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DEVELOPMENT OF NEW METHODS FOR PREPARATION OF OPTICALLY
ACTIVE HELICAL POLYMERS

A DISSERTATION
SUBMITTED TO THE FACULTY OF CLARK ATLANTA UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE DOCTOR OF PHILOSOPHY

BY
LISANDRA JUDITH ORTIZ-PEREZ

DEPARTMENT OF CHEMISTRY

ATLANTA, GEORGIA
MAY 2000
ABSTRACT

CHEMISTRY

ORTIZ-PEREZ, LISANDRA J. B.S UNIVERSITY OF PUERTO RICO CAYEY UNIVERSITY COLLEGE, 1993

DEVELOPMENT OF NEW METHODS FOR PREPARATION OF OPTICALLY ACTIVE HELICAL POLYMERS

Advisor: Dr. Ishrat M. Khan

Thesis dated May, 2000

Helix-sense-selective polymerization of poly(3-methyl-4vinylpyridine) have been carried out using the DPEDA\textsuperscript{\textdagger}Li\textsuperscript{\textdagger} (diphenylethylene diamine)/(−) and (+) DDB [2,3-methoxy-1,4-bis(dimethylamino) butane] optically active initiating complex at −78°C in toluene. The (−) initiating complex forms a dextrorotatory polymer and (+) complex results in the formation of the levorotatory polymer. The secondary structure has been confirmed using polarimetry and circular dichroism (CD) spectroscopy. The secondary structure is most likely helical because of the observed couplet in the CD spectra. Additionally, helix-sense-selection has been carried out by complexation of the racemic mixture of P3M4VP via acid-base interaction with (R) and (S) mandelic acid. The results are confirmed by CD.

The stereochemistry of the helical P(3M4VP) is most likely isotactic-like based on MM3 calculations.
ACKNOWLEDGMENTS

First and foremost, special thanks go to the Lord because without his guidance and blessings, this work would not have been accomplished.

Special thanks go to my advisor, Dr. Ishrat M. Khan, whose professional guidance and supportive friendship has provided me with a thorough knowledge and understanding of the material contained in this dissertation.

Special appreciation is also extended to Dr. John M. Browne, Dr. Myron Williams, Dr. Issifu Harruna, Dr. Cass Parker for serving on the reading committee and offering valuable insights and advice concerning this dissertation.

I also wish to express my sincerest gratitude to all my friends and co-workers at Clark Atlanta University for their encouragement and love over the years.

The Minority Biomedical Research Support Program (MBRS) is also thanked for financial support throughout my graduate career.

And last but not least, this work is dedicated to my parents Luz M. Perez and Efrain Ortiz in gratitude of their encouragement, sacrifice, dedication and unconditional love during the entire course of the work contained in this dissertation.

I can do all things through Christ which strengtheneth me.
Philippians 4:13
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<td>°C</td>
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<td>(-)-DMP</td>
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<td>(+)-S-Diphenyl (1-methyl-pyrrolidin-2-yl) methyl methacrylate</td>
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<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
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<td>DP</td>
<td>Degree of polymerization</td>
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<td>DPAA</td>
<td>N,N'-(diphenylacrylamide)</td>
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<td>DPEDA-Li</td>
<td>N,N'-Diphenylethlenediamine lithium amide</td>
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<tr>
<td>Ea</td>
<td>Activation energy</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>ee</td>
<td>Enantiomeric excess</td>
</tr>
<tr>
<td>EFF</td>
<td>Empirical force field</td>
</tr>
<tr>
<td>2Eh</td>
<td>Energy of opposing helical senses</td>
</tr>
<tr>
<td>Er</td>
<td>Energy of helix-sense reversal</td>
</tr>
<tr>
<td>°F</td>
<td>Fahrenheit</td>
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<tr>
<td>FLLi</td>
<td>Fluorenyllithium</td>
</tr>
<tr>
<td>F.W.</td>
<td>Formula weight</td>
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<td>g</td>
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<td>GC-MS</td>
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<td>GPC</td>
<td>Gel permeation chromatography</td>
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<td>H</td>
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<tr>
<td>ICD</td>
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<tr>
<td>K</td>
<td>Potassium</td>
</tr>
<tr>
<td>kcal</td>
<td>Kilocalory</td>
</tr>
<tr>
<td>kDa</td>
<td>Kilodalton</td>
</tr>
<tr>
<td>L</td>
<td>Liter</td>
</tr>
<tr>
<td>LDA</td>
<td>Lithium diisopropyl amine</td>
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<tr>
<td>LiAn</td>
<td>Lithium-R-N-(1-phenylethyl)anilide</td>
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<tr>
<td>M-</td>
<td>Minus</td>
</tr>
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M  Molar
m  Turns of the helical screw
M1  Monomer 1
M2  Monomer 2
3M2VP  3-Methyl-2-vinylpyridine
3M4VP  3-Methyl-4-vinylpyridine
(+)-MA  (+)-Mandelic acid
(-)-MA  (-)-Mandelic acid
MBNA  α-Methylbenzyl methacrylate
MBPI  N-[4-N'(α-Methylbenzyl) aminocarboxylphenyl]-itaconimide
min  Minutes
ml  Milliliter
mm  Meso-meso
MMA  Methyl methacrylate
mMePI  m-Methylphenyl isocyanate
MeOH  Methanol
Mn  Number molecular weight
m.p.  Melting point
(-)-MPP  (S)(-)-1-Methyl-2-(piperidinomethyl pyrrolidine)
(-)-MT  (-)-Menthanethiol
Mv  Viscosity molecular weight
Mw  Molecular weight
N  Degree of polymerization
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<tr>
<td>n</td>
<td>Number of monomer units in each turn</td>
</tr>
<tr>
<td>N</td>
<td>Residues reside in m turns</td>
</tr>
<tr>
<td>$n^2_D$</td>
<td>Refractometry index</td>
</tr>
<tr>
<td>1-Naph</td>
<td>1-Naphthyl</td>
</tr>
<tr>
<td>2-Naph</td>
<td>2-Naphthyl</td>
</tr>
<tr>
<td>NAPI</td>
<td>1-Naphthyl isocyanate</td>
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<td>n-Butyllithium</td>
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<td>n-Butyllithium-(-)-sparteine</td>
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<td>(+)- or (-)-n-Butyllithium-dimethoxy-1,4-bis(dimethyl-amino) butane</td>
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<td>NH</td>
<td>Amino group</td>
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<tr>
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<td>Nanometer</td>
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<td>Nuclear magnetic resonance</td>
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<td>(+)-NMT</td>
<td>(+)-Neomethanethiol</td>
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<td>(-)-NMT</td>
<td>(-)-Neomethanethiol</td>
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1PDBSM
PD2PMA
PDSMA
PEG
PEO
Ph
PICs
pMeOPI
p2,6MePI
P3M4VP
(+)PMP
PMPyDMA
poly-1
Poly[[(+)-PPymTMA]]
PPBI
PPDA
PPDLA
PPLA
ppm
PPymTMA
(+)-PPyoTMA
(-)-PPyoTMA
Palladium
1-Phenyl dibenzosuberyl methacrylate
Poly(diphenyl-2-pyridylmethyl methacrylate)
1-Phenyldibenzosuberyl methacrylate
Poly(ethylene glycol)
Poly(ethylene oxide)
Phenyl group
Polyisocyanates
p-Methylphenyl isocyanate
2,6-Dimethyl-phenyl isocyanate
Poly(3-methyl-4-vinylpyridine)
(S)-(+)1-(2-pyrrolidinylmethyl)-pyrrolidine
Poly(2-(6-methylpyridyl) diphenyl methyl methacrylate)
Poly[(4-dihydroxy borophenyl) acetylene]
Poly ((+)2-pyridyl-m-tolylmethyl methacrylate)
Poly(4-phenylbutyl isocyanates)
Poly(β-phenethyl-D-aspartate)
Poly(β-phenethyl-D-L-aspartate)
Poly(β-phenethyl-L-aspartate)
Parts per million
Phenyl-2-pyridyl-m-tolylmethyl methacrylate
(+)-phenyl-2-pyridyl-o-tolylmethyl methacrylate
(-)-phenyl-2-pyridyl-o-tolylmethyl methacrylate
PTrMA  Poly(triphenyl methacrylate)
R  Alkyl side chain
r1  Reactivity ratio 1
r2  Reactivity ratio 2
Rh(ndb)Cl  (norbornadiene)-rhodium(I)chloride
RNA  Ribonucleic acid
ROESY  Resonance overhauser effect spectroscopy
rrr  Racemo-racemo-racemo
RT  Room temperature
s  Singlet
(-)-Sp  (-)-Sparteine
ST  Styrene
t-BuLi-(−)-Sp  tert-butyllithium-(−)-sparteine
Tc  Ceiling temperature
Temp  Temperature
Tg  Glass transition temperature
TGTG  Trans-gauche, trans-gauche
Ti(IV)  Titanium IV
Ti(OC₄H₉)₄/Al((+)/2-2-methyl butyl)₃  Tetra ethoxy titanium/trimethyl aluminum
Tm  Melting temperature
TMEDA-BuLi  N,N’-Tetramethylethylenediamine-benzyllithium
TMS  Tetramethylsilane
TOCSY  Transfer correlation spectroscopy
<table>
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<tr>
<td>Tr</td>
<td>Triphenylmethyl</td>
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<tr>
<td>TrMA</td>
<td>Triphenylmethyl methacrylate</td>
</tr>
<tr>
<td>t-RNA</td>
<td>t-Ribonucleic acid</td>
</tr>
<tr>
<td>UV-Visible</td>
<td>Ultraviolet-visible</td>
</tr>
<tr>
<td>VCl$_3$Al(+(+)-2-2-methyl butyl)$_3$-Et$_2$O$_4$</td>
<td>Trichloro vanadium/tri(+)-tri (2,2-methyl butyl)</td>
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<tr>
<td>$[\alpha]_D$</td>
<td>Optical rotation at 589 nm</td>
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CHAPTER I
INTRODUCTION

There are many examples of synthetic macromolecules that have been demonstrated to have well-defined helical or secondary structures. Among the most comprehensively studied are the bulky methacrylates, which may be polymerized by chiral anionic initiators to obtain predominantly one-handed helical optically active polymers, e.g., poly(triphenylmethyl methacrylate) (PTrMA) and poly(diphenyl-2-pyridylmethyl methacrylate)(PD2PMA).\textsuperscript{1-4} These helical polymers are predominantly isotactic, and the stable helical conformation is maintained because the bulky side groups do not readily permit helix-to-helix interconversion. However, stereomutation has been observed for poly(diphenyl-2-pyridylmethyl methacrylate) at elevated temperatures.\textsuperscript{5} Optically active helical polymers have been successfully utilized as chiral stationary phases with good optical resolving abilities in high performance liquid chromatography (HPLC).\textsuperscript{6} Other examples of optically active helical polymers include poly(isocyanates), poly(isocyanides), poly(N,N'-disubstituted acrylamide) and poly(chloral).\textsuperscript{7-16} A number of interesting papers have reported on synthetic β-peptides with stable secondary helical structure or helical conformations.\textsuperscript{17-20} The secondary helical structure of these β-peptides is possible because of intramolecular hydrogen bonding, whereas the optically
active helical isotactic poly(bulky methacrylates) adopt the helical conformation because of steric reasons; i.e., the lowest energy conformation is the helix.

The motivation for this work results from a number of observations including the fact that in the solid-state isotactic \( \alpha \)-olefins and certain substituted styrenes are known to be in a low energy helical conformation with a trans-gauche (\(...TGTG...\)) type backbone conformation.\(^{21-22}\) Additional, observations include the preparation of isotactic poly(3-methyl-2-vinylpyridine) (P3M2VP) by anionic polymerization.\(^{23}\) The isotacticity of this polymer is probably a result of a favored helical conformation caused by the non-bonded interaction between the 3-methyl group and the penultimate pyridine group.\(^{24}\) It is not known if the helical conformation of poly(3-methyl-2-vinylpyridine) is energetically stable enough for preparing conformationally stable optically active polymers. Also, it is entailed to demonstrate that bulky groups, e.g., triphenylmethyl, may not be necessary to carry out helix-sense-selective polymerization of vinyl monomers.

Additionally, the development of a method for preparation of optically active helical poly(3-methyl-4-vinylpyridine) from a racemic mix of helices. The monomer, 3-methyl-4-vinylpyridine (3M4VP), was selected over 3-methyl-2-vinylpyridine (3M2VP) because it is possible to successfully polymerize this monomer with softer anions such as lithium amides,\(^{25,26}\) and lithium amide based optically active initiators are normally used to carry out helix-sense-selective polymerization.\(^1\) Therefore, the overall goal of this study is to develop new methods for preparing synthetic macromolecules with helical architectures.
CHAPTER II
BACKGROUND

Optically active polymers have aroused wide interest. One of the reasons for this may be ascribed to the chiral nature of living systems. A number of naturally occurring macromolecules such as proteins, nucleic acids, and polysaccharides are optically active. Chirality is essential for these macromolecules to exert their sophisticated functions in living systems in order to maintain life. Generally, macromolecules exist as a variety of conformational isomers. Introduction of stereoregularity in macromolecules may minimize the number of conformational isomers actually present, e.g., polymers with isotactic configuration having certain favorable conformational states and the conformer that is closely correlated with the specific functions may be energetically favorable.\(^2\)

Most naturally occurring polymers are optically active and some of them show characteristic functionalities such as molecular recognition ability and catalytic activity, owing to their specific chiral structure as represented by genes and proteins. In synthetic macromolecular chemistry, it seems that one of the most challenging tasks is to construct functional polymeric systems that will be effective in carrying out functional activities as those in living systems.\(^2\)
2.1 Helical Polymers

Macromolecules exist in a variety of conformational forms. These range from randomly coiled chains to more spatially ordered structures. Of particular interest are those polymers which adopt helical symmetry, either in solution or in the solid state. Helical geometry is a consequence of an orderly repetition of internal rotational angles along the polymer backbone and is commonly encountered among polymers of both natural and synthetic origin.\textsuperscript{16} As detailed by Cahn, Ingold and Prelog,\textsuperscript{28} a helix is characterized by a central axis (c-axis), a screw sense and a pitch. For a helical polymer, pitch (P), or the distance traveled along the c-axis corresponding to one full 360° turn, is related to n, the number of monomer units in each turn, and h, the monomer repeat height projected onto the c-axis, where N residues reside in m turns of the helical screw.\textsuperscript{16}

The most extensively studied class of macromolecules possessing helical order are the proteins and their synthetic analogues, the poly (\(\alpha\)-amino acids). The \(\alpha\)-helix, a right-handed helical structure with 3.6-3.7 residues per turn has long been recognized as an integral part of many proteins. First identified from X-ray diffraction studies by Pauling in 1951\textsuperscript{29}, the \(\alpha\)-helix exists both in the solid state and in solution. The helix derives considerable stabilization from internal hydrogen bonding between –NH- and carbonyl groups positioned at regular intervals along the helical coil. For \(\alpha\)-helices composed of the naturally occurring l-amino acids, a right-handed screw sense is energetically favored over the left-handed form, although a few exceptions are known.\textsuperscript{30} Other conformational arrangements of the poly(\(\alpha\)-amino acid) backbone have also been experimentally observed.\textsuperscript{16} Helical order is also encountered among the nucleic acids.
The double helical geometry of deoxyribonucleic acid (DNA) is particularly well known. A number of DNA polymorphs have been identified in the solid state depending upon the experimental conditions used to obtain fibers for X-ray diffraction studies.\textsuperscript{16} Helicity is also common to the third class of biopolymers, the polysaccharides. \(\alpha\)-Amylose, a major component of starch, forms helical structures in solution with 6 to 7 glucose units per turn.\textsuperscript{31} This helix is stabilized by hydrogen bonds which bridge the polymer's hydroxyl groups. The helical cavity of \(\alpha\)-amylose is large enough to easily accommodate a number of guest species, including water, iodine, benzene and a variety of aliphatic compounds.\textsuperscript{32} Other solid state helical structures have also been identified.\textsuperscript{33-34}

In contrast to their natural analogues, most synthetically derived macromolecules lack the secondary bonding forces which stabilize helical order in solution. For these polymers, helicity is generally reserved for the solid state where crystalline packing forces dictate conformational geometry. Because extended helices can be easily incorporated into a regular crystalline lattice, a helical arrangement of the polymer backbone is highly favored in the solid state. Indeed, the helix is the most common systematic, ordered structure encountered among the synthetic, crystalline polymers.\textsuperscript{35} Linear polyethylene, formaldehyde, thioformaldehyde, isotactic vinyl polymers of the form \(-(\text{CH}_2-\text{CHX})_n-\) also possess solid state helical order as do, polypropylene, polystyrene, poly(vinyl methyl ether), poly(1-hexene) and poly(vinyl cyclohexane).\textsuperscript{36-38}

It is only recently that the synthesis of optically active helical polymers in which activity arises from macromolecular asymmetry, i.e., a preferred or exclusive helical screw sense has been reported. Because polymers of this type lack main chain or side
asymmetric carbon atoms, right and left helical screws are energetically equivalent, and therefore, equally probable during the course of polymerization with simple initiators. However, a predominance of one helical screw direction can be obtained in one of two ways: (1) through a complete or partial resolution of a helical screw pair with the aid of a chiral substrate, or (2) through the use of chiral initiating species which preferentially induce the formation of one helical screw sense over the other. Presently, a limited number of optically active helical polymers have been prepared via these two routes. These include the polymers of trichloroacetaldehyde (chloral), triphenylmethyl methacrylate and the isocyanides.

Various optically active polymers have been utilized for chiral catalysts and adsorbents; most of those, however, are not the polymers prepared through asymmetric polymerization but chemically modified naturally occurring polymers and synthetic polymers derived from optically active monomers. The exceptions are one-handed helical polymers, especially polymethacrylates; they are used and commercialized as chiral stationary phase in high-performance liquid chromatography (HPLC).

Optically active polymers with a helical structure have been produced from several types of monomers. Such polymers may be prepared from other monomers by considering the spatial requirement for a specific conformation. The helical polymers have been effectively applied as the chiral HPLC stationary phase, this is the only successful application of the polymers prepared by asymmetric polymerization. The helical polymers may possibly be utilized for other purposes such as asymmetric polymer catalysts and polymer liquid crystals, in which the specific chiral structure of the polymers may play a significant role.
Some helical polymethacrylates are important because they exhibit excellent chiral recognition ability toward racemates when used as a chiral packing material for HPLC. One-handed helical polymers have been synthesized also from other types of achiral monomers including acrylates, acrylamides, choral, isocyanides, and isocyanates. However, helix-sense-selective polymerization is possible only by anionic and transition metal-mediated mechanisms so far and therefore, monomers suitable for this type of polymerization have been limited to those having only functional groups which would not inhibit polymerization reaction.

Okamoto reported on the anionic polymerization of N,N'-disubstituted acrylamides to yield crystalline polymers, the tacticity of the obtained polymers is isotactic.\textsuperscript{39,40} It has also been reported that N,N'-disubstituted acrylamides bearing bulky substituents such as N,N'-diphenylacrylamide (DPAA) afford optically active polymers in the anionic polymerization with chiral initiators.\textsuperscript{13,14}

The helix-sense-selective through free radical polymerization of 1-phenyldibenzosuberyl methacrylate (PDBSMA) is the first example of the synthesis of an optically active, helical polymer having an excessive single-handed helicity from an achiral monomer by radical polymerization.\textsuperscript{41,42} PDBSMA prepared by conventional free radical polymerization gives a highly isotactic polymer (mm > 99%). PDBSMA gives an almost perfectly isotactic conformation, similar to the one-handed helical polymer P(TrMA) obtained by anionic polymerization.\textsuperscript{41-43} The poly(PDBSMA) prepared by radical polymerization is an equimolar mixture of right- and left-handed helices. On the basis of the stereochemistry of PDBSMA polymerization, radical polymerization was investigated under chiral conditions.\textsuperscript{41,42} Chiral reaction conditions
were introduced by the use of (-)-dimethyl peroxycarbonate ((-)-DMP) and (-)-o-carbomethoxybenzoyl peroxide ((-)-CMBP) as an initiator, (+)- and (-)-neomethanethiol (NMT) and (-)-mentanethiol ((-)-MT) as a chain transfer agent, (-)- and (+)-menthol, (+)-neomenthol, and (+)-1-phenyl-1-butanol as a reaction solvent (additive), and (-)-phenyl-2-pyridyl-o-tolyl-methyl methacrylate (PPyoTMA) as a comonomer for copolymerization. The free radical polymerization of PDBSMA using optically active initiators, transfer agents, solvents, and a comonomer gave polymers showing optical activity (OP) and CD adsorption based on an excess right- or left-handed helical conformation. Helix-sense-selection in the homopolymerizations appeared to be mainly on differences in the rates of the termination (primary radical termination and radical quenching processes through chain transfer) for right- and left-handed helical growing radicals. This can be interpreted as helix-sense-selective inhibition of propagation. A similar concept has been proposed for helical polyisocyanide synthesis mediated by transition metal catalysis. On the basis of this mechanism, the THF-insoluble polymer having higher molecular weight might have greater excess of single-handed helicity than the benzene-hexane insoluble part having lower molecular weight though the chiroptical properties of the THF-insoluble polymer is currently unknown. The sense of helix in the copolymer was sensitive to the content of the optically active monomeric unit: more sporadically and more successively incorporated optically active monomeric units induced the opposite sense of helix.44

The methods of helix-sense-selective free radical polymerization are considered to be applicable to the wide range of PDBSMA derivatives and related bulky monomers having the functional groups which kill anionic species. However, higher
helix-sense-selectivity should be possible using properly designed structures of chiral additives.\textsuperscript{44}

It has been demonstrated that poly(phenylmethyl acrylate) may be synthesized in the same manner as PTrMA, i.e., living anionic polymerization. The results showed optical rotation isotacticity ([\alpha]\textsubscript{25}\textsubscript{365}^\circ=+102^\circ \text{ and } m=0.70), and the CD spectrum shows positive peaks at 210 and 230 nm, which may be ascribed to the absorption due to the aromatic and carbonyl groups, respectively. This spectral pattern is quite similar to that of the one-handed helical, optically active PTrMA. This suggests that the optical activity of the PTrA may be attributed to a partially one-handed helical structure of the polymer chain. The degree of one-handedness must be lower than that of a the PTrMA judging from the smaller optical activity and isotacticity of the polymer. Poly(TrA)s obtained in the asymmetric anionic polymerization using chiral complexes are optically active mainly due to the conformation. The isotactic part of the polymer probably has the helical conformation which induces dextrorotation. Polyacrylates and polymethacrylates bearing bulky ester group appear to have stable helical conformations.\textsuperscript{45}

Workers at the Italian School of Polymer Stereochemistry demonstrated that copolymers prepared from achiral and chiral vinyl monomers show disproportionately high optical activities. Although the optical rotatory dispersion of the backbone responsible for electronic transitions could not be directly observed, this characteristic was reasonably attributed to induced chiral conformations of the polymer chain.\textsuperscript{45,46} A significant amount of literature \textsuperscript{47-50} describe poly(n-hexyl isocyanates), in contrast to most synthetic polymers,\textsuperscript{51-53} as polymers adopting an extended helical conformation this picture offers a simple explanation for the surprising influence of the chiral comonomer.
Since the units between two helix reversals are constrained to a single helical sense, they must all be influenced toward either the left- (M) or right- (P) handed helical state by the presence in their midst of one or more chiral monomer units. A few chiral comonomers control the helix-sense of the otherwise indifferent hexyl isocyanate units, the latter unable to escape this influence except through rarely occurring helix reversals. A strong temperature dependence has been observed\textsuperscript{54} and phenomenologically related effect of deuterium stereogenicity, can be understood as arising from a diminishing number of helix-reversal states as energy is withdrawn, causing more units to act in concert.\textsuperscript{10}

Several polyisocyanates with optically active side groups have been studied mainly because the polyisocyanates favor one helical sense.\textsuperscript{10, 55-59} It has been reported that when butyl and 4-phenylbutyl isocyanates, which contain no asymmetric carbon, were polymerized with chiral anionic initiators such as lithium salts of (-)-menthol and (S)-(+)2-(1-pyrrolidinylmethyl) pyrroldine, the polymers obtained showed optical activity based on the prevailing helicity of the main chain induced by chiral initiator residues attaching to an initial chain end ($\alpha$-end) group of the polymer chain.\textsuperscript{60} Studies have been carried out on the polymerization of ortho-methylphenyl isocyanate (o-MePI), m-methylphenyl isocyanate (m-MePI), p-methylphenyl isocyanate (p-MeOPI), p-chlorophenyl isocyanate (p-CIPI), 2,6-dimethyl-phenyl isocyanate (2,6MePI), and 1-naphthyl isocyanate (NAPI) using optically active anionic initiators including lithium amides and alkoxides, to find whether or not the obtained polymers have a helical structure with an excess of a single screw sense have been determined. In most cases, a helix-sense selective polymerization product was observed.\textsuperscript{11}
The qualitative model of a chirally perturbed polyisocyanate chain, with long helical sequences separated by helical sense reversals, has been interpreted quantitatively by statistical thermodynamics. The change of the specific optical rotations with temperature depends on the following: the energy of a helix-sense reversal, $E_r$; the energy difference per monomer used between the opposing helical-senses, $2E_h$; and the degree of polymerization, $N$. Three cases of dynamic equilibrium were considered: (1) equilibrium between purely right-handed (P) and purely left-handed (M) short polymers; (2) equilibrium between many long alternating P and M helical sequences, separated by helix reversal states, in a very long polymer chain and (3) the general case of polymers of any length, including (1) and (2) as special cases. Calculations of the relationship between optical activity $[\alpha]_D$ and temperature prove that both cases 2 and 3 make an excellent fit to the corresponding measurements on poly((R)-1-deuterio-n-hexyl isocyanate) of MW 870 kDa, in dilute chloroform and hexane solutions. In the fit of the experimental data to the theory, cases 2 and 3 differ somewhat, yielding values of $2E_h$ and $E_r$ near to 1 and 4 kcal/mol. The results confirm a cooperative model proposed to account for the unusual sensitivity of this polymer to asymmetric deuterium substitution and yield the energy bias of the isotope effect, which would otherwise be extremely difficult to measure.\textsuperscript{58}

In contrast to polypeptides, which also form extended helical conformations in solution,\textsuperscript{61} polyisocyanates lack chirality in the monomeric precursors. This stereochemical distinction causes the polyisocyanates to adopt left-(M) and right-handed (P) helical conformations with equal probability. Goodman and Chen\textsuperscript{56,62} first took the opportunity offered by the pendant group in allowing incorporation of stereogenicity.
They synthesized polyisocyanates from two optically active monomers and found exceptionally high optical activities associated with the recurring amide group chromophore centered in the ultraviolet region. This observation implied that the left- and right-handed helices cast in diasteromeric states were no long equally related.\textsuperscript{63,64}

Helical polymers\textsuperscript{65} or macromolecules (e.g., DNA or helical polypeptides) are well known for their importance in nature. In proteins, helical rigidity acts to stabilize the three-dimensional structure. Changes in the helical structures\textsuperscript{16} (e.g., helix-helix or helix-coil transitions) can be triggered by temperature or pH changes. In polypeptides, for example, which are close to one of these conformational transitions, it has long been known to be possible to induce this transition photochemically.\textsuperscript{9,66,67}

Synthetic helical polymers (e.g., polyisocyanides,\textsuperscript{9,66,67} poly(tritylmethacrylates,\textsuperscript{68} and polychoral\textsuperscript{69}) can be prepared by polymerization reactions using chiral initiators. In these synthetic systems, helix-coil transitions are not seen. Their helical structures are not stabilized by H-bonds as in the natural polymers. Polyisocyanates\textsuperscript{47} prepared from chiral monomers play a special role in this context, because of the fact that a reversible shift of the equilibrium between P and M helices can be induced, e.g., by a temperature change in aprotic solvents.\textsuperscript{10} Since the polyisocyanate backbone has no chiral center, these polymers, prepared from achiral monomers, exist as a racemic mixture of P (right handed) and M (left handed) helices (or helical) segments within one long polymer chain. However, due to the high cooperativity within the helical polymer chains\textsuperscript{70}, small amounts (about 0.1 mol %) of chiral side groups in copolymers are sufficient to favor one twist sense in these so-called "Sergeants and Soldiers" copolymers.\textsuperscript{10,71,72} (P and M helices become diastereomers in the presence of the chiral
side groups). The induced chiral conformation of the polymer backbone can be detected directly by CD measurements in the absorption range of the polymer backbone (280 to <200nm).

The equilibrium between P- and M- helical polyisocyanate segments have been varied to determine the chirooptical properties of these polymers by the reversible photoisomerization of chiral azobenzene units. To perform this task, this photochemical switch with the - *a priori racemic* - polymer backbone was combined in such a way that the chiral induction from the chiral center (the primary source of chiral information) to the polymer helices should be very different for both photochemical isomers. Such materials are interesting for optical data storage. Principally, this is possible in two ways using the photochemically induced variation of the interaction of chiral side groups and the helical main chain. In one case this may lead to a shift of the equilibrium between P and M helices. Alternatively, changes of the Cotton effects of the azo chromophores can lead to strong changes in the optical rotation.\(^7\)

This method of obtaining optically active polymers is inconvenient because it requires expensive chiral starting material. Several other methods have been developed which only require an enantiomeric excess of monomer or small amounts of enantiomerically pure monomer incorporated with achiral monomer, known as "majority rules" and the "sergeant soldiers" experiments, respectively.\(^7\)

Both of these procedures rely on generating energetically favorable conformational states, and the excess chiral monomer bias in favor of the conformation. While these methods are improvements over polymerization of pure chiral starting material, they still require some enantiomerically pure monomers. There is interest in controlling the polymer
conformation by using chiral catalyst, where the sense of the helix is under kinetic control. In this way, optically active polymers can be prepared from optically inactive monomers. Green and co-workers’ goals include using a chiral catalyst to stereoselectively polymerize a racemic mixture of monomer, and using chiral catalysts to give optically active polymer from achiral monomer. The latter goal requires systems where the inversion barrier between helix-senses is high enough such that the polymer does not racemize as it spins off the catalyst. Anionic analogues of this kinetic approach include the polymerization of bulky acrylate esters in the presence of optically active complexing agents.

Bruce Novak’s group has developed living catalysts for preparing helical polyguanidines. These catalyst systems which are based on both titanium (IV) (Ti IV) and copper(II) complexes (Cu II) complexes are potential chiral catalyst for small molecule asymmetric synthesis. They reported their use in both helix-sense selective and stereoelective polymerizations.

Optically active polyguanidines were prepared from achiral carbodiimides using copper complexes equipped with chiral bisoxazoline ligands. Cu(OMe)Cl is a more efficient catalyst than the corresponding CuCl₂ derivatives, resulting in faster polymerizations and yielding polymers with higher optical rotations. The Cu(OMe)Cl-II complex showed preferential solubility in the (R)-monomer versus the (S)-monomer. Polymerizations were twice as fast for the (R)-monomer. Racemic mixtures of carbodiimides were polymerized with the chiral Cu(OMe)Cl-II catalyst to yield polymers with an enantiomeric excess of one helix-sense. The enantiomeric excess decreases with conversion as less R is available and more S is incorporated into the chain.
Contrary to long-standing belief, polyisocyanides do not adopt helical conformations. Rather their conformations are highly dependent on the bulk of the imine substituents: polymers with bulky tertiary and a limited number of bulky secondary substituents can adopt 4/1 helical conformations, but polymers with less bulky secondary and primary substituents do not. Evidence for this conformational dependency on comes from electron diffraction studies, molecular modeling, semi-empirical calculations, solutions $^{13}$C NMR, and two-dimensional $^{13}$C solid-state NMR. This trend is also supported by the polymerization of achiral monomers with optically active catalysts.$^{81}$

Millich$^{82-83}$ studied polymer properties of the polyisocyanides such as the relationship between viscosity and molecular weight and the configuration of the polymer chain. From viscosity behavior, Debye-Scherrer X-ray photographs, optical rotation data, and molecular models, Millich suggested that the polymers have rigid rod helical structures. Helicity should give rise to optical activity. Drenth’s and Novak’s laboratory$^{7,84}$ studies further confirm the suggestion; they were able to resolve a tert-butyl isocyanide oligomer into fractions with (+) and (-) signs of optical rotation.$^{85}$

The pioneering work by Millich and its extensions to synthesis, configuration, and chirality have established the rigid rod helical character of poly(iminomethylenes). These polymers are now easily available with a large variety of side chains. The combination of chirality and rigidity, coupled with easy accessibility of a variety of chains, is attractive for their application in enantioselectivity experiments, e.g., as selective supports in chromatography, as enantioselective catalysts, and as specific reagents with respect to substrates of biochemical importance.$^{144}$
Polyisocyanates, long studied as theoretical models for wormlike chains in dilute solution and liquid crystals, differ from their biological helical analogs in the absence of a pre-determined helical sense. These polymers have an unusual sensivity to chiral effects that arise from a structure in which alternating right- and left-handed long helical blocks are separated by infrequent and mobile helical reversals. Statistical thermodynamic methods yield an exact description of the polymer and the cooperative nature of its chiral properties. Minute energies that favor one of the helical senses drive easily measurable conformational changes, even though such energies may be extremely difficult to calculate from structural theory. In addition, the chiral nature of the polymer can be used to test theoretical ideas concerned with cholesteric liquid crystals, one of which solves the problem of assigning the helical sense.

Polyisocyanates (PICs) have the general formula (-CO-NR-)ₙ where R is an alkyl side chain. They are stiff polymers due to the partial double-bond character of the backbone amide bonds.⁴⁷,⁴⁸,⁸⁶-⁸⁹ The backbone is helical,⁹⁰-⁹⁶ due to steric hindrances which prevent the amide bonds from staying planar, whether trans or cis. The helices tend to be very long, because reversal of the helical sense requires that at least one monomer unit obtain a reversal conformation, such conformations are rare because their energy is much higher than that of the helical conformations of the monomer units. The helices may be either left-handed (M) or right-handed (P), and if a polyisocyanate has no chirotopic carbon on its side groups, the M and P helices are mirror images of each other and are equally distributed in solution. In a solution of such a polymer no optical rotation (OR) is observed.⁷¹
The Empirical Force Field (EFF) theoretical study of polyisocyanates yielded conformational and energetic data that give a detailed and comprehensive microscopic picture of these molecules. Many of these data are in agreement with experimental results. It is expected that the predictions made in some of the studies such as the soft intramolecular collective mode of conformational change, or the size of the kink along the chain at points of helical sense reversal, may stimulate further research.\textsuperscript{71}

Polyisocyanates are stiff helical polymers that differ from helical biopolymers such as nucleic acids and proteins in the absence of chiral information in the building blocks.\textsuperscript{47,53,97} This means that both the left- and right-handed helical senses are equally probable and that in long polymers, intramolecular helical reversals may occur. The cooperative stereochemical phenomena that arise from this structure allow very small chiral biases in each monomer unit of the polymer to be magnified to control the helical sense of large portions of the chain.

The polyisocyanate molecules are not perfect rods, and it was argued that the experimentally measured flexibility (relative to a perfectly stiff rod) was primarily due either to small torsional oscillations about the backbone rotational angles or to the existence of kinked helical reversals.\textsuperscript{82,83,98-100} One approach to resolving this question is the exclusion of the helical reversals from the chain by the incorporation of asymmetric pendant groups in the structure so that only one helical sense is formed. Large optical activities arising from the helical chromophore were then observed.\textsuperscript{56,57,63,64} In summary, the essential characteristics of a stiff helical structure in which the helical senses are both equally probable and easily interconvertible are the prerequisites for the unusual stereochemical properties described above.
There is an increasing synthetic interest in both molecular and supramolecular helical structures. The work described may encourage the search for parallel properties among these materials. Although the one-handed helicity of the polymers is apparent from their optical activity, it has been difficult to determine the helical polymer structures and thermodynamic parameters for the helix-helix transition. One reason for the difficulty is that those polymers are, as usual synthetic macromolecular compounds are, mixtures of very similar but not identical molecules (distribution of DP, slight difference in tacticity, etc.).

Restricting the conformational degrees of freedom within a polymer’s backbone can have the effect of extending the chain and endow the material with a number of interesting properties including high modulus and strength, chirality, and liquid crystallinity. Synthetic routes into rodlike polymers usually involve step growth processes, and consequently, it is often difficult to synthesize these materials with high molecular weights and with narrow polydispersities. In order to access materials with these attributes, living chain growth routes into extended chain polymers have been developed. In particular, Novak’s group has focused on living routes into polyisocyanides with bulky imine substituents that adopt 4/1 helices and alkyl polyisocyanates that adopt 8/3 helical conformations have been prepared. Although both helical, polyisocyanides and polyisocyanates have widely different conformational and rheological properties because of differences in their respective helix inversion barriers (> 27 kcal/mol vs 3-5 kcal/mol) and persistence lengths (30 Å vs 600 Å). There is been some interest in designing systems possessing the persistence lengths of polyisocyanates but with inversion barriers
approaching those observed for polyisocyanides, for various applications. The conceptual approach to this problem was to replace the carbonyl group in the polyisocyanate backbone with the more sterically demanding imine group of a polyisocyanide. Catalysts which allow for the living polymerization of carbodiimides have been developed. This system has proven itself to be quite versatile, as shown by the variety of conditions, including variations in the monomer and solvents as well as temperature extremes (polymerization have been accomplished from -40 to +107 °C), under which polymerization occurs. Preliminary results from light scattering, rheology, and other physical characterization techniques indicate that the properties these polymers display may be controlled by variation of the pendant groups along the polymer backbone, e.g., a new type of optically active N-[4-N'(α-methylbenzyl)aminocarbonylphenyl]-itaconimide(MBPI) was synthesized from itaconic anhydride, p-aminobenzoic acid and (R)-α-methylbenzylamine. The radical homopolymerization of MBPI was performed in THF at 60-130°C for 22 h to give optically active polymers having [α]_D^{25} = -46.6 to -51.8°. Anionic polymerizations of MBPI with n-butyllithium in THF and N,N'-dimethylformamide were performed, but yields were low. Radical copolymerization of MBPI (M1) were performed with styrene (ST,M2), methyl methacrylate (MMA,M2), or indene (ID,M2) in THF at 70°C. Monomer reactivity ratios (r1,r2) and Alfrey-Price Q-e values were determined.\textsuperscript{131} Chiroptical properties of the polymers and copolymers have been also investigated.

A racemic mixture (PPDLA) comprising an equal amount of optical antipodes, poly(β-phenethyl L-aspartate) (PPLA) and poly (β-phenethyl D-aspartate) (PPDA), was found to exhibit a moderately sharp and reversible transition at around 200°C.\textsuperscript{132} A
combined use of X-ray and cross polarization/magic angle spin nuclear magnetic resonance (CP/MAS NMR) methods revealed that the transition involves an interconversion of the screw-sense between the right- and left-handed \( \alpha \)-helical molecules. The backbone conformation and the molecular packing (tetragonal) were found to remain nearly identical before and after the transition. The transition mechanism previously deduced in the liquid-crystalline state seems to be consistent with experimental observations in the solid state. On the other hand, PPLA alone is known to transform from the right-handed \( \alpha \)-helix to the left-handed \( \pi \)-helix at about 130\(^\circ\)C; the crystallographic form concurrently changes from a tetragonal to a rectangular and eventually to a hexagonal arrangement at about 200\(^\circ\)C.\(^{132}\)

Polyesters having asymmetric carbons in their main chain have been synthesized and characterized by several authors in order to investigate the influence of the chirality to the physical properties of the polymers such as melting point, glass transition temperature, crystallinity, solubility in various solvents, and mechanical properties. Optically active polyesters were synthesized from chiral (2R,4R)-pentane-2,4-diol or its analogues and various aromatic diacid chlorides in refluxing 1,2-dichloroethane in the presence of pyridine. The resulting polyesters had inherent viscosities of 0.22-0.57dlg\(^{-1}\), and specific rotation from \( +4^\circ \) to \(-421^\circ \). The glass transition temperatures of the polymers range from 66 to 147\(^\circ\)C, and their initial decomposition temperatures were around 280\(^\circ\)C. No remarkable difference in thermal behavior was observed between the optically active polyesters and optically inactive polymers derived from the corresponding racemic diols.
2.2 Asymmetric Polymerization and Optically Active Polymers

Asymmetric polymerization, in which chirality is introduced to a polymer chain via a polymerization reaction, is one of the ways of synthesizing optically active polymers. Asymmetric polymerization can be classified into the following three major categories: (1) Enantiomeric polymerization (polymerization with asymmetric synthesis or asymmetric induction), (2) Enantioasymmetric (enantiomer- or asymmetric-selective or stereoselective) polymerization, and (3) Atropogenic (helix-sense-selective) polymerization.

Enantiomeric polymerization is based on the principle that an optically active polymer can be obtained if chiral centers are introduced into the polymer backbone by the polymerization or copolymerization reaction. This type of optically active polymers has been synthesized on numerous occasions. Natta, Farina, and co-workers presented the first successful examples of asymmetric polymerization of conjugated 1,3-diene monomers. They polymerized sorbates, β-styryl acrylates, and methyl-1,3-butadiene-1-carboxylate by ((+)-2-methylbutyl) lithium and butyllithium/(−)menthyI ethyl ether initiator systems, and 1,3-pentadiene in the presence of AlEt3/Ti ((−)-methoxy)4, Ti(OC4H9)4/ Al((+)-2-2-methyl butyl)3, and VCl3/Al ((+)-2-2-methylbutyl)3-Et2O catalysts to obtain optically active polymers. Asymmetric polymerization was also been performed for an allene monomer; (R)-2,3-Pentadiene gives an optically active polymer with an unique structure.

Enantioasymmetric or enantioselective polymerization is a type of polymerization in which one of the enantiomers from a racemic mixture of monomers is
polymerized preferentially. This is a kind of kinetic resolution of enantiomers. In enantioasymmetric polymerization, an optically inactive prochiral monomer or a prochiral monomer with optically active auxiliary is polymerized to give a polymer with configurational main-chain chirality. This type of polymerization has been reported for various types of olefinic compounds, although the degree of asymmetric selection or induction is unclear in most cases.

The polymers of dienes and cyclic olefins can be optically active when the chiral centers in the chain centers can be true asymmetric centers. However, for vinyl monomers (\(\text{CH}_2 = \text{CHX}\) and \(\text{CH}_2 = \text{CXY}\), 1-substituted and 1,1-disubstituted olefins), the isotactic and syndiotactic polymers can not be optically active even if significant asymmetric induction occurs at the chiral centers in the main chain, because the whole polymer chain has a mirror plane, ignoring the end groups, i.e., the chiral centers in the main chain are pseudoasymmetric. Therefore in order to obtain an optically active vinyl polymer, higher-order structural organization of the polymer is required.

The enantioasymmetric polymerizations of cyclic and olefinic compounds have been studied. The enantiomer selectivities observed in these polymerizations did not exceed 70% and were particularly low in the polymerization of olefinic monomers. A highly enantioasymmetric polymerization with selectivity over 90% was attained for the first time with the polymerization of racemic methacrylates such as, \(\alpha\)-methylbenzyl methacrylate (MBNA) using Grignard reagent-(-)-sparteine (Sp) complexes.\(^{134}\) The enantiomeric excess (\(ee\)) of the polymerized monomers at an early stage of the polymerization was 93% and the residual monomer was almost optically pure after 65-70% of the total monomer had been polymerized.
Atropogenic (helix-sense selective) polymerizations involve reactions in which polymers having chirality due to helicity are produced. Naturally occurring polymers such as proteins and deoxyribonucleic acid (DNA) possess characteristic helical structures which are stabilized through hydrogen bonds. The helix is one of the most fundamental conformations of macromolecules. The right-handed helix and left-handed helix are mirror images of each other. Therefore, helices can be chiral even if no other chiral centers are present. It is well known that stereoregular vinyl polymers often exist in a helical conformation in the solid state. For example, Natta et al.,\textsuperscript{135} showed that isotactic polypropylene is a mixture of equal amounts of right- and left-handed helices in the solid state although such helical structures are not stable in solution because of the thermodynamic tendency to assume a random conformation in solution (from lack of barriers to rotation). This result suggests that a vinyl polymer may possess a stable helical structure in the solution if a substituent is introduced on a side group that is bulky enough to prevent uncoiling of the helical polymer chain produced in the polymerization process. The existence of this type of optically active vinyl polymer was first reported in the literature for the atropogenic (helix-sense-selective) polymerization of triphenylmethyl methacrylate (TrMA) with chiral anionic initiators.\textsuperscript{136} In such a helical polymer, the right-handed helix and left-handed helix are energetically equivalent.\textsuperscript{27} However, the activation energy ($E_a$) for the helix-helix interconversion is large, such that once a helix is preferentially prepared, interconversion does not take place at room temperature.

Although many stereoregular polymers have a helical conformation in the solid state,\textsuperscript{16,137} most of them cannot maintain a helical conformation in solution, except for some polymers having an optically active side group like polyolefins,\textsuperscript{138} because the
dynamics of the polymer chain is extremely fast in solution. Therefore, isotactic polystyrene\textsuperscript{139,140} and polypropylene\textsuperscript{141} prepared with an optically active catalyst do not show optical activity due to a helical conformation, because thermodynamically a random conformation is preferred. However, it is possible to obtain optically active polymers whose chirality is based on the helical structure of single-screw sense by helix-sense-selective polymerization when rigidity of the polymer backbone or sterical repulsion of the side groups prevents random conformation. Clear atropogenic polymerizations have been attained for bulky methacrylates, isocyanides, chloral (trichloroacetaldehyde), and isocyanates. The screw sense of the helix is produced by the chirality of the initiator (catalyst) or monomer. In these examples, polyisocyanates are different from other polymers. In the asymmetric synthesis of helical bulky polymethacrylates, polychloral, and bulky polyisocyanides, the helical conformation is formed under kinetic rather than thermodynamic control (i.e., as the monomer inserts into the chain end, it adopts its helical conformation). Once formed, these conformations are locked in by the high helix inversion barriers of these polymers. In contrast, polyisocyanates have very low helix inversion barriers and as a result, the helical conformation of these polymers is under thermodynamic control (i.e., these helical polymers undergo rapid racemization (helical inversion) at normal temperatures). When an asymmetric initiator is used in the polymerization it becomes the end group of the polymer. Due to the formation of a new asymmetric center, the two forms of the helix are now diastereomers of one another and one form dominates due to thermodynamic reasons.\textsuperscript{2}

One of the most intriguing dissymmetric shapes is the helix. It was developed in natural systems in the early stages of evolution and used as the structural motif for the
molecules of life deoxyribonucleic acid and ribonucleic acid (DNA and RNA) and as an important conformational element that enforces long range order in biomacromolecules, e.g., enzymes. Helicity received attention in organic chemistry after the discovery of chirality at the end of the last century, but molecules with extended helical structures have been described only recently. Examples are the copper phenathroline-based helices reported by Lehn, he self-organized quadruple helices from amphiphilic molecules synthesized by Fuhrhop. In polymer chemistry, helical architectures have been studied since the pioneering work of Natta, Pino, and others. Most isotactic polymers exist as short range helices in solution. These are dynamic rather than static structures and the direction of the helical twist is very sensitive to small changes in polymer side-chain structure and the type of solvent.

In general, even when an enantiomerically pure monomer is polymerized, it is very difficult to identify whether the resulting polymer chain is a collection of diastereomeric segment-like conformations containing both plus (P-) and minus (M-) screw-senses or an enantiomerically pure conformation possessing only either P- and M-screw-sense. If an optically active polymer has a chromophoric main-chain adsorption due to helical conformation, the screw-sense could be to some extent characterized more by its circular dichroism (CD) and ultraviolet-visible (UV-Visible) spectroscopy than by less informative specific rotation. There have been several conformational studies using such chromophoric, optically active polymers induced by enantiomerically pure chiral pendants; polyacetylene, polydiacetylene, polythiophene, polyisocyanide, and polyisocyanate.
Triphenylmethyl methacrylate (TrMA) is the first example of a vinyl monomer which directly affords an optically active, highly isotactic polymer by polymerization with chiral initiators. Helical poly(TrMA) shows high chiral recognition ability as a stationary phase for optical resolution by (HPLC), and many racemic compounds have been resolved on this phase.\textsuperscript{4,6,54,147-150}

Bulky methacrylates such as triphenylmethyl methacrylate and 1-phenyldibenzosuberyl methacrylate give one-handed helical optically active polymers with almost perfect isotactic main chain configuration by polymerization with chiral anionic initiators. The radical polymerization and copolymerization of these monomers under chiral conditions also afford optically active polymers with prevailing one-handed helicity. N,N-disubstituted acrylamides also give optically active, helical polymers in the asymmetric anionic polymerization. Optically active polyisocyanates with a prevailing one-handed helical structure have been prepared in the copolymerization of an achiral isocyanate with a small amount of an optically active isocyanate and also in the polymerization of alkyl and aromatic isocyanates with optically active lithium alkoxide or amide compounds. The existence of a stable helical structure for polychloral has been demonstrated by studying the helical oligomers of choral. One-handed helical polyisocyanides have been prepared by the cyclopolymerization of bulky isocyanides and also by the cyclopolymerization of a 1,2-diisocyanobenzene derivative with the palladium (Pd) complex of a one-handed helical oligomer.

Helical optically active poly(triphenylmethyl methacrylate) shows remarkable chiral recognition ability when used as a stationary phase for HPLC to separate
enantiomers. The ester bond of this polymer is easily solvolyzed by methanol, a good eluant of HPLC, and the polymer gradually loses its chiral recognition ability.

On the other hand, helical polymers derived from cellulose and amylose, for example trisphenylcarbamates of these polysaccharides, show high chiral recognition and have been widely used to separate a wide range of racemates. In the polymers, the helical structures appear to play an essential role for chiral recognition, because the same derivates of oligosaccharides exhibit fairly low chiral recognition.

Methacrylates which have bulky achiral ester groups such as triarylmethyis afford optically active polymers arising from a one-handed helical structure, asymmetric polymerization leads to a right-handed or left-handed polymer depending upon the initiator, Figure 2.2.1. The specific rotation of the optically active polymer is related to the temperature of polymerization and overall helical purity of the polymer. Polymerization at low-temperature, particularly low-temperature initiation, is desirable for the formation of polymer of high optical rotation or purity. Subsequent addition of the monomer probably proceeds through the retention of the configuration to continue the formation of the isotactic right-handed or left-handed polymers, Figure 2.2.2.

![Figure 2.2.1 Structure of Helical Poly (Triphenylmethyl methacrylate) (PTrMA)](image_url)
Figure 2.2.2 Diagram of Left-handed and Right-handed Helices

The one-handed helical conformation of the polymers is maintained by sterical repulsion between the bulky ester groups. The stereochemistry of polymerization, the stereostructure of the obtained polymer, and the conformational transition sensitivity depend on the structure of the ester group.

2.3 Helix-sense-selective Polymerization of Methacrylates

Several triarylmethyl methacrylates, such as those shown in Figure 2.3.1, including diphenyl-2-pyridylmethyl methacrylate (D2PyMA) and diphenyl-4-pyridylmethyl methacrylate (D4PyMA) (Figure 2.3.2) may be polymerized into optically active helical polymers using a chiral anionic initiating system.

Figure 2.3.1 Structures of Triarylmethyl Methacrylates
2.3.1 Helix-sense-selective Polymerization of Triphenylmethyl Methacrylate (TrMA)

In 1968, Yuki et al. found that TrMA produces a highly isotactic polymer with n-butyllithium (n-BuLi) regardless of the solvent used. This was ascribed to the bulky triphenylmethyl groups which force the polymer chain to take a helical conformation. In 1979, Okamoto et al. homopolymerized TrMA with a chiral anionic initiator n-BuLi-(−)-sparteine complex. The chirality of the polymers is attributed to the stable helical conformation with one screw sense prevailing. Bulky triphenylmethyl groups restrict uncoiling of the helical polymer chain which is produced through the polymerization reaction and, hence, the first example of synthetic helical vinyl polymers, the atropogenic (helix-sense-selective) polymerization of triphenyl methacrylate (TrMA).²

The optically active TrMA was synthesized with sparteine-n-butyllithium(Sp-n-BuLi) in toluene at -78°C. The optically inactive PTrMA prepared with n-BuLi alone in tetrahydrofuran (THF) was a mixture of equal amounts of (+) and (−)-PTrMA helices.
Although the exact structure of helical PTrMA has not yet been determined, (+)-PTrMA has been postulated to possess a right-handed helix. The triphenylmethyl groups on the optically active PTrMA helix may take either a left-handed or a right-handed propeller structure.\textsuperscript{157,158} Optically active PTrMA exhibited remarkable chirality ([\(\alpha\)]\textsubscript{D} 60-390).\textsuperscript{58,159}

In the case of TrMA, the bulky triphenylmethyl group is responsible for the existence of optical activity. The polarity of the solvent is unimportant to the optical activity of PTrMA because the PTrMA obtain with Li(R)-N-(1-phenylethyl) anilide (LiAn) in THF and toluene showed similar negative rotations.\textsuperscript{136} The addition of LiAn to TrMA gives two anions whose yields may be controlled by the steric effect of (R)-N-(1-phenylethyl) anilino group. The asymmetric polymerization initiators of TrMA, lithium (R)-N-(1-phenylethyl) anilide (LiAn) and (-)-sparteine-butyllithium complexes (Sp-BuLi) are shown as follows (Figure 2.3.3).

![Diagram showing the structures of PTrMA, LiAn, and Sp-BuLi]  

Figure 2.3.3 Structures of PTrMA, LiAn and Sp-BuLi
2.3.2 Triphenylmethyl Methacrylates and Its Analogues

Polymerization of triphenylmethyl methacrylate (TrMA) giving a highly isotactic, optically active polymer is the first example of an optically active vinyl polymer whose chirality arises exclusively from the helical conformation of its main chain. The optical activity is lost when the part of the polymer of the trityl ether is converted into the methyl ester, indicating that the helical conformation is maintained by sterical repulsion of bulky trityl groups.

The polymer is prepared by anionic polymerization with the complexes of achiral organolithiums with optically active ligands or optically active organolithiums. (-)-Sparteine((-)-Sp),\textsuperscript{4,136,159-161} (S,S)-(+-) and (R,R)(-)-2,3-dimethoxy-1,4-bis (dimethylamino) butanes (+) and (-)-DDB\textsuperscript{4,153}, (S)-(+-)-1-(2-pyrrolidinylmethyl) pyrrolidine (+)-PMP and the ligands bearing biphenyl or binaphthyl moiety\textsuperscript{162-164} are effective for the complexes with achiral organolithiums.\textsuperscript{136,159} Optical activity seems to increase with degree of polymerization (DP). Chromatographic optical resolution of the mixture of right- and left-handed helical poly(TrMA)s ([α]\textsuperscript{25}D\textsuperscript{82°}) prepared in tetrahydrofuran gave a fraction of high optical activity ([α]\textsuperscript{25}D\textsuperscript{365°}) which is considered to contain pure one-handed helical polymer.\textsuperscript{165} One-handed helical poly(TrMA) shows high optical activity also in the solid state.\textsuperscript{166}

Diphenyl-4-pyridylmethyl methacrylate (D4PyMA) affords highly isotactic, optically active polymers when polymerized with (-)-Sp-BuLi and (+)-DDB-DPEDA-Li complexes.\textsuperscript{155,167} Although the optical activity of the polymers was rather low using (-)-Sp-BuLi system ([α]\textsuperscript{25}D\textsuperscript{546} = -40, (S,S)(+-)-2,3-dimethoxy-1,4-bis (dimethylamino) butane-lithium) ((+DDB-DPEDA-Li system)) ([α]\textsuperscript{25}D\textsuperscript{546} = [α]\textsuperscript{25}D\textsuperscript{546} = +14), the contents of
the prevailing helix in these polymers seem to be similar to that of optically active poly(TrMA), because the intensity of the CD spectra of the polymers was comparable to that of one-handed helical poly(TrMA).

2.3.3 Asymmetric Polymerization of Other Methacrylates

A number of triaryl methyl methacrylates are shown in Figure 2.3.1. Monomers such as diphenyl-2-pyridylmethyl methacrylate (D2PyMA) and D4PyMA can form stable helical polymers. In case of large groups, they may be too bulky to form a high polymer. On the other hand, in cases of relatively small groups such as, the diphenylethyl and diphenylmethyl, the groups are not bulky enough to maintain stable polymer helices in solution although highly isotactic polymers were obtained.\textsuperscript{167} D2PyMA can be polymerized with organolithium complexes of chiral ligands. D2PyMA forms a highly isotactic polymer as in the case of PTrMA. The helical structure of optically active PD2PyMA is less stable in solution than PTrMA.\textsuperscript{5}

Matsuda \textit{et. al.} synthesized 9-triptyceny1 methacrylate (Figure 2.3.4) and then polymerized it with chiral anionic initiators such as, (\textpm)-n-butyllithium-dimethoxy-1,4-bis(dimethylamino) butane (\textpm)-n-BuLi-DDB complex in toluene at low temperature.\textsuperscript{168} The polymer obtained showed a small negative rotation. Anionic polymerization of (\textpm)-S-diphenyl (1-methyl-pyrrolidin-2-yl) methyl methacrylate (DMPMA, Figure 2.3.5) is another example of asymmetric polymerization of methacrylates. This monomer can give an optically active polymer of helical conformation of a single screw-sense. The polymer exhibits a reversible helix-helix transition in a solution of methanol containing an acid.\textsuperscript{169}
Figure 2.3.4 Structure of 9-Triphenyl Methacrylate

Figure 2.3.5 Structure of DMPMA

Suda et al. found that the complexes of n-BuLi with their chiral biphenyl or binaphthyl ligands were able to polymerize both methyl methacrylate (MMA) and benzyl methacrylate, but did not give optically active products. They had proven that a bulky side group as the triphenylmethyl group is necessary for polymethacrylates to maintain a stable helical conformation in solution. N,N-Diphenylacrylamide, N-phenyl-N-(1-naphthyl) acrylamide and N-phenyl-N-(2-naphtyl)acrylamide (Figure 2.3.6) can be asymmetrically polymerized with Sp-n-BuLi complex to give optically active polymers $[\alpha]^{250}_{D}82.60$ The chirality of these polymers may be due to the one-handed helical conformation. The steric hindrance of the side group of the monomer is enough to maintain the helical conformation formed during the polymerization.
Mohri et al.\textsuperscript{170} prepared optically active poly(2-(6-methylpyridyl) diphenylmethyl methacrylate) (PMPyDMA) (Figure 2.3.7) with chiral anionic initiators, organolithium complexes of (S,S)-(+)\textemdash1,4-bis (dimethylamino) 2,3-dimethoxybutane (DDB). The polymer showed a large optical rotation due to the prevailing one-handed structure.

![Figure 2.3.6 Structures of N,N-Diphenylacrylamide, N-phenyl-N-(1-naphthyl) acrylamide, and N-phenyl-N-(2-naphthyl) acrylamide.](image)

Okamoto et al.\textsuperscript{70} reported that 4-phenylbutyl and butyl isocyanates (PBI and BI) gave optically active polymers by anionic polymerization with the (R)-(+)\textemdashN-benzyl-1-phenylethyl amine [(+)-BPEA]/lithium amide initiating complex. The BI and PBI are
helical polymers. The polyisocyanates obtained with tert-buthyllithium-(-)-sparteine (t-BuLi-(-)-Sp) are not optically active.

Recently Okamoto et al. carried out the polymerization of (-) and (+)-phenyl-2-pyridyl-o-tolylmethyl methacrylate (PPyTMA) with (-)-2 (R), 3(R)-dimethoxy-1,4-bis(dimethylamino) butane [(−)-DDB]-fluorenyllithium (FILi) complex.\textsuperscript{171} High enantiomeric selection was observed. They also demonstrated that in the polymerization of the optically active (+)-PPyTMA by (+)- and (-)-DDB-lithium amide complexes, only (-) polymers of almost the same optical rotation were obtained.\textsuperscript{172} It has been understood that the chiral ester group of (+)-PPyTMA forces the polymer chain to take the same helical structure regardless of the chirality of the ligand. In their study, in order to simplify the enantiomer-selective polymerization of (-) or (+)-PPyTMA, the living poly[(+)-PPyTMA] was used for initiating the polymerization, and it was clearly demonstrated that high enantiomer selection took place only by a helical growing end. (+)- and (-)-DDB-FILi and N,N'-tetramethyl-ethylenediamine-benzyllithium (TMEDA-BuLi) complexes were used as chiral and achiral initiators, respectively.

Optically active phenyl-2-pyridyl-o-tolylmethyl methacrylate (PPyoTMA) having various enantiomeric excesses was polymerized with diisopropyl peroxycdicarbonate in toluene at 40°C. Isotactic polymers were obtained. The polymers showed large optical rotations which are opposite in sign to the rotation of the starting monomer and the optical activity was higher than expected from the enantiomeric purity of the monomeric units in the polymer, indicating that a right- or left-handed helix was formed in excess from the steric effect of the chiral side group.\textsuperscript{173}
Triphenylmethyl methacrylate (TrMA) gives a highly isotactic, optically active polymer through asymmetric anionic polymerization using complexes of organolithium and chiral ligands.\textsuperscript{2,4,136} The optical activity of poly(TrMA) is based mainly on a one-handed helical conformation of the main-chain which is maintained by steric repulsion between the bulky side groups. The direction of the helix is controlled by the chirality of the ligands of the initiator complexes. Optically active phenyl-2-pyridyl-o-tolylmethyl methacrylate (PPyoTMA),\textsuperscript{171,173,174} a TrMA analog with a chiral ester group, also gives an optically active helical polymer by asymmetric anionic polymerization,\textsuperscript{173} however, in this polymerization, the helix-sense is controlled by the chirality of the ester group rather than by that of the initiator. This is in contrast to the fact that the helicity is controlled by the chiral ligand in the polymerization of phenyl-2-pyridyl-m-tolylmethyl methacrylate.\textsuperscript{171,175} A high enantiomer selectivity has been found for the polymerization of racemic PPyoTMA using optically active anionic initiators.\textsuperscript{173} In addition, it has also been found that the helical polymer anion consisting of pure enantiomeric monomeric units of PPyoTMA can discriminate between enantiomers of the racemic monomer and polymerizes exclusively one antipode when used as a polymeric initiator.\textsuperscript{173}

There is also interest in the helix-forming propensity and asymmetric induction leading to a one-handed helix based on the side chain chirality in the radical polymerization of PPyoTMA, and, also the copolymerization with TrMA and methyl methacrylate (MMA). The optically active PPyoTMA monomeric units can induce a single-handed helical conformation not only via homopolymerization but also in copolymerization with TrMA.\textsuperscript{176}
Asymmetric anionic polymerization of diphenyl-2-pyridylmethyl methacrylate by fluorenyllithium or N,N’-diphenylethlenediamine monolithium amide complex of (S)-(+)2-(1-pyrrolidinylmethyl)-pyrrolidine gave quantitatively an almost purely one-handed helical polymer with narrow molecular weight distribution. Triphenylmethyl methacrylate (TrMA) and diphenyl-2-pyridylmethyl methacrylate (D2PyMA) are the unique monomers which form only highly isotactic polymers regardless of polymerization conditions such as initiators and solvents. The polymerization of TrMA and D2PyMA with chiral anionic initiators gives optically active polymers with relatively stable helical conformation even in solution because of the bulkiness of the ester groups. (-)-Sparteine-fluorenyllithium (SpFILi) and (S,S)-(+)1,4-bis(dimethylamino)-2,3-dimethoxybutane-N,N’-diphenylethlenediamine monolithium amide (DPEDA-Li) complexes afford helical poly(D2PyMA)s. Anionic polymerization of (+)-S-diphenyl (1-methyl-pyrrolidin-2-yl) methyl methacrylate gave an optically active polymer of helical conformation of single screw-sense. The polymer exhibited a reversible helix-helix transition in a solution of methanol containing an acid.

Recently, it has been found that optically active poly(diphenyl-2-pyridylmethyl methacrylate) [poly(D2PyMA)] and poly((+)-phenyl-2-pyridyl-m-tolylmethyl methacrylate) [poly((+)-PPymTMA)] undergo a conformational change which induces inversion of the helicity of the polymer chain. Stereomutation of one-handed helical poly(D2PyMA) affords a mixture of right- and left-handed helices which are slowly interconvertible and separable by HPLC on a chiral stationary phase. On the other hand, (-)-poly((+)-PPymTMA) which is prepared by helix-sense-selective
polymerization at -78°C undergoes irreversible stereomutation to (+)-poly((+)-PPymTMA) due to the chiral side group of the polymer in solution at 60°C. This polymer may be the first example of a vinyl polymer which undergoes nearly perfect slow reversible transition from one helix to the other. Such a transition has been observed for poly-L-proline,\textsuperscript{178-181} its derivatives,\textsuperscript{182,183} and polynucleotides.\textsuperscript{184-187}

The stability of the helical conformation in optically active poly(triphenylmethyl methacrylate) (PTrMA) was investigated by heating the polymer solutions to 100°C. The optical rotation slowly disappeared with time, and some preliminary experiments showed that this phenomenon is not due to a typical racemization process, but is accompanied by a loss of triphenylmethyl (Tr) groups due to a secondary reaction. Experimental results in the presence of methanol indicated that the decrease of optical activity occurs from the final solution. In order to explain the above results, full characterization of copolymers obtained by interrupting the methanolysis at different conversions was performed. As a working hypothesis, it was assumed that the reaction starts at the end of the helices with a Tr-oxygen bond fission and the reaction proceeds along the chain mainly with formation of a block of PTrMA and one block of a probably random methacrylic acid anhydride/methacrylic acid copolymer.\textsuperscript{188}

In the field of high polymer, relationships between optical activity and conformation most have investigated the case of natural and synthetic polyaminoacids.\textsuperscript{181} Interesting results were obtained, the optical activity can be determined very easily and yield interesting information even when operating on fractionated polymers. Analogous investigations yielded interesting results also in the field of optically active vinyl polymers.\textsuperscript{138} In some cases, a remarkable dependence of optical activity on
stereoregularity was experimentally found and the optical activity was used to study the relationship between stereoregularity and conformation of the macromolecule in solution.\textsuperscript{189} For poly(\textalpha-olefins), investigations of their conformational equilibria in solution gave a linear dependence of optical activity on temperature. Due to the fact that the optical activity of vinyl polymers investigated is mainly related to the presence of asymmetric carbon atoms in the lateral chains, evaluation of the thermodynamic properties of the optically active macromolecular systems starting from the temperature coefficient of rotation is very complicated.\textsuperscript{188}

Chromatographic experiments indicate that the helical turn of PTrMA consists of three or four monomeric units and the stable helix starts to form over two turns.\textsuperscript{160,161} Furthermore, conformational energy calculation for suitable models of PTrMA gives the lowest energy with 3,6 monomer units per turn and 2.0 Å pitch per monomer unit.\textsuperscript{190}

2.4 Chiral Initiators for Asymmetric Polymerization

The key component of asymmetric polymerization is the chiral initiators. It is important to choose appropriate chiral ligands to prepare the chiral initiating complexes. It is known that TrMA may be polymerized with chiral initiators such as LiAn and (-)-Sp-BuLi to a highly isotactic helical polymer with large optical rotation.

Also, (-)-sparteine fluorenyllithium (Figure 2.3.8) complex affords poly(TrMA) of almost pure one-handedness accompanying with a small amount (\(\approx 10\%\)) of oligomers.\textsuperscript{153,191}
Figure 2.3.8 Structure of (-)-Sparteine-fluorenyllithium

Chiral ligands such as, (S)-(+)1-(2-pyrrolidinymethyl)-pyrrolidine (PMP), (+)-2,3-dimethoxy-1,4-bis (dimethylamino butane) [(+)-DDB], (-)-2,3-dimethoxy-1,4-bis(dimethylamino butane) [(-)-DDB], (-)-sparteine (Sp), (S)-(S)-1-methyl-2-(piperidinomethyl)pyrrolidine (MPP), (S,S)-(+)3, 4-dimethoxy-N (2-dimethylamino) ethyl) pyrrolidine (DDEP), and (S,S)-(+) N-N-benzyl-3,4-dimethoxypyrrroline (BDP) complexed with N,N'-diphenylethlenediamine monolithium amide (DPEDA-Li) can be used as chiral initiators for asymmetric polymerization of D2PyMA (Figure 2.3.2).\textsuperscript{155,165}

On the other hand, F1Li is not effective for the helix-sense-selective polymerization of D2PyMA. A mixture of (+)- and (-)-poly(D2PyMA)s was always obtained with fluorenyllithium.\textsuperscript{155} Sparteine complexes gave a polymer of low optical activity. DDB was a better chiral ligand and its complex, particularly the complex with DPEDA-Li, was effective in preparing PD2PyMA with high optical rotation. Lithium complexes of novel chiral ligands (Figure 2.3.9), derived from tartaric acid, gave optically active PD2PyMA in good yields.\textsuperscript{177}
2.5 Application of Chiral Polymers

Many optically active polymers have been used as chiral catalysts, chiral hosts or chiral absorbents.\(^{192,193}\) These polymers are usually naturally occurring polymers or polymers derived from optically active monomers. Optically active Poly-TrMA prepared by helix-sense-selective polymerization with one handed helix is extremely effective as a chiral stationary phase for optical resolution of various racemic compounds by high-performance liquid chromatography (HPLC).\(^{45}\) Various racemic compounds with aromatic groups were completely resolved by high-performance liquid chromatography on optically active (+)-poly(triphenylmethyl methacrylate) using methanol as eluent. Higher molecular weight (+)-PTrMA (DP>80) can be used as a chiral stationary phase if it is ground and sieved to small uniform particles. Merrifield succeeded in synthesizing long chain peptides using polymeric catalyst.\(^{194}\) Fridkin, Patchornik, and Katchalski used insoluble polymeric active ester of amino acids to acrylate the N-termini of peptides in solution.\(^{195}\) A polymeric analog can be devised for useful soluble reagent if there are
distinct advantages. The polymeric reagents have distinct advantages, such as ease of separation of a by-product from a reaction mixture, less toxicity and odor, and capable of being used in a continuous flow process instead of a batch process.

Much of the interest in optically active polymers stems from the potential of these materials for several specialized uses, viz., (i) chiral matrices for asymmetric synthesis, (ii) chiral stationary phases for the resolution of racemates, (iii) synthetic molecular receptors, and (iv) chiral liquid crystals for ferroelectric and nonlinear optical applications.

2.6 Synthetic Peptides

The research groups of Samuel Gellman and Dieter Seebach have independently reported synthetic molecular chains that can fold into a surprisingly stable new type of structure analogous to the α-helix. Instead of the α-amino acids found in natural proteins, the Gellman and Seebach systems are composed of linked β-amino-acid units. This has brought into focus efforts to design synthetic molecules that fold into well-defined three-dimensional structures. A goal of this emerging field is to extend the repertoire of folded molecular structures, beyond those that exist in nature. This work demonstrates that chains of naturally occurring α-amino acids or nucleic acids do not have the monopoly on folded structures, and that molecular engineers are not limited to the folding motifs found in nature.

The larger biological molecules, especially proteins and RNA, owe their complex activities to stable folded structures that result largely from a balancing of non-
covalent interactions. Attractive, repulsive, solvation and entropic forces strike a
dynamic balance that enables the flexible chains to fold into just a single functional
protein or RNA conformation, out of the astronomical number of possibilities. It is this
folding that turns the one-dimensional information of the genetic code into the three-
dimensional molecules that are responsible for life. So before synthetic molecules can be
designed and produced that approach the exquisite complexity of natural proteins or RNA
molecules, these same forces need to be harnessed in predictable ways.

Gellman and co-workers used nuclear magnetic resonance, circular dichroism
and X-ray crystallography to confirm that chains composed of six β-amino-acid units, in
this case trans-2-aminocyclohexanecarboxylic acid forms well-defined helices in
methanol solution and in the solid state.\textsuperscript{20} As predicted by computer simulations, the
helix is stabilized by hydrogen bonds between every third unit. This folding pattern
results in 14-atom ‘rings’ being formed by the hydrogen bonds, so Gellman has called the
structure the 14-helix.\textsuperscript{201} The 14-helix has a length of 5.0Å per turn, and an almost
perfect three-fold symmetry owing to its having 3.0 residues per turn. The standard α-
helix found in proteins has 3.6 residues and 5.6 Å turn. The authors used NMR to
measure the time it took for amide hydrogen atoms to exchange with hydrogens from the
solvent. The amide hydrogens usually exchange within minutes unless they are taking
part in strong hydrogen bonds, but the two interior hydrogen-bonded N-H (amine) in
Gellman’s 14-helix took more than two days to exchange. These extremely slow
exchange rates demonstrate the remarkable stability of this folded structure. In contrast,
α-amino-acid peptides in this size range rarely show any identifiable folding in solution,
a much less robust structure. The cyclohexyl rings presumably help to stabilize the
structure by restricting the conformational flexibility of the individual β-amino-acid units. The rings radiate out away from Gellman’s 14-helix to form three ‘stacks’. In addition, they are ideal sites for adding groups to make derivatives of the basic 14-helix.

Seebach et al.\textsuperscript{201} described β-amino-acid analogues prepared in two synthetic steps from the corresponding α-amino-acids. In this case, a -CH\textsubscript{2}- group was inserted between the α-carbon atom and carboxylic acid of each α-amino acid. Peptides resulting from these β-amino acids, called β-peptides, were investigated for folding. One of them showed behavior consistent with its being highly structured in solution. NMR spectra were used to construct a model of the structure in pyridine, the data were consistent with a 14-helix. The Seebach system does not have the cyclohexane rings of Gellman to restrict flexibility of the β-amino-acid units. So the preference of identifiable secondary structure in such a small β-peptide is extraordinary, especially when one considers that the extra -CH\textsubscript{2}- group of the β-amino acids might be expected to make the resulting β-peptides more flexible than α-amino-acid peptides, not more structured.

The groups of Gellman and Seebach have established that α-amino acids are not the only amino-acid building blocks that can form molecular chains with interesting folded structures. Their work is a nice complement to the growing number of studies using α-amino-acid building blocks,\textsuperscript{204} sometimes in conjunction with abiotic elements,\textsuperscript{205,206} to create novel folded structures. There is also a small but expanding list of entirely abiotic systems that use interactions such as metal binding to stabilize folded structures. A critical next step will be to ‘bundle’ abiotic folded elements into even larger, more complex structures that contain cavities in which binding and/or catalysis can take place.
It has been previously shown that β-amino acid oligomers "β-peptides" are suited for adoption of compact secondary structures stabilized by intramolecular hydrogen bonds. β-Peptides may be synthesized by the Arndt-Eistert homologation with concomitant peptide coupling and structure determination. The β-hexapeptide (H-B-HVal-B-HAla-B-HLeu)\(_2\)-OH was prepared from the component L-β-amino acids by conventional peptide synthesis, including fragment coupling. Cyclo-β-tri and cyclo-β-hexapeptide were also prepared. The β-amino acids were obtained from α-amino acids by Arndt-Eistert homologation. The β-peptides were characterized by CD and NMR spectroscopy (COSY, ROESY, TOCSY, and NOE-restricted modelling), and by X-ray crystal-structure analysis. β-Sheet-type structures (in the solid state) and a compact, left-handed or (M) 3-1 helix of 5Å pitch (in solution) were discovered. Comparison with the analogous secondary structures of α-peptides show fundamental differences, the most surprising one at this point being the greater stability of β-hexapeptide helices. There are structural relationships of β-peptides with oligomers of β-hydroxyalkanoic acids, and dissimilarities between the two classes of compounds are a demonstration of the power of H-bonding. The β-hexapeptide is stable to cleavage by pepsin at pH 2 in H\(_2\)O for at least 60 h at 37°C, while the corresponding α-peptide H-(Val-Ala-Leu)\(_2\)-OH is cleaved instantaneously under these conditions.

β-Amino acids are much less frequent in nature than α-amino acids. Not only are certain β-amino acids active as monomers biologically, they have also been found incorporated into naturally occurring peptides with important pharmacological properties. Because of the additional α-methylene group, β-amino acids represent a class of
conformationally more flexible compounds as compared to the α-amino analogues. In contrast, modern amino acid chemistry aims to develop conformationally restricted amino acids which, after incorporation into peptides, may enhance biological activity by decreasing the degree of freedom of the peptide to undergo rotation around certain single bonds. However, some peptides in which an α-amino acid residue was replaced by a β-amino-acid residue at a specific position in the peptide sequence have shown increased stability against certain peptidases with retention or improvement of the biological activity. An important class of β-amino acid derivatives are the β-lactam antibiotics.

The synthesis of β-amino acids has been extensively studied. Ideally, a route is chosen, from the large array of methods available for β-amino acid synthesis, in which the β-amino acids are cheap, enantioselectively prepared from a readily available starting material. α-Amino acids are cheap, enantiomerically pure, commercially available compounds which have frequently served as starting materials for the synthesis of β-amino acids. This conversion can be achieved in only two steps using the Arndt-Eister homologation of N-protected α-amino acids, a method which is especially attractive as the reactive intermediate arising from the Wolff rearrangement of a diazo ketone can be trapped with the amine functionality of an amino-acid derivative. By applying this strategy, a β-amino acid derivative is produced with concomitant peptide coupling. Chain elongation at the N-terminus, by N-deprotection and repetition of the Arndt-Eister homologation with another α-amino acid-derived diazo ketone, produces a peptide which contains a sequence of β-amino acids.201

Short-chain α-peptides are known not to form secondary structures in solution. To the surprise of many chemists, analogs such as the β-hexapeptide consisting
of β-rather than α-amino acids, adopt stable helical backbone conformations in methanol. Apparently, the additional -CH₂- group in each amino acid residue of the β-hexapeptide does not lead to a more extended, flatter conformational-energy hypersurface, but to more pronounced minima as compared to those of corresponding α-peptides. The conformational preferences of α-peptides has been added another element of conformational order the staggering of the ethane bonds in the β-amino-acid residues.⁰²¹

2.7 Induced Helices

The equilibrium in a dynamic racemic mixture may be displaced to favor one enantiomer by a nonracemic chiral entity external to the chiral racemic structure. Ciardelli have come across this phenomenon in a stiff helical macromolecule where cooperative interactions give rise to an easily measurable excess of one helical sense even though the energetic preference per monomer unit is far smaller than has been possible to determine previously.⁰¹⁹

Boronic acids are known to form a complex with diol-containing compounds including carbohydrates, and boronates immobilized in polymer matrices and have been exploited in affinity chromatography⁰²⁰,⁰²¹ for the separation of tRNA, glycoproteins, and carbohydrates enantiomers.⁰²¹,⁰²² Aromatic boronic acids have been used as synthetic carriers of carbohydrates and ribonucleosides for selective membranes transport,⁰²³-⁰²⁵ chemosensors⁰²⁶-⁰²⁹ and receptors⁰³⁰-⁰³⁵ of mono- and disaccharides, and chiral resolving agents of diols and diamines in NMR.⁰³⁶,⁰³⁷ In these studies, covalent complex formation between the aromatic boronic acids and diols or carbohydrates was the key for molecular
recognition.\textsuperscript{209-228} However, limited studies have dealt with the complex formation of aromatic boronic acids with other difunctional chiral molecules such as amino alcohols, hydroxycarboxylic acids, dicarboxylic acids, diamines, and amino acids.\textsuperscript{214,229-237}

Recently, Yashima \textit{et. al.} have found that an achiral, stereoregular poly((4-carboxyphenyl)acetylene) can change its structure into a prevailing one-handed helix upon complexation with chiral amines, and its helical sense can be used as a probe for the chirality assignment of amines using the circular dichroism (CD) of the complexes.\textsuperscript{238} The polymer, however, is not sensitive to other important chiral molecules in organic and natural products chemistry (for instance, diols, polyols, and carboxylic acids). They reported formation of various kinds of acyclic and cyclic chiral complex molecules with two or more functional groups including carbohydrates and steroids with a novel stereoregular poly(phenylacetylene) derivative, poly((4-dihydroxyborophenyl)acetylene) (poly-1), which induced a prevailing helical conformation accompanied by a split-type induced CD (ICD). Although the CD exciton chirality method developed by Nakanishi and Harada\textsuperscript{239} has been extensively applied for determining the absolute configurations of chiral molecules, the method requires the introduction of chromophores suitable for the exciton coupling at hydroxy or amino groups.\textsuperscript{240-244}

The complexes showed characteristic, split-type ICD, and the enantiomers gave ICDs which are mirror images. Poly-1 formed complexes with other chiral molecules such as 1,2-amino alcohols, 1,1- and 1,2-hydroxycarboxylic acids, a 1,4-diamine, and a 1,2-dicarboxylic acid. These ICD results indicate that these chiral molecules can sufficiently interact with the boronic acid residues of poly-1 to induce the helical conformation with a predominant screw sense,\textsuperscript{238} probably by tetragonal (sp\textsuperscript{3}}
hybridization) complex formation with the chiral molecules in solution.\textsuperscript{209-212,220-225} The split-type and magnitude of the Cotton effects seem to be closely correlated with the stereochemistry and configuration of the molecules.

Poly-1 provides a new promising probe for chirality assignments and stereochemical studies of various kinds of chiral molecules including carbohydrates and steroids; and will be applicable as a sensory system of chiral molecules including biopolymers such as polysaccharides, glycoproteins and RNA. Poly-1 also has applications for solid membrane transport system.\textsuperscript{245}

Most primary amines and amino alcohols of the same configuration gave the same sign for the induced Cotton effect; however, secondary and/or tertiary amines used in the present study tended to show Cotton effect signs opposite to those of the primary amines and amino alcohols of the same configuration. The magnitude of the ICD increases with an increase in the bulkiness of the chiral amines. The complexation dynamics during the formation of the helical structure of poly-1 with achiral amines were investigated on the basis of the spin-spin relaxation behavior and \textsuperscript{1}H NMR, CD, and optical rotatory dispersion (ORD) titrations. The complex formation of poly-1 with chiral amines such as 1-(1-naphthyl) ethylamine and 2-amino-1-propanol exhibits a positive nonlinear effect between the enantiomeric excess of the chiral amines, amino alcohols and the observed ellipticity of the Cotton effects. The excess enantiomer bound to poly-1 may induce an excess of a single-handed helix (right- or left-handed helix), which may result in a more intense ICD than that expected from the enantiomeric excess of the amine. Moreover, it was found that the coexistence of achiral amines such as 1-aminoethanol also induce an excess of one helical sense of poly-1.
Okamoto et. al. has found the stereoregular poly(phenylacetylenes), such as poly((4-carboxyphenyl) acetylene), poly((4-dihydroxyborophenyl) acetylene), and poly((4-N,N’-diisopropylaminomethyl) phenylacetylene) form a predominantly one-handed helix upon complexation with optically active compounds, such as amines, sugars, and acids, respectively, and the complexes exhibit a characteristic induced circular dichroism (ICD) in the UV-visible region. The Cotton effect signs of ICDs can be used as a probe for the assignments of the absolute configuration of the chiral compounds. 

Polyacetylenes were prepared bearing a carboxy or amino group by polymerization of propiolic acids esters and propargylamines with [[norbornadiene]-rhodium(I) chloride]$_2$ [Rh(nbd)Cl]$_2$ as a catalyst in order to investigate whether these aliphatic polyacetylenes would form an induced helix upon complexation with optically active compounds as seen in cases of the poly(phenylacetylene) derivatives bearing functional groups. It was found that poly(1,1-diethylpropargylamine) can form an induced helix upon complexation with optically active acids, e.g., (R)- and (S)-mandelic acids. This maybe the first example of the prevailing helix formation of an optically inactive, aliphatic polyacetylene ascribed to acid-base interaction.
CHAPTER III
EXPERIMENTAL SECTION

3.1 Apparatus

Vacuum Line

Figure 3.1.1 shows the schematic of the vacuum line used to provide the vacuum environment for the polymerization reactions. The vacuum source consisted of a mechanical pump. A low temperature liquid nitrogen trap was in line to prevent reaction vapors from entering the pump. The reaction vessels were connected to the high-vacuum line via three-way stopcocks. Generally, the vacuum pressure provided by the system was approximately $10^{-4}$ torr.

Apparatus for the purification of 1,2-Dianilinoethane

The apparatus in which the 1,2-dianilinoethane was purified was essentially a round bottomed flask (100 ml) with a fused side arm. The side arm contained four breakseals (Figure 3.1.2).

Apparatus for Purification of Chiral Ligands: (+)-DDB and (-)-DDB and 3M4VP

The apparatus for the purification of chiral ligands: $(\pm)$-DDB and 3M4VP is shown in Figure 3.1.3. It was prepared by attaching a side flask (100 ml) and four breakseals. The chiral ligands were kept in the side flask.
Figure 3.1.1 The Vacuum Line
To Vacuum Line

Figure 3.1.2 Apparatus for purification of DPEDA
To Vacuum Line

Figure 3.1.3 Apparatus for purification of (+)-DDB, (-)-DDB and 3M4VP
Apparatus for the Polymerization

Anionic polymerization was performed in a 100 ml round bottomed flask as shown in Figure 3.1.4. Three breakseal ampoules, containing purified 3M4VP, DPEDA and (+)-DDB or (-)-DDB, were fused on the flask. Butyllithium was injected in the fourth side arm. The assembled apparatus was attached to the vacuum line through the joint.

3.2 Reagents

Azo-bis-isobutyronitrile

Azo-bis-butyronitrile (Aldrich 98%, F.W. 164.21, m.p. 103-105°C) was recrystallized from methanol and stored under vacuum conditions.

Benzene

Benzene (Fisher certified) was stirred and dried from CaH₂.

Butyl catechol

Butyl catechol (Aldrich, 97%, F.W. 166.22, m.p. 52-55°C, b.p. 285°C) was used as received.

n-Butyllithium

n-Butyllithium (Aldrich, 2.0M solution in hexane, F.W. , m.p. 64.06, d 67°C) was used as received without further purification.

Calcium Hydride

Calcium Hydride (CaH₂) (Aldrich, 40 mesh, 95%, F.W. 42.10, d 1.900 g/ml) was used as received.
Figure 3.1.4 Apparatus for the Polymerizations
Chloroform

Chloroform (Aldrich, 99.8%, A.C.S. Reagent, F.W. 119.38, m.p. -63°C, b.p. 61°, n²⁰ 1.4460, d 1.492 g/ml) was used as received.

Chloromethylmethyl ether

Chloromethylmethyl ether (ClCH₂OCH₃) (Aldrich, FW 80.51, b.p. 55-57° n²⁰ 1.3960, d 1.060 g/ml, F.p. 15°C was used as received.

1,2-Dianilinoethane

1,2-Dianilinoethane (Aldrich, 99%, F.W. 212.30, m.p. 65-67°C) was dried three times azeotropically using benzene, vacuumed and separated into breakseals.

Diethyl ether

Diethyl ether (Aldrich, Anhydrous, 99+% F.W. 74.12, b.p 34.6°C, n²⁰ 1.3035, d 0.706 g/ml) was dried by refluxing over CaH₂ just before use.

Diisopropyl amine

Diisopropyl amine (Aldrich, redistilled, 99.5% F.w. 143.23, m.p. -61° b.p. 84° n²⁰ 1.3920 d 0.722 g/ml Fp -6°C was dried by refluxing over CaH₂ just before use.

(R,R)(-)-2,3-Dimethoxy-1,4-bis(dimethylamino)butane [(-)-DDB]

(R,R)(-)-2,3-Dimethoxy-1,4-bis(dimethylamino)butane (DDB) (Aldrich, 96%, F.W. 204.32, b.p. 62-64 °C/ 3 mm, n²⁰ 1.4345, d 0.896 g/ml, [α]²²D -14.5°) was dried by distilling over CaH₂ under reduced nitrogen pressure and separated into breakseals just before use.

(S,S)(+)-2,3-Dimethoxy-1,4-bis(dimethylamino)butane [(+)-DDB]

(S,S)(+)-2,3-Dimethoxy-1,4-bis(dimethylamino)butane (DDB) (Aldrich, (96%, F.W.204.32, b.p. 62-64 °C/ 3 mm, n²⁰ 1.4343, d 0.896 g/ml, [α]²²D +14.5°) was dried by
distilling over CaH₂ under reduced nitrogen pressure and separated into breakseals just
before use.

**Magnesium sulfate**

Magnesium sulfate (Fisher certified, anhydrous, F.W. 120.37) was used as received.

**(R)-Mandelic acid**

Mandelic Acid (Aldrich, F. W. 152.15, m.p. 131-133 °C, [α]²³_D -153°, c = 2.5
H₂O) was used as received.

**(S)-Mandelic acid**

Mandelic acid (Aldrich, F.W. 152.15, m.p. 131-134°, [α]²⁰_D + 154°, c = 2.8 H₂O) was used as received.

**Methanol**

Methanol (Aldrich, 99%, A.C.S. Reagent, F.W. 32.04, mp -98°, bp 64.7°, n²⁰_D
1.3290, d 0.791 g/ml, Fp 11°C was used as received.

**Poly(ethylene glycol)**

Poly(ethylene glycol) (PEG) (Aldrich, d 1.204. Crystalline powder. Average Mₙ
3,400, Viscosity (210°F) 90 centistokes. Tm 62°C) was used as received.

**Poly(ethylene oxide)**

Poly(ethylene oxide) (PEO) (Aldrich, Powder Average Mv 600,000, Tm 65°C. Inhibited with 200-500 ppm BHT) was used as received.

**2-Propanol**

2-Propanol (Fisher, histological grade, F.W. 60.10, mp -89.5°, bp 82.4°, n²⁰_D
1.3770, d 0.785 g/ml, Fp 53°F(11°C)) was used as received.
Tetrahydrofuran

Tetrahydrofuran (THF) (Fisher certified, F.W. 72.11, b.p. 65.8-66.1°C, d 0.885 g/ml) was refluxed and distilled from sodium and benzophenone just before use.

Toluene

Toluene (Fisher certified, F. W. 97.18, b.p. 110°C, \( n^\circ_{D} 1.4950 \), d 0.915 g/ml) was purified by reflux over benzophenone and distilled just before use.

3.3 Procedures

3.3.1 Procedure for the Synthesis of 3-methyl-4-vinylpyridine

4-(\( \beta \)-methoxyethyl)-3-methylpyridine: THF (340 ml) was placed into a three-necked 500 ml flask, maintained under dry nitrogen. To the flask containing THF 15.7 ml of 3,4-lutidine (15g, 0.14 mol) was added and the solution was cooled to −78°C and 74 ml of n-BuLi (2.0 M, 0.15 mol) was added. The solution turned dark orange and was stirred at −78°C for 15 minutes. The carbanion was terminated with excess chloromethylmethylether (14.5 ml or 0.20 mol). To the reaction mixture, 500 ml of 50:50 ethyl ether/pentane mixture was added and the solution was extracted three times with 375 ml of deionized water. The solution was dried over MgSO\(_4\). After concentrating the ethyl ether/pentane solution, 4-(\( \beta \)-methoxyethyl)-3-methylpyridine was obtained by flash chromatography on a column of basic alumina with 90:5:5 hexanes:THF:CH\(_3\)OH as a eluant. Distillation gave the pure 4-(\( \beta \)-methoxyethyl)-3-methylpyridine in 67% yield. Elemental Analysis: Theoretical: 71.54% C, 8.61% H, 9.27% N, 10.59% O; Found: 70.50% C, 8.93% H, 9.20% N, 11.37% O.
**3-methyl-4-vinylpyridine:** To a chilled (-78°C) THF solution (385 ml), containing 4-(β-methoxyethyl)-3-methylpyridine (9.07 g, 0.060 mol), potassium tert-butoxide (13.35 g, 0.119 mol) was added in one portion. The cooling bath was removed, and the mixture was allowed to warm up to room temperature and stirred for 2.5 hr. Tert-butyl catechol (0.5 g) was added as a polymerization inhibitor. The mixture was diluted with diethyl ether (400 ml) and extracted (3x150 ml) with deionized water. The solution was dried over MgSO₄ and purified by flash chromatography on a column of basic alumina with 90:5:5 hexanes:THF:CH₃OH as the eluant. Removal of the solvent under reduced pressure gave pure 3-methyl-4-vinylpyridine. [4g (44%)] as a clear oil: ¹H NMR(CDCl₃) δ:8.30(s), 8.28(d), 7.20(d), 6.80(m), 5.75(d), 5.40(d), 2.20(s). Elemental Analysis: Theoretical 80.72 % C, 7.56 % H, 11.76 % N; Found: 79.37 % C, 7.88 % H, 11.42 % N.

### 3.3.2 Polymerization Reactions

A series of poly(3-methyl-4-vinylpyridines), (P3M4VP), were synthesized by the anionic living polymerization technique. All reagents used were stringently purified. High-vacuum line (10⁻³~10⁻⁵ torr) and breakseal techniques were used for the preparation of the polymers.

### 3.3.3 Radical Polymerization

In a 500 ml round bottom flask was placed 0.100 mg of 2,2-azo-bis-methyl-2-methyl propionate (AIBN), recrystallized in acetone. Benzene (1 g) dried overnight by calcium hydride (CaH₂) was distilled over the AIBN via vacuum. Then, 0.5 g of
monomer (3-methyl-4-vinylpyridine) was added in one portion. The system was sealed under vacuum and the mixture was stirred in an oil bath at 50 °C for 72 hr. The product was precipitated in 150 ml of toluene and dried in a vacuum oven overnight. The polymer was obtained in 3.22 % yield.

3.3.4 LDA (Lithium diisopropyl amine) polymerization

To a 100 ml round bottomed flask was placed 3.7 x 10⁻³ g (3.7x10⁻⁵ moles, 5.1 x 10⁻³ ml) diisopropyl amine dried over calcium hydride (CaH₂). THF/Toluene (90/10) (25 ml), dried over sodium/benzophenone was distilled in via vacuum line. Then 2.3 x 10⁻² ml (3.7 x 10⁻⁵ moles, 1.6M) of n-BuLi was added and the reaction run for 30 minutes; a milky yellow color was formed changing to a more intense yellow and finally a dark orange. This was followed by the addition of 3-methyl-4-vinpyridine (0.5 g, 0.0042 mol). The reaction was stirred at -78°C for 16 hr. The living polymer was terminated by approximately 1 ml of methanol. The polymer was precipitated in approximately 150 ml of methanol and dried in a vacuum oven overnight. The purified polymer yield was 66%.

3.3.5 DPEDA (N,N'-diphenylethylenediamine) polymerization

DPEDA⁻Li⁺ was prepared by lithium-hydrogen exchange. First, the 100 ml round bottom flask was placed on vacuum line. Then the breakseal of 1,2-dianilinoethane was broken by a magnetic hammer and 1,2-dianilinoethane (0.013 g, 0.0042 mol) was added at room temperature. It was evacuated on a high-vacuum line and the flask was refilled with nitrogen. The flask was evacuated and refilled with nitrogen at least three times. This was followed by addition of n-BuLi (0.030 ml, 6.0 x
10^{-5} \text{ mol} \) under nitrogen gas by using a syringe at room temperature for 1 h. Then 0.5 g (0.0042 mol) of 3-methyl-4-vinylpyridine was added to the reaction at -78 °C. The reaction was stirred for 48 hr and the reaction was terminated with approximately 1 ml of methanol. The polymer was purified by precipitation into approximately 150 ml of hexane. The purified polymer yield was 71%.

3.3.6 n-BuLi Polymerization

n-BuLi $4.2 \times 10^{-3} \text{ ml (8.1} \times 10^{-3} \text{ moles, 2.0M)}$ was added into the reaction vessel, Figure 3.1.4. The purified toluene was then transferred from the solvent flask to the reaction vessel by distillation (Figure 3.1.4). Then 3M4VP (0.5 g, 0.042 mol) monomer was added as a 50% toluene solution to the initiator at -78°C. The reaction was stirred for 2 hr and terminated with approximately 1 ml of methanol. The polymer was recovered by precipitation into ~150 ml of methanol. The purified polymer yield was 72%.

3.3.7 Synthesis of Optically Active Poly(3-methyl-4-vinylpyridine)

All reagents used were stringently purified and dried. Vacuum line ($\sim 10^{-4}$ torr) breakseal technique was used for the preparation of the polymer. The N,N’-diphenylethylenediamine monolithium amide (DPEDA-Li) complex with (+) and (-) DDB was used as initiator.

3.3.8 Polymerization of 3-methyl-4-vinylpyridine with Optically Active Initiators

Polymerization was carried out using a chiral initiating complex. The chiral initiator was prepared by exchanging hydrogen and lithium between 1,2-dianilinoethane
and n-BuLi in toluene. First, the 100 ml two-necked flask was evacuated on a high vacuum line. Then the breakseal of 1,2-dianilinothane was broken by a magnetic hammer and 1,2-dianilinothane (0.013 g, 0.0042 mol) was added at room temperature. It was evacuated on a high-vacuum line to remove all the moisture and air. After that, the flask was refilled with nitrogen. The flask was evacuated and refill with nitrogen at least three times. This was followed by addition of n-BuLi (0.030 ml, 6.0 x 10⁻⁵ mol), under the protection of nitrogen, by using a syringe at room temperature for one hour. Then (+) or (-)-2,3-dimethoxy-1,4-bis butane [(+)+ or (-) DDB] (0.015 g, 7.2 x 10⁻⁵ mol) was added by breaking the ampoule under vacuum. The addition of 3-methyl-4-vinylpyridine (0.5g, 0.042 mol) was followed after 30 min. The polymer was terminated with approximately 1 ml of methanol and was precipitated in approximately 150 ml of cold hexanes. Yield obtained was approximately 55%.

3.3.9 Preparation of the P3M4VP/ Mandelic Acid Complex

The optically inactive or a racemic mix of helical P3M4VP (0.50g) was complexed with (R) and (S) mandelic acid 1:2, 1:1.5, 1:1 and 5:1 mandelic acid/P3M4VP monomer repeat unit ratios in THF, D₂O, methanol and H₂O solvents. The mixtures were stirred for 8 hr and were poured on poly(ethylene) plates and dried. CD measurements were carried out on the dried under vacuum at RT.

3.3.10 Preparation of the (+) and (-) helical P3M4VP:PEO:PEG Matrix

(+ or -) P3M4VP (0.5g, 0.0042 mol) was prepared by helix-sense-selective polymerization at -78°C, and as soon as the reaction was terminated by transfering
methanol into the reaction flask, 0.5g of PEO (600K) and 0.5g of PEG (3K) were added to the solution. The resulting mixture was co-precipitated into cold hexanes. The precipitate was transferred into a petri dish and the solvent evaporated in a vacuum oven at 25°C, CD measurements were carried out on the solid samples.

3.4 Characterization of P3M4VP

3.4.1 $^1$H and $^{13}$C Nuclear Magnetic Resonance (NMR)

Routine $^1$H NMR and $^{13}$C NMR spectra were recorded on a Bruker ARX 400 spectrometer in CDCl$_3$. Tetramethylsilane (TMS) was used as the internal standard. $^{13}$CP-MAS was obtained using a Bruker MSL-200 spectrometer.

3.4.2 Gel Permeation Chromatography (GPC)

The molecular weight measurements were performed on a Water GPC 150-C system. Three high porosity crosslinked polystyrene columns, (HR1, HR3, HR4) were connected in series. THF solvent was used as the mobile phase. The flow rate was 2.0 ml/min and the GPC measurements were carried out at 30°C. The solution concentration was 0.1 %. A set of narrow molecular weight distribution polystyrene standards MW's 760; 13,700; 43,900; 186,000; 233,000 (Polysciences) were utilized to calibrate the molecular weight measurements.

3.4.3 Differential Scanning Calorimetry (DSC)

The glass transition temperatures ($T_g$) were determined on a Perkin Elmer DSC-4 equipped with a thermal data station. The test specimen was packed in a standard
aluminum pan holder and scanned at a heating rate of 20°C/min under a nitrogen atmosphere. The sample was first heated to 200°C and quench cooled at a rate of 320°C/min to -80°C before obtaining thermograms. The glass transition temperatures were taken at the midpoints of the heat capacity changes.

3.4.4 Polarimetry

Optical rotation was measured at -4°C using a Rudolph Autopol III polarimeter. It was employed to determine optical activities at 589 nm. Measurements were performed at 0.02 mol/L concentration.

3.4.5 Circular Dichroism

The P3M4VP/mandelic acid complexes and the P3M4VP/PEO/PEG complexes were studied using a JASCO-J 720 spectropolarimeter. The concentrations used for the measurements were 0.1 % solution.

3.4.6 Computational Chemistry

Molecular mechanics MM3 and PM3 calculations were carried out using ALCHEMY obtained from SciVision®.
CHAPTER IV

RESULTS AND DISCUSSION

The monomer, 3-methyl-4-vinylpyridine (3M4VP) was synthesized in two steps. The first involved the synthesis of 4-(β-methoxyethyl)-3-methylpyridine. The reaction was carried under nitrogen and the yield was 65% Scheme 1.

The second step involved the synthesis of the monomer 3M4VP. It is important to keep the reaction under the protection of nitrogen. The yield of the monomer was 44% Scheme 1.

The 400 MHz \(^1\text{H}\) NMR spectrum of 3-methyl-4-vinylpyridine is shown in Figure 4.1.1. The spectrum shows peaks at δ: 8.30 (s), 8.28 (d), 7.20 (d), 6.80 (m), 5.75 (d), 5.40 (d), 2.20 (s). Anal. Calc: C, 80.73%; H, 7.56%; N, 11.76%. Found: C, 79.37%; H, 7.8%; N, 11.42%. The 400 MHz \(^1\text{H}\) NMR spectrum of 3-methyl-4vinylpyridine is shown in Figure 4.1.2. NMR spectrum and elemental analysis data are consistent with the structure of the monomer. The overall purity of the monomer was determined by GC/MS, Figure 4.1.3. GC shows a retention time of 3.5 min. The MS show a M+ 1 of 119 and a fraction of 91 representing the fraction of pyridine with a methyl group attached to it.

In Tables 1 and 2 the polymerization conditions for 3-methyl-4-vinylpyridine using radical and different anionic initiators are listed (Scheme 1- Scheme 6). The \(^1\text{H}\) NMR spectrum and \(^{13}\text{C}\) CP-MAS spectrum of P3M4VP are provided in Figures 4.1.4 and
4.1.5, respectively. The structure of the polymer is consistent with the spectral information. The low yield for the radically prepared polymer are likely because of a lower ceiling temperature \( T_c \) of the system. The ceiling temperature of \( \alpha \)-methylstyrene and \( \alpha \)-methyl-o-methoxystyrene are 0 and \(-25^\circ\text{C}\), respectively\(^{14}\) due to steric reasons. Similar result is expected for the system of 3-methyl-4-vinylpyridine because of the similar steric arrangements this means a low \( T_c \). Poly(3-methyl-4-vinylpyridine) is a white powder with an observed \( T_g \) of \(~110^\circ\text{C}\). The DSC chromatogram shows a large endothermic curve; this endotherm at the \( T_g \) corresponds to the energy needed for a transition from a helical conformation to a random coil conformation, i.e., the energy required to increase the free volume of the polymer from the compact helical conformation to the random coil conformation (Figure 4.1.6). However, further work will be have to be carried out to determine the exact process giving rise to this endotherm.

Asymmetric anionic polymerization of 3-methyl-4-vinylpyridine with DPEDA\(^{1}\) Li\(^{\text{(+)}}\)/optically active ligand complexes was carried out at \(-78^\circ\text{C}\) in toluene, and the optical rotation and molecular weight results are tabulated in Table 2. The polymers were precipitated into cold hexanes, and yields of the purified polymer were approximately 50%. Direct analysis by \(^1\text{H} \) NMR of the polymeric reaction mixture upon termination by methanol indicated the absence of any residual monomer; i.e., most of the monomer under these conditions is converted to polymer.\(^{5}\) The 50% yield for the purified polymer is a result of the precipitation process used; hexanes were quickly poured out before all the polymer particles have settled to the bottom of the beaker.
Scheme 1. Synthesis of 3-methyl-4-vinylpyridine
Figure 4.1.1 $^1$H-NMR of 3-methyl-4-vinylpyridine
Figure 4.1.2 $^{13}$C-NMR of 3-methyl-4-vinylpyridine
Figure 4.1.3 GC/MS of 3-methyl-4-vinylpyridine
Figure 4.1.4 $^1$H-NMR of poly(3-methyl-4-vinylpyridine)
Figure 4.1.5 $^{13}$C CP/MAS NMR of poly (3-methyl-4-vinylpyridine)
Figure 4.1.6 DCS Chromatogram of poly(3-methyl-4-vinylpyridine)
Table 1. Polymerizations of 3-Methyl-4-Vinylpyridine Using Different Initiators

<table>
<thead>
<tr>
<th>Initiator</th>
<th>Solvent</th>
<th>Temp (°C)</th>
<th>Time(hr)</th>
<th>Yield (%)</th>
<th>Mw</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIBN</td>
<td>Benzene</td>
<td>60</td>
<td>72</td>
<td>3.2</td>
<td>17 700</td>
<td>17 000</td>
</tr>
<tr>
<td>n-BuLi</td>
<td>THF(90)/Toluene(10)</td>
<td>-78</td>
<td>2</td>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDA</td>
<td>THF(90)/Toluene(10)</td>
<td>-78</td>
<td>16</td>
<td>66</td>
<td>36 800</td>
<td>36 000</td>
</tr>
<tr>
<td>DPEDA(+)</td>
<td>Toluene</td>
<td>-78</td>
<td>48</td>
<td>71</td>
<td>31 300</td>
<td>29 400</td>
</tr>
</tbody>
</table>

GPC in toluene using Waters Styragel columns HR1, HR3, HR4 at a flow of 1.5 mL/min. Molecular weights are relative to polystyrene standards.

Table 2. Anionic Polymerization of 3-methyl-4-vinylpyridine with the Complexes of DPEDA(+)Li(+) with Optically Active Ligands

<table>
<thead>
<tr>
<th>Run</th>
<th>Chiral ligand</th>
<th>Time(hr)</th>
<th>[α]_s89</th>
<th>Mw</th>
<th>Mn</th>
<th>Conc (g/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(+)-DDB</td>
<td>72</td>
<td>(-) 4.0</td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>(-)-DDB</td>
<td>72</td>
<td>(+) 14.2</td>
<td></td>
<td></td>
<td>0.014</td>
</tr>
<tr>
<td>3</td>
<td>(+)-DDB</td>
<td>72</td>
<td>(-) 4.0</td>
<td>28 700</td>
<td>27 000</td>
<td>0.014</td>
</tr>
<tr>
<td>4</td>
<td>(-)-DDB</td>
<td>72</td>
<td>(+) 14.7</td>
<td>14 000</td>
<td>13 000</td>
<td>0.014</td>
</tr>
</tbody>
</table>

[monomer]/[initiator] = 70 in toluene. GPC in toluene using Waters Styragel HR1, HR3, HR4 at flow rate of 1.5 mL/min. Molecular weights are relative to polystyrene standards. Indetermination value for [α] is ±0.1. Concentration used in the determination of optical rotation.
Scheme 2. Polymerization of 3-methyl-4-vinylpyridine with optically active initiators.
Scheme 3. Radical polymerization
Scheme 4. LDA (Lithium diisopropyl amine) polymerization of 3-methyl-4-vinylpyridine.
Scheme 5. DPEDA(-)Li(+) (N,N'-diphenylethylenediamine-lithium) polymerization of 3-methyl-4-vinylpyridine.
Scheme 6. n-BuLi polymerization of 3-methyl-4-vinylpyridine
This strategy was applied to minimize helix-to-helix interconversion during the purification process. The theoretical molecular weight of the optically active polymers, based on the monomer-to-initiator ratio, is approximately 8000, and the $M_w$ and $M_n$, relative to polystyrene standards, determined by GPC results in an overestimation of the molecular weights. GPC data also indicate that the molecular weight distributions of the optically active polymers are fairly narrow.

The optical rotations of the polymers were measured in two ways: (a) as soon as the polymerization was terminated at $-78^\circ$C by addition of CH$_3$OH, a sample was taken out of the reaction flask and the rotation was measured, (b) the rotation was measured again after precipitation into cold hexanes. The $\lbrack \alpha \rbrack ^{d}_{589}$ values determined by both methods were consistent; a correction was applied to take into account the rotation due to the optically active ligand when method the first method was used. With the (+) DDB/DPEDA$^{(\pm)}$Li$^{(\pm)}$ initiating complex, polymers with $\lbrack \alpha \rbrack ^{d}_{589}$ of 4.00 are obtained; while the (-) DDB/DPEDA$^{(\pm)}$Li$^{(\pm)}$ initiating complex produces polymers with $\lbrack \alpha \rbrack ^{d}_{589}$ – (+) 14.00. The difference in the observed optical rotations may have to do with a number of reasons including the diastereomeric transition states involved in the helix-sense (left or right) selective polymerization and/or with the nature of the formation of the chiral initiating complexes and the energetics of the complexation.$^{15}$ The (2S,4S)-DDB and its enantiomer the (2R,4R)-DDB are used as chiral ligands. When the (2S,4S)-DDB chiral ligand is used, the diastereomeric transition states involved in the stereodifferentiation step would have the stereochemistry of either [S,S,S$^\#$] or[S,S,R$^\#$], where S$^\#$ and R$^\#$ denotes the stereocenters generated during the transition state. The difference in energies of these two diastereomeric transition states determines the degree of stereoselection.
However, when the (2R,4R)-DDB chiral ligand is used, the stereochemistry of the diastereomeric transition states would be either \([R,R,S^*] \) or \([R,R,R^*] \). The energy difference between the two sets of diastereomeric transition states do not have to be equal because of the dynamic nature of chelated ion-pairs and, therefore, may be one plausible explanation for the difference in the observed optical activities, i.e., stereoselection.

Additionally, a dependence on the molecular weight and molecular weight distribution on optical rotation is possible.\(^1\) At \(-4^\circ C\), the optical activity of homogeneous solutions of both the (-) and the (+) poly(3-methyl-4-vinylpyridine) decreased with time to zero rotation (Figure 4.1.7). The loss of optical activity is most likely because of helix-to-helix interconversion resulting in racemization. Because helix-to-helix interconversion is an intramolecular process one would expect to be linear dependence of the loss of optical activity with time, Figure 4.1.7. While in the solution at \(-4^\circ C\), mutarotation is observed; the polymers are stable (i.e. no change in optical activity) in solid state at room temperature or lower. The polymers were stored in a refrigerator for several months without any loss of optical activity. Helix-to-helix interconversion is not observed at \(-78^\circ C\). These observation favor the formation of polymer with higher structural orders. The zero order plot of the loss of optical activity is indicative of an intramolecular process and therefore an overall structural organization of unimacromolecular nature, i.e. resulting in change in the \([\alpha] \) value. If this is indeed the case, a CD spectra should indicate the presence of such a higher order structure. However, it is difficult to obtain CD at room temperature in solution as during the setting up process of the experiment the optically active helical P(3M4VP) loses its optically activity because of helix-to-helix interconversion and only a racemic mix of helices are quickly present. Therefore, the CD
Figure 4.1.7 Graph of Optical Loss Activity
spectra in solution at room temperature do not show Cotton effects attributable to secondary structure. In order to lock in the secondary or helical conformation, as soon as the living (+) P3M4VP and (-) P3M4VP was terminated by methanol at \(-78^\circ\text{C}\), PEG (MW 3000) and PEO (MW 600,000) was added to the solution and a resulting polymer mixture was precipitated into cold hexanes. In this fashion the secondary a helical structure may be locked into the solid matrix (i.e., composite of P3M4VP, PEG and PEO). This matrix is elastomeric and may be fabricated into films for CD measurement. The CD spectra of the (+) P3M4VP and (-) P3M4VP in such a matrix are shown in Figure 4.1.8. The CD spectra show mirror images with Cotton effect signals at 212, 223 and 231 with an isobastic point representative of secondary conformation. The observed couplet is indicative of a helical conformation.\(^{39}\)

The dynamic nature of helix-to-helix interconversion in solution at \(-4^\circ\text{C}\) is indicated by the zero order loss of optically activity of the helical polymers. Being trapped in a PEO/PEG matrix, the activation in the matrix will be higher because of the free volume requirement of the helix-to-helix interconversion process, which results in an increasing in the temperature. This indeed is observed when the (+) or (-) P3M4VP/PEG/PEO matrices are heated at 60°C for 30 minutes. The Cotton effects are lost because of either racemization, helix-to-helix interconversion or helix-coil transition, Figure 4.1.9.

The stereochemistry of the polymer is not currently known and difficult to determine because the rigid polymer structure is not amenable for obtaining high resolution NMR \(^{13}\text{C}\) spectra necessary for stereochemistry assignments. However, MM3 calculations support the formation of isotactic helical poly(3-methyl-4vinylpyridine).
Figure 4.1.8 CD spectra of 1:1 P3M4VP/PEO/PEG Matrix
In Figure 4.1.10, a helical conformation of isotactic (mmm) tetrad is shown. Small differences in energy were found for the different isomers of the 3-methyl-4-vinylpyridine dimers and trimers, due to the fact the end groups were able to undergo conformational changes that affected the optimized energy of the entire molecule. No stable helix was found for the rrr tetrad, which supports our premise that an isotactic vinyl polymer may be necessary for preparing conformationally stable helices. Both the MM3 and PM3 calculations showed that the helical isotactic tetrarners and pentamers are more stable than the non-helical form. The results are shown in Table 3.

Figure 4.1.9 Helical Conformation of isotactic (mmm) tetrad.
Figure 4.1.10 CD spectra of 1:1:1 P3M4VP/PEO/PEG Matrix heated at 60°C for 30 mins.
Table 3. Calculated energy (Kcal/mole) of 3-Methyl-4-Vinylpyridine Oligomers.

<table>
<thead>
<tr>
<th>Oligomer</th>
<th>Strain Energy (MM3)</th>
<th>Hf (PM3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mmm helix</td>
<td>75.7</td>
<td>54.2</td>
</tr>
<tr>
<td>mmm non-helix</td>
<td>83.6</td>
<td>60.8</td>
</tr>
<tr>
<td>Mmmm helix</td>
<td>98.2</td>
<td>75.5</td>
</tr>
<tr>
<td>Mmmm non-helix</td>
<td>100.1</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Further, an isotactic (mmmmmmmm) heptamer was modeled by molecular mechanics MM3 and again the helical conformation of heptamer is the minimum energy (Figures 4.1.11, and 4.1.12). The left handed helix was modeled by (2S, 4R, 6S, 8R, 10S, 12R, 14S)-2,4,6,8,10,12,14-hepta(3-methyl-4-pyridyl) hexadecane and its enantiomer (2R, 4S, 6R, 8S, 10R, 12S, 14R)-2,4,6,8,10,12,14-hepta(3-methyl-4-pyridyl) hexadecane formed the right-handed helix. The steric energies and heats of formation for the left and right-handed helices obtained by MM3 are almost equal, reflecting that these are conformational enantiomeric structure. Even Ab initio PM3 calculations give comparable formation energies for the two enantiomers. While the absolute stereochemical characterization of poly(3-methyl-4vinylpyridine) is currently being worked out using oligomeric model compounds with multidimensional NMR spectroscopy, our computational studies using MM3 and PM3 seems to favor the formation of isotactic helical polymers.

Table 4. Molecular Modeling (MM3) and PM3 Calculations for Left- and Right-Handed Helices

<table>
<thead>
<tr>
<th></th>
<th>MM3 Steric Energy Kcal/mol</th>
<th>MM3 Hf kcal/mol</th>
<th>PM3 Hf kcal/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heptameric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>left-handed helix</td>
<td>131.5</td>
<td>157.0</td>
<td>163.1</td>
</tr>
<tr>
<td>Heptameric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>right-handed helix</td>
<td>133.1</td>
<td>158.0</td>
<td>182.8</td>
</tr>
</tbody>
</table>
Figure 4.1.11 Left-Helical Conformation of isotactic (mmmmmm) heptamer.
Figure 4.1.12 Right-Helical Conformation of isotactic (mmmmmm) heptamer.
It may be concluded that isotactic poly(3M4VP) forms stable helical conformation and non-asymmetric or achiral polymerization of the monomer 3M4VP results in the formation of a racemic mixture of left and right-handed helices. At $-78^\circ$C, it is possible to carry out helix-sense-selective polymerization as helix-to-helix interconversion does not take place at such low temperature e.g. the activation energy $E_a$ for helix-to-helix interconversion is sufficient to lock in the conformation at $-78^\circ$C. Additionally, because of steric effect or free volume requirements for helix-to-helix interconversion, the helices are stable in the solid state, i.e., a predominance of either the left or right helices do not racemize in the solid state.

Because of the dynamic helical nature of P(3M4VP), it should be possible to carry out the preparation of a predominately one-handed helical P(3M4VP) starting with a racemic mixture through complexation with an enantiomer. The resulting complexes should be diastereomers and of non-equal energy. Hence, complexation with an enantiomeric compound should result in a shift of the equilibrium towards the energetically favored diastereomer i.e. result is the helix selection process. The overall process can be followed by CD spectroscopy.

The complexation of optically inactive, helical P3M4VP was carried out with (R) and (S) mandelic acids at 1:2, 1:1.5, 1:1. 5:1 mandelic acid/ monomer repeat unit ratios in THF, $D_2O$, MeOH, and H$_2$O solvents. Complexation of the oxygen of the mandelic acid and the nitrogen of the P3M4VP showed a Cotton Effect around 226 nm in the CD, (R) or (S) - mandelic acid has an absorption at 268-270 nm at the CD measurements.

CD spectra of P3M4VP in the presence of optically active carboxylic acids were measured in order to investigate whether the racemic mix will respond to chiral
compounds; showing the characteristic ICD. Figures (4.1.13-4.1.25) show the CD of P3M4VP in the presence of (R) and (S) - mandelic acid in THF, methanol, D₂O and H₂O. The CD spectra of a number of P3M4VP/(R) or (S) mandelic acid complexes show are mirror image. The Cotton effects spectra are indicative of the formation of enantiomeric structures.

THF as solvent of complexation seems to be the most effective complexation solvent for observing induced circular dichroism (ICD) because of helicity enrichment process through acid-base interactions in these systems, Figures 4.1.13-4.1.15. The ICD is more pronounced at an 1:2 mandelic acid/monomer repeat unit ratio as the mandelic acid content is increased; in (Figures 4.1.14 and 4.1.15), the complexes showed characteristic, split-type ICD, and the mandelic acid enantiomers show ICD’s which are mirror images. Figure 4.1.13 shows two cotton effects with images around 213 and 221 nm and at least two isobestic points. These results indicate that a helical conformation with right- or left-helicity in excess formed through acid-base interaction with enantiomers of mandelic acid.

The most pronounced ICD in D₂O was observed at a ratio of 1:2 of mandelic acid/monomer, (Figure 4.1.16-4.1.19). There are two Cotton effects with images at 210 and 220 nm; also three isobestic points are observed. In Figures 4.1.20-4.1.22, the mirror images cotton effects are observed between 210-220 nm at the three different ratios 1:2, 1:1.5 and 1:1 mandelic acid/ monomer ratios in H₂O. In H₂O, all ICD’s are split-type, indicating that H₂O is a better solvent than D₂O. Again, these results are (H₂O and D₂O) indicative of a helical conformation with a right-
Figure 4.1.13 CD spectra of 1:2 (R) and (S) MA/P3M4VP in THF.
Figure 4.1.14 CD spectra of 1:1 (R) and (S) MA/P3M4VP in THF.
Figure 4.1.15 CD spectra of 5:1 (R) and (S) MA/P3M4VP in THF.
Figure 4.1.16 CD spectra of 1:1.5 (R) and (S) MA/P3M4VP in D$_2$O.
Figure 4.1.17 CD spectra of 1:2 (R) and (S) MA/P3M4VP in D$_2$O.
Figure 4.1.18 CD spectra of 1:1 (R) and (S) MA/P3M4VP in D$_2$O.
Figure 4.1.19 CD spectra of 5:1 (R) and (S) MA/P3M4VP in D$_2$O.
Figure 4.1.20 CD spectra of 1:2 (R) and (S) MA/P3M4VP in H₂O.
Figure 4.1.21 CD spectra of 1:1 (R) and (S) MA/P3M4VP in H₂O.
Figure 4.1.22 CD spectra of 1:1.5 (R) and (S) MA/P3M4VP in H₂O.
or left-handed helicity in excess is formed on the basis of the chirality of mandelic acid. In H₂O the most pronounced ICD is observed at an mandelic acid/monomer repeat units ratio of 1:2.

In methanol 1:1 and 1:2 mandelic acid/monomer repeat unit complexes show ICDs which are split-type with opposite Cotton effect sign observed at 220 nm. However, increasing the mandelic acid concentrations to 5:1 mandelic acid/monomer complex (Figure 4.1.23 and 4.1.25), cotton effects observed at 230 is due to mandelic acid of the same sign and the two ICDs are somewhat superimposable, further studies are required to understand this interesting ICD observation. Similar types of sign reversal in ICD have been observed by Meijr in helical poly(thiophene) with optically active substitutes.²⁰²

The results shown here are representative of the stereoselection of one-handed helix versus the other by the enantiomer mandelic acid. In the case of (R)-mandelic acid, the induction or stereoselection of the (+) helix was preferred, whereas in the case of (S)-mandelic acid the induction or stereoselection of the (-) helix was preferred. This stereoselection is due to the fact that the non-optically active or optically inactive polymer is a racemic mixture of helical P3M4VP, where left- and right-handed helices are present in equal concentrations. Taking this into consideration, the mixture of enantiomers can be separated by assistance of a chiral molecule, in this case mandelic helices and the mandelic acid form diastereomers. This mean that in the case of [RR] or [RS] and the opposite case is the one [RS] [SS]. One of the diastereomers is energetically acid plays the role of a chaperoning. When the racemic mixture of
Figure 4.1.23 CD spectra of 1:2 (R) and (S) MA/P3M4VP in CH$_3$OH.
Figure 4.1.24 CD spectra of 1:1 (R) and (S) MA/P3M4VP in CH₃OH.
Figure 4.1.25 CD spectra of 5:1 (R) and (S) MA/P3M4VP in CH₃OH.
Figure 4.1.26 CD spectra of 1:1.5 (R) and (S) MA/P3M4VP in CH$_3$OH.
P3M4VP enantiomers is in contact with (R) or (S)-mandelic acid, the complexation between the more stable than the other one, and the stable diastereomer is the one whose CD is dominant. It should be noted that for the P3M4VP/(R) or (S) mandelic acid complexes only show good CD with well differentiated Cotton effects in the solid films, in the solution states are cotton effects are not well defined and, most likely, effected the dynamic nature of the helical complexes.

Therefore, the helicity selection from a racemic helical P(3M4VP) is possible through acid-base interaction with (R) or (S)-mandelic acid. This is a new method for preparing helical synthetic polymeric architectures.
CHAPTER V

CONCLUSION

This work successfully demonstrated the development of two new methods of preparing synthetic polymeric architectures.


2. Also, helix-sense-selection i.e. preparation of a predominantly left or right helical polymer, has been carried out by complexation of the racemic mixture of P3M4VP with a chiral chaperone.

The development of these two methods should be instrumental in the preparation of new generation of synthetic polymers with helical architectures.
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