ASYMMETRIC CATALYSIS INVOLVING HETEROCYCLIC COMPOUNDS (REVIEW)

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The newest advances in the realization of asymmetric reactions with the aid of both heterogeneous and metal-complex catalysts are examined. Heterocyclic compounds are used as prochiral substrates and chiral ligands in the compositions of the catalysts. Chief attention is directed to the relationship between the enantioselectivity and the structures of the heterocyclic compounds.

The formation and conversion of two diastereomeric transition states that have different free energies and react at different rates lie at the foundation of asymmetric catalysis. Asymmetric catalysis can be defined as the transformation of a prochiral molecule (or a prochiral group) under the influence of a substance and a chiral compound (previously bonded or unbonded with the catalyst) that enters into diastereomeric transition states (a complex or surface formations). The substance-catalyst, which selectively changes the kinetics of the process but preserves its stoichiometric and thermodynamic conditions, does not change, in principle, in this process and participates in cyclical elementary processes to form diastereomeric transition states, the different rates of conversion of which also determine the stereochemical transformation. Asymmetric catalysis, as a more general concept, includes several types of catalytic transformations.

Enantioselective Catalysis. Enantioselective catalysis is the formation from a prochiral molecule such as ketone $R^1R^2C{=}O$ (1) of primarily one of two enantiomers as a result of the addition of an achiral agent (hydrogen) under the influence of chiral catalyst K_R or K_S (a metal-complex catalyst or a metal catalyst modified by an optically active compound) [reaction (1) in the scheme presented below]. The reaction in this case proceeds through the formation of diastereomeric semihydrogenated intermediate complexes with the participation of a catalyst (M_1 and M_2) that are converted to the final compound at different rates.

Stereoelective Catalysis. Stereoelective catalysis is the selective decomposition (or transformation of the enantiotopic groups) of a racemate such as the dehydrogenation of an alcohol (2) with one chiral center (or a diastereomer if R^1 or R^2 are chiral); in the racemate under the influence of chiral catalyst K_R (K_S) the enantiomers are converted at unequal rates through diastereomeric states M_1 and M_2 via pathway (2).

Stereoselective Catalysis. Stereoselective catalysis is the conversion under the influence of an achiral catalyst of a molecule (3) that contains one or both chiral groups R^1 and R^2 via pathways (1), (2), or (3) indicated in the scheme. The process leads to the primary formation of one of the diastereomers and, after removal of the auxiliary chiral group, to an excess of one of the enantiomers.

This classification encompasses all of the known cases of asymmetric catalysis. In our review we will examine examples of the application of heterocyclic compounds only in enantioselective catalysis that is realized under the influence of both metal-complex catalysts and heterogenized complexes and heterogeneous catalysts primarily in reactions involving halogenation of C=C and C=O bonds, as well as in hydroformylation. The material is examined from the point of view of the effect of both the structure of the ligand of the complex catalyst and the structure of the substrate molecule on the enantioselectivity.

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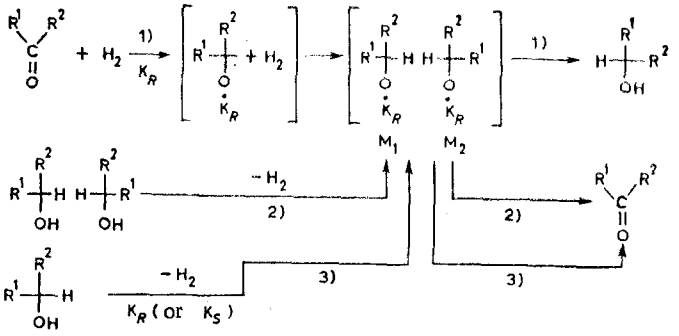


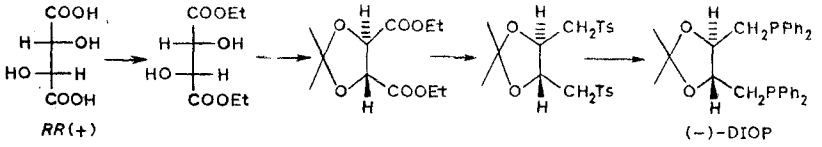
The efficiency of an enantioselective reaction is characterized by the optical yield p (in percent), which is determined, in practice, by measuring the optical rotation of the reaction product by polarimetry or by measuring the ratio of the enantiomers by gas-liquid chromatography (GLC). For brevity, the enantioselectivity of a reaction is subsequently depicted in the form of a notation such as p = R-(–), 25% (the configuration of the reaction product, the sign of the optical rotation, and the optical yield are indicated). The efficiency of asymmetric catalysis in a number of examples of homogeneous metal-complex and heterogeneous catalysis is presently almost 100%, owing largely to the use of heterocyclic compounds.

$$p = \frac{[R]-[S]}{[R]+[S]} = \frac{[\alpha]_{obs}}{[\alpha]_{pure}} \cdot 100.$$

Hydrogenation, Metal Complex Catalysts

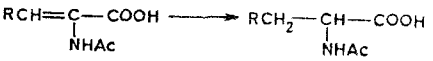
A number of reviews [1-4] on enantioselective hydrogenation on rhodium catalysts with chiral phosphines have been published; however, in these reviews no attention has been paid to the role that heterocyclic compounds play in these reactions as components of the catalysts — chiral ligands — and as substrates.

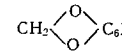
An effective and accessible diphosphine ligand (DIOP) has been synthesized on the basis of (+)-tartaric acid [5, 6] via the scheme



The relative simplicity of its preparation, the accessibility of the starting natural chiral compound, and the high effectiveness of Rh complexes that contain DIOP have drawn attention to this new ligand, and it has rapidly become a general and accessible reagent that is used in a number of preparative syntheses of optically active compounds, particularly natural amino acids [7-10]. A chiral complex containing DIOP is obtained under conditions that exclude contact with the air by the addition of a solution of the ligand in a mixture with triethylamine to a benzene solution of the [RhCl(cyclooctene)$_2$] complex. Hydrogenation is carried out at room temperature and atmospheric pressure and gives the products in very high optical yields. Reaction products with p = 63 and 72% were obtained even in the first study [5] involving the hydrogenation of atropic acid and N-acylaminoacrylic acid. When P/Rh > 2, the catalyst is deactivated as a consequence of the formation of an inactive complex. The [Rh·DIOP] complex is particularly effective in the asymmetric synthesis of amino acids by means of hydrogenation of the C=C bond in substituted aminoacrylic acids or their amides. High effectiveness of the catalyst is observed if the substrate molecule has two functional groups that are capable of coordinating with Rh. The use of adamantyl or bornyl esters or N-benzoyl derivatives of aminoacrylic acids [11], as well as aliphatic in place of aromatic substituents, decreases the p values, and some compounds (N-acetamidocinnamic acid azlactone, benzoylhydantoin, and dehydrobenzoylvaline) are not hydrogenated at all.

It is known that enrichment in the enantiomer may occur in the recrystallization of optically active amino acids, and it is therefore important to evaluate the effectiveness of catalytic chiral systems precisely in the catalysis step prior to workup and purification of the catalyzate. The following results were obtained in the synthesis of R-amino acids on the [Rh·DIOP] catalyst in the catalysis step:

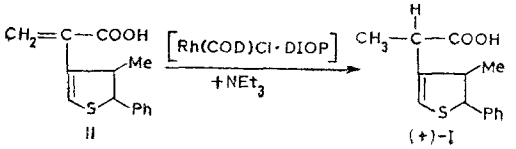


R	H	Ph	HOPh		*i*-Pr
p, %	75	72	80	79	22

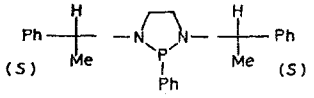
A complex based on (—)-DIOP, which is obtained from natural RR-(+)-tartaric acid, leads to unnatural amino acids of the D series. To obtain L-amino acids one must use (+)-DIOP; however, the latter can be prepared only from unnatural (—)-tartaric acid, and this substantially decreases the practical value of the synthesis of amino acids by this method. Replacement of (—)-DIOP by its diarsine analog [12] makes it possible to obtain natural amino acids, but the products are obtained in low optical yields.

The DIOP ligand is a typical C-chiral diphosphine. The high enantioselectivity of the action of Rh complexes based on it is explained by the configurational rigidity of the ligand molecule and the trans orientation of the dioxolane ring relative to the chelate node. This model satisfactorily explains the asymmetrizing activity of the complex [13].

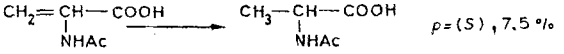
The [Rh·DIOP] complex has found practical application in the synthesis of acid (+)-I, which has anti-inflammatory action, by hydrogenation of II. Although a sulfur atom of a thiophene ring is present in acid II, hydrogenation proceeds smoothly, and the optical yield (88%) turns out to be higher than in the case of hydrogenation of an analog of II, viz., atropic acid, on this complex [14].



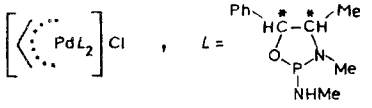
A number of chiral diaminodi- and monophosphines have been synthesized on the basis of chiral α-phenylethylamine [15]. One such chiral ligand is a diazaphospholane derivative:



The Rh complex with this ligand displayed slight effectiveness in hydrogenation [16], while the corresponding diphosphine proved to be very effective.



Oxaazaphospholane derivatives in Pd complexes also do not display high enantioselectivity [17-19].

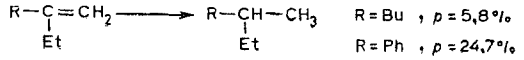


The presence of C and P chiral centers in the ligand molecule was established by circular dichroism. Hydrogenation of N-acetamidocinnamic acid and its azlactone and dimethyl itaconate on the Pd complex with this ligand proceeded with p = 16.4, 4.0, and 9.9%, respectively. This complex is one of the few Pd chiral complexes that are capable of asymmetric hydrogenation. The low p values are evidently associated with partial decomposition of the complex during the reaction and precipitation of the metal.

Ligands with two phosphine groups and an NH (or NR) group have been obtained on the basis of hydroxyproline [20]:

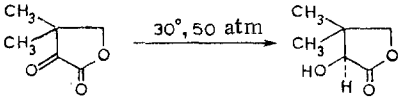
III R=H ; IV R=COOBu-*t* ; V R=Ac ; VI R=Me_3CCO ; VII R=COO-cholesteryl

An Rh catalyst was obtained *in situ* by reaction of the ligand with the [RhCl(1,5-hexadiene)] complex and was investigated in the hydrogenation of substituted aminoacrylic acids. Substitution in the NH group of the ligand increases p, and it was observed that added triethylamine affects p, whereas this effect is absent in the case of the [Rh III] complex as a consequence of interaction of the NH group with the carboxy group of the substrate. The [Rh·IV·NEt_3] system displays high enantioselectivity in a less polar solvent [20]. The following results (p in parentheses) were obtained with other substrates: Z-α-methyl cinnamate (15%) and dimethyl itaconate (24%); p = 29.5% on the [Rh·VII] complex [21]. In addition, olefins are hydrogenated asymmetrically on the latter complex:

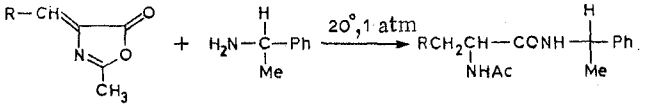


If the NH group in the III ligand is acylated (ligands V and VI), the addition of triethylamine impairs the enantioselectivity and may even lead to the opposite (as compared with the action of the complex with III) configuration of the hydrogenation product [21].

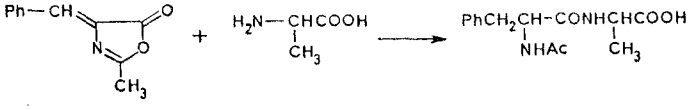
A comparison of the effectiveness of Rh complexes with the IV ligand with other ligands was made in the case of the hydrogenation of itaconic acid [22]. Methyl succinate with p = 92% was obtained when the reaction was carried out at 20°C and 20 atm with the addition of triethylamine to the [Rh·IV] complex. This complex surpasses other complexes with respect to its effectiveness after its conversion to the [Rh L(dicyclooctadiene)]$^+ClO_4^-$ cationic complex in the case of an equimolar NEt_3:substrate ratio. The role of triethylamine consists in activation of the substrate and the formation of a carboxylate anion, which is included in the coordination sphere of the complex. Complexes with ligands IV and VII are capable of hydrogenation of not only the olefin bond but also the keto group. Thus ketopantoyllactone is hydrogenated to R-(—)-pantoyllactone with p = 86.7% [23].



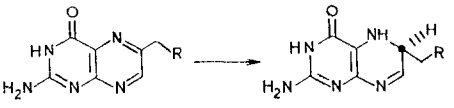
Enantioselective reductive aminolysis of acylaminoacrylic acid azlactones to give the corresponding amides, the saponification of which gives α-amino acids, takes place in the presence of metal-complex catalysts based on [Rh—α-phenylethylamine] [24]. The optical yield in the catalysis step reaches 40-60%, while crystallization of the reaction product leads to optically pure amino acids.



The catalysis is obtained by reduction of $RhCl_3$ (or $PdCl_2$) in aprotic solvents containing S-(—)-α-phenylethylamine. Hydrogen, $NaBH_4$, and S-(—)-α-phenylethylaminoborane are used as the reducing agents. A chiral nucleophile such as, in addition to phenylethylamine, (S)-alanine or some other amino acid serves as an essential part of the catalytic system. In this case a dipeptide is formed in the reaction, and this is of considerable practical interest in view of the fact that dipeptides are assimilated more readily than α-amino acids.



Chiral Rh-amide catalysts for the hydrogenation of unsaturated acids are obtained in situ by the action of $NaBH_4$ on the [py_3RhCl] complex in a solution of an optically active amide such as α-phenylethylformamide. The synthesis of folic acid serves an an example of the use of this complex [25].

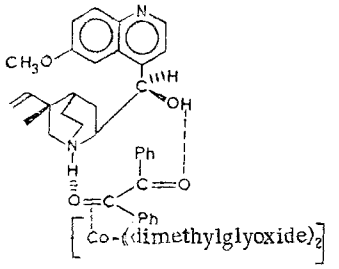


In addition to rhodium-phosphine catalysts, effective cobalt-containing systems have been recently developed. It is known that the [Co(dimethylglyoxime)$_2$·amine] complex is active

in the hydrogenation of the keto group. This complex acquires enantioselective properties after a chiral amine or amino alcohol is included in its composition. Thus benzil is hydrogenated with p = 61.5% on a Co complex containing quinine [26].

$$PhCOCOPh \longrightarrow S\text{-}(+)\text{-}PhCH(OH)COPh$$

The reaction is realized under mild conditions (20°C, 1 atm) in benzene or tetrahydrofuran (THF) at a substrate:Co ratio of 10:20 and a quinine:Co ratio of two. The hydrogenation of other α-diketones also leads to S-(+)-benzoins. The introduction of various chiral amines and amino alcohols as ligands into the complex showed that the configuration of the resulting benzoin is determined by the configuration of the chiral centers bonded to the NH_2 and OH groups in the ligand molecule. Thus when brucine, O-acetylquinine, or α-phenylethylamine is introduced into the [Co(dimethylglyoxime)$_2$] complex, the complex is not capable of bringing about enantioselective hydrogenation, whereas the introduction of quinine, quinidine, or cinchonidine is equally effective (p = 33%). If hydrogenation is carried out at the interface in a benzene–water mixture, the substrate and quinine are found in the benzene layer, and the complex is found in the aqueous layer; the occurrence of an asymmetric reaction therefore indicates that the amino alcohol does not enter the complex directly. This unusual mechanism for the formation of optically active benzoin has been investigated in detail in the case of a chelate [27, 28] formed *in situ* from quinine and benzylamine in solution in propanol–toluene. The proposed scheme for the reaction mechanism assumes simultaneous coordination at one catalytic center of substrate, quinine, and hydrogen molecules.

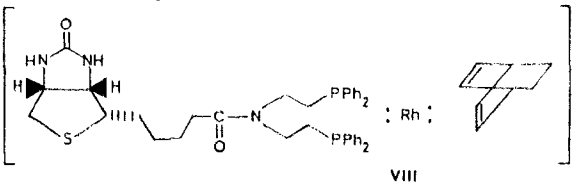


This scheme is based on the assumption that the chiral center in the ligand–quinine system is bonded to the substrate rather than to Co. The diagram of the active center resembles the structure of an enzyme system in which the center that determines the stereochemistry of the reaction is separated from the catalytically active center. This scheme makes it possible to explain the observed independence of p on the overall reaction rate. This essentially distinguishes the Co chiral system from a heterogeneous-catalytic system (enantioselective hydrogenation on metals modified by optically active compounds) in which one observes an antibatic dependence of the optical yield on the overall rate of hydrogen absorption [29].

Heterogenized Metal-Complex Catalysts

The bonding of a catalytically active complex with a polymeric base provides a number of advantages, since this catalyst can be readily separated from the reaction mixture and used repeatedly in a cyclical process. Definite advances in the development of heterogenized chiral Rh complexes attached to a polymeric base and active in enantioselective hydrosilylation have recently been made; these catalysts are less effective in enantioselective hydrogenation.

Little use has thus far been made of heterocyclic compounds in such systems. A catalytic system formed by bonding of $Rh(PPh_3)_3$ to proteins, which leads to the production of a chiral catalyst for the enantioselective hydrogenation of N-acetamidoacrylic acid, is described in [30]. In this case the chiral tertiary structure of the protein (avidin, lysozyme, and albumin) creates the necessary chiral environment for a catalytically active metal-complex catalyst. A system containing avidin, which was found to consist of four identical subunits bonded to biotin, has been investigated in detail. The synthesis of the complex is realized by conversion of biotin to a diphosphine, which reacts with an Rh complex *in situ* to give the chiral catalytically active VIII complex:



VIII

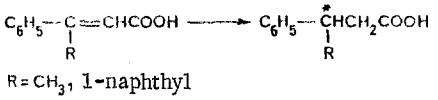
The protein and complex VIII are added to a solution of the substrate (N-acylaminoacrylic acid), and hydrogenation is carried out at 1.5 atm and 0°C for 48 h. Optically active N-AcAla is formed. Complex VIII itself is a chiral catalyst, and the introduction of protein has little effect on the overall reaction rate. However, whereas the optical yield was less than 2% without a protein, the introduction of an equivalent of avidin increases p to 44%. Lysozyme and albumin are ineffective: p is less than 2-5%.

Hydrogenation on Heterogeneous Catalysts

Metal catalysts for hydrogenation modified by treatment with solutions of optically active compounds that are capable of complexing acquire the ability to effect enantioselective hydrogenation. A large amount of experimental data was obtained in studies of Ni, Co, and other catalysts [29]. Keto esters, β-diketones, unsaturated acids, and olefins served as the principal subjects of the investigations. Hydroxy and amino acids, inasmuch as they are compounds that give sufficiently stable complexes with the metals that serve as hydrogenation catalysts, were used as modifiers.

Heterocyclic compounds have found limited application in this form of catalysis.

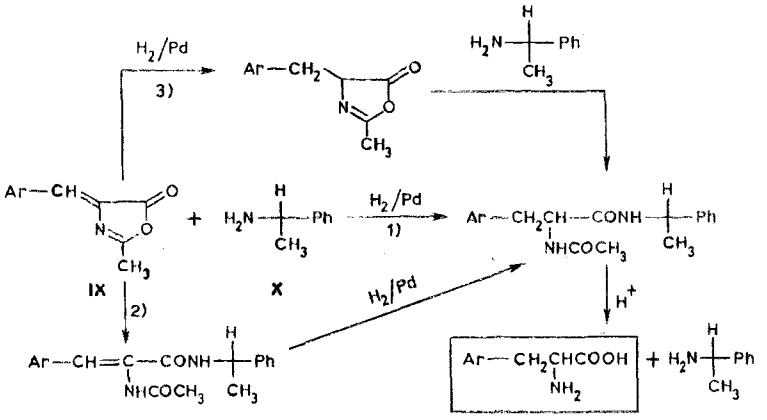
The first indications of the modifying effect of the addition of hydroquinone on platinum oxide in the hydrogenation of β-methyl- and β-(α-napthyl)-cinnamic acids can be found in [31]. Optically active dihydro acids with $[\alpha]_D$ +4.5 and −0.5°, respectively, are formed.



In one of the first papers by Isoda and co-workers [32] it was shown that the hydrogenation (50°C, 80 atm) of acetamidocinnamic acid azlactone over Raney nickel modified with L-tyrosine leads to phenylalanine with p = 50%. However, Izumi and co-workers [33] later were unable to obtain an optically active product of hydrogenation of the azlactone on Ni modified by an amino acid under these conditions. In [34] it was reported that the hydrogenation of the azlactone on Pd in the presence of L-tyrosine also leads to phenylalanine in high optical yield (p = 60%). However, these data have not been confirmed (see [29]). Only in a patient [35] is it reported that a suspension of 5% Pd/C in ethanol treated with an amino acid at 50-60°C acquires the ability to hydrogenate α-N-acetamidocinnamic acid (55°C, 140 atm) to give an optically active N-acetyl-L-phenylalanine, from which L-phenylalanine is obtained after hydrolysis; however, its optical purity is not indicated. The chiral amino acid complex of Pd that is formed on the catalyst surface is evidently weakly bonded to the massive catalyst, readily dissolves, and undergoes partial hydrogenolysis.

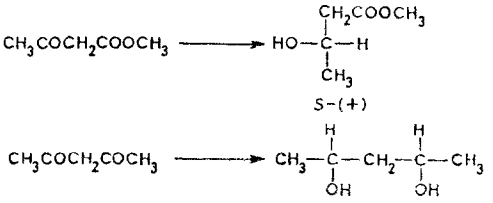
A similar pattern is observed when a Pd catalyst is used in a new method for the synthesis of amino acids by hydrogenation of azlactones [36-42]. Saturation of the C=C bond and opening of the azlactone ring to give up to 80% of that diastereomer, the hydrolysis of which then gives optically pure R-(−)-phenylalanine, occur in the reaction of Pd formed *in situ* from $PdCl_2$ in the presence of S-(−)-phenylethylamine.

The production of amino acids by hydrogenation of azlactones is known: for example, on a Pd catalyst applied to natural silk as a dissymmetric support α-acetamidocinnamic acid azlactone is hydrogenated to R-(+)-phenylalanine in 16% overall yield with p = 35.6% [43]. However, rhodium-phosphine catalysts, which are used successfully in the enantioselective hydrogenation of precursors of amino acids, prove to be ineffective as applied to azlactones. The method proposed in [39] is therefore of particular interest for the synthesis of diverse natural amino acids. The process is characterized by the fact that the nucleophilic agent — a chiral amine or an amino acid (when the product is dipeptide) — can be recycled without a loss of optical activity. The process takes place under mild conditions, viz., at 0-40°C and atmospheric pressure. The elucidation of the reaction mechanism showed that pathway (3) is a more probable reaction pathway than pathway (2), although pathway (1), viz., synchronous reaction of azlactone IX with hydrogen and with amine X on the surface of a palladium catalyst modified with chiral amine II, is also not excluded.



This method for the reductive aminolysis of azlactones has been used for the preparative synthesis of some valuable natural amino acids. A precursor of an amino acid, the reductive aminolysis of which on a Pd catalyst and subsequent hydrolysis of the resulting amide lead to optically pure (p = ∿100%) 3,4-dihydroxyphenylalanine or DOPA — a preparation for the treatment of Parkinson's disease — is obtained starting from vanillin (or isovanillin). Phenylalanine and tyrosine and its methyl ester are obtained in high optical yields under similar conditions.

Metal catalysts for the hydrogenation of prochiral compounds that contain C=C or C=O bonds, after treatment with optically active compounds that are capable of complexing with transition metals, acquire the ability to effect an asymmetric reaction, and the product has optical activity. The large amount of data thus far accumulated on the hydrogenation of keto esters and β-diketones on modified (in this way) Ni, Cu, Co, Ru, and other binary catalysts are presented in a book [29].



The problem was examined theoretically from the point of view of complexing of chiral ligands on a catalyst surface in [44]. Conditions for the preparation of effective catalysts were found. For example, Raney Ni modified with RR-(+)-tartaric acid with added NaBr effects the hydrogenation of acetylacetone to pentanediol with p = 100%. Modification with amino acids is less effective, and p may reach 10-20%. The enantioselectivity of an Ni catalyst modified with amino acids depends both on the nature of the amino acid and on the modification conditions (the temperature and the pH of the solution of the amino acid). The investigated amino acids can be divided into several types as modifiers with respect to the effect of the modification temperature: those that change the configuration and sign of the optical rotation of the product of hydrogenation of methyl acetoacetate, viz., methyl β-hydroxybutyrate, from S-(+) to R-(−) as the modification temperature is increased from 0 to 100°C (proline) and those that do not change the configuration (tryptophan). The dependence of p on the modification temperature could not be investigated in the case of histidine, since the amino acid complexes too strongly with the catalyst and suppresses the catalytic activity.

Studies of the effect on the optical yields of the addition to the reaction sphere of foreign substances that are not hydrogenated but substantially change the reaction rate and the optical yield are of particular interest. In this respect several heterocyclic compounds have been investigated as solvents and catalyst poisons [45].

A study of the hydrogenation of ethyl acetoacetate on Raney Ni modified with (+)-tartaric acid in solution in tetrahydrofuran (THF) or dioxane showed that p increases as the dielectric constant of the medium increases and is somewhat higher in THF than in dioxane or for ethyl acetoacetate without a solvent [46] (p = 16.3, 13.3, and 15.6, respectively).

According to [47], the mechanism of the action of metal catalysts modified by chiral ligands consists in the creation, as a result of modification on the catalyst surface, of

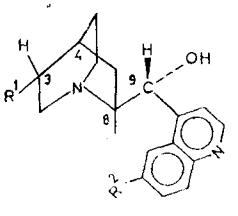
dissymmetric catalytic centers that effect enantioselective hydrogenation. Nonstereoselective hydrogenation to give a racemic reaction product occurs on the adjacent unmodified centers [48, 49]. Treatment of the catalyst surface with a catalyst poison that selectively blocks only the unmodified centers may raise the optical yield of the reaction product owing to an increase in the fraction of functioning modified centers. This study was realized in the case of Raney Ni modified with (+)-tartaric acid, which accomplishes enantioselective hydrogenation of ethyl or methyl acetoacetate. The introduction of thiophene into the reaction sphere decreases the overall rate markedly and changes the optical yield substantially [46]. However, the addition of pyridine increases somewhat the optical yield at the start of the reaction [50].

According to the data in [51], the hydrogenation of methyl benzoylformate (XI) in methyl propionate at 20°C and an initial hydrogen pressure of 60 atm on 5% Pt/C modified with cinchonidine at a substrate:solvent:catalyst ratio of 20:60:1 leads to methyl R-(—)-mandelate with p = 81.9%. In alcohols p decreases to 62-75%. Similar results were obtained when 5% Pt/Al_2O_3 modified with 1% alcohol solutions of chinchonidine at 20°C was used as the catalyst. Hydrogenation of ester XI was carried out at 20°C and a hydrogen pressure of 50 atm in benzene. It was found that prior heating of the catalyst in a hydrogen atmosphere at 400-500°C increases p from 34% (without such treatment) to 82-83% [52].

$$\underset{\text{XI}}{\text{PhCOCOOMe}} \longrightarrow \text{PhCH(OH)COOMe};\quad \underset{\text{XII}}{\text{CH}_3\text{COCOOMe}} \longrightarrow \text{CH}_3\text{CH(OH)COOMe}$$

The hydrogenation of methyl pyruvate (XII) to methyl lactate was investigated on the same catalyst at 20°C and 70 atm.

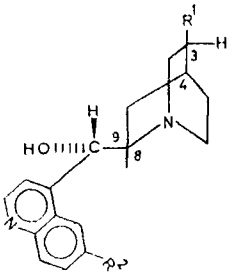
The catalyst was also heated beforehand at 400°C in a hydrogen atmosphere. Modification was carried out at 20°C with 1% alcohol solutions of quinine, quinidine, cinchonine, and cinchonidine. The reaction was carried out in methanol and benzene. The results show that modification with cinchonidine and quinine leads to the S-(+) ester and that this process is more efficient (p > 80%) than modification with cinchonine and quinidine, which gives the R-(—) enantiomer when the reaction is carried out in both methanol and in benzene (similar data were also obtained in the hydrogenation of ethyl benzoylformate in benzene, except that in this case esters with a configuration that is the opposite of the configuration of the lactates are formed). This is evidently associated with the fact that cinchonidine and quinine have the 3S4S8S9R configuration of the chiral centers, whereas quinidine and chinchonine have a 3S4S8R9S configuration of the chiral centers. Thus the $C_{(8)}$ and $C_{(9)}$ centers in the modifier molecule, which enter into a dissymmetric cluster on the surface of the metal catalyst, are decisive in the determination of the configuration of the chiral center in the hydrogenation product, as has been proposed for Cu and Ni modified catalysts [29].



3S4S8S9R

quinine R^1 = —CH=CH_2; R^2 = OCH_3

cinchonidine R^1 = —CH=CH_2; R^2 = H



3S4S8R9S

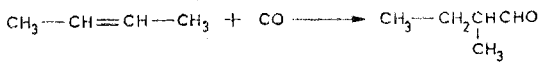
quinidine R^1 = —CH=CH_2; R^2 = OCH_3

cinchonine R^1 = —CH=CH_2; R^2 = H

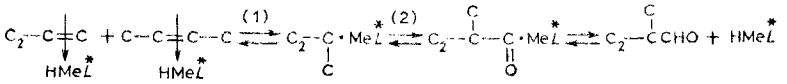
Similar dependences of the enantioselectivity on the configurations of the chiral centers in these alkaloids when they are used as catalysts were previously found in cyanohydrin synthesis and in several other reactions involving homogeneous catalysis [53].

Hydroformylation

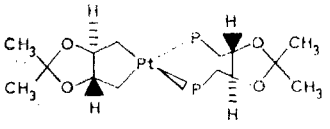
A rhodium catalyst containing DIOP has been used in the hydroformylation of olefins. The hydroformylation of aliphatic olefins proceeds under milder conditions than the hydroformylation of aromatic olefins; the enantioselectivity increases as the temperature is decreased. Aldehydes are formed with p = 27% on the [$RhH(CO)(PPh_3)_3$•DIOP] catalytic system at 25-95°C [54, 55].



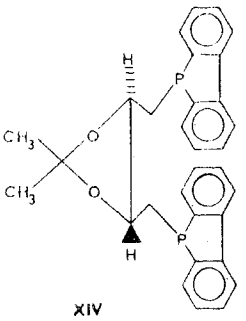
In the presence of this catalyst cis-2-butene (with C_{2v} symmetry) gives, like the trans isomer, an aldehyde with the same S configuration but different optical yields [p = (+), 27.0%; (+) 3.2%]. This indicates that the reaction proceeds through stereochemically identical transition states, while the R aldehyde (p = 18.8%) is formed from 1-butene. 2-Methylbutanal with a single configuration and close p values is formed from isomeric butenes on similar complexes with other metals such as [Pt·DIOP]; this is completely different from the effect of the Rh complex. This difference is explained by the fact that the asymmetric reaction proceeds on the Rh complex until CO is incorporated in the olefin molecule, whereas it proceeds after this step on the Pt complex:



This indicates different structures of the catalytically active complexes and, consequently, that not only the chiral ligand but also the stereochemistry of the complex itself and the nature of the central metal atom affect the asymmetric reaction [56]. In fact, it has been shown in the case of [Pt·DIOP] by measuring the temperature dependence of the ^{31}P NMR spectra that in the complex one DIOP ligand exists in the chair conformation, while the other exists in the boat conformation [57]. As a result, a chiral environment is created about the central Pt atom during the stereospecific formation of this complex. The high effectiveness of complexes with DIOP also in the case of enantioselective hydrogenation is possibly explained by this structure.



XIII



XIV

In analog of DIOP, viz., XIV, has been used as a chiral ligand. The rhodium catalyst with this ligand proved to be more effective in the hydroformylation of olefins than the complex with DIOP (it is less effective than Rh·DIOP in enantioselective hydrogenation). Aldehydes with the following values were obtained in the hydroformylation of styrene, 1-butene, and cis-2-butene: S(+), 44.3%; S(+), 20.4%; R(–), 16.9% [58].

Olefins undergo hydrocarboxylation in the presence of the [Pd·DIOP] complex, which is formed *in situ:*

In contrast to hydroformylation, this reaction takes place with α-methylstyrene in higher optical yield than with styrene [59].

Upon the whole, although p reached 40% in individual cases, hydroformylation proceeds with low p values. However, the possibility of obtaining difficult-to-obtain optically active aldehydes and branched acids by this method justifies further research in this direction.

Thus from this brief review it may be concluded that, because of their polydentate character and increased ability to undergo complexing, it is expedient to use heterocyclic compounds as chiral ligands. The most effective chiral ligands in the production of catalytic systems have been found precisely among heterocyclic compounds. The use of heterocyclic compounds as substrates is justified in view of the great importance of heterocycles as biologically active compounds.

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PYROLOCYANINES.

17.* SYMMETRICAL FLAVYLOCYANINES BASED ON METHOXY-SUBSTITUTED 4-METHYLFLAVYLIUM SALTS

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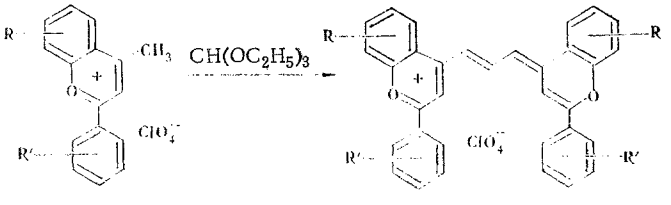
UDC 547.814.5.07:541.651:668.819.45:543.422

Symmetrical flavylocyanines in which electron-donor substituents (methoxy groups) are present alternately in the 5, 6, 7, 8, 2', 3', and 4' positions of the flavylium rings were synthesized. The characteristics of the long-wave absorption bands of the resulting flavylocyanines are discussed with the aid of quantum-chemical methods. It is shown that not only the position but also the form of their absorption bands can be changed purposefully by introduction of substituents in the heteroresidues of symmetrical polymethine dyes.

In the pyrylocyanine series the effect of annelation of benzene rings to the heteroresidues, as well as the effect of replacement of the oxygen atoms in the latter by sulfur or selenium atoms, on the spectral properties has been studied systematically [2]. Within the framework of our systematic investigation of this group of dyes it seemed of interest to also study the effect of substituents on their color. This problem was also worthy of consideration because of the fact that pyrylocyanines have recently found application in the technology of silverless light-sensitive materials [3] and quantum electronics [4], in which compounds that absorb over strictly predesignated wavelength ranges are required. In the present paper we describe symmetrical flavylocarbocyanines that contain methoxy groups in various positions of the flavylium residues. We selected trimethylidynecyanines as the subjects of the investigation, since, in contrast to monomethlidynecyanines, their molecules do not display effects due to close orientation of the rings [5], and solvation effects are not manifested as markedly as in the case of dyes with longer chromophores [6]. This should make it possible to follow more distinctly the influence of the electronic effects of substituents on the color.



Ia-h II, III a-g

a R=5-OCH_3; b R=6-OCH_3; c R=7-OCH_3; d R=8-OCH_3; e R'=2'-OCH_3; f R'=3'-OCH_3; g R'=4'-OCH_3; h R'=2'-OH; II R=R'=H. Where not indicated, R or R'=H.

*See [1] for communication 16.

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