Y^-$  is  $R_4NY$ , where each R is independently  $C_{1-10}$  alkyl and Y is selected from I, Br and Cl.

7. The process according to claim 6, wherein the source of  $Y^-$  is  $Bu_4NBr$ .

8. The process according to any one of claims 1 to 7, wherein the aluminium(salen) catalyst of formula I is symmetrical, such that  $R^1=R^{13}$ ,  $R^2=R^{14}$ ,  $R^3=R^{15}$ ,  $R^4=R^{16}$ ,  $R^5=R^9$ ,  $R^6=R^{10}$ ,  $R^7=R^{11}$ , and  $R^8=R^{12}$ .

9. The process according to claim 8, wherein  $R^1$ ,  $R^5$ ,  $R^9$ , and  $R^{13}$  are identical,  $R^2$ ,  $R^6$ ,  $R^{10}$  and  $R^{14}$  are identical,  $R^3$ ,  $R^7$ ,  $R^{11}$ , and  $R^{15}$  are identical, and  $R^4$ ,  $R^8$ ,  $R^{12}$  and  $R^{16}$  are identical.

10. The process according to any one of claims 1 to 9, wherein X is  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3.

11. The process according to claim 10, wherein X is  $-C_2H_4-$  or  $-C_3H_6-$ .

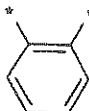
12. The process according to any one of claims 1 to 9, wherein X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted.

13. The process according to claim 12, wherein X represents:

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14. The process according to claim 12, wherein X represents:



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15. The process according to any one of claims 1 to 14, wherein Y-Q is  $\text{CR}^{\text{C1}}=\text{N}$ .

16. The process according to claim 15, wherein Y-Q is  $\text{CH}=\text{N}$ .

- 10 17. The process according to any one of claims 1 to 16, wherein  $\text{R}^4 = \text{R}^8 = \text{R}^{12} = \text{R}^{16} = \text{H}$ .

- 15 18. The process according to any one of claims 1 to 17, wherein  $\text{R}^1, \text{R}^2, \text{R}^3, \text{R}^5, \text{R}^6, \text{R}^7, \text{R}^9, \text{R}^{10}, \text{R}^{11}, \text{R}^{13}, \text{R}^{14}$ , and  $\text{R}^{15}$  are independently selected from H,  $\text{C}_{1-7}$  alkyl, ether and nitro.

19. The process according to any one of claims 1 to 17, wherein the amount of catalyst of formula I is from 0.1 to 10 mol%.

- 20 20. The process according to claim 19, wherein the amount of catalyst of formula I is from 0.1 to 2.5 mol%.

21. The process according to any one of claims 1 to 20, wherein the amount of the source of Y- is 0.1 to 10 mol%.

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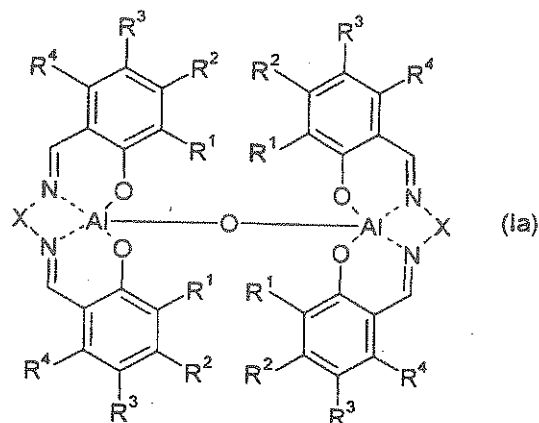
22. The process according to claim 21, wherein the amount of the source of Y- is 0.1 to 2.5 mol%.

- 30 23. The process according to any one of claims 1 to 22, wherein the reaction is carried out at a temperature of between 0 and  $40^\circ\text{C}$  and a pressure of between 0.5 and 2 atm.

24. The process according to any one of claims 1 to 23, wherein the reaction is carried out for 3 to 24 hours.

25. A process for the production of dimeric aluminium(salen) catalysts of formula

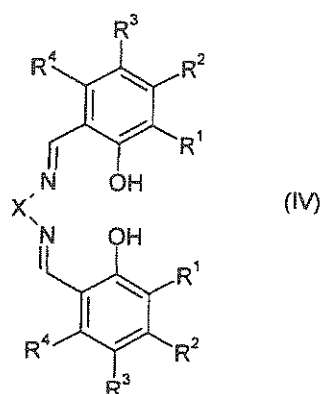
5 la:



wherein each of  $R^1$ ,  $R^2$ ,  $R^3$  and  $R^4$  is independently selected from H, halo, optionally substituted  $C_{1-20}$  alkyl, optionally substituted  $C_{5-20}$  aryl, optionally substituted  $C_{3-20}$  heterocyclyl, ether, ammonium and nitro;

10 X is either of the formula  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where  $n$  is 2, 3, 4, or 5 and  $p$  is 1, 2, or 3, or represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted.

comprising treating a salen ligand of formula IV:

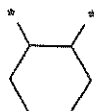


15 with  $Al(OR^0)_3$  in an organic solvent, wherein  $R^0$  is  $C_{1-4}$  alkyl or  $C_{5-7}$  aryl.

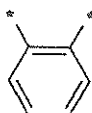
26. The process according to claim 25, wherein the organic solvent is an aprotic solvent.

20 27. The process according to claim 26, wherein the aprotic organic solvent is toluene.

28. The process according to any one of claims 25 to 27, wherein  $R^0$  is  $C_{1-4}$  alkyl.
29. The process according to claim 28, wherein  $R^0$  is ethyl.
- 5 30. The process according to any one of claims 25 to 29, wherein X is  $-(CH_2)_n-$  or  $-O-(CH_2)_p-O-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3.
31. The process according to claim 30, wherein X is  $-C_2H_4-$ .
- 10 32. The process according to any one of claims 25 to 29, wherein X represents a divalent group selected from  $C_{5-7}$  arylene,  $C_{5-7}$  cyclic alkylene and  $C_{3-7}$  heterocyclylene, which may be optionally substituted.
- 15 33. The process according to claim 32, wherein X represents:

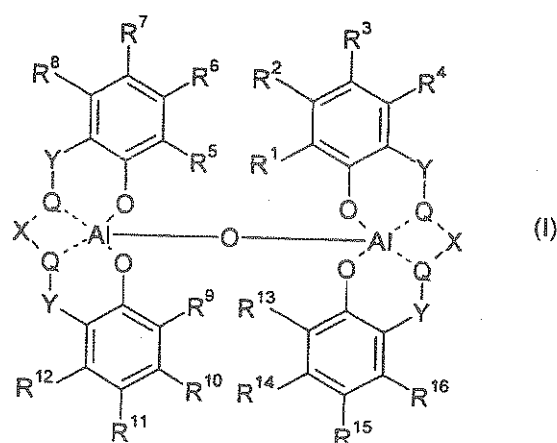


34. The process according to claim 32, wherein X represents:



- 20 35. The process according to any one of claims 25 to 34, wherein  $R^4$  is H.
36. The process according to any one of claims 25 to 35, wherein  $R^1$ ,  $R^2$  and  $R^3$  are independently selected from H,  $C_{1-7}$  alkyl, ether and nitro.
- 25 37. A dimeric aluminium(salen) catalyst of formula I:

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wherein:

Y-Q is  $\text{CR}^{\text{C1}}=\text{N}$  or  $\text{CR}^{\text{C1}}\text{R}^{\text{C2}}-\text{NR}^{\text{N1}}$ , where  $\text{R}^{\text{C1}}$ ,  $\text{R}^{\text{C2}}$  and  $\text{R}^{\text{N1}}$  are independently selected from H, halo, optionally substituted  $\text{C}_{1-20}$  alkyl, optionally substituted  $\text{C}_{5-20}$  aryl, ether and nitro;

each of the substituents  $\text{R}^1$ ,  $\text{R}^2$ ,  $\text{R}^3$ ,  $\text{R}^4$ ,  $\text{R}^5$ ,  $\text{R}^6$ ,  $\text{R}^7$ ,  $\text{R}^8$ ,  $\text{R}^9$ ,  $\text{R}^{10}$ ,  $\text{R}^{11}$ ,  $\text{R}^{12}$ ,  $\text{R}^{13}$ ,  $\text{R}^{14}$ ,  $\text{R}^{15}$ , and  $\text{R}^{16}$ , is independently selected from H, halo, optionally substituted  $\text{C}_{1-20}$  alkyl, optionally substituted  $\text{C}_{5-20}$  aryl, optionally substituted  $\text{C}_{3-20}$  heterocyclyl, ether, ammonium and nitro;

X is either of the formula  $-(\text{CH}_2)_n-$  or  $-\text{O}-(\text{CH}_2)_p-\text{O}-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3, or represents a divalent group selected from  $\text{C}_{5-7}$  arylene,  $\text{C}_{5-7}$  cyclic alkylene and  $\text{C}_{3-7}$  heterocyclylene, which may be optionally substituted,

wherein:

(a) at least one of  $\text{R}^1$ ,  $\text{R}^2$ ,  $\text{R}^3$ ,  $\text{R}^4$ ,  $\text{R}^5$ ,  $\text{R}^6$ ,  $\text{R}^7$ ,  $\text{R}^8$ ,  $\text{R}^9$ ,  $\text{R}^{10}$ ,  $\text{R}^{11}$ ,  $\text{R}^{12}$ ,  $\text{R}^{13}$ ,  $\text{R}^{14}$ ,  $\text{R}^{15}$ , or  $\text{R}^{16}$  is nitro; or

(b) at least one of  $\text{R}^1$ ,  $\text{R}^2$ ,  $\text{R}^3$ ,  $\text{R}^4$ ,  $\text{R}^5$ ,  $\text{R}^6$ ,  $\text{R}^7$ ,  $\text{R}^8$ ,  $\text{R}^9$ ,  $\text{R}^{10}$ ,  $\text{R}^{11}$ ,  $\text{R}^{12}$ ,  $\text{R}^{13}$ ,  $\text{R}^{14}$ ,  $\text{R}^{15}$ , or  $\text{R}^{16}$  is ether.

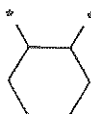
38. The catalyst according to claim 37, wherein the catalyst of formula is symmetrical, such that  $\text{R}^1=\text{R}^{13}$ ,  $\text{R}^2=\text{R}^{14}$ ,  $\text{R}^3=\text{R}^{15}$ ,  $\text{R}^4=\text{R}^{16}$ ,  $\text{R}^5=\text{R}^9$ ,  $\text{R}^6=\text{R}^{10}$ ,  $\text{R}^7=\text{R}^{11}$ , and  $\text{R}^8=\text{R}^{12}$ .

39. The catalyst according to claim 38, wherein  $\text{R}^1$ ,  $\text{R}^5$ ,  $\text{R}^9$ , and  $\text{R}^{13}$  are identical,  $\text{R}^2$ ,  $\text{R}^6$ ,  $\text{R}^{10}$  and  $\text{R}^{14}$  are identical,  $\text{R}^3$ ,  $\text{R}^7$ ,  $\text{R}^{11}$ , and  $\text{R}^{15}$  are identical, and  $\text{R}^4$ ,  $\text{R}^8$ ,  $\text{R}^{12}$  and  $\text{R}^{16}$  are identical.

40. The catalyst according to any one of claims 37 to 39, wherein X is  $-(\text{CH}_2)_n-$  or  $-\text{O}-(\text{CH}_2)_p-\text{O}-$ , where n is 2, 3, 4, or 5 and p is 1, 2, or 3.

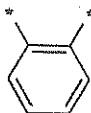
41. The catalyst according to claim 40, wherein X is  $-\text{C}_2\text{H}_4-$ .
42. The catalyst according to any one of claims 37 to 39, wherein X represents a  
5 divalent group selected from  $\text{C}_{5-7}$  arylene,  $\text{C}_{5-7}$  cyclic alkylene and  $\text{C}_{3-7}$  heterocyclylene, which may be optionally substituted.

43. The catalyst according to claim 42, wherein X represents:



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44. The catalyst according to claim 42, wherein X represents:



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45. The catalyst according to any one of claims 37 to 44, wherein Y-Q is  $\text{CR}^{\text{Q}}=\text{N}$ .
46. The catalyst according to claim 45, wherein Y-Q is  $\text{CH}=\text{N}$ .

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47. The catalyst according to any one of claims 37 to 46, wherein  $\text{R}^4 = \text{R}^8 = \text{R}^{12} = \text{R}^{16} = \text{H}$ .
48. The catalyst according to any one of claims 37 to 47, wherein  $\text{R}^1, \text{R}^2, \text{R}^3, \text{R}^5, \text{R}^6, \text{R}^7, \text{R}^9, \text{R}^{10}, \text{R}^{11}, \text{R}^{13}, \text{R}^{14}$ , and  $\text{R}^{15}$  are independently selected from H,  $\text{C}_{1-7}$  alkyl, ether and nitro.