Screw Sense Selective Polymerization of Achiral Isocyanides Catalyzed by Optically Active Nickel(II) Complexes

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Abstract: Poly(isocyanides), $(RN{=}C{<})_n$, can be prepared from isocyanides, $RN^+{\equiv}C^-$, by the catalytic action of nickel(II) compounds. The main chain of these polymers is a rigid helix. This helical conformation results from a restricted rotation around the single bonds that connect the main-chain carbon atoms. Polymerization of achiral isocyanides generally gives a racemic mixture of left- and right-handed helices, whereas polymerization of optically active isocyanides results in helices with an excess of one screw sense. We describe a procedure for obtaining poly(isocyanides) with predominantly one screw sense, starting from an achiral monomer. A catalyst is prepared by adding an optically active amine to a tetrakis(isocyanide)nickel(II) perchlorate complex. Polymerization of various achiral isocyanides with this catalyst yields optically active polymers with an enantiomeric excess up to 83%.

In the presence of protonic acids, Lewis acids, or Ni(II) salts as catalysts, isocyanides polymerize to give poly(isocyanides), also called poly(iminomethylenes) or poly(carbonimidoyls).[1,2] Ni(II) salts are versatile catalysts and, in our opinion, the most suited for our experiments. Poly(isocyanides) are unusual polymers in

$$n\mathrm{RN^+{\equiv}C^-} \xrightarrow{\mathrm{Ni(II)}} (\mathrm{RN{=}C{<}})_n$$

the sense that each atom of their main chain carries a side chain.[1,2] This feature causes a restricted rotation around the single bonds that connect the main-chain carbon atoms. Two conformations are possible around the single bonds, viz. *R* and *S*.[3] If the polymer is highly isotactic (meaning that the configuration is the same around all the single bonds), a stable helix will be the result.[4] The helix is right handed (*P*) if the aforementioned configurations are all *S* and left-handed (*M*) if they are all *R*.[5]

Following initial suggestions by Millich, we established experimentally that polymers of isocyanides have a helical structure.[6-9] The polymer of *tert*-butyl isocyanide was completely resolved into *P* and *M* screws, which were shown to have negative and positive optical rotations, respectively.[7,8]

In the past, several procedures for obtaining optically active poly(isocyanides) have been developed in our laboratory. One procedure involves the polymerization of optically active monomers. When one enantiomer of a chiral isocyanide is polymerized, the resulting polymer will be a mixture of diastereoisomeric molecules having *P* and *M* screws. This mixture will contain an excess of one of the screw senses. This was observed for approximately 20 different optically active isocyanides.[10-12] In another procedure, we prepared optically active polymers by specifically inhibiting the growth of one screw sense of a racemic pair of helices.[5,13] Finally, in one case an optically active poly(isocyanide) was obtained by resolution.

A convenient way of preparing optically active polymers is the use of chiral initiators (e.g., see ref 14). In this way a racemic mixture of optically active monomers can be polymerized stereoselectively.[14a,c,f,i,j] This procedure was used by Yuki et al.[14c-f] to prepare stable helical polymers from bulky methacrylic acid esters and by Vogl[14l,m] to prepare helical polymers from chloral.

The resolution of poly(*tert*-butyl isocyanide) indicates that polymerization of isocyanides proceeds stereoselectively with respect to the screw sense. Therefore, it should be possible to obtain optically active polymers by using chiral catalysts. In the present paper we describe the synthesis of optically active poly(isocyanides) by using Ni(II) complexes of optically active amines as catalysts.[15] The prevailing screw sense of the polymers is derived from CD spectra and compared to the one predicted by the polymerization mechanism.

Scheme I

$$\mathrm{RNH_2} \rightarrow \mathrm{RNHCHO} \rightarrow \mathrm{RN^+{\equiv}C^-}$$
$$\mathbf{1} \qquad\quad \mathbf{2} \qquad\quad \mathbf{3}$$

a, R = *n*-C_4H_9; **b**, R = $CH(CH_2CH_3)_2$; **c**, R = *t*-C_4H_9; **d**, R = *t*-C_5H_{11}; **e**, R = 2,6-$Cl_2C_6H_3$; **f**, R = $C(CH_3)_2C_6H_5$; **g**, R = 2,6-(*i*-$C_3H_7)_2C_6H_3$; **h**, R = 2-(*t*-$C_4H_9)C_6H_4$; **i**, R = $C_6H_5CH_2$; **j**, R = C_6H_5; **k**, R = 4-$CH_3OC_6H_4$; **l**, R = 4-CH_3O-2-$CH_3C_6H_3$; **m**, R = 4-$(CH_3)_2NC_6H_4$; **n**, R = 2-$C_6H_5C_6H_4$; **o**, R = 2,4,6-$(CH_3O)_3C_6H_2$; **p**, R = 2,6-$F_2C_6H_3$

Table I. Screw Sense Selective Polymerization of *tert*-Butyl Isocyanide by Tetrakis(*tert*-butyl isocyanide)nickel(II) Perchlorate and Optically Active Initiators

initiator[a]	$[\alpha]^{20}_D$,[b] deg	ee,[c] %	screw sense[d]
(*S*)-(+)-$C_2H_5CH(CH_3)NH_2$	−3.5	7	*P*
(*S*)-(−)-$C_6H_5CH(CH_3)NH_2$	−28.7	61	*P*
(*R*)-(+)-$C_6H_5CH(CH_3)NH_2$	+29.0	62	*M*
(*S*)-(−)-c$C_6H_{11}CH(CH_3)NH_2$	−23.2	50	*P*
(*S*)-(−)-$C_6H_5CH(CH_3)NH(CH_3)$	0	0	*P* + *M*
(*S*)-(−)-$C_6H_5CH(CH_3)N(CH_3)_2$	0	0	*P* + *M*
(*S*)-(−)-1-naphthylethylamine	−19.6	44	*P*
L-(−)-ephedrine	+6.3	13	*M*
(*R*,*R*)-1,2-diaminocyclohexane	5.3	11	*M*
L-isoleucine methyl ester	−4.2	11	*P*
L-prolinol	3.7[e]	36	*M*
L-phenylalaninol	21.8	37	*M*
L-valine methyl ester	−11.6	24	*P*
L-phenylalanine ethyl ester	0	0	*P* + *M*
L-alanine methyl ester	−21.9	47	*P*
L-cysteine methyl ester	−2.9	6	*P*

[a] Catalyst 1.0 mol % Ni(C≡N-*t*-$C_4H_9)_4(ClO_4)_2$; molecular weights of the polymer samples are in the range $\bar{M}_n$ 2000–3000 (end-group determination by ^{1}H NMR); yields of poly(*tert*-butyl isocyanide) 40 ± 10%. [b] In $CHCl_3$, *c* 0.5–1.0. [c] Enantiomeric excess calculated by comparing the $\Delta\epsilon$ values in the CD spectra of the polymer samples with the $\Delta\epsilon$ value of optically pure (*M*)-(+)-poly(*tert*-butyl isocyanide); see ref 11. [d] Determined from the CD spectra of the polymer samples; see ref 11. [e] Optical rotation is lower than expected from the ee value, probably owing to an end-group effect.

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Results

The isocyanides used in this study were synthesized from the corresponding amines according to the general procedure shown in Scheme I. The amines **1a–d** and **1f** were N-formylated with an excess of ethyl formate.[16] The anilines **1e**, **1g**, **1i**, **1l**, and **1o** were treated with formic acid/acetic anhydride to give the N-formylated products. Anilines **1h**, **1j**, **1k**, **1m**, **1n**, and **1p** were formylated with formic acid in toluene.[17] Isocyanides **3a–d** were synthesized from the formamides **2a–d** by dehydration with 4-toluenesulfonyl chloride at reduced pressure.[18] Isocyanides **3e–p** were obtained from formamides **2e–p** by dehydration with trichloromethyl chloroformate ($Cl_3COCOCl$) and *N*-methylmorpholine at low temperatures.[19]

According to the mechanism we previously reported,[1] the polymerization reaction is initiated by attack of a nucleophile on an isocyanide that is coordinated to the nickel center (Figure 1). For the polymerizations described in this paper we first prepared the complex $Ni(C{\equiv}NR)_4(ClO_4)_2$ from $Ni(ClO_4)_2{\cdot}6H_2O$ and 4 equiv of isocyanide. These complexes were isolated and dried at 40 °C in vacuo to remove all water.[20] The complexes were dissolved in dry dichloromethane and treated with 1 equiv of an optically active nucleophile, Nu*, to give the complex $Ni(C{\equiv}NR)_3[C(Nu^*){=}NR](ClO_4)_2$.[15] Polymerization was carried out by adding 1 mol % of this complex to the isocyanide with or without solvent.

Table II. Screw Sense Selective Polymerization of *tert*-Butyl Isocyanide by $Ni(C{\equiv}NR)_4(ClO_4)_2$ and (*S*)-(−)-1-Phenylethylamine[a]

R in $Ni(C{\equiv}NR)_4(ClO_4)_2$	$[\alpha]^{20}_D$,[b] deg	ee,[c] %	screw sense[d]
t-C_4H_9	−28.7	61	*P*
t-C_5H_{11}	−25.8	58	*P*
2-(t-C_4H_9)C_6H_4	−37.7	83	*P*
2,6-(i-C_3H_7)$_2C_6H_3$	−10.1	22	*P*

[a] Molecular weights of the polymer samples are $\bar{M}_n$ 2500 ± 500 (end-group determination by ^1H NMR); yields of poly(*tert*-butyl isocyanide) 35 ± 5%. [b] *c* 0.02–0.01, $CHCl_3$. [c] Calculated by comparison with the CD spectrum of completely resolved poly(*tert*-butyl isocyanide); cf. ref 11. [d] Derived from the CD spectra of the polymers.

Table III. Screw Sense Selective Polymerization of Isocyanides with $Ni(C{\equiv}N$-t-$C_4H_9)_4(ClO_4)_2$ and (*S*)-(−)-1-Phenylethylamine

R in $RN^+{\equiv}C^-$	yield, %	$[\alpha]^{20}_D$,[a] deg	screw sense[b]	av mol wt[c]
t-C_4H_9	32	−28.7	*P*	2400[d]
t-C_5H_{11}	30	−9.7	*P*	3200[d]
n-C_4H_9	75	0	*P* + *M*	>30000
$CH(CH_2CH_3)_2$	70	0	*P* + *M*	*e*
$C_6H_5CH_2$	90	0	*P* + *M*	*e*
$C_6H_5C(CH_3)_2$	10	−5.7	*P*	*e*
C_6H_5	80	0	*P* + *M*	>40000
4-$CH_3OC_6H_4$	75	0	*P* + *M*	>45000
4-CH_3O-2-$CH_3C_6H_3$	90	0	*P* + *M*	*e*
2,6-$F_2C_6H_3$	50	0	*P* + *M*	*e*
2,6-$Cl_2C_6H_3$	30	70	*M*	*e*
2-t-$C_4H_9C_6H_4$	46	0	*P* + *M*	11500
2-$C_6H_5C_6H_4$	65	0	*P* + *M*	18400
4-$(CH_3)_2NC_6H_4$	88	*f*	*P* or *M*	≈5000

[a] *c* 0.02–0.1, $CHCl_3$. [b] Derived from the CD spectra of the polymers. [c] Determined by measuring intrinsic viscosities (toluene at 30.00 °C), Mark–Houwink equation $[\eta] = 1.4 \times 10^{-9} \bar{M}_w^{1.75}$. [d] End-group determination by means of ^1H NMR. [e] Molecular weight could not be determined due to low solubility of the polymer. [f] Optical rotation could not be measured due to strong absorption of the solution.

The results of the polymerization reactions of *tert*-butyl isocyanide using various optically active amines as initiator are given in Table I. All polymer samples have molecular weights in the range from 2200 to 3400 (end-group determination by ^1H NMR, see Experimental Section; the end groups are Nu* and H). They showed optical rotations and CD spectra characteristic for right-handed or left-handed helices. The enantiomeric excess was calculated by comparing the CD spectra of the polymer samples with the CD spectrum of completely resolved (*M*)-(+)-poly(*tert*-butyl isocyanide).[11]

We also tried to obtain optically active polymers by using chiral additives in the reaction mixture or by polymerizing in a chiral solvent. We used l-borneol, cinchonine, (*R*,*R*)-DIOP, (*S*,*S*)-chiraphos, neomenthyldiphenylphosphine, and (2*S*,2′*S*)-2-(hydroxymethyl)-1-[(1-methylpyrrolidin-2-yl)methyl]pyrrolidine[21] as optically active additives and (*S*)-sec-butyl alcohol as a chiral solvent. As monomers we used *tert*-butyl isocyanide and 4-methoxyphenyl isocyanide. Polymers were isolated in 20–80% yield. None, however, were optically active.

Table I shows that the highest stereoselectivity is obtained when (*R*)- or (*S*)-1-phenylethylamine is used as the initiator. This high chiral induction is reduced to zero when the amino group is mono- or di-N-methylated. In the latter case, the yield of the resulting polymer also decreases dramatically. When the phenyl group of (*S*)-(−)-1-phenylethylamine is replaced by an ethyl group, the chiral induction also decreases. The same occurs when the phenyl group is converted into a cyclohexyl group. Several esters of amino acids have been tried as optically active initiators. A decrease in chiral induction was found when going from alanine methyl ester to valine methyl ester to isoleucine methyl ester. When

(4) If the configurations around the single bonds are alternating *R* and *S*, a syndiotactic structure will result. If the configurations are randomly *R* and *S*, an atactic structure is formed. Strictly speaking, the terms isotactic, syndiotactic, and atactic cannot be used for polymers of the type described in this paper, as they refer to polymer chains that contain chiral centers.

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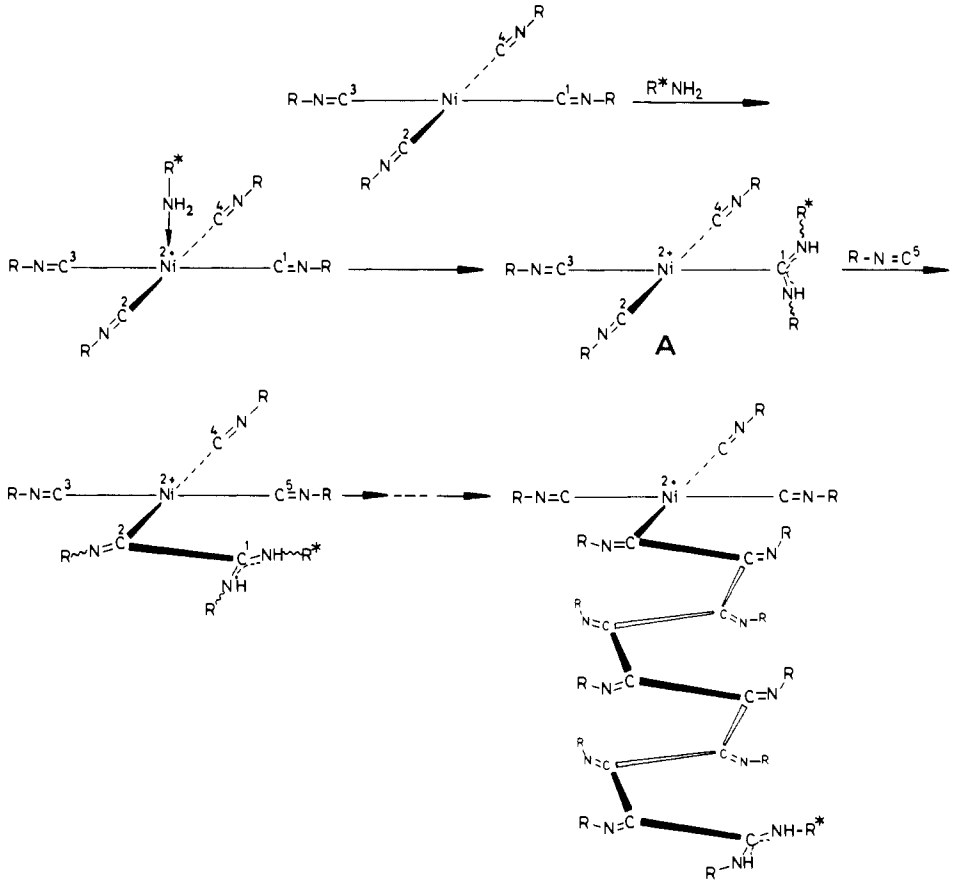

Figure 1. Mechanism of polymerization of isocyanides.

cysteine methyl ester was used as initiator, a low optical activity was observed for the polymer. When phenylalanine ethyl ester is used, no optical activity is obtained at all. However, when the ester function is reduced to an alcohol group (L-phenylalaninol), a relatively high chiral induction is observed.

Optically active alcohols and their corresponding sodium salts were also tried as initiators. These experiments resulted in low polymer yields and no chiral induction at all. This is probably due to the low reactivity of alcohols toward coordinated isocyanides.

The effect of varying the type of isocyanide ligand in the catalyst was tested as follows. One equivalent of (*S*)-1-phenylethylamine was added to $Ni(C{\equiv}NR)_4(ClO_4)_2$, and the resulting complexes were used as catalyst in the polymerization of *tert*-butyl isocyanide (Table II). By using $Ni(2\text{-}t\text{-}C_4H_9C_6H_4N{\equiv}C)_4(ClO_4)_2$ as catalyst, an enantiomeric excess of 83% was achieved. The complex $Ni[2,6\text{-}(i\text{-}C_3H_7)_2C_6H_3N{\equiv}C]_4(ClO_4)_2$ gave a relatively low enantiomeric excess. This can be ascribed to the fact that the initiator does not react with the coordinated isocyanide, because of steric hindrance. Attempts have also been made to obtain the catalytic complexes from optically active isocyanides such as (*S*)-1-phenylethyl, (*S*)-1-(methoxycarbonyl)-2-methylpropyl, and 1-(*S*),2(*S*)-1-(methoxycarbonyl)-2-methylbutyl isocyanide. However, due to interference of the polymerization process these complexes could not be isolated.

As the highest chiral induction was obtained with 1-phenylethylamine as the initiator, this nucleophile was used to obtain optically active polymers not only from *tert*-butyl isocyanide but from other isocyanides as well. The results are given in Table III. Optically active polymers could only be obtained from the sterically hindered tertiary aliphatic isocyanides, 2,6-dichlorophenyl isocyanide, and the almost unreactive 4-(dimethylamino)phenyl isocyanide. The optical rotation of the latter polymer could not be determined due to the dark color of the polymer solution. However, the CD spectrum of the polymer indicated that we were dealing with an optically active polymer. Isocyanides with two ortho substituents that are more bulky than the chloro group could not be tested, as they do not polymerize because of their steric hindrance. From 2,4,6-trimethoxyphenyl isocyanide only oligomeric material could be obtained which contained large amounts of free isocyanide and showed no optical activity. Aromatic isocyanides with low steric hindrance at the ortho positions, as well as primary and secondary aliphatic isocyanides, gave racemic mixtures of right- and left-handed helices.

The screw sense of poly(isocyanides) can be derived from their CD spectra.[7,11] In Figure 2, the CD spectra of poly(*tert*-butyl isocyanide), poly(*tert*-pentyl isocyanide), poly(α,α-dimethylbenzyl isocyanide), poly(2,6-dichlorophenyl) isocyanide, and 4-(dimethylamino)phenyl isocyanide are given. The observed positive couplets for the first three polymers point to right-handed helices. The polymerization of 2,6-dichlorophenyl isocyanide was carried out with (*R*)-(+)- instead of (*S*)-(−)-1-phenylethylamine as the initiator, which resulted in polymers having a negative couplet, indicative of a left-handed helix. The polymer of 4-(dimethylamino)phenyl isocyanide shows a large CD signal, but has no clear couplet. This CD signal cannot result from the optically active initiator, as it is far too large to be caused by the small amount of incorporated initiator (less than 0.1 mol %). Thus, the CD spectrum must result from the polymer itself. The absence of a clear couplet could be due to a distortion in the regularity of the polymer helix. Molecular models show that in polymers of aromatic isocyanides that have no ortho substituents syn–anti isomerism is possible. As a consequence, the aromatic rings of the polymer do not form regular stacks. As a result, the CD spectrum is modified as compared to regularly stacked polymers, which show a clear couplet in the $n \rightarrow \pi^*$ absorption region. The occurrence of irregular stacked rings also follows from the ^1H and ^{13}C NMR spectra of poly(4-methoxyphenyl isocyanide) and poly(4-tolyl isocyanide), which display two NMR peaks for the methoxy and methyl substituents.[22,23]

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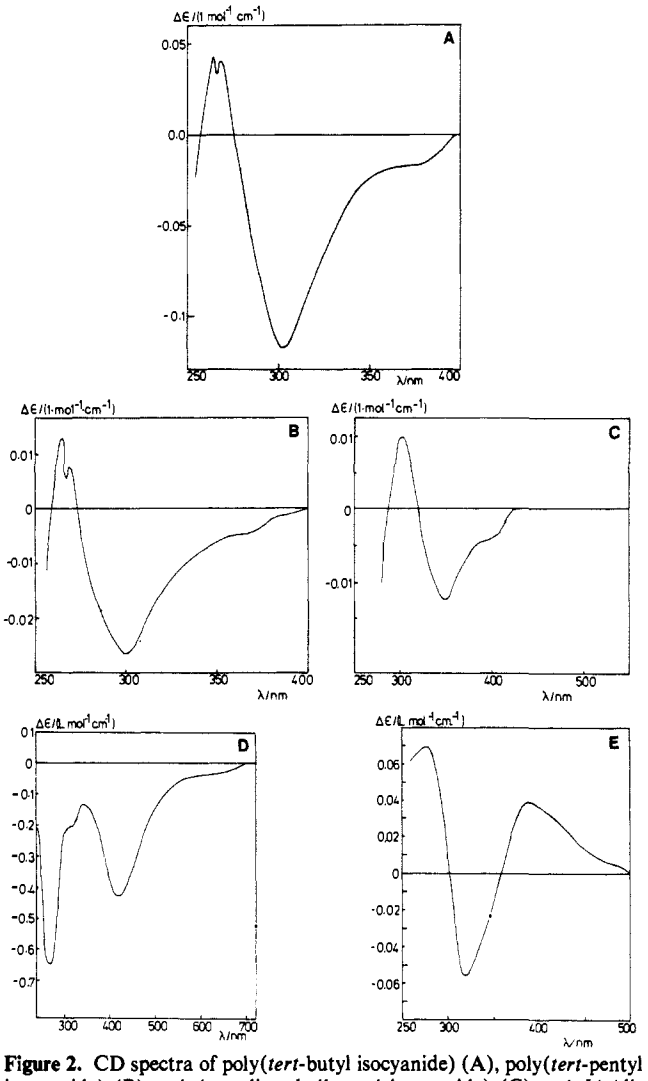

Figure 2. CD spectra of poly(*tert*-butyl isocyanide) (A), poly(*tert*-pentyl isocyanide) (B), poly(α,α-dimethylbenzyl isocyanide) (C), poly[4-(dimethylamino)phenyl isocyanide (D), and poly(2,6-dichlorophenyl isocyanide) (E).

Discussion

Previously, we proposed that isocyanides polymerize via a series of consecutive insertion reactions around the nickel(II) center.[1] The reaction starts from a square-planar nickel–isocyanide complex. A nucleophile (in our case an amine) will enter by coordination to the nickel center[24] and react with a coordinated isocyanide (see Figure 1). In the resulting complex, the plane of the ligand C(X)=NR (Figure 1A) is approximately perpendicular to the plane of the isocyanide carbons and nickel, with R either in the *E* or in the *Z* configuration. Free rotation around the bond from C^1 to Ni is not possible for steric reasons. Since carbon atom C^1 now has a carbenic character it can attack a neighboring isocyanide.[25] Such an attack is facilitated when a new isocyanide C^5=NR is substituted for C^1(X)=NR. In the case of an achiral isocyanide and an achiral initiator, the possibilities of attack by C^1 on C^2 or C^4 are equal. In the case of a chiral isocyanide or a chiral initiator, one of these attacks will predominate. In Figure 1 it has occurred on C^2. When the sequence of insertions continues in the direction $C^1 \rightarrow C^2 \rightarrow C^3 \rightarrow C^4$, a left-handed helix is formed. A right-handed helix will be formed when the reaction sequence is $C^1 \rightarrow C^4 \rightarrow C^3 \rightarrow C^2$.

From the results of Tables I–III it follows that isocyanides can be polymerized enantioselectively by the use of an optically active initiator. The highest optical activity is obtained with (*S*)-(−)-1-phenylethylamine. We believe that this is due to an interaction of the phenyl ring of the amine with the nickel center (see Figure 3), causing the substituents at the chiral carbon atom to become fixed. ^{13}C NMR spectra show that conformations in which the $CH(CH_3)C_6H_5$ moiety is in the trans position with respect to the nickel center are also possible.[26] The same holds for the conformation where the $CH(CH_3)C_6H_5$ moiety as well as the isocyanide substituent are oriented cis with respect to the nickel center.[26] The occurrence of more conformations is also observed for related palladium(II)- and platinum(II)–carbene complexes.[27] These additional conformations could explain why the enantiomeric excess is not higher than 61%.

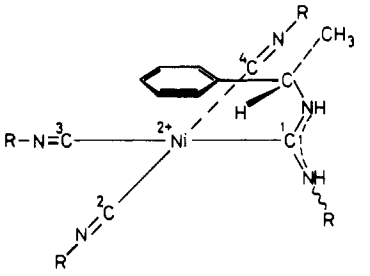

Figure 3. Starting complex for the polymerization of isocyanides with (*S*)-(−)-1-phenylethylamine as the initiator.

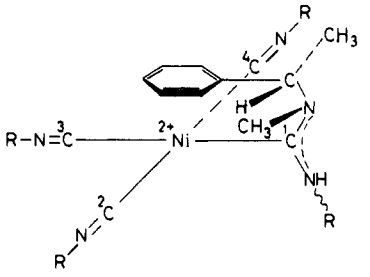

Figure 4. Starting complex for the polymerization of isocyanides with (*S*)-(−)-(1-phenylethyl)methylamine as the initiator.

When the phenyl group is replaced by an ethyl group as in (*S*)-*sec*-butylamine, the enantiomeric excess is reduced from 61 to 7%. When (*S*)-(−)-1-cyclohexylethylamine is used as the initiator, the ee decreases from 61 to 50%. If only the steric factor is important, an increase in the ee would be expected, as the cyclohexyl group is more bulky than the phenyl group.[28] The data above support the presence of an interaction between the phenyl ring and the nickel center. Figure 3 shows the complex resulting from the reaction of (*S*)-(−)-1-phenylethylamine with $Ni(C{\equiv}NR)_4(ClO_4)_2$. The methyl group points in the direction of C^4 and the hydrogen atom in the direction of C^2. The nucleophilic attack by C^1 will preferentially take place on C^2 as this is the sterically least hindered side. The fifth isocyanide will coordinate below the plane of the Ni and isocyanide carbons, since the upper side is shielded by the phenyl ring. The polymer chain will grow upwards and a right-handed helix will be formed, which was confirmed experimentally. When (*S*)-(−)-(1-phenylethyl)-methylamine is used as the initiator, no chiral induction is observed. For steric reasons the *N*-methyl group will be orientated *E* with respect to the methyl group of the chiral center (see Figure 4). In this situation there is almost no difference in steric hindrance between attack on C^2 and C^4, and a racemic mixture of *P* and *M* screws will be obtained. The tertiary amine (*S*)-(−)-(1-phenylethyl)dimethylamine as the initiator gives very low yields of polymer and no chiral induction. This could be due either to

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(28) As a relative measure of steric hinder, the λ steric parameter can be used. See also: Kagan, H. B. *Stereochemistry*; Thieme (Stuttgart): Stuttgart, FRG, 1977; Vol. 3, p 26. (R, λ): H, 0.00; CH_3, 1.00; $CH(CH_3)_2$, 1.27; C_6H_5, 1.23; c-C_6H_{11}, 1.33; H_5C_2OCO, 0.90.

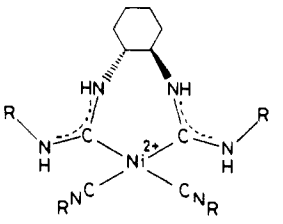

Figure 5. Starting complex for the polymerization of isocyanides with (*R,R*)-1,2-diaminocyclohexane as the initiator.

a low reactivity resulting from steric hindrance or to the fact that no proton transfer is possible from the amine function to the isocyanide nitrogen. The enantiomeric excess obtained with (*S*)-(−)-1-(1-naphthyl)ethylamine was lower than with (*S*)-(−)-1-phenylethylamine, probably because the bulky 1-naphthyl group does not coordinate well to the nickel center.

Table I shows that, when (*R,R*)-1,2-*trans*-diaminocyclohexane is used as initiator, the chiral induction is very low. We tentatively explain this from the fact that each of the amino groups can react simultaneously with a coordinated isocyanide (see Figure 5).

The experiments using amino acid esters as initiators gave remarkable results. We expected that an increase in bulkiness of the alkyl group of the amino acid would result in a higher chiral induction. However, a decrease in optical activity of the polymer was found when the bulkiness of the initiators increased, as is shown by the optical activity of poly(*tert*-butyl isocyanide) obtained with alanine, valine, and isoleucine methyl esters as the initiators (see Table I). This could indicate that coordination of the ester function to the nickel center becomes more difficult on increasing bulkiness of the alkyl group (see Figure 6). Consequently, the groups H and R^1 at the chiral carbon atom are less inclined to take on fixed orientations, and therefore, the chiral induction of the polymerization reaction will become lower.

Phenylalanine ethyl ester has two functions that can interact with the nickel viz., the ester group and the phenyl ring. When the phenyl ring is replaced by the ester function as interacting group, an opposite screw sense will be obtained. This antagonism between the two coordinating groups results in an absence of chiral induction. In the case of phenylalaninol, however, a relatively high optical activity of the polymer is found. Here, the ester group is reduced to an alcohol and only the phenyl ring will coordinate to the nickel. The fact that the initiator contains two nucleophiles (OH and NH_2) is of little consequence as the amino group is far more reactive in the addition to an isocyanide than the alcohol function. Cysteine methyl ester has a second nucleophile consisting of an SH group, which is appreciably more nucleophilic than an OH group. This means that both the NH_2 and the SH function can act as initiator, resulting in a low optical activity of the polymer (Table I).

The low reactivity of alcohols toward coordinated isocyanides is also the reason that no optically active polymer can be obtained with a chiral alcohol as the initiator. In fact, the polymer yields are extremely low (<5%).

Apart from the initiator, the isocyanide ligand in the catalytic complex also has an influence on the stereoselectivity of the polymerization (Table II). The high enantiomeric excess obtained with the ligand 2-*tert*-butylphenyl isocyanide in the catalytic complex is probably due to the extreme bulkiness of this isocyanide. As a result, the group R of this isocyanide will be forced into the *E* position with respect to the nickel center. The group R* of the nucleophile will then point in the direction of the nickel center, which enhances its coordination. A poor enantioselectivity is obtained when 2,6-diisopropylphenyl isocyanide is used as ligand in the catalytic complex. This isocyanide is too sterically hindered for the nucleophile to react. IR experiments show that the amine coordinates weakly to the nickel center but cannot react with the coordinated isocyanide.

The method described here for stereoselective polymerization of *tert-butyl isocyanide* is also applicable to other isocyanides, provided that these isocyanides are bulky and polymerize slowly (Table III). Optically active polymers have been obtained from *tert*-butyl, *tert*-pentyl, α,α-dimethylbenzyl, 2,6-dichlorophenyl, and 4-(dimethylamino)phenyl isocyanide. No enantioselective polymerization could be achieved with primary and secondary aliphatic isocyanides and nonsterically hindered aromatic isocyanides. These isocyanides are very reactive and are therefore not sensitive to a slight difference in activation energy between the formation of the two screw senses. It is also possible that less sterically hindered isocyanides give rise to racemization of the polymer chain during the first propagation steps.

No optically active polymers can be obtained with chiral additives or a chiral solvent. The chiral additives cannot come close to the reaction center, because the isocyanides encapsulate this center. The same occurs when nickel complexes with optically active ligands are used. These ligands are rapidly replaced by the isocyanide that is to be polymerized, because the latter is present in great excess.

Conclusion

The method described here is a convenient way to prepare optically active homopolymers from achiral isocyanides. A high enantioselectivity can be obtained (83%). Because the substituent R in the isocyanide can be varied, this method can lead to a variety of useful optically active polymers.

Experimental Section

Analytical Techniques. Infrared (IR) spectra were recorded on Perkin-Elmer 297 and 283 spectrophotometers. Ultraviolet (UV) spectra were obtained on a Perkin-Elmer 200 spectrophotometer. Circular dichroism (CD) spectra were recorded on a Jobin Yvon Dichrographe III apparatus. Optical rotations were measured on a Perkin-Elmer 241 polarimeter. ^{1}H NMR spectra were obtained on a Varian EM390 instrument. Chemical shifts (δ) are reported downfield from internal tetramethylsilane. Abbreviations used are s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), and br (broad). Melting points were determined on a Mettler FP5/FP51 photoelectric melting point apparatus. Solution viscosity data were obtained with a Cannon-Ubbelohde viscometer. Viscosity average molecule weights ($\bar{M}_v$) were calculated by the Mark–Houwink equation $[\eta] = 1.4 \times 10^{-9} \bar{M}_v^{1.75}$.[11b] Number average molecular weights ($\bar{M}_n$) were estimated by end-group determination using ^{1}H NMR. The end groups of the polymers are fragments of the chiral initiators R*NH_2 or R*OH, i.e., H(C=NR)$_n$NHR* or H(C=NR)OR*. Values for $\bar{M}_n$ were calculated from the peak ratios of R and R* in the ^{1}H NMR spectrum. Estimated error ±15%.

Monomers. Amine **1f** was synthesized from the corresponding alcohol by treatment with PBr_3 and subsequent reaction with liquid ammonia.[29]

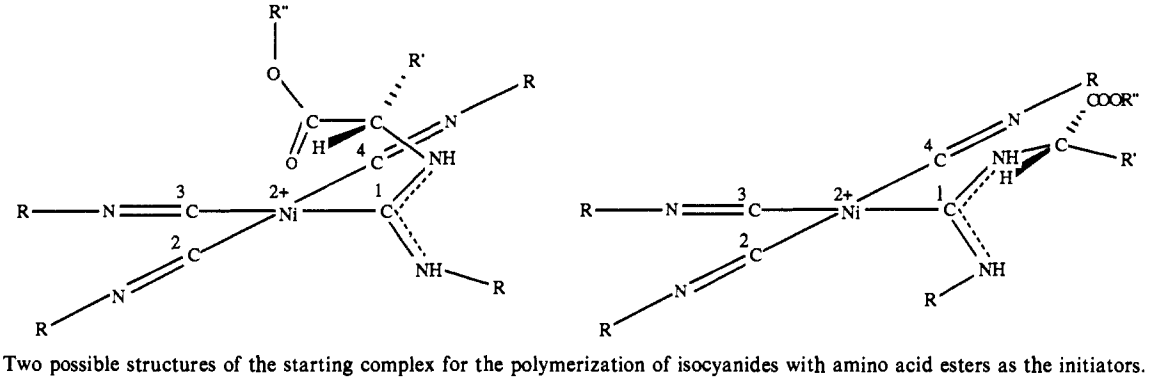

Figure 6. Two possible structures of the starting complex for the polymerization of isocyanides with amino acid esters as the initiators.

2-*tert*-Butylaniline was prepared by nitration of *tert*-butylbenzene.[30] The ortho product was separated from the para product by repeated distillation. The nitro group was reduced with Raney nickel and hydrogen, giving 2-*tert*-butylaniline.[31] Aniline **1o** was obtained by nitration of 1,3,5-trihydroxybenzene,[32] subsequent methylation of the hydroxy groups, and reduction of the nitro group.[31] Optically active *sec*-butylamine was obtained from the racemic amine through fractional crystallization of its bitartrate from water, according to the literature.[33] Optically active 1-phenylethylamine was prepared according to a literature procedure.[34] Amino acids were esterified with dry HCl gas in methanol or ethanol.[35] The amino alcohols were obtained from the amino acid esters by reduction with $LiAlH_4$.[36] (*S*)-(−)-(1-Phenylethyl)methylamine was prepared by N-formylating (*S*)-(−)-1-phenylethylamine[16] and subsequent reduction with $LiAlH_4$.[37] (*S*)-(−)-(1-Phenylethyl)dimethylamine was synthesized from *S*-(−)-1-phenylethylamine with formaldehyde and formic acid.[38] (*S*)-(−)-1-Cyclohexylethylamine was obtained by reduction of (*S*)-(−)-1-phenylethylamine with PtO_2 and hydrogen.[39] The other chiral initiators were commercial products.

***N*-Formyl-1-butylamine (2a).** Butylamine was N-formylated with a 10% excess of ethyl formate[16] in an almost quantitative yield: bp 121–122 °C (17 mmHg); IR (neat) 1660 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.05 (s, 1 H, CHO), 6.7 (br, 1 H, NH), 3.23 (m, 2 H, CH_2), 1.46 (m, 4 H, CH_2CH_2), 0.93 (m, 3 H, CH_3).

1-Butyl Isocyanide (3a). Formamide **2a** was converted into the isocyanide by the method of Casanova[18] but at a lower pressure (0.5 mmHg) than recommended: yield 82%; IR (CH_2Cl_2) 2153 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.37 (3 t, 2 H, CH_2), 1.60 (m, 4 H, CH_2CH_2), 0.97 (t, 3 H, CH_3).

***N*-Formyl-3-pentylamine (2b).** 3-Pentylamine was N-formylated with a 10% excess of ethyl formate[16] in an almost quantitative yield: bp 121–123 °C (20 mmHg); IR (neat) 1670 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.3 + 8.2 + 8.0 (3 s, 1 H, CHO), 6.2 (br, 1 H, NH), 3.9 + 3.2 (2 m, 1 H, CH), 4.57 (m, 4 H, CH_2), 0.97 (t, 6 H, CH_3).

3-Pentyl Isocyanide (3b). Formamide **2b** was converted into the isocyanide by the method of Casanova[18] but at a lower pressure (0.5 mmHg) than recommended: yield 87%; IR (CCl_4) 2136 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.33 (m, 1 H, CH), 1.53 (m, 4 H, CH_2), 1.03 (t, 6 H, CH_3).

***N*-Formyl-*tert*-butylamine (2c).** This compound was prepared as described for **2a** in an almost quantitative yield: bp 94–95 °C (21 mmHg); IR (neat) 1660 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.0 (m, 1 H, CHO), 6.8 and 5.9 (2 br, 1 H, NH), 1.28 (3 s, 9 H, CH_3).

***tert*-Butyl Isocyanide (3c).** This isocyanide was prepared from **2c** as described for **3a** in 80% yield: IR (CH_2Cl_2) 2140 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.43 (3 s, 9 H, CH_3).

***N*-Formyl-*tert*-pentylamine (2d).** This compound was synthesized as described for **2a** in 67% yield: bp 112–114 °C (22 mmHg); IR (neat) 1675 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.3–7.8 (m, 1 H, CHO), 7.3–5.3 (br, 1 H, NH), 1.60 (2 q, 2 H, CH_2), 1.30 (2 s, 6 H, CH_3), 0.90 (2 t, 3 H, CH_3).

***tert*-Pentyl Isocyanide (3d).** This isocyanide was prepared from **2d** as described for **3a** in 88% yield: IR (CCl_4) 2131 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.63 (3 q, 2 H, CH_2), 1.37 (3 s, 6 H, CH_3) 1.03 (t, 3 H, CH_3).

***N*-Formyl-2,6-dichloroaniline (2e).** In 200 mL of dry CH_2Cl_2 was dissolved 53.6 g of 2,6-dichloroaniline (0.33 mol) and the resultant mixture was cooled on an ice bath. A mixture of 40 mL of formic acid (1.06 mol) and 40 mL of acetic anhydride (0.42 mol) was stirred for 1 h and then added to the reaction mixture at such a rate that the temperature was kept between 5 and 10 °C. Subsequently, the reaction mixture was stirred for 20 h at room temperature. The solvents were evaporated in vacuum, and the product was treated 3 times with 50 mL of toluene, which was removed under vacuum. The product was recrystallized from toluene: yield 53.4 g of white crystals (85%); mp 179.1 °C; IR (KBr) 1675 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.4 (m, 1 H, CHO), 7.3 (m, 4 H, C_6H_3 + NH).

2,6-Dichlorophenyl Isocyanide (3e). This isocyanide was synthesized from **2e** according to a modification of the method of Skorna and Ugi.[19] The procedure was as follows. Into a round-bottomed flask equipped with a magnetic stirrer and a CO_2/acetone reflux condenser kept at −30 °C, were brought 30 g of **2f** (0.16 mol), 40 mL of dry *N*-methylmorpholine (0.36 mol) and, as a solvent, 200 mL of dry CH_2Cl_2. At a temperature of −30 °C, 6.9 mL of diphosgene (80 mmol) in 65 mL of dry CH_2Cl_2 was introduced into the stirred reaction mixture over a period of 1 h. The reaction mixture was then stirred for another hour. The cooling bath was removed, and immediately 150 mL of water was added to the reaction mixture. The still cold organic layer was separated and washed 3 times with 150 mL of an aqueous 5% $NaHCO_3$ solution and once with 150 mL of water. The CH_2Cl_2 layer was dried over Na_2SO_4. The crude reaction product was purified by column chromatography (silica gel, CH_2Cl_2): yield 17.6 g (65%); IR (CH_2Cl_2) 2120 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.33 (m, 3 H, C_6H_3).

2-Phenyl-2-bromopropane. A solution of 33 g of PBr_3 (0.12 mol) in 55 mL of chloroform was added dropwise at 40 °C to a stirred solution of 50 g of α,α-dimethylbenzyl alcohol (0.36 mol) in 700 mL of chloroform. The reaction mixture was stirred for 2 h at 40 °C. The chloroform layer was separated from the viscous inorganic layer and poured into 500 mL of ice water. The organic layer was separated, washed twice with a saturated aqueous Na_2CO_3 solution and once with water, and dried over $MgSO_4$. The chloroform was removed under reduced pressure. After distillation a colorless liquid was obtained; boiling region 57–80 °C (0.05 mmHg). The product contained 31% of the elimination product α-methylstyrene. The product was used without further purification for the synthesis of **1f**. The yield of 2-phenyl-2-bromopropane was 57%: ^1H NMR ($CDCl_3$) δ 7.2 (m, 5 H, C_6H_5), 2.15 (s, 6 H, CH_3).

α,α-Dimethylbenzylamine (1f). This amine was obtained by treatment of 2-phenyl-2-bromopropane with liquid ammonia.[29] After evaporation of the ammonia, the product was dissolved in 1 M aqueous HCl and the α-methylstyrene was extracted with diethyl ether. The water layer was brought to pH 14, and the free amine was extracted with ether. The ether layer was dried over $MgSO_4$ and the ether removed under reduced pressure. The yield was 53%: IR (neat) 3350 and 3275 (NH_2) cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.4 (s, 6 H, CH_3), 1.6 (s, 2 H, NH_2), 7.2 (m, 5 H, C_6H_5).

***N*-Formyl-α,α-dimethylbenzylamine (2f).** Amine **1f** was N-formylated according to a literature procedure in an almost quantitative yield:[16] ^1H NMR ($CDCl_3$) δ 7.8 (m, 2 H, CHO, NH), 7.2 (s, 5 H, C_6H_5), 1.7 (s, 6 H, CH_3).

α,α-Dimethylbenzyl Isocyanide (3f). This isocyanide was prepared as described for **3e**: yield 96%; IR (neat) 2135 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.2 (m, 5 H, C_6H_5), 1.7 (3 s, 6 H, CH_3).

***N*-Formyl-2,6-diisopropylaniline (2g).** In 200 mL of dry CH_2Cl_2 was dissolved 60 g of 2,6-diisopropylaniline (0.34 mol). A mixture of 40 mL of formic acid (1.06 mol) and 40 mL of acetic anhydride (0.42 mol) was stirred for 1 h and then added to the reaction mixture at such a rate that the temperature was kept between 5 and 10 °C. Subsequently, the reaction mixture was stirred for 16 h at room temperature and refluxed for 4 h. The solvent was evaporated under vacuum, and the residue was dissolved in $CHCl_3$ and washed 3 times with a saturated aqueous $NaHCO_3$ solution and with water. The organic layer was dried on Na_2SO_4, and the $CHCl_3$ was evaporated in vacuum. The product was recrystallized from diethyl ether: yield 47 g (66%); mp 160.0 °C; IR (KBr) 1660 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.2–7.6 (m, 1 H, CHO), 8.3–6.8 (br, 1 H, NH), 7.05 (s, 3 H, C_6H_3), 3.08 (m, 2 H, CH), 1.17 (d, 12 H, CH_3).

2,6-Diisopropylphenyl Isocyanide (3g). This isocyanide was synthesized according to the procedure described for **3e**: yield 72%; IR 2120 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.06 (m, 3 H, C_6H_3), 3.32 (m, 2 H, CH), 1.28 (d, 12 H, CH_3).

2-*tert*-Butylnitrobenzene. *tert*-Butylbenzene was nitrated and purified according to a literature procedure:[30] yield 70%; bp 125–128 °C (20 mmHg); IR (neat) 1540, 1380 (NO_2) cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.4 (m, 4 H, C_6H_4), 1.50 (s, 9 H, CH_3).

2-*tert*-Butylaniline (1h). This aniline was obtained by hydrogenation of 2-*tert*-butylnitrobenzene with Raney nickel:[31] yield 76%, bp 111–113 °C (20 mmHg); IR (neat) 3400 + 3380 (NH_2) cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.8 (m, 4 H, C_6H_4), 3.7 (br, 2 H, NH_2), 1.4 (s, 9 H, CH_3).

***N*-Formyl-2-*tert*-butylaniline (2h).** Aniline **1h** was N-formylated according to a literature procedure:[16] yield 49%; mp 73.8 °C; IR (KBr) 1680 (C=O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.4 (2 s, 1 H, CHO), 7.2 (m, 5 H, NH, C_6H_4), 1.4 (s, 9 H, CH_3).

2-*tert*-Butylphenyl Isocyanide (3h). This isocyanide was prepared from **2h** as described for **2e**: yield 83%; bp 59–61 °C (0.04 mmHg); IR (neat) 2110 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.3 (m, 4 H, C_6H_4), 1.5 (s, 9 H, $C(CH_3)_3$).

***N*-Formylbenzylamine (2).** Benzylamine was N-formylated as described for **2g** in 78% yield: mp 59.6 °C; IR (KBr) 1645 (C=O) cm^{-1};

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^{1}H NMR ($CDCl_3$) δ 8.16 (s, 1 H, CHO), 7.30 (s, 5 H, C_6H_5), 4.42 (d, 2 H, CH_2).

Benzyl Isocyanide (3i). This isocyanide was prepared from **2i** as described for **3e**: yield 83%; colorless liquid; IR (CH_2Cl_2) 2154 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.31 (s, 5 H, C_6H_5), 4.56 (3 s, 2 H, CH_2).

***N*-Formylaniline (2j).** Aniline was formylated according to a literature procedure:[17] yield 95%; mp 50.0 °C; IR (KBr) 1680 (C=O) cm^{-1}.

Phenyl Isocyanide (3j). Formamide **2j** was converted into the isocyanide as described for **3e**. The product was purified by distillation: yield 74%; bp 61–62 °C (21 mmHg); IR (CH_2Cl_2) 2130 (C≡N) cm^{-1}.

***N*-Formyl-4-anisidine (2k).** This formamide was prepared from 4-anisidine according to a literature procedure:[17] yield 85%; mp 80.2 °C; IR (KBr) 1670 (C=O) cm^{-1}.

4-Methoxyphenyl Isocyanide (3k). This isocyanide was prepared from **2k** as described for **3e**: yield 70%; IR (CH_2Cl_2) 3128 (C≡N) cm^{-1}.

***N*-Formyl-4-methoxy-2-methylaniline (2l).** 4-Methoxy-2-methylaniline was formylated as described for **2g**. The product was recrystallized from toluene/hexane: yield 88%; mp 102.4 °C; IR (KBr) 1690 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.3 (s, 1 H, CHO), 7.5 (br, 1 H, NH), 7.7–6.6 (m, 3 H, C_6H_3), 3.78 (2 s, 3 H, CH_3), 2.23 (2 s, 3 H, CH_3).

4-Methoxy-2-methylphenyl Isocyanide (3l). This isocyanide was prepared from **2l** as described for **3e**: yield 74%; bp 80–83 °C (2×10^{-4} mmHg); IR (CH_2Cl_2) 2120 (C≡N) cm^{-1}; ^{1}H NMR (CCl_4) δ 7.5–6.3 (m, 3 H, C_6H_3), 3.75 (s, 3 H, OCH_3), 2.23 (s, 3 H, CH_3).

***N*-Formyl-4-(dimethylamino)aniline (2m).** *N*,*N*-Dimethyl-4-phenylenediamine was N-formylated according to a literature procedure:[17] yield 76%; mp 108.5 °C; IR (KBr) 1675 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.4–7.9 (m, 1 H, CHO), 8.0 (br, 1 H, NH), 7.3–6.3 (m, 4 H, C_6H_4), 2.70 (s, 6 H, CH).

4-(Dimethylamino)phenyl Isocyanide (3m). This isocyanide was prepared from **2m** as described for **3e**: yield 79%; IR (CH_2Cl_2) 2118 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.17 and 6.55 (2 d, 4 H, C_6H_4), 2.95 (s, 6 H, CH_3).

***N*-Formyl-2-aminobiphenyl (2n).** 2-Aminobiphenyl was N-formylated according to a literature procedure:[17] yield 96%; IR (KBr) 1675 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.8–8.2 (m, 1 H, CHO), 8.2 (br, 1 H, NH), 7.40 (s, 5 H, C_6H_5), 7.26 (2 s, 4 H, C_6H_4).

2-Isocyanobiphenyl (3n). This isocyanide was prepared from **2n** as described for **3e**: yield 75%; IR (CH_2Cl_2) 2120 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.07 (s, 5 H, C_6H_5), 7.00 (s, 4 H, C_6H_4).

2,4,6-Trihydroxynitrobenzene. 1,3,5-Trihydroxybenzene was nitrated according to a literature procedure:[32] yield 62%; mp 190 °C; IR (KBr) 3350 (OH), 1640, 1440 (NO_2) cm^{-1}; ^{1}H NMR (DMSO-d_6) δ 10.2 and 8.8 (2 br, 3 H, OH), 5.83 and 5.60 (2 s, 2 H, C_6H_2).

2,4,6-Trimethoxynitrobenzene. This compound was prepared from 2,4,6-trihydroxynitrobenzene and dimethyl sulfate according to a literature procedure:[31] yield 68%; mp 143.1 °C; IR (KBr) 1230 (OCH_3) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.01 (s, 2 H, C_6H_2), 3.86 (s, 9 H, OCH_3).

2,4,6-Trimethoxyaniline (1o). The nitro group of 2,4,6-trimethoxynitrobenzene was hydrogenated with Raney nickel according to a literature procedure:[31] yield 75%; bp 138–139 °C (0.6 mmHg); IR (neat) 3440 and 3320 (NH_2), 2830 (OCH_3), 1200 (OCH_3) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.05 (s, 2 H, C_6H_2), 3.73 (s, 6 H, OCH_3), 3.67 (s, 3 H, OCH_3), 3.4 (br, 2 H, NH_2).

***N*-Formyl-2,4,6-trimethoxyaniline (2o).** This compound was prepared from **1o** as described for **2e** in a 98% yield: mp 145.1 °C; IR (KBr) 1660 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.5–8.1 (m, 1 H, CHO), 6.8 (br, 1 H, NH), 6.03 (s, 2 H, C_6H_2), 3.73 (s, 9 H, OCH_3).

2,4,6-Trimethoxyphenyl Isocyanide (3o). This isocyanide was prepared from **2o** as described for **3e** in a 41% yield: IR (CH_2Cl_2) 2120 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 5.92 (s, 2 H, C_6H_2), 3.76 (s, 6 H, OCH_3), 3.70 (s, 3 H, OCH_3).

***N*-Formyl-2,6-difluoroaniline (2p).** This formamide was synthesized from 2,6-difluoroaniline according to a literature procedure[17] in a quantative yield: mp 123.4 °C; IR (KBr) 1665 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.3 (m, 1 H, CHO), 7.3 (br, 1 H, NH), 6.9 (m, 3 H, C_6H_3).

2,6-Difluorophenyl Isocyanide (3p). This isocyanide was prepared from **2p** as described for **3e** in a 15% yield. The low yield was caused by polymerization of the isocyanide during the purification procedure on the silica gel column: IR (CH_2Cl_2) 2115 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.9 (m, 3 H, C_6H_3).

Catalysts. Tetrakis(*tert*-butyl isocyanide)nickel(II) Perchlorate. This complex was prepared by adding 4 equiv of *tert*-butyl isocyanide to a stirred 0.20 M solution of $Ni(ClO_4)_2 \cdot 6H_2O$ in 96% ethanol/ether 1:1 (v/v) at 0 °C as described previously.[20] The complex separated from the solution and was collected by filtration and washed with cold ethanol/ether and cold ether. The complex was dried at 40 °C at 0.02 mmHg: yield 92%; IR (CH_2Cl_2) 2245 (C≡N) cm^{-1}; ^{1}H NMR (CD_3CN) δ 1.61 (s, CH_3).

Tetrakis(*tert*-pentyl isocyanide)nickel(II) Perchlorate. This complex was prepared as described for $Ni(C{\equiv}N\text{-}t\text{-}C_4H_9)_4(ClO_4)_2$, using 96% ethanol/ether 1:3 (v/v) as solvent. The yield was 80%: IR (CH_2Cl_2) 2223 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.89 (q, 2 H, CH_2), 1.63 (s, 6 H, CH_3), 1.15 (t, 3 H, CH_3). Anal. Calcd for $C_{24}H_{44}Cl_2N_4NiO_8$ (646.25): C, 44.61; H, 6.86; Cl, 10.97; N, 8.67; Ni, 9.08; O, 19.81. Found: C, 44.51; H, 6.83; Cl, 10.88; N, 8.63; Ni, 9.22; O, 19.81.

Tetrakis(2-*tert*-butylphenyl isocyanide)nickel(II) Perchlorate. This complex was prepared as described for $Ni(C{\equiv}N\text{-}t\text{-}C_4H_9)_4(ClO_4)_2$: yield 85%; IR ($CH_2Cl_2$) 2220 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.5 (m, 4 H, C_6H_4), 1.50 (s, 9 H, CH_3).

Tetrakis(2,6-diisopropylphenyl Isocyanide)nickel(II) Perchlorate. This complex was prepared as described for $Ni(C{\equiv}N\text{-}t\text{-}C_4H_9)_4(ClO_4)_2$: yield 76%; IR ($CH_2Cl_2$) 2222 (C≡N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.1 (m, 3 H, C_6H_3), 3.5 (m, 2 H, CH), 1.25 (d, 12 H, CH_3). Anal. Calcd for $C_{52}H_{68}Cl_2N_4NiO_8$ (1006.81): C, 62.03; H, 6.81; Cl, 7.04; N, 5.57; Ni, 5.83; O, 12.71. Found: C, 61.88; H, 6.67; Cl, 7.12; N, 5.50; Ni, 5.90; O, 12.70.

The optically active nickel catalysts were prepared in situ by adding optically active amine (0.7 mmol) to $Ni(CNR)_4(ClO_4)_2$ (0.7 mmol) dissolved in CH_2Cl_2 (10 mL). After the resultant mixture was stirred for 15 min, the CH_2Cl_2 was removed under vacuum and the catalyst was dried at 20 °C and 0.01 mmHg. The catalysts were directly used for the polymerization reactions without further purification; yield 100%. Two optically active catalysts were fully characterized:[26] **Tris(*tert*-butyl isocyanide)[(*S*)-(−)-(1-Phenylethyl)amino(*tert*-butylamino)carbene]nickel(II) Perchlorate.** From $Ni(CN\text{-}t\text{-}C_4H_9)_4(ClO_4)_2$ and (*S*)-(−)-1-phenylethylamine: $[\alpha]^{20}D$ 13.7° (*c* 0.22, $CHCl_3$); IR (CH_2Cl_2) 3280 (NH), 2250 (sh) and 2226 (C≡N), 1570 (NCN) cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 22.77, 23.40, and 24.90 (3 s, $CHCH_3$), 28.55–30.78 (m, $C(CH_3)_3$, 53.02–61.66 (m, $C(CH_3)_3$ + *C*H), 120.23–123.71 (m, C≡N), 125.97–129.15 (m, C arom), 141.55, 142.32, and 143.03 (3 s, substituted C arom), 175.18, 179.20, and 181.37 (3 s, C carbene); ^{1}H NMR ($CDCl_3$) δ 8.57 + 6.89 (2 d, 1 H, CHN*H*), 8.04 + 7.75 + 6.46 (3 s, 1 H, NH), 7.7–7.0 (m, 5 H, C_6H_5), 5.92 + 5.66 + 5.01 (3 m, 1 H, CH), 1.70 (d, 3 H, CH), 1.6–0.8 (m, 36 H, CH_3); FAB mass spectroscopy, *m*/*e* 610 $(M - ClO_4^-)^+$, 527 $(M - ClO_4^- - t\text{-}C_4H_9N{=}C)^+$, 454 $(M - ClO_4^- - HClO_4 - C_4H_8)^+$; 444 $(M - ClO_4^- - 2t\text{-}C_4H_9N{=}C)^+$, 427 $(M - ClO_4^- - HClO_4 - t\text{-}C_4H_9N{=}C^+$, 361 $(M - ClO_4^- - 3t\text{-}C_4H_9N{=}C)^+$; 345 $(M - 2ClO_4^- - 2t\text{-}C_4H_9N{=}C)^+$; 288 $(M - ClO_4^- - HClO_4 - 2t\text{-}C_4H_9N{=}C - C_4H_8)^+$; 262 $(M - 2ClO_4^- - 3t\text{-}C_4H_9N{=}C)^+$. Anal. Calcd for $C_{28}H_{47}Cl_2N_5NiO_8$ (711.31): C, 47.28; H, 6.67; Cl, 9.97; N, 9.85; Ni, 8.25; O, 18.00. Found: C, 47.00; H, 6.73; Cl, 9.97; N, 9.73; Ni, 8.27; O, 18.36. **Tris(*tert*-pentyl isocyanide)[(*S*)-(−)-(1-Phenylethyl)amino(*tert*-pentylamino)carbene]nickel(II) Perchlorate.** From $Ni(CN\text{-}t\text{-}C_5H_{11})_4(ClO_4)_2$ and (*S*)-(−)-1-phenylethylamine: $[\alpha]^{20}_D$ 9.3° (*c* 0.45, $CHCl_3$); IR (CH_2Cl_2) 3280 (NH), 3059 (CH arom), 2974, 2939, and 2880 (CH aliph), 2220, 2240 (sh), and 2190 (sh) (C≡N), 1570, 1585 (sh), and 1537 (NCN), 1090 and 620 (ClO_4^-) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 8.78 and 6.67 (2 d, 2 H, CHNH), 8.02 and 6.33 (2 s, 2 H, NH), 7.62–7.28 (m, 5 H, C_6H_5), 5.83 and 4.99 (2 m, 1 H, CH), 1.92–0.47 (m, remaining H); ^{13}C NMR ($CDCl_3$) δ 179.2 and 175.4 (2 s, C carbene), 142.5 and 141.6 (2 s, C^1 arom), 129.3–126.1 (m, C arom), 123.4 (br, C≡N), 64.2 (br, *C*-N=C), 61.1 and 54.1 (2 s, CH), 59.7 and 58.3 (2 s, CNH), 35.5 and 33.3 (2 s, CH_2CNH), 34.5 (s, $CH_2CN{=}C$), 28.2 and 26.5 (2 s, $(CH_3)_2CNH$), 27.1 (s, $(CH_3)_2CN{=}C$), 23.8 and 23.0 (2 s, CH_3CH), 8.2 (s, $CH_3CH_2CN{=}C$), 7.8 (s, CH_3CH_2CNH); FAB mass spectrum, *m*/*e* 666 $(M - ClO_4^-)^+$, 569 $(M - ClO_4^- - t\text{-}C_5H_{11}NC)^+$, 505 $(M - 2ClO_4^- - t\text{-}C_5H_{11}NC + Cl^-)^+$, 373 $(M - 2ClO_4^- - 2t\text{-}C_5H_{11}NC)^+$, 311 $(M - 2ClO_4^- - 3t\text{-}C_5H_{11}NC + Cl^-)^+$, 276 $(M - 2ClO_4^- - 3t\text{-}C_5H_{11}^-)^+$; Anal. Calcd for $C_{32}H_{55}Cl_2N_5NiO_8$ (767.43): C, 50.08; H, 7.22; Cl, 9.24; N, 9.13; Ni, 7.65; O, 16.67. Found: C, 50.06; H, 7.29; Cl, 9.25; N, 9.10; Ni, 7.63; O, 16.65; UV (CH_2Cl_2) λ 248 nm (ϵ 11 800), 281 (5370), 330 (310).

Polymerization. General Procedure. The appropriate isocyanide (10.0 mmol) and optically active nickel catalyst (0.1 mmol, see above) were stirred neat or in the presence of 1 mL of *n*-hexane (in the case of solid isocyanides) at ambient temperature. When IR indicated that all monomer had been converted into oligomer or polymer (1–5 days), the volatile components were removed under vacuum. The residue was dissolved in $CHCl_3$ (2 mL) and added dropwise to a mixture of methanol and water (3:1 v/v, 35 mL). By this procedure the remaining catalyst is decomposed into $Ni(ClO_4)_2 \cdot 6H_2O$ and dissolved into the methanol/water mixture. The resulting yellow precipitate was collected by filtration, washed with methanol/water and methanol, and dried in vacuum at 50 °C. Yields, optical rotation values, and molecular weights are given in Tables I–III. The remaining physical data are as follows:

Poly(*tert*-butyl isocyanide): pale yellow solid; IR (KBr) 1630, 1670 (sh) (C=N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.35 (CH_3).

Poly(*tert*-pentyl isocyanide): white solid; IR (KBr) 1641 (C=N) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 0.5–2.0 (br, CH_3, CH_2CH_3).

Poly(*n*-butyl isocyanide): yellow-brown solid; IR (KBr) 1639 (C=N) cm^{-1}; ^1H NMR (CCl_4) δ 0.95-1.45 (br, 7 H, $(CH_2)_2CH_3$), 3.35 (br, 2 H, NCH_2).

Poly(3-pentyl isocyanide): pale yellow solid; IR (KBr) 1623 (C=N) cm^{-1}.

Poly(benzyl isocyanide): brown solid; IR (KBr) 1630 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.0-5.0 (br, 2 H, CH_2), 6.5-7.5 (br, 5 H, ArH).

Poly(α,α-dimethylbenzyl isocyanide): pale yellow solid; IR (KBr) 1620 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.60 (br, 6 H, CH_3), 6.3 (br, 5 H, ArH).

Poly(phenyl isocyanide): yellow solid; IR (KBr) 1643 (C=N) cm^{-1}; ^1H NMR (CCl_4) δ 6.35 (br, ArH).

Poly(4-methoxyphenyl isocyanide): yellow solid; IR (KBr) 1630 (C=N) cm^{-1}; ^1H NMR (CCl_4) δ 3.25-3.70 (br, 3 H, CH), 6.30 (br, 4 H, ArH).

Poly(4-methoxy-2-methylphenyl isocyanide): yellow solid; IR (KBr) 1630 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) δ 0-2.0 (br, 3 H, CH_3), 2.5-4.0 (br, 3 H, OCH_3), 5.0-7.0 (br, 3 H, ArH).

Poly(2,6-difluorophenyl isocyanide): yellow solid; IR (KBr) 1650 (C=N) cm^{-1}.

Poly(2,6-dichlorophenyl isocyanide): yellow solid; IR (KBr) 1630 (C=N) cm^{-1}.

Poly(2-*tert*-butylphenyl isocyanide): yellow solid; IR (KBr) 1618 (C=N) cm^{-1}.

Poly(2-biphenyl isocyanide): yellow solid; IR (KBr) 1615 (C=N) cm^{-1}; ^1H NMR ($CDCl_3$) $\delta \approx 7$ (br, ArH).

Poly[4-(dimethylamino)phenyl isocyanide]: yellow-brown solid; IR (KBr) 1605 (C=N) cm^{-1}.

Polymerization in the Presence of Chiral Additives Other Than Chiral Amines. In a typical procedure, 4-methoxyphenyl isocyanide (220 mg, 1.65 mmol), anhydrous $NiCl_2$ (1.2 mg, 9.2×10^{-3} mmol), and (*S,S*)-chiraphos [2*S*,3*S*-(-)-bis(diphenylphosphino)butane; 44.4 mg, 0.10 mmol] were stirred in $CHCl_3$ (2 mL) for 12 h at ambient temperature. The mixture was concentrated, and added to excess methanol. The precipitate was isolated by filtration, washed with methanol, and dried under vacuum at 50 °C; yield 138.2 mg (63%) of poly(4-methoxyphenyl isocyanide). The polymer showed no optical rotation and had physical properties as described above.

Similar experiments were carried out under various conditions using l-borneol, cinchonine, (*R,R*)-DIOP, neomenthyldiphenylphosphine, and (2*S*,2′*S*)-2-(hydroxymethyl)-1-[(methylpyrrolidin-2-yl)methyl]-pyrrolidine as additives. Polymer yields amounted to 60-70%. None of the polymers showed optical rotation.

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Registry No. 1e, 608-31-1; **1f**, 585-32-0; **1g**, 24544-04-5; **1h**, 6310-21-0; **1l**, 102-50-1; **1o**, 14227-17-9; **2a**, 871-71-6; **2b**, 59734-20-2; **2c**, 2425-74-3; **2d**, 23602-10-0; **2e**, 10113-35-6; **2f**, 42044-69-9; **2g**, 84250-69-1; **2h**, 99858-67-0; **2i**, 6343-54-0; **2l**, 7402-54-2; **2m**, 18606-63-8; **2n**, 5346-21-4; **2o**, 115591-40-7; **2p**, 74702-43-5; **3a**, 2769-64-4; **3a** (homopolymer), 28391-59-5; **3b**, 115591-41-8; **3b** (homopolymer), 115591-43-0; **3c**, 7188-38-7; **3c** (homopolymer), 28513-62-4; **3d**, 13947-76-7; **3d** (homopolymer), 106926-90-3; **3e**, 6697-95-6; **3e** (homopolymer), 114487-72-8; **3f**, 1195-99-9; **3f** (homopolymer), 114487-73-9; **3h**, 104876-31-5; **3h** (homopolymer), 115591-46-3; **3i**, 10340-91-7; **3i** (homopolymer), 60406-17-9; **3j**, 931-54-4; **3j** (homopolymer), 28390-20-7; **3k**, 10349-38-9; **3k** (homopolymer), 28390-21-8; **3g**, 2008-61-9; **3l**, 1930-89-8; **3l** (homopolymer), 115591-44-1; **3m**, 7050-85-3; **3m** (homopolymer), 115591-48-5; **3n**, 3128-77-6; **3n** (homopolymer), 115591-47-4; **3o**, 115603-32-2; **3p**, 115591-42-9; **3p** (homopolymer), 115591-45-2; (*S*)-(+)-$C_2H_5CH(CH_3)NH_2$, 513-49-5; (*S*)-(-)-$C_6H_5CH(CH_3)NH_2$, 2627-86-3; (*R*)-(+)-$C_6H_5CH(CH_3)NH_2$, 3886-69-9; (*S*)-(-)-*c*-$C_6H_{11}CH(CH_3)NH_2$, 17430-98-7; (*S*)-(-)-1-naphthylethylamine, 10420-89-0; (L)-(-)-ephedrine, 299-42-3; (*R,R*)-1,2-diaminocyclohexane, 20439-47-8; (L)-isoleucine methyl ester, 2666-93-5; (L)-prolinol, 23356-96-9; (L)-phenylalaninol, 3182-95-4; (L)-valine methyl ester, 4070-48-8; (L)-alanine methyl ester, 10065-72-2; (L)-cysteine methyl ester, 2485-62-3; 2-phenyl-2-bromopropane, 3575-19-7; α,α-dimethylbenzyl alcohol, 617-94-7; tetrakis(*tert*-butyl isocyanide)nickel(II) perchlorate, 40667-87-6; tetrakis(*tert*-pentyl isocyanide)nickel(II) perchlorate, 106859-37-4; tetrakis(2-*tert*-butylphenyl isocyanide)nickel(II) perchlorate, 115603-69-5; tetrakis(2,6-diisopropylphenyl isocyanide)nickel(II) perchlorate, 115650-89-0; tris(*tert*-butyl isocyanide)[(*S*)-(-)-(1-phenylethyl)amino(*tert*-butylamino)carbene]nickel(II) perchlorate, 115603-71-9; tris(*tert*-pentyl isocyanide)[(*S*)-(-)-(1-phenylethyl)amino(*tert*-pentylamino)carbene]nickel(II) perchlorate, 115603-73-1.

"Hydrophobic" Binding of Water-Soluble Guests by High-Symmetry, Chiral Hosts. An Electron-Rich Receptor Site with a General Affinity for Quaternary Ammonium Compounds and Electron-Deficient π Systems

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Abstract: Several members of a new class of water-soluble macrocycles with well-defined, hydrophobic binding sites have been prepared and their binding properties analyzed. These hosts are built up from ethenoanthracene units and exist in meso (C_{2h}) and *d,l* (D_2) forms. The latter have been synthesized enantiomerically pure, the key step being a highly selective asymmetric Diels-Alder reaction. Several of these hosts display a strong and fairly general affinity for quaternary ammonium compounds. We ascribe this effect to an ion-dipole attraction between the positively charged guests and the electron-rich π systems of the hosts. In addition, neutral guests with electron-deficient π systems are preferentially bound, suggesting the operation of favorable host-guest, donor-acceptor π-stacking interactions. Preliminary studies with chiral guests reveal some enantiospecific binding, with preferences as large as 3:1 observed.

Host-guest chemistry continues to develop as a major subdiscipline of modern chemistry.[1] The pioneering studies on crown ethers and related structures laid the foundations for the field. They established that when appropriate amounts of preorganization[2] and complementarity between host and guest are designed

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(1) For a general introduction to the host-guest field, see: *Top. Curr. Chem.* **1981**, *98*; **1982**, *101*; **1983**, *113*; **1984**, *125*; **1986**, *132*.

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