Enantioselective Catalytic Aziridinations and Asymmetric Nitrene Insertions into CH Bonds

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I. Introduction

Aziridines are the nitrogen analogues of epoxides and exhibit similar reactivity patterns as electrophilic reagents.[1] They undergo highly regio- and stereoselective transformations and, therefore, are useful building blocks for organic synthesis.[2] In addition, aziridines may exhibit antitumor or antibiotic activity or still other biological properties, which makes them attractive synthetic targets in their own right.[3] The asymmetric synthesis of aziridines[4,5] and their applications[6] have been reviewed recently. This review will focus on catalytic asymmetric methods for aziridine synthesis based on formal nitrene transfer to olefins or, alternatively, on carbene transfer to imines. The insertion of nitrenes into CH bonds, which may compete with aziridination, will be included, as well as some systems for nitrene transfer which are either not (yet) catalytic nor enantioselective, but may have the potential of becoming so. The topic has been partially reviewed in 1996[7] and, more comprehensively, in 1997[8] and 1999,[9] although the latter reviews are not generally accessible. The literature has been reviewed until end 2002.

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II. Aziridination via Nitrene Transfer to Olefins

A. Background

The possibility of transferring nitrenes to olefins by means of transition metal catalysts was recognized well before asymmetric catalysis was established. Early attempts using tosyl azide in conjunction with Cu(I) catalysts met only limited success, however.[10] Model systems destined to mimic catalysis by cytochrome P-450, capable of effecting oxygen transfer from iodosylbenzene to organic acceptors, in the presence of metal tetraphenylporphyrins were developed.[11] The analogous formal nitrene transfer appeared feasible, once the required nitrogen precursors, sulfonyliminoiodinanes, were available.[12,13] Breslow and Gellman reported inter- and intramolecular CH insertions by tosylimino phenyliodinane (TsN=IPh) in the presence of Mn(III)- or Fe(III)-porphyrins[14] or $[Rh_2(OAc)_4]$.[15] The aziridination of olefins by TsNI=Ph under catalysis by Fe- or Mn-porphyrins was developed by Mansuy et al.,[16] while Groves and Takahashi described the stoichiometric aziridination of olefins with an in situ generated (porphyrine)manganese−imido complex.[17] Although at the time these investigations were of only limited practical applicability, they prepared the ground for the development of efficient systems for synthetic catalytic nitrene transfer.

B. Cu-Catalyzed Aziridination

1. Aziridination with Bis(Oxazoline) Ligands

The group of Evans developed the formal nitrene transfer to olefins with TsN=IPh into a synthetically useful method.[18] Cu(I) and Cu(II) salts in MeCN were found to be the most efficient catalyst/solvent combination for nitrene transfer. Yields of aziridines were in the range of 23−95% when the olefin was used in 5-fold excess over TsN=IPh and in the presence of 5−10 mol % of catalyst. The aziridination of oct-4-

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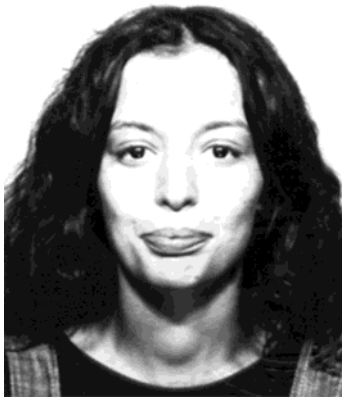
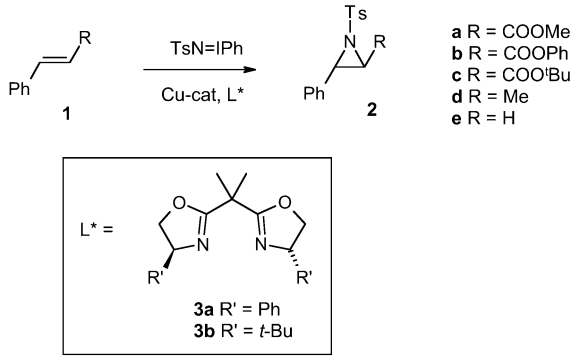
Professor Paul Müller received his Ph.D. in chemistry at the Swiss Federal Institute of Technology, Zurich (ETHZ), in 1966. Subsequently, he spent three years as research associate at the University of Illinois at Chicago and at the University of Chicago. He joined the University of Geneva as "Chef de Travaux" in 1969 and was promoted to the rank of full professor in 1982. He is the author of close to 200 publications. His research interests are in the areas of asymmetric catalytic transfer of carbenes and nitrenes, desymmetrization of small ring compounds with nucleophiles and bases, and reactive intermediates.



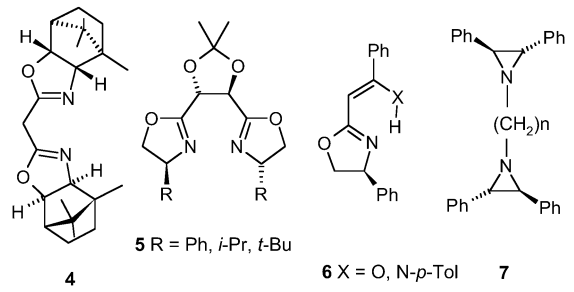
Corinne Fruit was born in France in 1975. She received her Ph.D. degree from the University of Rouen in 2001, where she worked with Professor Guy Queguiner on synthesis and metalation of diazinic thioamides and on Negishi cross-coupling reaction. She undertook postdoctoral studies at the University of Ottawa in Canada with Professor Alex Fallis in collaboration with Aegera Therapeutics Inc. (Montreal), working on the synthesis of heterocyclic compounds at therapeutics aim (neuronal protection). She currently holds a postdoctoral position at the University of Geneva with Professor Paul Müller, working on asymmetric catalysis in transfer of nitrenes.

ene was stereospecific; however, in the case of *trans*-stilbene and β-methylstyrene, only partial stereospecificity was observed, and stereospecificity was found dependent on the ligand or counterion of the metal. Subsequently, enantioselective nitrene transfer was achieved with a selection of bis(oxazoline) ligands such as **3**.[19] Reactions were carried out with 5% of CuOTf and 6% of ligand and required ca. 24 h to go to completion. Cinnamate esters (**1a**−**c**) were particularly well suited as substrates and afforded

Scheme 1



Scheme 2



aziridines **2** with enantioselectivities in the range of 94−97% and with yields of 60−63% in benzene (with olefin as limiting reagent). However, simple olefins such as *trans*-β-methylstyrene (**1d**) and styrene (**1e**) were significantly less suited and gave only 70% and 63% ee, respectively. Representative examples are given in Table 1.

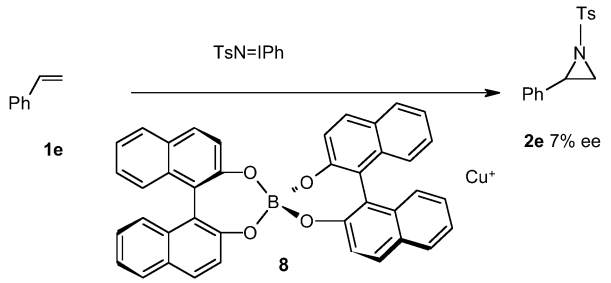
The work of Evans inspired the development of bis(oxazoline) analogues[20] which were tested with styrene as substrate. One of the earliest reports on asymmetric aziridination of styrene (**1e**) is that of Masamune, who isolated the aziridine **2e** in 91% yield and with an ee of 88% with the camphor-derived bis(oxazoline) ligand **4** (Scheme 2).[21] However, this impressive result could not be reproduced.[19] Tartrate-derived bis(oxazoline) ligands (**5**) were also tested for aziridination of styrene[22] and conjugated dienes[23] but produced only marginal enantioselectivity. Improvement of the aziridination system was attempted by several groups. Thus, Andersson et al. proposed the replacement of TsN═IPh by NsN═IPh (*p*-nitrophenylsulfonyl iminoiodinane) in order to improve yields of aziridines. Enantioselectivities comparable to those achieved by Evans with the same bis(oxazoline) ligands were obtained.[24] In addition, Andersson investigated anionic di-imine ligands **6** and reported enantioselectivities of up to 34% for the same reaction,[25] and an ee of 33% with the chiral bis(aziridine) ligand **7**.[26]

Llewellyn et al. observed that the enantioselectivity of the aziridination of styrene with bis(oxazoline)-

Table 1. Aziridination of Olefins with Bis(oxazoline)−Copper Complexes

olefin	cat.	solvent, conditions	yield, %	ee, %	conf.
methyl cinnamate (**1a**)	**3a**	C_6H_6 (24 h, 21 °C)	63	94	(*S*)
phenyl cinnamate (**1b**)	**3a**	C_6H_6 (24 h, 21 °C)	64	97	(*S*)
t-butyl cinnamate (**1c**)	**3a**	C_6H_6 (24 h, 21 °C)	60	96	(*S*)
trans-β-methylstyrene (**1d**)	**3b**	MeCN (3 d, −20 °C)	62	70	(*S*)
styrene (**1e**)	**3b**	styrene (2.5 h, 0°C)	89	63	(*R*)

Scheme 3



copper catalysts was dependent upon the counterion.[27] This suggested the possibility of asymmetric aziridinations by means of association of the copper ion with a chiral anion via ion pairing. This concept was realized by means of a chiral boronate having binaphthol ligands (**8**), although at this time, the observed enantioselectivity is only 7% (Scheme 3).

The group of Hutchings prepared a copper exchanged zeolite (CuHY) which was found highly efficient as heterogeneous catalyst for the aziridination of olefins using TsN=IPh.[28] Modification of this zeolite with bis(oxazoline) ligands such as **3a**,**b** lead to an enantioselective aziridination catalyst. The aziridinations were studied using styrene (**1e**) in acetonitrile as model substrate. The highest yields of aziridine **2e** were obtained when the nitrene donor was added in slight excess over styrene, and NsN=IPh was found to be the most efficient nitrene source. Under carefully controlled conditions, the yield of **2e** reached 77% with 95% ee at 25 °C or, alternatively, 99% yield with 80% ee. Thus the heterogeneous catalyst can give higher enantioselectivity than the corresponding homogeneous catalyst.[29] The details of the system are not yet fully understood, but an EPR study provided direct experimental evidence for a copper(II)−bis(oxazoline) complex inside the Y zeolite pores.[30] The catalyst may be recovered; leaching of Cu from the zeolite can be limited, and the leached copper apparently does not interfere with the aziridination process.[31]

2. Aziridination with Chiral Diimine-Based Catalysts

The group of Jacobsen optimized chiral 1,2-diimine derivatives[32] with copper(II) salts and found high enantioselectivities for olefins carrying at least one aromatic substituent.[33] The crucial step in the catalyst design was the recognition that multiple coordination sites on the copper were crucial to catalysis of the aziridination. Two coordination sites were superior to four. The best ligand was the bis(imine) **9** derived from 1,2-diaminocyclohexane and 2,6-dichlorobenzaldehyde (Scheme 4). The Jacobsen system is complementary to the one developed by Evans in the sense that it affords high enantioselectivities with *cis*-olefins, while the latter method is more suited for the trans isomers. The most spectacular result of Jacobsen is that obtained with 6-cyano-2,2-dimethylchromene (**1i**), which afforded the aziridine **2i** with >98% ee (Scheme 4). However, aziridination of simple olefins resulted only in low enantioselectivities. Thus, styrene (**1e**) reacted with an ee of only 66% (Table 2). Furthermore, the Jacobsen system

Scheme 4

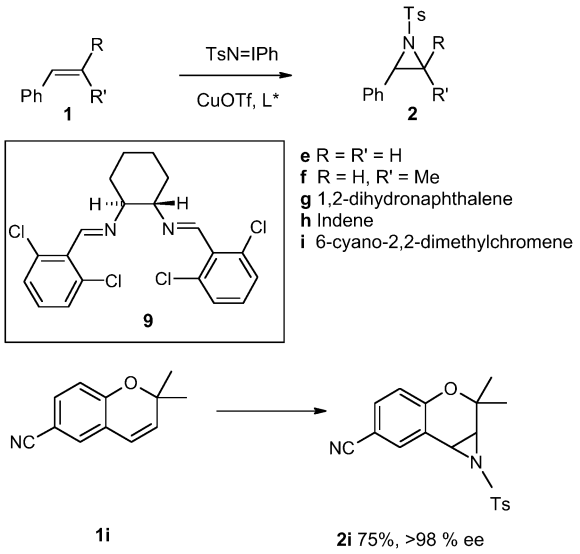


Table 2. Cu-Catalyzed Aziridination of Olefins with Jacobsen's Ligand 9[a]

olefin	aziridine, yield, %	ee, %	abs. conf.
styrene (**1e**)	79	66	(*R*)
cis-*β*-methylstyrene (**1f**)	79 (*c*/*t* = 3:1)	67 (cis)	(1*R*,2*S*)
		81 (trans)	(1*S*,2*S*)
1,2-dihydronaphthalene (**1g**)	70	87	(1*R*,2*S*)
indene (**1h**)	50	58	(1*R*,2*S*)
6-cyano-2,2-dimethylchromene (**1i**)	75	>98	(3*R*,4*R*)

[a] −40 to −78 °C, CH_2Cl_2, 4 Å sieves, 5−10 mol % of Cu, 6−12 mol % of **9**.

suffers from low turnovers, requiring 5−10 mol % of catalyst.

In variation of the approach of Jacobsen, Kim, and collaborators applied C_2-symmetric bis(ferrocenyldiamines) **10** as ligands for Cu-catalyzed asymmetric aziridinations and observed acceptable yields and enantioselectivities with simple olefins, such as styrene or hexene.[34] These reactions proceeded in 3 h at room temperature with a 10-fold excess of olefin and 10 mol % of catalyst. Along similar lines, a chiral salen type ligand derived from binaphthyldiimine (**11**) was tested with styrene and was found to be unsatisfactory, giving enantioselectivities in the range of 20%; however, the same ligand was more effective with indene (**1h**) and with cinnamate esters (Table 3).[35]

A series of acyclic and cyclic enol derivatives were subjected to Cu-catalyzed asymmetric aziridination with TsN=IPh and ligands **3a** and **9**, and enantioselectivities of up to 52% were achieved.[36]

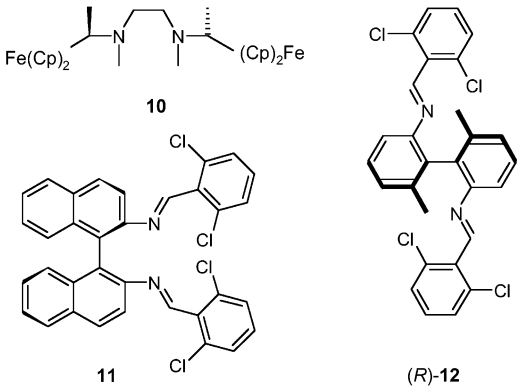
Scott et al. introduced monomeric copper complexes of biaryl Schiff bases **12** (Scheme 5) as catalysts for aziridination with TsN=IPh.[37] These catalysts gave up to 99% ee in the aziridination of 6-acyl-2,2-dimethylchromene (**1j**) and 88−98% in that of cinnamate esters **1c**. Essentially linear plots were obtained for ee_{ligand} versus $ee_{product}$, and the ee of the product did not vary significantly with % conversion. These results are consistent with the presence of a

Table 3. Cu-Catalyzed Aziridination of Olefins with Ligands 10[a] and 11[b]

olefin	ligand	aziridine, yield, %	ee, %	abs. conf.
trans-β-methylstyrene (**1d**)	**10**	75	69	n.i.
styrene (**1e**)	**10**	88	74	n.i.
trans-stilbene (**1l**)	**10**	65	68	n.i.
1-hexene (**1m**)	**10**	68	70	n.i.
methyl cinnamate (**1a**)	**11** (20 °C)	90	69	(2*S*,3*R*)
phenyl cinnamate (**1b**)	**11**(−20 °C)	90	88	(2*S*,3*R*)
t-butyl cinnamate (**1c**)	**11**(−20 °C)	91	97	(2*S*,3*R*
styrene (**1e**)	**11** (20 °C)[c]	92	22	(*S*)
indene (**1h**)	**11** (20 °C)	25	64	(1*S*,2*R*)
indene (**1h**)	**11**(−20 °C)	25	73	(1*S*,2*R*)

[a] Conditions:[34] in MeCN, r.t.; [olefin] = 7.5 mmol; [TsN=IPh] = 0.73 mmol; [catalyst] = 0.08 mmol, 3 h. (b) Conditions:[35] in CH_2Cl_2 with MS 4Å; [olefin] = 1.23 mmol; [TsN=IPh] = 0.25 mmol; [catalyst] = 0.013 mmol; 24 h. (c) Without MS.

Scheme 5

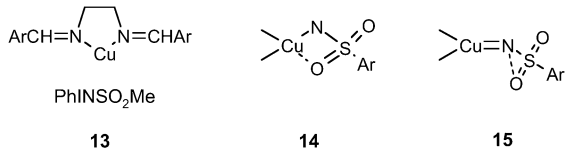


catalyst which contains one ligand only, and whose nature does not change during the course of the reaction. Simple alkenes such as styrene (**1e**) were converted with lower selectivities. This lack of selectivity was attributed to the absence of secondary binding interactions in the case of styrenes lacking polar substituents (Table 4). Reactions proceeded well in CH_2Cl_2 or MeCN within minutes at room temperature. Thus the Scott system is superior to the other Cu-catalyzed aziridinations with respect to reactivity, and comparable with respect to selectivity.

3. Mechanism of the Cu-Catalyzed Aziridination

The main mechanistic issues of the Cu-catalyzed aziridination of olefins are the formation of a copper−nitrene intermediate, the oxidation state of the metal, and the nature of the nitrene transfer. Experimental evidence for a metallonitrene intermediate has been

Scheme 6



provided by Jacobsen.[38] The enantioselectivity of aziridination of several olefins in the presence of Cu-**9** catalyst was found to be independent of the substituents on the iodobenzene moiety, demonstrating that the iodobenzene is not involved in the transfer of the nitrene. This rules out a Lewis acid mechanism involving PhI in the selectivity-determining step. In addition, when tosylnitrene (TsN:) was generated photochemically from TsN_3 in the presence of Cu-**9**, aziridination of styrene proceeded with the same enantioselectivity as that with TsN=IPh catalyzed by Cu-**9**. DFT calculations of a model for the Jacobsen system (**13**) revealed a copper-bound sulfonyl nitrene (**14**) as reactive intermediate, in which one of the oxygen atoms of the sulfonyl group is coordinated to the metal (Scheme 6).[39] In contrast, DFT calculations for the metallonitrene (**15**) of the Scott system showed no such metal−oxygen interaction but, rather, an interaction between one of the sulfonyl oxygens with the nitrogen of the nitrene (Scheme 6).[40]

The involvement of a metallonitrene intermediate seems now well accepted. Kinetic investigations of Jacobsen revealed that the reaction was second-order overall, i.e., first-order with respect to catalyst concentration and olefin; this is consistent with rate-limiting attack of the metallonitrene on the olefin.[38] However, further kinetic studies of Andersson and Norrby showed that the reaction is zero-order in olefin, despite the fact that single experiments appear to obey first-order kinetics.[39] This corresponds to rate-limiting formation of the metallonitrene, in agreement with the DFT calculations.

Since bis(oxazoline) catalysts derived from Cu(I) and Cu(II) result in the same level of asymmetric induction, it was suggested that the metal is in the +II oxidation state in the catalyst, and TsN=IPh may oxydize Cu(I) to Cu(II). However, the investigations of the Jacobsen group suggested a Cu(III)−nitrene species as reactive intermediate in a Cu(I)/Cu(III) catalytic cycle. The calculations of Andersson and Norrby confirm that the active catalyst is a Cu(I) species, and that Cu(II) may enter the Cu(I)/Cu(III) catalytic cycle via reaction with TsN=IPh. Scott, in turn argued that conversion of Cu(I) to Cu(II) is not essential for catalytic activity; either Cu(II) is also

Table 4. Cu-Catalyzed Aziridination of Olefins with the Biphenyl Ligand (*R*)-12[a]

olefin (**1**)	*t*	aziridine (**2**) yield, %	ee, %	abs. conf.
t-butyl cinnamate (**1c**)	−40 °C	77	89	(2*S*,3*R*) (−)
t-butyl *p*-bromocinnamate (**1c′**)	r.t.	45	96	(−)
t-butyl *p*-bromocinnamate (**1c′**)	−40 °C	59	98	(−)
trans-β-methylstyrene (**1d**)	−40 °C	88 (*t*/*c* = 97:3)	28 (trans)	(2*R*,3*R*)
styrene (**1e**)	r.t.	91	27	n.i.
trans-stilbene (**1l**)	−40 °C	66	5.1	n.i.
1,2-dihydronaphthalene (**1g**)	r.t.	60	54	(2*S*,3*R*)
6-acylchromene (**1j**)	−40 °C	87	99	n.i.

[a] In CH_2Cl_2, 5 mol % of metal salt, 6 mol % of ligand, 5 equiv of olefin, 1 equiv of TsN=IPh.

an active catalyst, or a fraction of it is reduced in situ to Cu(I).

The stereochemistry of the aziridination is ambiguous. Evans reported stereospecific aziridination of *cis*-oct-4-ene with Cu catalysts, but aziridination of *cis*-*β*-methylstyrene (**1d**) and *cis*-stilbene was accompanied by formation of the trans aziridines in various amounts, depending on the counterion. Strongly coordinating counterions such as acetylacetonate or chloride favored formation of the *trans*-aziridine. Experiments using radical clocks to provide evidence for a two-step radical pathway for aziridination were not conclusive, however. In contrast, the aziridinations with Jacobsen's Cu-diimine system were clearly not stereospecific, but aziridination of *cis*-stilbene using the Cu-diimine ligand of Scott afforded a 5:95 trans/cis mixture of aziridines (at −40 °C), and no *cis*-aziridine was ever observed upon reaction of the *trans*-cinnamate esters.[37] Thus, the current experimental evidence suggests the existence of two competitive pathways for aziridination: a concerted nitrene transfer, by analogy to the concerted and stereospecific transfer of metallocarbenes to olefins,[41] and a two-step pathway, probably involving radicals.[42] The radical pathway is favored by substrates providing significant stabilization of the intermediate radicals.

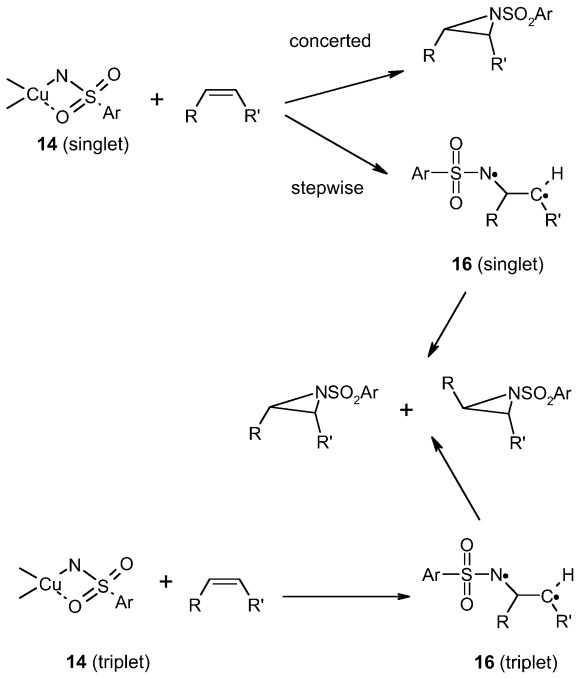
The DFT calculations of Andersson and Norrby indicate that the ground state of the intermediate metallonitrene is a triplet, which is energetically very close to the singlet. Stereospecific aziridination may occur from the singlet metallonitrene (**14**), and the nonspecific aziridination from its triplet state, or from the intermediate singlet biradical **16**, formed upon radical addition of the metallonitrene **14** to the olefin.

The electronic substituent effect of the aziridination has been examined by competition experiments. Müller et al. reported a ρ-value of −0.49 (vs σ^+) for reaction of substituted styrenes with NsN═IPh/[Cu(acac)$_2$] in CH_2Cl_2,[43] while Scott et al. found $\rho = -0.65$ (vs σ) for cinnamate esters reacting with TsN═IPh in the presence of Cu-**12**. This is in the range typical for concerted carbene transfer to olefins[44] and indicates an early transition state with only minor buildup of positive charge. Pérez and co-workers fitted the relative rate constants for TsN═IPh aziridination of substituted styrenes with a Cu-hydridotrispyrazolylborate catalyst in CH_2Cl_2 with a four-parameter equation using Hammett's σ^+ and Jackson's $\sigma^\cdot$ constants for radicals.[45] Values for $\rho^+ = -0.28$ and $\rho^\cdot = +0.34$ were deduced and interpreted in terms of an electrophilic nitrene with radical character.[46] The significance of this result is however difficult to assess: The rate constants included only six experimental points in a very narrow rate range of 0.4 log units, which is an insufficient base for a four-parameter equation.

4. Recent Developments

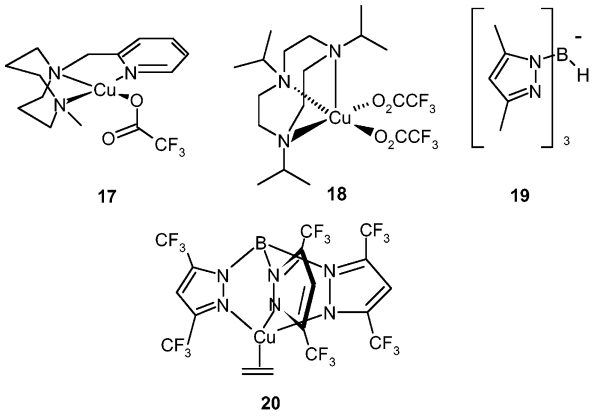
Several new achiral ligands have been introduced for Cu-catalyzed aziridinations with TsN═IPh with potential for development of asymmetric reactions. Thus Halfen et al. described the synthesis of a Cu-1-(2-pyridylmethyl)-5-methyl-1,5-diazacyclooctane trifluoroacetate complex **17** which exhibited remarkable efficiency in the aziridination of styrene (**1e**) (reaction within 1.5 h).[47] The Cu-1,4,7-tri*iso*propyl-1,4,7-triazacyclononane-bis(trifluoroacetate) (**18**) was equally reactive,[48] while catalysts having two pyridylmethyl-appended diazacycloalkane ligands exhibited significantly lower reactivity.[49] A procedure for in situ generation of Brookhart's Cu-tris(3,5-trimethylpyrazolyl)borate catalyst (**19**) was developed; the catalyst exhibited moderate activity with arene-substituted olefins but was less satisfactory with olefins having only aliphatic substituents.[50] The tris(pyrazolyl)-borate ligands were stabilized with trifluoromethyl substituents and formed copper(I) ethylene adducts (**20**), which were efficient catalysts for aziridination.[51]

Scheme 7

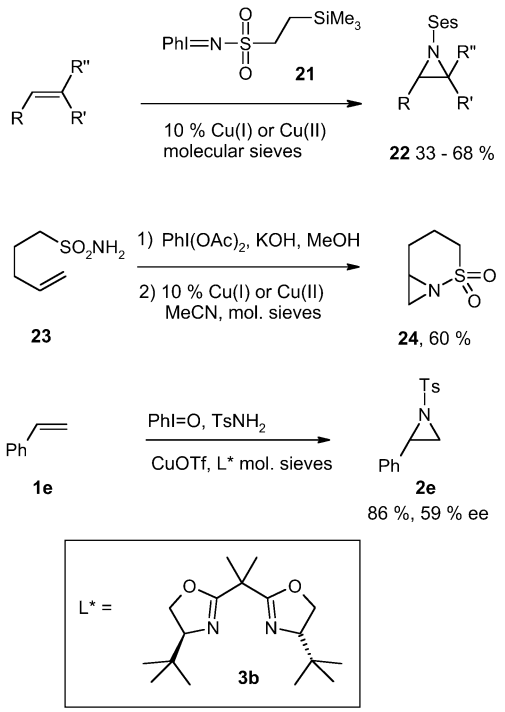


The synthetic potential of the aziridination was markedly improved by the discovery of Dauban and Dodd that, contrary to the generally held opinion,[52] phenyl imino iodinanes derived from aliphatic sulfonamides are isolable. They introduced SesN═IPh (**21**) (Ses = trimethylsilylethanesulfonyl) as aziridination reagent and obtained aziridination yields in the range of 40−68% for simple olefins with CuOTf as catalyst.[53] The Ses-reagent was used for aziridination of 11-pregnen-3,20-dione which proceeded in 53% yield.[54] The successful isolation of phenyl iminoiodinanes derived from unsaturated sulfonamides opened the possibility of intramolecular aziridinations which proceeded in acceptable yields with CuOTf as catalyst,[55] and a representative example is given below (Scheme 9). The asymmetric intramolecular aziridination has been reported recently, but with Rh(II) rather than Cu(I) catalysts (see below). A still more recent promising development is the in situ generation of phenyl iminoiodinanes from sulfonamides[56] and sulfamates[57] with iodosylbenzene in the presence of molecular sieves under conditions used for aziridination. The reaction conditions are

Scheme 8



Scheme 9



compatible with the presence of asymmetric ligands of the bis(oxazoline)-type **3**.

Another direction of research in view of asymmetric aziridination deals with replacement of the iminoiodinane as nitrene precursor. An obvious alternative is chloramine-T hydrate [TsNClNa·$(H_2O)_3$]. A Cu-*N*-(2-pyridinylmethylene)-1-pentanamine catalyst produced aziridination of olefins in up 76% yield.[58] The procedure does not require the hazardous dehydration of the chloramine trihydrate, which is necessary for the procedure of Komatsu with CuOTf as catalyst,[59] or in the aziridination catalyzed by phenyltrimethylammonium tribromide[60] or pyridinium hydrobromide perbromide.[61] The diastereoselectivity of the aziridination of chloramine-T catalyzed by phenyltrimethylammonium tribromide may differ from that catalyzed with copper salts. Thus aziridination of 4-*tert*-butyldiphenylsilyloxy-cyclopent-1-ene is trans-selective with Cu(I)/NsN=IPh and cis-selective with chloramine-T/$PhNMe_3^+Br_3^-$.[62] Bromamine-T has also been used as nitrene precursor in Cu-catalyzed aziridinations, and good results have been reported when the reactions were carried out under ultrasound irradiation.[63] The potential of both chloramine-T and bromamine-T as nitrene source in the asymmetric aziridination with copper-exchanged zeolite has been examined; however, TsN=IPh was found to be far superior.[64]

C. Rhodium(II)-Catalyzed Aziridination and CH Insertion

1. Aziridination

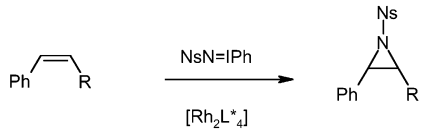
Rh(II) catalysts are complementary in scope to Cu(I) catalysts in asymmetric carbene transfer reactions.[65] Their use in nitrene transfer was envisaged very early, but was abandoned when copper catalysts were found superior in aziridinations using TsN=IPh.[18] Subsequent investigations showed, however, that the combination of $[Rh_2(OAc)_4]$ with NsN=IPh in CH_2Cl_2 was efficient for this transformation.[66] The aziridination of hex-2-ene and β-methylstyrene was fully stereospecific, but *cis*-stilbene afforded a low yield of 18% of a cis/trans mixture of aziridines. The Hammett plot (vs σ^+) for aziridination of substituted styrenes yielded a ρ-value of -0.60.[43] The possible intervention of radical pathways was tested using a vinyl substituted cyclopropane as radical clock, but no products derived from ring-opening were observed under the conditions of the aziridination. However, when electron-rich olefins were used as substrates, some of the aziridines underwent ring-opening and subsequent cycloaddition to the olefin present in excess to afford pyrrolidines.

Screening experiments for enantioselective aziridinations with styrene (**1e**) and *cis*-β-methylstyrene (**1f**) revealed that Pirrung's $[Rh_2\{(R)\text{-bnp}\}_4]$ catalyst Rh-**25**[67] gave the highest enantioselectivity, with 55% and 73%, respectively. An analogue of Doyle's Rh(II)-carboxamidate catalyst, $[Rh_2\{2S\text{-bepy}\}_4]$ (Rh-**26**), performed less satisfactorily, with ee's of 27% and 35%, respectively. Other chiral Rh(II) catalysts were significantly less efficient and lead to no or only marginal enantioselectivity.

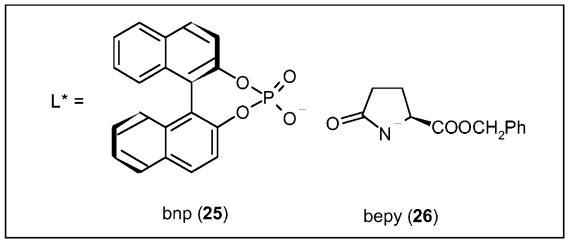
When NsN_3 was decomposed photochemically in the presence of $[Rh_2\{(R)\text{-bnp}\}_4]$ (Rh-**25**) and styrene, the ee of the aziridine (**2e**) was only 17% instead of the 55% resulting from the aziridination with NsN=IPh. Apparently, trapping of the intermediate nitrene is less efficient than in the case of the Cu-catalyzed aziridination, where the ee of the aziridination starting from NsN_3 is identical to that starting from NsN=IPh.

Guthikonda and Du Bois described Rh(II)-catalyzed olefin aziridinations using the in situ generated phenyliodinane derived from trichloroethylsulfamate ester (**27**) (Scheme 11).[68] The iodinane was generated with $PhI(OAc)_2$ in the presence of MgO. The most suitable catalyst was $[Rh_2(tfacam)_4]$ (tfacam = CF_3CONH_2). The aziridination of β-methylstyrene was found to be stereospecific. Yields of aziridines were in the range of 57−95% when the olefin was the limiting component, and the system was suitable for olefins having aryl and alkyl substituents. The procedure was successfully extended to other sulfamate esters and to intramolecular aziridinations, as well as to phosphoramidates. It seems promising for

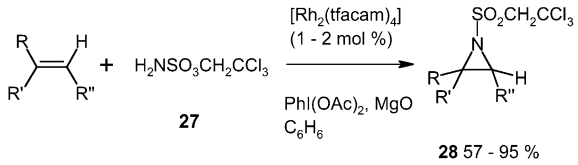
Scheme 10



2e R = H, L* = bnp (**25**): 74 %, 55 % ee
2e R = H, L* = bepy (**26**): 71 %, 27 % ee
2f R = Me, L* = bnp (**25**): 80 %, 73 % ee
2f R = Me, L* = bepy(**26**): 70 %, 35 % ee



Scheme 11



28 57 - 95 %

asymmetric aziridinations, although other carboxamidate complexes decomposed under the conditions of the reaction.

An intramolecular aziridination using in situ generated phenyliodinanes available from unsaturated sulfonamides and $PhI(OAc)_2$ in the presence of Al_2O_3 and Rh(II) catalysts has been reported by the group of Che.[69] Three chiral catalysts were examined. Doyle's $[Rh_2\{(4S)\text{-meox}\}_4]$ catalyst Rh-**30** was the most suitable of them, giving a yield of 54% (based on 78% conversion) and an ee of 49%.

Rojas and collaborators have used Rh(II)-catalyzed decomposition of phenyliodinanes prepared in situ from carbamates and PhI=O for amidoglycosylation of allal carbamates such as **32**. The reaction proceeds via a hypothetical intermediate aziridine **33** which suffers attack by acetate to afford ring-opened acetate **34**. The reactions proceed also with Cu-catalysis, albeit with lower yield.[70]

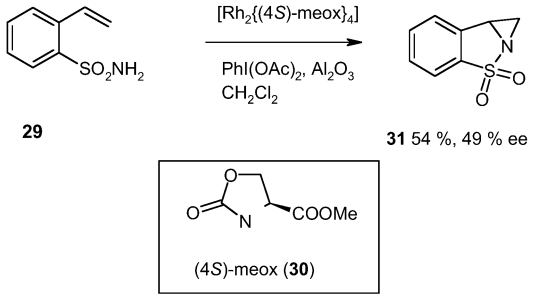
The $PhI(OAc)_2$-mediated aziridination of the indolyl substituted carbamate **35** in the presence of $[Rh_2(OAc)_4]$ results in formation of a zwitterion **36** which undergoes addition of AcOH to afford the spiro-oxazolidinone **37**. An intermediate metallonitrene is implicated. However, cycloalkenyl carbamates such as **38** react with $PhI(OAc)_2$ even in the absence of catalyst to afford **39** in 75% yield.[71] This suggests that the intermediate phenyliodinane reacts directly with the electron-rich double bond of the olefin. This is the first uncatalyzed aziridination of a phenyliodinane. The analogous uncatalyzed intramolecular cyclopropanation of phenyliodonium methanides has been observed repeatedly, however.[72]

2. CH Insertion

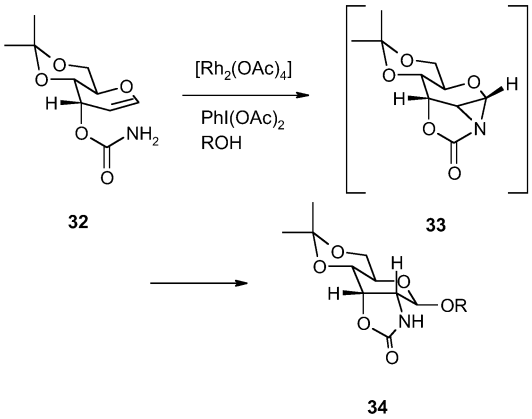
The transition metal-catalyzed aziridination with TsN=IPh is often accompanied by competing insertion into CH bonds.[73] This is particularly the case with Rh(II) catalysts, and insertion products for inter- and intramolecular CH insertions with $[Rh_2(OAc)_4]$ were already reported in 1982.[14,15] The Rh(II)-catalyzed intermolecular insertion with NsN=IPh has been investigated in some detail.[74] Rh(II)-carboxylates were found to be superior catalysts than the Rh(II)-carboxamidates. With olefinic substrates, aziridination predominated over CH insertion, except in the case of cyclohexene and cyclopentene. The highest yields of insertion products resulted with substrates having activating substituents, such as phenyl groups or oxygen atoms attached to the reacting carbon. Under optimized conditions, and with a large excess of substrate, yields of up to 84% were obtained. A Hammett plot for nitrene insertion of substituted ethylbenzenes gave a ρ-value of -0.89 (vs σ^+), and the intramolecular isotope effect determined with 1,3-dideuterated adamantane was 3.5. Radical clocks provided no evidence for intermediate radicals, and it was found that the insertion proceeds with retention of configuration. The possibility of realizing asymmetric CH insertions was established with indane (**40**), and an ee of 31% resulted upon reaction with NsN=IPh in the presence of Pirrung's $[Rh_2\{(R)\text{-bnp}\}_4]$ catalyst Rh-**25**. Ikegami's $[Rh_2\{(S)\text{-ptpa}\}]$ catalyst[41] Rh-**41** was less suitable and gave only 7% ee (Scheme 15). However, the reaction was not further optimized.

The in situ generation and Rh(II)-catalyzed decomposition of imino phenyliodinanes from carbamates[76] and sulfamate esters[77] as described by Espino and Du Bois markedly enlarged the potential of the nitrene insertion. The method is similar to that proposed by Dauban, but uses $PhI(OAc)_2$ in conjunction with MgO rather than PhI=O (Scheme 16).

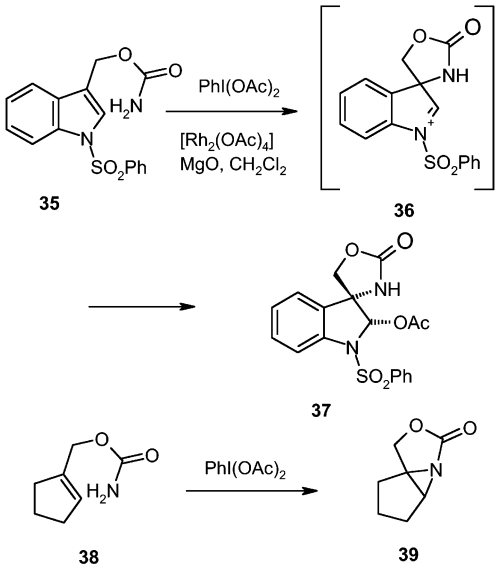
Scheme 12



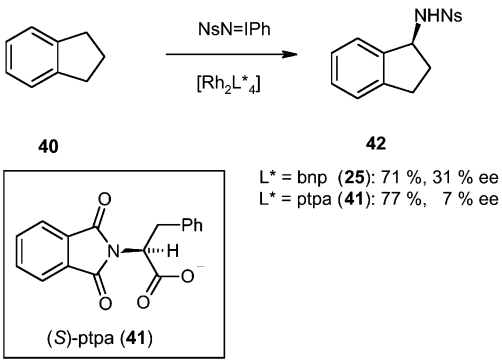
Scheme 13



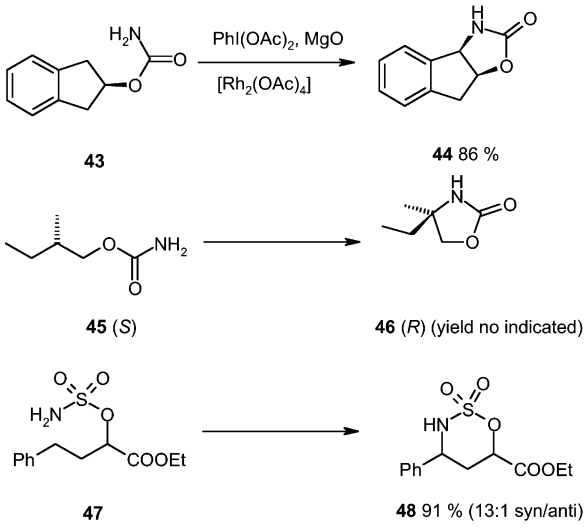
Scheme 14



Scheme 15

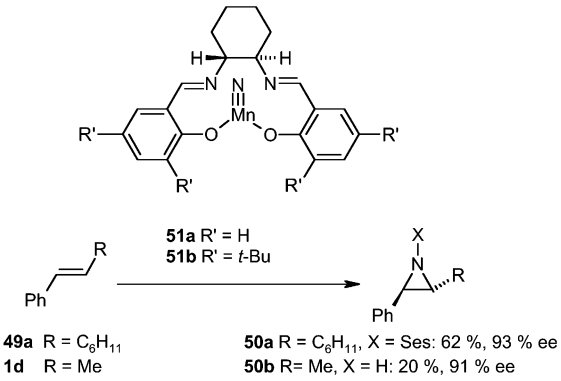


Scheme 16



Yields of insertion products, oxazolidinones (**44**, **46**) and oxathiazinanes (**48**), respectively, are typically in the range of 75−91%. In both systems, the reaction proceeds with retention of configuration at the carbon undergoing insertion and is analogous to the corresponding CH insertions of metallocarbenes.[78] Although at the time of this writing asymmetric CH insertions with chiral Rh(II) catalysts have not been reported, all the requirements needed are fulfilled for further development in this direction.

Scheme 17



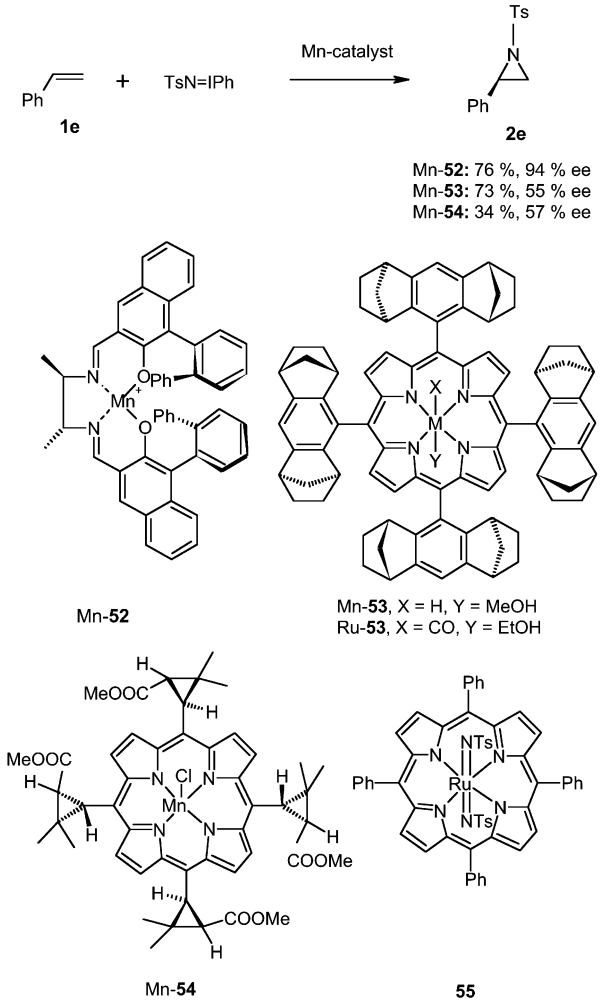
D. Catalysis by Other Metals

1. Mn Catalysis

The first racemic olefin aziridination with TsN═IPh and Mn- or Fe-porphyrin catalysts was described by Mansuy.[16] Initial experiments to extend this chemistry to chiral Mn(III) salen complexes provided aziridines from styrene and *cis*-*β*-methylstyrene, but without induction.[79] A stoichiometric aziridination procedure was then developed, using nitridomanganese complexes, first described by Groves,[17,80] and successfully exploited by Du Bois, Carreira, and coworkers, for the amidation of enol ether derivatives, where aziridines are likely to be formed as intermediates.[81] The reaction was further developed by Komatsu and collaborators, using a chiral 1,2-diaminocyclohexane based nitridomanganese complex **51a** (Scheme 17).[82] The complex reacted with olefins such as **49a** in the presence of Ts_2O or sulfonyl chlorides to afford sulfonated aziridines **50a** in yields of 50−87% and with up to 93% ee. The reaction was stereospecific with *β*-methylstyrene. When acid chlorides were used instead of sulfonyl chlorides as initiators, the reaction afforded oxazolines, presumably via intermediate aziridines in yields ranging from 53% to 85%. Enantioselectivity for oxazoline formation was high (85−92%) in the case of trans-disubstituted styrenes, but much less with α-methylstyrene, cis-disubstituted styrenes and with styrene itself. The chiral salen manganese(V) nitrido complexes may also be activated by Brønsted or Lewis acids such as trifluoroacetic acid (TFA) or BF_3. In this case, olefin aziridination proceeds to the unprotected aziridine. Thus, *trans*-*β*-methylstyrene (**1d**) reacted at −78 °C in the presence of **51b** and 3 equiv of TFA to afford **50b** with 91% ee, albeit with a yield of only 20%.[83]

Catalytic and asymmetric Mn-catalyzed aziridinations using an optimized salen complex **52** have been developed by Nishikori and Katsuki, who reached up to 94% ee for aziridination of styrene with TsN═IPh.[84] The presence of catalytic quantities of 4-phenyl-pyridine-*N*-oxide was required to obtain high enantioselectivities. A chiral Mn(III)−porphyrin complex Mn-**53** in conjunction with TsN═IPh provided aziridination products in moderate yield and enan-

Scheme 18



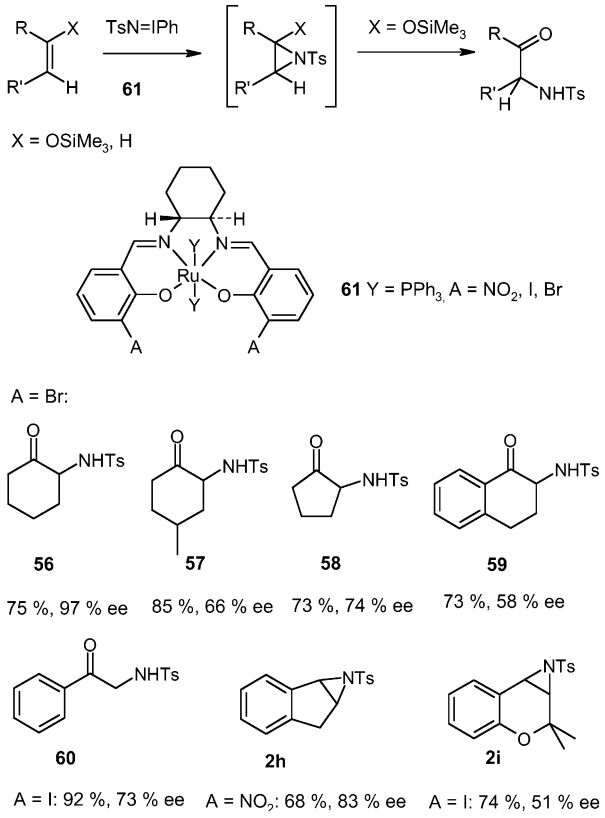
tioselectivity.[85,86] Marchon and collaborators, in turn, examined a chiral Mn(III)-porphyrin catalyst **54** and reported an ee of 57% for styrene aziridination with TsN=IPh.[87] The same ligand combined with Fe(II) afforded also an active catalyst; however it produced the aziridines with opposite abs. configuration than the Mn(III)-complex.

2. Ru Catalysis

While nitrido manganese porphyrins played a crucial role in the development of Mn-catalyzed aziridinations, their ruthenium counterparts were isolated and characterized only very recently. They react with silyl enol ethers upon activation with TFA to afford *N*-trifluoroacetylated ketones. Under the same conditions, indane reacts by CH insertion to afford *N*-trifluoroacetyl indan-1-ylamine.[88]

Stable bis(tosyl)imidoruthenium(VI)−porphyrin complexes **55** have been prepared by ligand displacement from [Ru(II)(por)(CO)(MeOH)] with TsN=IPh and characterized by X-ray crystallography. They were efficient for stoichiometric aziridination of a variety of olefins.[89] The mechanism of the reaction has been investigated.[90] The reaction is not stereospecific. The reactivity of the olefins (log k) is linearly related to their oxidation potential ($E_{1/2}$), and the Hammet ρ-value (vs σ^+) is −1.1. The secondary deuterium isotope effect at the β-carbon of styrene

Scheme 19[a]



[a] Conditions: catalyst/substrate/TsNIPh = 1 : 8 : 12; in CH_2Cl_2, r.t., 2 h. Yields with respect to converted substrate.

was found to be $k_H/k_D = 0.85$, while that at the α-carbon was $k_H/_D = 0.97$, indicating significant sp^2 to sp^3 rehybridization at C(β), but no change at C(α), consistent with a stepwise aziridination mechanism, presumably involving a radical intermediate.

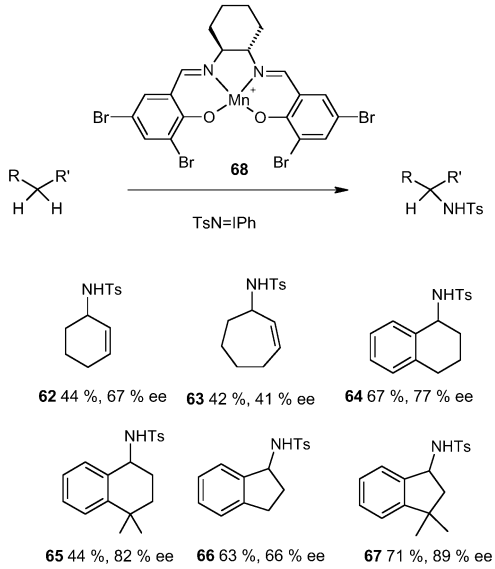
The chiral Ru-porphyrin Ru-**53** affords chiral aziridines, but the enantioselectivity is only about half of that obtained with authentic Mn-**53**.[85] However, enantioselectivities of up to 97% were reported for amidation of silyl enol ethers with the chiral Ru-based Schiff base catalyst **61**.[91] The amidation proceeds via intermediate aziridines. With olefins as subtrates, the aziridines are isolable. The yields given in Scheme 19 refer to converted substrate, which is low (20−60% with aliphatic derivatives).

An achiral Ru-porphyrin catalyst was attached to poly(ethylene glycol) to yield a soluble polymer supported catalyst applicable to olefin epoxidation, cyclopropanation, and aziridination.[92] Methyltrioxorhenium (MTO) is also capable of nitrene transfer with TsN=IPh; however, the yields are low, in the range of 28−32% with styrenes. α-Methylstyrene, with 70% yield, is exceptionally reactive, however, although the product rearranges partially to the corresponding imine under the reaction conditions.[93]

3. Mn- and Ru-Catalyzed CH Insertions

Products derived from formal CH insertions upon decomposition of TsN=IPh in the presence of Mn-porphyrins have been reported by Mansuy and collaborators, and rationalized in terms of a radical mechanism.[73] More recently, Ru- and Mn-tetrakis-

Scheme 20[a]



[a] Conditions: in $Cl_2CHCHCl_2$, -40 °C, 24 h; 0.4 mmol of substrate, 0.17 mmol of TsN=IPh, 10 μmol of catalyst, 50 mg of molecular sieves.

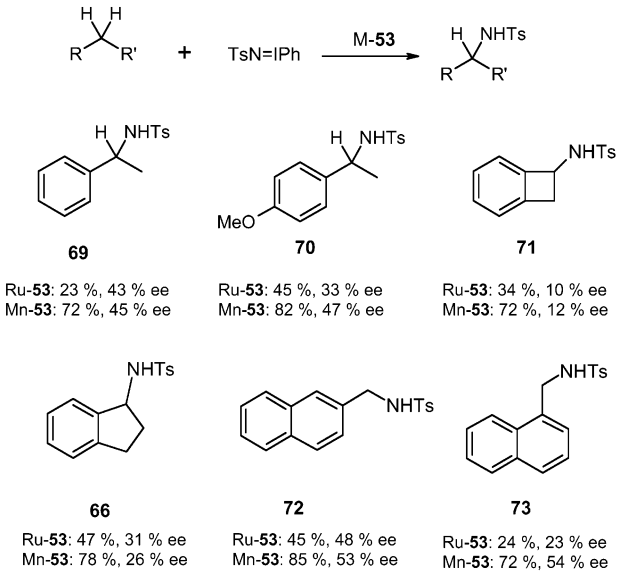
(pentafluorophenyl)porphyrins have been applied as catalysts to the reaction, and high yields and good substrate conversions have been achieved.[86,94] Equilenin was selectively amidated at C(11) by TsN=IPh in 45% yield.[95] An asymmetric CH insertion using a substituted (salen)Mn(III) catalyst **68** with TsN=IPh afforded insertion products with ee's up to 89%. Cycloalkenes provided substantial amounts of insertion, rather than aziridination products. (Scheme 20).[96]

The bis(tosyl)amidoruthenium complex of 1,4,7-trimethyl-1,4,7-triazanonane reacted with cyclohexene in the presence of $AgClO_4$ to afford the allylic sulfonamide. Likewise, ethylbenzene, cumene, indane, and tetralin underwent insertion into the benzylic position, and the reaction became catalytic when TsN=IPh was the terminal nitrogen source.[97]

Selective amidation of unfunctionalized hydrocarbons has been effected with Ru cyclic amine or bipyridine complexes with TsN=IPh with yields of up to 93% (based on converted substrate) and with conversions of 40−70%. A mechanism involving hydrogen atom abstraction was proposed. These Ru catalysts were also successfully applied to amidation using in situ generation of imino phenyliodinanes with $PhI(OAc)_2$ in the presence of $TsNH_2$, $MsNH_2$, and even benzamide, $PhC(O)NH_2$.[98] The chiral Ru(II)-porphyrin catalyst Ru-**53** of Che catalyzed tosylamidation of ethylbenzene and methylnaphthalenes in moderate yields and enantioselectivities in the range of 6−54%. The corresponding Mn(III) complex was significantly more effective.[99]

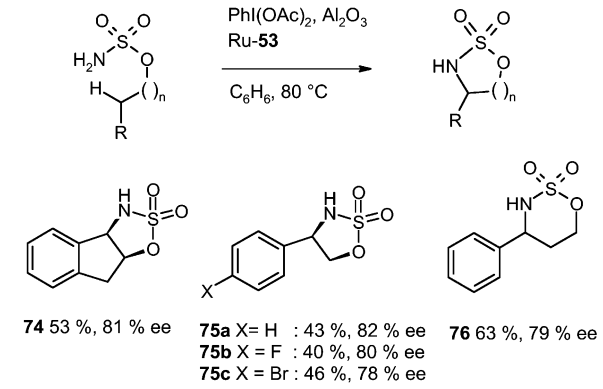
The reactive species in the reaction of Ru-**53** was identified as a bis(tosylamido)Ru(VI) intermediate, which was spectroscopically characterized. In the case of Mn-**53**, however, an electrospray MS of the reaction mixture provided evidence for a manganese mono-tosylamido intermediate. The intramolecular version of the reaction was investigated using in situ generated phenyliodinanes derived from sulfamate

Scheme 21[a]



[a] Conditions: TsN=IPh/substrate 1 : 5; 1 mol% catalyst with respect to TsN=IPh; in CH_2Cl_2, 40 °C., 2h. Yields rel. to TsN=IPh.

Scheme 22



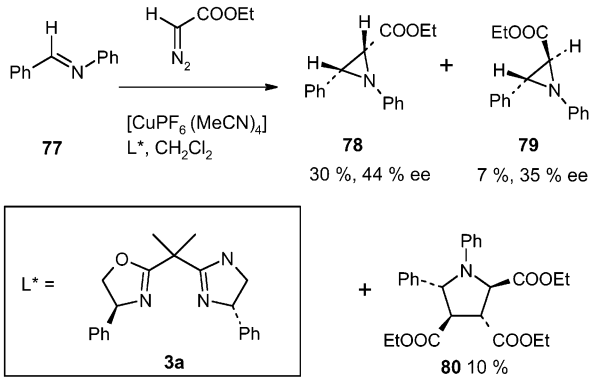
esters, which were generated with $PhI(OAc)_2$ and Al_2O_3, and typical examples are shown below (Scheme 22).[100] At lower temperature, the enantioselectivity of the reaction was better; however, this improvement was offset by lower yields of insertion products.

III. Aziridination via Carbene Addition to C=N Double Bonds

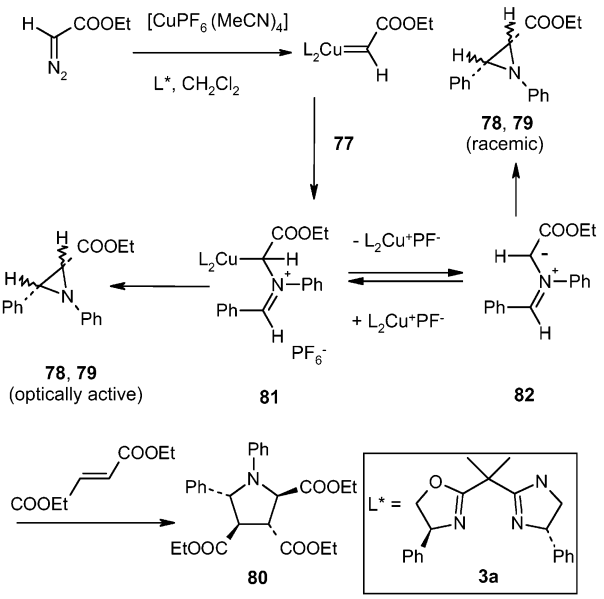
A. Addition of Metallocarbenes to Imines

The reaction of carbenes with Schiff bases to afford aziridines is well-known.[101] A recent example of this is the addition of trimethylsilyldiazomethane to *N*-sulfonylimines in dioxane at 40 °C [102] or in refluxing toluene.[103] The formation of aziridines upon transition metal-catalyzed decomposition of diazo compounds in the presence of C=N double bonds is also well established. Thus, Baret et al. reported aziridination of imines by ethyl diazoacetate in the presence of copper powder[104] and a Simmons−Smith reaction of an imino ester.[105] Phenyldiazomethane adds to imines in the presence of zinc iodide.[106] The first aziridination of a carbodiimide by diazoacetate esters in the presence of Cu(I) or Rh(II) catalysts was

Scheme 23



Scheme 24

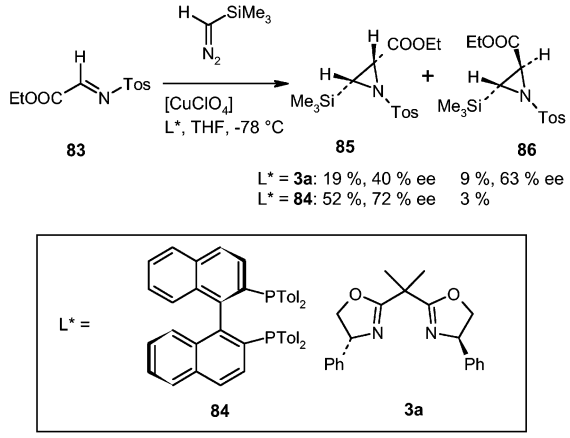


reported in 1976, but subsequent investigations showed that the isolated product was an oxazoline.[107] The $[Rh_2(OAc)_4]$-catalyzed decomposition of ethyl diazoacetate[108] or methyl phenyldiazoacetate[109] in the presence of imines does, however, furnish aziridines, and an intramolecular carbenoid addition of an imino ether has been reported.[110] A heterogeneous catalyst using Rh(III)- or Mn(III)-exchanged montmorillonite K 10 clay produces aziridines in up to 75% yield with methyl diazoacetate and diarylimines.[111]

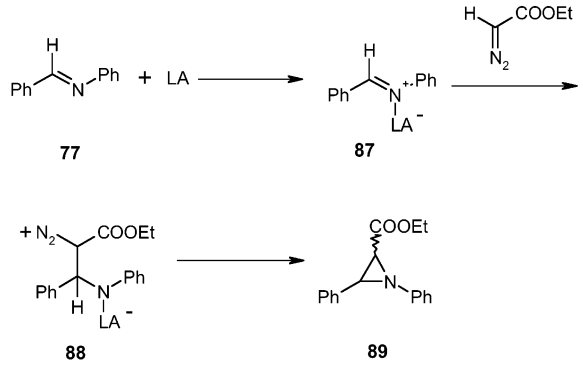
Initial experiments toward enantioselective aziridinations of imines with diazoacetate esters were not encouraging: with chiral Rh(II)-carboxylate catalysts, poor yields of aziridines were obtained and the products were racemic.[108] This failure was attributed to the intermediacy of ylides, formed between the metallocarbene and the lone pair of the nitrogen of the imine substrate. Similarily, addition of ethyl diazoacetate to imines under catalysis by $[Cu(OTf)_2]$ produced aziridines in yields of up to 90%, but in the presence of chiral bis(oxazoline) ligands, the yields dropped to 50−60%, and the aziridines were racemic.[112]

The first asymmetric aziridination of imines was reported by Jacobsen.[113] Addition of ethyl diazoacetate to diphenylimine (**77**) in the presence of a Cu(I)-bis(oxazoline) catalyst **3a** afforded a cis/trans

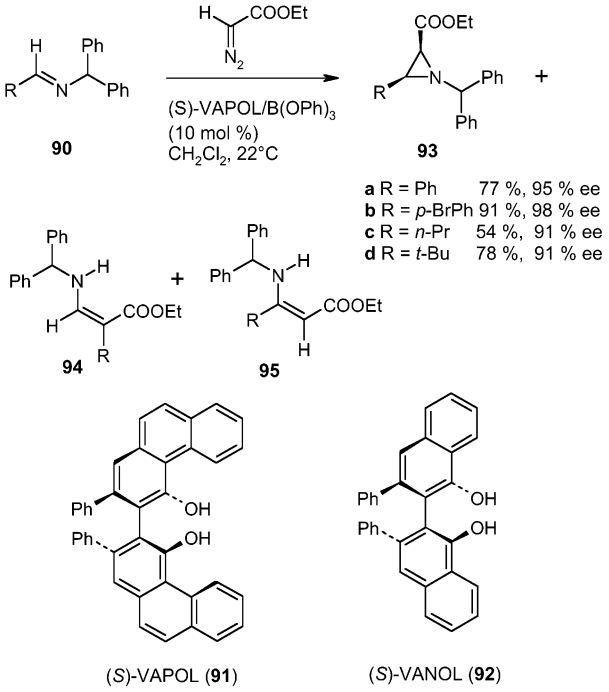
Scheme 25



Scheme 26



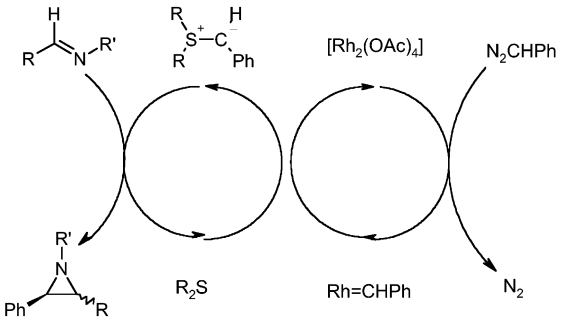
Scheme 27



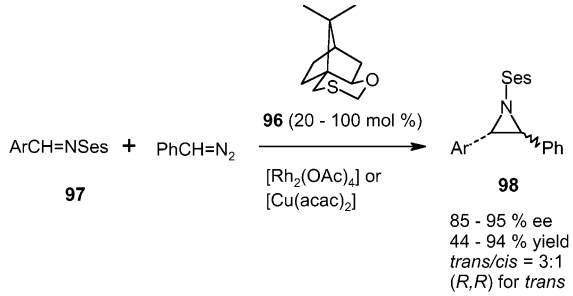
mixture of enantioenriched aziridines **78** and **79** in modest yield together with racemic oxazolidine **80** as secondary product (Scheme 23).

A mechanism was proposed in which attack of the imine by the metallocarbene affords a Cu-complexed azomethine ylide intermediate **81** which subsequently breaks down to afford chiral aziridines or,

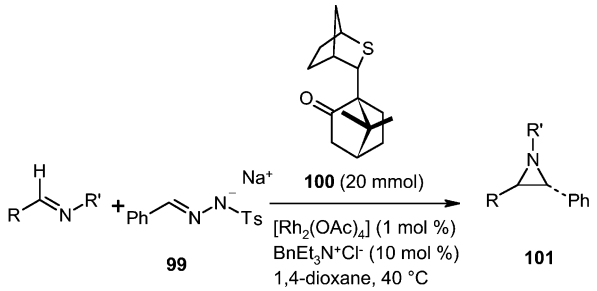
Scheme 28



Scheme 29



Scheme 30



	R	R'	Yield	d.r.	ee (*t*:*c*)
101a	*p*-ClPh	TcBoc	56 %	6:1	94:90
101b	*p*-ClPh	Ses	82 %	2:1	98:81
101c	C_6H_{11}	Ses	50 %	2.5:1	98:98
101d	*t*-Bu	Ts	53 %	2:1	73:95

alternatively, dissociates to a free azomethine ylide **82**. This then cyclizes to racemic aziridines, or undergoes cycloaddition with diethyl fumarate (formed upon diazo decomposition of ethyl diazoacetate) to furnish the pyrrolidine **80**.

Trimethylsilyldiazomethane adds to imino esters **83** in the presence of chiral Cu-BINAP or bis(oxazoline) catalysts **84** and **3a**, respectively, to afford aziridines **85** and **86** with high *cis*-stereospecificity and with ee's up to 72% (Scheme 25). Ethyl diazoacetate was found less suitable for this reaction. It was suggested that the aziridination with trimethylsilyldiazomethane proceeds via attack of the diazo compound on the Lewis acid activated imine (see below), while that of ethyl diazoacetate involves a metallocarbene intermediate.[114]

B. Lewis-Acid-Catalyzed Aziridination of Imines.

Brookhart and Templeton developed an aziridination procedure based on Lewis-acid-catalyzed addition of ethyl diazoacetate to imines.[115] The Lewis acids used were BF_3, $AlCl_3$, and $TiCl_4$, and yields of aziridines were in the range of 42−93%. The typical secondary products of carbenoid reactions, i.e., diethyl fumarate and maleate, were not observed under the conditions of the reaction, and it was concluded that a mechanism involving attack of the diazo compound to a Lewis-acid activated imine **87** was operative. Enamines were isolated as secondary products, and their formation was attributed to proton loss of the intermediate adduct **88**.

A wide range of Lewis acids was found to be effective as catalysts for aziridination of imines, such as $SnCl_4$,[116] methylrhenium trioxide,[117] a tungsten(II) methylene complex,[118] the iron Lewis acid $[(\eta^5\text{-}C_5H_5)Fe(CO)_2(THF)]^+[BF_4]^-$,[119] lanthanide triflates,[120] $[InCl_3]$,[121] and $[Mo(OTf)(\eta^3\text{-}C_3H_5)(CO)_2(phen)]$.[122] A set of chiral ligands was tested in combination of $[Zn(OTf)_2]$ and $[Yb(OTf)_3]$, but only low ee's were obtained.[123]

The breakthrough occurred in 1999, when Wulff reported the aziridination of benzhydryl imines **90** with ethyl diazoacetate in the presence of VAPOL-BH_3.[124] The system provided aziridines **93** with very high cis diastereoselectivity and up to 99% ee. Further optimization resulted in an improved catalyst obtained from $B(OPh)_3$ and VAPOL (**91**) or VANOL (**92**).[125] These ligands produced aziridines with cis/trans ratios in the range of >50:1 and enantioselectivities 90−98% ee. Some secondary products **94** and **95** were observed in the range of a few percent. The system was applied to an efficient synthesis of (−)-chloroamphenicol. Other ligands such as BINOL or BANOL were less efficient for these transformations.[126]

C. Aziridination via Chiral Sulfonium Ylides

As an extension of his methodology for epoxide synthesis, Aggarwal has developed an aziridination procedure based on asymmetric carbene transfer via a chiral, in situ generated sulfonium ylide.[127] The generation of aziridines from sulfur ylides and imines is a known process;[128] Aggarwal's innovation consists of the generation of a carbene via diazo decomposition with $[Rh_2(OAc)_4]$ or $[Cu(acac)_2]$, its association to a chiral sulfide, and subsequent transfer to an appropriate imine.

Asymmetric reactions were examined using *N*-Ses-aldimines (**97**), phenyldiazomethane, and a chiral sulfide **96** derived from (+)-camphorsulfonyl chloride. The procedure afforded aziridines **98** with a trans/cis ratio of ca. 3:1, and ee's of 85−95%. Replacement of $[Rh_2(OAc)_4]$ by $[Cu(acac)_2]$ had no effect on the enantioselectivity, when equimolar amounts of sulfide and imine were used; however, a slight decrease in ee was observed when the amount of sulfide was reduced to 20 mol %. The effect was attributed to direct aziridination of the imine with the copper-complexed carbene, competing with the ylide pathway. This direct aziridination is, however, not competitive in the case of $[Rh_2(OAc)_4]$.[129]

The procedure is applicable to other imines bearing electron-withdrawing groups such as $POPh_2$, COOBn, COO*t*-Bu, etc., and may be extended to other diazo compounds such as *N*,*N*-diethyldiazoacetamide or

ethyl diazoacetate, although enantioselectivities in these latter cases are in the range of only 30−58% (with *trans*-(*R*,*R*)-2,5-dimethylthiolane). Further improvement resulted by the in situ generation of the diazo precursor via deprotonation of tosyl hydrazones **99** in dioxane at 40 °C.[130] The TcBoc activated imines and sulfide **100** provided the best combination with respect to yield, enantioselectivity, and diastereoselectivity of aziridines **101**. The amount of sulfide could be reduced to 5% without loss of yield and enantioselectivity, and the procedure became applicable to imines derived from aliphatic aldehydes and alkenyl diazomethanes.

IV. Conclusion

Until a few years ago, the field of asymmetric catalytic aziridination was relatively underdeveloped in comparison to that of asymmetric epoxidation or cyclopropanation of olefins. This might change. Three different approaches for catalytic aziridinations have been developed: nitrene transfer to olefins, carbene transfer to imines via metal carbenes, and carbene transfer to imines via chiral sulfonium ylides. Substantial progress has been made with repect to all these approaches: the efficiency of the catalytic systems has been much improved, and synthetically useful enantioselectivities have been achieved in selected reactions. Further research should focus on catalysts tailored to specific substrates and reagents and develop the approaches into synthetically interesting methodologies.

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VI. References

(1) (a) Padwa, A.; Murphree, S. S. In *Progress in Heterocyclic Chemistry*; Gribble, G. W., Gilchrist, T. L. Eds.; Elsevier Science: Oxford, 2000; Vol. 12, Chapter 4.1, p 57. (b) Padwa, A.; Pearson, W. H.; Lian, B. N.; Bergmeier, S. C. In *Comprehensive Heterocyclic Chemistry II*; Katritzky, A. R., Reese, C. W.; Scriven, E. F., Eds.; Pergamon: Oxford, 1996; Vol. 1A, p 1. (c) Padwa, A.; Woolhouse, A. D. In *Comprehensive Heterocyclic Chemistry*; Lwowski, W., Ed.; Pergamon Press: Oxford, 1984; Vol. 7, pp 47−93. (d) Deyrup, J. A. In *The Chemistry of Heterocyclic Compounds*; Hassner, A., Ed.; Wiley: New York, 1983; Vol. 42, Part 1, pp 1−214.

(2) (a) Yan, Z.; Weaving, R.; Dauban, P.; Dodd, R. H. *Tetrahedron Lett.* **2002**, *43*, 7593. (b) Sim, T. B.; Kang, S. H.; Lee, K. S.; Lee, W. K. Yun, H.; Dong, Y.; Ha. H.-J. *J. Org. Chem.* **2003**, *68*, 104. (c) Park, C. S.; Kim, M. S.; Sim, T. B.; Pyun, D. K.; Lee, C. H.; Choi, D.; Lee, W. K.; Chang, J.-W.; Ha, H.-J. *J. Org. Chem.* **2003**, *68*, 43. (d) Sabitha, G.; Babu, R. S.; Rajkumar, M.; Yadav, J. S. *Org. Lett.* **2002**, *4*, 343. (e) Wang, B. M.; Song, Z. L.; Fan, C. A.; Tu, Y. Q.; Shi, Y. *Org. Lett.* **2002**, *4*, 363. (f) Righi, P.; Scardovi, N.; Marotta, E.; Holte, P. T.; Zwanenburg, B. *Org. Lett.* **2002**, *4*, 497. (g) Kim, B. M.; So, S. M.; Choi, H. J. *Org. Lett.* **2002**, *4*, 949. (h) Madhushaw, R. J.; Hu, C.-C.; Liu, R.-S. *Org. Lett.* **2002**, *4*, 4151. (i) Hancock, M. T.; Pinhas, A. R. *Organometallics* **2002**, *21*, 5155. (j) White, R. D.; Wood, J. L. *Org. Lett.* **2001**, *3*, 1825. (k) Syam Kumar, U. K.; Ila, H.; Junjappa, H.; Lee, W. K. *Org. Lett.* **2001**, *3*, 4193. (l) Pyun, D. K.; Lee, C. H.; Ha, H.-J.; Park, C. S.; Chang, J.-W.; Lee, W. K. *Org. Lett.* **2001**, *3*, 4197. (m) Flock, S.; Frauenrath, H. *Synlett* **2001**, 839. (n) Paul, B. J.; Hobbs, E.; Buccino, P.; Hudlicky, T. *Tetrahedron Lett.* **2001**, *42*, 6433. (o) Wu, M.-J.; Hou, X.-L.; Dai, L.-X. *J. Org. Chem.* **2000**, *65*, 1344. (p) Dodd, R. H. *Molecules* **2000**, *5*, 293. (q) Padwa, A.; Murphree, S. S. *Prog. Heterocycl. Chem.* **1999**, *11*, 66. (r) Dauban, P.; De Saint-Fuscien, C.; Dodd, R. H. *Tetrahedron* **1999**, *55*, 7589.

(3) (a) Kasai, M.; Kono, M. *Synlett* **1992**, 778. (b) Brown, F. *Vaccine* **2002**, *20*, 322. (c) Regueiro-Ren, A.; Borzilleri, R. M.; Zheng, X.; Kim, S.-H.; Johnson, J. A.; Fairchild, C. R.; Lee, F. Y. F.; Long, B. H.; Vite, G. D. *Org. Lett.* **2001**, *3*, 2693. (d) Louw, A.; Swart, P.; Allie, F. *Biochem. Pharmacol.* **2000**, *59*, 167. (e) Dvorakova, K.; Payne, C. M.; Tome, M. E.; Briehl, M. M.; McClure, T.; Dorr, R. T. *Biochem. Pharmacol.* **2000**, *60*, 749. (f) Burrage, T.; Kramer, E.; Brown, F. *Vaccine* **2000**, *18*, 2454. (g) Fürmeier, S.; Metzger, J. O. *Eur. J. Org. Chem.* **2003**, 649.

(4) Tanner, D. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 599.

(5) Osborn, H. M. I.; Sweeney, J. *Tetrahedron: Asymmetry* **1997**, *8*, 1693.

(6) (a) Aires-de-Sousa, J.; Prabhakar, S.; Lobo, A. M.; Rosa, A. M.; Gomes, M. J. S.; Corvo, M. C.; Williams, D. J.; White, A. J. P. *Tetrahedron: Asymmetry* **2001**, *12*, 3349. (b) Zwanenburg, B.; ten Holte, P. *Stereoselective Heterocyclic Synthesis III*; Metz, P., Ed.; Topics in Current Chemistry 216; Springer-Verlag: Berlin, Heidelberg, 2001; p 93. (c) McCoull, W.; Davis, F. A. *Synthesis* **2000**, *10*, 1347. (d) Sweeney, J. B. *Chem. Soc. Rev.* **2002**, *31*, 247.

(7) (a) Müller, P.; Baud, C.; Jacquier, Y.; Moran, M.; Nägeli, I. *J. Phys. Org. Chem.* **1996**, *9*, 341. (b) Lautens, M.; Klute, W.; Tam, W. *Chem. Rev.* **1996**, *96*, 49.

(8) Müller, P. In *Advances in Catalytic Processes*; Doyle, M. P., Ed.; JAI Press: Greenwich, CT, 1997; Vol. 2, pp 113−151.

(9) Jacobsen, E. N. In *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer-Verlag: Berlin, 1999; Vol. 2, pp 607−618.

(10) Kwart, H.; Khan, A. A. *J. Am. Chem. Soc.* **1967**, *89*, 1950.

(11) (a) Groves, J. T.; Nemo, T. E.; Myers, R. S. *J. Am. Chem. Soc.* **1979**, *101*, 1032. (b) Chang, C. K.; Kuo, M.-S. *J. Am. Chem. Soc.* **1979**, *101*, 3413. (c) Mansuy, D.; Bartoli, J.-F.; Momenteau, M. *Tetrahedron Lett.* **1982**, *23*, 2781.

(12) Abramovitch, R. A.; Bailey, T. D.; Takaya, T.; Uma, V. *J. Org. Chem.* **1974**, *39*, 340.

(13) Yamada, A.; Yamamoto, T.; Okawara, M. *Chem. Lett.* **1975**, 361.

(14) Breslow, R.; Gellman, S. H. *J. Chem. Soc., Chem. Commun.* **1982**, 1400.

(15) Breslow, R.; Gellman, S. *J. Am. Chem. Soc.* **1983**, *105*, 6729.

(16) (a) Mansuy, D.; Mahy, J.-P.; Dureault, A.; Bedi, G.; Battioni, G. *J. Chem. Soc., Chem. Commun.* **1984**, 1161. (b) Mahy, J.-P.; Battioni, P.; Mansuy, D. *J. Am. Chem. Soc.* **1986**, *108*, 1079. (c) Mahy, J.-P.; Bedi, G.; Battioni, P.; Mansuy, D. *J. Chem. Soc., Perkin Trans. 2* **1988**, 1517.

(17) Groves, J. T.; Takahashi, T. *J. Am. Chem. Soc.* **1983**, *105*, 2073.

(18) (a) Evans, D. A.; Faul, M. M.; Bilodeau, M. T. *J. Org. Chem.* **1991**, *56*, 6744. (b) Evans, D. A.; Faul, M. M.; Bilodeau, M. T. *J. Am. Chem. Soc.* **1994**, *116*, 2742.

(19) Evans, D. A.; Faul, M. M.; Bilodeau, M. T.; Anderson, B. A.; Barnes, D. M. *J. Am. Chem. Soc.* **1993**, *115*, 5328.

(20) (a) Ghosh, A. K.; Mathivanan, P.; Cappiello, J. *Tetrahedron: Asymmetry* **1998**, *9*, 1. (b) Rechavi, D.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 3467.

(21) Lowenthal, R. E.; Masamune, S. *Tetrahedron Lett.* **1991**, *32*, 7373.

(22) Harm, A. M.; Knight, J. G.; Stemp, G. *Tetrahedron Lett.* **1996**, *37*, 6189.

(23) Knight, J. G.; Muldowney, M. P. *Synlett* **1995**, 949.

(24) (a) Södergren, M. J.; Alonso, D. A.; Andersson, P. G. *Tetrahedron: Asymmetry* **1997**, *8*, 3563. (b) Södergren, M. J.; Alonso, D. A.; Bedekar, A. V.; Andersson, P. G. *Tetrahedron Lett.* **1997**, *38*, 6897.

(25) Bertilsson, S. K.; Tedenborg, L.; Alonso, D. A.; Andersson, P. G. *Organometallics* **1999**, *18*, 1281.

(26) (a) Tanner, D.; Andersson, P. G.; Harden, A.; Somfai, P. *Tetrahedron Lett.* **1994**, *35*, 4631. (b) Tanner, D.; Harden, A.; Johansson, F.; Wyatt, P.; Andersson, P. G. *Acta Chem. Scand.* **1996**, *50*, 361.

(27) Llewellyn, D. B.; Adamson, D.; Arndtsen, B. A. *Org. Lett.* **2000**, *2*, 4165.

(28) Gullick, J.; Taylor, S.; Kerton, O.; McMorn, P.; King, F.; Hancock, F. E.; Bethell, D.; Bulman Page, P. C.; Hutchings, G. J. *Catal. Lett.* **2001**, *3*−*4*, 151. Taylor, S.; Langham, C.; Piaggio, P.; Bethell, D.; Lee, D. F.; McMorn, P.; Bulman Page, P. C.; Willock, D. J.; Sly, C.; Hancock, F. E.; King, F.; Hutchings, G. J. *Appl. Catal. A* **1999**, *182*, 85; Langham, C.; Taylor, S.; Bethell, D.; McMorn, P.; Bulman Page, P. C.; Willock, D. J.; Sly, C.; Hancock, F. E.; King, F.; Hutchings, G. J. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1043; Langham, C.; Piaggio, P.; Bethell, D.; Lee, D. F.; McMorn, P.; Bulman Page, P. C.; Willock, D. J.; Sly, C.; Hancock, F. E.; King, F.; Hutchings, G. J. *Chem. Commun.* **1998**, 1601.

(29) (a) Gullick, J.; Taylor, S.; McMorn, P.; Bethell, D.; Bulman-Page, P. C.; Hancock, F. E.; King, F.; Hutchings, G. J. *J. Mol. Cataly. A: Chemical* **2002**, *182*−*183*, 571. (b) Gullick, J.; McMorn, P.; Bethell, D.; Bulman Page, P. C.; Hancock, F. E.; King, F.; Hutchings, G. J. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1714.

(30) Traa, Y.; Murphy, D. M.; Farley, R. D.; Hutchings, G. J. *Phys. Chem. Chem. Phys.* **2001**, *3*, 1073.
(31) Taylor, S.; Gullick, J.; McMorn, P.; Bethell, D.; Bulman Page, P. C.; Hancock, F. E.; King, F.; Hutchings, G. J. *J. Chem. Soc., Perkin Trans. 2* **2001**, 1724.
(32) Li, Z.; Conser, K. R.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1993**, *115*, 5326.
(33) Bennani, Y. L.; Hanessian, S. *Chem. Rev.* **1997**, *97*, 3161.
(34) (a) Cho, D.-J.; Jeon, S.-J.; Kim, H.-S.; Cho, C.-S.; Shim, S.-C.; Kim, T.-J. *Tetrahedron: Asymmetry* **1999**, *10*, 3833. (b) Cho, D.-J.; Jeon, S.-J.; Kim, H.-S.; Kim, T.-J. *Synlett* **1998**, 617. (c) Song, J. H.; Cho, D.-J.; Jean, S. J.; Kim, Y.-H.; Kim, T. J.; Jeong, J. H. *Inorg. Chem.* **1999**, *38*, 893.
(35) Shi, M.; Wang, C.-J.; Chan, A. S. C. *Tetrahedron: Asymmetry* **2001**, *12*, 3105.
(36) Adam, W.; Rosachmann, K. J.; Saha-Möller, C. R. *Eur. J. Chem.* **2000**, 557.
(37) Gillespie, K. M.; Sanders, C. J.; O'Shaughnessy, P.; Westmoreland, I.; Thickitt, C. P.; Scott, P. *J. Org. Chem.* **2002**, *67*, 3450. Sanders, C. J.; Gillespie, K. M.; Bell, D.; Scott, P. *J. Am. Chem. Soc.* **2000**, *122*, 7132.
(38) Li, Z.; Quan, R. W.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1995**, *117*, 5889.
(39) Brandt, P.; Södergren, M. J.; Andersson, P. G.; Norrby, P. O. *J. Am. Chem. Soc.* **2000**, *122*, 8013.
(40) Gillespie, K. M.; Crust, E. J.; Deeth, R. J.; Scott, P. *J. Chem. Soc., Chem. Commun.* **2001**, 785.
(41) Doyle, M. P. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed; VCH Publishers: New York, 1999; pp 63−99.
(42) Zhang, W.; Lee, N. H.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1994**, *116*, 425.
(43) Müller, P.; Baud, C.; Jacquier, Y. *Can. J. Chem.* **1998**, *76*, 738.
(44) Davies, H. L. M.; Panaro, S. A. *Tetrahedron* **2000**, *56*, 4871.
(45) (a) Dinçtürk, S.; Jackson, R. A. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1127. (b) Jiang, X.-K.; Ji, G.-Z. *J. Org. Chem.* **1992**, *57*, 6051. (c) Fischer, T. H.; Meierhoefer, A. W. *J. Org. Chem.* **1978**, *43*, 224.
(46) Diaz-Requejo, M. M.; Pérez, P. J.; Brookhart, M.; Templeton, J. L. *Organometallics* **1997**, *16*, 4399. Diaz-Requejo, M. M.; Pérez, P. J. *J. Organomet. Chem.* **2001**, *617−618*, 110.
(47) Halfen, J. A.; Fox, D. C.; Mehn, M. P.; Que, L., Jr. *Inorg. Chem.* **2001**, *40*, 5060.
(48) Halfen, J. A.; Hallman, J.; Schultz, J. A. Emerson, J. P. *Organometallics* **1999**, *18*, 5435.
(49) Halfen, J. A.; Uhan, J. M.; Fox, D. C.; Mehn, M. P.; Que, L., Jr. *Inorg. Chem.* **2000**, *39*, 4913.
(50) Handy, S. T.; Czopp, M. *Org. Lett.* **2001**, *3*, 1423.
(51) Dias, H. V. R.; Lu, H.-L.; Kim, H.-J.; Polach, S. A.; Goh, T. K. H. H.; Browning, R. G.; Lovely, C. J. *Organometallics* **2002**, *21*, 1466.
(52) Stang, P. J.; Zhdankin, V. V. *Chem. Rev.* **1996**, *96*, 1123.
(53) Dauban, P.; Dodd, R. H. *J. Org. Chem.* **1999**, *64*, 5304.
(54) Di Chenna, P. H.; Dauban, P.; Ghini, A.; Burton, G.; Dodd, R. H. *Tetrahedron Lett.* **2000**, *41*, 7041. Di Chenna, P. H.; Dauban, P.; Ghini, A.; Baggio, R.; Garland, M. T.; Burton, G.; Dodd, R. H. *Tetrahedron* **2003**, *59*, 1009.
(55) Dauban, P.; Dodd, R. H. *Org. Lett.* **2000**, *2*, 2327.
(56) Dauban, P.; Sanière, L.; Tarrade, A.; Dodd, R. H. *J. Am. Chem. Soc.* **2001**, *123*, 7707.
(57) Duran, F.; Leman, L.; Ghini, A.; Burton, G.; Dauban, P.; Dodd, R. H. *Org. Lett.* **2002**, *4*, 2481.
(58) Albone, D. P.; Aujla, P. S.; Taylor, P. C. *J. Org. Chem.* **1998**, *63*, 9569.
(59) Ando, T.; Minakata, S.; Ryu, I.; Komatsu, M. *Tetrahedron Lett.* **1998**, *39*, 309.
(60) Jeong, J. U.; Tao, B.; Sagasser, I.; Henniges, H.; Sharpless, K. B. *J. Am. Chem. Soc.* **1998**, *120*, 6844.
(61) Ali, S. L.; Nikalje, M. D.; Sudalai, A. *Org. Lett.* **1999**, *1*, 705.
(62) Caine, D.; O'Brien, P.; Rosser, C. M. *Org. Lett.* **2002**, *4*, 1923.
(63) Chanda, B. M.; Vyas, R.; Bedekar, A. V. *J. Org. Chem.* **2001**, *66*, 30; Vyas, R.; Chanda, B. M.; Bedekar, A. V. *Tetrahedron Lett.* **1998**, *39*, 4715.
(64) Gullick, J.; Taylor, S.; McMorn, P.; Bethell, D.; Bulman Page, P. C.; Hancock, F. E.; King, F.; Hutchings, G. *J. Mol. Catal.* **2002**, *189*, 85.
(65) (a) Doyle, M. P.; Davies, S. B.; May, E. J. *J. Org. Chem.* **2001**, *66*, 8112; Doyle, M. P.; Davies, S. B.; Hu, W. *Org. Lett.* **2000**, *2*, 1145. Doyle, M. P.; Hu, W. *Org. Lett.* **2000**, *2*, 1777. Doyle, M. P.; Chapman, B. J.; Hu, W.; Peterson, C. S.; McKervey, M. A.; Garcia, C. F. *Org. Lett.* **1999**, *1*, 1327. Doyle, M. P.; Forbes, D. C. *Chem. Rev.* **1998**, *98*, 911. (b) Müller, P.; Bernardinelli, G.; Nury, P. *Tetrahedron: Asymmetry* **2002**, *13*, 551. Müller, P.; Tohill, S. *Tetrahedron* **2000**, *56*, 1725. Müller, P.; Imogaï, H. *Tetrahedron: Asymmetry* **1998**, *9*, 4419. (c) Qu, Z.; Wang, J. *J. Org. Chem.* **2001**, *66*, 8139.
(66) Müller, P.; Baud, C.; Jacquier, Y. *Tetrahedron* **1996**, *52*, 1543.
(67) Pirrung, M. C.; Zhang, J. *Tetrahedron Lett.* **1992**, *33*, 5987.
(68) Guthikonda, K.; Du Bois, J. *J. Am. Chem. Soc.* **2002**, *124*, 13672.
(69) Liang, J.-L.; Yuan, S.-X.; Chan, P. W. H.; Che, C.-M. *Org. Lett.* **2002**, *4*, 4507.
(70) Levites-Agababa, E.; Menhaji, E.; Perlson, L. N.; Rojas, C. M. *Org. Lett.* **2002**, *4*, 863.
(71) Padwa, A.; Stengel, T. *Org. Lett.* **2002**, *4*, 2137.
(72) (a) Müller, P.; Boléa, C. *Helv. Chim. Acta* **2001**, *84*, 1093; Müller, P.; Boléa, C. *Synlett.* **2000**, 826. Müller, P.; Fernandez, D. *Helv. Chim. Acta* **1995**, *78*, 947. (b) Moriarty, R. M.; Prakash, O.; Vaid, R. K.; Zhao, L. *J. Am. Chem. Soc.* **1989**, *111*, 6443. Moriarty, R. M.; Prakash, O.; Vaid, R. K.; Zhao, L. *J. Am. Chem. Soc.* **1990**, *112*, 1297.
(73) Mahy, J.-P.; Bedi, G.; Battioni, P.; Mansuy, D. *New. J. Chem.* **1989**, *13*, 651. Mahy, J.-P.; Bedi, G.; Battioni, P.; Mansuy, D. *Tetrahedron Lett.* **1988**, *29*, 1927.
(74) Nägeli, I.; Bernardinelli, G.; Jacquier, Y.; Moran, M.; Müller, P. *Helv. Chim. Acta* **1997**, *80*, 1087.
(75) Hashimoto, S.; Watanabe, N.; Sato, T.; Shiro, M.; Ikegami, S. *Tetrahedron Lett.* **1993**, *34*, 5109. Hashimoto, S.; Watanabe, N.; Ikegami, S. *Synlett.* **1994**, 353.
(76) Espino, C. G.; Du Bois, J. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 598.
(77) Espino, C. G.; Wehn, P. M.; Chow, J.; Du Bois, J. *J. Am. Chem. Soc.* **2001**, *123*, 6935. Fleming, J. J.; Fiori, K. W.; Du Bois, J. *J. Am. Chem. Soc.* **2003**, *125*, 2028.
(78) Müller, P.; Boléa, C. *Helv. Chim. Acta* **2002**, *85*, 483.
(79) O'Connor, K. J.; Wey, S.-J.; Burrows, C. J. *Tetrahedron Lett.* **1992**, *33*, 1001.
(80) Groves, J. T.; Takahashi, T.; Butler, W. M. *Inorg. Chem.* **1983**, *22*, 884.
(81) Du Bois, J.; Hong, J.; Carreira, E. M.; Day, M. W. *J. Am. Chem. Soc.* **1996**, *118*, 915; Du Bois, J.; Tomooka, C. S.; Hong, J.; Carreira, E. M. *J. Am. Chem. Soc.* **1997**, *119*, 3179. Du Bois, J.; Tomooka, C. S.; Hong, J.; Carreira, E. M. *Acc. Chem. Res.* **1997**, *30*, 364; Du Bois, J.; Tomooka, C. S.; Hong, J.; Carreira, E. M.; Day, M. W. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1645.
(82) Nishimura, M.; Minakata, S.; Takahashi, T.; Oderaotoshi, Y.; Komatsu, M. *J. Org. Chem.* **2002**, *67*, 2101; Nishimura, M.; Minakata, S.; Thongchant, S.; Ryu, I.; Komatsu, M. *Tetrahedron Lett.* **2000**, *41*, 7089. Minakata, S.; Ando, T.; Nishimura, M.; Ryu, I.; Komatsu, M. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 3392.
(83) Ho, C.-M.; Lau, T.-C.; Kwong, H.-L.; Wong, W.-T. *J. Chem. Soc., Dalton Trans.* **1999**, 2411.
(84) Katsuki, T. *Synlett* 2003, 281; Nishikori, H.; Katsuki, T. *Tetrahedron Lett.* **1996**, *37*, 9245; Noda, K.; Hosoya, N.; Irie, R.; Ito, Y.; Katsuki, T. *Synlett* **1993**, 469.
(85) Lai, T.-S.; Kwong, H.-L.; Che, C.-M.; Peng, S.-M. *Chem. Commun.* **1997**, 2373.
(86) Liang, J.-L.; Huang, J.-S.; Yu, X.-Q.; Zhu, N.; Che, C.-M. *Chem. Eur. J.* **2002**, *8*, 1563.
(87) Simonato, J.-P.; Pécaut, J.; Scheidt, R.; Marchon, J.-C. *Chem. Commun.* **1999**, 989.
(88) Leung, A. K.-Y.; Huang, J.-S.; Liang, J.-L.; Che, C.-M.; Zhou, Z.-Y. *Angew. Chem.* **2003**, *42*, 340.
(89) Au, S.-M.; Fung, W.-H.; Cheng, M.-C.; Che, C.-M.; Peng, S.-M. *Chem. Commun.* **1997**, 1655.
(90) Au, S.-M.; Huang, J.-S.; Yu, W.-Y.; Fung, W.-H. Che, C.-M. *J. Am. Chem. Soc.* **1999**, *121*, 9120.
(91) Liang, J.-L.; Yu, X.-Q.; Che, C.-M. *Chem. Commun.* **2002**, 124.
(92) Zhang, J.-L.; Che, C.-M. *Org. Lett.* **2002**, *4*, 1911.
(93) Jeon, H.-J.; Nguyen, S. T. *Chem. Commun.* **2001**, 235.
(94) Yu, X.-Q.; Huang, J.-S.; Zhu, N.; Che, C.-M. *Org. Lett.* **2000**, *2*, 2233.
(95) Yang, J.; Weinberg, R.; Breslow, R. *Chem. Commun.* **2000**, 531.
(96) Kohmura, Y.; Katsuki, T. *Tetrahedron Lett.* **2001**, *42*, 3339.
(97) Au, S.-M.; Zhang, S.-B.; Fung, W.-H.; Yu, X.-Q.; Che, C.-M.; Cheung, K.-K. *Chem. Commun.* **1998**, 2677.
(98) Au, S.-M.; Huang, J.-S.; Che, C.-M.; Yu, W.-Y. *J. Org. Chem.* **2000**, *65*, 7858.
(99) Zhou, X.-G.; Yu, X.-Q.; Huang, J.-S.; Che, C.-M. *Chem. Commun.* **1999**, 2377.
(100) Liang, J.-L.; Yuan, S.-X.; Huang, J.-S.; Yu, X.-Q.; Che, C.-M. *Angew. Chem., Int. Ed. Engl.* **2002**, *41*, 3465.
(101) (a) Kirmse, W. *Carbene Chemistry*, 2nd ed.; Academic Press: New York, 1971; p 412. (b) March, J. *Advanced Organic Chemistry, Reaction Mechanisms and Structure*, 2nd ed; McGraw-Hill: New York, 1977; p 888. (c) Badea, F.; Condeiu, C.; Gherghiu, M.; Iancu, A.; Iordache, F.; Simion, C. *Rev. Roumaine Chim.* **1992**, *37*, 393.
(102) Aggarwal, V. K.; Alonso, E.; Ferrara, M.; Spey, S. E. *J. Org. Chem.* **2002**, *67*, 2335; Aggarwal, V. K.; Ferrara, M. *Org. Lett.* **2000**, *2*, 4107.
(103) Hori, R.; Aoyama, T.; Shioiri, T. *Tetrahedron Lett.* **2000**, *41*, 9455.
(104) Baret, P.; Buffet, H.; Pierre, J.-L. *Bull. Soc. Chim. Fr.* **1972**, 2493.
(105) Baret, P.; Buffet, H.; Pierre, J.-L. *Bull. Soc. Chim. Fr.* **1972**, 825.
(106) Bartnik, R.; Mloston, G. *Synthesis* **1983**, 924.
(107) Hubert, A. J.; Feron, A.; Warin, R.; Teyssié, P. *Tetrahedron Lett.* **1976**, 1317; Drapier, J.; Feron, A.; Warin, R.; Hubert, A. J.; Teyssié, P. *Tetrahedron Lett.* **1979**, 559.

(108) Moran, M.; Bernardelli, G.; Müller, P. *Helv. Chim. Acta* **1995**, *78*, 2048.
(109) Doyle, M. P.; Hu, W.; Timmons, D. J. *Org. Lett.* **2001**, *3*, 933.
(110) Wright, D. L.; McMills, M. C. *Org. Lett.* **1999**, *1*, 667.
(111) Mohan, J. M.; Uphade, B. S.; Choudary, V. R.; Ravindranathan, T.; Sudalai, A. *J. Chem. Soc., Chem. Commun.* **1997**, 1429.
(112) Rasmussen, K. G.; Jørgensen, K. A. *J. Chem. Soc., Chem. Commun.* **1995**, 1401.
(113) Hansen, K. B.; Finney, N. S.; Jacobsen, E. N. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 676.
(114) Juhl, K.; Hazell, R. G.; Jørgensen, K. A. *J. Chem. Soc., Perkin Trans. 1* **1999**, 2293.
(115) Casarubbios, L.; Pérez, J. A.; Brookhart, M.; Templeton, J. L. *J. Org. Chem.* **1996**, *61*, 8358.
(116) Ha, H.-J.; Kang, K.-H.; Suh, J.-M.; Ahn, Y.-G. *Tetrahedron Lett.* **1996**, *37*, 7069.
(117) Zhu, Z.; Espenson, J. H. *J. Org. Chem.* **1995**, *60*, 7090. Zhu, Z.; Espenson, J. H. *J. Am. Chem. Soc.* **1996**, *118*, 9901.
(118) Gunnoe, T. B.; White, P. S.; Templeton, J. L.; Casarrubios, L. *J. Am. Chem. Soc.* **1997**, *119*, 3171.
(119) Mayer, M. F.; Hossain, M. M. *J. Org. Chem.* **1998**, *63*, 6839.
(120) (a) Xie, W.; Fang, J.; Li, J.; Wang, P. G. *Tetrahedron* **1999**, *55*, 12929. (b) Nagayama, S.; Kobayashi, S. *Chem. Lett.* **1998**, 685.
(121) Sengupta, S.; Mondal, S. *Tetrahedron Lett.* **2000**, *41*, 6245.
(122) Morales, D.; Pérez, J.; Riera, L.; Corzo-Suárez, R.; García-Granda, S.; Miguel, D. *Organometallics* **2002**, *21*, 1540.
(123) Rasmussen, K. G.; Jørgensen, K. A. *J. Chem. Soc., Perkin Trans. 1* **1997**, 1287.
(124) Antilla, J. C.; Wulff, W. D. *J. Am. Chem. Soc.* **1999**, *121*, 5099.
(125) Antila, J. C.; Wulff, W. D. *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 4518.
(126) Loncaric, C.; Wulff, W. D. *Org. Lett.* **2001**, *3*, 3675.
(127) Aggarwal, A. K.; Thompson, A.; Jones, R. V. H.; Standen, M. C. H. *J. Org. Chem.* **1996**, *61*, 8368; Aggarwal, V. K. *Synlett.* **1998**, 329.
(128) (a) Franzen, V.; Driesen. H. E. *Chem. Ber.* **1963**, *96*, 1881. (b) Corey, E. J.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *85*, 1353. (c) Tewari, R. S.; Awasthi, A. K.; Awasthi, A. *Synthesis* **1983**, 330. (d) Li, A. H.; Dai, L. X.; Hou, X. L.; *J. Chem. Soc., Perkin Trans. 1* **1996**, 867; Li, A. H.; Zhou, Y. G.; Dai, L. X.; Hou, X. L.; Xia, L. J.; Lin, L. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1317; Yang, X. F.; Zhang, M. J.; Hou, X. L.; Dai, L. X. *J. Org. Chem.* **2002**, *67*, 8097.
(129) Aggarwal, V. K.; Ferrara, M.; O'Brien, C. J.; Thompson, A.; Jones, R. V. H.; Fieldhouse, R. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1635.
(130) Aggarwal, V. K. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 1433.

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