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Asymmetric metal complex catalysis in the series of monofunctional substrates: the lower the catalyst symmetry, the higher the enantioselectivity

V A Pavlov, T N Pavlova

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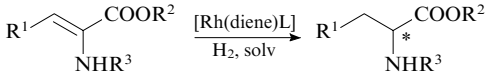
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Abstract. The title statement is derived from analysis of 90 asymmetric reactions (addition, reduction, oxidation, *etc.*) of monofunctional substrates such as benzaldehyde, acetophenone or thioanisole catalyzed by metal complexes with C_1-, C_2- and C_3-symmetric chiral ligands. The advantage of complexes with C_1-symmetric ligands is manifested as higher *ee* values of the reaction products compared with C_2 complexes as catalysts (the average *ee* values are 97% and 85%, respectively). The possible catalytic cycles of effective asymmetric reactions under the action of C_2-complexes proposed by different authors attest to C_1 symmetry of the key intermediate that controls the asymmetric induction. If the key intermediate retains the initial C_2 symmetry, the reaction enantioselectivity is usually low. The bibliography includes 162 references.

I. Introduction

A rapidly developing method for the preparation of optically active compounds is based on asymmetric homogeneous reactions catalyzed by metal complexes with chiral ligands. The enantioselectivity of the reactions is implemented in asymmetric induction (intramolecular diastereoselectivity). This phenomenon has attracted the attention of chemists for a long time (the Cram, the Prelog and other rules). Currently, there exist two hypotheses explaining the asymmetric induction in the reactions provided by metal complexes. The first hypothesis is based on the spatial interaction between the substrate and the chiral complex according to the 'lock and key' principle during the catalytic reaction.[1–3] If the transition state (the key intermediate) responsible for the asymmetric induction is asymmetric (having C_1 symmetry, non-symmetric, devoid of symmetry elements), the enantiomeric excess (*ee*) of the reaction product should be high. The chiral molecular recognition and induction are based, according to another hypothesis,[4,5] on helical electronic effects in the metal complex (catalyst) and the coordinated substrate.

According to the first hypothesis, the symmetry difference (C_1 or C_2) in the series of chiral ligands may have no effect on the reaction enantioselectivity. For example, the substrates coordinated in the intermediate complex by two or three functional groups may form products with as high *ee* values as possible under the action of complexes with either C_2-symmetric ligands **1**–**3** [reactions (1) and (2)]† or asymmetric ligands.[1]



(1)

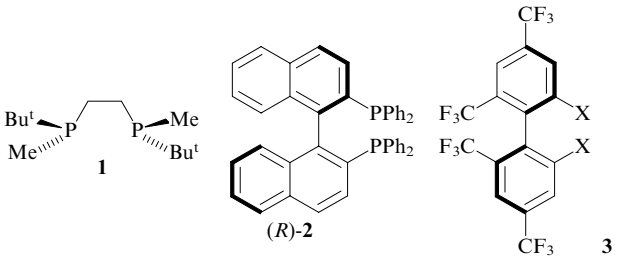
R^1	R^2	R^3	L	diene	*ee* (%)	Ref.
Ph	Me	Ac	**1**	nbd	99.9	6, 7
Ph	H	Bz	(*R*)-**2**	cod	100	8
H	Me	Ac	**3**	cod	99.9	9

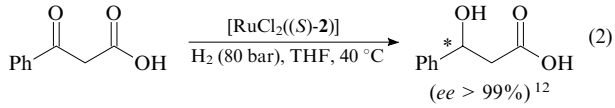
nbd is norbornadiene, cod is cycloocta-1,5-diene, solv is solvent.

† More than 20 bidentate C_2-ligands of rhodium catalysts for reaction (1) with *ee* > 99% are known, and the search for new efficient C_2-symmetric ligands is still in progress,[10,11] although the practical value of this search for this particular reaction is moderate.

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(2)

This is related to the fact that C_2 symmetry of the catalytic complex is lost in the first step of reaction (1) after the substrate coordination (the Halpern mechanism [13–16] or the Imamoto hydride mechanism [17,18]), asymmetric induction taking place in the asymmetric intermediate (see review [3]). However, if the intermediate responsible for the asymmetric induction retains C_2 symmetry of the catalytic complex, for example, in the case of monofunctional prochiral substrates, reactions have moderate enantioselectivity.[1] Reactions of this type include some catalytic processes [alkylation of benzaldehyde with dialkylzinc without addition of Ti(OPr^i)$_4$, transfer hydrogenation of acetophenone, hydrogenation of ketopantolactone, hydrogenation of acetophenone and monofunctional arylalkenes on Rh and Ir complexes, conjugated addition of diethylzinc to chalcone] and also some transformations in which the metal complex participates in stoichiometric amount. All these reactions are catalyzed by complexes with bidentate C_2-symmetric ligands.[1] It can be seen that most of substrates used in these reactions have no other functional groups.

It should be emphasized that the symmetry of the ligand (and the catalytic complex) ‡ can have a crucial effect on the reaction mechanism, as it dictates the arrangement of the donor groups, the similarity and the difference of their electronic properties, *etc*.

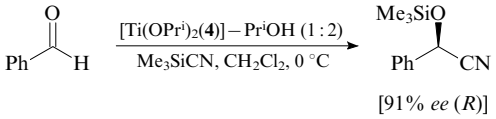
The above-mentioned difference in the enantioselectivity of several catalytic reactions proceeding through C_2- and C_1-symmetric intermediates for monofunctional substrates requires investigation of whether this phenomenon is unique or common for these reactions. This review considers the published data about the reactions of monofunctional prochiral substrates catalyzed by complexes with C_2-ligands in which the asymmetric induction occurs in the step of formation of either C_1- or C_2-symmetric intermediates. The reactions induced by complexes with C_2-ligands whose enantioselectivity is affected by achiral additives are analyzed. The reactions of monofunctional substrates catalyzed by complexes with C_1-ligands are considered. The enantioselectivities of reactions carried out under identical experimental conditions are compared depending on the catalyst symmetry, *i.e*., for complexes of the same metal with C_2- or C_1-symmetric ligands with the same donor atoms. The reactions are formally classified according to the monofunctional substrates used: prochiral aromatic aldehydes, ketones, α-keto esters, imines, sulfides, and alkenes.

‡ Of course, for non-rigid molecules in solution (homogeneous catalysis), only approximate symmetry can be considered.

II. Addition reactions in the series of monofunctional aromatic substrates catalyzed by metal complexes with C_2-symmetric ligands

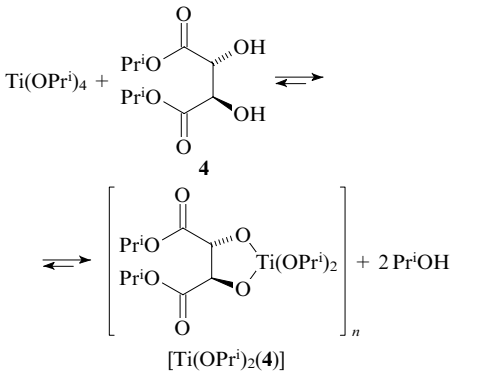
1. Cyanosilylation and cyanoformylation of aromatic aldehydes in the presence of Ti, V, Sm and Al complexes

The enantioselective catalytic cyanosilylation of aldehydes is an efficient route to chiral cyanohydrin derivatives,[19] which are subsequently converted to biologically active compounds.[20–22] An example is reaction (3).[23]



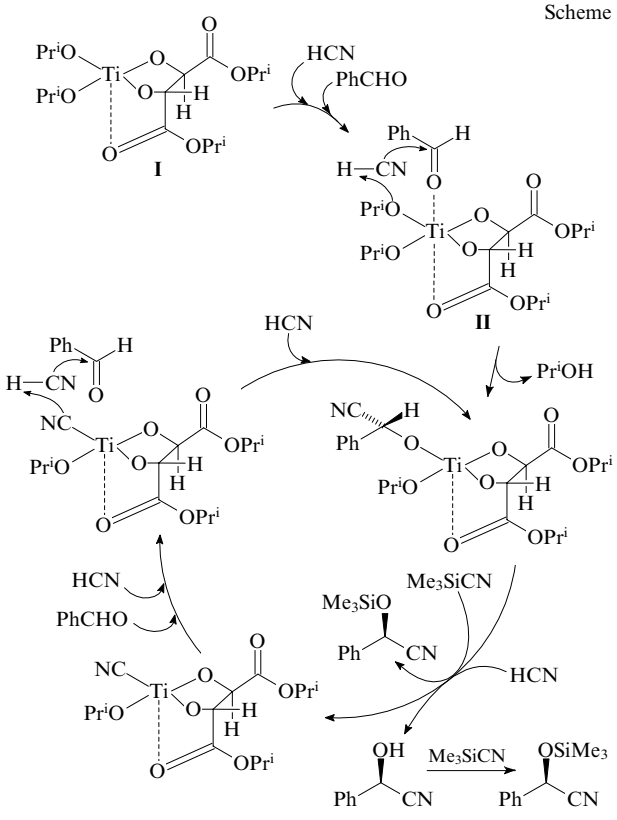
(3)

The catalytic complex is formed by reaction (4) from chiral diisopropyl tartrate (**4**).§



(4)

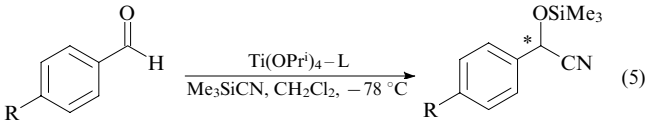
Scheme 1



§ Here and below, for the sake of simplicity, free and coordinated ligands have the same designation (the same number), even if protons are lost upon coordination, as for example, for diisopropyl tartrate.

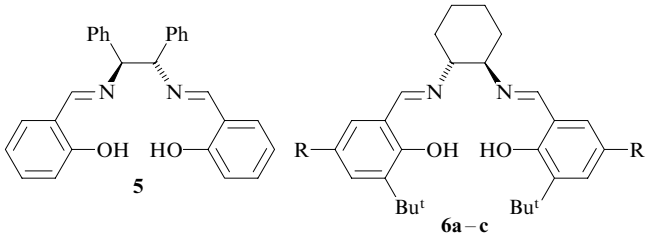
Hayashi *et al.*[23] proposed a possible mechanism for reaction (3) (Scheme 1). Hydrogen cyanide evolved upon the reaction of trimethylsilyl cyanide with isopropyl alcohol reacts with benzaldehyde. The compound thus formed is coordinated by the titanium complex **I** to give intermediate **II**. This asymmetric intermediate is responsible for the asymmetric induction.

High enantioselectivity was also found for reactions (5) and (6) of cyanosilylation of aromatic aldehydes catalyzed by the complexes $Ti(OPr^i)_4$ and $TiCl_4$ with C_2-symmetric salen ligands **5**, **6**.

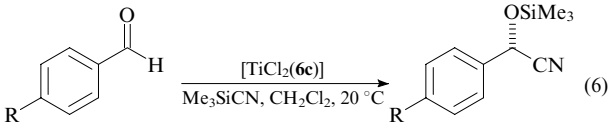


(5)

R	L	*ee* (%)	Ref.	R	L	*ee* (%)	Ref.
H	**5**	87 (*R*)	24, 25	H	**6b**	75 (*S*)	27
H	**6a**	76 (*S*)	26	H	**6c**	72 (*S*)	26, 28
MeO	**6a**	94 –	26	Me	**6c**	88 –	26, 28



R = MeO (**a**), H (**b**), Bu^t (**c**).

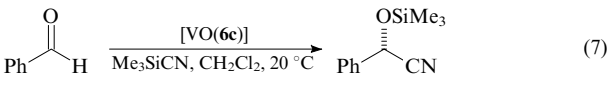


(6)

R = H, 75% *ee* (*S*); Me, 72% *ee* (configuration is not indicated).[26, 28]

In all of the listed reactions, the *ee* values of products fall within a rather narrow range (72% – 87%), except for reaction (5) involving *para*-methoxy-substituted benzaldehyde (94% *ee*). Note relatively low temperature dependence (in the range of –78 °C to 20 °C) of the enantioselectivity of reactions (5) and (6) induced by complexes with the ligand (*R*,*R*)-**6c**.

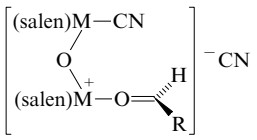
Among known metal – salen complexes, the (salen)oxovanadium complex catalyzes the cyanosilylation of benzaldehyde with the highest enantioselectivity [reaction (7)],[29, 30] the (*R*,*R*)-isomer of the catalyst producing predominantly the (*S*)-product.



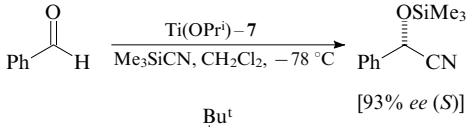
[94% *ee* (*S*)]

(7)

A schematic structure for the key intermediate (transition state) for reactions of type (5) – (7) has been proposed.[31] It can be seen that this intermediate is asymmetric.

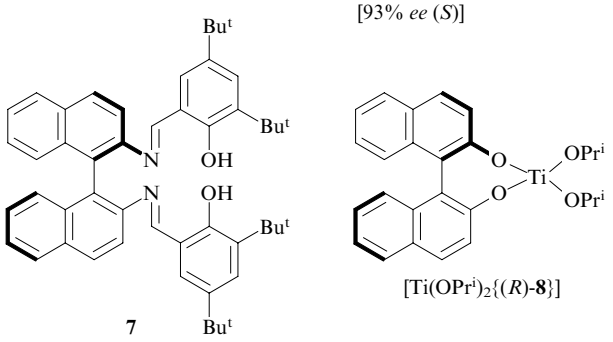


High enantioselectivity was found for reaction (8) induced by the Ti complex with the C_2-symmetric Schiff base **7**.[32]



[93% *ee* (*S*)]

(8)

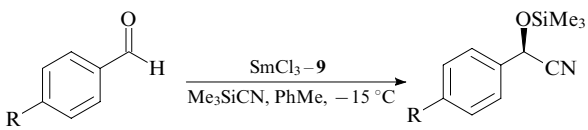


[Ti(OPr^i)2{(*R*)-**8**}]

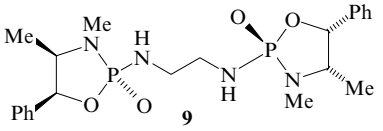
The Ti complex based on ligand **7** can be compared,in some measure, with [$Ti(OPr^i)_2${(*R*)-**8**}], because the chiral fragments and the metal atoms in these complexes are the same. Nevertheless, cyanosilylation of benzaldehyde on the Ti complex with ligand **8** at 0 °C is much less enantioselective (*ee* < 10%) [33] than reaction (8). Previously, it was noted [2] that for some reactions, the lower the conformational rigidity of the C_2-symmetric structure of the catalytic complex, the higher the enantioselectivity all other factors being the same. This may be attributable to the possible distortion of the C_2-geometry of the intermediate responsible for the asymmetric induction. Ligand **8** and the corresponding titanium complex have more rigid structures than ligand **7** and the Ti complex with this ligand. This may be the reason for low enantioselectivity of the Ti – **8** system-catalyzed reactions compared with the reactions induced by the Ti – **7** system; moreover, this indirectly implies that the structure of the intermediate involving ligand **7** deviates from C_2 symmetry. Since the product yields obtained with both complexes are comparable, the temperature conditions of the reaction should not affect considerably the asymmetric induction in the intermediates based on these complexes.

L	*T*/°C	Yield (%)
7	–78	92
8	0	90

Reaction (9) has high enantioselectivity in the presence of samarium complex with C_2-symmetric ligand **9**.[34]



(9)

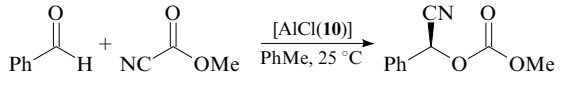


9

R	*ee* (*R*) (%)
H	84
MeO	90

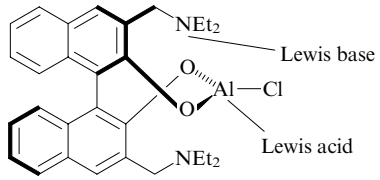
Presumably, the mechanism of reaction (9) is similar to the mechanisms of analogous metal complex-catalyzed cyanosilylation reactions (3) and (5)–(7).

A relatively high enantioselectivity was found for the cyanoformylation reaction (10) catalyzed by bifunctional aluminium complex [AlCl(**10**)].[35]



(10)

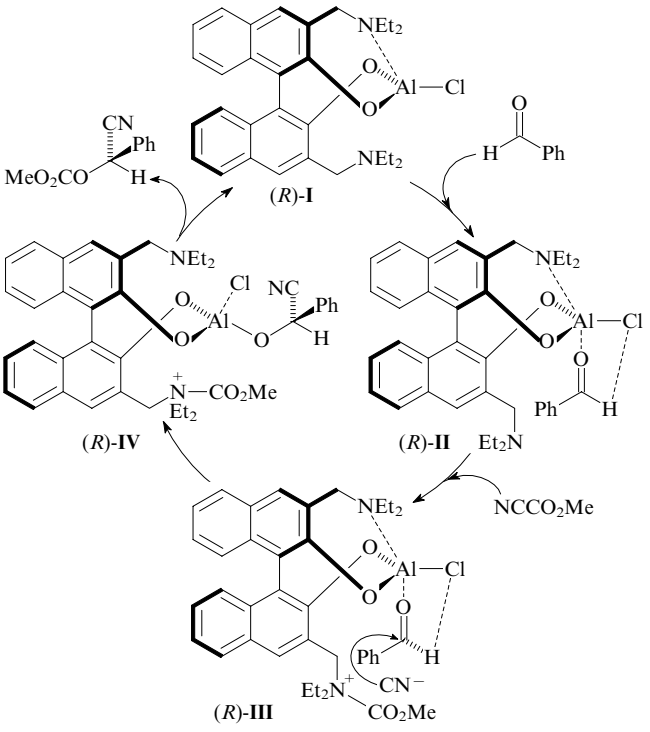
[78% *ee* (*S*)]



[AlCl(**10**)]

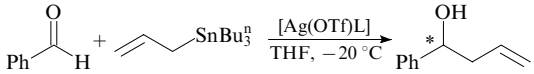
The addition of molecular sieves MS 4 Å to the reaction mixture did not result in the expected increase in the enantioselectivity (papers that attest to a beneficial influence of molecular sieves on the asymmetric induction are considered in Section V). A mechanism of this catalytic reaction consistent with obtained experimental data was proposed [35] (Scheme 2). According to this mechanism, the asymmetric induction takes place at the step of formation of the asymmetric key intermediate (*R*)-**III**.

Scheme 2



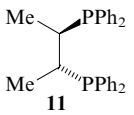
2. The addition of allyl reagents to benzaldehyde and acetophenone in the presence of silver and titanium complexes

The asymmetric allylation of benzaldehyde with allyltributylstannane occurs in the presence of silver complexes [reaction (11)].[36]



(11)

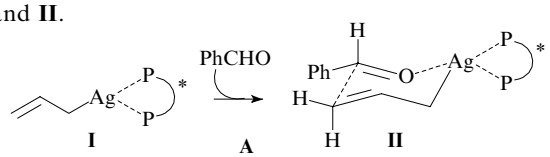
L	*ee* (%)	Configuration of the product
(*S*)-**2**	96	*S*
11	2	*R*



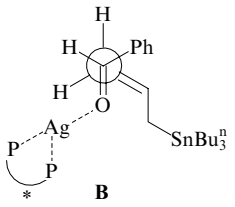
11

The striking difference between the enantioselectivities of reaction (11) induced by complexes with ligands (*S*)-**2** and **11** may be attributed to the stereochemical difference of the mechanisms of their catalytic action.

The asymmetric induction in cyclic mechanism **A** (see Ref. 36) is controlled by non-symmetric intermediates **I** and **II**.

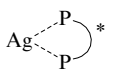


I **A** **II**

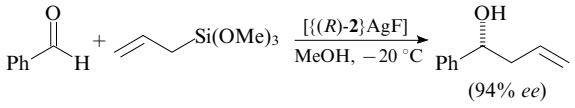


B

According to acyclic mechanism **B** (see Refs 36 and 37), the asymmetric induction is performed by the C_2-symmetric fragment.



If one assumes that complexes [{(*S*)-**2**}AgOTf] and [(**11**)AgOTf] catalyze reaction (11) according to mechanisms **A** and **B**, respectively, the pronounced difference between the enantioselectivities of this reaction under the action of these complexes becomes obvious. Much the same mechanism **A** can account for the high enantioselectivity of reaction (12), *viz*., the addition of allyltrimethoxysilane to benzaldehyde in the presence of complex [{(*R*)-**2**}AgF].[38]



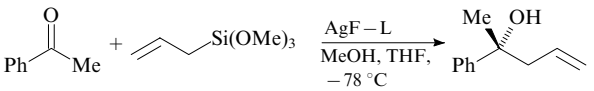
(12)

(94% *ee*)

The similarity of the cyclic mechanisms of reactions (11) and (12) is supported by the compliance of the configurations of ligand **2** and the reaction products [*S* in reaction

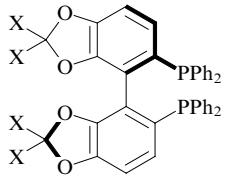
(11) and *R* in reaction (12)] and by some experimental data.[36–38]

More moderate *ee* values are observed in reaction (13) with acetophenone as the substrate and the AgF–ligand **2**, **12** or **13** system as the catalyst[39]

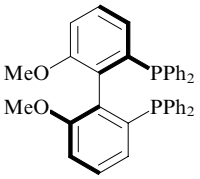


(13)

L	*ee* (*R*) (%)	L	*ee* (*R*) (%)
(*R*)-**2**	63	(*R*)-**12b**	82
(*R*)-**12a**	46	**13**	74



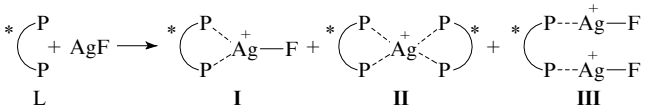
12a,**b**



13

X = H (**a**), F (**b**).

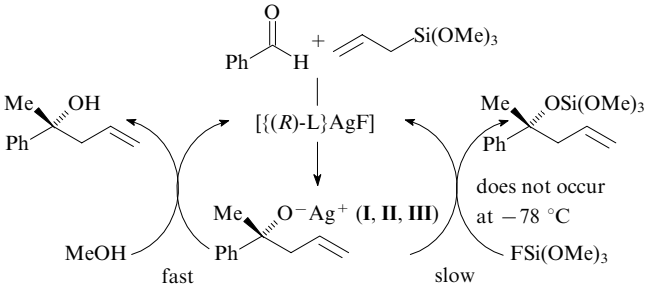
The catalytic reaction (13), like reaction (12), starts with the formation of C_2-symmetric complexes **I**, **II**, **III**.



L	The ratio **I** : **II** : **III**	L	The ratio **I** : **II** : **III**
(*R*)-**2**	32 : 43 : 25	(*R*)-**12b**	86 : 5 : 9
(*R*)-**12a**	43 : 49 : 18	**13**	42 : 33 : 25

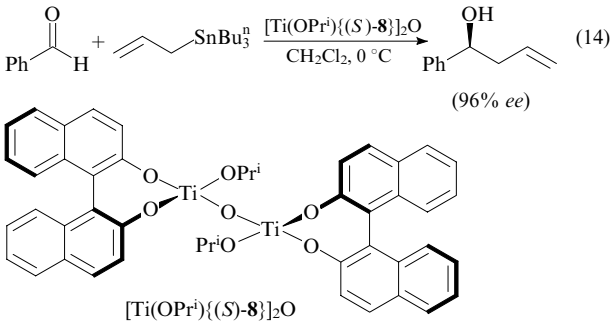
The ratios of these complexes for each of the ligands used were determined from the ^{31}P NMR spectra recorded at −78 °C.[39] The possible catalytic cycle of acetophenone allylation[39] is depicted in Scheme 3. The highest enantioselectivity of the reaction (82% *ee*) is observed in the presence of the catalytic complex [{(*R*)-**12b**}AgF] of which 86% is the type **I** complex. This corresponds to the proposed catalytic cycle, as the more uniform the C_1-symmetric cyclic complex **A** in the above-described mechanism, the higher the expected *ee* value.

Scheme 3



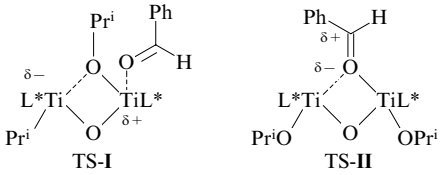
L = **2**, **12a**,**b**, **13**.

The binuclear titanium complex, being a Lewis acid, is an excellent catalyst of the allylation of benzaldehyde [reaction (14)].[40]



(14)

Hanawa *et al.*[40] discussed the structures of two possible transition states (TS-**I** and TS-**II**) responsible for the asymmetric induction.

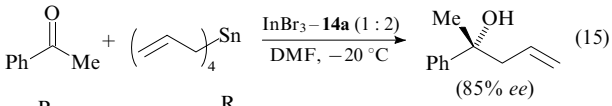


L* is (*S*)-binaphthoxy.

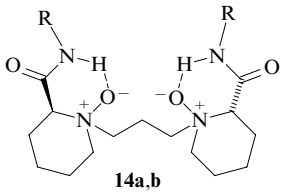
In the authors' opinion, the asymmetric structure TS-**I** is more consistent with experimental data.

3. Allylation of acetophenone, aromatic α-keto ester and α-keto phosphonate in the presence of indium(III) bis(*N*-oxide) complexes

Good enantioselectivity was found for allylation of aromatic keto derivatives [reactions (15)–(17)] under the action of indium complexes with bis(*N*-oxides) **14**, **15**.



(15)



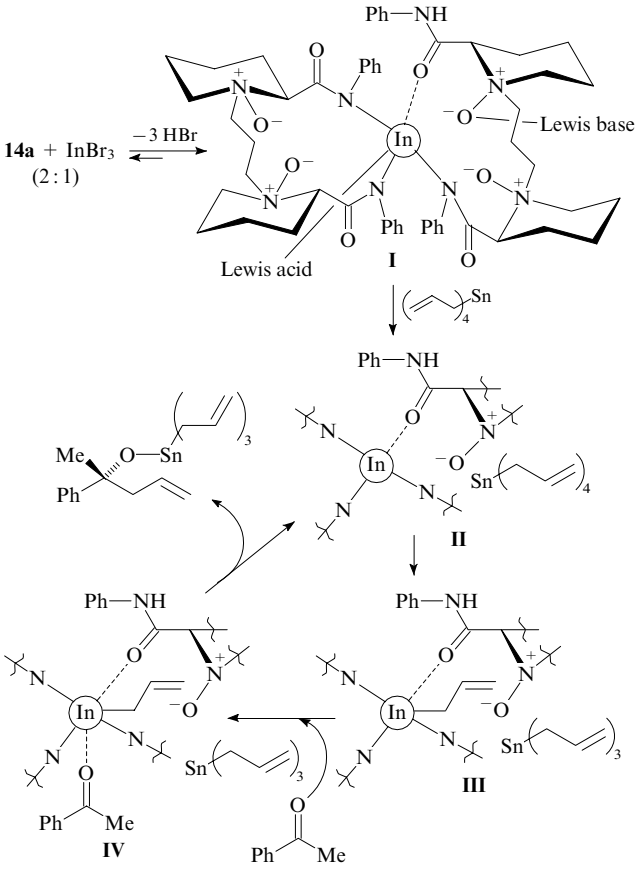
14a,**b**

R = Ph (**a**), cyclo-C_5H_9 (**b**).

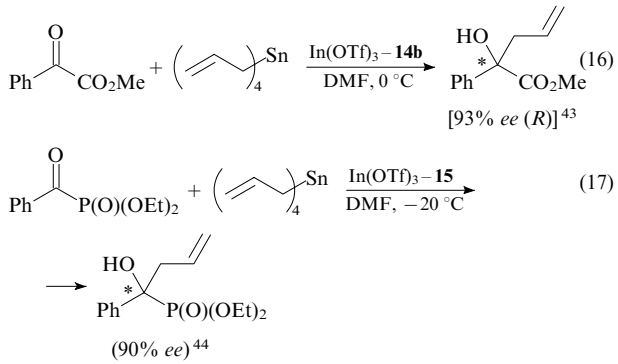
Zhang *et al.*[41] proposed a catalytic cycle for reaction (15) (Scheme 4), which is based on the assumption that the metal coordinates two bis(*N*-oxide) **14a** molecules thus giving a complex with four-coordinate metal environment[42] (complex **I**). The authors believe[41] that this structure of the intermediate complex can account for both the catalyst activity and the asymmetric induction. This complex acts as a bifunctional catalyst. The *N*-oxide as a Lewis base activates tetraallyltin, while the indium atom as a Lewis acid activates the ketone. As can be seen from Scheme 4, all intermediates (**I**–**IV**) of this cycle are asymmetric. The asymmetric induction occurs at the step of formation of the key intermediate **IV**.

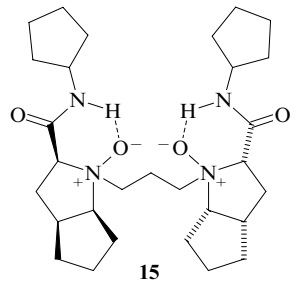
Similar mechanisms with asymmetric key intermediates controlling the asymmetric induction were proposed for the reactions involving In complexes with other C_2-symmetric

Scheme 4



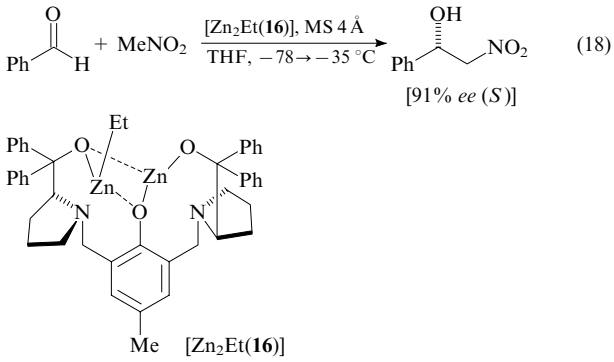
bis(*N*-oxides) [the configuration of the product of reaction (17) was not determined].[43,44]





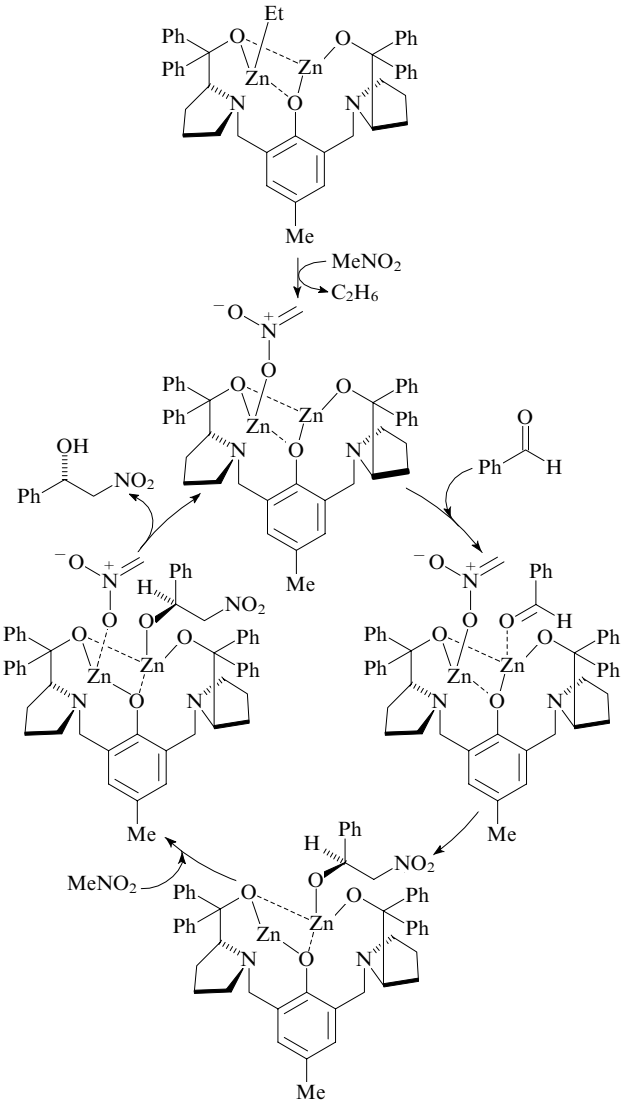
4. Nitroaldol reaction of aldehydes and α-keto esters (the Henry reaction) catalyzed by zinc and copper complexes

The Henry reaction of aromatic aldehydes or α-keto esters with nitromethane catalyzed by chiral metal complexes [reactions (18)–(20)] affords optically active products, which can be converted to valuable compounds.[45] The catalyst of reaction (18) is prepared by the reaction of C_2-symmetric triol **16** with two equivalents of Et_2Zn.[46]

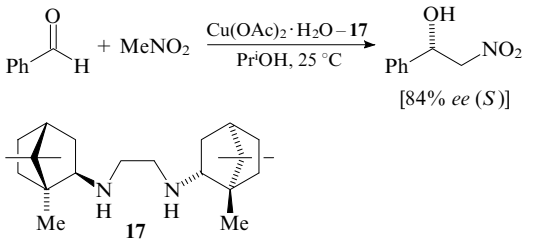


Trost and Yeh[46] proposed a possible catalytic cycle for reaction (18) (Scheme 5). It can be seen that all intermediates of the catalytic cycle are non-symmetric, *i.e.*, the asymmetric induction occurs at the step of formation of the asymmetric intermediate. The putative mechanism does not disclose the role of molecular sieves; therefore, this reaction is not included in Section V where the role of these additives is discussed.

Scheme 5

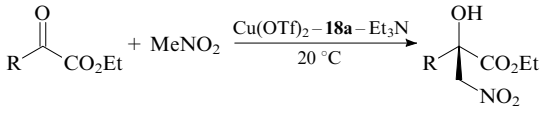


A similar reaction (19) is catalyzed by the copper complex with dibornyldiamine ligand **17**.[47]



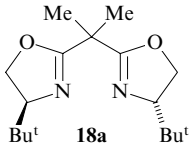
(19)

The copper complex with chiral bisoxazoline **18a** and with Et_3N additive performs the nitroaldol reaction of α-keto ester [reaction (20)].[48]



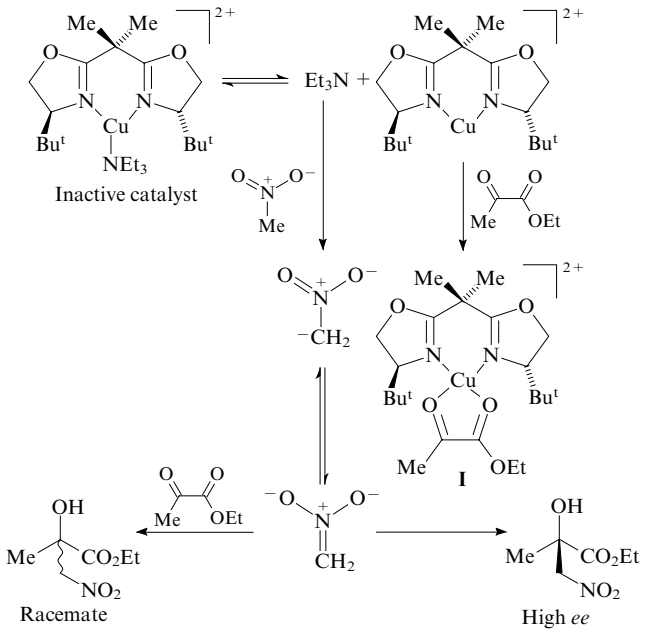
(20)

R	*ee* (%)
Me	92
Ph	86
4-ClC_6H_4	88



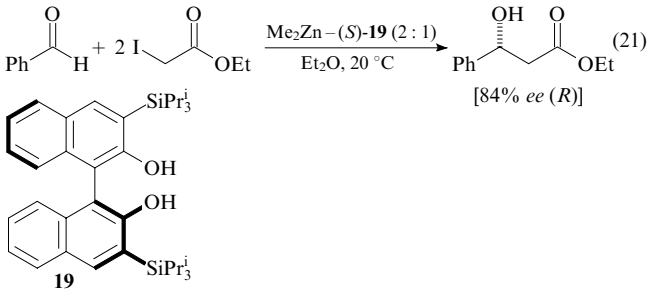
The enantioselectivity of reaction (20) barely depends on the nature of the keto ester. Christensen *et al.*[48] proposed a possible mechanism (Scheme 6) in which the key intermediate **I** responsible for the asymmetric induction has an asymmetric structure. The racemate is formed as the minor product. Since, according to this mechanism, the triethylamine molecule does not affect the structure of the catalytically active intermediate, this reaction is not included in Section IV, which considers the influence of achiral additives on the enantioselectivity.

Scheme 6



5. The reaction of benzaldehyde with α-halogeno ester under the action of dimethylzinc (the Reformatsky reaction)

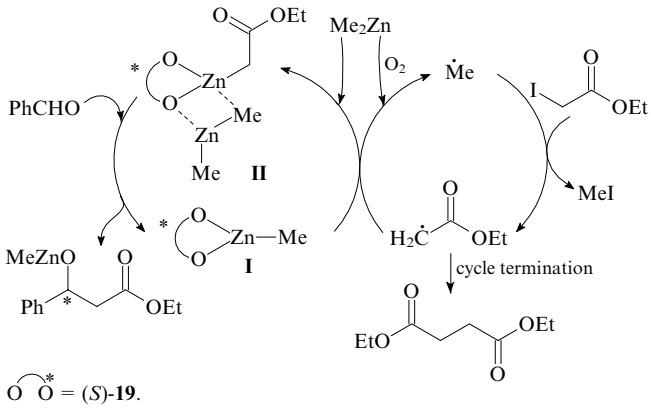
An example of the classical Reformatsky reaction[49, 50] in the asymmetric homogeneous catalytic version is reaction (21) involving ligand **19**.[51]



(21)

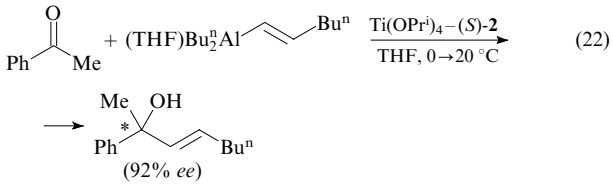
A possible catalytic cycle of this reaction is shown in Scheme 7. According to Fernandez-Ibanez *et al.*,[51] this is based on C_2-symmetric complex **I**, which loses C_2-symmetry during the reaction thus forming intermediate **II**; it is the latter that controls the asymmetric induction. This mechanism resembles the catalytic cycle of the Reformatsky reaction for imines.[52] It has also common features with the mechanism involving organozinc intermediates.[53]

Scheme 7



6. Vinylation of acetophenone with the vinylaluminium reagent catalyzed by a titanium complex

The $Ti(OPr^i)_4$ – (*S*)-**2** system catalyzes reaction (22) with high enantioselectivity (the product configuration is not indicated).[54]

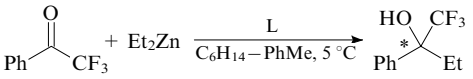


(22)

For most of reactions of monofunctional substrates considered in Section II, the possible catalytic cycles have been discussed. It can be seen from analysis of these cycles that the key intermediates of the reactions that control the asymmetric induction are asymmetric. In this respect, the reactions considered here are similar to the reactions of tri- and bifunctional substrates [reactions (1) and (2)]. However, unlike reactions (1) and (2), in the case of reactions (3)–(22), the highest enantioselectivity does not exceed 94%–96% (ee_{max} = 96%).

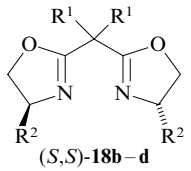
7. Catalytic reactions involving C_2-symmetric ligands proceeding with low enantioselectivities

The earlier analysis[1] of the published experimental data concerning the addition of diethylzinc to benzaldehyde in the presence of C_2-symmetric diols, diamines and other related compounds [in the absence of $Ti(OPr^i)_4$] showed very low enantioselectivity of this reaction. Therefore, the exceptionally low enantioselectivity of related reaction (23) catalyzed by ligands **18**, **20**–**22** comes as no surprise.[55]

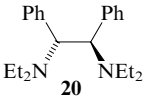


(23)

L	*ee* (%)	L	*ee* (%)
18a	37	**20**	6
18b	8	**21a**	0
18c	7	**21b**	0
18d	1	**22**	0

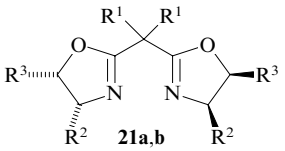


(*S*,*S*)-**18b**–**d**

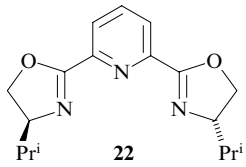


20

R^1 = Me: R^2 = Pr^i (**b**), Ph (**c**);
R^1 = Et, R^2 = Pr^i (**d**).



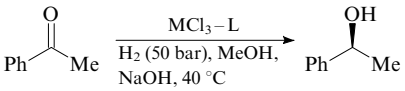
21a,**b**



22

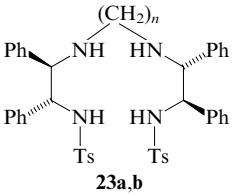
R^1 = Me, R^2 = Bn, R^3 = H (**a**);
R^1 = H, R^2 = R^3 = Ph (**b**).

A possible interpretation of this phenomenon was given previously,[1] being related apparently to the C_2-symmetric structure of the intermediate complex responsible for the asymmetric induction (see also Scheme 10 in Section IV). Yet another reaction with moderate enantioselectivity is the hydrogenation of acetophenone in the presence of rhodium, iridium and ruthenium complexes with C_2-symmetric ligands **23a**,**b** [reaction (24)].[56]



(24)

M	L	*ee* (%)
Rh	**23a**	12
	23b	12
Ir	**23a**	25
	23b	37
Ru	**23a**	0
	23b	0



23a,**b**

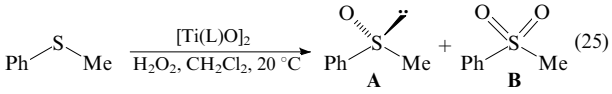
n = 2 (**a**), 3 (**b**).

The reaction mechanism was not discussed. A possible reason for the low enantioselectivity of reaction (24) may also be the C_2-symmetric structure of the key intermediate.

III. Oxidation of aryl sulfides in the presence of metal complexes with C_2- and C_3-symmetric ligands

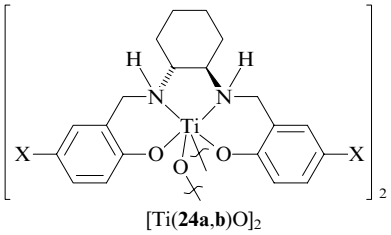
1. Oxidation of sulfides on titanium complexes

Optically active sulfoxides resulting from the asymmetric oxidation of prochiral sulfides in the presence of chiral metal complexes are valuable synthons;[57,58] some of these are biologically active.[59,60] Examples are provided by reactions (25)–(27) induced by titanium complexes with salan C_2-ligands **24**, **25**.[61]



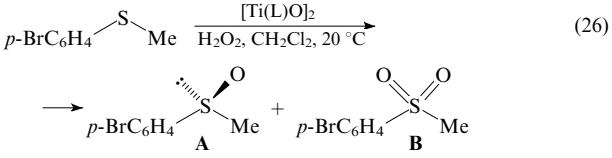
(25)

L	*ee* (*R*) (%)	Yield (%)	
		A	**B**
24a	45.0	77.5	12.0
24b	46.7	76.0	16.5



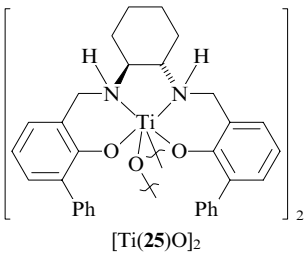
[Ti(**24a**,**b**)O]$_2$

X = H (**a**), Br (**b**).

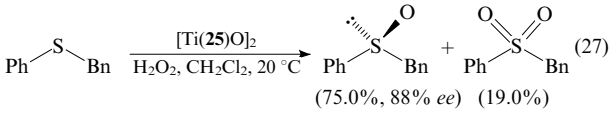


(26)

L	*ee* (%)	Yield (%)	
		A	**B**
24b	39 (*R*)	68.3	10.7
25	16 (*S*)	72.5	13.5

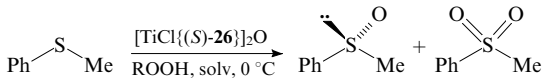


[Ti(**25**)O]$_2$



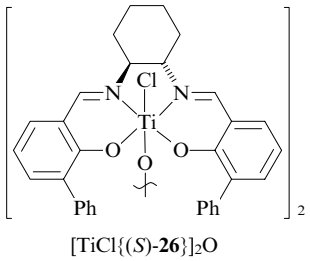
(27)

One more example is reaction (28) taking place in the presence of titanium salen C_2-complex.[62]



(28)

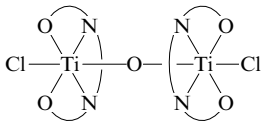
R	solv	*ee* (%)	R	solv	*ee* (%)
Ph_3C	MeOH	63	Bu^t	CH_2Cl_2	8
Ph_3C	CH_2Cl_2	26	Ph(Me)CHCH$_2$	CH_2Cl_2	19



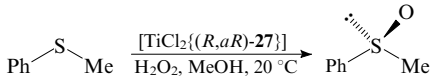
[TiCl{(*S*)-**26**}]$_2$O

These reactions have moderate enantioselectivity except for reaction (27), which involves the complex with ligand **25**. For reaction (28), the *ee* value appreciably depends on the nature of the hydroperoxide and the solvent. The structure of Ti complex with ligand (*S*)-**26** was studied by X-ray diffraction.[62]

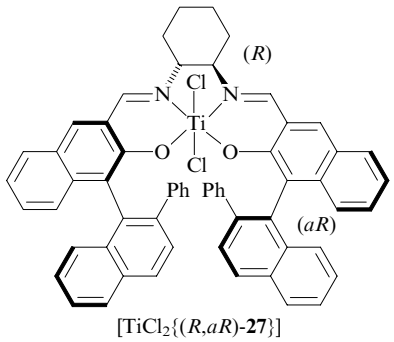
The binuclear complex has C_2 symmetry. This structure, which is reproduced in the key intermediate responsible for the asymmetric induction, may be the reason for relatively low enantioselectivity of reactions (25), (26) and (28).



The reaction (29) carried out in the presence of C_2-symmetric complex [TiCl$_2${(*R*,*aR*)-**27**}] also has low enantioselectivity.[63]

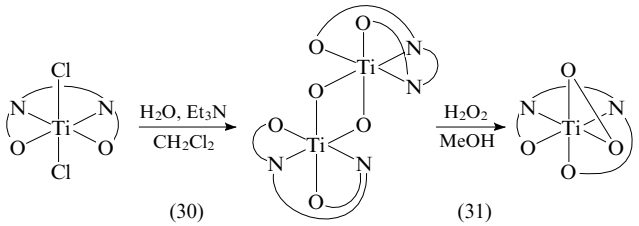


(29)



[TiCl$_2${(*R*,*aR*)-**27**}]

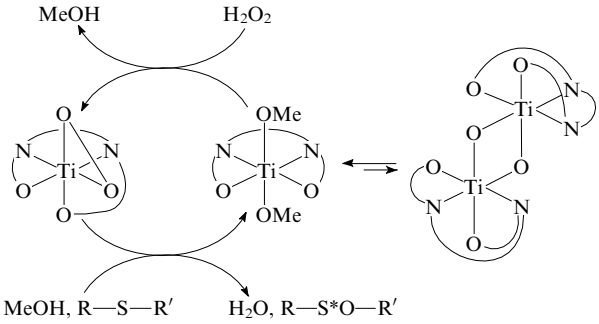
A similar complex [TiCl$_2$(**6c**)] can be converted to dimeric C_2-symmetric titanium μ-oxo-salen complex [reaction (30)].[30,64] The subsequent reaction (31) affords asymmetric peroxo complex, which performs reaction (29) with rather high enantioselectivity [82% *ee* (*S*)].[63]



(30) (31)

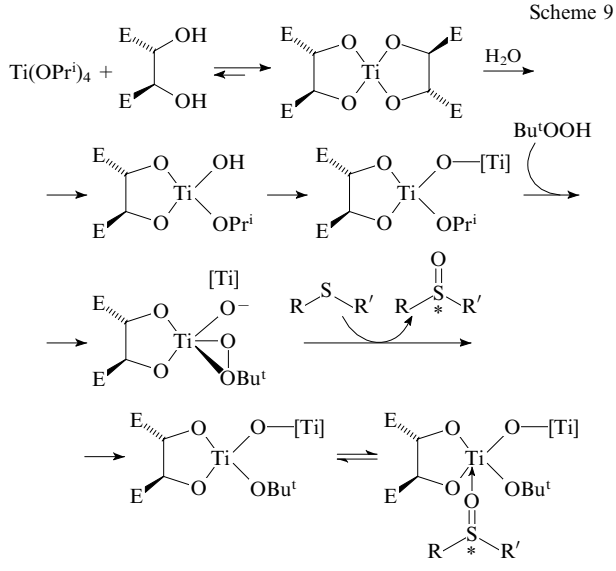
Saito and Katsuki[65] proposed a possible catalytic cycle for this reaction (Scheme 8). It can be seen that the intermediate complex that controls the asymmetric induction is asymmetric.

Scheme 8



The oxidation of the sulfide 4-MeC$_6$H$_4$SMe [reaction (32)] has a moderate enantioselectivity when carried out with the Ti(OPr^i)$_4$–(*R*)-**8**–2 H$_2$O [H$_2$O$_2$, PhMe, −20 °C, 73% *ee* (*R*)][66] and Ti(OPr^i)$_4$–F$_8$-**8** (1 : 2) systems (F$_8$-**8** is 5,5′,6,6′,7,7′,8,8′-octafluoro-1,1′-binaphthyl-2,2′-diol) [Bu^{t}OOH, CH$_2$Cl$_2$, −50 °C, 60% *ee* (*S*)].[67] The highest enantioselectivity of the oxidation of this substrate was observed with the Ti(OPr^i)$_4$–(+)-diethyl tartrate–H$_2$O catalytic system (1 : 2 : 1) and different hydroperoxides (Bu^{t}OOH, 89% *ee*; PhMe$_2$COOH, 96% *ee*; Ph$_3$COOH, 16% *ee*).[68,69] A possible mechanism of this reaction was proposed (Scheme 9),[70] the asymmetric induction being related to the step of formation of the non-symmetric key

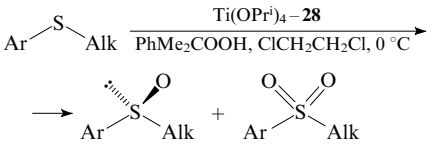
Scheme 9



E = CO_2Et; R = Me; R′ = Ph, Bn, n-C_8H_{17} (Oct^n), *etc.*

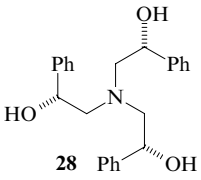
intermediate. Thus, the high enantioselectivity of sulfide oxidation (96% *ee*) in the presence of complexes with C_2-symmetric ligands, as in the case of reactions (3)–(22) is caused by the asymmetric structure of the key intermediate.

The oxidation of sulfides under discussion also proceeds enantioselectively under the action of Ti complexes with C_3-symmetric ligand **28** [reaction (33)].[71]

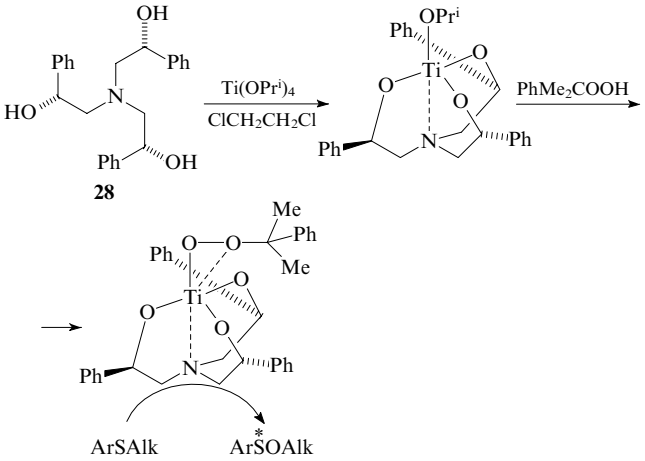


(33)

Ar	Alk	*ee* (*S*) (%)
4-MeC$_6$H$_4$	Me	45
Ph	Bn	84

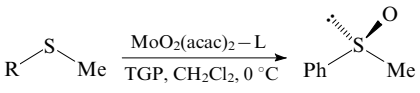


A possible route to the C_1-symmetric key intermediate of this reaction that controls the asymmetric induction was proposed.[72]



2. Oxidation of methyl phenyl sulfide induced by molybdenum, niobium, zirconium and other metal complexes

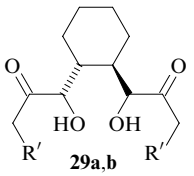
In the presence of molybdenum complexes with ligands **29** as the catalysts, the oxidation of aryl methyl sulfides [reaction (34)][73] has good enantioselectivity.



(34)

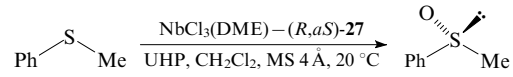
TGP is trityl hydroperoxide.

R	L	*ee* (*S*) (%)
Ph	**29a**	68
Ph	**29b**	79
4-MeC$_6$H$_4$	**29b**	81



R′ = CPh$_3$ (**a**), C(C$_6$H$_4$Pr^i-4)$_3$ (**b**).

The enantioselectivity increases if reaction (34) is accompanied by the kinetic resolution on the complex [MoO_2(acac)$_2$(**29b**)] at −40 °C [R = Ph, 92% *ee* (*S*); R = 4-MeC$_6$H$_4$, 94% *ee* (*S*)].[73] A high enantioselectivity is also attained in reaction (35) catalyzed by the $NbCl_3$(DME) – {(*R*,*aS*)-**27**} system (DME is dimethoxyethane).[74]

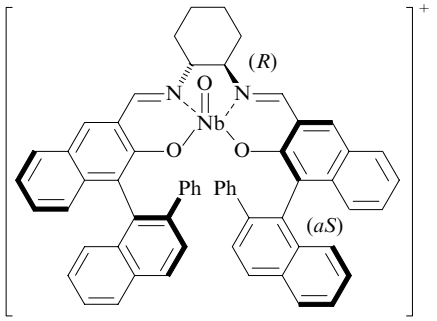


(35)

UHP is urea hydroperoxide.

$NbCl_3$(DME) : (*R*,*aS*)-**27**	*ee* (*S*) (%)
1 : 1	82
1 : 2	86

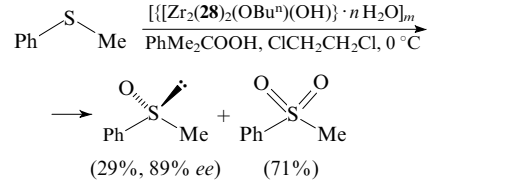
The structure of the complex formed *in situ* from $NbCl_3$(DME) and ligand (*R*,*aS*)-**27** (1 : 1) was studied by mass spectrometry. It was found that niobium(III) is oxidized to niobium(V).[74]



[NbO{(*R*,*aS*)-**27**}]

Thus, the catalytic complex becomes asymmetric; therefore, there are grounds for assuming that the key intermediate in reaction (35) is also asymmetric. Analogous manganese[75] and vanadium[76] salen complexes provide lower enantioselectivity in the reaction in question.

The zirconium complex obtained by the reaction of C_3-symmetric ligand **28** and Zr(OBu^n)$_4$ (1 : 1) in the presence of 2.5 equiv. of H_2O catalyzes reaction (36) with high enantioselectivity.[72]



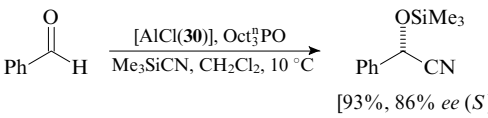
(36)

n = 3, 4.

The mechanism of this reaction is not obvious due to the intricate structure of the catalytic complex. However, as a result of such structure, this complex may be non-symmetric. Hence, it is quite possible that the key intermediate, which controls the asymmetric induction, is asymmetric.

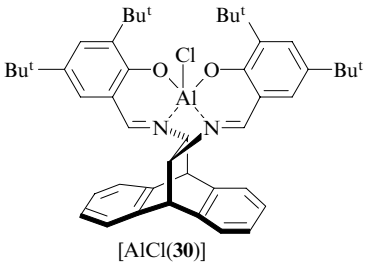
IV. Beneficial effect of achiral auxiliary reagents on the enantioselectivity of reactions catalyzed by metal complexes with C_2-ligands

A surprising example of the sensitivity of the *ee* value of a catalytic reaction product to the presence of achiral auxiliary reagents (AAR) is cyanosilylation of benzaldehyde under the action of C_2-symmetric aluminium complex with ligand **30** [reaction (37)].[77]

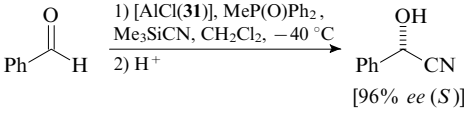


(37)

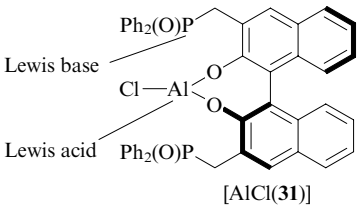
Without the addition of trioctylphosphine oxide, the *ee* value decreases to zero, the product yield being 90%.



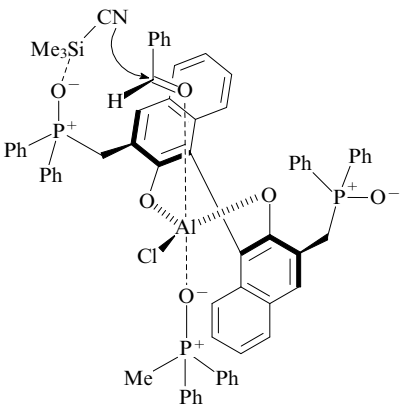
This increase in the enantioselectivity may be caused by the loss of C_2-symmetry by the key intermediate of this reaction upon the addition of AAR. A much less pronounced relative increase in the enantioselectivity (from 79% to 96%) is observed upon the addition of phosphine oxide in analogous reaction (38) catalyzed by the complex [AlCl(**31**)].[78]



(38)

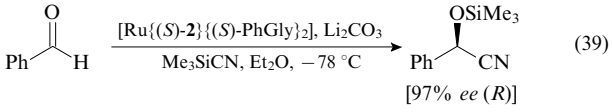


A possible structure of the key intermediate of reaction (38) responsible for the asymmetric induction has been proposed.[78]

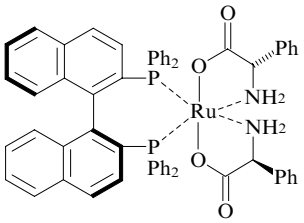


The coordination of diphenylphosphine oxide (AAR) by aluminium atom removes the C_2 symmetry axis of the catalytic complex that participates in the formation of the asymmetric key intermediate of the reaction.

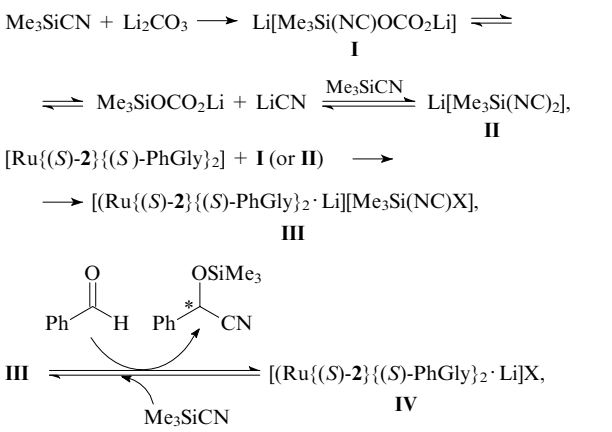
High enantioselectivity (*ee* reaches 97%) was noted for cyanosilylation of benzaldehyde in the presence of Ru complex with C_2-symmetric ligand and Li_2CO_3 as the AAR [reaction (39)].[79]



(39)



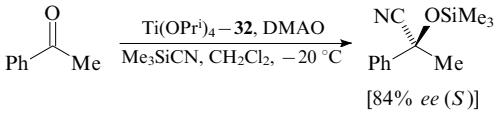
A possible mechanism of this reaction was proposed.[79]



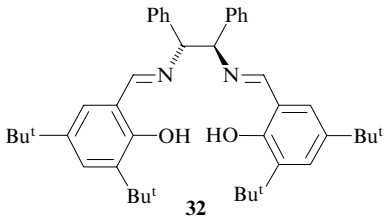
X = OCO_2Li, NC.

The asymmetric induction is accomplished at the formation of intermediate **III**, which cannot be C_2-symmetric.

The cyanosilylation of acetophenone in the presence of *N*,*N*-dimethylaniline *N*-oxide (DMAO) as the AAR and the C_2-symmetric complex with ligand **32** is also characterized by higher enantioselectivity than this reaction without AAR [reaction (40)].[80] Without AAR, the *ee* value is only 66% (the product configuration was not indicated).

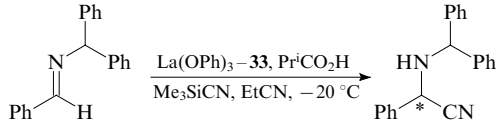


(40)

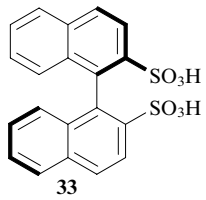


The addition of trimethylsilyl cyanide to imines (the Strecker reaction[81,82]) in the presence of C_2-symmetric complexes with ligand **33** and AAR (Pr^iCO_2H) can proceed

with good enantioselectivity [reaction (41)].[83] In the absence of AAR, the *ee* value reaches only 57%.

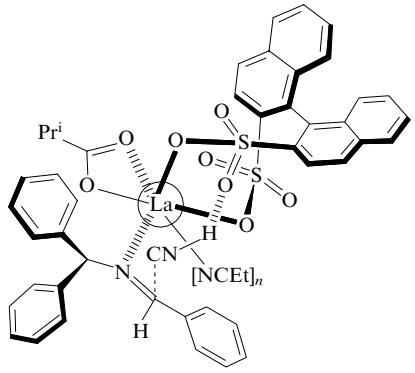


(41)

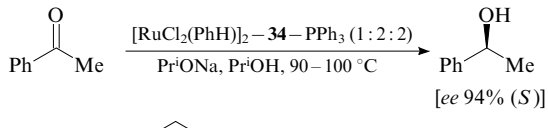


33

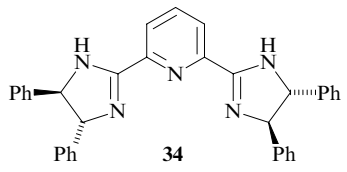
Hatano *et al.*[83] postulated a catalytic cycle and proposed a possible transition complex (the key intermediate).



The AAR (Pr^iCO_2H) is incorporated in the structure of this C_1-symmetric intermediate. Thus, the asymmetric induction in reaction (41) is controlled by the asymmetric intermediate. The increase in the symmetry of the catalytic complex with the loss of AAR reduces the process enantioselectivity and, conversely, a decrease in the symmetry of the key intermediate upon the introduction of the AAR can considerably increase the *ee*. Apart from reaction (37) mentioned above, the reaction accompanied by hydrogen transfer in the presence of ligand **34** [reaction (42)] can serve as an example of this situation.[84] When no triphenylphosphine is added, the *ee* value is only 7%.

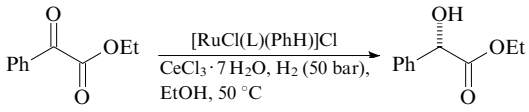


(42)



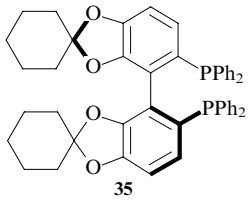
34

A somewhat smaller difference between the product *ee* in the presence and in the absence of AAR was observed in similar reactions accompanied by hydrogen transfer,[85,86] in the addition of nitroalkanes to aromatic nitroalkenes[87] (the Michael reaction), in the reaction of benzaldehyde with ethyl diazoacetate[88] and, for example, in the hydrogenation of aromatic α-keto esters involving phosphine **35** [reaction (43)].[89]



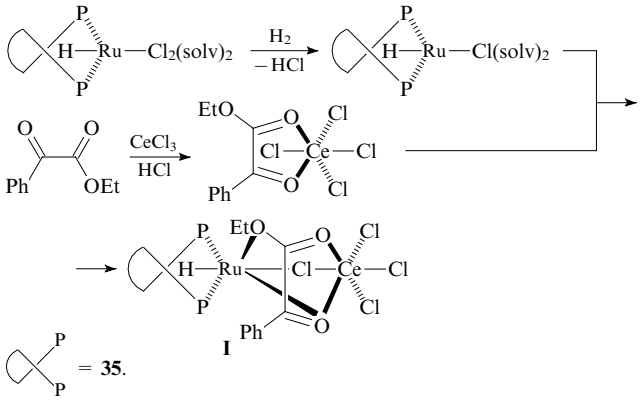
(43)

L	*ee* (*S*) (%)		L	*ee* (*S*) (%)	
	AAR	no AAR		AAR	no AAR
(*S*)-**2**	88	81	(*S*)-**12b**	93	71
(*S*)-**12a**	96	84	**35**	95	85

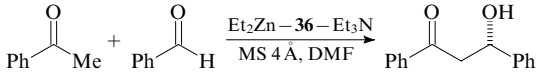


35

As can be seen from experimental data for reaction (43), the addition of AAR ($CeCl_3 \cdot 7\,H_2O$) to the reaction mixture resulted in all cases in higher enantioselectivity. A possible mechanism was proposed for this reaction where the key intermediate has C_1 symmetry.

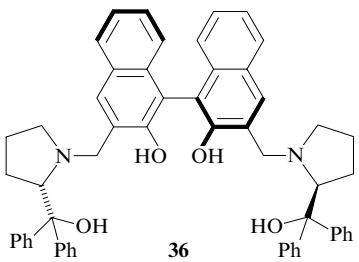


Interesting conclusions can be drawn from analysis of the aldol reaction of acetophenone and benzaldehyde in the presence of ligand **36** [reaction (44)].[90]



(44)

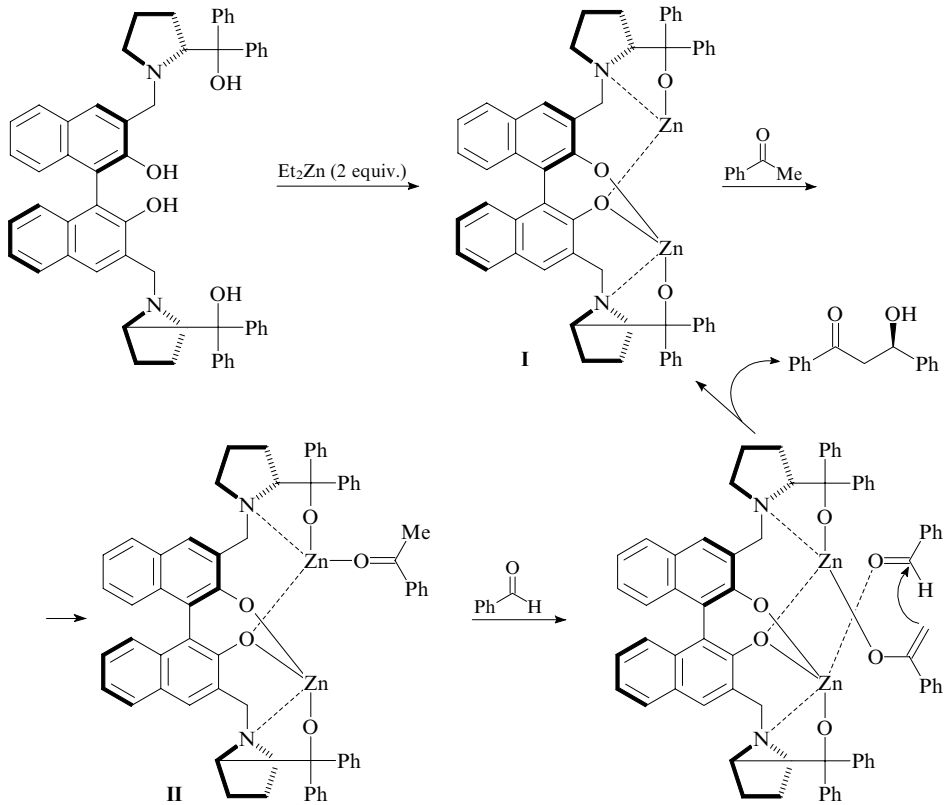
AAR	*T*/°C	*ee* (*S*) (%)
Et_3N	0	79
Et_3N	20	58
–	20	38



36

Li *et al.*[90] believe that the mechanism proposed previously[91–93] is applicable to this reaction (Scheme 10). How-

Scheme 10

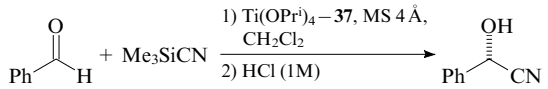


ever, in our opinion, this mechanism does not reflect the participation of the AAR (Et_3N) in reaction (44). The catalytic complex **I** involved in the formation of key intermediate **II**, which controls the asymmetric induction, has C_2 symmetry. Therefore, this mechanism corresponds to a reaction with low enantioselectivity [38% *ee* (*S*)].

Thus, in all of the studied reactions that have high enantioselectivity ($ee_{max} = 96\%$) and involve auxiliary reagents, the C_2 symmetry of the starting catalytic complex is lost in the step preceding the formation of the key intermediate, which controls the asymmetric induction. If this does not occur and the key intermediate remains C_2-symmetric, the reaction has low enantioselectivity.

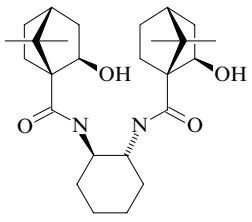
V. The increase in the enantioselectivity upon the addition of molecular sieves in the reactions performed in the presence of C_2-symmetric metal complexes

The addition of molecular sieves (MS 4 Å, MS 3 Å) to the reaction mixture increases the enantioselectivity of catalytic reactions induced by metal complexes with C_2-symmetric ligands.[1] Striking examples of this effect are provided by reactions (45)–(49) involving chiral ligands **8**, **18c** and **37**.

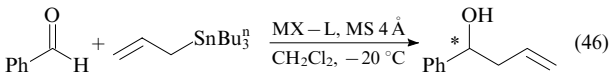


(45)

T/°C	MS	Yield (%)	*ee* (*S*) (%) (Ref. 94)
−78	4 Å	79	94
0	–	78	20

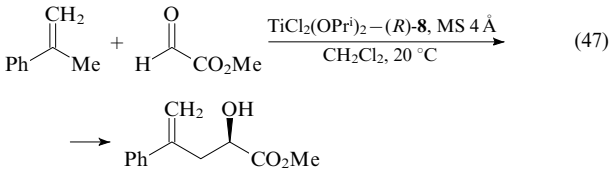


37



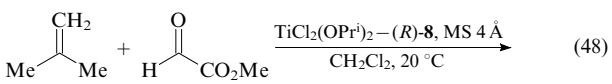
(46)

MX	L	MS	*ee* (%)	Ref.
$Ti(OPr^i)_4$	(*R*)-**8**	4 Å	96 (*R*)	95, 96
$TiCl_2$	(*S*)-**8**	4 Å	97 (*S*)	97
$InCl_3$	(*S*)-**8**	4 Å	92 (*S*)	98
$In(OPr^i)_3$	(*S*)-**8**	–	0	98



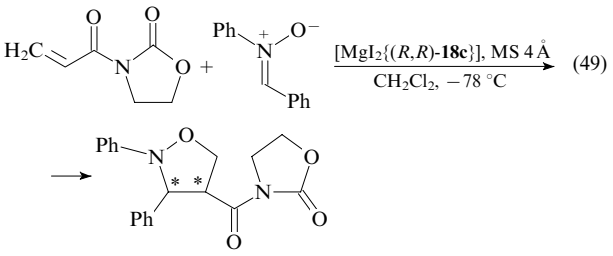
(47)

[95% *ee* (*R*); without MS 10% *ee*][99]

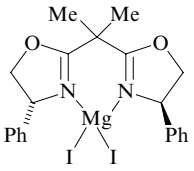


(48)

[95% *ee* (*R*); without MS 7% *ee*][99]



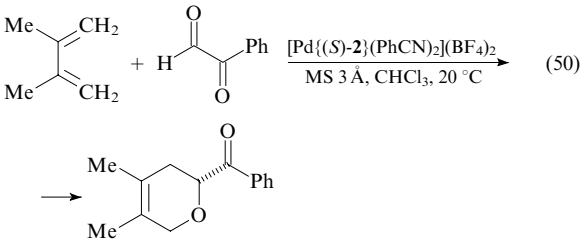
[82% *ee* $(3S,4R)_{endo}$; without MS 36% *ee*] [100]



[MgI_2\{(*R*,*R*)-**18c**\}]

An increase in the enantioselectivity of the reaction catalyzed by complexes with C_2-symmetric ligands in the presence of molecular sieves can be attributed, as in the case of achiral auxiliary reagents, to the loss of C_2- symmetry by the catalytic complex and thus by the key intermediate responsible for the asymmetric induction.[1] Indeed, metal chelates tend to be adsorbed by apical vacancies on the chemisorbent surface. If the C_2 symmetry axis lies in the plane of the chelate ring, the adsorbed complex loses it and becomes asymmetric. There is indirect evidence supporting this view.

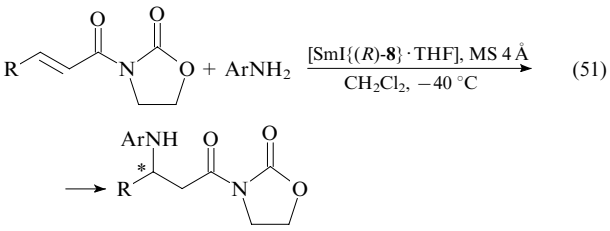
The Diels–Alder reaction is catalyzed by a Pd complex with C_2-symmetric ligand [reaction (50)].[101]



[96% *ee* (*R*); without MS 79% *ee*]

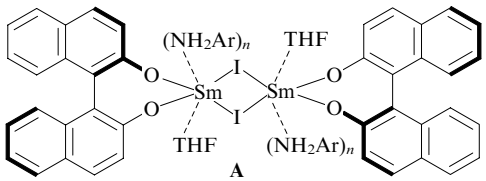
It can be seen that in the presence of molecular sieves, the reaction enantioselectivity is much higher. The crystal structure of the complex [Pd{(*S*)-**2**}$(PhCN)_2$]$(PF_6)_2$ was studied by X-ray diffraction analysis.[101] The coordination polyhedron of the complex (the metal atom coordinating two phosphorus atoms of the ligand and two benzonitrile molecules) has a somewhat distorted C_2-symmetric square planar structure. It is quite possible that this flat molecule is adsorbed during the reaction by a Pd apical vacancy on the surface of the chemisorbent (MS 3 Å). The C_2 symmetry axis of the adsorbed complex is lost in this case, and the asymmetric induction is controlled by the asymmetric intermediate.

Meanwhile, the catalytic Michael reaction [reaction (51)] provides very low *ee* values of the products even in the presence of molecular sieves.[102]

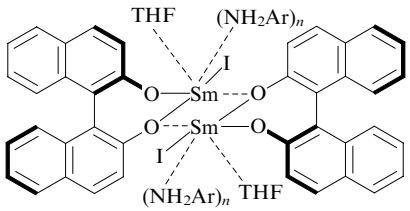


R	Ar	*ee* (%)
Ph	4-$MeOC_6H_4$	28
Pr^n	2-$MeOC_6H_4$	18

It was assumed [102] that binuclear dimers, precursors of the key intermediate, are formed during the reaction.



A



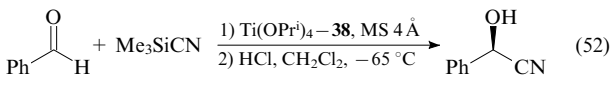
B

It can be seen that both dimers (**A** and **B**) are C_2-symmetric (note that in the publication,[102] *R*,*S*-dimer is mistakenly drawn instead of the *R*,*R*-dimer). Dimer **A** has a planar structure and can be coordinated on the adsorbent surface only by the plane normal to the C_2 symmetry axis, which is thus retained. The coordination of dimer **B** on the adsorbent surface is unlikely due to steric restrictions; if it still takes place, the C_2 axis is also retained. Therefore, in both cases, the intermediates that control the asymmetric induction are not asymmetric. This is confirmed by low enantioselectivity of reaction (51).

VI. Reactions in the series of monofunctional aryl substrates catalyzed by metal complexes with asymmetric ligands

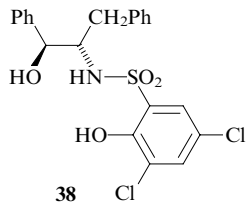
1. Cyanosilylation of benzaldehyde and acetophenone in the presence of titanium and aluminium complexes

As shown by reactions (52)–(54),¶ cyanosilylation of benzaldehyde and acetophenone is performed with high enantioselectivity on titanium complexes with asymmetric ligands **38**–**40**.[103–105]

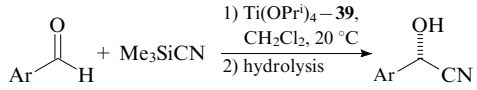


[96% *ee* (*R*)] [103]

¶ In the study cited,[103] (*R*)-RCH_2OH is erroneously drawn instead of (*R*)-RCH(CN)OH as the product of reaction (52).

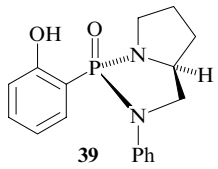


38

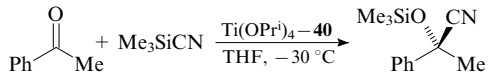


(53)

Ar	*ee* (*S*) (%) (Ref. 104)
Ph	94
4-MeOC$_6$H$_4$	98

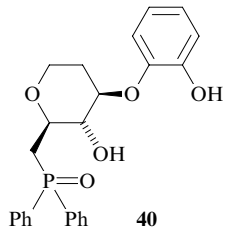


39



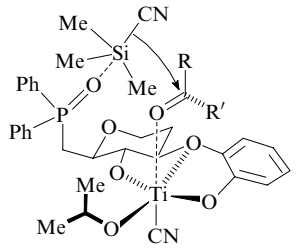
(54)

[92% *ee* (*R*)] [105]

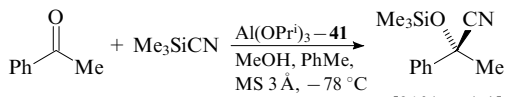


40

For reaction (54), Hamashima *et al.*[105] proposed the possible transition complex in which titanium and oxygen atoms of phosphine oxide activate the ketone and the cyanide as a Lewis acid and a Lewis base, respectively.

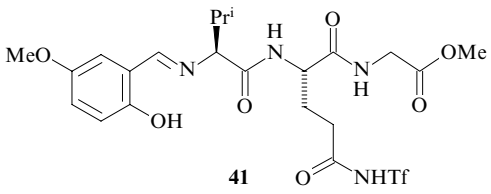


Reaction (55) in the presence of aluminium complex with peptide **41** may proceed by a similar mechanism (with allowance for replacement of the ligand phosphine oxide group by the amide group).[106]



(55)

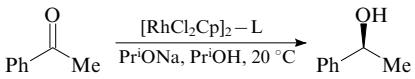
[91% *ee* (*R*)]



41

2. Hydrogen transfer hydrogenation of aromatic ketones and imines in the presence of Rh, Ir and Ru complexes

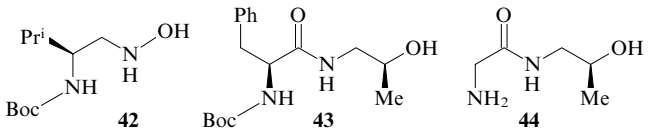
Note that the search for new chiral C_2-symmetric ligands for hydrogen transfer hydrogenation has been terminated in recent years due to its inefficiency.[1] Reactions (56)–(63) induced by complexes with C_1-symmetric ligands **42**–**49** confirm this conclusion.

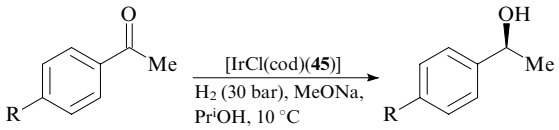


(56)

Cp = η^5-C_5H_5, Boc is *tert*-butyloxycarbonyl.

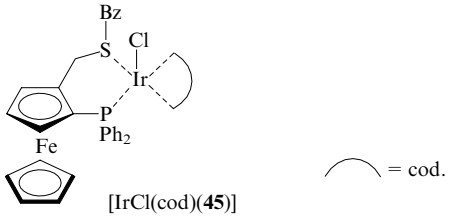
L	*ee* (*S*) (%)	Ref.
42	97	107
43	96	108
44	96	108



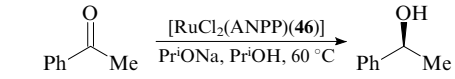


(57)

R	*ee* (*S*) (%) (Ref. 109)
H	87
F	> 99

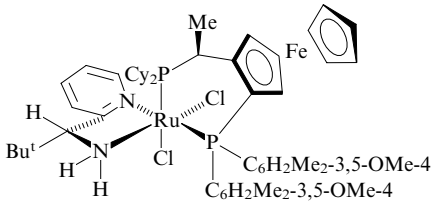


[IrCl(cod)(**45**)]



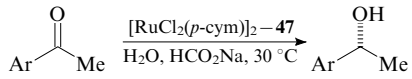
(58)

[97% *ee* (*S*)] [110]



[RuCl$_2$(ANPP)(**46**)]

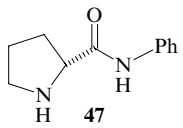
ANPP is 2-(1-aminoneopentyl)pyridine, Cy is cyclohexyl.



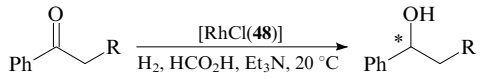
(59)

p-cym is *p*-cymol.

Ar	*ee* (*R*) (%) (Ref. 111)	Ar	*ee* (*R*) (%) (Ref. 111)
Ph	63	2-$MeOC_6H_4$	> 99
2-MeC_6H_4	> 99	2-ClC_6H_4	> 99

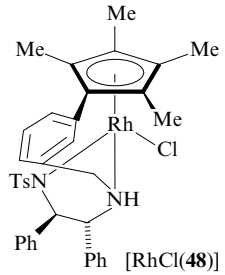


47

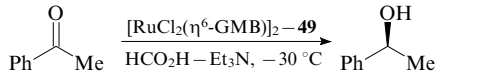


(60)

R	*ee* (%) (Ref. 112)	R	*ee* (%) (Ref. 112)
H	98 (*R*)	OPh	99 (*S*)
Cl	99.6 (*S*)	OH	98 (*S*)



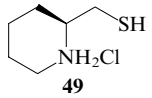
[RhCl(**48**)]



(61)

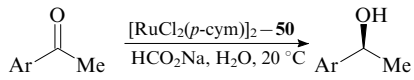
[90% *ee* (*S*)] [113]

GMB is hexamethylbenzene.



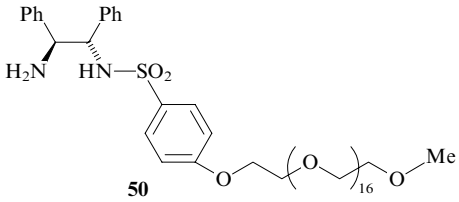
49

It can be seen from the presented data that most of the indicated complexes catalyze hydrogen transfer hydrogenation with a very high enantioselectivity (96% – 99% *ee*). Substituents in acetophenone increase the *ee* values of the product (*ee* > 99%). The mechanisms of hydrogen transfer hydrogenation of ketones in the presence of, for example, Ru complexes with ligands **46**, **47** have been thoroughly studied.[114–116] Reactions of this type also demonstrate very high enantioselectivity on complexes with ligands attached to a support surface [for example, in reaction (62) involving ligand **50**].[117]



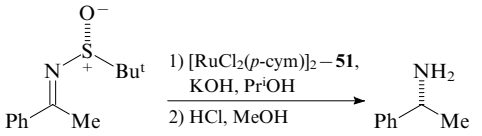
(62)

Ar	*ee* (*S*) (%)
Ph	96
4-FC_6H_4	99



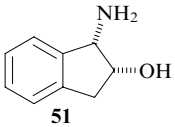
50

Ruthenium complexes, for example, with ligand **51** catalyze hydrogen transfer hydrogenation of imines with very high enantioselectivity [reaction (63)].[118]



(63)

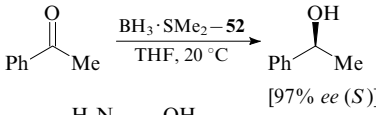
[98% *ee* (*R*)]



51

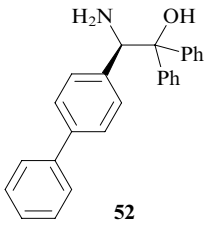
3. Reduction of acetophenone with boron complexes

The catalytic system formed *in situ* from amino alcohol **52** and borane dimethyl sulfide reduces acetophenone with high enantioselectivity [reaction (64)].[119]



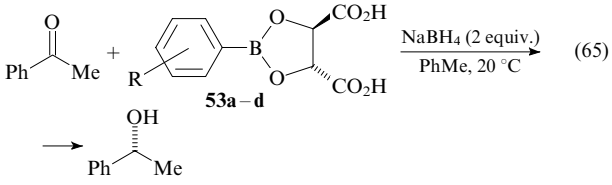
(64)

[97% *ee* (*S*)]



52

Acetophenone is reduced with organoboron derivatives of D-tartaric acid **53a** – **d** in the presence of $NaBH_4$ [reaction (65)] with even higher enantioselectivity.[120]

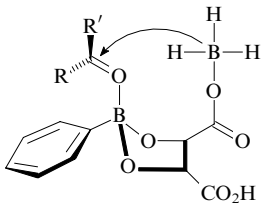


53a – **d**

(65)

Compound **53**	R	*ee* (*R*) (%)	Compound **53**	R	*ee* (*R*) (%)
a	3-NO_2	99	**c**	4-F	90
b	H	85	**d**	4-Cl	99

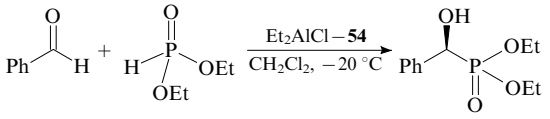
Since reagents **53a** – **d** have non-planar (pyramidal) structure, they are asymmetric. The structure of the key intermediate of reaction (65), which controls the asymmetric induction, is shown below.



R = Ph, 2-MeC$_6$H$_4$, Bu^t, Pr^i, etc.; R′ = Me, Et, CH$_2$Br, *etc.*

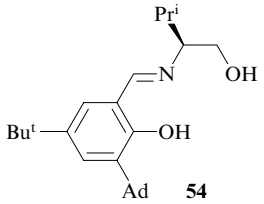
4. Hydrophosphonylation of benzaldehyde (the Pudovik reaction) under the action of aluminium and titanium complexes

Enantioselective hydrophosphonylation is represented most vividly by reactions (66)[121] and (67) with participation of chiral ligands **54** and **55**.[122]



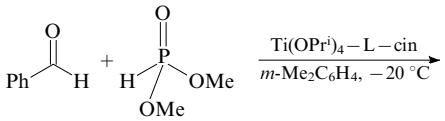
(66)

[97% *ee* (*S*)]

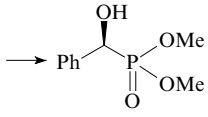


54

Ad is adamantyl.

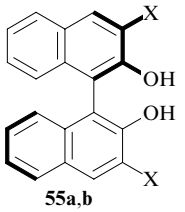


(67)

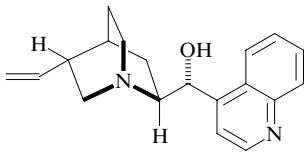


[99% *ee* (*S*)]

L = **55a**,**b**.



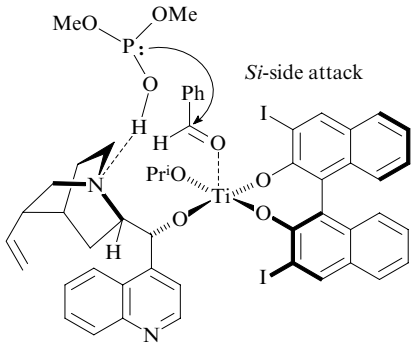
55a,**b**



cin

X = I (**a**), 3,5-(CF$_3$)$_2$C$_6$H$_3$ (**b**).

In reaction (67), the catalytic systems are formed by Ti(OPr^i)$_4$ and two ligands, binapthyldiol **55a** or **55b**, and an additional cinchonine (cin) ligand. Both systems perform this reaction with equal enantioselectivity.[122] The alkaloid cinchonine forms a bifunctional catalyst with the complex [Ti(OPr^i)(**55**)]. The structure of the possible key intermediate of the reaction is presented below.

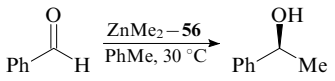


Si-side attack

The Ti^{IV} atom coordinates the aldehyde in a chiral structure, while the nitrogen atom of the alkaloid interacts with the phosphite. This reaction could be placed in Section IV if the additional ligand was achiral.

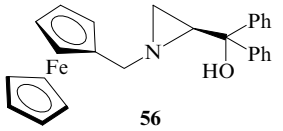
5. The addition of dialkylzinc to aromatic aldehydes, imines and acyclic enones in the presence of C_1-ligands

As in the case of hydrogen transfer hydrogenation (Section VI.2), all ligands effective in the asymmetric addition of dialkylzinc to aldehydes, imines and acyclic enones [without Ti(OPr^i)$_4$] found in recent years had asymmetric structures [for example, ligands **56**–**60** in reactions (68)–(71)].[123–127]

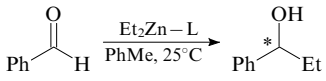


(68)

[89.9% *ee* (*S*)][123]

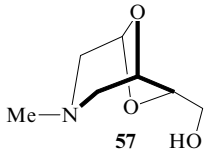


56

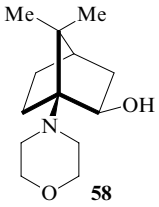


(69)

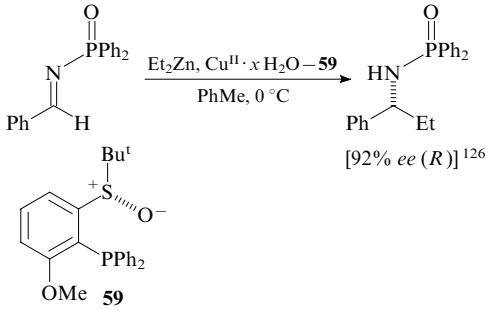
L	*ee* (%)	Ref.
57	96 (*S*)	124
58	94 (*R*)	125



57



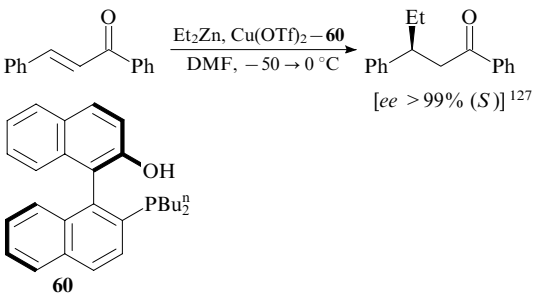
58



(70)

[92% *ee* (*R*)][126]

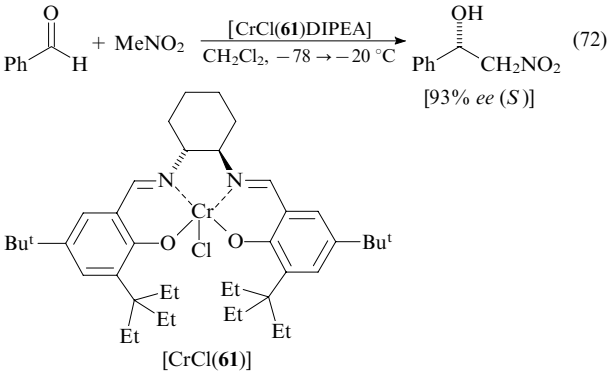
59



(71)

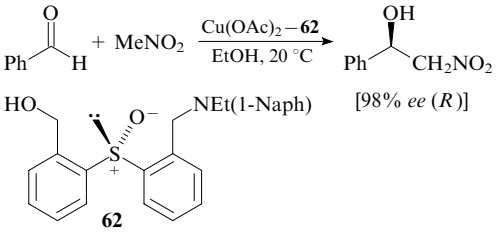
6. Nitroaldol reaction of aromatic aldehydes (the Henry reaction) and other addition reactions to benzaldehyde and acetophenone catalyzed by Cr, Cu and Ir complexes

Asymmetric versions of the Henry reaction in the presence of Cr^{III} and Cu^{II} complexes with ligands **61**, **62** show high *ee* values of products [reactions (72)[128] and (73)[129]].



(72)

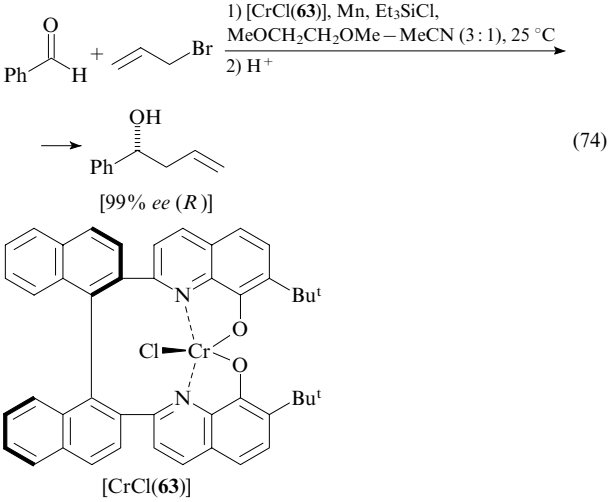
DIPEA is diisopropylethylamine.



(73)

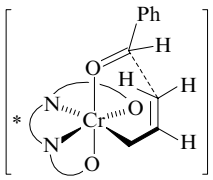
Naph is naphthyl.

The allylation of benzaldehyde proceeds with very high enantioselectivity in the presence of chromium complexes [reaction (74)].[130]



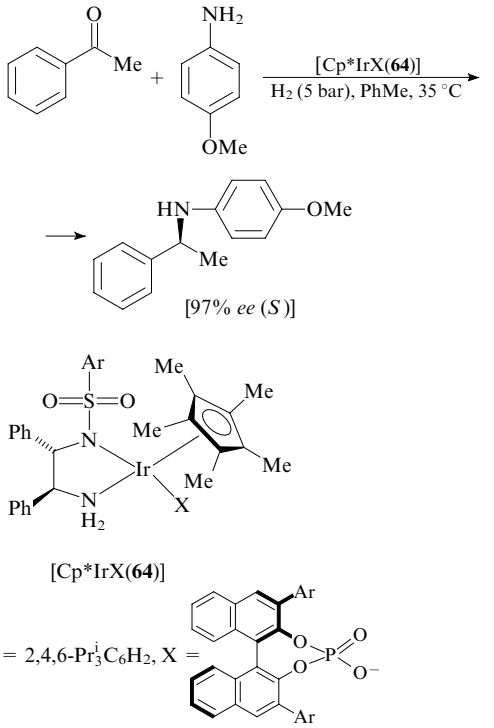
(74)

It was assumed[130] that the key intermediate responsible for the asymmetric induction of this reaction has the following structure (the chiral ligand is shown conditionally by four donor atoms).



Thus, as was to be expected, the asymmetric induction for the C_1-symmetric catalytic complex [CrCl(**63**)] occurs at the step of asymmetric key intermediate.

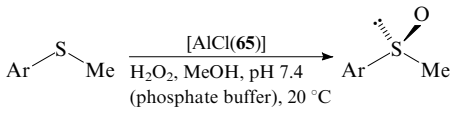
The reductive amination of acetophenone is catalyzed with high enantioselectivity by the iridium complex with bulky ligands; reaction (75) involving ligand **64** may serve as an example.[131]



(75)

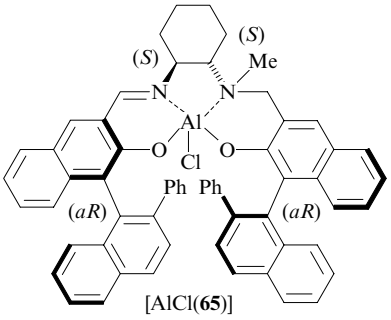
7. The oxidation of aryl sulfides induced by aluminium, iron and vanadium complexes

Aluminium salalen complexes (for example, with ligand **65**) are efficient catalysts for the asymmetric oxidation of sulfides [reaction (76)].[132]



(76)

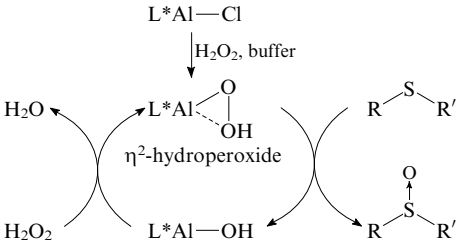
Ar	*ee* (*S*) (%)	Ar	*ee* (*S*) (%)
Ph	98	2-ClC_6H_4	> 99
2-$MeOC_6H_4$	96	3-ClC_6H_4	98
4-$MeOC_6H_4$	99	4-ClC_6H_4	99



[AlCl(**65**)]

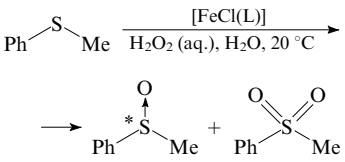
The high enantioselectivity of this reaction almost does not vary depending on the positions of substituents in the aromatic ring of ketone. A possible catalytic cycle is presented in Scheme 11.[132] It was assumed[132] that the C_1-symmetric η^2-hydroperoxide key intermediate is responsible for asymmetric induction.

Scheme 11



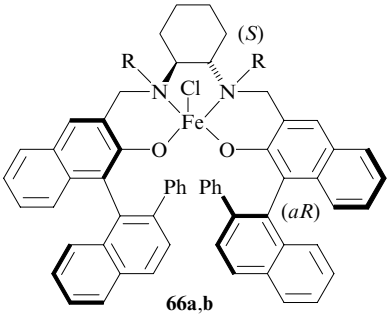
L = **65**.

High enantioselectivity was also found for the oxidation of methyl phenyl sulfide under the action of iron complexes with salan ligands **66**, **67** in the presence of water [reaction (77)].[133, 134]



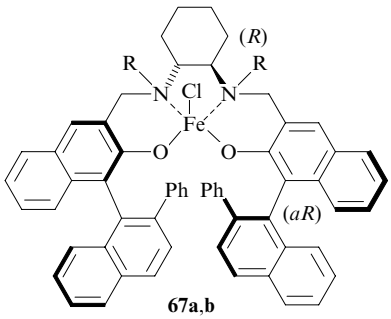
(77)

L	*ee* (%)	L	*ee* (%)
66a	88 (*S*)	**67a**	10 (*R*)
66b	96 (*S*)	**67b**	10 (*S*)



66a,**b**

R = H (**a**), Me (**b**).

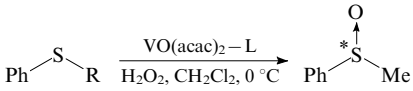


67a,**b**

R = H (**a**), Me (**b**).

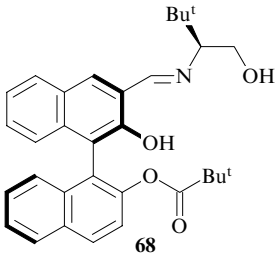
Note the enormous difference between the *ee* values of the reaction product depending on the configuration matching between the two chiral fragments of the complexes: for both studied complexes, high enantioselectivity is achieved only for (*S*,*aR*)-isomers. A possible explanation for this finding is, in our opinion, the C_2-symmetric structure of the key intermediate as the binuclear complex formed through μ-Cl-bridging bonds under the reaction conditions when the ligand structure is (*R*,*aR*); the C_2-symmetry of the key reaction intermediate is expected to entail low *ee* of the products.

Alkyl phenyl sulfides are also oxidized rather enantioselectively in the presence of vanadium complexes with Schiff bases **68**, **69** [reaction (78)].[135]

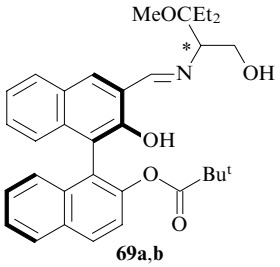


(78)

R	L	*ee* (%)	R	L	*ee* (%)
Me	**68**	86 (*S*)	Bn	**69b**	96 (*R*)
Bn	**69a**	96 (*S*)	Me	**69a**	84 (*S*)



68



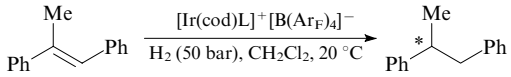
69a,**b**

Isomers: (*aR*,*R*) (**a**), (*aR*,*S*) (**b**).

As can be seen, benzyl phenyl sulfide is oxidized according to reaction (78) with higher enantioselectivity than thioanisole.

8. Hydrogenation of arylalkenes in the presence of iridium complexes

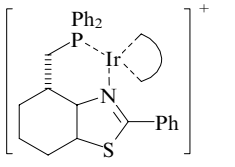
Iridium complexes with C_1-symmetric (P,N)-ligands **70**–**74** are fairly enantioselective catalysts of hydrogenation of non-functionalized arylalkenes. Reaction (79) can serve as an example.[136–139]



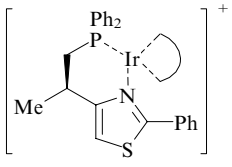
(79)

Ar_F = 3,5-$(CF_3)_2C_6H_3$.

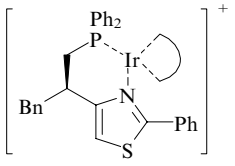
L	*ee* (%)	Ref.	L	*ee* (%)	Ref.
70	99 (*S*)	136	**73**	>99 (*R*)	138
71	>99 (*S*)	137	**74**	89 (*R*)	139
72	96 (*R*)	137			



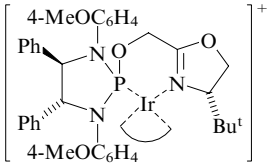
[Ir(cod)(**70**)]+



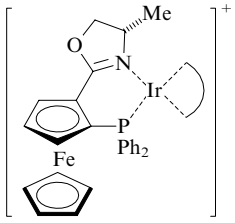
[Ir(cod)(**71**)]+



[Ir(cod)(**72**)]+



[Ir(cod)(**73**)]+



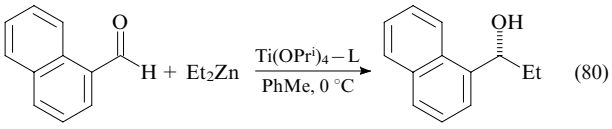
[Ir(cod)(**74**)]+

⌒ = cod.

To summarize analysis of the reactions catalyzed by complexes with C_1-symmetric ligands, note that the range of product *ee* values is much narrower ($ee_{max} \geqslant 99\%$) than that in reactions involving C_2-symmetric compounds.

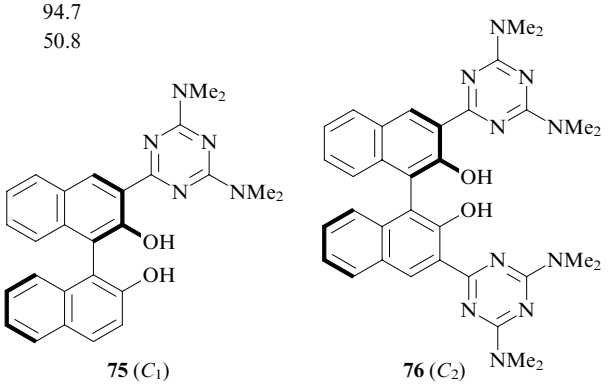
VII. Comparison of the enantioselectivities for reactions catalyzed by complexes of the same metals with C_2- and C_1-symmetric ligands having similar structures under the same conditions

As has already been noted, in the alkylation of aldehydes with dialkylzinc in the presence of chiral ligands [without addition of $Ti(OPr^i)_4$] and in the hydrogen transfer hydrogenation of ketones in the presence of Rh, Ir and Ru complexes, the reaction enantioselectivity is higher for C_1-symmetric ligands than for C_2-ligands.[1] The same trend is confirmed by most recent experimental data [reactions (80)[140] and (81)[141]] where diethylzinc alkylation was carried out in the presence of $Ti(OPr^i)_4$ and ligands **75**, **76** and hydrogenation of ketones proceeded in the presence of auxiliary ligands (diamines, DAM) and ligand **77**.

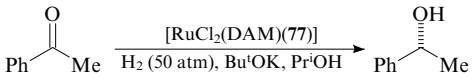


(80)

L	*ee* (*R*), %
75	94.7
76	50.8

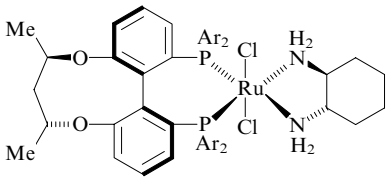


75 (C_1) **76** (C_2)

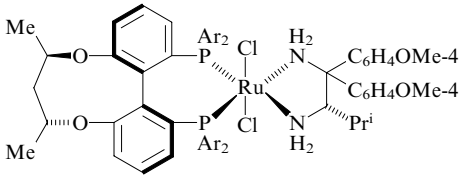


(81)

Complex	Symmetry	*ee* (*R*) (%)
[$RuCl_2$(DAM-1)(**77**)]	C_2	91.2
[$RuCl_2$(DAM-2)(**77**)]	C_1	99.8



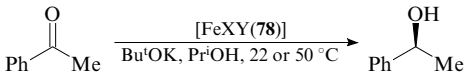
[$RuCl_2$(DAM-1)(**77**)] (C_2)



[$RuCl_2$(DAM-2)(**77**)] (C_1)

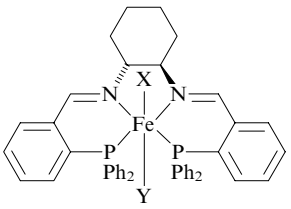
Ar = 3,5-$Me_2C_6H_3$.

In the case of hydrogen transfer hydrogenation, an even greater [than in reaction (81)] enantioselectivity difference between C_1- and C_2-complexes based on ligands **78** was found in reaction (82).[142]



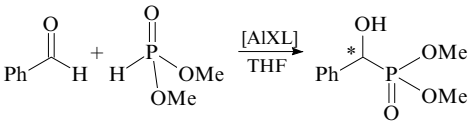
(82)

X	Y	Symmetry	*ee* (*S*) (%)
NCMe	NCMe	C_2	27
NCMe	$NCBu^t$	C_1	76



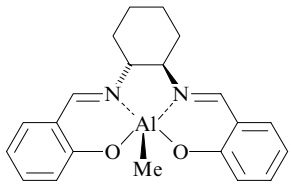
[FeXY(**78**)]

Yet another reaction demonstrating the effect of the symmetry of ligands with similar structures on the process enantioselectivity is hydrophosphonylation of benzaldehyde (the Pudovik reaction) in the presence of salen, salan and salalen aluminium complexes [reaction (83)].[143–145]

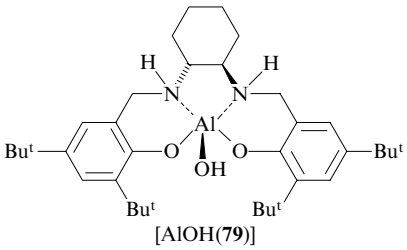


(83)

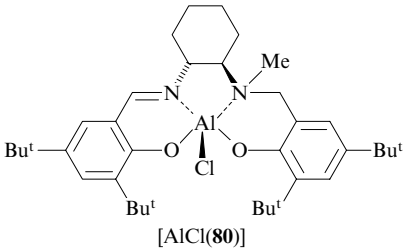
X	L	T/°C	*ee* (%)	Ref.
Me	(*R*)-**26**	−75 → 20	37–41 (*R*)	143
OH	**79**	0	59 (*S*)	144
Cl	**80**	−15	87 (*S*)	145



[AlMe{(*R*)-**26**}]

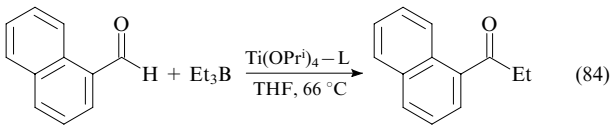


[AlOH(**79**)]



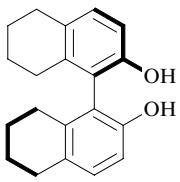
[AlCl(**80**)]

All three complexes [AlXL] have C_1-symmetry but the molecules [AlMe{(*R*)-**26**}] and [AlOH(**79**)] contain C_2-symmetric chiral salen and salan fragments, respectively, whereas the complex [AlCl(**80**)] is devoid of symmetry elements. It is this complex that provides the highest enantioselectivity of reaction (83). A less pronounced difference between the *ee* values of the products formed on C_1- and C_2-complexes was found for the alkylation of aldehydes with triethylborane in the presence of the $Ti(OPr^i)_4$–chiral ligand **8**, **81** or **82** system [reaction (84)].[146]

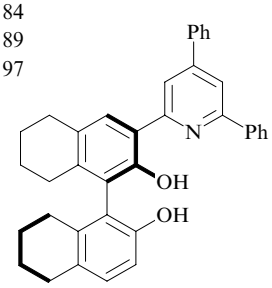


(84)

L	Symmetry	*ee* (*R*) (%)
(*R*)-**8**	C_2	84
81	C_2	89
82	C_1	97

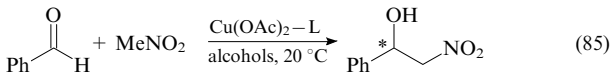


81 (C_2)



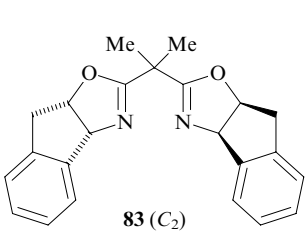
82 (C_1)

A more complicated relationship between the catalyst symmetry and the enantioselectivity was found for the nitroaldol Henry reaction induced by the Cu(OAc)$_2$–N,N-ligand (**18d**, **83**–**88**) and Cu(OAc)$_2$–N,S-ligand (**89**, **90**) systems [reactions (85)–(89)].[147–152]

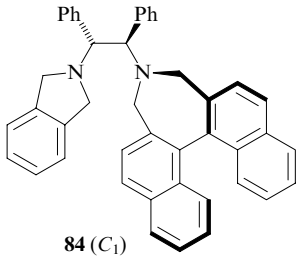


(85)

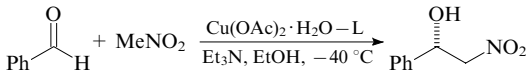
L	Symmetry	*ee* (%)	Ref.
(*S*,*S*)- **18d**	C_2	95 (*S*)	147
83	C_2	94 (*R*)	148
84	C_1	91 (*S*)	149



83 (C_2)

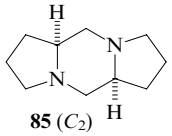


84 (C_1)

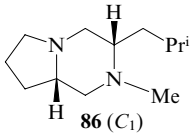


(86)

L	Symmetry	*ee* (*S*) (%) (Ref. 150)
85	C_2	92
86	C_1	89



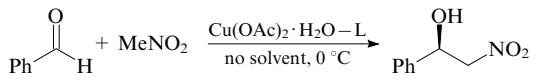
85 (C_2)



86 (C_1)

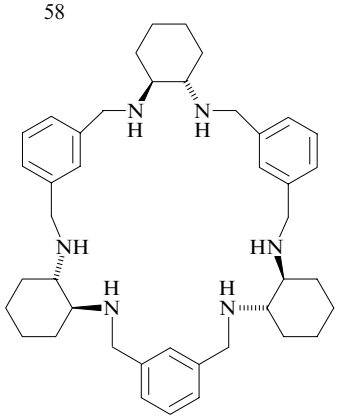
Reactions (85) and (86) are catalyzed by C_2- and C_1-complexes with almost equally high enantioselectivity under comparable conditions. However, another example of analogous Henry reaction involving the Cu(OAc)$_2$–N,N-ligand system (**87**, **88**) is known to show an obvious depen-

dence of the product *ee* value on the symmetry of the catalytic complex [reaction (87)].[151]

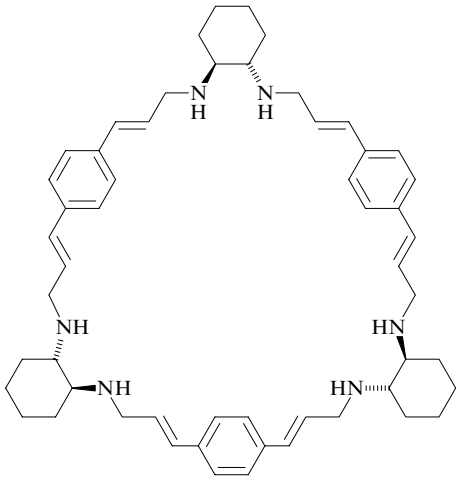


(87)

L	*ee* (*R*) (%)
87	86
88	58

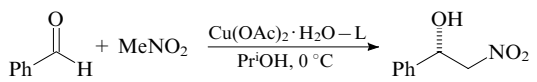


(*S*,*S*,*S*,*S*,*S*,*S*)-(+)-**87**



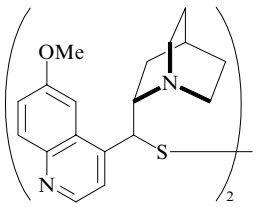
(*S*,*S*,*S*,*S*,*S*,*S*)-(+)-**88**

Analysis of the molecular models of complexes formed by cyclic hexamines **87**, **88** with $Cu(OAc)_2$ leads to the conclusion that only the complex with ligand **88** can be either C_2- or C_3-symmetric. Therefore, in this reaction, the highest enantioselectivity is displayed by the Cu complex with ligand **87**, which has a distorted C_2- or C_3-symmetry. The same type of advantage of a less symmetric structure of the catalytic complex as regards the enantioselectivity is observed in the Henry reaction induced by $Cu(OAc)_2$ complexes with amino sulfides (**89**) and amino thiols (**90**) [reaction (88)][152] and with substituted diamines (**91a**,**b**) [reaction (89)].[153]

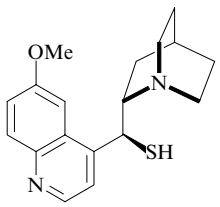


(88)

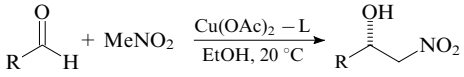
L	Symmetry	*ee* (*S*) (%)
89	C_2	52
90	C_1	83



89 (C_2)

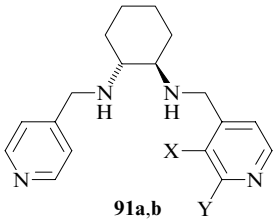


90 (C_1)



(89)

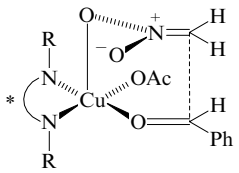
R	L	Symmetry	*ee* (*S*) (%)
Ph	**91a**	C_2	84
Bu^t	**91a**	C_2	85
Ph	**91b**	C_1	93
Bu^t	**91b**	C_1	99



91a,**b**

X = Y = H (**a**);
X = OH, Y = Bu^t (**b**).

As a result of consideration of spatial and electronic factors, a model of the transition state of the Henry reaction involving copper diamine complexes [reaction (85)–(87) and (89)] was proposed.[149]



As can be seen, in the case of C_2-symmetric ligands, asymmetric induction is performed at the step of formation of the asymmetric key intermediate.

Thus, comparison of the reactions catalyzed by C_2- and C_1-complexes under identical conditions shows that the enantioselectivity is either higher for the C_1-complex or equally high for both C_2- and C_1-catalysts.

VIII. Conclusion

The review considers about 90 asymmetric catalytic reactions of simple monofunctional substrates, which are coordinated in the key intermediate by only one (reacting) group (one-point binding). The high degree of freedom of the coordination of these substrates imposes restrictions on the structure and symmetry of the catalytic complex as compared, for example, with catalytic reactions of amino acid precursors as substrates (three-point binding).[154] For reactions having high enantioselectivity, the C_2-symmetric catalytic complex † should either have intricate structure [reac-

† In the reactions of non-functionalized substrates catalyzed by C_3-symmetric complexes, the trends listed above cannot be followed as the number of available examples is too small (see review [1]).

tions (3), (7)–(9), (11), (12), (14), (16), (18), (36)] or contain an additional achiral ligand [reactions (37)–(43)]; alternatively, molecular sieves must be added to the reaction mixture [reactions (45)–(50)] Nevertheless, the highest enantioselectivity of the reactions catalyzed by complexes with C_2-symmetric ligands is not higher than 96% ($ee_{max} = 96\%$). All effective enantioselective reactions of this type for which a possible sequence of intermediates (catalytic cycle) was reasonably proposed include asymmetric structures as the key intermediates. In these cycles, the initial C_2-symmetry of the catalytic complex is lost before the formation of the key intermediate, which controls the asymmetric induction [see Schemes 1–9 and structures of the key intermediates for reactions (5)–(7), (11), (37), (38), (40), (42)]. If this condition is not fulfilled and the key intermediate retains the C_2-symmetry, for example, in reaction (23), as in the mechanism of the related reaction of diethylzinc addition to benzaldehyde without introduction of $Ti(OPr^i)_4$ (see Ref. 1) or in reactions (24)–(26), (28), (29), (45) (see Scheme 10) and (51), the reaction enantioselectivity is low or does not exceed 70%. For reactions with the loss of C_2-symmetry, the key intermediate [reactions (3), (5)–(22), (27), (32)–(50)], the average *ee* value of the product is 85%.

In the reactions catalyzed by C_1-symmetric complexes, the highest enantioselectivity increases, ee_{max} reaches values of >99%. The average *ee* values of the product of these reactions is also much higher [$ee_{av} = 97\%$ for reactions (52)–(79)]. This enantioselectivity of reactions involving C_2- and C_1-symmetric complexes is retained also for most of the studied cases where one can compare catalysts of different symmetry [reactions (80)–(84), (87)–(89)] for one and the same reaction, the same metal and the same conditions.

It should be emphasized that this type of relationship between reaction enantioselectivity and the catalyst symmetry is observed only for simple monofunctional substrates such as benzaldehyde, acetophenone, thioanisole and so on that are coordinated in the key intermediate only by the reacting group. If substrates can be coordinated by two or three groups, they are able to react with very high enantioselectivity also under the action of complexes with C_2-ligands. A simple explanation can be suggested for the dependence of enantioselectivity on the substrate structure. Multifunctional substrates acquire additional difference (compared to monofunctional substrates) between the free activation energies of their *proS*- and *proR*-positions as a result of two- or three-point binding in the key intermediate. This results in higher enantioselectivity. Hydrogenation of β-keto esters on the C_2-complex Ru-BINAP [Ru-(**2**)] with 100% conversion and 99.9% *ee* can serve as an illustration.[155] It is of interest that this parameters of an asymmetric catalytic reaction are comparable with the corresponding parameters of a similar enzyme-induced reaction. The bioreduction of β-keto ester by various types of carbonyl reductase proceeds to a conversion of 91%, 95% and 99%, the *ee* being 95%, 99% and 100%, respectively.[156–158] The chiral C_2-symmetric metal complexes as catalysts of reactions of substrates capable of two- or three-point binding can compete with enzymes not only as regards the enantioselectivity but also as regards the productivity. Pavlov *et al.*[159] showed that hydrogenation of methyl acetoacetate on the complex [RuCl(η^6-cym){(*R*)-**2**}]Cl has high enantioselectivity and conversion at the molar ratio substrate : catalyst = 70 000. The similarity of enzymes and metal complexes as catalysts is also in the covalent interaction between the catalyst and the substrate in the transition state.[160] However, asymmetric induction of metal complexes with C_2-symmetric chiral ligands is not encountered in the metabolism of living organisms. The linear DNA polymer consists of four nucleotides in an irregular sequence as a basis for genetic difference. Two DNA molecules form a double helix through hydrogen bonding between complementary nucleotides. Both helices and the α-helix of peptides has *P*-configuration. The structures of all helices are asymmetric.[161] The proteins are composed only of L-amino acids, and only D-nucleotides form DNA. Polysaccharides are also composed of D-monosaccharides (with rare exceptions). All these compounds are chiral (asymmetric). The above-listed enantiomers are the same in the living systems of humans, animals and microbes.[162] C_2-Symmetric chiral compounds are known in nature only as plant products [D-(+)-tartaric acid, some alkaloids, lignanes, *etc*.]. All these compounds are minor rather than major products of plant metabolism. Thus, the advantages of C_1-symmetric chiral compounds over C_2-symmetric chiral compounds are not reduced to asymmetric catalytic reactions of monofunctional substrates but extends also to biochemical reactions.

References

1. V A Pavlov *Tetrahedron* **64** 1147 (2008)
2. V A Pavlov *Usp. Khim.* **73** 1269 (2004) [*Russ. Chem. Rev.* **73** 1173 (2004)]
3. V A Pavlov *Usp. Khim.* **71** 39 (2002) [*Russ. Chem. Rev.* **71** 33 (2002)]
4. D Z Wang *Tetrahedron* **61** 7125 (2005)
5. D Z Wang *Tetrahedron* **61** 7134 (2005)
6. T Imamoto, J Watanabe, Y Wada, H Masuda, H Yamada, H Tsuruta, S Matsukawa, K Yamaguchi *J. Am. Chem. Soc.* **120** 1635 (1998)
7. A Ohashi, S Kikuchi, M Yasutake, T Imamoto *Eur. J. Org. Chem.* 2535 (2002)
8. A Miyashita, A Yasuda, H Takaya, K Toriumi, T Ito, T Souchi, R Noyori *J. Am. Chem. Soc.* **102** 7932 (1980)
9. C-J Wang, F Gao, G Liang *Org. Lett.* **10** 4711 (2008)
10. Y Zou, H Geng, W Shang, S Yu, X Zhang *Tetrahedron Lett.* **50** 5777 (2009)
11. K Kurihara, Y Yamamoto, N Miyaure *Tetrahedron Lett.* **50** 3158 (2009)
12. B J Flowers, R Gautreau-Servise, P G Jessop *Adv. Synth. Catal.* **350** 2947 (2008)
13. A S C Chan, J Halpern *J. Am. Chem. Soc.* **102** 838 (1980)
14. A S C Chan, J J Pluth, J Halpern *J. Am. Chem. Soc.* **102** 5952 (1980)
15. P S Chua, N K Roberts, B Bosnich, S J Okrasinski, J Halpern *J. Chem. Soc., Chem. Commun.* 1278 (1981)
16. J M Brown, P A Chaloner *J. Am. Chem. Soc.* **102** 3040 (1980)
17. I D Gridnev, N Higashi, K Asakura, T Imamoto *J. Am. Chem. Soc.* **122** 7183 (2000)
18. I D Gridnev, M Yasutake, N Higashi, T Imamoto *J. Am. Chem. Soc.* **123** 5268 (2001)
19. J-M Brunel, I P Holmes *Angew. Chem., Int. Ed.* **43** 2752 (2004)
20. F-X Chen, X Feng *Curr. Org. Synth.* **3** 77 (2006)
21. T R J Achard, L A Clutterbuck, M North *Synlett* 1828 (2005)
22. M Kanai, N Kato, N Ichikawa, M Shibasaki *Synlett* 1491 (2005)
23. M Hayashi, T Matsuda, N Oguni *J. Chem. Soc., Perkin Trans 1* 3135 (1992)
24. W Pan, X Feng, L Gong, W Hu, Z Li, A Mi, Y Jiang *Synlett* 337 (1996)
25. Y Jiang, L Gong, X Feng, W Hu, W Pan, Z Li, A Mi *Tetrahedron* **53** 14327 (1997)

26. Y Belokon', M Flego, N Ikonnikov, M Moscalenko, M North, C Orizu, V Tararov, M Tasinazzo *J. Chem. Soc., Perkin Trans. 1* 1293 (1997)
27. Y Belokon', N Ikonnikov, M Moscalenko, M North, S Orlova, V Tararov, L Yashkina *Tetrahedron: Asymmetry* **7** 851 (1996)
28. Yu N Belokon', L V Yashkina, M A Moskalenko, A A Chesnokov, V S Kublitskii, N S Ikonnikov, S A Orlova, V I Tararov, M Nort *Izv. Akad. Nauk, Ser. Khim.* 2040 (1997) [a]
29. Y N Belokon', M North, T Parsons *Org. Lett.* **2** 1617 (2000)
30. Y N Belokon', B Green, N S Ikonnikov, M North, T Parsons, V I Tararov *Tetrahedron* **57** 771 (2001)
31. Y N Belokon', J Hunt, M North *Synlett* 2150 (2008)
32. X-G Zhou, J-S Huang, P-H Ko, K-K Cheung, C-M Che *J. Chem. Soc., Dalton Trans.* 3303 (1999)
33. M Mori, H Imma, T Nakai *Tetrahedron Lett.* **38** 6229 (1997)
34. W-B Yang, J-M Fang *J. Org. Chem.* **63** 1356 (1998)
35. J Casas, A Baeza, J M Sansano, C Najera, J M Saa *Tetrahedron: Asymmetry* **14** 197 (2003)
36. A Yanagisawa, H Nakashima, Y Nakatsuka, A Ishiba, H Yamamoto *Bull. Chem. Soc. Jpn.* **74** 1129 (2001)
37. G E Keck, K A Savin, E N K Cressman, D E Abbot *J. Org. Chem.* **59** 7889 (1994)
38. A Yanagisawa, H Kageyama, Y Nakatsuka, K Asakawa, Y Matsumoto, H Yamamoto *Angew. Chem., Int. Ed.* **38** 3701 (1999)
39. M Wadamoto, H Yamamoto *J. Am. Chem. Soc.* **127** 14556 (2005)
40. H Hanawa, T Hashimoto, K Maruoka *J. Am. Chem. Soc.* **125** 1708 (2003)
41. X Zhang, D Chen, X Liu, X Feng *J. Org. Chem.* **72** 5227 (2007)
42. F Delpech, I A Guzei, R F Jordan *Organometallics* **21** 1167 (2005)
43. K Zheng, B Qin, X Liu, X Feng *J. Org. Chem.* **72** 8478 (2007)
44. J Huang, J Wang, X Chen, Y Wen, X Liu, X Feng *Adv. Synth. Catal.* **350** 287 (2008)
45. C Palomo, M Oiarbide, A Laso *Eur. J. Org. Chem.* 2561 (2007)
46. B M Trost, V S C Yeh *Angew. Chem., Int. Ed.* **41** 861 (2002)
47. N Sanjeevakumar, M Periasamy *Tetrahedron: Asymmetry*. **20** 1842 (2009)
48. C Christensen, K Juhl, R G Hazell, K A Jørgensen *J. Org. Chem.* **67** 4875 (2002)
49. S Reformatsky *Ber. Dtsch. Chem. Ges.* **20** 1210 (1887)
50. R Ocampo, W R Dolbier Jr *Tetrahedron* **60** 9325 (2004)
51. M A Fernandez-Ibanez, B Macia, A J Minnaard, B L Feringa *Angew. Chem., Int. Ed.* **47** 1317 (2008)
52. P G Cozzi *Adv. Synth. Catal.* **348** 2075 (2006)
53. M Kitamura, S Suga, M Niwa, R Noyori *J. Am. Chem. Soc.* **117** 4832 (1995)
54. D B Biradar, H-M Gau *Org. Lett.* **11** 499 (2009)
55. K Yearick, C Wolf *Org. Lett.* **10** 3915 (2008)
56. J E D Martins, D J Morris, M Wills *Tetrahedron Lett.* **50** 688 (2009)
57. H Pellissier *Tetrahedron* **62** 5559 (2006)
58. I Fernandez, N Khair *Chem. Rev.* **103** 3651 (2003)
59. J Legros, J R Dehli, C Bolm *Adv. Synth. Catal.* **347** 19 (2005)
60. A M Rouhi *Chem. Eng. News* **81** (39) 34 (2003)
61. K P Bryliakov, E P Talsi *Eur. J. Org. Chem.* 3369 (2008)
62. C Sasaki, K Nakajima, M Kojima, J Fujita *Bull. Chem. Soc. Jpn.* **64** 1318 (1991)
63. B Saito, T Katsuki *Tetrahedron Lett.* **42** 3873 (2001)
64. Y N Belokon', B Green, N S Ikonnikov, V S Larichev, B V Lokshin, M A Moscalenko, M North, C Orizu, A S Peregudov, G I Timofeeva *Eur. J. Org. Chem.* 2655 (2000)
65. B Saito, T Katsuki *Tetrahedron Lett.* **42** 8333 (2001)
66. N Komatsu, Y Nishibayashi, T Sugita, S Uemura *Tetrahedron Lett.* **33** 5391 (1992)
67. L J P Martyn, S Pandiaraju, A K Yudin *J. Organomet. Chem.* **603** 98 (2000)
68. S H Zhao, O Samuel, H B Kagan *Tetrahedron* **43** 5135 (1987)
69. P Pitchen, E Dunach, M N Deshmukh, H B Kagan *J. Am. Chem. Soc.* **106** 8188 (1984)
70. H B Kagan, F Rebiere *Synlett* 643 (1990)
71. F Di Furia, G Licini, G Modena, R Motterle, W A Nugent *J. Org. Chem.* **61** 5175 (1996)
72. M Bonchio, G Licini, F Di Furia, S Mantovani, G Modena, W A Nugent *J. Org. Chem.* **64** 1326 (1999)
73. A Basak, A U Barlan, H Yamamoto *Tetrahedron: Asymmetry* **17** 508 (2006)
74. T Miyazaki, T Katsuki *Synlett* 1046 (2003)
75. M Palucki, P Hanson, E N Jacobsen *Tetrahedron Lett.* **33** 7111 (1992)
76. K Nakajima, K Kojima, M Kojima, J Fujita *Bull. Chem. Soc. Jpn.* **63** 2620 (1990)
77. Z Zeng, G Zhao, Z Zhou, C Tang *Eur. J. Org. Chem.* 1615 (2008)
78. Y Hamashima, D Sawada, M Kanai, M Shibasaki *J. Am. Chem. Soc.* **121** 2641 (1999)
79. N Kurono, K Arai, M Uemura, T Ohkuma *Angew. Chem., Int. Ed.* **47** 6643 (2008)
80. F Chen, X Feng, B Qin, G Zhang, Y Jiang *Org. Lett.* **5** 949 (2003)
81. M S Taylor, E N Jacobsen *Angew. Chem., Int. Ed.* **45** 1520 (2006)
82. S J Connon *Angew. Chem., Int. Ed.* **47** 1176 (2008)
83. M Hatano, Y Hattori, Y Furuya, K Ishihara *Org. Lett.* **11** 2321 (2009)
84. S Enthaler, B Hagemann, S Bhor, G Anilkumar, M K Tse, B Bitterlich, K Junge, G Erre *Adv. Synth. Catal.* **349** 853 (2007)
85. H Shimizu, D Igarashi, W Kuriyama, Y Yusa, N Sayo, T Saito *Org. Lett.* **9** 1655 (2007)
86. X-Q Zhang, Y-Y Li, H Zhang, J-X Gao *Tetrahedron: Asymmetry* **18** 2049 (2007)
87. X Yang, X Zhou, L Lin, L Chang, X Liu, X Feng *Angew. Chem., Int. Ed.* **47** 7079 (2008)
88. B M Trost, S Malhotra, B A Fried *J. Am. Chem. Soc.* **131** 1674 (2009)
89. Q Meng, Y Sun, V Ratovelomanana-Vidal, J P Genet, Z Zhang *J. Org. Chem.* **73** 3842 (2008)
90. H Li, C-S Da, Y-H Xiao, X Li, Y-N Su *J. Org. Chem.* **73** 7398 (2008)
91. Y M A Yamada, N Yoshikawa, H Sasai, M Shibasaki *Angew. Chem., Int. Ed.* **36** 1871 (1997)
92. N Yoshikawa, N Kumagai, S Mutsunaga, G Moll, T Ohshima, T Suzuki, M Shibasaki *J. Am. Chem. Soc.* **123** 2466 (2001)
93. Q Wang, S-Y Chen, X-Q Yu, L Pu *Tetrahedron* **63** 4422 (2007)
94. C-D Hwang, D-R Hwang, B-J Uang *J. Org. Chem.* **63** 6762 (1998)
95. G E Keck, L S Geraci *Tetrahedron Lett.* **34** 7827 (1993)
96. G E Keck, K H Tarbet, L S Geraci *J. Am. Chem. Soc.* **115** 8467 (1993)
97. A L Costa, M G Piazza, E Tagliavini, C Trombini, A Umani-Ronchi *J. Am. Chem. Soc.* **115** 7001 (1993)
98. Y-C Teo, K-T Tan, T-P Loh *Chem. Commun.* 1318 (2005)
99. K Mikami, M Terada, T Nakai *J. Am. Chem. Soc.* **112** 3949 (1990)
100. K V Gothelf, R G Hazell, K A Jørgensen *J. Org. Chem.* **63** 5483 (1998)
101. S Oi, E Terada, K Ohuchi, T Kato, Y Tachibana, Y Inoue *J. Org. Chem.* **64** 8660 (1999)
102. I Reboule, R Gil, J Collin *Eur. J. Org. Chem.* 532 (2008)
103. J-S You, H-M Gau, M C K Choi *Chem. Commun.* 1963 (2000)
104. J-M Brunel, O Legrand, G Buono *Tetrahedron: Asymmetry* **10** 1979 (1999)
105. Y Hamashima, M Kanai, M Shibasaki *J. Am. Chem. Soc.* **122** 7412 (2000)
106. H Deng, M P Isler, M L Snapper, A H Hoveyda *Angew. Chem., Int. Ed.* **41** 1009 (2002)
107. K Ahlford, A B Zaitsev, J Ekström, H Adolfsson *Synlett* 2541 (2007)
108. J Wettergren, A B Zaitsev, H Adolfsson *Adv. Synth. Catal.* **349** 2556 (2007)
109. E Le Roux, R Malacea, E Manoury, R Poli, L Gonsalvi, M Peruzzini *Adv. Synth. Catal.* **349** 309 (2007)
110. W Baratta, G Chelucci, E Herdtweck, S Magnolia, K Siega, P Rigo *Angew. Chem., Int. Ed.* **46** 7651 (2007)

111. S Zeror, J Collin, J-C Fiaud, L A Zouioueche *Adv. Synth. Catal.* **350** 197 (2008)
112. D S Matharu, D J Morris, A M Kawamoto, G J Clarkson, M Wills *Org. Lett.* **7** 5489 (2005)
113. M Ito, Y Shibata, A Watanabe, T Ikariya *Synlett* 1621 (2009)
114. X Wu, J Xiao *Chem. Commun.* 2449 (2007)
115. J E D Martins, G J Clarkson, M Wills *Org. Lett.* **11** 847 (2009)
116. H Ooka, N Arai, K Azuma, N Kurono, T Ohkuma *J. Org. Chem.* **73** 9084 (2008)
117. J Liu, Y Zhou, Y Wu, X Li, A S C Chan *Tetrahedron: Asymmetry* **19** 832 (2008)
118. D Guijarro, O Pablo, M Yus *Tetrahedron Lett.* **50** 5386 (2009)
119. M Braun, M Sigloch, J Cremer *Adv. Synth. Catal.* **349** 337 (2007)
120. S Eagon, J Kim, K Yan, D Haddenham, B Singaram *Tetrahedron Lett.* **48** 9025 (2007)
121. X Zhou, X Liu, X Yang, D Shang, J Xin, X Feng *Angew. Chem., Int. Ed.* **47** 392 (2008)
122. F Yang, D Zhao, J Lan, P Xi, L Yang, S Xiang, J You *Angew. Chem., Int. Ed.* **47** 5646 (2008)
123. M-C Wang, Q-J Zhang, G-W Li, Z-K Liu *Tetrahedron: Asymmetry* **20** 288 (2009)
124. D Scarpi, E G Occhaito, A Guarna *Tetrahedron: Asymmetry* **20** 340 (2009)
125. Z-L Wu, H-L Wu, P-Y Wu, B-J Uang *Tetrahedron: Asymmetry* **20** 1556 (2009)
126. J Chen, D Li, H Ma, L Cun, J Zhu, J Deng, J Liao *Tetrahedron Lett.* **49** 6921 (2008)
127. K Ito, S Eno, B Saito, T Katsuki *Tetrahedron Lett.* **46** 3981 (2005)
128. R Kowalszyk, P Kwiatkowski, J Skarzewski, J Jurszak *J. Org. Chem.* **74** 753 (2009)
129. M Rachwalski, S Lesniak, E Sznajder, P Kielbasinski *Tetrahedron: Asymmetry* **20** 1547 (2009)
130. G Xia, H Yamamoto *J. Am. Chem. Soc.* **128** 2554 (2006)
131. G Li, B Villa-Marcos, J Xiao *J. Am. Chem. Soc.* **131** 6967 (2009)
132. K Matsumoto, T Yamaguchi, T Katsuki *Chem. Commun.* 1704 (2008)
133. H Egami, T Katsuki *J. Am. Chem. Soc.* **129** 8940 (2007)
134. H Egami, T Katsuki *Synlett* 1543 (2008)
135. Y-C Jeong, Y D Huang, S Choi, K-H Ahn *Tetrahedron: Asymmetry* **16** 3497 (2005)
136. C Hedberg, K Killstrlm, P Brandt, L K Hansen, P G Andersson *J. Am. Chem. Soc.* **128** 2995 (2006)
137. P Cheruku, A Paptchikhine, M Ali, J-M Neudorfl, P G Andersson *Org. Biomol. Chem.* **6** 366 (2008)
138. M Schonleber, R Hilgraf, A Pfaltz *Adv. Synth. Catal.* **350** 2033 (2008)
139. X Li, Q Li, X Wu, Y Gao, D Xu, L Kong *Tetrahedron: Asymmetry* **18** 629 (2007)
140. Q-S Guo, B Liu, Y-N Lu, F-Y Jiang, H-B Song, J-S Li *Tetrahedron: Asymmetry* **16** 3667 (2005)
141. W Li, X Sun, L Zhou, G Hou, S Yu, X Zhang *J. Org. Chem.* **74** 1397 (2009)
142. C Sui-Seng, F Freutel, A J Lough, R H Morris *Angew. Chem., Int. Ed.* **47** 940 (2008)
143. J P Duxbury, A Cawley, M Thornton-Pett, L Wantz, J N D Warne, R Greatrex, D Brown, T P Kee *Tetrahedron Lett.* **40** 4403 (1999)
144. C V Ward, M Jiang, T P Kee *Tetrahedron Lett.* **41** 6181 (2000)
145. B Saito, H Egami, T Katsuki *J. Am. Chem. Soc.* **129** 1978 (2007)
146. T Ukon, T Harada *Eur. J. Org. Chem.* 4405 (2008)
147. S K Ginotra, V K Singh *Org. Biomol. Chem.* **5** 3932 (2007)
148. D A Evans, D Seidel, M Rueping, H W Lam, J T Shaw, C W Downey *J. Am. Chem. Soc.* **125** 12692 (2003)
149. T Arai, M Watanabe, A Yanagisawa *Org. Lett.* **9** 3595 (2007)
150. S Selvakumar, D Sivasankaran, V K Singh *Org. Biomol. Chem.* **7** 3156 (2009)
151. K Tanaka, S Hachiken *Tetrahedron Lett.* **49** 2533 (2008)
152. M Zelinska-Blajet, J Skarzewski *Tetrahedron: Asymmetry* **20** 1992 (2009)
153. G Zhang, E Yashima, W-D Woggon *Adv. Synth. Catal.* **351** 1255 (2009)
154. V A Pavlov *Usp. Khim.* **70** 1175 (2001) [*Russ. Chem. Rev.* **70** 1037 (2001)]
155. Y Sun, X Wan, M Guo, D Wang, X Dong, Y Pan, Z Zhang *Tetrahedron: Asymmetry* **15** 2185 (2004)
156. H Engelking, R Pfaller, G Wich, D Weuster-Botz *Tetrahedron: Asymmetry* **15** 3591 (2004)
157. N A Salvi, S Chattopadhyay *Tetrahedron: Asymmetry* **15** 3397 (2004)
158. M Wada, M Kataoka, H Kawabata, Y Yasohara, N Kizaki, J Hasegawa, S Shimizu *Biosci. Biotechnol. Biochem.* **62** 280 (1998)
159. V A Pavlov, E V Starodubtseva, M G Vinogradov, V A Ferapontov, O R Malyshev, G L Khais *Izv. Akad. Nauk, Ser. Khim.* 725 (2000) [a]
160. X Zhang, K N Houk *Acc. Chem. Res.* **38** 379 (2005)
161. M Nogradi *Stereochemistry* (Budapest: Akadémiai Kiadó, 1981)
162. I Hargittai, M Hargittai *Symmetry through the Eyes of a Chemist* (Weinheim: VCH, 1986)

[a] — *Russ. Chem. Bull., Int. Ed. (Engl. Transl.)*