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

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Abstract: Poly(isocyanides), (RN=NC)n, can be prepared from isocyanides, RN+=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 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).2,3 Ni(II) salts are versatile catalysts and, in our opinion, the most suited for our experiments. Poly(isocyanides) are unusual polymers in 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.3,5

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 stereospecifically.14a,c,15 This procedure was used by Yuki et al.14c-f to prepare stable helical polymers from bulky methacrylic acid esters and by Vogl14g,h 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

\[ n \text{RN}^+\equiv \text{C}^- \xrightarrow{\text{Ni(II)}} (\text{RN}≡\text{C})_n \]

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\[ \text{RN}^+\equiv \text{C}^- \xrightarrow{\text{Ni(II)}} (\text{RN}=\text{C})_n \]
Table II. Screw Sense Selective Polymerization of tert-Butyl Isocyanide by Ni(C≡N)R4(COCl)2 and (S)-(−)-1-Phenylethylamine

<table>
<thead>
<tr>
<th>R in Ni(C≡N)R4(COCl)2</th>
<th>[%]</th>
<th>screw sense</th>
<th>av mol wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-C4H9</td>
<td>32</td>
<td>−28.7</td>
<td>P</td>
</tr>
<tr>
<td>t-C6H11</td>
<td>30</td>
<td>−9.7</td>
<td>P</td>
</tr>
<tr>
<td>n-C4H9</td>
<td>75</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>CH2(CH3)2CH3</td>
<td>70</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>CH2CH2CH3</td>
<td>90</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>C6H5C(CH2)2CH3</td>
<td>10</td>
<td>−5.7</td>
<td>P</td>
</tr>
<tr>
<td>CH3</td>
<td>80</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>4-CH3OC4H4</td>
<td>75</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>4-CH3O-2-CH2CH3</td>
<td>90</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>2,6-F6C6H4</td>
<td>50</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>2-C6H5CH3</td>
<td>30</td>
<td>70</td>
<td>M</td>
</tr>
<tr>
<td>2,4-C6H5CH3</td>
<td>46</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>2-C6H4CH2NC8H8</td>
<td>65</td>
<td>0</td>
<td>P + M</td>
</tr>
<tr>
<td>2-C6H3NC8H8</td>
<td>88</td>
<td>f</td>
<td>P or M</td>
</tr>
</tbody>
</table>

(4) If the configurations around the single bonds are alternating R and S, a syndiotactic structure will result. If the configurations are randomly distributed, the term 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.


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==NR)4(ClO4)2, and the resulting complexes were used as catalyst in the polymerization of tert-butyl isocyanide (Table II). By using Ni(2-t-CH2=CH2N==ClO4)2 as catalyst, an enantiomeric excess of 83% was achieved. The complex Ni(2,6-((t-CH2)=CH2)2CH2N==ClO4)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 enantiomeric material, which 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 polypoly(isocyanides) can be derived from their CD spectra. Figure 2 shows the CD spectra of poly(tert-buty1 isocyanide), poly(tert-pentyl isocyanide), polya(a,a-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 → π* absorption region. The occurrence of irregularly stacked rings also follows from the 1H and 13C 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

Figure 1. Mechanism of polymerization of isocyanides.

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 and react with a coordinated isocyanide (Figure 1A). In the resulting complex, 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 to Ni is not possible for sterical reasons. Since carbon atom C now has a carbenic character it can attack a neighboring isocyanide. Such an attack is facilitated when a new isocyanide C═NR is substituted for C₁(X)=NR. In the case of a chiral isocyanide and an achiral initiator, the possibilities of attack by C₁ on C₂ or C₄ 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 C². When the sequence of insertions continues in the direction C₁→C²→C₃→C₄, a left-handed helix is formed. A right-handed helix will be formed when the reaction sequence is C₁→C₄→C₁→C².

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. ¹³C NMR spectra show that conformations in which the CH(CH₃)₂C₆H₄ moiety is in the trans position with respect to the nickel center are also possible. The same holds for the conformation where the CH(CH₃)₂C₆H₄ moiety as well as the isocyanide substituent are oriented cis with respect to the nickel center. The occurrence of more conformations is also observed for related palladium(II)- and platinum(II)-carbene complexes. These additional conformations could explain why the enantiomeric excess is not higher than 61%.

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-cyclohexylisocyanide 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. 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═NR)₃(CO₂)₃. The methyl group points in the direction of C₄ and the hydrogen atom in the direction of C². The nucleophile attack by C₁ will preferentially take place on C₄ 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-phenylethylmethylamine is used as the initiator, no chiral induction is observed. For steric reasons the N-methyl group will be oriented 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 C² and C₄, and a racemic mixture of P and M screws will be obtained. The tertiary amine (S)-(-)-1-phenylethylmethylamine as the initiator gives very low yields of polymer and no chiral induction. This could be due either to (26) Kamer, P. C. J.; Nolte, R. J. M.; Drenth, W. Recl. Trav. Chim. Pays-Bas 1988, 107, 175-181.

(28) As a relative measure of steric hinder, the A stereic parameter can be used. See also: Kagan, H. B. Stereochemistry; Thieme (Stuttgart): Stuttgart, FRG, 1977; Vol. 3, p 35. (R, X) : H, 0.00; CH₃, 1.00; CH(CH₃)₂, 1.27; C₆H₅, 1.23; -C₆H₅, 1.33; H₂C=O, 0.90.

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-phenylethylmethylamine 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 the 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 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 NH₂) 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 NH₂ 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 in 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. 1H 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 molecular weights (Mv) were calculated by the Mark–Houwink equation [η] = 1.4 × 10⁹ M^0.53. Number average molecular weights (Mn) were estimated by end-group determination using 1H NMR. The end groups of the polymers are fragments of the chiral initiators R*NH₂ or R*OH, i.e., H(C=NR)NHR* or H(C=NR)OH*. Values for Mv were calculated from the peak ratios of R and R* in the 1H NMR spectrum. Estimated error ±15%.

**Monomers.** Amine H was synthesized from the corresponding alcohol by treatment with PBr₃ and subsequent reaction with liquid ammonia. 29

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

Figure 6. Two possible structures of the starting complex for the polymerization of isocyanides with amino acid esters as the initiators.
2-tert-Butylxline was prepared by nitration of tert-butylbenzene. The ortho product was separated from the para isomer by repeated dec".

ation. The nitro group was reduced with Raney nickel and hydrogen, giving 2-tert-butylxline. Aniline 1b was obtained by nitration of 1,3,5-trihydroxybenzene, subsequent methylation of the hydroxy groups, and reduction of the nitro group. Optically active sec-butylxline was obtained from the racemic amine through fractional crystallization of its bitartrate from water, according to the literature. Optically active 1-phenylethylamine was prepared according to a literature procedure. Amino acids were esterified with dry HCl gas in methanol or ethanol 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 product was recrystallized from diethyl ether: yield 76%, bp 111-113 °C (0.1 mmHg). The crude product was dissolved in 40 mL of acetic acid (1.06 mol) and 60 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 solvent was evaporated in vacuum, and the residue was treated with 3 times with 50 mL of toluene, which was removed under vacuum. The product was recrystallized from toluene: yield 53.4% of white crystals (85%); mp 179.1 °C; IR (KBr) 1675 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 8.4 (m, 1 H, CHO), 7.3 (m, 4 H, CH₃) + NH.


2,6-Dichlorophenyl Isocyanide (3e). This isocyanide was synthesized from 2e according to a modification of the method of Skonna and Ugi. The reaction was carried out in refluxing xylene with a magnetic stirrer and a CO₂/aceton 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 CH₂Cl₂. At a temperature of −30 °C, 6.9 mL of diphenyl (80 mmol) in 65 mL of dry CH₂Cl₂ was introduced into the stirred reaction mixture over a period of 1 h. The reaction mixture was then stirred for another 2 h. The boiling 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% NaHCO₃ solution and once with 150 mL of water. The CH₂Cl₂ layer was dried over Na₂SO₄. The crude reaction product was purified by column chromatography (silica gel, CH₂Cl₂): yield 96% (65 g); IR (CH₂Cl₂) 2120 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 7.3 (3 H, CH₃), 7.2 (3 H, CH₃), 6.4 (2 H, CH₂).

2-Phenyl-2-bromopropane. A solution of 33 g of PBr₃ (0.12 mol) in 55 mL of chloroform was added dropwise at 40 °C to a stirred solution of 50 g of a,a-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 Na₂CO₃ solution and once with water, and dried over MgSO₄. The chloroform was removed under reduced pressure. After distillation a colorless liquid was obtained; boiling range 57-80 °C (0.05 mmHg). The product contained 31% of the elimination product α-methylpyrene. The product was used without further purification for the synthesis of phenyl-2-bromopropane. (3f) The yield of phenyl-2-bromopropane was 57%: 1H NMR (CDCl₃) δ 7.2 (3 H, CH₃), 7.1 (3 H, CH₃), 6.4 (2 H, CH₂).

α,a-Dimethylbenzylamine (1f). This amine was obtained by treatment of 2-phenyl-2-bromopropane with liquid ammonia. 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 MgSO₄ and the ether removed under reduced pressure. The yield was 53%: IR (neat) 3350 and 3275 (NH-) cm⁻¹; 1H NMR (CDCl₃) δ 1.4 (s, 6 H, CH₃), 1.6 (2 s, 2 H, NH₃). The compound was purified by column chromatography (silica gel, CH₂Cl₂) (36 g, 65%); 1H NMR (CDCl₃) δ 7.2 (5 H, CH₃), 1.7 (3 s, 6 H, CH₃).

α,a-Dimethylbenzyl isocyanide (2f). Amine 1f was N-formylated according to a literature procedure in an almost quantitative yield. 1H NMR (CDCl₃) δ 7.8 (m, 2 H, CHO), 7.2 (s, 5 H, CH₃), 1.7 (s, 6 H, CH₃).
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1H NMR (CDCl₃) δ 8.16 (1 H, CHO), 7.30 (5 H, C₆H₅), 4.42 (2 H, CH₂). Benzylo Isonicyclane (3). This isonicyclane was prepared from 2i as described for 3e: yield 83%; colorless liquid; IR (CHCl₃) 2154 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 7.31 (5 H, C₆H₅), 4.56 (3 s, 2 H, CH₂).

N-Formyl-4-anisidine (2k). Aniline was formulated according to a literature procedure. The product was purified by distillation: yield 74%; bp 61-62°C (21 mmHg); IR (CHCl₃) 2130 (C=O) cm⁻¹.

4-Methoxyphenyl isonicyclane (3l). This isonicyclane was prepared from 2a as described for 3e: yield 70%; IR (CHCl₃) 3128 (C=O) cm⁻¹.

N-Formyl-4-methoxy-2-methyl-aniline (2l). 4-Methoxy-2-methyl-aniline was formulated as described for 2g. The product was recrystallized from toluene/hexane: yield 88%; mp 102.4°C; IR (KBr) 1690 (C=O) cm⁻¹; 1H NMR (CDCl₃) 7.84 (1 H, CHO), 7.44 (2 H, CH₃), 6.88 (2 H, CH₃), 3.92 (3 s, 3 H, OCH₃), 2.28 (3 s, 3 H, CH₃).

4-Methoxyphenyl isonicyclane (3m). This isonicyclane was prepared from 2m as described for 3e: yield 79%; IR (CHCl₃) 2118 (C=O) cm⁻¹; 1H NMR (CDCl₃) 7.17 and 6.55 (2 d, 4 H, CH₂), 2.95 (2 s, 6 H, CH₃).

2-Isocyanobiphenyl (3n). This complex was prepared as described for Ni(C≡N-C₆H₅)(ClO₄)₂: IR (KBr) 1680 (C=O) cm⁻¹; 1H NMR (CDCl₃) 7.5 (m, 4 H, C₆H₅), 1.50 (s, 9 H, CH₃).

Tetrakis[tert-butyl isonicyclane]nickel(II) Perchlorate. This complex was prepared as described for Ni(C≡N-C₆H₅)(ClO₄)₂: yield 76%; IR (CHCl₃) 2222 (C=O) cm⁻¹; 1H NMR (CDCl₃) 7.1 (m, 3 H, CH₃), 3.5 (m, 2 H, CH₂), 1.25 (d, 12 H, CH₃). Anal. Calc. for C₂₄H₂₄NiCl₂O₄: C, 61.83; H, 8.03; N, 12.71. Found: C, 61.88; H, 8.67; Cl, 7.12; N, 5.50; Ni, 9.50; O, 12.70.
Poly(n-butyl isocyanide): yellow-brown solid; IR (KBr) 1639 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 1.05–1.45 (br, 7 H, (CH₂)₇H), 3.35 (br, 2 H, NCH₂)

Poly(benzyl isocyanide): brown solid; IR (KBr) 1630 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 4.0–5.0 (br, 2 H, CH₂), 6.5–7.5 (br, 5 H, ArH)

Poly(α,α-dimethylbenzyl isocyanide): pale yellow solid; IR (KBr) 1620 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 2.60 (br, 6 H, CH₂), 6.3 (br, 5 H, ArH).

Poly(phenyl isocyanide): yellow solid; IR (KBr) 1643 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 6.35 (br, ArH).

Poly(4-methoxy-2-methylphenyl isocyanide): yellow solid; IR (KBr) 1630 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 2.50–3.40, 6.2–6.4 (br, 3 H, CH₃), 6.3–6.6 (br, 3 H, ArH).

Poly(2,6-difluorophenyl isocyanide): yellow solid; IR (CDCl₃) 1615 (C=O) cm⁻¹.

Poly(2-tert-butylphenyl isocyanide): yellow solid; IR (KBr) 1615 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 7.0 (br, ArH).

Poly(2-hexylphenyl isocyanide): yellow solid; IR (KBr) 1615 (C=O) cm⁻¹; 1H NMR (CDCl₃) δ 7.0 (br, ArH).

Poly[(dimethylaminophenyl)isocyanide]: yellow-brown solid; IR (KBr) 1605 (C=O) cm⁻¹.

Polymerization in the Presence of Chiral Additives Other Than Chiral Amines. In a typical procedure, 4-methoxyphenyl isocyanide (200 mg, 1.65 mmol), anhydrous NiCl₂ (1.2 mg, 9.2 × 10⁻³ mmol), and (S,S)-chiraphos [25,35,37,39-((S,)-diethylphosphino)butane; 44.4 mg, 0.10 mmol] were stirred in CHCl₃ (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 1-borneol, cinchonine, (R,R)-DIOP, neomenthyl diphenylphosphine, and (S,2′)-(S)-1,2-hydroxy(2-methylpyrrolidin-2-yl)methylpyrrolidine 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, 585-12-0; 1g, 24544-04-5; 1h, 6310-21-0; 1i, 10, 520-10-1; 1j, 14227-17-9; 1k, 871-71-6; 2a, 59734-20-2; 2b, 2425-74-3; 2d, 23602-10-0; 2e, 10113-35-6; 2f, 24044-69-9; 2g, 84250-69-1; 2h, 998857-67-0; 2i, 6343-54-2; 2j, 7402-54-2; 2k, 18606-63-2; 2n, 5346-21-4; 2o, 115591-40-7; 2p, 74704-43-3; 2q, 2769-64-4; 2r, (homopolymer), 28391-59-3; 2s, 115591-41-8; 2t, (homopolymer), 115591-43-0; 3a, 7185-38-7; 3b, 28513-62-4; 3d, 13947-76-7; 3d, poly(benzyl isocyanide), 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; 3j, (homopolymer), 60406-17-9; 3k, 931-54-4; 3k, (homopolymer), 28390-20-7; 3l, 10349-38-9; 3l, (homopolymer), 28390-21-8; 3m, 2008-61-9; 3m, 1930-89-8; 3n, (homopolymer), 115591-44-1; 3n, (homopolymer), 115591-48-5; 3p, 3128-77-6; 3p, (homopolymer), 115591-47-4; 3q, 115603-32-2; 3r, 115591-42-9; 3s, (homopolymer), 115591-45-2; (S)-(+)-C₆H₅CH(CH₃)NH₂, 513-49-5; (S)-(−)-C₆H₅CH(CH₃)NH₂, 2627-86-3; (R)-(−)-C₆H₅CH(CH₃)NH₂, 3886-96-9; (S)-(−)-C₆H₅CH(CH₃)NH₂, 17430-98-7; (S)-(−)-1-naphthylethylamine, 104260-89-0; (S)-(−)-ephedrine, 299-42-3; (R,R)-1,2-diaminocyclohexane, 20419-47-8; (S)-(−)-Phenylnalal, 3182-95-4; (S)-(−)-valine methyl ester, 4070-48-8; (S)-(−)-alanine methyl ester, 10065-72-2; (S)-(−)-cysteine methyl ester, 2485-62-2; 2-phenyl-2-bromopropane, 3575-19-7; α,α-dimethylbenzyl alcohol, 617-94-7; tetrakis(tert-butyliiso cyanide)nickel(II) perchlorate, 40667-87-6; tetrakis(tert-butyliiso cyanide)nickel(II) perchlorate, 106859-37-4; tetrakis(2-tert-butyliiso cyanide)nickel(II) perchlorate, 115603-69-5; tetrakis(2,6-disopropylphenyl isocyanide)nickel(II) perchlorate, 115650-89-0; tris(tert-butyliiso cyanide)(S)-(−)-(1-phenylethylamino)[(tert-butylinocarbene]nickel(II) perchlorate, 115603-71-9; tris(tert- pentyliiso cyanide)(S)-(−)-(1-phenylethylamino)(tert-pentylaminocarbene]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 (d,l) and Diastereomer 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 a 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.

Host–guest chemistry continues to develop as a major sub-discipline of modern chemistry. The pioneering studies on crown ethers and related structures laid the foundations for the field.

They established that when appropriate amounts of preorganization and complementarity between host and guest are designed


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