Abstract

LI, HAIBO. Investigation of helicity of water soluble polycarbodiimides and preparation of nano particles with amphiphilic polycarbodiimides. (Under the direction of Bruce M. Novak.)

As a helical polymer, polycarbodiimides have been investigated for a period of time. But few water soluble polycarbodiimides had been synthesized and characterized. Since solubility of polycarbodiimides can be controlled by their side arms, achiral or chiral carbodiimides bearing hydrophilic tertiary amino group have been prepared. Single-handed sense hydrophilic polycarbodiimides were prepared from chiral monomers by achiral metal catalyst or from achiral monomers by chiral catalyst to give polycarbodiimides with predominately helical sense. The water solubility of these polycarbodiimides bearing tertiary amino groups is improved when they are methylated by methyl camphorsulfornic acid ester. Configurational and conformational predominately helical polycarbodiimides behave with different way when they are heated. For the former case, the polymers rearrange to their Thermodynamic Control Conformation (TCC) from Kinetic Control Conformation (KCC); for the later one, the polymer became racemic when annealed. The activation energies for the conformational change can be determined through Arrhenius plot analysis. Compared to the neutral polycarbodiimides bearing tertiary amino groups, the corresponding ionic polymers have higher activation energies. Helical induction of the water-soluble polycarbodiimides also has been investigated. CD spectrum was run for both the neutral and ionic polycarbodiimides and peptide mimics were found.

In addition to the hydrophilic monomers, chiral or achiral hydrophobic carbodiimides were also synthesized and polymerized. Through living polymerizations, the amphiphilic polycarbodiimides were prepared from metal catalysts. Crew-cut nanoparticles have been prepared through a phase inversion method. Different conditions have been tried to achieve nano particles with different morphologies and sizes. In the nano particle preparation, water amount, acid amount and molecular weight play important roles in preparation of nano particles. TEM was used to characterize the nano particles. Amphiphilic polycarbodiimides with optical active hydrophobic blocks were synthesized and applied in the preparation of a nano-superhelix.

INVESTIGATION OF HELICITY OF WATER SOLUBLE POLYCARBODIIMIDES AND PREPARATION OF NANO PARTICLES FROM AMPHIPHILIC POLYCARBODIIMIDES

By

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Dedication

This work is dedicated to my family, including my parents, my sisters and my wife.

Thank you for your love, support, and encouragement.

Biography

The author was born on Mar 19 1974 in Hebei Province, China. After six years study in 1st Middle School of Cixian County, he attended Hebei University and received his BS degree in 1995. In 1995, he began his graduate study in Changchun Institute of Applied Chemistry, Chinese Academy of Science and worked with Dr. Jiping Xu. His research was on the preparation and characterization of polyimide asymmetric membranes. After he received his MS degree in 1998, he began to work in Shanghai Institute of Organic Chemistry, Chinese Academy of Science as a full time research assitant. In Augest 2001, he joined Department of Chemistry, North Carolina State University pursuing a Ph D degree. His thesis is on the investigation of helicity of water soluble polycarbodiimides and preparation of nano particles with amphiphilic polycarbodiimides. His advisor is Dr. Bruce M. Novak.

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Table of Content

List of Figures ix

List of Schemes xv

List of Tables xvii

Chapter I

Water Soluble Helical Polymers and Polycarbodiimides

1.1 Short history of polymer 1

1.2 Water soluble polymers 2

1.3 Chirality overview and helical polymers 6

1.3.1 Eantiomers and diasterereomers 6

1.3.2 Characterization of chiral substances with chiroptical method 9

1.3.3 Configurational and conformational chiral compounds 12

1.3.4 Helical compounds 13

1.3.5 Water soluble helical polymers 14

1.3.5.1 Water soluble chitosan 16

1.3.5.2 Water soluble polypeptides 17

1.3.5.3 Hydrophilic polysilanes 19

1.3.5.4 Water soluble polyphenylacetylenes 20

1.3.5.5 Water soluble polyisocyanides 22

1.3.5.6 Water soluble polyisocyanates 23

1.4 Carbodiimide and polycarbodiimide 24

1.4.1 Structure of carbodiimides 24

1.4.2 Living polymerization of carbodiimides 26

1.5 Properties of helical polymers 30

1.5.1 Formation of one handed helical polymers 30

1.5.1.1 Preparation of one handed helical polymer from chiral monomers 32

1.5.1.2 Preparation of one handed helical polymers with chiral catalysts 33

1.5.1.3 Achievement of one handed helix by helical induction 33

1.5.2 Chiral Amplification 34

1.5.3 Cooperativity 35

1.6 Reference 37

Chapter II

Investigation of Helicity of Water Soluble Polycarbodiimides

2.1 Review of single handed polycarbodiimides 42

2.1.1 Polymerization of chiral monomers 44

2.1.2 Polymerization of achiral monomers with chiral catalysts 45

2.1.3 Helical induction 46

2.2 Helical induction of ionic polycarbodiimides by counter ions 48

2.2.1 Helical induction of ionic symmetric nonfluxional polycarbodiimides 49

2.2.2 Helical induction of ionic fluxional polycarbodiimides 54

2.3 Preparation of water soluble polycarbodiimide from chiral catalysts 64

2.4 Helical inversion of ionic polymer with different counter ions 74

2.5 Water soluble polycarbodiimides prepared from chiral monomers 85

2.6 Water soluble polycarbodiimides as peptide mimics 93

2.7 Effect of the pendant group size on the backbone conformation..... 98

2.8 Summary 101

2.9 Experiment section..... 103

2.10 References..... 130

Chapter III

Preparation of Nano Particles from Amphiphilic Polycarbodiimides

3.1 Introduction..... 132

3.1.1 Crew-cut micelles and star micelles..... 132

3.1.2 Self assembly of optical active amphiphiles 138

3.1.3 Materials for nanoparticles..... 140

3.2 Synthesis of amphiphilic polycarbodiimides 142

3.3 Effect of water content on the aggregates..... 143

3.4 Effect of water amount on nano particles in the presence of acid 144

3.5 Effect of acid on the nano particles..... 149

3.6 Effect of polymer concentration on the nano particles 152

3.7 Effect of molecular weight on the nano particles 155

3.8 Attempt to prepare super helix with chiral amphiphilic polycarbodiimides..... 158

3.9 Conclusion 167

3.10 Experimental section..... 168

3.11 References 177

List of Figures

Figure 1.1 Natural Water soluble Polymers; (a) DNA, (b) Amylpectin, (c) Protein 3

Figure 1.2 α-helix and β-sheet (a) α-helix (b) β-sheet 5

Figure 1.3 Eantiomers and diasteriomers in 2,3,4-trihydroxy-butanal 8

Figure 1.4 Basic elements of a polarimeter 10

Figure 1.5 Block diagram of a CD spectrometer 11

Figure 1.6 Recombination of circularly polarized light at different conditions 12

Figure 1.7 Conformational chiral compounds 13

Figure 1.8 Helical Hexahelicene 14

Figure 1.9 Hydrophilic helical polymers 15

Figure 1.10 Synthesis of naphthoyl chitosan 16

Figure 1.11 Preparation and polymerization of NCA 18

Figure 1.12 Synthetic water soluble peptides 18

Figure 1.13 Synthesis of a hydrophilic polysilylene 19

Figure 1.14 Synthesis of poly($PBGA_m$) and poly(PGA_m) 21

Figure 1.15 Preparation of polyisocynide 22

Figure 1.16 Polymer of isocyanopeptide and the helical structure model 23

Figure 1.17 Synthesis of a water soluble polyisocyanate 24

Figure 1.18 Relationship among polyisocynide, polyisocynate, polycarbodiimide and its monomer 26

Figure 1.19 Enantiomeric conformations of carbodiimides 26

Figure 1.20 The mechanism of polymerization of carbodiimide monomer using

a Ti (IV) catalyst 28

Figure 1.21 Effective catalysts for the polymerization of carbodiimides 29

Figure 1.22 Optical inactive helical polymer chain 30

Figure 1.23 Polymers composed of chiral monomers 31

Figure 1.24 Amplification of chirality 35

Figure 1.25 Cooperativity within a helical polymer chain 36

Figure 2.1 An energy diagram of helical inversion of a helical polymer 43

Figure 2.2 Examples of carbodiimides used in polymerization studies..... 44

Figure 2.3 Preparation of chiral catalysts ((S)-Binol-Ti) and ((R)-Binol-Ti) 45

Figure 2.4 Helical induction of polycarbodiimide using (1S)-10-camphorsulfonic acid . 47

Figure 2.5 Annealing behaviors of ionic polycarbodiimides 54

Figure 2.6 Sergeant soldier effect of random copolyisocyanates prepared

from (R)-2,6-dimethylheptyl isocyanate (sergeant) and n-hexyl isocyanate (soldier) 57

Figure 2.7 Protonated poly-**5** formed from a mixed acid solution of (S)-camphorsulfonic

acid and methylsulfonic acid 58

Figure 2.8 Correlation of observed optical rotation of poly-**5** and the concentration

of CSA 61

Figure 2.9 Correlation of observed optical rotation of poly-**6** and the concentration

of CSA 62

Figure 2.10 Correlation of observed optical rotation of poly-**7** and the concentration

of CSA 63

Figure 2.11 Synthesis of optical active poly(N-hexyl-N'-phenylcarbodiimide)s using

chiral titanium complexes 65

Figure 2.12 CD spectra of enantiomeric polycarbodiimides, poly(8)-(S-cat) and poly(8)-(R-cat) 67

Figure 2.13 The specific optical rotation of poly(8)-(R-cat) as a function of time and temperature 68

Figure 2.14 The racemization rate of poly(8)-(R-cat) using function of temperature and time 69

Figure 2.15 Arrhenius plot for annealing of poly(8)-(R-cat) 70

Figure 2.16 CD spectra for poly(8)MeI-(S-cat) and poly(8)MeI-(R-cat) 72

Figure 2.17 The specific optical rotation of poly(8)MeI-(R-cat) as a function of time and annealing temperature 72

Figure 2.18 The racemization rate of poly(8)MeI-(R-cat) 73

Figure 2.19 Arrhenius plot for annealing of poly(8)MeI-(R-cat) 73

Figure 2.20 The specific optical rotation of poly(8)(S)-Me-CSA-(R-cat) as a function of time and annealing temperature 76

Figure 2.21 The racemization rate of poly(8)(S)-Me-CSA-(R-cat) as a function of time and annealing temperature 76

Figure 2.22 Arrhenius plot for annealing of poly(8)(S)-Me-CSA-(R-cat) 77

Figure 2.23 The specific optical rotation of poly(8)(R)-Me-CSA-(R-cat) as a function of time and annealing temperature 77

Figure 2.24 The racemization rate of poly(8)(R)-Me-CSA-(R-cat) as a function of time and annealing temperature 78

Figure 2.25 Arrhenius plot for annealing of poly(8)(R)-Me-CSA-(R-cat)..... 78

Figure 2.26 The specific optical rotation of poly(8)(R/S)-Me-CSA-(R-cat)

as a function of time and annealing temperature 79

Figure 2.27 The racemization rate of poly(8)(R/S)-Me-CSA-(R-cat) as a function

of time and annealing temperature..... 79

Figure 2.28 Arrhenius plot for annealing of poly(8)(R/S)-Me-CSA-(R-cat) 80

Figure 2.29 Annealing of poly(8)(S)-Me-CSA-(R-cat),

poly(8)(R)-Me-CSA-(R-cat) and poly(8)(R/S)-Me-CSA-(R-cat) at 75 ^{0}C 82

Figure 2.30 CD spectra of poly(8)(S)-Me-CSA-(R-cat),

poly(8)(R)-Me-CSA-(R-cat) and poly(8)(R/S)-Me-CSA-(R-cat) 82

Figure 2.31 CD spectra of poly(8)(S)-Me-CSA-(R-cat),

poly(8)(R)-Me-CSA-(R-cat) and poly(8)(R/S)-Me-CSA-(R-cat) 83

Figure 2.32 The CD spectra for poly(9)MeI and poly-10..... 87

Figure 2.33 Change of Cotton effect during annealing

for poly(N-(R)-2,6-dimethylheptyl-N'-phenylcarbodiimide)..... 89

Figure 2.34 Annealing of poly(9)MeI in different solvents..... 90

Figure 2.35 CD spectra of virgin and annealed poly(9)MeI..... 90

Figure 2.36 CD spectra of annealed poly(9)MeI at different temperatures..... 92

Figure 2.37 The CD spectra for poly(1)-(R-cat) and poly(4)-(R-cat) in aqueous solution95

Figure 2.38 The CD in aqueous solution of poly-L-glutamic acid..... 95

Figure 2.39 CD spectra of ionic polycarbodiimides,

poly(1)(R/S)-Me-CSA-(R-cat.), poly(1)(R/S)-Me-CSA-(R-cat.),

poly(1)(R/S)-Me-CSA-(R-cat.), and poly(1)(R/S)-Me-CSA-(R-cat.) in water 98

Figure 2.40 The CD spectra of poly(1)(R/S)-Me-CSA-(R-cat)

and poly(1)THFFBr-(R-cat)..... 100

Figure 2.41 The CD spectra of poly(3)(R/S)-Me-CSA-(R-cat)

and poly(3)THFFBr-(R-cat)..... 100

Figure 3.1: Star micelle and crew-cut micelle 134

Figure 3.2: The TEM images of vesicles 137

Figure 3.3: The TEM images of bowl aggregates..... 137

Figure 3.4 Oligothiophene with homo chiral side chain and it super helix 138

Figure 3.5. The TEM images of aggregates from quasi-helical polymers..... 139

Figure 3.6 TEM pictures of the aggregates formed made from poly(1-*b*-13)MeI with

different amount of water..... 144

Figure 3.7 TEM pictures for nano particles formed made from poly(1-*b*-13)MeI in

the presence of acid with different amount of water..... 148

Figure 3.8 TEM pictures for nano particles made from poly(1-*b*-13)MeI with

different amount of acid..... 150

Figure 3.9 Dendric nano particles made from poly(1-*b*-13)MeI 152

Figure 3.10 TEM pictures of nano particles made from poly(1-*b*-13)MeI with

different concentrations of polymer..... 154

Figure 3.11 TEM pictures of nano particles made from poly(1-*b*-13)MeI with

different molecular weight..... 157

Figure 3.12 CD spectrum for poly(1-*b*-14)-1 and poly(1-*b*-14)-2..... 161

Figure 3.13 TEM pictures of nano particles made from poly(1-*b*-14)MeI-1 and poly(1-*b*-14)MeI-2 162

Figure 3.14 CD spectrum for poly(1-*b*-15)..... 164

Figure 3.15 TEM pictures of nano particles made from poly(1-*b*-15)MeOTs 166

List of Schemes

Scheme 2.1 Synthesis of hydrophilic monomers bearing functionalized side chains 48

Scheme 2.2 Synthesis of hydrophilic polymers from monomer 1 to 4..... 51

Scheme 2.3 Preparation of ionic polymers from non-ionic amine containing polycarbodiimides 53

Scheme 2.4 Synthesis of methyl substituted carbodiimides 56

Scheme 2.5 Preparation of fluxional polycarbodiimides with methyl substituents..... 56

Scheme 2.7 Synthesis of hydrophilic carbodiimide, monomer 8 66

Scheme 2.8 Preparation of optical active hydrophilic polycarbodiimides using (R)-BINOL-Ti and (S)-BINOL-Ti..... 66

Scheme 2.9 Methylation of predominately handed helical polycarbodiimides..... 71

Scheme 2.10 Preparation of ionic, single helical sense polycarbodiimides with different counter ions 75

Scheme 2.11 Synthesis of chiral hydrophilic monomers 9, 10 and 11 84

Scheme 2.12 Polymerization of hydrophilic monomers 9 and 10 85

Scheme 2.13 The synthesis of conformational predominately one-handed helical polymers using chiral catalyst, (R)-BINOL-Ti 93

Scheme 2.14 Synthesis of ionic polycarbodiimides 97

Scheme 2.15 Synthesis of ionic polycarbodiimides bearing tetrahydrofurfuryl side Chains 99

Scheme 3.1 Preparation of amphiphilic polycarbodiimides 142

Scheme 3.2 Synthesis of amphiphilic copolymers with chiral hydrophobic blocks..... 159

Scheme 3.3 Synthesis of poly(1-*b*-15)MeOTs..... 163

List of Tables

Table 2.1 Specific Optical Rotation Values of Symmetric Ionic Polycarbodiimides..... 53

Table 2.2. Mixed Acids Applied to Poly-5 61

Table 2.3. Mixed Acids Applied to Poly-6 62

Table 2.4 Mixed Acids Applied to Poly-7 63

Table 3.1 Conditions for the Aggregates Preparation From Poly(1-*b*-13)MeI..... 144

Table 3.2 Conditions for the Nano Particles Preparation from Poly(1-*b*-13)MeI 147

Table 3.3. Conditions for the Nano Particles Preparation from Poly(1-*b*-13)MeI 150

Table 3.4 Conditions for the Nano Particles Preparation from Poly(1-*b*-13)MeI 154

Table 3.5 Same Polymer with Different Molecular Weight 156

Table 3.6 Conditions for the Nano Particles Preparation from Poly(1-*b*-13)MeI 157

Table 3.7 Conditions for the Nano Particles Preparation from Polymer 30 161

Chapter I Water Soluble Helical Polymers and Polycarbodiimides

1.1 Short history of polymers

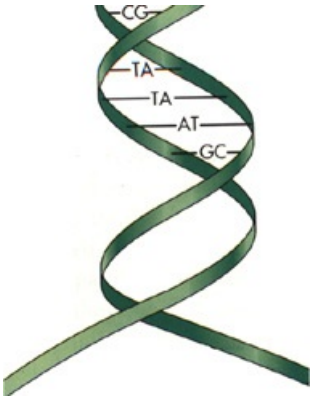
It is well known that polymers are one of the most important materials in this world. According to the sources, they can be devided into two categories: the natural polymers and synthetic polymers. For natural polymers, they exist in a number of different repeat units, including natural rubber and biopolymers such as polysaccharides, proteins, and nucleic acids, which play very important role in biological organization. As early as 2th century, a Chinese named Lun Cai made paper from plant fiber. In the fifteen century, it is speculated that children of Mayan people in centrul America played ball from natural rubber. In 1839, Charles Goodyear discovered vulcanization by heating natural rubber mixed with sulfur. The vulcanized rubber is more durable that natural rubber, which is still used in automobile tires. It is not until one century ago that people have started to make the synthetic polymers. In 1907, Leo Bakeland fabricated a synthetic thermoset: Bakelite. Its hardness and high heat resistivity made it an electrical insulator. It was only after the essential characteristics of polymers had been clarified in 1930's that science of polymers was established. After that, different monomers for new polymer fabrication have been employed, different theory have been developed, and new characterization methods have been created. Polyvinyl chloride, polystyrene, nylon and polyethylene were prepared following that time line.[1] To date, these polymers are still widely used.[2]

Polymers have a major impact on the way we live. Rubbers, plastics and fiber are the most often used polymers. Polymers are generally used for their mechanical features. If a polymer is synthesized for a specific purpose or the polymer has a functional group which

makes the polymer reactive, it can be defined as “functional polymer”. For the later case, the function of polymer could be either a chemical function such as reactivity or a physical function like a peptide analog. In the past decades, a number of functional polymers have been developed, such as drug delivery media, semi-penetration membrane, light sensitive polymers and polymer nanoparticles.[1]

1.2 Water soluble polymers

Water soluble polymers are substances which dissolve, disperse or swell in water and change the physical property of the aqueous system in the form of gellation, thickening or emulsification. Water soluble polymers can be obtained from different sources. Judged by the way they are fabricated, water soluble polymers can be synthetic, semisynthetic or natural. Basically, water soluble polymers are made by connecting monomer unit together to form a long polymer chain bearing hydrophilic groups. The hydrophilic groups that the polymer bear can be anionic, cationic or nonionic depending on monomers used in the process of polymerization and modification for the polymer.[2, 3.] For the ionic polymers, the counter ions also affect their solubility. The traditional water soluble polymers includes: PAA (polyacylic acid), PVOH (polyvinyl alcohol), PAM (polyacrylamide), PEG (polyethylene glycols) and quarternary ammonium polymers. If a special crosslinking agent is used to modify some of these water soluble polymers to give a three dimension stucture, the polymer would lose their solubilities in water. Instead they become superabsorbent polymers which absorb and retain water-based fluids.



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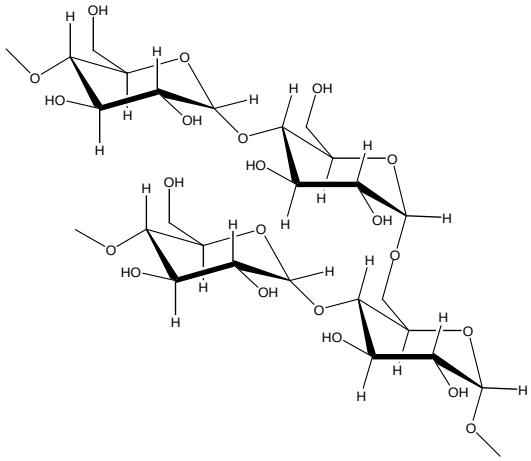

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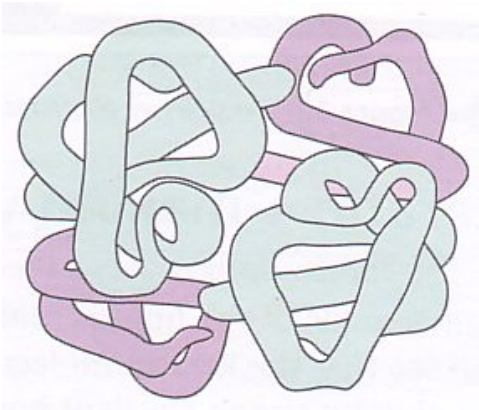


(c)

Figure 1.1 Natural Water soluble Polymers; (a) DNA, (b) Amylpectin, (c) Protein.

Since 1970's, due to environmental concern and the realization that the cheap oil product was gone, people found that water based formulation can match the petroleum-based formulation in cost, performance and environmental acceptability. Water soluble polymers have been using widely in a number of field such as: cosmetics, detergent, oral care, industrial water treatment, geothermal, waste water treatment, water purification and reuse,

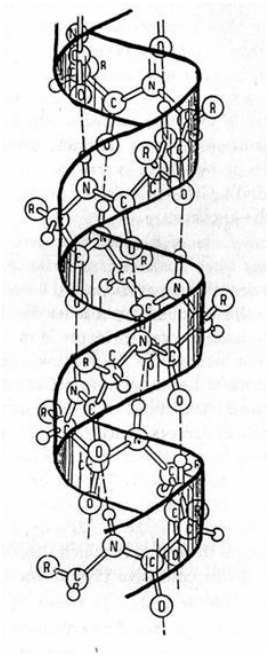
pulp and paper production, sugar refining and many more. Besides, water soluble polymers play a very important role in increasing the oil recovery yield. Also, water soluble polymers play important role in biological systems. The water soluble biopolymers represent a big family of polymers including polynucleotide, polypeptide and polysaccharides.[2] Figure 1.1 shows some of these natural polymers. DNA is a highly ordered antiparallel double stranded helix with charged, alternating deoxyribose phosphate repeating units, intermolecularly bound by pendent base hydrogen bond; polysaccharide is a polymer with anhydroglucose as the repeating units. For protein, the repeating units are amino acids. Naturally occurring polypeptides are synthesized biologically as a result of template assembly of selected amino acids.[2, 4] Each peptide has a unique structure and specific molecular weight. In recent years, due to the development of solid state synthesis, simple peptide can be fabricated artificially. Most peptides are water soluble or water-dispersible. The pendent groups of peptide can be categorized into four types, hydrophobic, polar, acid and basic. The solubilities of peptides in water depend on the polar and hydrogen bonding sites on the molecule; different pH value also gives different solubilities of peptides.[4]

The structural feature of peptides can be described in terms of primary, second and tertiary structures. The primary structure reflects the number and sequences of the amino acid residues on the peptide chain; the secondary structure reflects the periodic or the nonperiodic feature. Since peptides are stabilized by the hydrogen bonding between the hydrogen donor and hydrogen acceptor, the arrangement of the secondary structure give rise to the tertiary structure.[4]

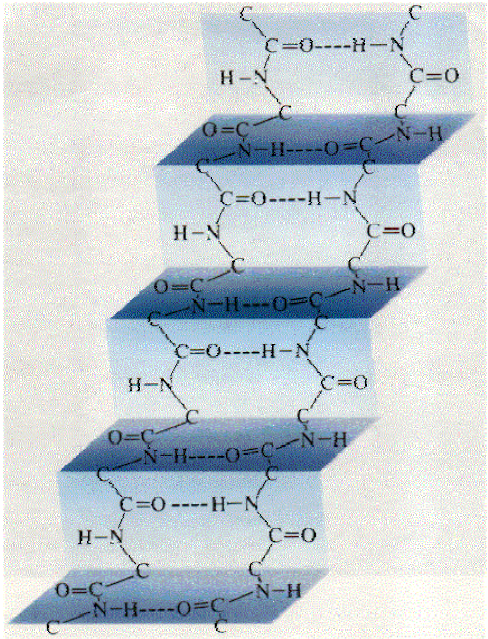
α-Helix and β-sheet are very common secondary structure for peptides (Figure 1.2). The

α helix comprises a screw-like arrangement of the peptide backbone which is stabilized by intramolecular hydrogen bonds aligned parallel to the helix axis. A helix is characterized by the number of amino acid residues per turn (n) and the helix pitch (h, repeat distant). Helices are chiral. The direction of the helical turns can be “P” (plus) for clockwise or “M” for anti-clockwise. The β-sheet is different from the α-helix, as the hydrogen bond occurs between two neighboring peptide chains, drawing two parallel or antiparallel peptide chain together to give a regular folded sheet.[4]

A lot of very important physiological and biochemical functions of life are influenced by peptides. To date, only a few studies have been taken toward the synthesis of water soluble polymers for peptide mimics. To achieve the artificial peptide mimics, it is very necessary to synthesize and characterize the single handed water soluble helical polymers.



(a)



(b)

Figure 1.2 α-helix and β-sheet (a) α-helix (b) β-sheet.

1.3 Chirality overview and helical polymers

Chiral compound have unique property and are of importance in pharmaceutical, chemical and biological significance. Chirality didn't come to people's attention until 1800's century when people found that certain substances could rotate the plane of the polarization of a light beam.[5] Later lord Kelvin defined the chiral and chirality, a concept that we know today. Everything have mirror images. But not everything are superimposable on their mirror images in three dimentions. That's why a glove for left hand can not fit a right hand. If a molecule is not superimposable on its mirror image, it called chiral. Likewise, achiral compound have superimposable images. For most organic compound, chirality originated from the fact that this organic compound containing at least one chiral atom. In organic chemistry, a carbon bearing four different groups makes it a chiral center. All four different substituted groups of this compound are always orientated in a way that no matter how the molecule is rotated, it can't be placed directly on its mirror image. Bromochlorofluoromethane is an example, because it can't superimpose on its mirror image. Optical activity is the ability of chiral substances to rotate the plane of a polarized light.

1.3.1 Eantiomers and diasterereomers

A chiral molecule and its mirror image are enantiomers. When polarized light travels through separate solutions of enantiomers, the plane of the polarized light is rotated to the opposite directions in equal amount. Isomers are indicated as (-) if they rotate the light to the left or (+) if they rotate the light to the right. This property helps to distinguish one from the other in the lab.[6]

$$[\alpha] = \frac{100\alpha}{cl} \qquad 1.1$$

$$\%ee = \frac{[R]-[S]}{[R]+[S]} \qquad 1.2$$

Except their abilities to rotate light, enaitomers have the same physical properties such as melting point, density and so on. A material with an excess of one enatiomer is optically active, which can be measured using an instrument called polarimeter.[7] The degree of rotation is called optical rotation. The optical rotation value observed in the polarimeter depends on the structure of the substance, the number of the molecules encountered by the light and measurement condition, including temperature, wavelength and solvent. To account for the effects of the concentration and path length, the term specific rotation has been defined. With a symbol [α], the specific optical rotation is calculated according to eq. 1.1, in which α is the observed optical rotation; c is the concentration of sample in grams per 100 mL of measured solution; l is the length of the cell in decimeters. Single-wavelength measurement is usually taken at 589 nm, the mission line of sodium arc lamp. This wavelength are called D line, and optical rotation measurement made at this wavelength are known as $[\alpha]_D$.[6,7] Unequal mixture of enantiomers are also optical active. The optical rotation value is proportional to the composition. Like eq. 1.2 shows, enanatiomeric excess is another way to express the purity of chiral substances.

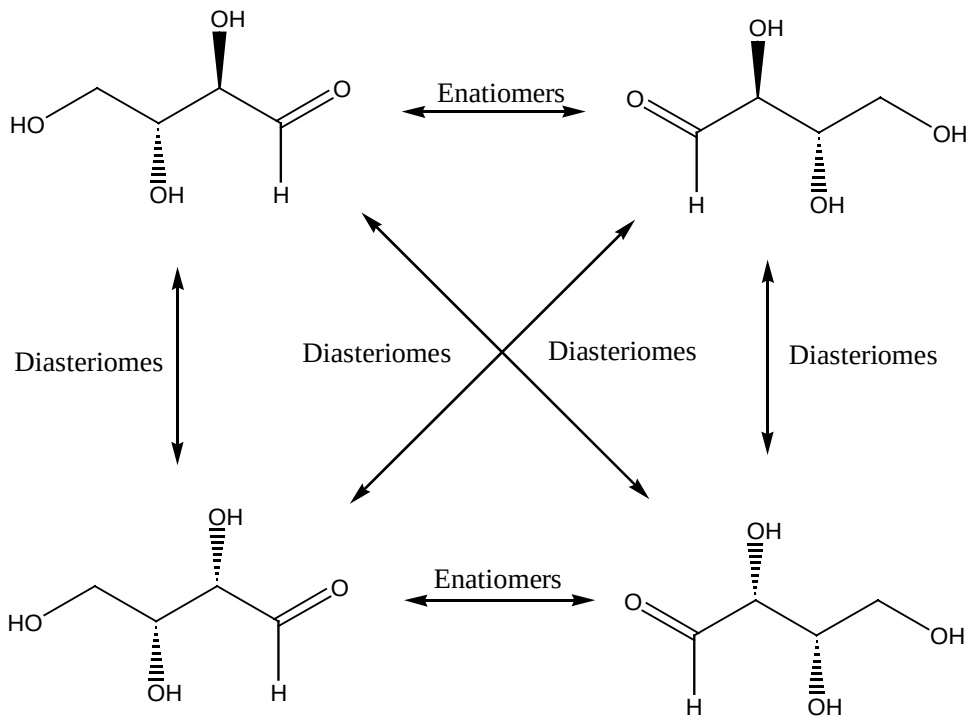


Figure 1.3 Eantiomers and diasteriomers in 2,3,4-trihydroxy-butanal.

In achiral environments, enatiomers show the same chemical properties. But enatiomers don't react with chiral chemicals at the same rate. A racemic mixture is the term used to describe the mixture of equal amount of enantiomers. Racemic mixtures are optically inactive because of mutual nullification between the two enatiomers. The reactions of a racemic mixture with achiral reagents give rise to another recemic mixture. But, if a racemic mixture reacts with a chiral compound, the enatiomers may not react at the same rate or give different yield so that product from one enantiomer predominates.

Diasteriomers includes all steroisomers which are not superimposable on their mirror images. Unlike enantiomers, disteriomers may have different physical properties and chemical reactivity. They usually have different solubilities, boiling point, melting point,

chromatographic mobility and so on. The optical rotation value of diasteriomers may be different in sign and magnitude. The difference in their chemical reactivities can be vary, for example, from differences in reaction rates, or yield, to totally different product, dependinig on the stereochemistry and reaction mechanism.[6] In addition, diasteriomers can be distinguished from one another using the conventional analytical techniques, such as NMR.

The introduction of chiral carbon to an organic compound results more diasteriomers. For a chiral organic compound with more than one chiral carbon atoms, the maximum diasteriomers number is 2^n, where n is the number of chiral centers. In the case of a compound of 2,3,4-trihydroxy-butanol, there are total four possible stereoisomers and six possible relationships between any two of them.[6] Two comparisons out of six are mirror images but not superimposable on each other, and therefore enatiomers. The rest comparisons are diasteriomers. Figure 1.3 shows the diasteriomer and enantiomer relationship of 2,3,4-trihydroxy-butanol.

1.3.2 Characterization of chiral substances with chiroptical method

Chiroptical methods refer to detection based on the interaction between a chiral center in the analyte and the incident polarized electromagnetic radiation. This category includes polarimetry, optical rotatory dispersion (ORD) and circular dichroism (CD).[7] As we know, light is the electromagnetic radiation, which can be considered as two wave motions: oscillating electric and magnetic field. Electric and magnetic fields are propagated in a way that each of them is generated by the other which is perpendicularly in orientation. The energy associated with these fields is equal in magnitude, but most optical measurements, such as UV and CD, are connected only with electric field. Natural light is unpolarized, so

vectors of it electric field oscillates in all directions perpendicular to the direction of propagation. But a natural light can be filtered by a special prism, a so-called polarizer, so that oscilations in all directions except one are not allowed to pass through. The emergent light is linearly polarized and its electric field only vibrates in one plane. If the polarized light is cast into a chiral substances or its solution in a flow cell, as long as the light can pass through, the plane of polarized light is rotated to an angle depending on the nature of the substances, its concentration, the temperature and so on. In a polarimeter, a second polarizing prism in the light path is used as an analyzer. To obtain the rotated angle of the polarized light, the second polarizing prism is rotate until it blocks all light. From the angle with which the two polarizers are placed, the original α can be read. Figure 1.4 shows how the measurement works.[7]

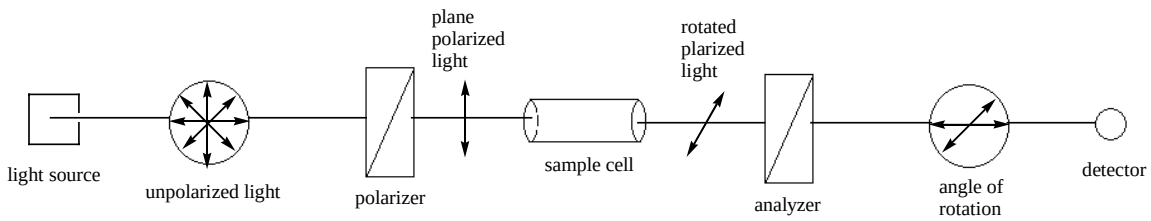


Figure 1.4 Basic elements of a polarimeter.

Circular Dichroism (CD) and UV-vis spectroscopy share the same origins in photophysical process: at specific wavelength, a molecule is elevated from its electronic ground state to and electronically excited state and an electron is excited from an occupied orbital to a higher energy, unoccupied orbital.

Isotropic light is used for UV-vis measurement, but polarized light is used for CD spectroscopy. As a result of this difference, the UV-vis spectra always has positive sign while

that of CD could be positive or negative.

The filtration of isotropic light by a polarizer gives rise to polarized light and polarized light can be broken down into left and right circularly polarized light. An optical element called as photoelastic modulator (PEM) can split a polarized light into two circularly polarized components (Figure 1.5). It comprises a piezoelectric transducter on which a transparent quartz plate is fastened. The birefringent quartz plate oscallats with such a way that a $\pm 45^0$ phase difference of the plane polarized light is achieved when it reaches the quartz plate. The 90^0 phase difference of the input polarized light yield the left and right circularly polarized lights alternatively .[8]

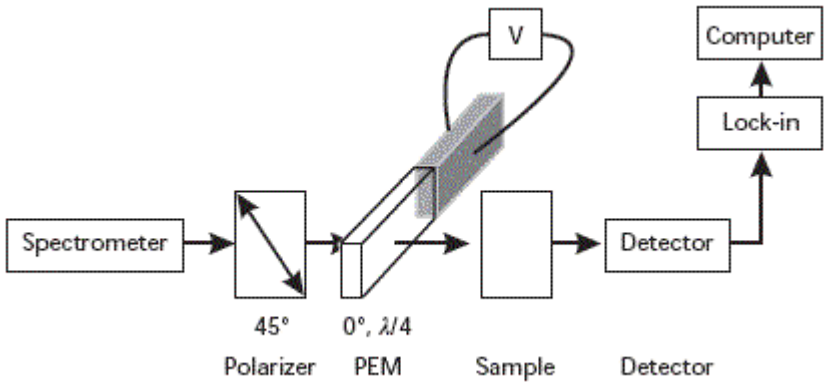


Figure 1.5 Block diagram of a CD spectrometer.

The left and right circularly polarized lights are like a helical thread.[8] For optical inactive media, the left and right circularly polarized light have the same absorption coefficient and travel with the same speed. So the recombination of left and right polarized light yields linearly polarized light (Figure 1.6). In an optically active sample, left and right circularly polarized light have different absorption coefficients. Inside an absorption band, the vectors

of the emitted circularly polarized lights are not symmetric any more. Recombination of the helical sense vectors of E_L and E_R resulted in a ellipse, the major axis of which is rotated from the lineally polarized light plane by an angle α. A mathematical deduction from this ellipse gives rise to Δε, the absorption coefficient difference of the two circularly polarized light. The CD spectrum is a record of the Δε versus the wavelength.[8]

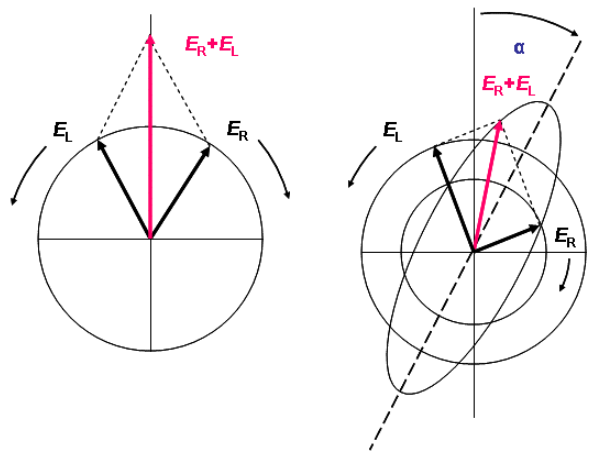
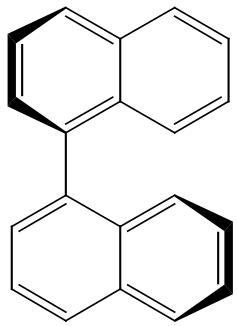


Figure 1.6 Recombination of circularly polarized light at different conditions.

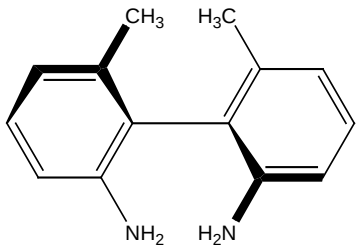
1.3.3 Configurational and conformational chiral compounds

Chirality is derived from the fact that a substance cannot be superimposable on its mirror image. Most chiral organic compounds have chiral centers. So no matter how a chiral molecule is orientated in space, all atoms in it can't fit the positions of those in their mirror image. The chirality of this kind of compounds is derived from the configuration of the chiral center. But restricted rotation around an axis and a helical structure can also result in optical activity. The source of this kind of chirality is derived from the fixed comformation of a molecule made by steric repulsion or stereoelectronic effects. Figure 1.7 shows two

conformational chiral compounds in which the rotation barrier is so high that the conversion of one into its enantiomer through a rotational process is impossible.[6] Conformational chirality can change under different temperatures, pH values or other means.[9, 10]



S-(+)-1,1'-Binaphthyl



R-(+)-2,2'-Diamino-6,6'-dimethylbiphenyl

Figure 1.7 Conformational chiral compounds.

1.3.4 Helical compounds.

Another class of conformational asymmetric compounds is a helix that has a structure generated from the combined rotation and translation of a point around a line, the helix axis. The structure of compound in Figure 1.8, hexahelicene is an example.[7,11,12] Usually, among a helix structure, the static constraints are so strong and energy inversion barrier is so high that the interconversion between right and left handed enaitiomers is difficult. Like an ordinary chiral center distinguished by R or S, the spin direction of a helix could be M and P.

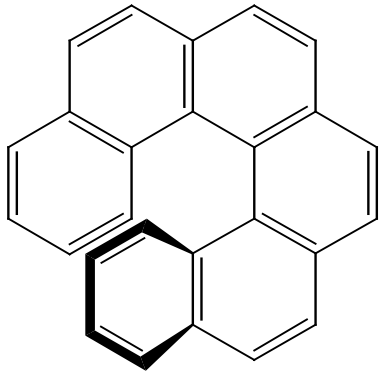


Figure 1.8 Helical Hexahelicene.

1.3.5 Water soluble helical polymers

As introduced before, both DNA and peptide have helical structures. The characteristic feature of DNA is its double strand helix connected by H bonding. Peptide can also have α helix structure depending on the structure of amino acid residue in the backbone, which is also a result of H bond interaction.[4] The key structure of a helical polymer can be characterized as a central axis, a screw sense and a pitch. The helical polymer pitch, P, is the distance traveled along the c-axis corresponding to one full 360 degree turn; h is the repeating unit height projected on the c axis, where P= n × h. For both artificial and natural helical polymers, the helix is designed by N/m, where N residues reside in m turns of the helical screw.[13]

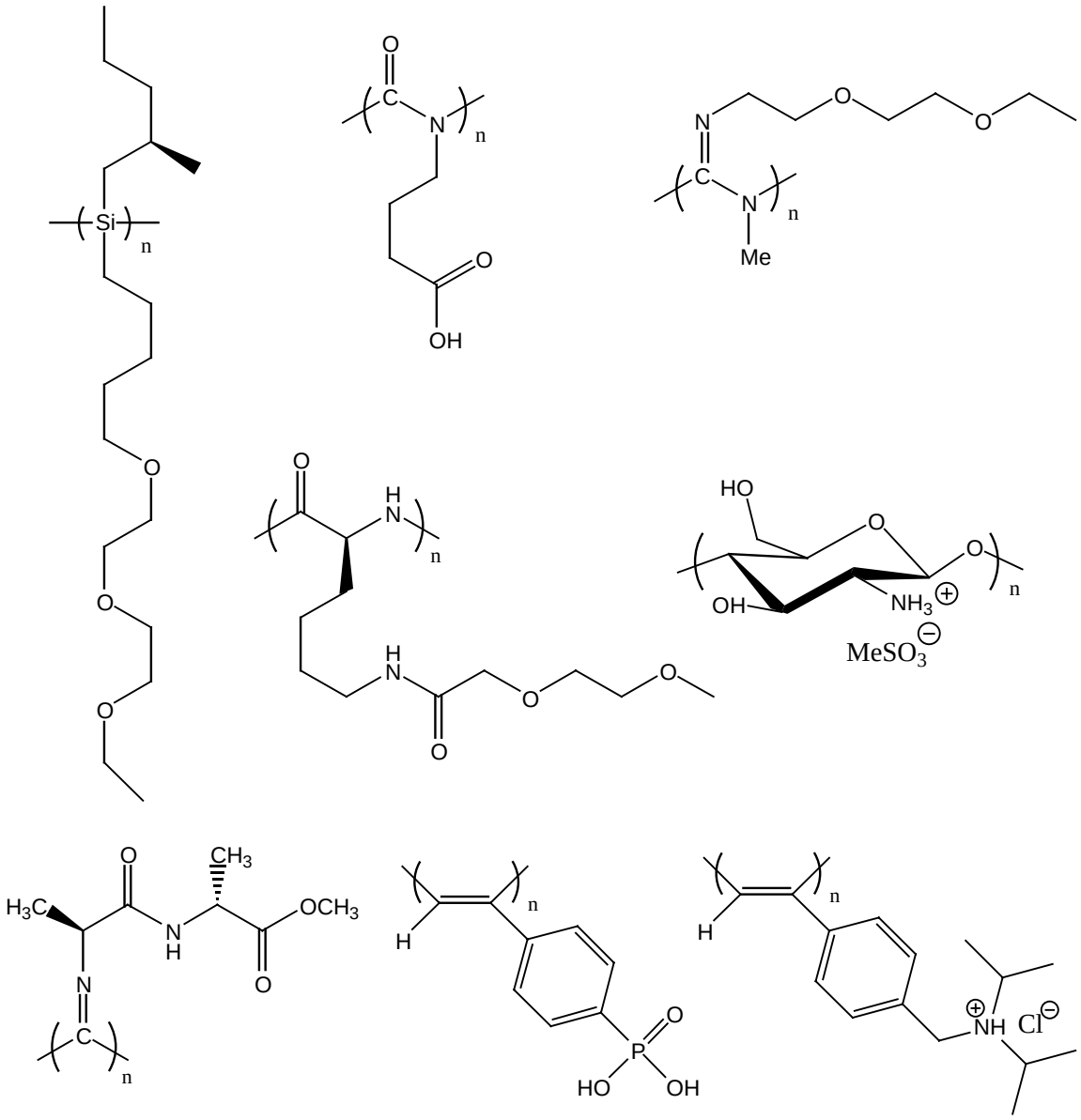


Figure 1.9 Hydrophilic helical polymers.

Polymers in Figure 1.9 are water soluble helical polymers.[14-21] All structures here have the basic feature of the helical polymer that they have short repeating units and bulky pedant groups. The helical structures are adopted due to any combination of three reasons: 1) the

stereo repulsion of the bulky side groups forces the backbone to adopt a helical way to reduce as much steric strain as possible; 2) the stereoelectronic effect from the backbone locks in the conformation, the backbone just take a helical structure to meet the requirement of its bond lengths and bone angles; and 3) Induction effect between the pendant groups and the inducing reagents or the hydrogen bonds among the pendant groups.

1.3.5.1 Water soluble chitosan

The early interest of chemist toward the natural water soluble polymer was associated with food, leather, paper and textile industries and to a lesser extent, the cosmetics and pharmaceutical industries.[2] With a new interest in the modified water soluble polymers, polymer chemists naturally turned their attention to polysaccharides, cellulose derivatives, starch and protein, the most dominant natural polymers, and conducted chemistry reactions on these polymers.

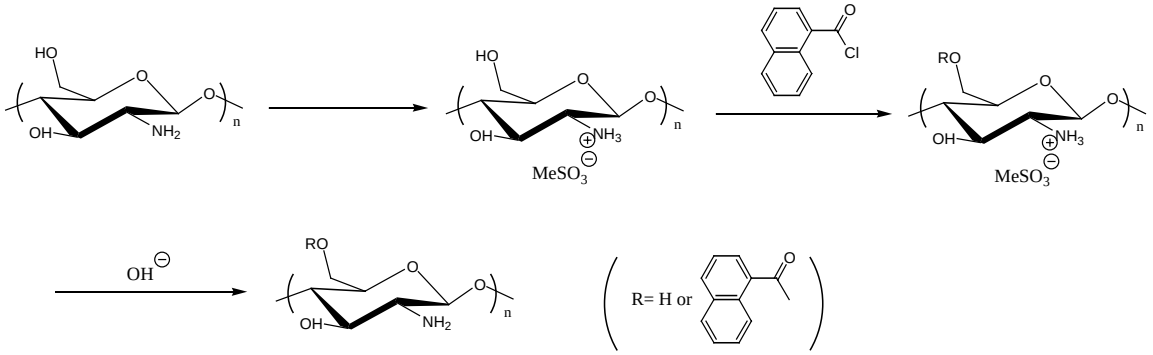


Figure 1.10 Synthesis of naphthoyl chitosan.

As a derivative of its parents polysaccharide chitin, chitosan is capable of forming a rigidly helical conformation in the crystalline state. A study conducted by Ogawa and coworkers show that the chitosan molecules take different helical structure by combining

different counter ions.[22-25] In order to investigate the solution behavior of chitosan by CD spectropolarimetry, Sakurai and coworkers prepared naphthoyl chitosan by running reactions shown in Figure 1.10.

This naphthoyl chitosan is soluble in DMSO. In solution phase, revealed by CD spectroscopy, the polymer adopts a helical structure. With the concentration of the polymer increased, reversion of the helical sense occurs; and when water was added to the polymer solution in DMSO, the CD signal weakened, which indicate that the helical chain suffers a conformational transition from a helix to a looser conformation. The helical structure of the polymer is stabilized by the intromolecular H bond interaction. When water concentration is increased, the stabilization machanism of the helical structure is broken by intermolecular H bonding. This experiment also shows that the helical structure of chitosan is very fragile.

1.3.5.2 Water soluble polypeptides

Inspired by the natural α-helix structure in the peptide, polymer chemists synthesized and characterized water soluble polypeptides with single repeating unit. Each amino acid has two reactive functional groups, but direct step polymerization over these monomers may be problematic due to the difficulty in activation of amino acid, the work up of the reaction and control of the stereochemistry and molecular weight. A better monomer, α-aminoacid-N-Carboxyanhydrides, (NCA)s, is always used for the preparation of homo polypeptide. Figure 1.11 shows the reaction about NCAs.[26]

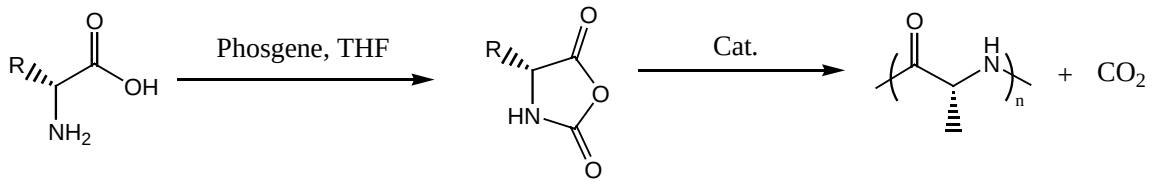


Figure 1.11 Preparation and polymerization of NCA.

Both homo and co polypeptide can be prepared from NCAs. Also, different groups can be introduced to the polymer side chain by choosing different substituted NCAs. For the ring open polymerization of NCAs, there are several initiators to be employed, such as Lewis acids or Lewis bases. Recently, Deming investigated the living polymerization of NCA with organometallic compounds, such as Ni(COD) and $(PMe_3)_4Co$.[27-29] When DMF or THF is used for the polymerization, NCA monomers are converted into polymers with narrow molecular weight distributions and the molecular weight can be defined by the monomer to initiator ratio.

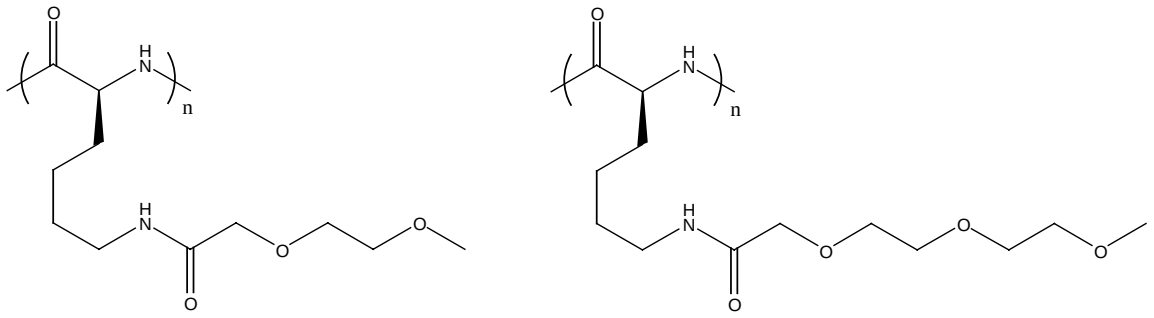


Figure 1.12 Synthetic water soluble peptides.

Most helical peptide cannot adopt a complete α-helix. But two water soluble synthetic peptides show in Figure 1.12, which were prepared by Deming with his organometallic

catalysts, are 100% α-helical in pH 7 at 25 ^{0}C. The structure is supported by both CD and X-ray scattering experiments.[30]

1.3.5.3 Hydrophilic polysilanes

Polysilanes are another family of helical polymers, with a characteristic 7/3 helical structure (7 repeating units per 3 turns) in the crystalline state.[31, 32] Most polysilanes are prepared by the sodium-mediated condensation of the corresponding dichlorodiorganosilanes in an inert solvent using Wurtz coupling reaction.[33, 34] Electron excitation from Siσ to Siσ* orbital imparts the backbone with a strong UV and CD signals around 300-400 nm.[35,36]

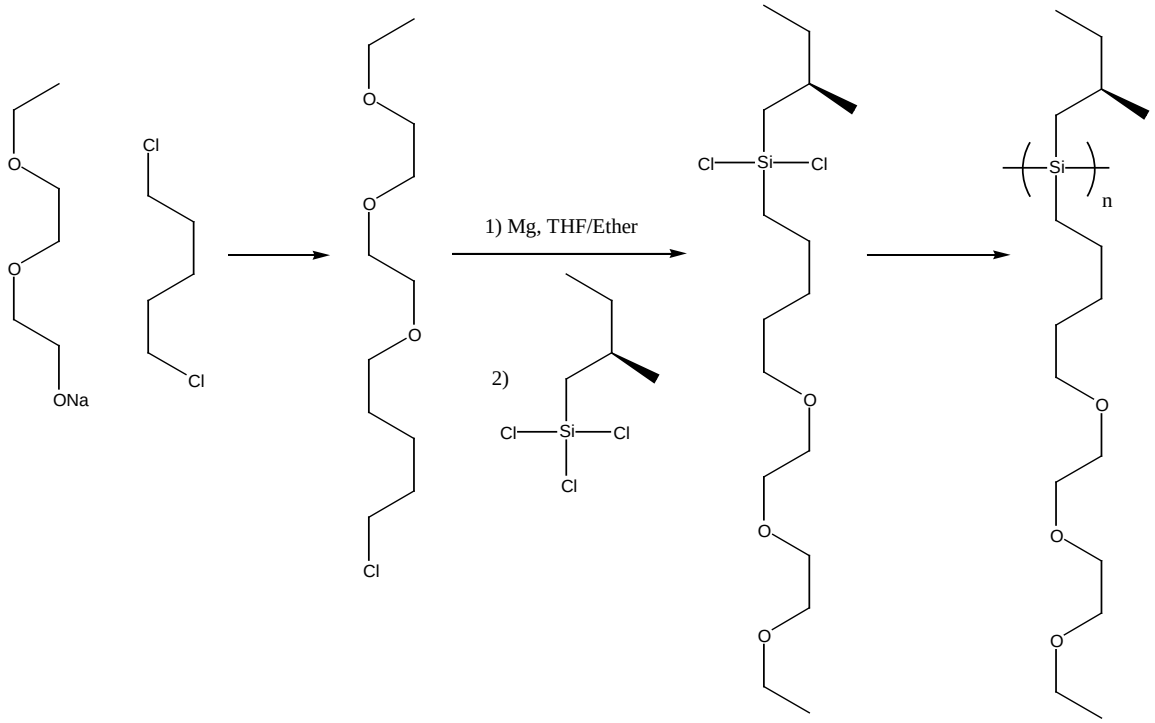


Figure 1.13 Synthesis of a hydrophilic polysilylene.

By employing dichlorosilane with hydrophilic pedant groups, Michiya Fujiki synthesized a hydrophilic polysilylens (Figure 1.13).[14] The polymer can be dissolved in

ethanol. Theoretically, the solubility of these polymers can be controlled by introduction of different pedant groups. But due to the harsh condition for polymerization (reflux at 100-120^{0}C with Na in toluene), monomers with specific functional groups that react with Na cannot be employed.

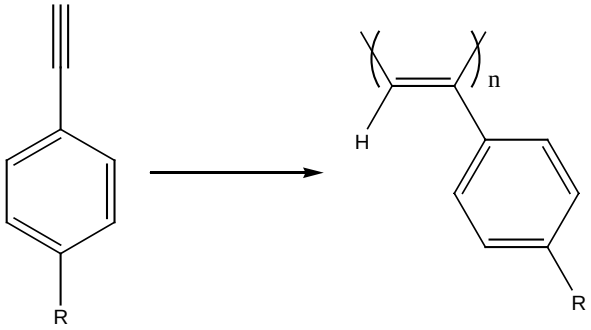
From this chiral monomer, a single helical sense polymer was prepared and single handed helical polymer was achieved. The inversion energy of the backbone is low, so response to any subtle change in solution, the helical structure can adjust itself to the thermodynamically stable conformation. The polymer solution in ethanol has a very neat UV and CD spectra around 310 nm. The CD spectra versus temperature were investigated. From 60^{0}C to –104^{0}C, as temperature decrease, helical screw pitch became tight. But below –60^{0}C, opposite screw-sense helical segment of minor fraction was found.

1.3.5.4 Water soluble polyphenylacetylenes

Eq. 1.3 shows the preparation of poly(cis-phenylacetylene), which is also a class of helical polymers.[37] When R is a hydrophilic group such as carboxylate, amino, phosphate groups or a peptide, the polymer can be water soluble. Also, the polymer itself can be anionic or cationic, depending on the monomers used for polymerization.[18,21,38,39,40] Yoshio Okamoto synthesized poly(cis-acetylene) with a organometallic catalyst. This polymer is helical but not optical active. In this unbiased polymer, none of the two helical senses predominate. Along the molecule, the chain of the backbone may adopt an “M” helical structure for several turns but then take a P sense in the next. Segments of left and right handed helical structure have the same energy and equal population.

With poly(phenylacetylene) bearing pendant carboxylic acid groups, Okamoto

investigated the helical induction by adding chiral amine to polymer solutions.[37,39,40] Between the two types of the helical segments, only one helical structure is favored by the acidic helix-chiral base interaction. So helical inversion occurs minimizing the disfavored helical segments to give rise to a prevailing one-handed helical conformation.



1.3

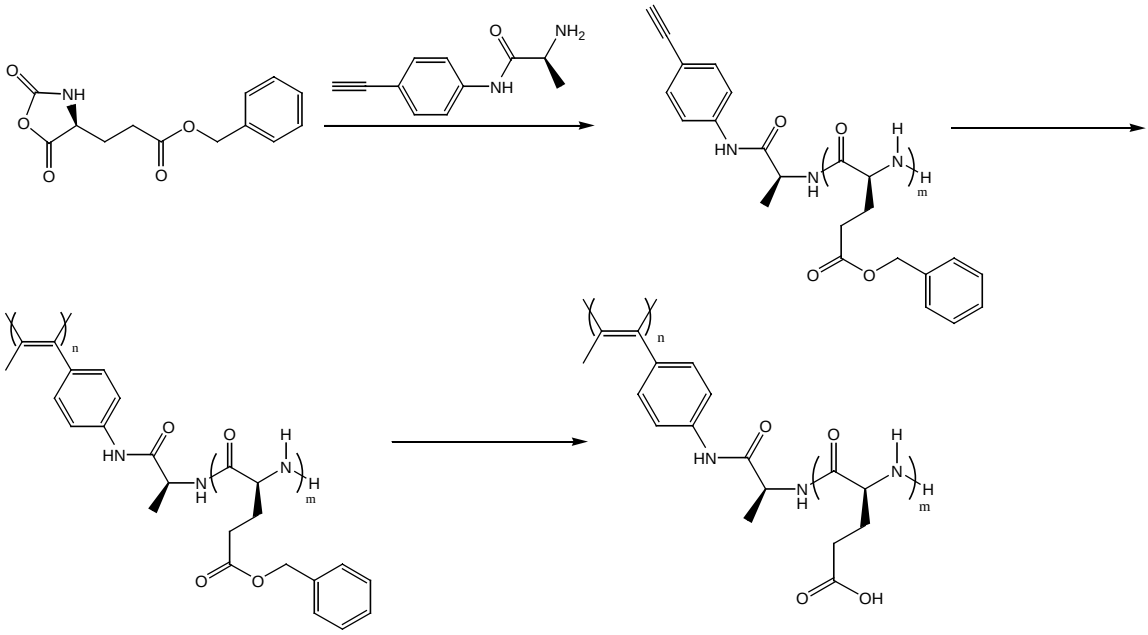


Figure 1.14 Synthesis of poly(PBGA$_m$) and poly(PGA$_m$).

To further investigate this helical induction of polyphenylacetylene, Eiji Yashima

synthesized poly(phenylacetylene) derivatives bearing a poly(γ-benzyl-L-glutamate) [poly-(PBGA$_m$)] or poly(L-glutamic acid) [poly(PGA)] (Figure 1.14).[18] For a poly(PBGA$_m$) solution in DMSO, the prevailing one-handed helix formation of polypeptide triggered a induced circular dichoism of the backbone; for poly(PGA), the conformation convertion of the polypeptide between random coil and regular helix can be controlled by different pH, likewise, when conformational change of the pedant peptide occur from random coil to helix, the backbone also takes a one handed helical structure in response.

1.3.5.5 Water soluble polyisocyanides

Polyisocyanides have a very unique structure in polymers, the repeating unit of which is a carbon atom bonded to nitrogen with a double bond. Any pedant groups the nitrogen atom bears introduce the steric hindrance among the repeating units. The C-C bond in the backbone has to rotate to a specific angle so as to give a stable, rigid helix. The polyisocyanide is prepared using a nickel salt (**Figure 1.15**). Optical active catalysts can yield one handed helical polymer.[41-44]

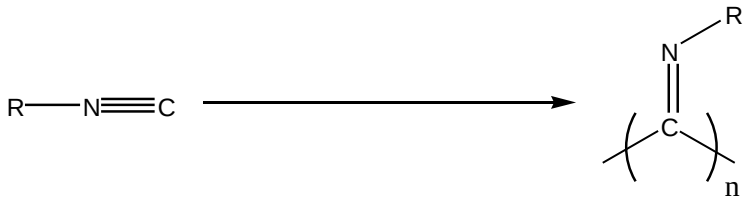


Figure 1.15 Preparation of polyisocynide.

Polyisocynides have a stable 4/1 helix and adopt a wormlike conformation in solution with a relatively short persistence length. The persistence length is the average length over which the polymer chain keeps straight. The inversion barrier for this polymer is very high,

so the one handed polyisocynide prepared through optical active catalyst is stable.[19, 41, 45]

Nolte polymerized isocyanopeptides to prepare high molecular mass polymer that fold in a proteinlike fashtion to give helical strands in which the peptide chains are arranged in a β-sheet.[45] The β-sheet is stabilized by the H bond among the amino acid residues in the peptide side arms. The isocyanopeptide polymers have a central helical core that acts as a director for the β-sheet arrangement of the peptide pedant groups (Figure 1.16). Both Ni salt and acid can catalyze the polymerization of the isocyanopeptide.

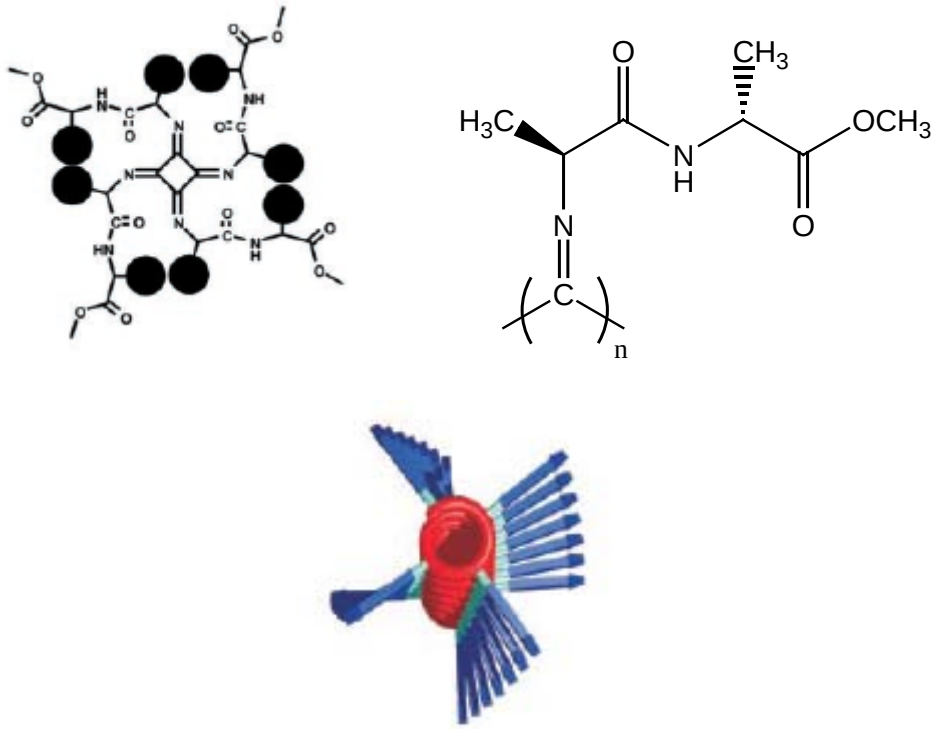


Figure 1.16 Polymer of isocyanopeptide and the helical structure model.[45]

1.3.5.6 Water soluble polyisocyanates

Polyisocyanates have long persistence length and comparatively low inversion barrier.

The polymer is helical as a result of combination of steric hindrance and conjugation in the amide bond. The ceiling temperature for this temperature is low so that the yields for the polymerization of isocyanate with bulky side groups are low. By polymerizing an isocynate with polar oxyethylene group in the side chain, Mark Green and his group members prepared a water soluble polyisocyanate (Figure 1.17).[15]

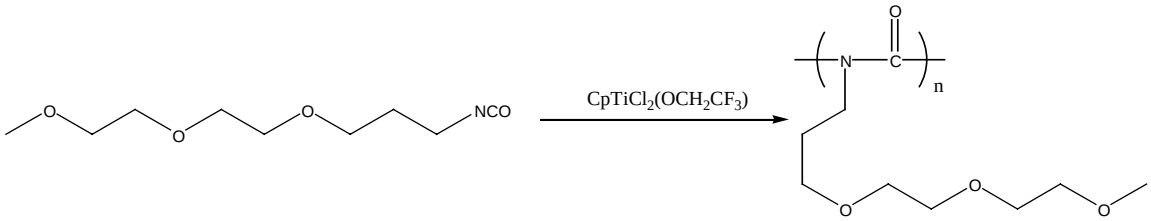


Figure 1.17 Synthesis of a water soluble polyisocyanate.

1.4 Carbodiimide and polycarbodiimide

1.4.1 Structure of carbodiimides

One potential application of helical polymers is they could be used as biomimics for peptides or DNAs. Polycarbodiimide combines many of the virtues of the helical polymers discussed before, which in many respects make them candidates for biomimetic applications. The following are some of their key features.

- Constant and stable 6/1 helical structure in both bulky and solution.
- Backbone made of guanidines, which are biological entities.
- UV and CD active
- Wide range of solubilities.
- Inversion barier can be tuned by pedant groups
- Tolerate both high and low pH extremes.

- Can be prepared through living polymerization.

As Figure 1.18 shows, the polycarbodiimides are hybrids of polyisocyanides and polyisocyanates.

Both molecular orbital theory and X-ray study reveal that a N,N'-di-substitute carbodiimide is not linear.[46] The NCN bond angle varies from 166^0 to 170^0. The dihedral angle of the cumulenic π bond plane is nearly 90 degree so as to introduce charality to the molecule (Figure 1.19).[46] NMR studies indicate that the inversion barrier between the two enatiomers is between 6-9 kcal/mol. Due to low barrier of isomerization, most carbodiimides are racemized at room temperature.[47, 48]

There are several synthetic routes to prepare carbodiimides, which includes reaction between isocyanates and phosphorus oxide,[49] Tieman Rearrangement[50] and dehydration from ureas and thioureas.[51-56] In the previous work to prepare hydrophobic carbodiimides, dehydration procedure using triphenylphosphine, bromine, triethylamine have been used. But this may not work if the side arm of the urea bears a strong tertiary amino group or oxyethylene group.

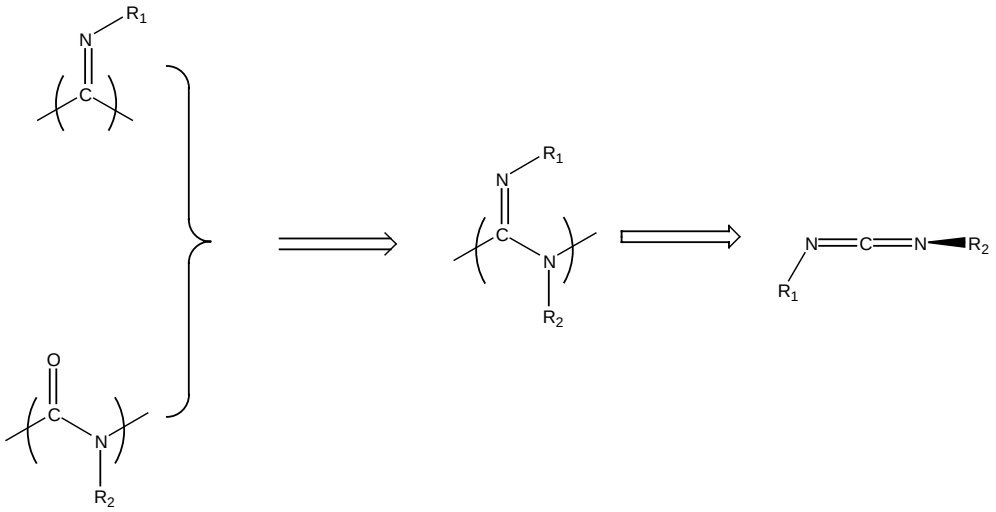


Figure 1.18 Relationship among polyisocynide, polyisocynate, polycarbodiimide and its monomer.

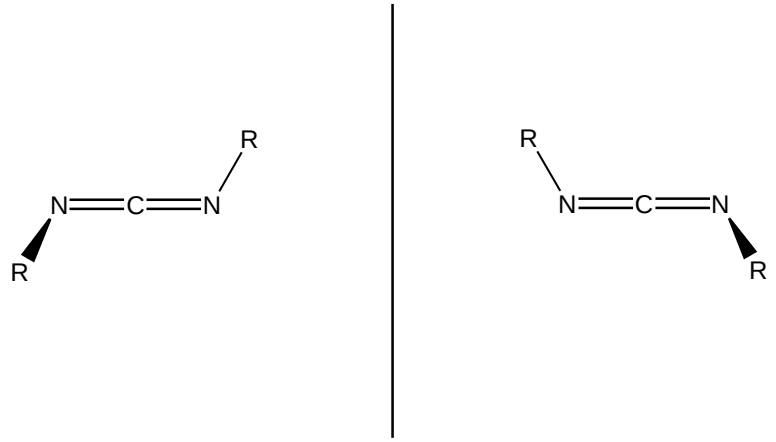


Figure 1.19 Enantiomeric conformations of carbodiimides.

1.4.2 Living polymerization of carbodiimides

Living polymerizations are polymerizations that proceed with an initiation rate near the propagation rate and without termination and transfer from growing end group to solvent, a formed polymer chain or a monomer. For a strict living polymerization reaction, the molecular weight is governed by monomer to initiator ratio.[57] Additional advantage of living polymeriztion is its application in preparation of block polymer, since the polymer can be synthesized in stages, each stage containing a different monomer.

Carbodiimide is a reagent to activate the carboxylic acid for the amide preparation. The nitrogen atoms are nucleophilic and carbon atom between the two nitrogens is very electrophilic. Many nucleophilic reagents can react with carbodiimides to open the C=N double bond. Years ago, chemists initiated the polymerization of carbodiimides with Na/DMF, CH_3I, $AlBr_3$, allyl lithium and $Hg(Et)_2$.[58, 59] With different reaction conditions and

different initiators, same polymer with low molecular weight was obtained. To be strict, the product is not a polymer in real sense so further characterization was doomed meaningless.

The Novak group then studied the polymerization of carbodiimides with transition metal complex as the initiator. Figure 1.20 is an example of a polymerization of a carbodiimide catalyzed by a titanium(IV) complex.[60] To initiate the polymerization, a monomer is inserted into the Ti-nucleophile bond to form an intermediate amidinate complex with the nucleophile bonded to the carbodiimide carbon. Propagation follows as a monomer coordinates to titanium and inserts into the Ti-amidinate bond until the reaction reaches an equilibrium depending on the temperature and the nature of the monomers. The end amidinate group is incorporated into the complex and result in a reduction in the rate of polymerization but better control. The polymerization is living because the end polymer unit bonded to metal is stable to solvent as well as polymer chain and doesn't undergo termination.

Several transition metals such as Ti, Cu and Ni complexes have been made and investigated for the polymerization.[60-62] Figure 1.21 shows some of the organometallic complexes used for polymerization. The polymerization is influenced by not only the metals but also the ligands. Generally speaking, bulky or electrodonating groups bonded to the metal tend to decrease the reaction rate. Some of the copper salts are even active initiators for polymerization, so that carbodiimide dissolved in water also can be polymerized under these conditions with this catalyst.

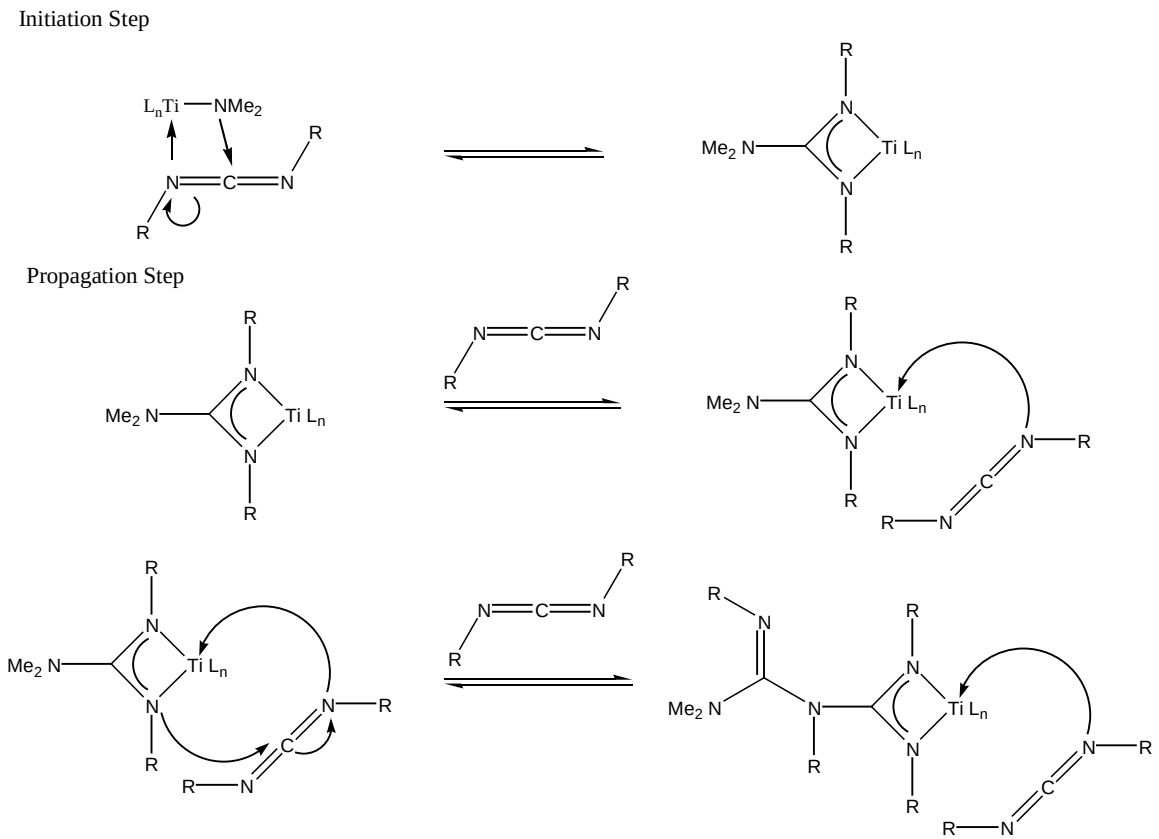


Figure 1.20 The mechanism of polymerization of carbodiimide monomer using a Ti (IV) catalyst.

For many living polymerizations, if a specific functional end group is introduced at the polymer chain, the desired reaction is performed after all of the monomers are consumed. Different from this, functionalized initiators can also be used. For the polymerization catalyzed by transition metal complexes, a nucleophilic functional group can be introduced to the end of polymer chain in the initiation step. With catalyst **vii** in Figure 1.21, Lu synthesized polycarbodiimides bearing thiol end groups and investigated their adsorption on gold surfaces.[63,64]

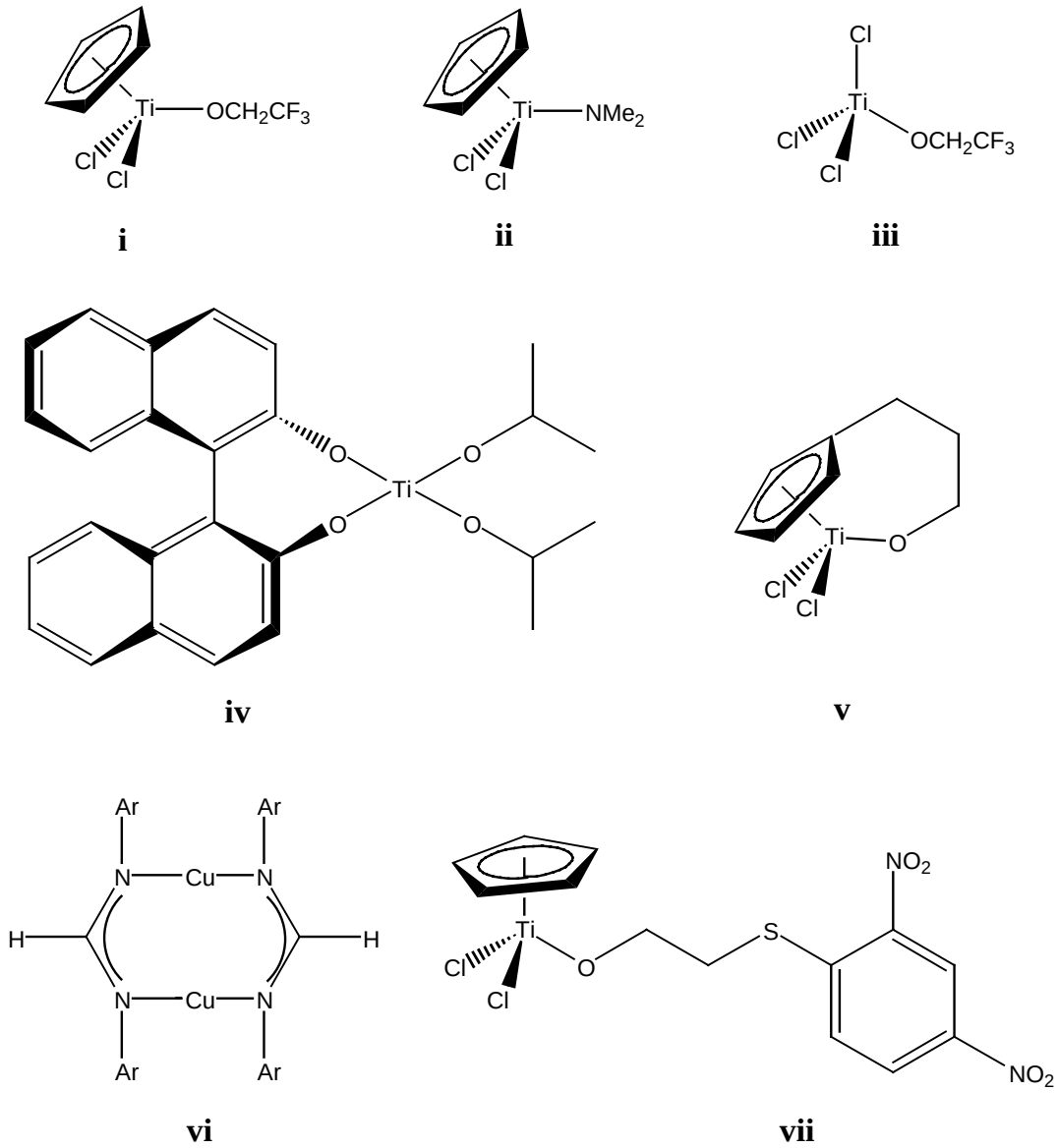


Figure 1.21 Effective catalysts for the polymerization of carbodiimides.

1.5 Properties of helical polymers

1.5.1 Formation of one handed helical polymers

Most synthetic helical polymers are not optical active, because the polymer chains exist as a mixture of blocks of right and left-handed helix connected by helical reversals (Figure 1.22). Helical reversals are conformations separating the different handed segments.[65, 66]

Without chiral stimuli, there is no energetic gap between the left and right-handed helix, so neither sense is more thermodynamically preferred. Many applications of helical polymers, however, require single handed conformations.

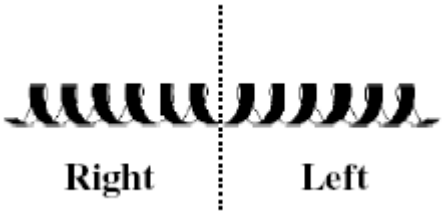


Figure 1.22 Optical inactive helical polymer chain.

Usually when an inversion occurs from one helical sense to the other, it has to overcome an inversion barrier. According to the inversion frequency between the two helical segments, the helical polymer chains can be categorized into two types: fluxional chains and nonfloxional chains.[67] Fluxional polymers usually have low inversion barrier and more helical reversals. So, in room temperature, inversion occurs frequently between the two helices and the reversible equilibrium between the two helixes reversals can be observed sometimes. When the fluxional polymer subject to a chiral perturbation, such as chiral induction, the polymer chain can changed its conformation rapidly to response. Likewise, it undergoes racemization when the asymmetry interaction is removed. Nonfluxional helices have higher inversion barrier and less helical reversals. In room temperature, their conformations are locked. Polypeptides, polyisocyanates, polyphenylacetylenes are examples of fluxional helical polymers and the polyisocyanide is an example of the other type. Polycarbodiimides can be both depending on its side chain structures. Without methyl pendant groups, in most conditions, polycarbodiimides are nonfluxional.

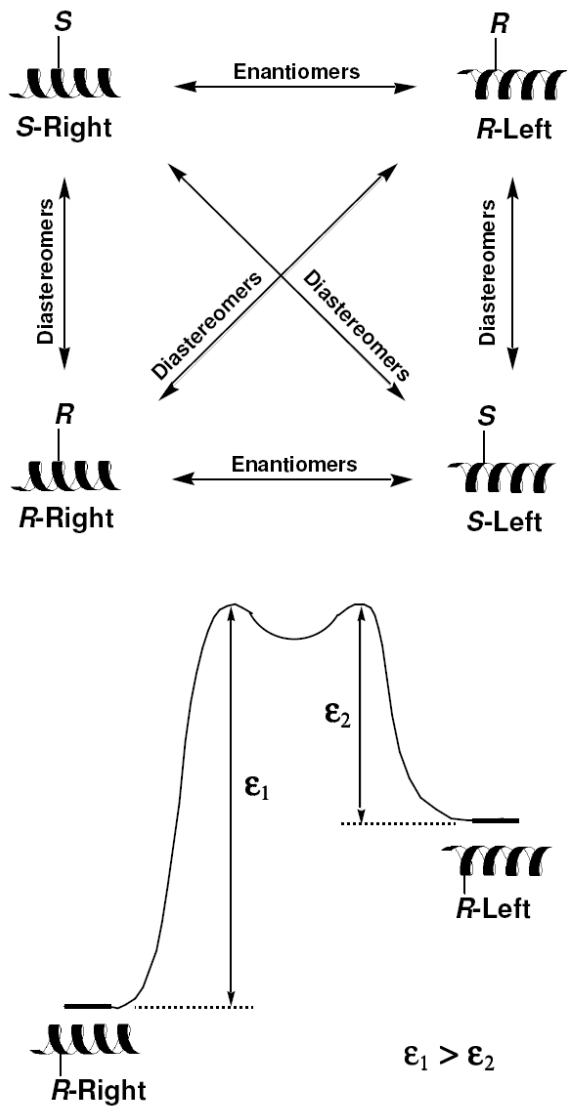


Figure 1.23 Polymers composed of chiral monomers.

1.5.1.1 Preparation of one handed helical polymer from chiral monomers[45,69,70,62]

Many single handed helical polymers, like polysilanes, polyisocyanides and polypeptides mentioned before, are prepared from chiral monomers. For an optical inactive helical polymer, the left handed helical segments and right handed helical segment have the same population and energy magnitude. Helical inversion doesn't occur for one helices to give

predominating biased helical polymers unless the polymer interacts with a chiral stimuli. The left and right handed helical structure are enantiomers. When there exists a chiral center in the polymer molecule, due to the steric hindrance, the chiral center effects the two type of helical segments differently, so one of the two type of helical segment is preferred energetically. Figure 1.23 reveals the interaction of helices and chiral centers on the polymer repeating units. ε_1 and ε_2 are activation energy for helical inversions of two diastereomeric helical segments. During the polymerization of the chiral monomers, the energetically preferred helical structure predominates. But there can still exist minor opposite helical segments and defects.

Both the pedant groups and the backbone could bear the chiral center. For polypeptides[30] and chitosans,[17] their backbone bears chiral centers; but for polyisocyanates,[69, 70] polyisocyanide,[45] polycarbodiimides[62] and polysilanes[14, 71] whose monomers have side arms, their pendant groups bear the chiral centers. Generally speaking, when the chiral center is on the pedant groups, the closer the chiral center is to the backbone, the more bulky and rigid the pedant group is, the stronger interaction is between the chiral center and the backbone.[68]

Virgin polymers preparaed from chiral monomers may not have a regular helical structure or have large number of defects (such as helical reversals). So when a chiral nonfluxional polymer is prepared, there arises a situation involved both the Kinetically Controlled Conformation (KCC) and Thermodynamically Controlled Conformation (TCC), the chiral polymers have to undergo annealing to move to TCC from KCC.[68] For polymer such as polysilanes, polyisocyanates and polypeptides, the inversion barriers are low enough for the inversion to occur in room temperature or even lower so that the annealing is taken

naturally to give one handed helices. But for polycarbodiimides, with higher inversion barriers, the polymer needs to be heated to adopt the thermodynamically stable state.[62,63,68]

1.5.1.2 Preparation of one handed helical polymers with chiral catalysts

Optical active polyisocyanide and polycarbodiimide have been synthesized with chiral catalysts.[41-44] Enatiomeric catalysts give enatiomeric biased polymers. These polymers are in a conformational helical structure, but their racemization is favored by entropy. With lower inversion barriers, one handed polyphenylacetalenes, polysilanes and polyisocyanates can't be prepared through chiral catalyst in room temperature. Most one handed polycarbodiimides prepared through chiral catalysts are racemized in high temperature (60-80 ^{0}C) unless they have very bulky pedant goups.[67]

1.5.1.3 Achievement of one handed helix by helical induction

The structure of a helical polymer is effected by a number of factors, no matter if they are in solution or in the bulk, an example is the chitosan discussed in an earlier section. Chitosan keeps its helical structure in its DMSO solution, but when water was added, the helical structure collapses due to the hydrogen bonds between the polymer molecule and the solvent.[17] Another example is a peptide,[30,39] they only adopt the α-helix under properly pH values.

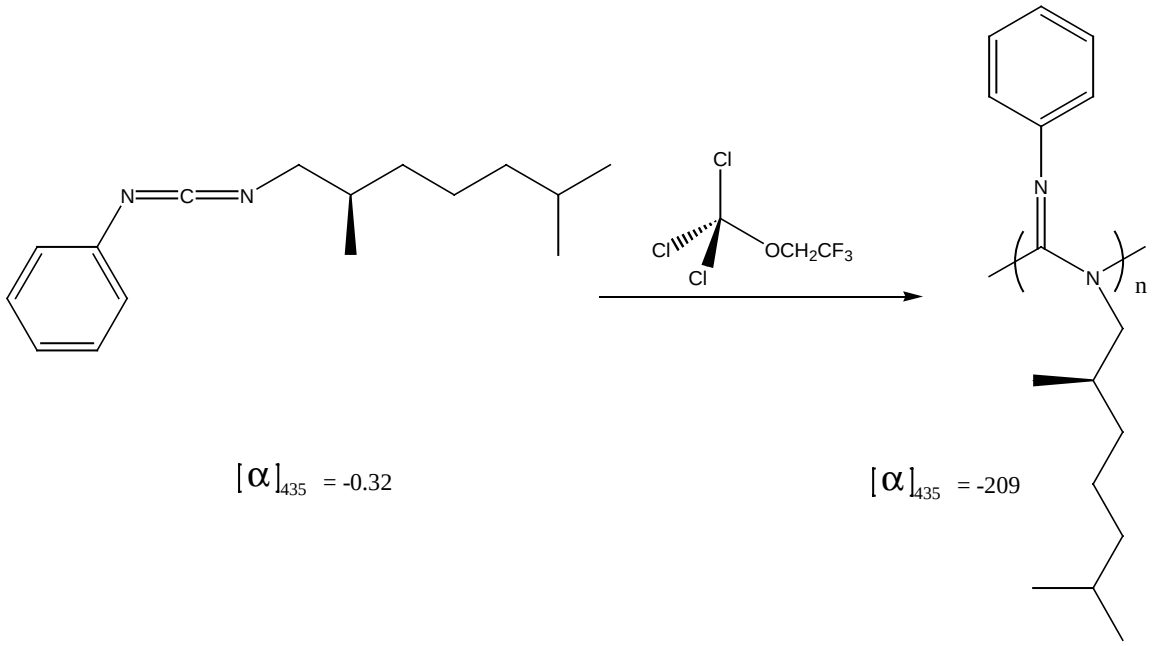
Optical inactive helical polymers are also subject to chiral stimuli in solution phase. Predominating one handed polyphenylacetalene bearing carboxylate pedant groups was observed when chiral amines were added to this polymer solution.[37,39] The ion pairs resulted from the neutralization between the chiral amine and the polyphenylacetylene drive the helical induction, during which one type of helical segments undergoes inversion to the other

type that the chiral anion favors.

Schlitzer investigated the helical induction by added chiral camphorsulfonic acid (CSA) to an achiral polycarbodiimide.[68] The backbone of polycarbodiimide is made of repeating units of guanidines, a strong base. When excess chiral CSA is added, acid-base interaction occurs to force the whole polymer chain adopt a single handed helical structure determined by the chirality of the acid.

1.5.2 Chiral amplification

In 1970s' Goodman and Chen prepared optical active helical polyisocyanate from chiral monomers with optically inactive catalysts.[72] Compared to the monomers, the synthesized polyisocyanates showed exceptionally high optical activities. There are other examples, such as a chiral polyisocyanate synthesized by the Green group and a chiral polycarbodiimide synthesized by Lu in the Novak group (Figure 1.24), showing the same feature.[66,70]



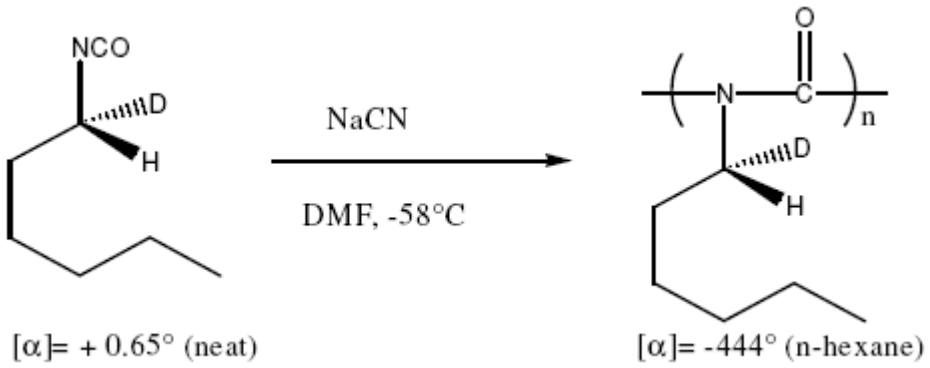


Figure 1.24 Amplification of chirality.

1.5.3 Cooperativity

The creation of one handed helix is closely related with coperativity, which reflects the effectiveness of the interaction between the repeating units within a polymer chain. For helical polymers, this is expressed in the propagation and maintenance of the helical sense. When a chiral perturbation is introduced into the polymer chain, a local helical segment will would adopt a prefered conformation in response and the helical sense can be extended and transfered along to the polymer chain. How the information of the perturbation is maintained depends on the degree of cooperativity, which is influenced by the stiffness of the backbone and sterics of the pedant groups. Figure 1.25 indicates how a perturbation achieves a single handed helice through cooperativity.

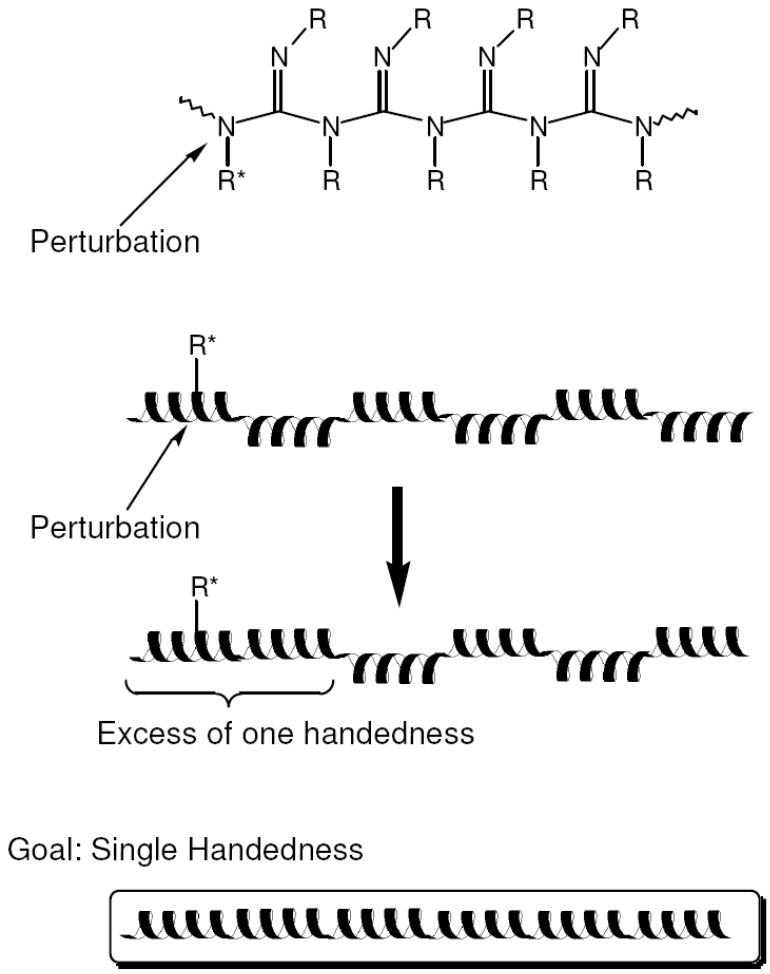


Figure 1.25 Cooperativity within a helical polymer chain.

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Chapter II Investigation of Helicity of Water Soluble Polycarbodiimides

2.1 Review of single handed polycarbodiimides

Optical inactive helical polymers comprise of both left and right handed helices of equal population and energy magnitude. The left and right handed helices are mirror images of each other. Along a polymer chain, there may be many helical segments, left or right handed, which exist in a way that each helical segment is connect to the another sense segment through helical reversals. The length of the helical segment depend on nature of the polymer, the molecule weight and polymerization conditions. Polymer chains can therefore adopt one type of helical structure for several turns and then adopt the other for the next several turns. For fluxional helical polymers, the inversion between the two different types of helices occurs frequently in room temperature, but their average lifespan and length of the segments are still same so that the polymer itself doesn't show chirality. The helical reversals introduce bends along the polymer chain, so the population of the reversals affects the persistence length. The more reversals in a polymer chain, the shorter the persistence length.[1,2]

The inversion barrier is the required activation energy to switch one-handed helix into the other helical sense (Figure 2.1). The inversion barrier of a helical polymer is controlled by the stiffness of its backbone and the size of the pendant groups. Polycarbodiimide combines some of the features of both polyisocyanates and polyisocyanides. Polyisocyanates are fluxional polymers and polyisocyanides are nonfluxional ones. The inversion barriers of polycarbodiimides are most affected by the pendant groups. Small pendant groups tend to decrease the inversion barrier, so polycarbodiimides bearing methyl groups are fluxional due

to its lower inversion barriers.

Three methods have been tried to achieve single handed polycarbodiimides: polymerization of chiral monomers with achiral catalyst; polymerization of achiral monomers with chiral catalyst and helical induction of achiral polymers in solution by external influence.

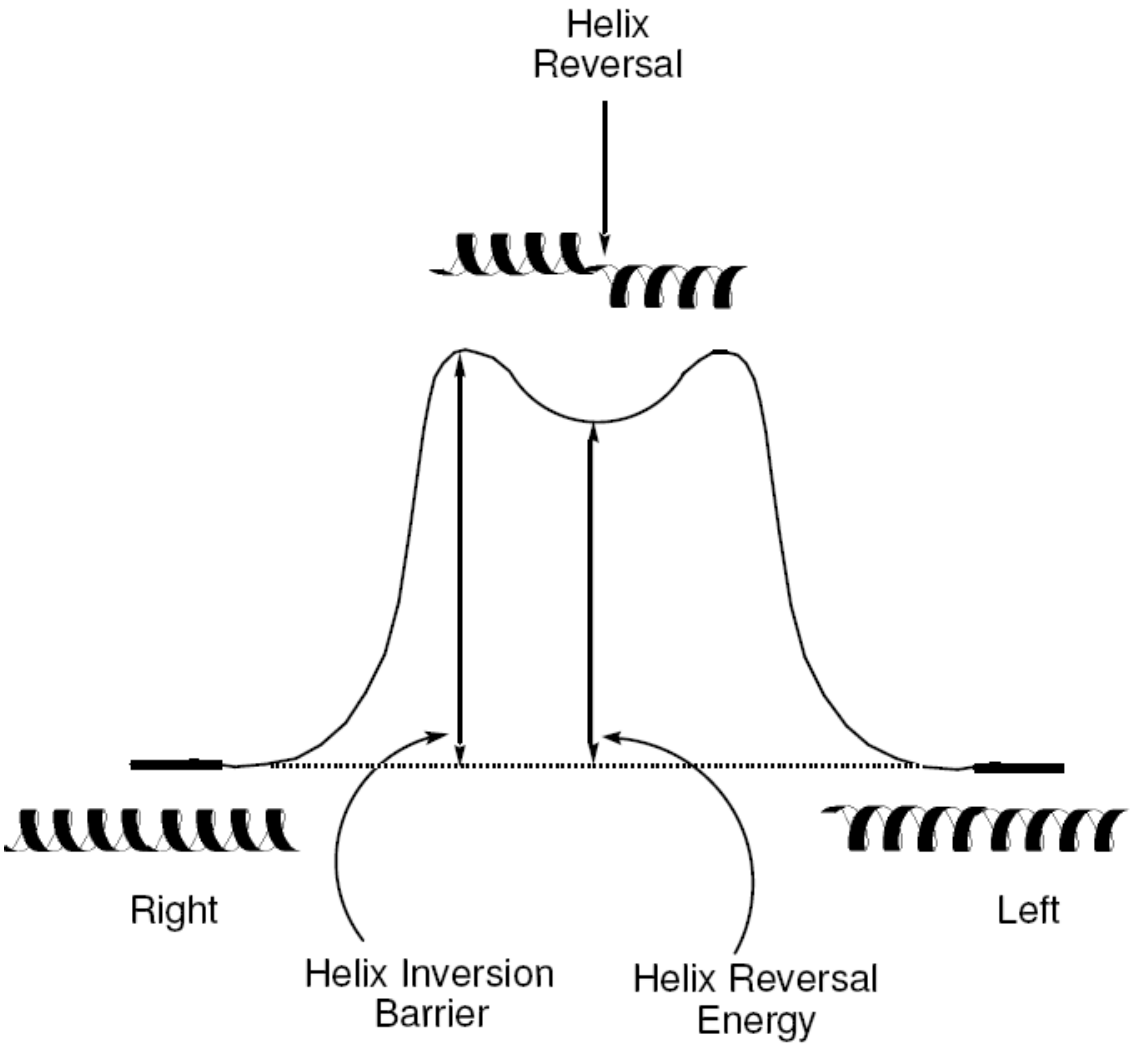


Figure 2.1 An energy diagram of helical inversion of a helical polymer.

2.1.1 Polymerization of chiral monomers

Polymerization of carbodiimides with chiral pendant groups has been investigated using titanium catalysts. Monomers in Figure 2.2 are examples of chiral carbodiimides. During polymerization of bulky carbodiimides, to reduce the steric hindrance between the chiral pendant groups of monomer and those of end repeating unit in the polymer chain, the monomer can only access and chelate the metal with a specific orientation. As a result, the monomer is incorporated into the preferred helical structure. The virgin polymer is in its KCC (Kinetic Control Conformation) state. When heated, the polycarbodiimides can be annealed to reach the TCC (Thermodynamic Control State). But for polycarbodiimides bearing methyl groups, the TCC is reached at room temperature because of its low inversion barrier.

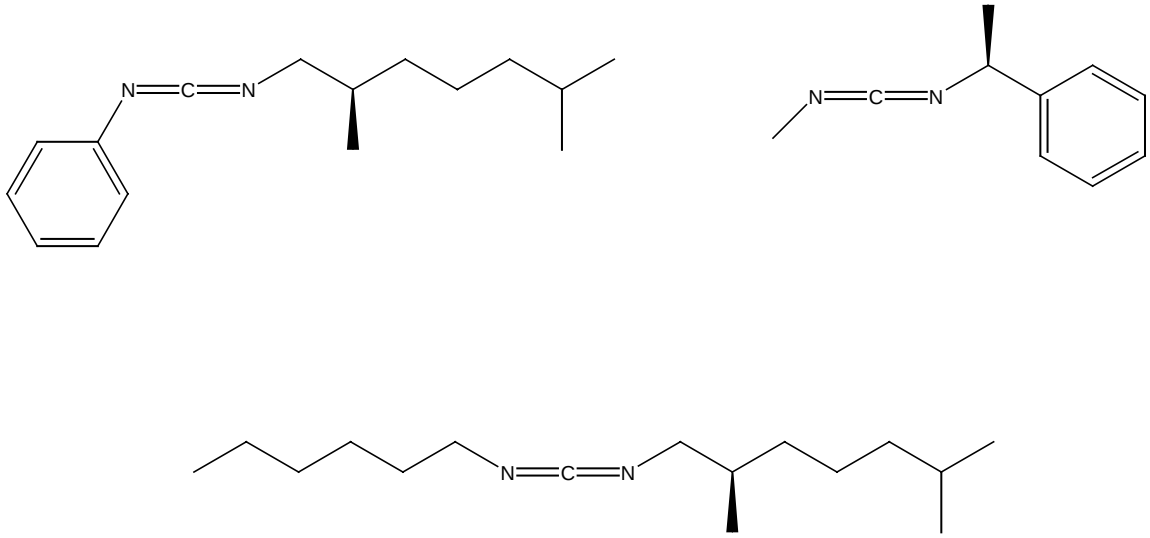


Figure 2.2 Examples of carbodiimides used in polymerization studies.

The annealing of chiral polycarbodiimides can be monitored by using a polarimeter. Large optical rotation changes are typically observed during the annealing process. The rate

of the optical rotation changing versus the temperature has been found to obey Arrhenius behavior. The higher the temperature is the faster the optical rotation changes.

The size and placement of the chiral centers are responsible for the cooperativity of these polycarbodiimides. Generally speaking, the closer and the larger the chiral center is to the backbone, the greater effect it has on the backbone conformation since helical structure of the backbone originates from the steric interaction of the chiral center between neighboring repeat units.[3]

2.1.2 Polymerization of achiral monomers with chiral catalysts

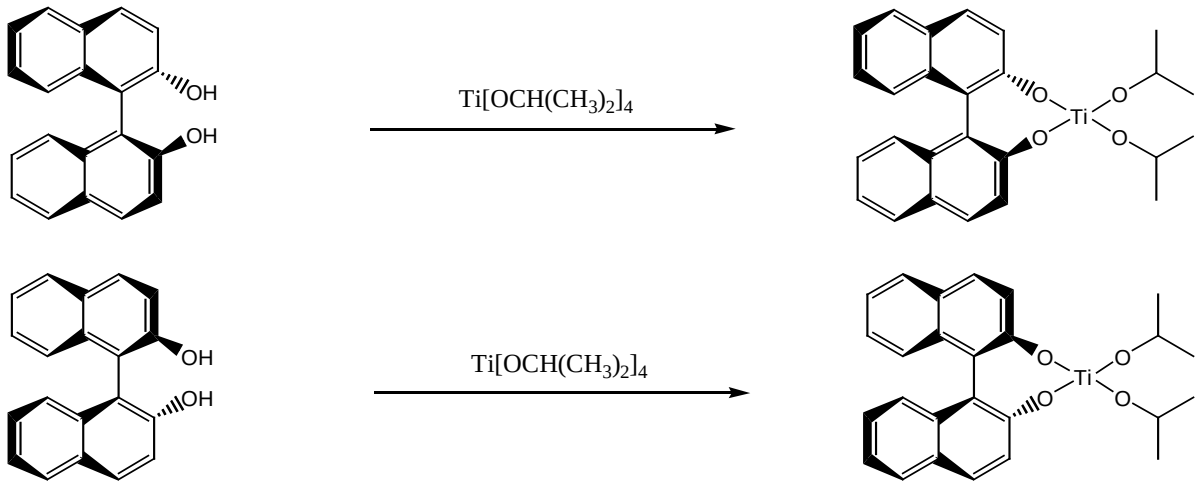


Figure 2.3 Preparation of chiral catalysts ((S)-Binol-Ti) and ((R)-Binol-Ti).

Compared to single handed polymer preparation from chiral monomers, optical active polymer created from chiral catalysts are more economic, since chiral monomers are more expensive and difficult to synthesize. Also, single handed helical polymers prepared through chiral catalysts can show better cooperativity. Eanantiomeric catalysts give enantiomeric polymers, and the conformational helicity of these polymers originated from the chiral

catalysts.[1,4] Optical active stable polyisocyanides have been reported to be prepared through chiral catalysts. Inversion barrier of polycarbodiimides vary depending on the size and nature of the pendant groups. Unless the other group is very bulky, single handed polycarbodiimides bearing methyl groups cannot be prepared using chiral catalyst, since their inversion barrier is too low to lock in the helical conformation.

A number of titanium(IV) catalysts have been synthesized in Novak group.[4, 5, 6] Modification of catalysts has been accomplished by the employment of chiral ligands. Gonglu Tian reacted enantiomeric binaphthols with titanium salt to yield the enantiomeric titanium catalysts (Figure 2.3).[4] These catalysts initiate the polymerization reaction the same way the achiral catalysts do to afford the amidinate complex, which act as the propagation species for the polymerization. Being governed by the chiral active catalytic sites, the achiral monomers are incorporated into the polymer chain to give a single handed helix.

At high temperature, the thermal motion of the polymer chain becomes active, so in most cases, the helical inversion of the single handed polymers proceed until they become racemic. The rate of racemization depends on the temperature, solvent and the size of the pendant groups.

2.1.3 Helical induction

The backbone of the polycarbodiimide is a guanidine, which is a strong base, so addition of acid to the polymer solution yields ion pairs due to acid-base chemistry. If the counter ions are chiral, an induction effect occurs to give a biased helical polycarbodiimides. Schlitzer investigated the helical induction of polycarbodiimides using chiral camphorsulfornic acids (Figure 2.4).[2,7]

The ionic interaction between the charged backbone and its chiral counter ions induces the racemic polymer chain to adopting a preferred handness, so that the polymer display a large optical rotation. When heated, the optical rotation of the ionic pair complexes increase but doesn't show a plateau, which is different from the annealing behavior of most other polycarbodiimides.[2,7]

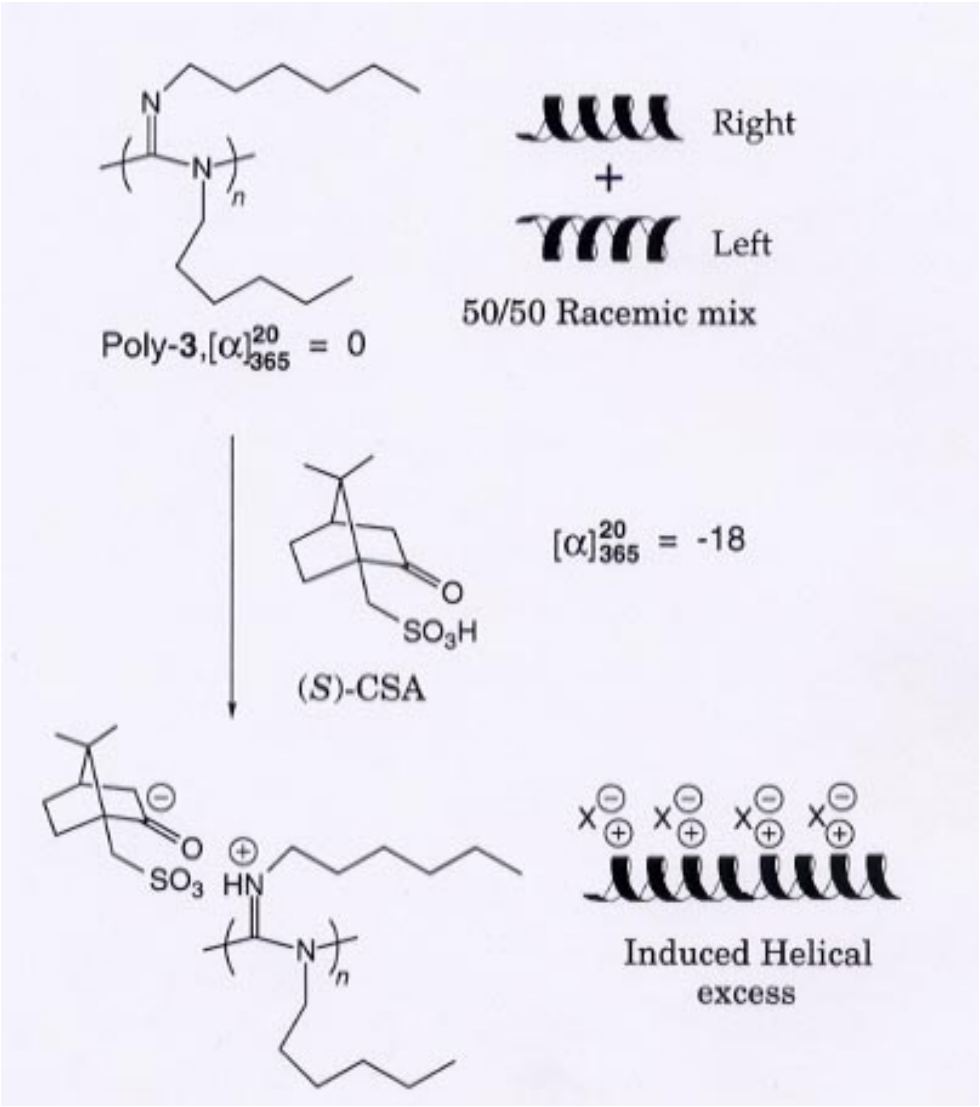
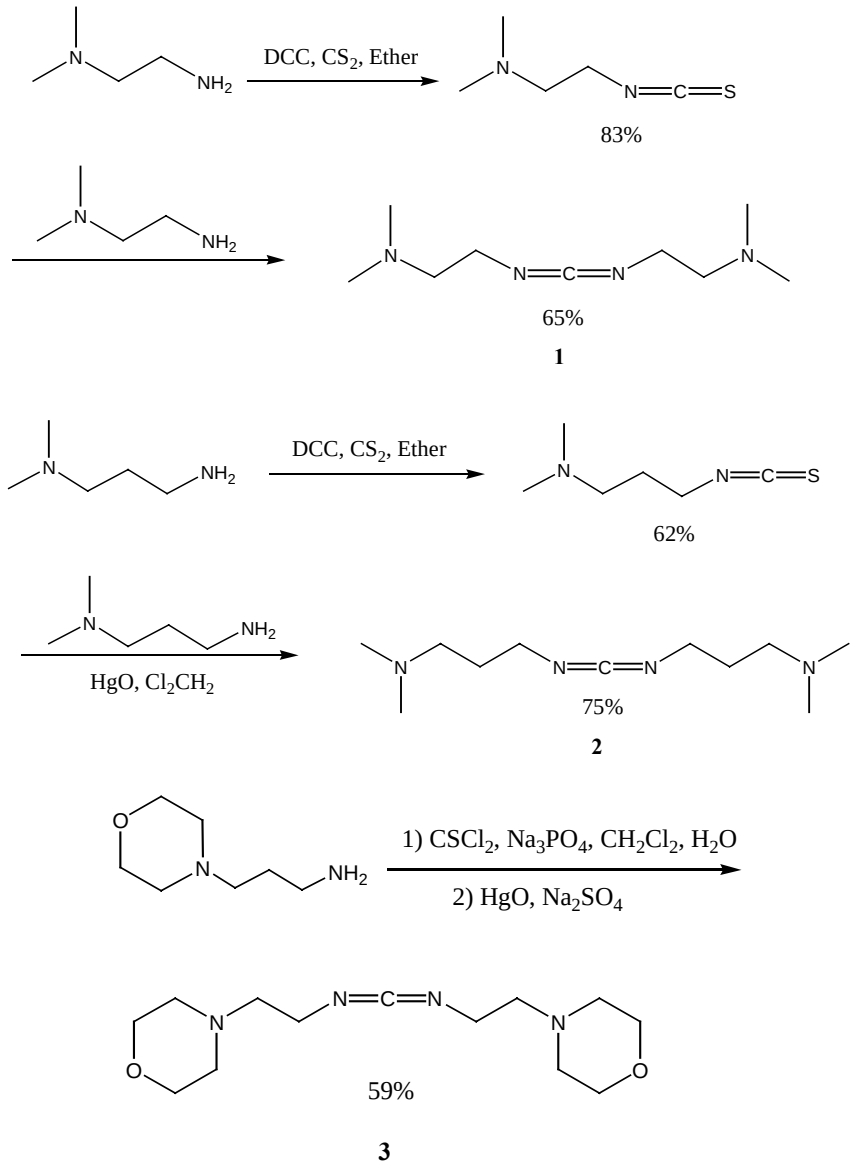
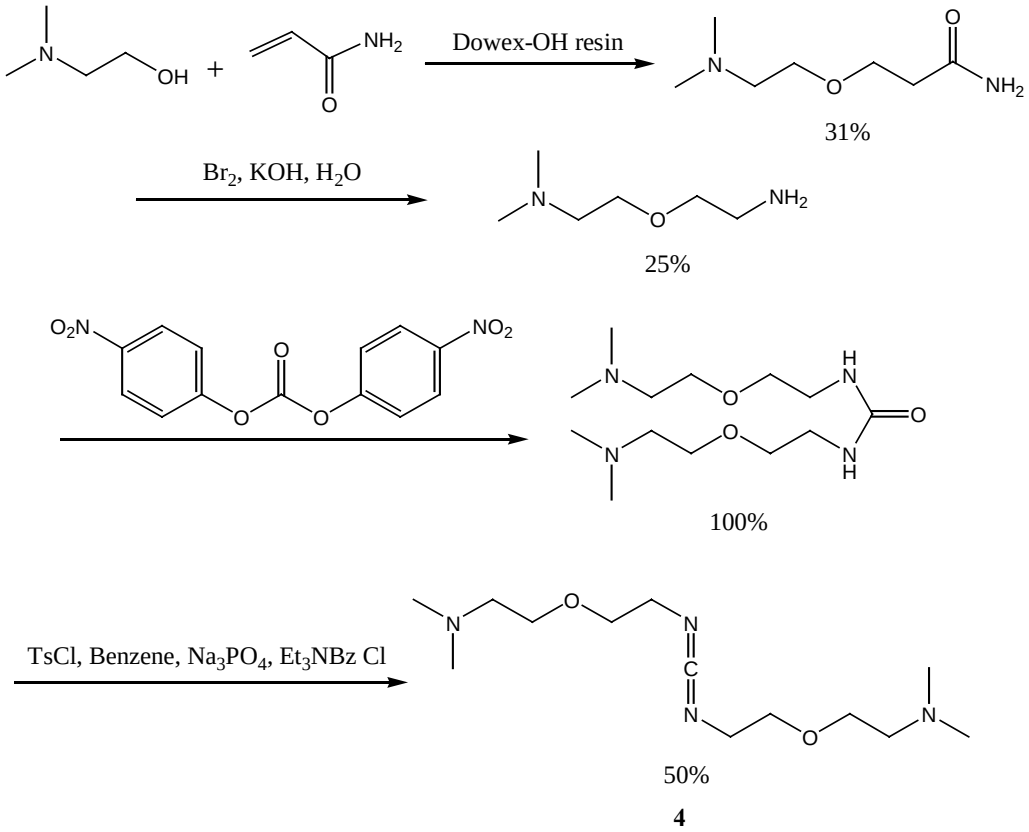


Figure 2.4 Helical induction of polycarbodiimide using (1S)-10-camphorsulfonic acid.

2.2 Helical induction of ionic polycarbodiimides by counter ions



Scheme 2.1 Synthesis of hydrophilic monomers bearing functionalized side chains.



Scheme 2.1 Synthesis of hydrophilic monomers (continued).

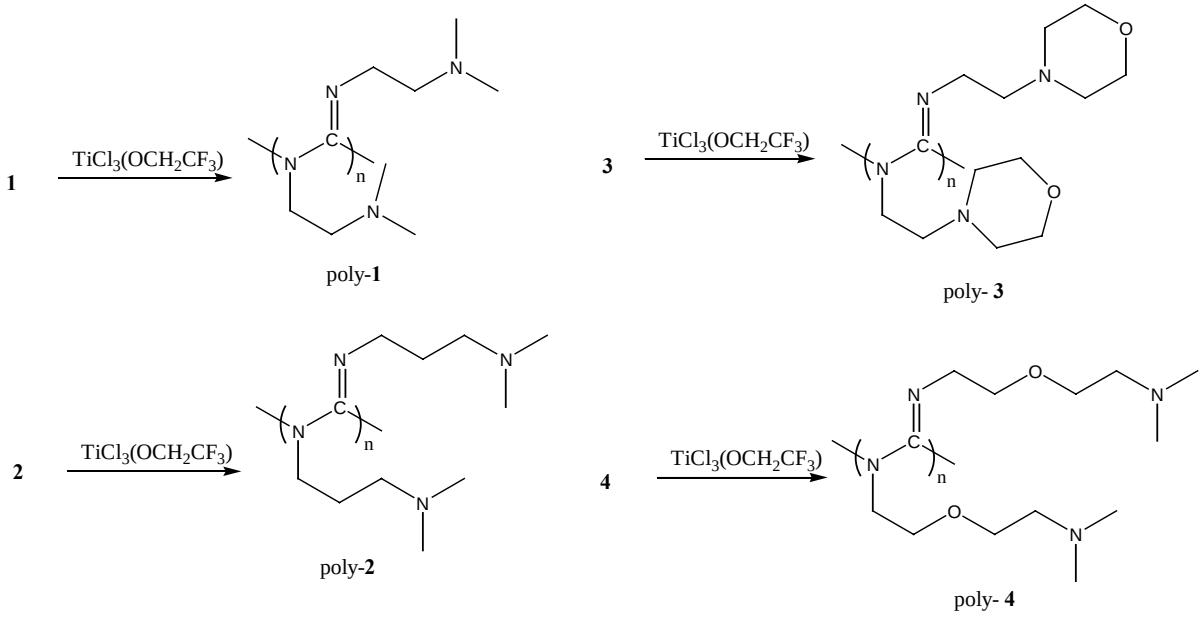
2.2.1 Helical induction of ionic symmetric nonfluxional polycarbodiimides

Water soluble polymers can be either ionic or neutral polymers. In the former case, the ionic moiety commonly is a carboxylate, phosphate or tetraalkylammonium ion. To extend the helical induction study by Schlitzer, polycarbodiimides bearing trtraalkylammonium pendant groups were prepared. Schlitzer had studied the helical induction by camphorsulfonate ion with the protonated backbone. Likewise, with polycarbodiimides bearing ionic pendant groups, same methods can be employed for investigation of helical induction.

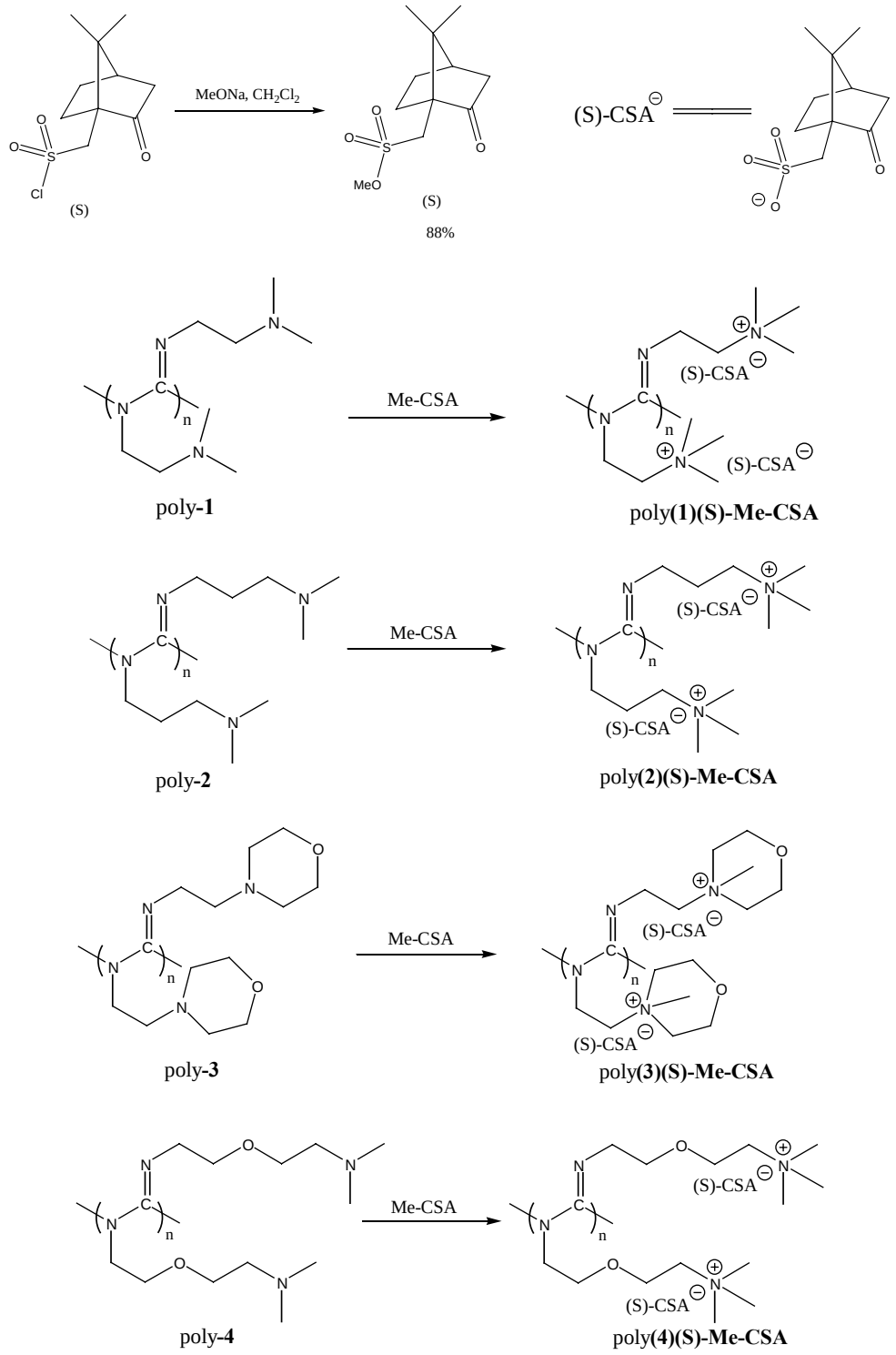
A series of monomers with symmetric hydrophilic side arms were synthesized (Scheme 2.1). The same procedure was used for monomers **1** and **2**. Dehydration of ureas or thioureas is always used to yield carbodiimides.[8-13] In this preparation, the first step is the preparation of a isothiocyanate. Compared with isocyanates of low molecular weight, the boiling points of the isothiocyanates are higher making them easier to work up (Scheme 2.1). The reactions of these isothiocyanates with an amine give rise to thioureas with the pendant basic dimethyl amino groups. Finally a facile dehydration by HgO and Na_2SO_4 gives the symmetric carbodiimides. An easier procedure has developed for the preparation of monomer **3**: the reaction of thiophosgene with two equivalents amine followed by dehydration. Sodium phosphate is used to scavenge the protons produced in the first stage of the reaction. In synthesis of monomer **4**, a Michael addition is catalyzed by the Dowex resin to give the amide, followed by a Huffman rearrangement to yield the amine. The urea is then prepared by qualitative reaction of the amine with an active carbonate. The dimethyl amino group in the side arm is so basic that few organic bases could be employed to prevent the side arms from being protonated during the dehydration. Therefore the dehydration is performed with assistance of phase transfer catalyst in order to increase the solubility of sodium phosphate in benzene, the solvent for reaction.

These monomers were polymerized by the titanium (IV) catalyst to yield the corresponding polymers (Scheme 2.2). Ionic polymer could be made by reaction of these polycarbodiimides with both chiral acids and chiral methylating reagents (Scheme 2.3). Solubility of both salts prepared from the polymers with camphorsulfonic acid and methyl camphorsulfonic acid ester were tested, and the latter one had a better solubility in organic

solvents such as dioxane. So no more investigation was performed on the protonated polymeric salt.



Scheme 2.2 Synthesis of hydrophilic polymers from monomer **1** to **4**.



Scheme 2.3 Preparation of ionic polymers from non-ionic amine containing polycarbodiimides.

Table 2.1 Specific Optical Rotation Values of Symmetric Ionic Polycarbodiimides

	Poly**(1)(S)-Me-CSA**	Poly**(2)(S)-Me-CSA**	Poly**(3)(S)-Me-CSA**	Poly**(4)(S)-Me-CSA**
$[\alpha]_D$	13.64	20.67	1.32	13.09

In Schlitzer's induction experiment, when chiral camphorsulfonic acid was added, the polycarbodiimides show optical rotation but no active CD spectra.[2,7] An explanation accounting for this is that the ionic interaction of the charged backbone and the counter ions draws them closer so that the pendant groups of the polymer were pushed into a helical order that the chiral camphorsulfonate ion favors, but backbone doesn't response as much as the pendant groups do to give a regular biased helix.

Table 2.1 show the optical rotation data of the new ionic polymers in room temperature. The CD spectra were run for these samples but no peak were found. The polymers in Table 2.1 did not display significant optical rotation amplification, as polycarbodiimides do when they adopt a biased helical structure.

Annealing of these polymers was performed to further investigate the chiral induction. In Schlitzer's induction experiment, when heated, the solution of chiral acid and polymer complex show a constant increase of optical rotation, which is believed due to the induced helical inversion of the backbone.[2] The polymer he employed is nonfluxional dihexyl polycarbodiimides, the helical inversion of which wouldn't occur unless it was heated. For the new ionic polycarbodiimides, if their optical rotation values change when the polymers were heated, there is for sure a relationship between the chiral counter anion and the

polymeric cation.

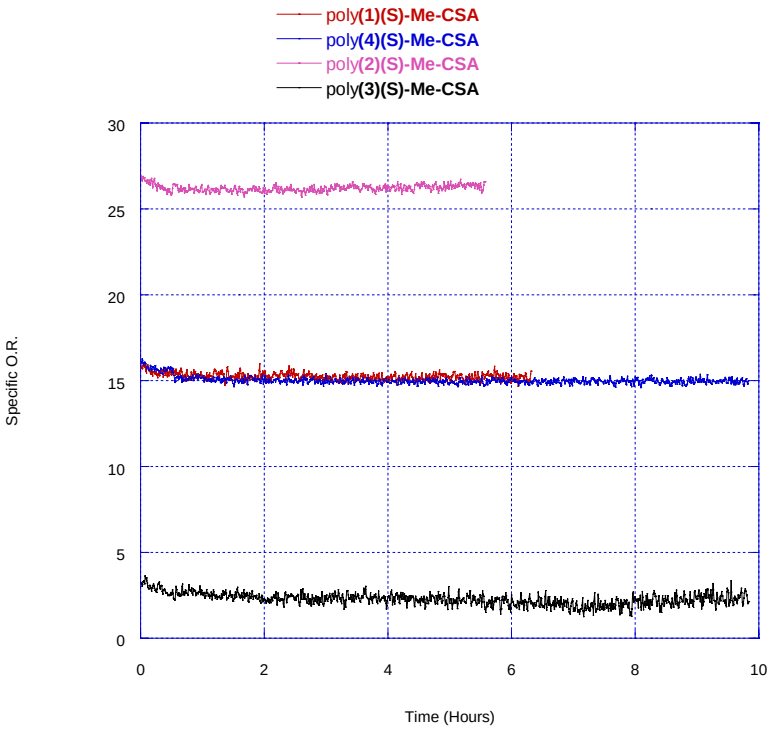


Figure 2.5 Annealing behaviors of ionic polycarbodiimides.

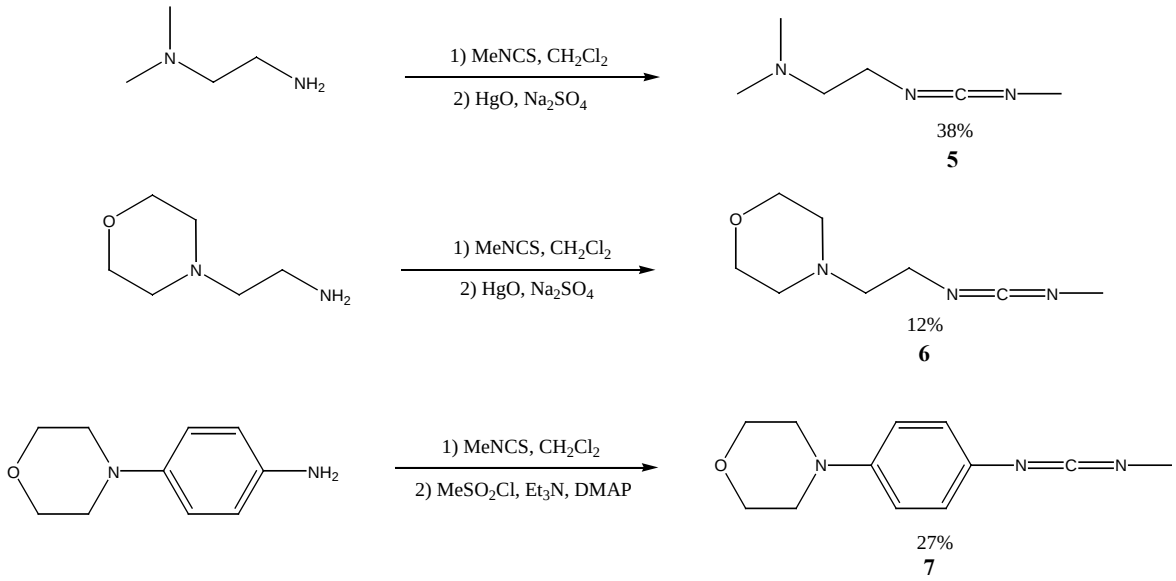
These ionic polymers have good solubility in a wide range of solvents including water, dioxane, dimethyl formamide (DMF) and chloroform, which makes them candidates for block amphiphilic polymers for self assembly study. Figure 2.5 shows their annealing behavior in DMF at 55 ^{0}C and 589 nm. Their optical rotation values of the polymers don't change when they were heated. Due to the lack of significant optical rotation change, we believe no induction was observed in these systems. It may be the case that the chiral center is two far from the backbone.

2.2.2 Helical induction of ionic fluxional polycarbodiimides

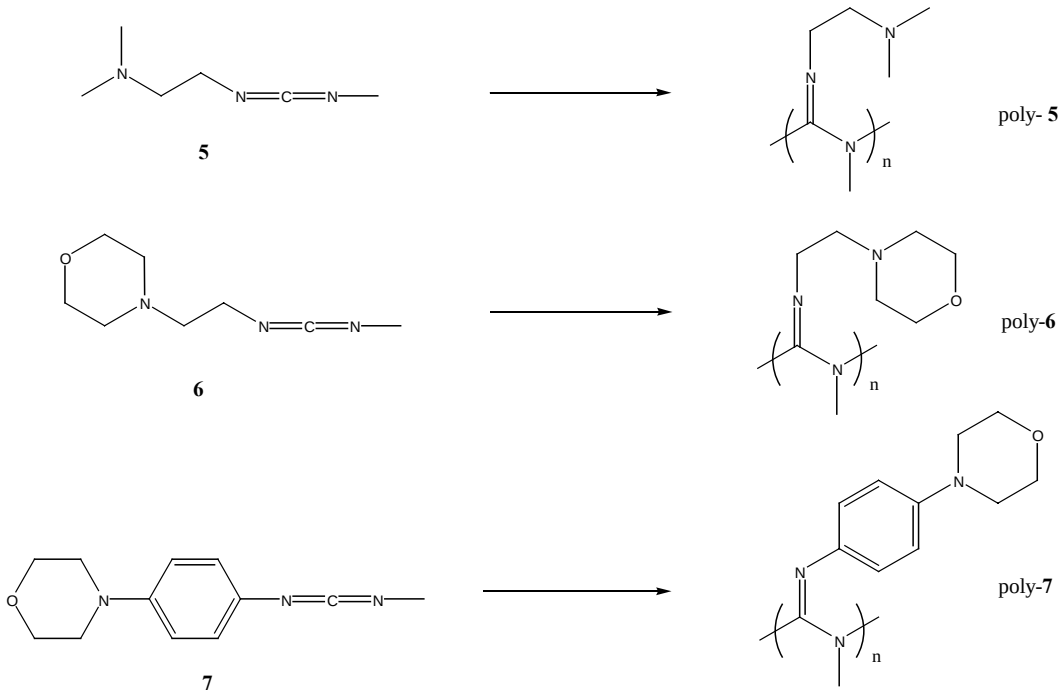
The annealing experiment and the optical rotation value measurement does not provide proof for a strong interaction between the cationic polymer pendant groups and the anionic counter ion. So if there is an experiment can be performed to separate the contribution from the polymer and the counter ion, the induction effect can be judged. Compared with nonfluxional polymers, fluxional ones can response instantly to the helical induction. To investigate the affect of the activation barrier on helical inducing, we turned to the sergeant-soldier principle with fluxional polycarbodiimides.[14,15]

The inversion barriers of polycarbodiimides decrease as the pendant groups become smaller. Methyl substituted polycarbodiimides are usually fluxional due to their low inversion barriers. If helical induction occurs between the interaction of counter anion and the cationic polymer, the polymer chains response with a way that the counter ions favor. Several carbodiimides bearing a methyl pendant group have been synthesized and their corresponding polymers were synthesized in bulk using titanium(IV) catalyst. (Scheme 2.4 and Scheme 2.5).

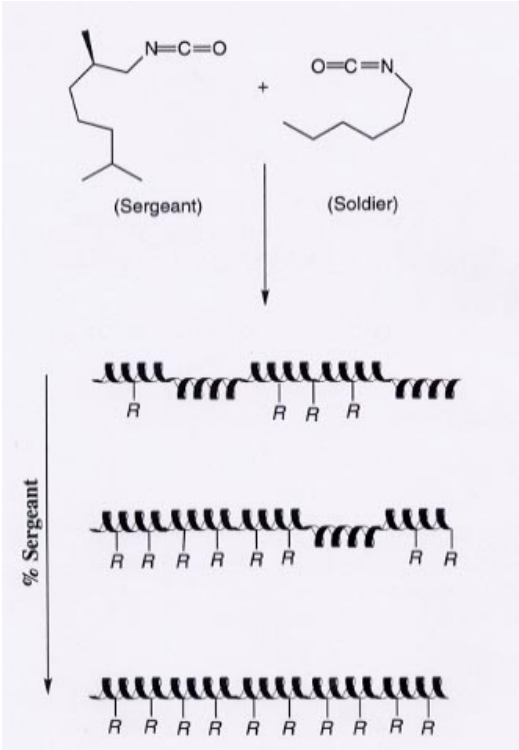
The three polymers were synthesized with different structure features. Poly-**5** and poly-**6** have a flexible linker, an ethylene group, between the backbone and ionic interaction site, while poly-**7** has a rigid one, the phenyl group. Both poly-**6** and poly-**7** have morpholine groups which results in more steric demanding ammonium group when they are protonated. Due to the difference between linkers and amino groups, the ionic interactions may affect these polymers differently.



Scheme 2.4 Synthesis of methyl substituted carbodiimides.



Scheme 2.5 Preparation of fluxional polycarbodiimides with methyl substituents**.**



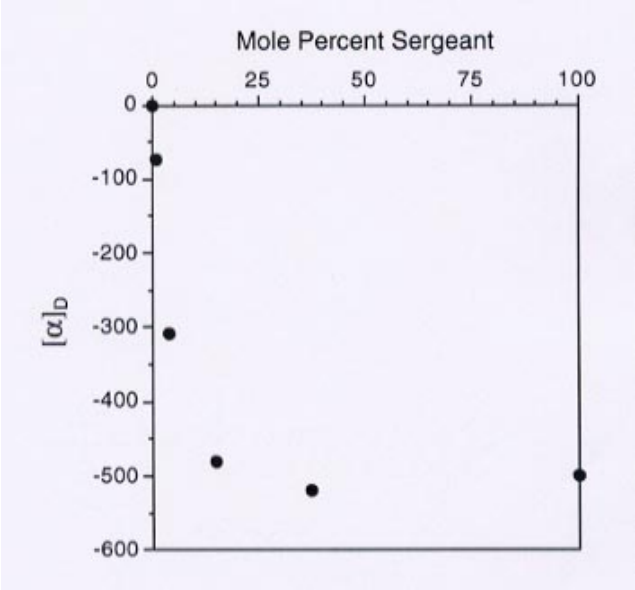


Figure 2.6 Sergeant soldier effect of random copolyisocyanates prepared from (R)-2,6-dimethylheptyl isocyanate (sergeant) and n-hexyl isocyanate (soldier).[14,15]

When a chiral perturbation in the polymer chain influences its conformation, the polymer obeys the sergeant-soldier principle.[14,15] For optical inactive helical polymers, repeat units in different helical segments adopt different handed conformations. Helical inversion can occur for helical segments which inverts the helix to the opposite sense. When the polymer is subjected to a chiral stimulant from either the polymer itself or in solution, the local segment could maintain or convert its conformation sense to meet the demand of the chiral stimulant. This affect is passed from repeat unit to repeat unit down the polymer chain. As a result, the interaction of chiral stimulant with the local repeating unit is amplified.

Mark Green and his coworkers found the sergeant soldier effect when he investigated random copolymers made from (R)-2,6-dimethylheptyl isocyanate and n-hexyl isocyanate (Figure 2.6)**.** The optical rotation value of the copolymer increases very quickly when the concentration of the chiral repeating units is low. When it exceeds about 30%, the optical rotation value reaches a constant value. The chiral repeating units serve as the sergeant because it dictates the sense of the neighboring achiral repeating units, so that a biased helical sense structure is formed.

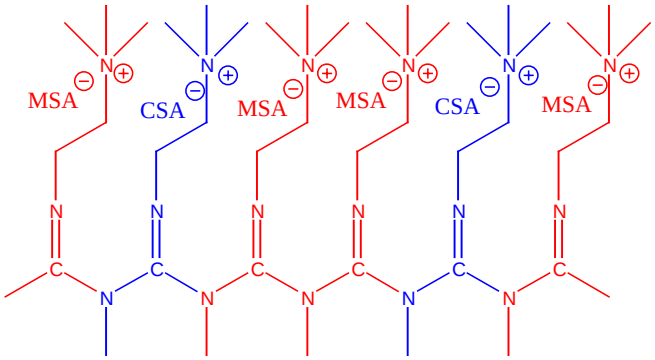


Figure 2.7 Protonated poly-**5** formed from a mixed acid solution of (S)-camphorsulfonic acid and methylsulfonic acid.

The polymeric salt prepared from the fluxional polymers, poly-**5**, -**6** and -**7** and chiral camphorsulfonic acid are optical active. To work out the induced optical rotation value of the ionic fluxional polymer, the basic polycarbodiimdes were protonated by mixed acid solution of (S)-camphorsulfonic ((S)-CSA) acid and methylsulfonic acid (MSA) at a fixed concentration (Figure 2.7). The repeating units binding camphorsulfonic acid serve as sergeants and the repeating units binding methylsulfonic acid serve as soldiers. When the percentage of (S)-CSA goes up, the specific optical rotation of the polymer increases until it becomes a constant value, and this is shown in Scheme 2.6. In the polymeric salt solution, the contribution of optical rotation from the CSA is always proportional to its concentration. So after the optical rotation value of the polymer reached a plateau, the total optical rotation value is linear with the concentration of the CSA.

$$\alpha_{total} = \alpha_{CSA} + \alpha_{MSA} + \alpha_{polymer} \qquad 2.1$$

MSA is not optical active

$\boldsymbol{\alpha_{polymer}}$ = constant when [CSA] is high enough

$$\alpha_{CSA} = \frac{[\alpha]_{CSA} \times l \times [c]_{CSA}}{100} \qquad 2.2$$

[α]: specific optical rotation; l: length in decimeters;

$[c]_{CSA}$: concentration of CSA, grams per 100 mL of solution

Due to sergeant soldier effect, in the plateau:

$$\alpha_{total} = \frac{[\alpha]_{CSA} \times l \times [c]_{CSA}}{100} + \alpha_{polymer} \qquad 2.3$$

$$[\alpha]_{polymer} = \frac{100 \times \alpha_{polymer}}{[c]_{polymer} \times l} \qquad 2.4$$

Multiply of 2.3 by $\frac{100}{[c]_{polymer} \times l}$ gives

$$\frac{100 \times \alpha_{total}}{[c]_{polymer} \times l} = \frac{[\alpha]_{CSA}}{[c]_{polymer}}[c]_{CSA} + [\alpha]_{polymer} \qquad 2.5$$

If $\alpha_{observation} = \frac{100 \times \alpha_{total}}{[c]_{polymer} \times l}$ and $k = \frac{[\alpha]_{CSA}}{[c]_{polymer}}$, then

$$\alpha_{observation} = k[c]_{CSA} + [\alpha]_{polymer} \qquad 2.6$$

Scheme 2.6 Mathematical derivations of the correlation of observed optical rotation to concentration of CSA.

To test in influence of chiral acid under these conditions, optical rotation values were measured for the ionic polymer, which is protonated by mixed acids of CSA and MSA at a fixed concentration. Solubility turned out to be an issue. Poly-**7** was polymerized in chloroform, from which it precipitated, and the neutral polymer was not soluble in any solvent. Its MSA salt was water soluble but its CSA salt was not. So among the ionic polymer samples made from poly-**7** and mixed acids, the highest molar ratio of CSA to mix acids was limited to 60%.

Table 2.2. Mixed Acids Applied to Poly-5

Concentration of Polymer (g/100ml)	Concentration of CSA (g/100ml)	CSA/(CSA+MSA) or CSA/polymer repeating unit	$\alpha_{observation}$
0.2016	0.0107	3.0%	-1.00
0.2016	0.0299	8.2%	0.53
0.2016	0.0363	9.9%	1.33
0.2016	0.0556	15.2%	3.48
0.2016	0.0727	20.0%	4.84
0.2016	0.1090	30.0%	8.24
0.2016	0.1453	40.0%	12.63
0.2016	0.1827	50.0%	16.27
0.2016	0.2180	60.0%	20.93
0.2016	0.2565	70.0%	25.71
0.2016	0.2928	80.1%	29.39
0.2016	0.3291	90.0%	32.65
0.2016	0.3655	100.0%	37.02

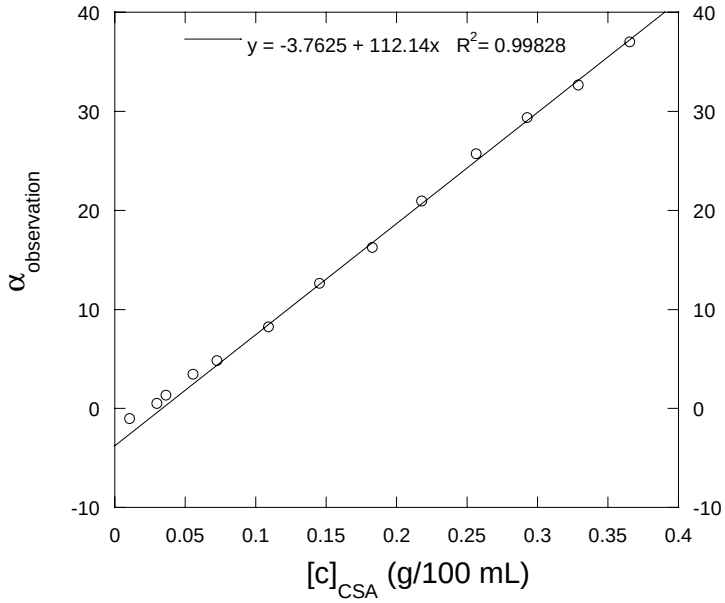


Figure 2.8 Correlation of observed optical rotation of poly-**5** and the concentration of CSA.

Table 2.3. Mixed Acids Applied to Poly-6

Concentration of Polymer (g/100 mL)	Concentration of CSA (g/100 mL)	CSA/(CSA+MSA)	$\alpha_{observation}$
0.2012	0.0085	3.1%	-1.18
0.2012	0.0214	7.8%	-0.36
0.2012	0.0321	11.7%	0.25
0.2012	0.0427	15.6%	0.96
0.2012	0.0534	19.5%	2.64
0.2012	0.0812	29.7%	5.85
0.2012	0.1090	39.8%	9.03
0.2012	0.1368	50.0%	11.99
0.2012	0.1646	60.2%	14.97
0.2012	0.1924	70.3%	18.73
0.2012	0.2308	84.4%	23.18
0.2012	0.2736	100.0%	26.71

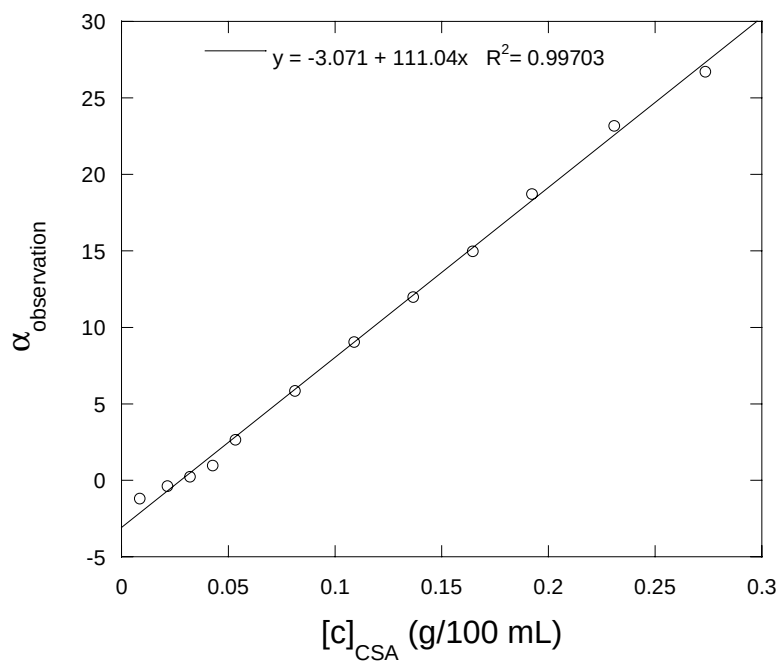


Figure 2.9 Correlation of observed optical rotation of poly-**6** and the concentration of CSA.

Table 2.4 Mixed Acids Applied to Poly-7

Concentration of Polymer (g/100 mL)	Concentration of CSA (g/100 ml)	CSA/(CSA+MSA)	$\alpha_{observation}$
0.2009	0.0064	3%	-0.65
0.2009	0.0171	8%	0.05
0.2009	0.0214	10%	0.26
0.2009	0.0427	20%	1.31
0.2009	0.0641	30%	2.39
0.2009	0.0855	40%	6.39
0.2009	0.1069	50%	8.35
0.2009	0.1282	60%	11.21

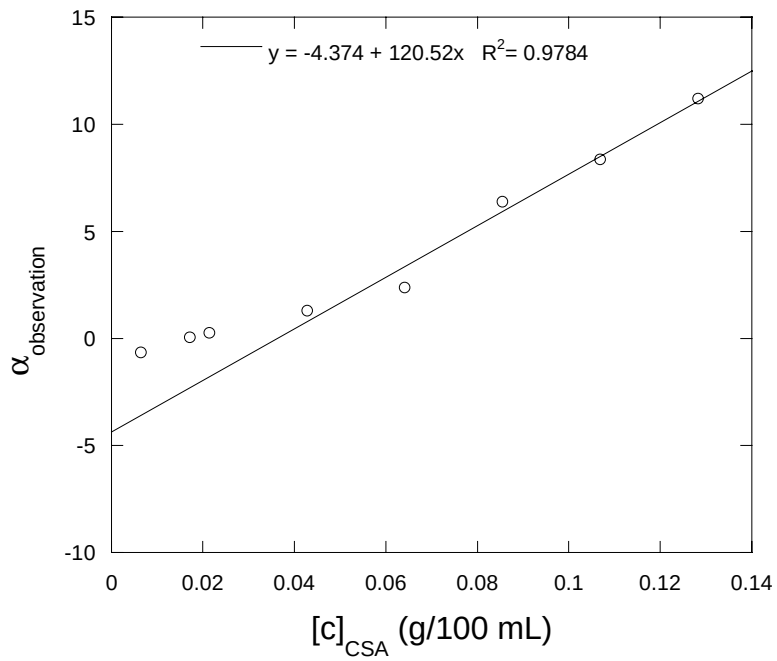


Figure 2.10 Correlation of observed optical rotation of poly-**7** and the concentration of CSA.

The linear correlations is between the concentrations of CSA and observed optical rotation are shown in Figure 2.8**,** Figure 2.9 and Figure 2.10 for poly-**5**, poly-**6** and poly-**7**. In all three figures, when the concentration of CSA exceeds a value around 0.05 g/mL, the observed optical rotation value of the samples fits a linear function very well, which suggests that the optical rotation contributed from the polymer has already reached a plateau. The interception of the curve in y axis is the specific optical rotation of ionic polymer, where the contribution of CSA is zero.

For poly(di-N-hexylcarbodiimide), when they were protonated by the chiral acid, high optical rotations were observed. However, when their pendant groups were protonated by chiral acid, these polycarbodiimides bearing amino groups show only weak helical induction (Figure 2.8, Figure 2.9 and Figure 2.10**).** This indicates that in spite of their structural differences, the distance form the chiral interacting site to the backbone is too great to have a strong influence.

Among the helical polymers, poly(phenylacetylene) has been the most extensively investigated in terms of helical induction.[16-21] With low inversion barriers and flexible backbone, ionic poly(phenylacetylene)s can adopt a conformation that is induced by chiral counter ions.[16-21] Compared to poly(phenylacetylene)s, polycarbodiimides with their 6/1 helix is more rigid. It is only when the backbone is protonated by chiral acid that the polymer displays strong induced helicity. We believe this is because the ionic interaction between the backbone and the counter ion are stronger and more influential than the ionic interaction on the side chains.

2.3 Preparation of water soluble polycarbodiimide from chiral catalysts

Several chiral titanium catalysts have been made for preparation of optical-active, single-handed, nonfluxional polycarbodiimides.[1,4] Figure 2.11 shows the synthesis of enantiomeric poly(N-hexyl-N'-phenylcarbodiimide)s using the enantioneric catalysis of (R)-BINOL-Ti and (S)-BINOL-Ti. The CD spectra of these two polymers are essentially mirror image to each other.[1,4]

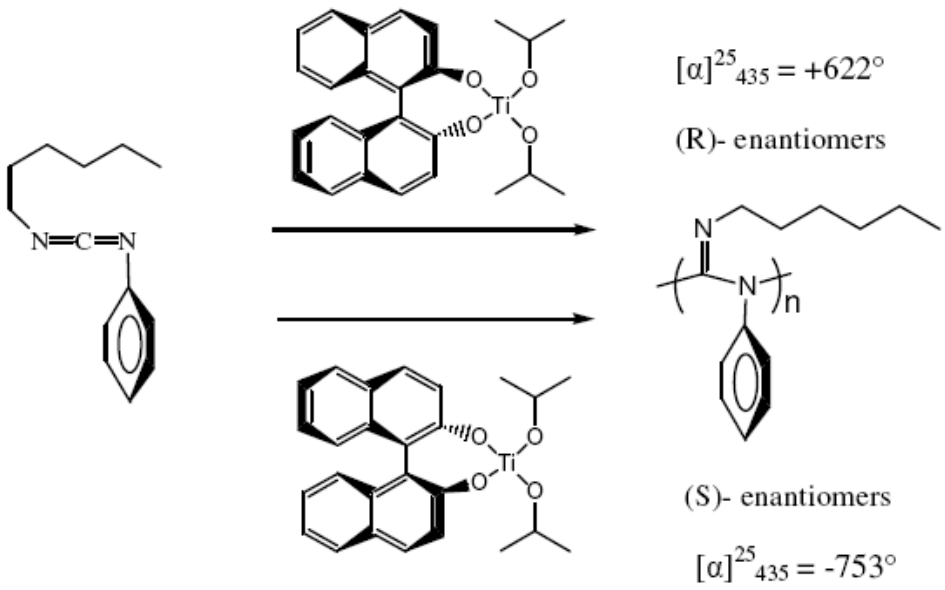
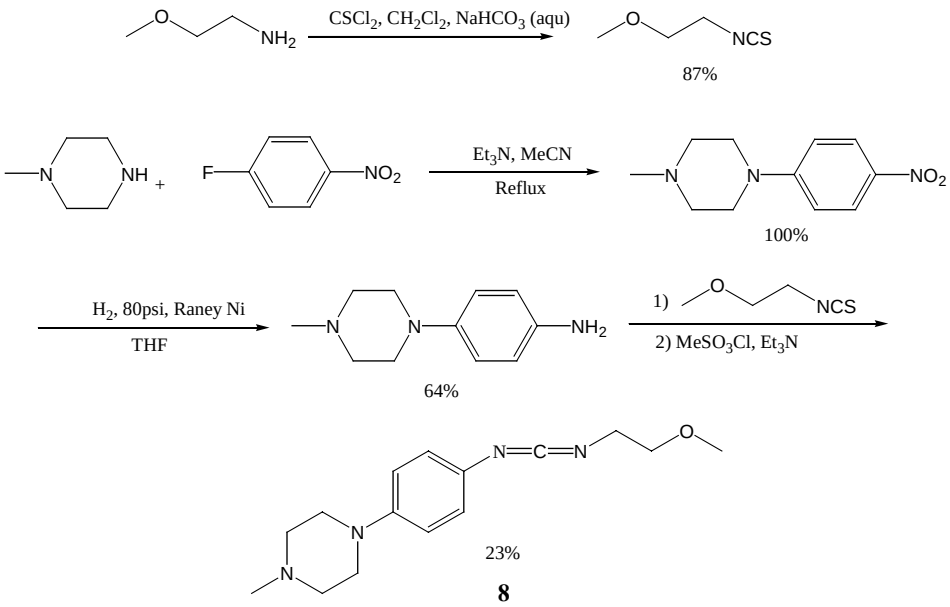
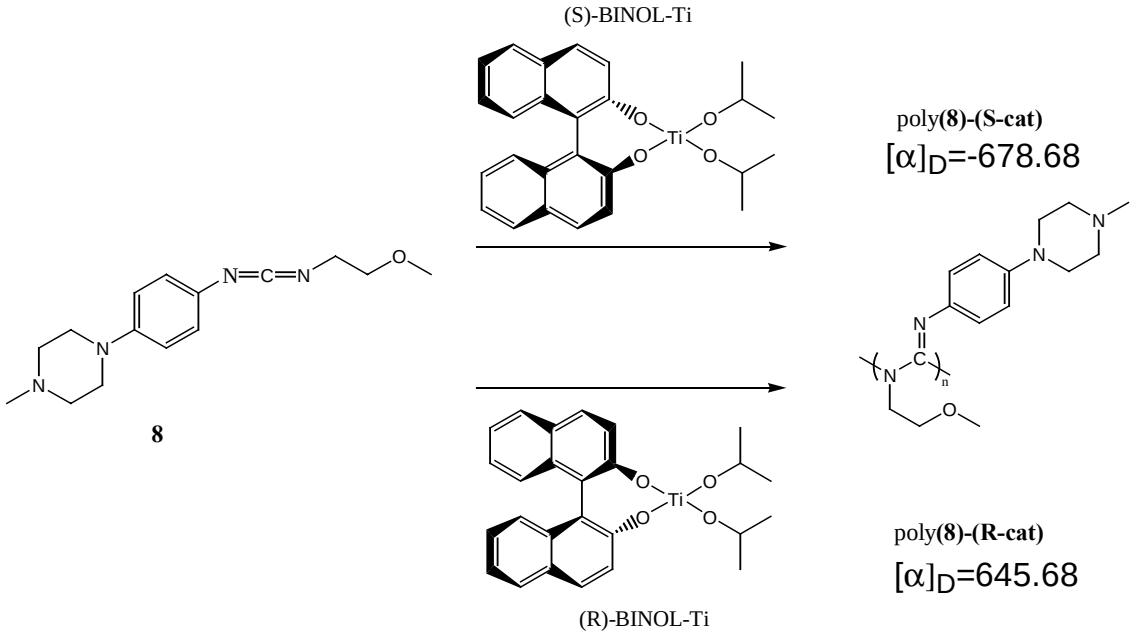


Figure 2.11 Synthesis of optical active poly(N-hexyl-N'-phenylcarbodiimide)s using chiral titanium complexes.

There has been much effort put into the investigation of polycarbodiimides, but little has been done toward the preparation of optical active water soluble polycarbodiimides. Since chiral titanium catalysts can initialize polymerization to prepare optical active polycarbodiimides, water soluble polymer can be prepared from corresponding hydrophilic monomers. Scheme 2.7 and scheme 2.8 show the synthesis of hydrophilic monomers and their polymers using chiral titanium catalysts, (R)-BINOL-Ti and (S)-BINOL-Ti.



Scheme 2.7 Synthesis of hydrophilic carbodiimide, monomer **8**.



Scheme 2.8 Preparation of optical active hydrophilic polycarbodiimides using (R)-BINOL-Ti and (S)-BINOL-Ti.

Monomer **8** was prepared through a four-step reaction sequence. Both the isothiocyanate and amine for the monomer are hydrophilic. The isothiocyanate was prepared by reaction of amine with thiophosgene in the presence of a weak base. The amine was synthesized by a two step reaction, the first one of which is an aromatic nucleophilic substitution between 1-methyl piperazine and 1-fluoro-4-nitrobenzene, followed by the catalytic reduction of the nitro group by hydrogen. Helix-sense selective polycarbodiimides were prepared from the enantiomeric catalysts (Scheme 2.8). The specific optical rotation of poly**(8)-(S-cat)** and poly**(8)-(R-cat)** are –678.68 (c = 0.23) and 645.68 (c = 0.15) respectively, which indicates the chiral ligands of enantiomeric catalysts indeed affected the conformation of the polymer chain.

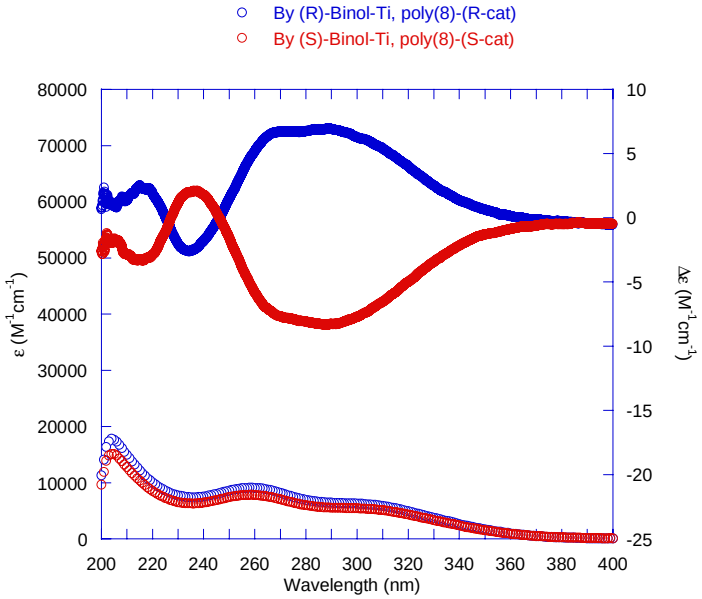


Figure 2.12 CD spectra of enantiomeric polycarbodiimides, poly**(8)-(S-cat)** and poly**(8)-(R-cat)**.

The polymers have good solubility in alcohols, chloroform and THF, but not in water. CD spectra of these chiral polymers were run in methanol. Their spectra are mirror images of each other. In the polycarbodiimides, both the phenyl and the guanidine groups have UV-Vis absorbance bands, so, both groups have CD absorbance bands when they are asymmetrical. In Figure 2.12, the major band between 250 nm and 350 nm are attributed to the phenyl group in the polycarbodiimides and the minor bands between 230 and 250 are due to the guanidine in the backbone.

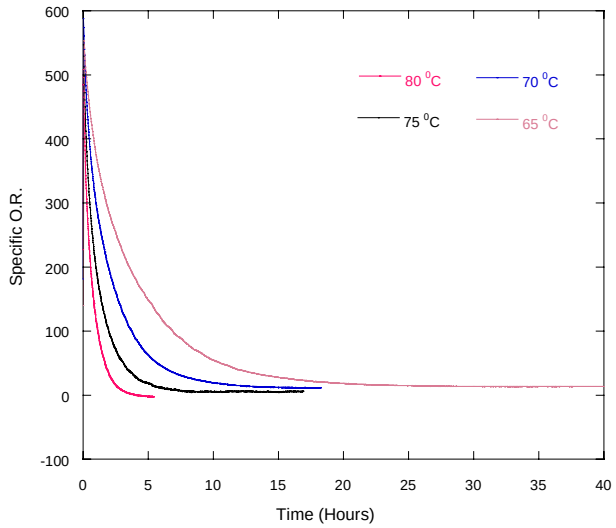
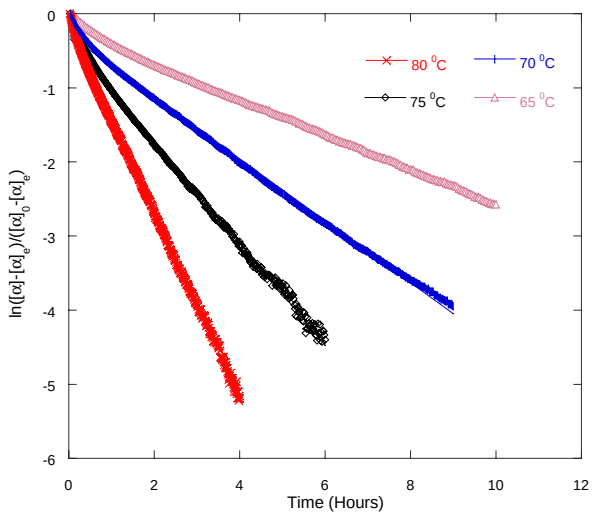


Figure 2.13 The specific optical rotation of poly**(8)-(R-cat)** as a function of time and temperature.

The conformational biased helical sense polycarbodiimides made from the chiral catalysts are not stable toward racemization at high temperature unless there are bulky pendant groups at their side arms.[5] Hence, the optical activity of poly**(8)-(S-cat)** and poly**(8)-(R-cat)** are temperature dependent. Figure 2.13 shows the change in specific optical

rotation values of poly**(8)-(R-cat)** as a function of time at different temperatures (c = 0.2 in DMF). The higher the temperature is, the faster the polymer loses the optical activity. This phenomenon can be described as the conversion of the chains from predominately one helical sense to the racemic mixture of two helical sense through a helical inversion process.



65 ^{0}C: Y = -0.1694 - 0.2424X R^2 = 0.9974

70 ^{0}C: Y = -0.2860 - 0.4181X R^2 = 0.9971

75 ^{0}C: Y = -0.3152- 0.6936X R^2 = 0.9958

80 ^{0}C: Y = -0.1804- 1.2506X R^2 = 0.9992

Figure 2.14 The racemization rate of poly**(8)-(R-cat)** using function of temperature and time.

The annealing behaviors of the poly**(8)-(R-cat.)** in different temperature provide information on the kinetic behavior to racemization. In previous studies of racemization of single handed conformational helical polymers, their annealing behavior is first order racemization with respect to polymer concentration and shows a linear correlation of

$\ln\{([\alpha]-[\alpha]_\infty)/([\alpha]_0-[\alpha]_\infty)\}$ versus time in different temperatures. The process of the data for poly**(8)-(R-cat)** follows the same pattern and the same analysis was applied. The apparent activation energy barriers for racemization can be calculated from the Arrhenius plot.[1, 2] The E_a for this process was measured to be 25.7 kcal/mol.

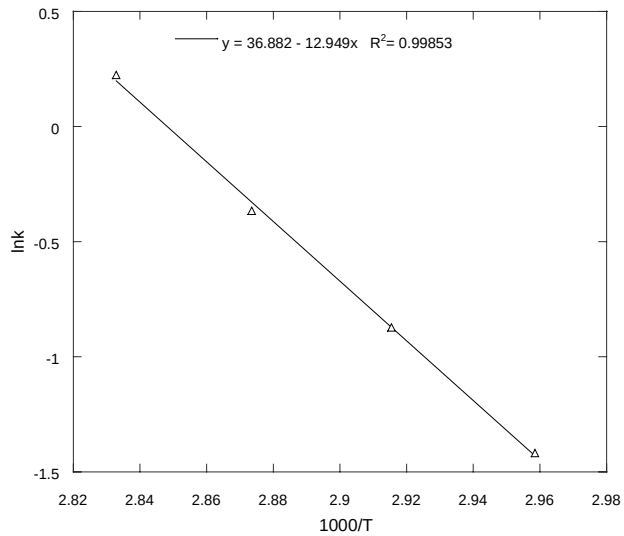
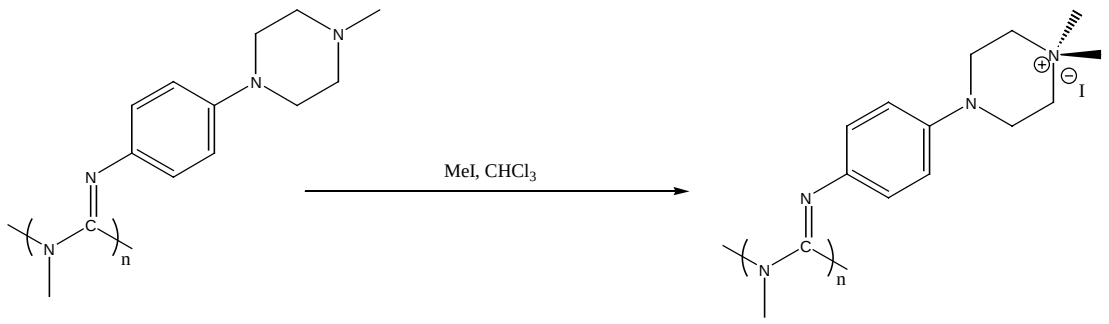


Figure 2.15 Arrhenius plot for annealing of poly**(8)-(R-cat)**.

With tertiary amines in their pendant groups, poly**(8)-(S-cat)** and poly**(8)-(R-cat)** can be methylated to give polycarbodiimides bearing tetraammonium groups (Scheme 2.9). The reactions are performed in $CHCl_3$, and the products precipitated as the reactions proceeded. Theoretically, both nitrogen atoms in the piperizine can be alkylated. Due to the stereo hindrance of the nitrogen bonded to the phenyl group as well as the precipitation of the polymer during the methylation reaction, only one of the tertiary amino groups in the piperizine ring has been methylated, as evidenced by element analysis for iodide.

The pendant groups bearing ion pairs lend very good water solubility to the methylated

polymers. Specific optical rotation of poly**(8)MeI-(S-cat)** and poly**(8)MeI-(R-cat)** are –384° and 387° respectively. The methylation doesn't change the helical structure of the polymer but does increase the molecular weight number of the repeating units. So compared to the neutral polymer, the ionic polymers show an apparent decrease in their specific optical rotations.



poly**(8)-(S-cat)** ⟶ poly**(8)MeI-(S-cat)** $[\alpha]_D$ = -384°

poly**(8)-(R-cat)** ⟶ poly**(8)MeI-(R-cat)** $[\alpha]_D$ = 387°

Scheme 2.9 Methylation of predominately handed helical polycarbodiimides.

CD was run for the aqueous solution of the ionic polymers and their spectra were analogous to those of the neutral ones, except that the highest absorbance for the neutral polymer occurs around 290 nm while those of the ionic polymers have their highest absorbance around 275 nm, which suggest the polymers maintain their helical structures and the changes of the spectra are due to the pendant phenyl group (Figure 2.16).

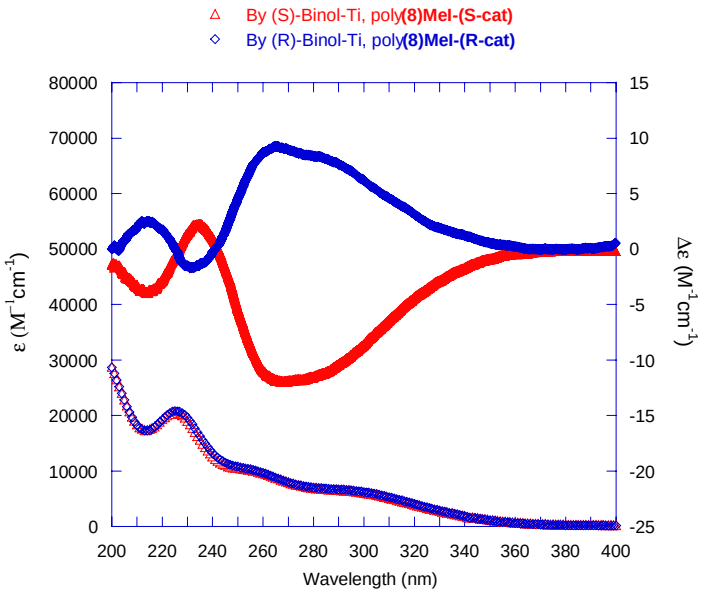


Figure 2.16 CD spectra for poly**(8)MeI-(S-cat)** and poly**(8)MeI-(R-cat)**.

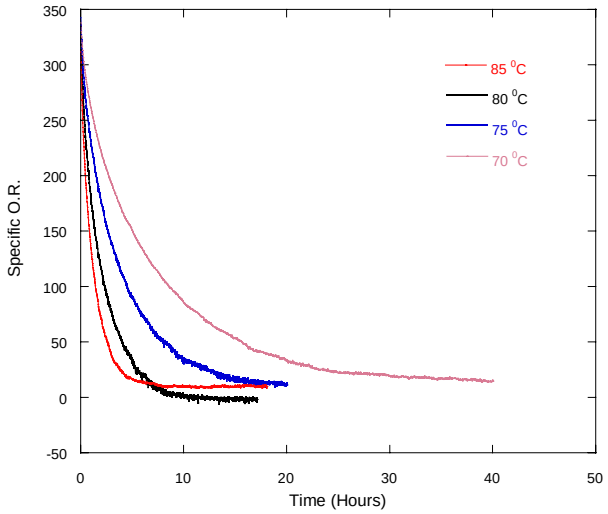
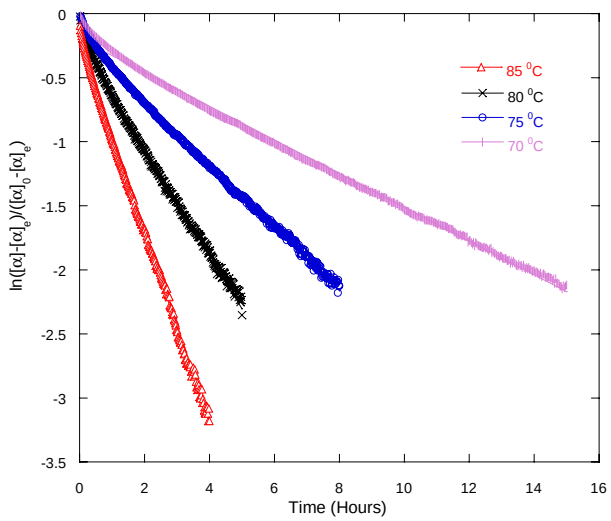


Figure 2.17 The specific optical rotation of poly**(8)MeI-(R-cat)** as a function of time and annealing temperature.



70 ^{0}C: Y = -0.1956 – 0.1317X R^2 = 0.9966

75 ^{0}C: Y = -0.1744 – 0.2488X R^2 = 0.9963

80 ^{0}C: Y = -0.2031 – 0.4205X R^2 = 0.9950

85 ^{0}C: Y = -0.2086 – 0.7455X R^2 = 0.9985

Figure 2.18 The racemization rate of poly**(8)MeI-(R-cat)**.

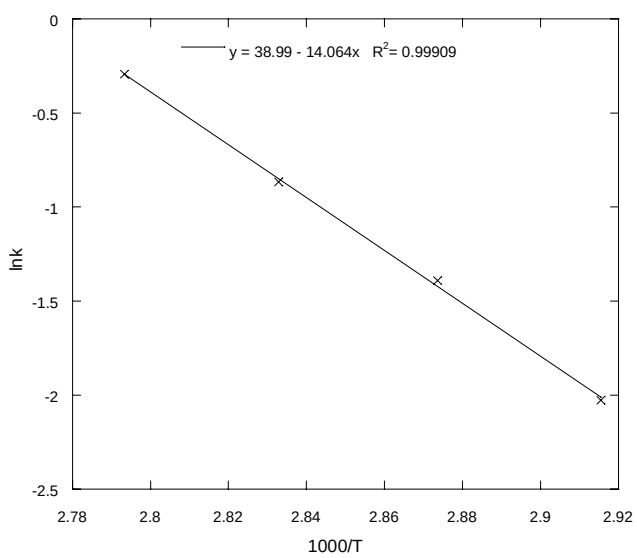
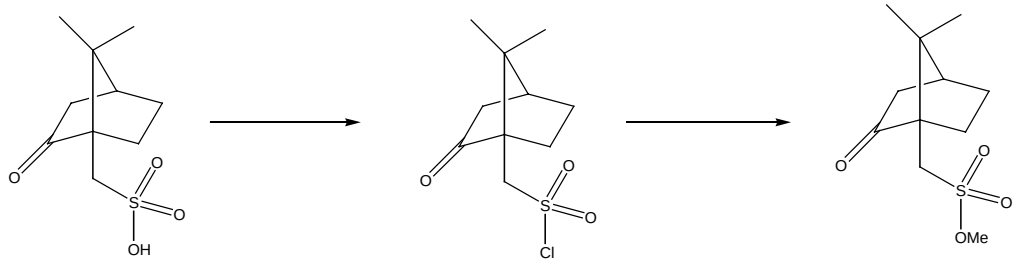


Figure 2.19 Arrhenius plot for annealing of poly**(8)MeI-(R-cat)**.

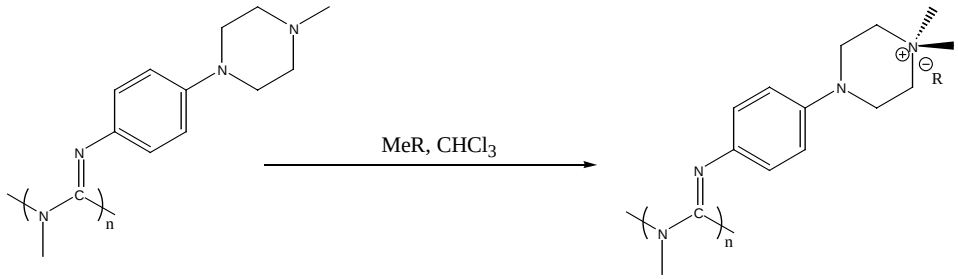
With the similar pattern to the data process of poly**(8)-(R-cat)**, the K_{obs} for poly**(8)MeI-(R-cat)** is determined to be 28 kcal/mol (Figure 2.18 and Figure 2.19), a value higher than that of the neutral polymer. It is already known that introduction of bulkier pendant groups helps to increase the inversion barrier. The ionic pendant groups can also increase the inversion barrier in a different way from just adding bulk, in that the helical structure is kinetically stabilized by charge repulsion as well. So the introduction of charge to pendant groups is another way to stabilize the conformation of the helical polycarbodiimides.

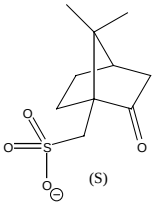
2.4 Helical inversion of ionic polymer with different counter ions

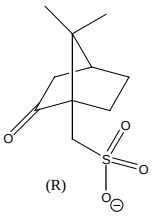
The helical induction of the ionic polycarbodiimides by their counter ions suggests that there is a relationship between the ionic polymers and the chiral counter ions. The enantiomeric or racemic ionic interaction site should affect the ionic polymer differently. So for ionic, single handed polycarbodiimides, if the enantiomeric or racemic counter ions changes their annealing behavior, they may response in two ways: their apparent inversion energy may be different due to the opposite role the enantiomeric counter ions play and the annealing of polymers may not lead to racemic state in both cases.



(R) and (R/S) (R), 93% and (R/S), 93% (R), 68% and (R/S), 76%



poly**(8)(S)-Me-CSA-(R-cat)** R =  (S) $[\alpha]_D = 236^o$

poly**(8)(R)-Me-CSA-(R-cat)** R =  (R) $[\alpha]_D = 209^o$

poly**(8)(R)-Me-CSA-(R/S-cat)** R = (R/S) $[\alpha]_D = 248^o$

Scheme 2.10 Preparation of ionic, single helical sense polycarbodiimides with different counter ions.

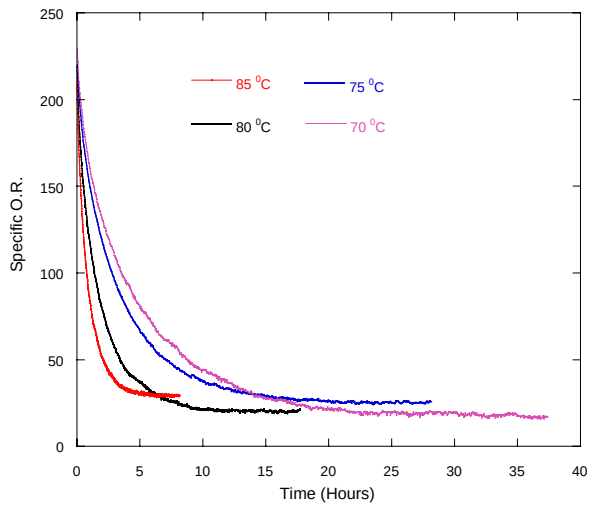
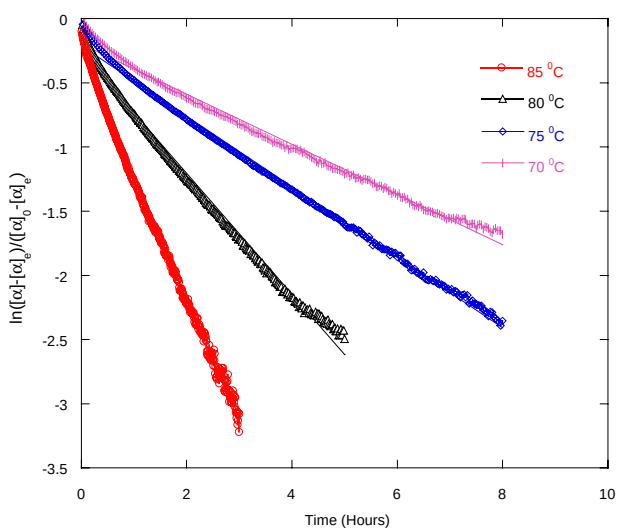


Figure 2.20 The specific optical rotation of poly**(8)(S)-Me-CSA-(R-cat)** as a function of time and annealing temperature.



70 ^{0}C: Y = -0.1972 – 0.1954X R^2 = 0.9897

75 ^{0}C: Y = -0.2109 – 0.2746X R^2 = 0.9966

80 ^{0}C: Y = -0.2644– 0.4706 X R^2 = 0.9920

85 ^{0}C: Y = -0.2677– 0.9592 X R^2 = 0.9965

Figure 2.21 The racemization rate of poly**(8)(S)-Me-CSA-(R-cat)** as a function of time and annealing temperature.

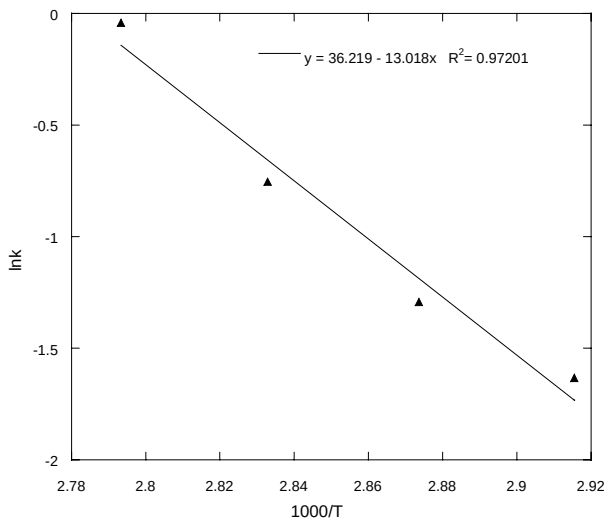


Figure 2.22 Arrhenius plot for annealing of poly**(8)(S)-Me-CSA-(R-cat)**.

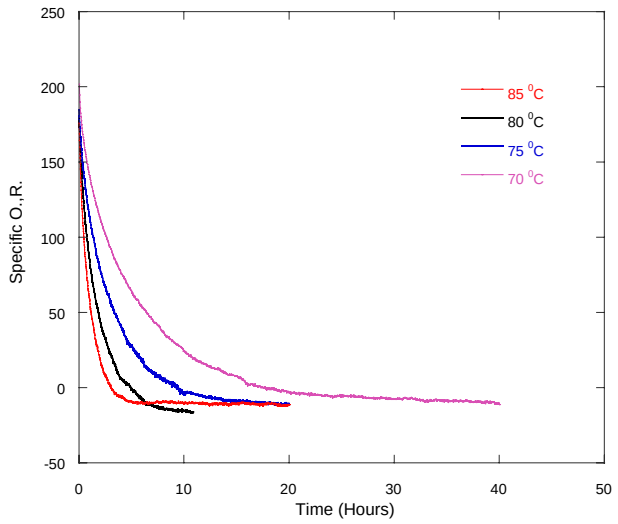
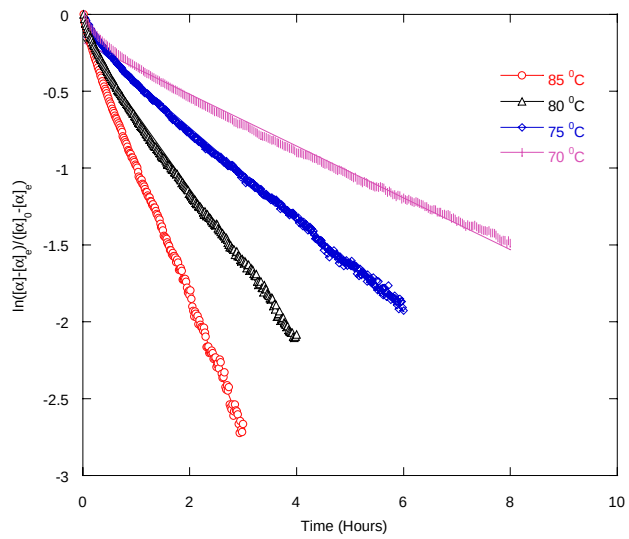


Figure 2.23 The specific optical rotation of poly**(8)(R)-Me-CSA-(R-cat)** as a function of time and annealing temperature.



70 ^{0}C: Y = -0.1813 – 0.1687 X R^2 = 0.9906

75 ^{0}C: Y = -0.1400 – 0.2990 X R^2 = 0.9962

80 ^{0}C: Y = -0.1573 – 0.4892 X R^2 = 0.9960

85 ^{0}C: Y = -0.1058– 0.8672 X R^2 = 0.9983

Figure 2.24 The racemization rate of poly**(8)(R)-Me-CSA-(R-cat)** as a function of time and annealing temperature.

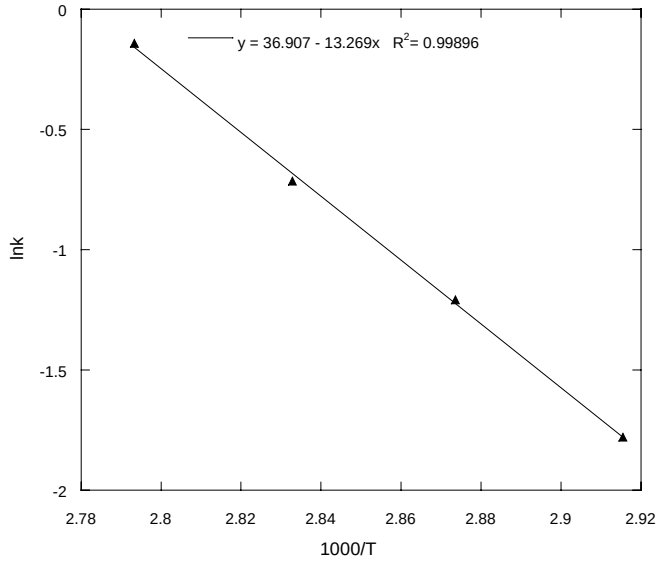


Figure 2.25 Arrhenius plot for annealing of poly**(8)(R)-Me-CSA-(R-cat).**

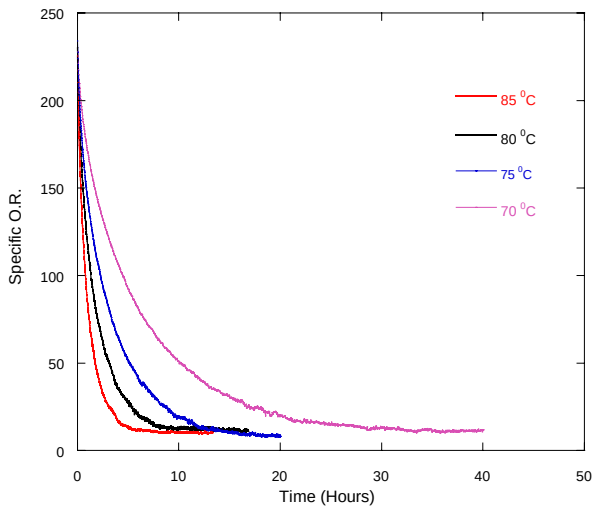
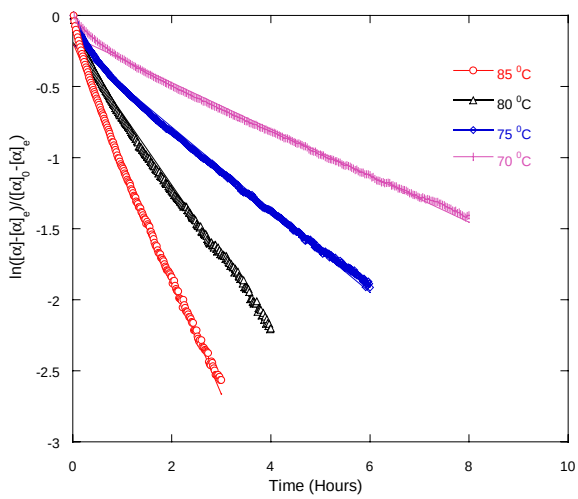


Figure 2.26 The specific optical rotation of poly**(8)(R/S)-Me-CSA-(R-cat)** as a function of time and annealing temperature.



$$70\ ^{0}C: Y = -0.1448 - 0.1635\ X \qquad R^2 = 0.9940$$

$$75\ ^{0}C: Y = -0.2049 - 0.2904\ X \qquad R^2 = 0.9934$$

$$80\ ^{0}C: Y = -0.1847 - 0.5043\ X \qquad R^2 = 0.9944$$

$$85\ ^{0}C: Y = -0.1901 - 0.8240\ X \qquad R^2 = 0.9950$$

Figure 2.27 The racemization rate of poly**(8)(R/S)-Me-CSA-(R-cat)** as a function of time and annealing temperature.

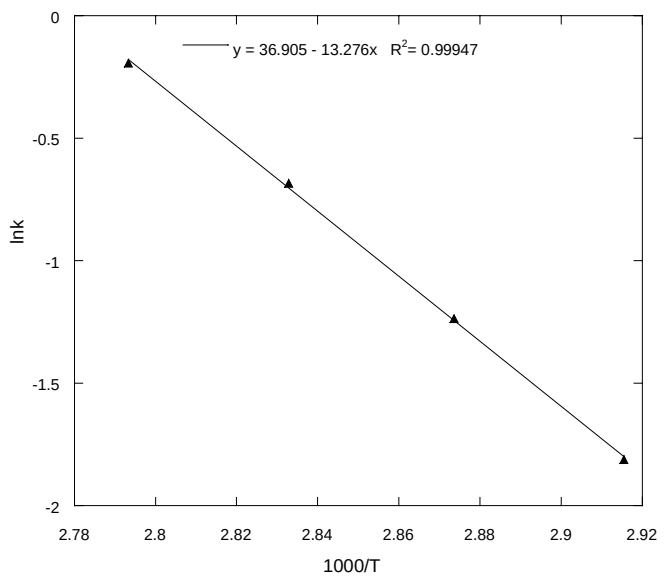


Figure 2.28 Arrhenius plot for annealing of poly**(8)(R/S)-Me-CSA-(R-cat)**.

Enantiomeric and racemic camphorsulfonic acid methyl esters were synthesized and used as the methylating reagents. Poly**(8)-(R-cat)** was allowed to react with (S)-, (R)- and the racemic methyl camphorsulfonic acid esters to give the corresponding ionic polymers. Like poly**(8)MeI-(R-cat)**, the polymers prepared in Scheme 2.10 also show much lower specific optical rotation value than the neutral polymer. When heated, these ionic polymers also undergo annealing and ultimately reach a plateau value (Figure 2.20, Figure 2.23, Figure 2.26). The E_a for poly**(8)(S)-Me-CSA-(R-cat)**, poly**(8)(R)-Me-CSA-(R-cat)** and poly**(8)(R/S)-Me-CSA-(R-cat)** are 25.9 kcal/mol, 26.4 kcal/mol and 26.4 kcal/mol respectively, according to the racemization rate plots (Figure 2.21, Figure 2.24, Figure 2.27) and Arrhenius plots (Figure 2.22, Figure 2.25, Figure 2.28). If the error is considered in the Arrhenius plot, the K_{obs} of the three ionic polymers are essentially the same, which suggests that the enantiomeric or achiral counter ions of the ionic polymer do not accelerate or hinder

the racemization, although the helical induction experiments show there is interaction between the counter ions and the ionic polycarbodiimides.

The ionic polymers were annealed at 75 ^{0}C (c = 0.2, aqueous solution) (Figure 2.29). The annealed ionic polymers are still optical active. To further investigate their helical structures, CD spectra was run for the virgin and annealed polymers (Figure 2.30 and Figure 2.31). The phenyl pendant group of polycarbodiimide has CD absorbance band from 360 nm to 250 nm and enantiomeric camphorsulfonic acids have CD absorbance band from 310 nm to 260 nm. The combination of the CD band of the counter ions and the polymers themselves give the spectra shown in Figure 2.30. Figure 2.31 shows the CD spectra of the annealed ionic polymers. The major absorbance band between 310 nm and 260 nm of poly**(8)(S)-Me-CSA-(R-cat)** and poly**(8)(R)-Me-CSA-(R-cat)** are mirror images of each other and no absorbance was found between 360 nm and 310 nm, which is due to the enantiomeric camphorsulfonic acid, and the phenyl group in the polycarbodiimdes do not appear to be aligned in a helical order any more.

Another interesting phenomena for the CD spectra is that the absorbances with a maximum at 230 nm are observed for all three annealed ionic polymers, including poly**(8)(R/S)-Me-CSA-(R-cat),** the ionic polymer bearing the racemic counter ions. For the virgin ionic polymers, the major absorbance band (360 nm – 250 nm) is due to the pendant phenyl group and the minor absorbance band (maximum at 230 nm) is due to the guanidine backbone. During the annealing, the movement of the pendant group and the backbone may not be synchronized, since the major absorbance band vanishes, the backbones are still not fully racemized.

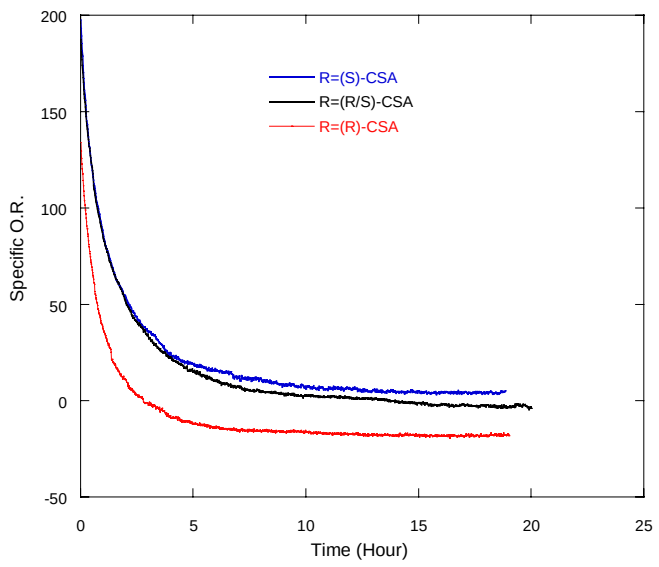


Figure 2.29 Annealing of poly**(8)(S)-Me-CSA-(R-cat)**, poly**(8)(R)-Me-CSA-(R-cat)** and poly**(8)(R/S)-Me-CSA-(R-cat)** at 75 ^{0}C.

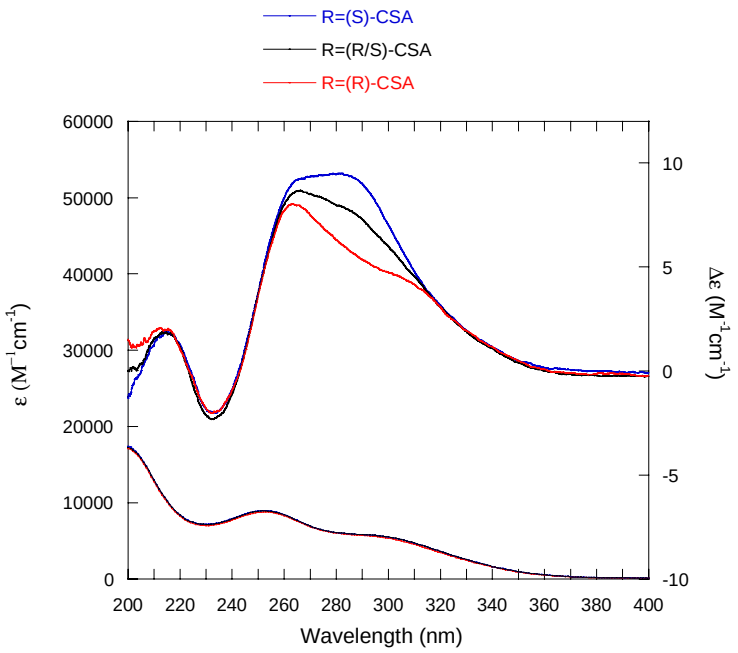


Figure 2.30 CD spectra of poly**(8)(S)-Me-CSA-(R-cat)**, poly**(8)(R)-Me-CSA-(R-cat)** and poly**(8)(R/S)-Me-CSA-(R-cat).**

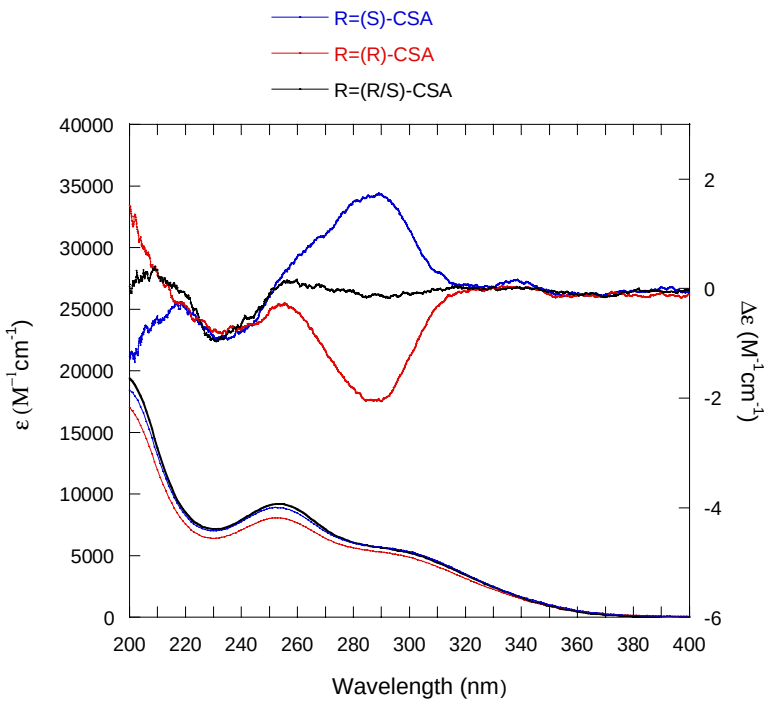
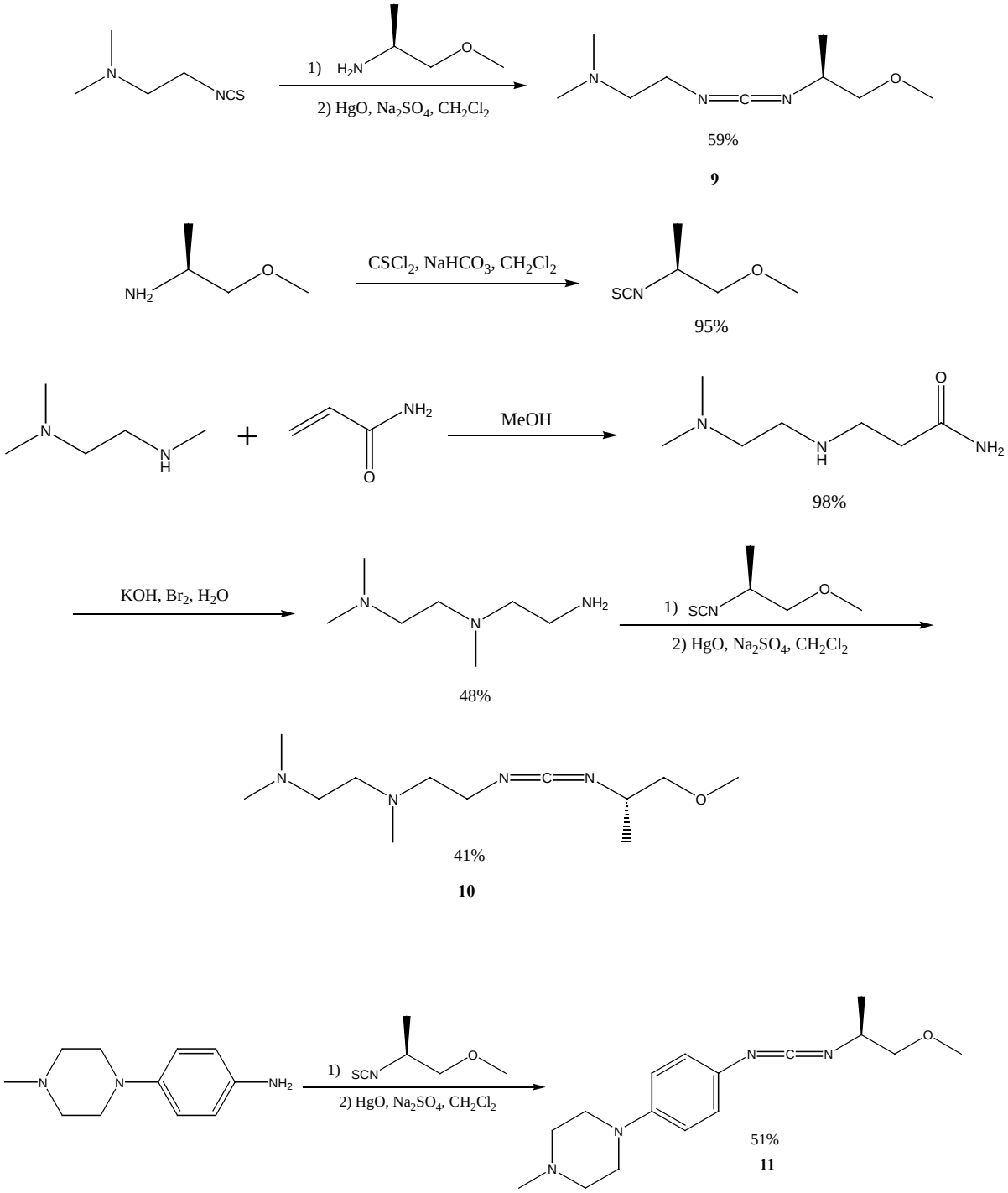
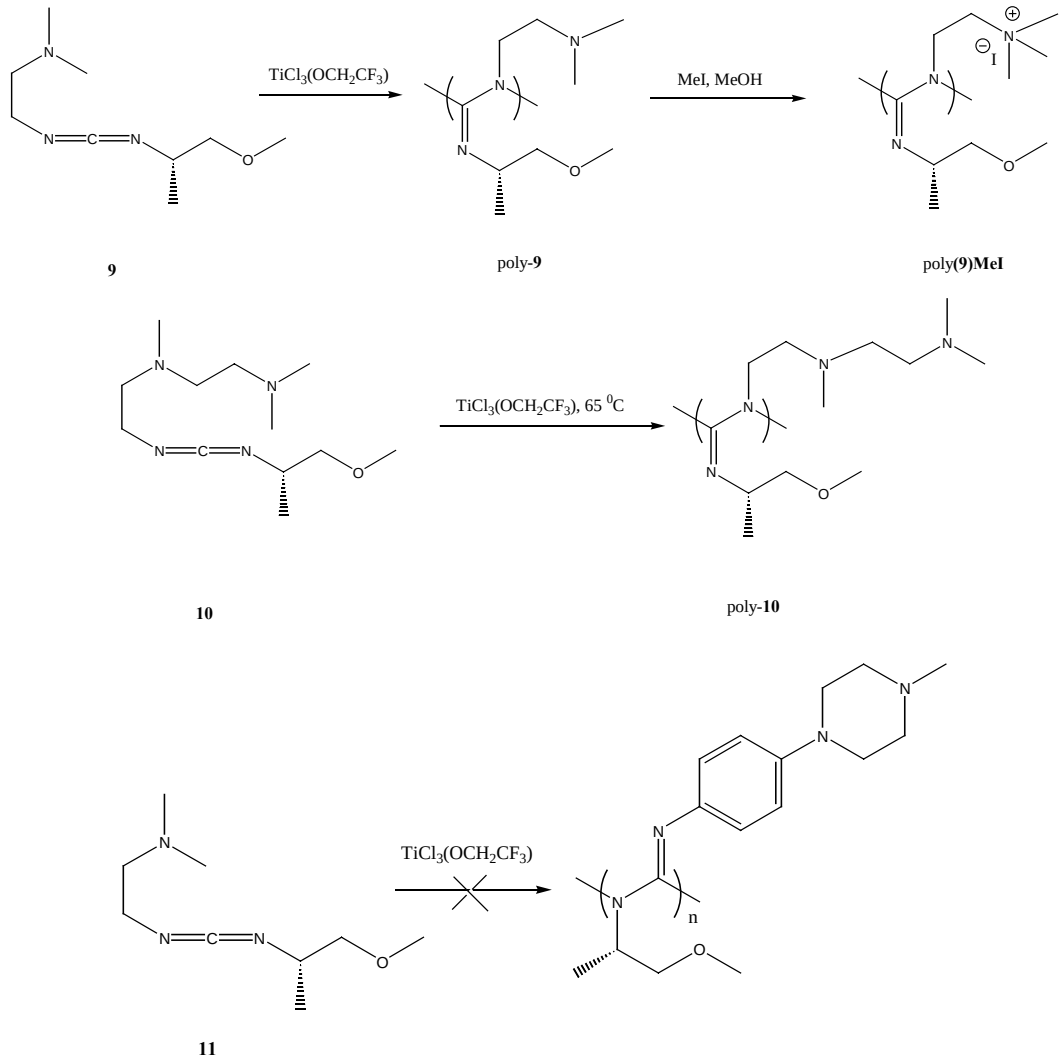


Figure 2.31 CD spectra of poly**(8)(S)-Me-CSA-(R-cat)**, poly**(8)(R)-Me-CSA-(R-cat)** and poly**(8)(R/S)-Me-CSA-(R-cat).**



Scheme 2.11 Synthesis of chiral hydrophilic monomers **9**, **10** and **11**.



Scheme 2.12 Polymerization of hydrophilic monomers **9** and **10.**

2.5 Water soluble polycarbodiimides prepared from chiral monomers

Schlitzer and Lu have employed chiral monomers to prepare the biased screw sense polycarbodiimides.[1,2,4] During the polymerization, the monomer can only access the living end-group with a specific orientation so that it is incorporated into the polymer chain with a

biased helical order. Since the solubility of the polymer is closely related with the property of the pendant groups, optical active water soluble polycarbodiimides can be achieved by employing hydrophilic chiral monomers.

New hydrophilic chiral monomers were synthesized and they share one thing in common: one pendant group of each carbodiimide is derived from the same chiral amine, 1-methoxy-propyl-2-amine (Scheme 2.11). Same procedure was used in the last step to yield all three monomers. The pendant tertiary amino groups allow their polymer to be methylated to increase their water solubility.

Same titanium catalyst was used for the polymerization of hydrophilic monomers **9**, **10** and **11** in bulk (Scheme 2.12). The polymerization of these monomers was slow and took two weeks for the polymerization for monomer **9** at room temperature and one week for monomer **10** at 65 ^{0}C. Monomer **11** can't be polymerized, even it was heated at 65 ^{0}C. In the Novak group, a series of titanium catalysts were developed for the polymerization of carbodiimides and the catalyst used here, $TiCl_3(OCH_2CF_3)$, was proved to be the most active one. The chiral center in the side arms of these monomer is the origin of the predominating single handedness of the polymer. The closer the chiral center is to the backbone, the stronger influence the asymmetry exerts on the conformation adoption of the polymer to result in a increased cooperativity.[22] But the stereo hindrance between the active chain end and monomer results in the decreased polymerization rate. Hence any promotion for stereoselectivity gives rise to a demotion for reaction rate.

Poly-**9** is not soluble in nearly all solvents. After methylation, the ionic polymer is soluble in alcohol, DMF and mixed solvent of alcohol and water. Poly-**10** has very good

water solubility, probably due to its longer hydrophilic pendant groups. The CD spectra were run for poly**(9)MeI** (solution in PrOH + H_2O 1:1 mixed solvent) and poly-**10** (aqueous solution) (Figure 2.32). In these spectra, strong Cotton effects were observed at 240 nm with a negative sign and 200 nm with a positive sign. In addition, the former absorbance band bears a shoulder at 220 nm.

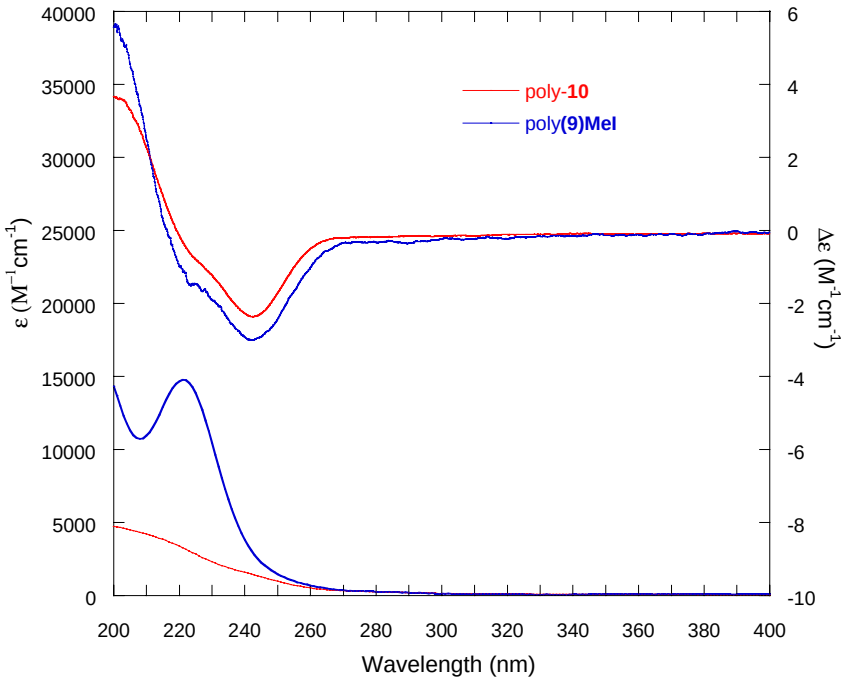


Figure 2.32 The CD spectra for poly**(9)MeI** and poly-**10**.

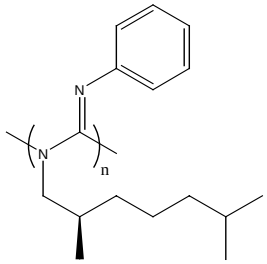
Chiral compounds with carbonyl groups are some of the most compounds investigated using CD spectroscopy. They always show their CD absorbance bands at a different wavelength range from those in their UV absorbance, because the two absorbances originate from different mechanisms.[22,23] Their UV absorbance is due to the π—π* transition while the CD Cotton effect is due to the n—π* transition. The n—π* transition occurs in the range of

270 nm-300 nm, which involves the promotion of an electron from a nonbonding p orbital on oxygen to the antibonding π* orbital associated with the entire group. The transition is symmetry forbidden, but because of the vibronic coupling, it gives a weak band in UV spectroscopy. The π—π* transition occurs from 180-190 nm. It is allowed in UV spectroscopy and hence results in a much stronger absorbance band. Compared to the π—π* transition, the n—π* transition is more sensitive to solvents. But in CD spectroscopy, the two transitions switch their intensities so that the n—π* gives rises to the active Cotton effect.

For chiral compounds bearing carboxylate or amide groups, their CD spectra is different from those of ketones, due to the change of their asymmetric feature for their molecular orbital. Their π—π* transitions become active for CD spectroscopy. So for peptides with α helical structure, strong Cotton effects are observed around 200 nm. As a potential peptide mimic, polycarbodiimides with a guanidine backbone have analogous behavior in their CD spectroscopy. In Figure 2.32, the cotton effect with positive sigh at 200 nm is due to the π—π* transition of the guanidine bond, according to the attribution of UV absorbance band around this wavelength.[24,25]

Polymerization of chiral carbodiimides gives polymers with conformations under kinetically control (KCC), a state which is thought to be a higher energy level conformation with defects and helical reversals along the polymer chain. Earlier, Lu investigated the annealing behavior of poly(N-(R)-dimethylheptyl-N'-phenylcarbodiimide) using dynamic polarimetry and CD spectroscopy to monitor the change of the conformation of the polymer (Figure 2.33). During the annealing, large changes occur with the specific optical rotation value changing from –200 to +250 ($[\alpha]_{435}$, c = 0.2 in toluene). The Cotton effect changes

from negative to positive in sign when the solution of polymer in octane was heated at 80 ^{0}C. The negative absorbance band with a maximum at 250 nm reduced gradually as the absorbance band with a maximum at 261 nm grow until the annealing was complete, which suggests that the pendant phenyl group may change its orientation when annealed.[1,4] But due to the lack of an absorbance band for the backbone, its change upon annealing was not revealed.



Poly(N-(R)-2,6-dimethylheptyl-N'-phenylcarbodiimide)

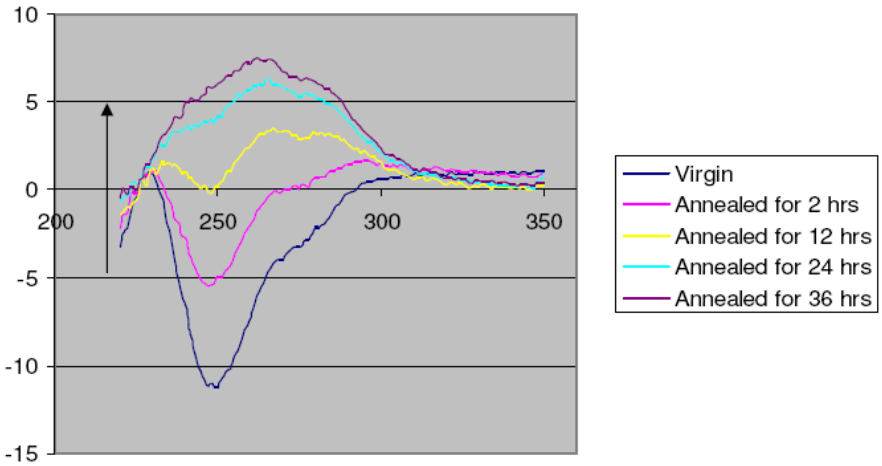


Figure 2.33 Change of Cotton effect during annealing for poly(N-(R)-2,6-dimethylheptyl-N’-phenylcarbodiimide).

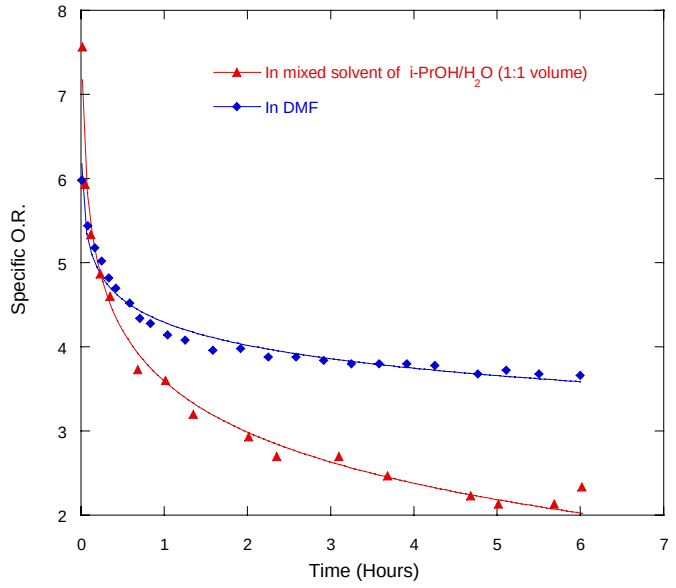


Figure 2.34 Annealing of poly**(9)MeI** in different solvents.

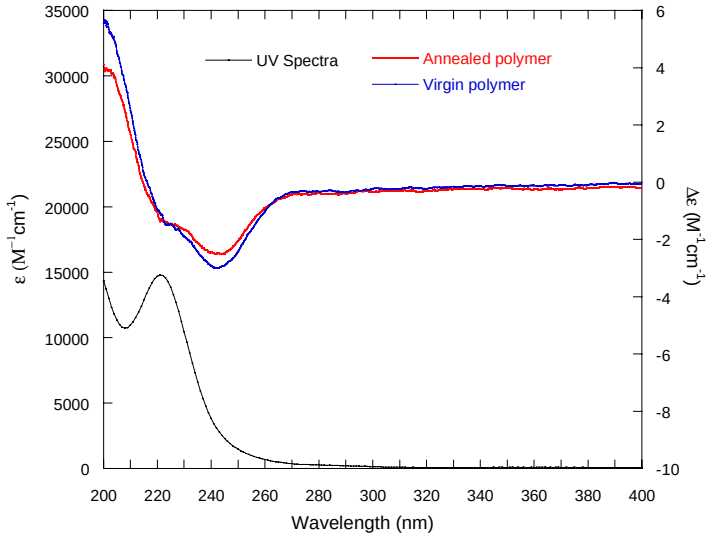


Figure 2.35 CD spectra of virgin and annealed poly**(9)MeI**.

Solutions of poly**(9)MeI** in both DMF and a mixed solvent of i-propanol and water (1:1, volume) were annealed. For both solutions, the specific optical rotation changed only slightly,

probably due to the lack of bulky pendant group (Figure 2.34). Measuring the CD spectra for both the virgin and annealed polymer solution in i-PrOH/H_2O (1:1, volume) makes it possible to investigate the movement of the guanidine backbone, because the solvent does not absorb where the guanidine chromophore does. Figure 2.35 shows the CD spectra of both the virgin and annealed poly**(9)MeI**. Compared to the virgin polymer, the annealed polymer shows a slightly weaker cotton effect, which suggests that there is not much change occurring to the conformation of the polymer. Annealing experiments were also performed with aqueous solution of poly-**10**, but the polymer precipitated when the solution was heated. According to the result of Lu's annealing experiments, the pendant phenyl group changes its orientation, which results in the dramatic change of Cotton effect in CD spectra.[1,7] In summary, for both annealing experiments, the backbone and the pendant groups of polycarbodiimides may undergo different motions during annealing, but backbone motions seem to be minimal.

Polycarbodiimides can possibly serve as a potential peptide mimics due to their analog structures. But peptide can be deformed in higher temperature. To investigate the heat resistance of the polycarbodiimide, the CD spectra was also run for annealed poly**(9)MeI** at different temperatures ranging from 25 ^{0}C to 75 ^{0}C, in 10 ^{0}C intervals (Figure 2.36). According to these CD spectra, poly**(9)MeI** maintains a stable helical structure even at higher temperatures.

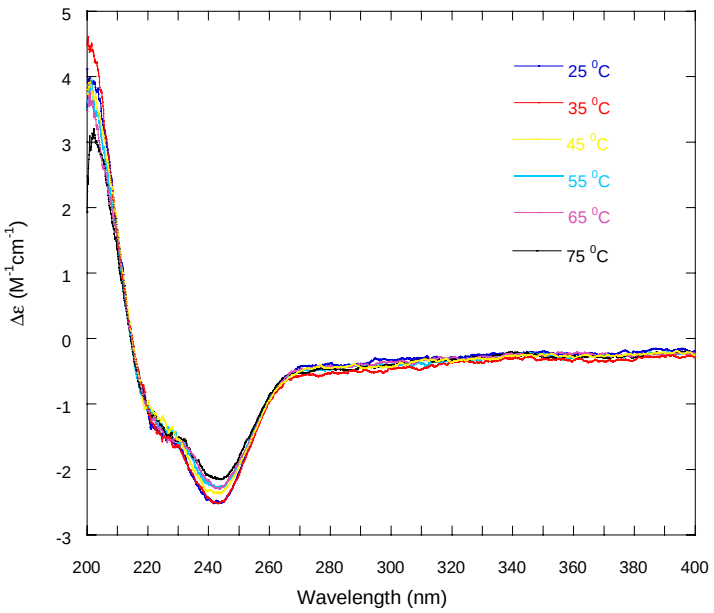
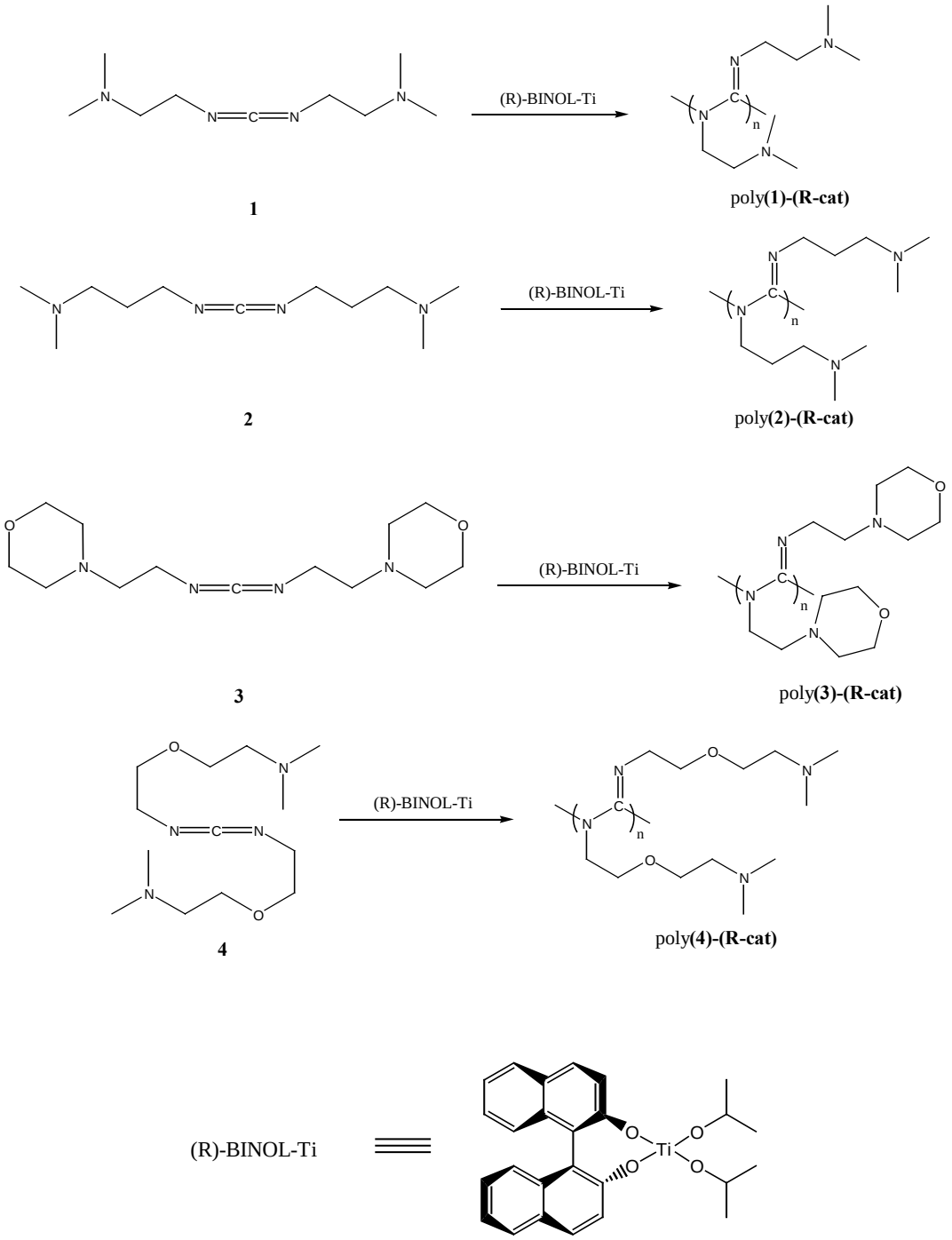


Figure 2.36 CD spectra of annealed poly**(9)MeI** at different temperatures.

2.6 Water soluble polycarbodiimides as peptide mimics



Scheme 2.13 The synthesis of conformational predominately one-handed helical polymers using chiral catalyst, (R)-BINOL-Ti.

Conformational one handed helical polycarbodiimides were synthesized using the (R)-BINOL-Ti (Scheme 2.13). Among four of the polymers, poly**(1)-(R-cat)** and poly**(4)-(R-cat)** were formed to be water soluble. So CD spectra were run of these polymers in aqueous solution (Figure 2.37). The spectrum for poly**(1)-(R-cat)** shows three absorbance bands with maximum at 242 nm, 220nm and 200 nm and poly**(4)-(R-cat)** have a very broad absorbance band from 260 nm to 225 nm and a band with a maximum at 200 nm. The absorbance bands of the CD and UV spectra that occur at the same wavelengths are from the same electron transitions, although their intensity may change due to different factors. The UV spectra of poly**(1)-(R-cat)** and poly**(4)-(R-cat)** both have a major absorbance band from 265 nm to 200 nm. The shoulder at 240 nm is due to the n—π* transition, which suggests that the corresponding CD absorbance around this wavelength is also from the same origin. Likewise, the absorbance bands with maximum at 220 nm and 200 nm are due to the π—π* transition. Since the polycarbodiimides and the peptides have similar backbones, analysis of peptides should be helpful in understanding the helical structure of the polycarbodiimides.

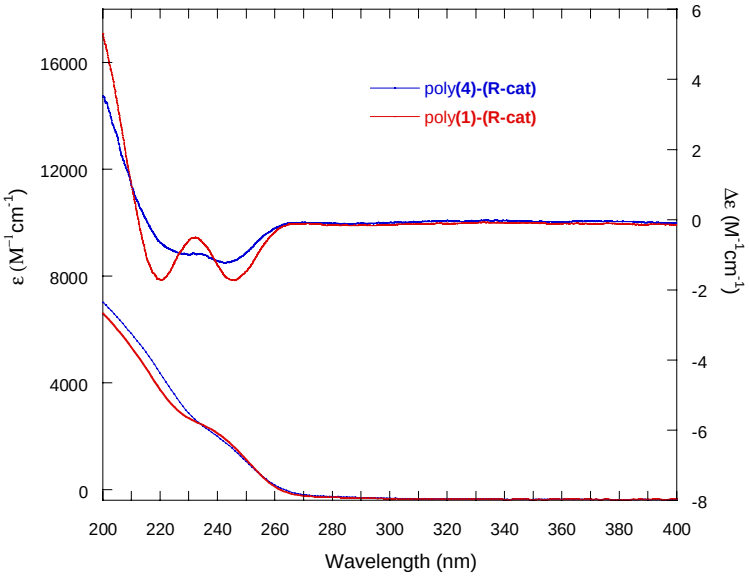


Figure 2.37 The CD spectra for poly**(1)-(R-cat)** and poly**(4)-(R-cat)** in aqueous solution.

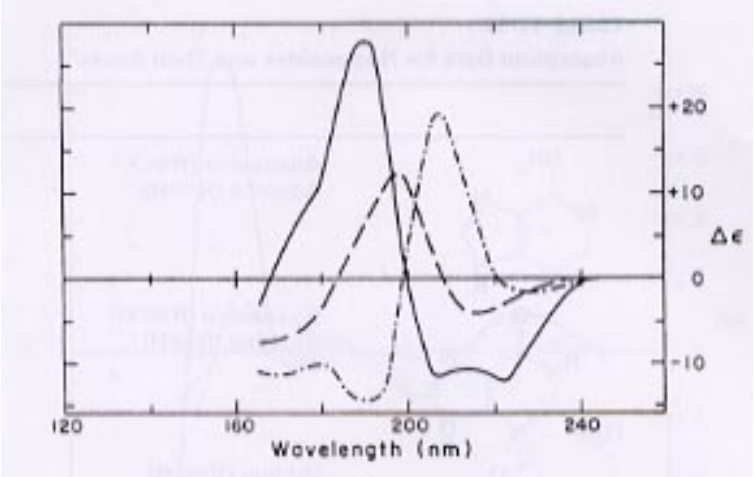
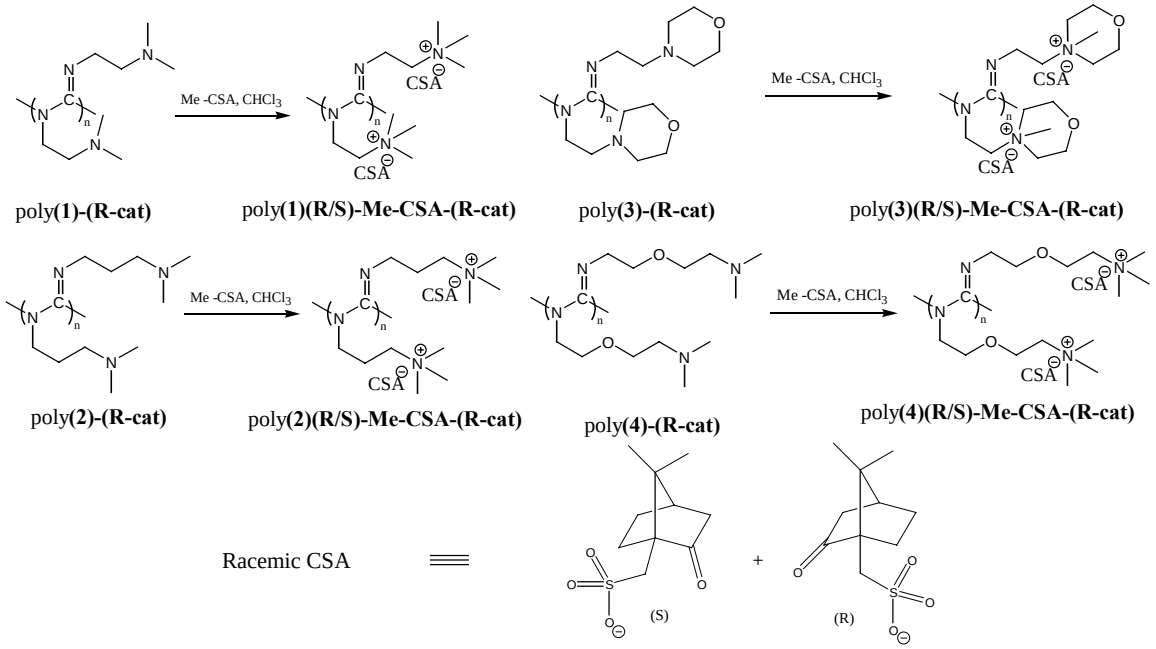


Figure 2.38 The CD in aqueous solution of poly-L-glutamic acid at pH 4.5 adopting α helical structure (—); poly(Lys-Leu) in 0.1M NaF at pH 7 adopting β sheet (– – –) and poly(Ala2-Gly2) adopting β turn (–.–.–).[25]

Figure 2.38 shows the CD spectra for the three possible secondary structure of peptides. The curve shown with the solid line represents the spectra of poly-L-glutamic acid, a peptide

that is almost entirely in an α-helical structure at pH 4.[24,25] There are total three absorbance bands for its CD spectrum, the maximums of which occur at 220 nm, 208 nm and 192 nm. The negative 220 nm band in the CD spectrum arises from the n—π* transition and the 208 nm and 192 nm Cotton effects are due to the split π—π* transition of the amide group parallel and perpendicular to the helix axis.[24,25] For the optical active polycarbodiimides, the Cotton effects with maximums at 200 nm and 220 nm should also be due to the π—π* transition of the guanidine group parallel and perpendicular to the helix axis, but more characterization is needed to assign the two Cotton effects to these two transitions.

Both polymerization of chiral monomers with achiral catalyst or achiral monomers with chiral catalysts give rise to the predominately one-handed helical polymers. Figure 2.32 and Figure 2.37 show the CD spectra of both types. The two groups of CD spectra share a lot of common features except that the CD spectra in Figure 2.37 have a full Cotton effect at 220 nm, while the same absorbance band in Figure 2.32 is seen as a small shoulder of the Cotton effect at 242 nm. These differences suggest that there may be differences between the conformational chiral and configurational chiral helical polycarbodiimides. The single handed conformational helicity of the polycarbodiimides prepared from the chiral catalyst results from the conformation of the polymer produced, while the backbone conformation of a polycarbodiimide with a chiral side chain is decided by the chiral center in the pendant group. Judging from the Cotton effect at 220 nm, the symmetric pendant groups of conformational helical polymers obtained from chiral catalysts may endow them with higher helical order than configurational helical polymers with asymmetric side chains.



Scheme 2.14 Synthesis of ionic polycarbodiimides.

Polycarbodiimides bearing tertiary amino groups were allowed to react with racemic methyl camphorsulfonic acid ester to yield the ionic polymers. After the reactions, poly**(2)(R/S)-Me-CSA-(R-cat)** and poly**(3)(R/S)-Me-CSA-(R-cat)** displayed very good water solubility. The CD spectroscopy was run for aqueous solutions of all the ionic polymers. The spectrum of poly**(4)(R/S)-Me-CSA-(R-cat)** is different from the rest in its shape. The spectra of poly**(1)(R/S)-Me-CSA-(R-cat)** and poly**(4)(R/S)-Me-CSA-(R-cat)** show their Cotton effects at similar wavelength to those of their neutral polymer precursor. Hence, methylation of polycarbodiimides bearing tertiary amino groups is a way to increase their water solubility without changing the helical conformations of their backbones.

The CD spectrum for poly**(1)(R/S)-Me-CSA-(R-cat)** in mathanol was also run. It did not show any essential differences from its CD spectra obtained from its aqueous solution, which

suggests the helical structure is stable in different solvents.

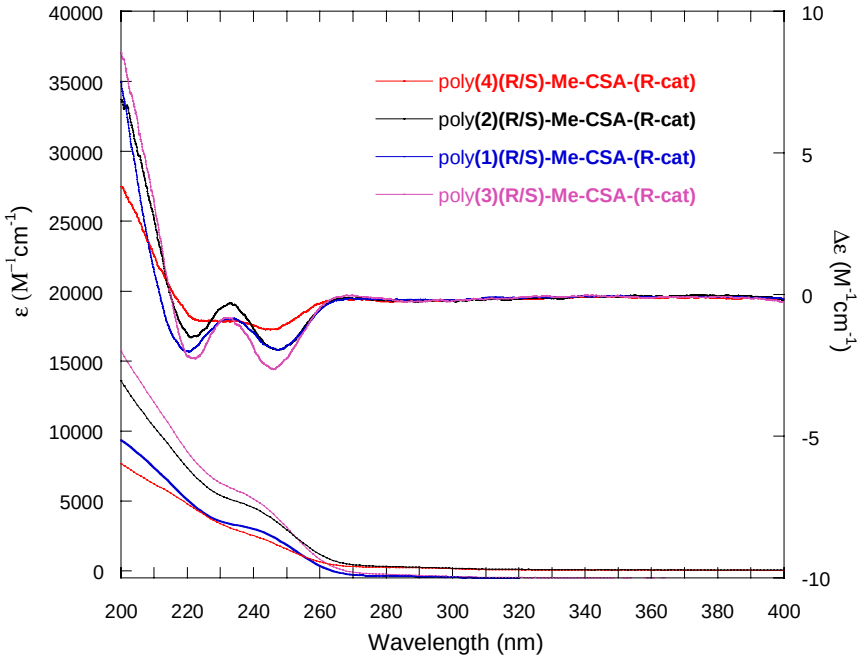
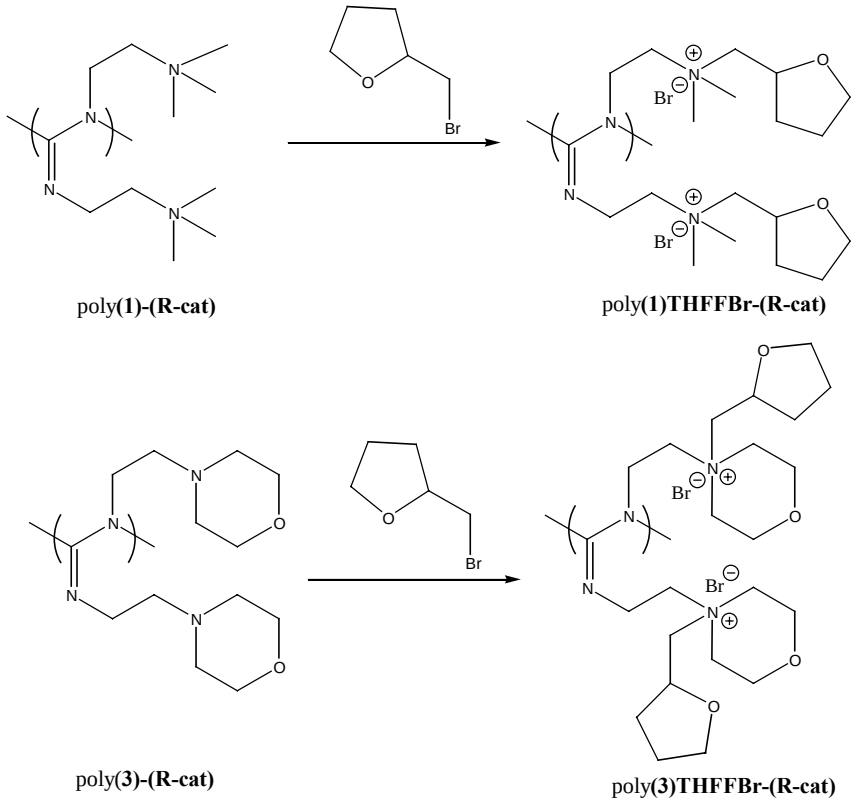


Figure 2.39 CD spectra of ionic polycarbodiimides, poly**(1)(R/S)-Me-CSA-(R-cat.)**, poly**(1)(R/S)-Me-CSA-(R-cat.)**, poly**(1)(R/S)-Me-CSA-(R-cat.)**, and poly**(1)(R/S)-Me-CSA-(R-cat.)** in water

2.7 Effect of the pendant group size on the backbone conformation

For some helical polymers such as polysilanes and polyacetylenes with flexible backbones, the pendant groups may play an important role in governing their helical structures.[16-21,26,27] Without a UV absorbance band, water is the best solvent for spectroscopic investigations of the backbone of the polycarbodiimides. But due to lack of water solubility, few investigations have been performed focusing directly on the backbone of the polycarbodiimides.



Scheme 2.15 Synthesis of ionic polycarbodiimides bearing tetrahydrofurfuryl side chains.

Bulky groups can be introduced onto the side chains through alkylation reactions. Poly**(1)-(R-cat)** and Poly**(3)-(R-cat)** were treated with tetrahydrofurfuryl bromide (THFFBr) to yield water soluble ionic polymers (Scheme 2.15). The morpholine side chains in poly**(3)THFFBr-(R-cat)** make its side arms more bulky than that of poly**(1)(THFFBr)-(R-cat)**. The CD spectra for the two ionic polymer were run in aqueous solutions and comparisons were made between the methylated and the tetrahydrofurfurylated polymers (Figure 2.40 and Figure 2.41).

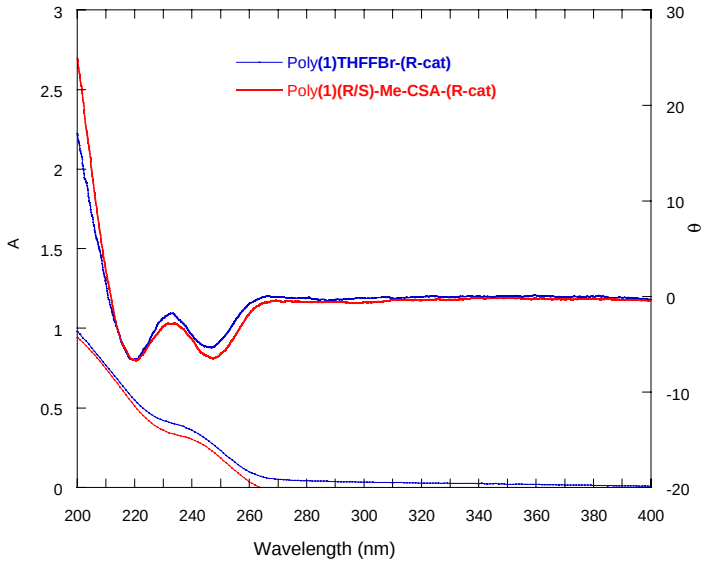


Figure 2.40 The CD spectra of poly**(1)(R/S)-Me-CSA-(R-cat)** and poly**(1)THFFBr-(R-cat).**

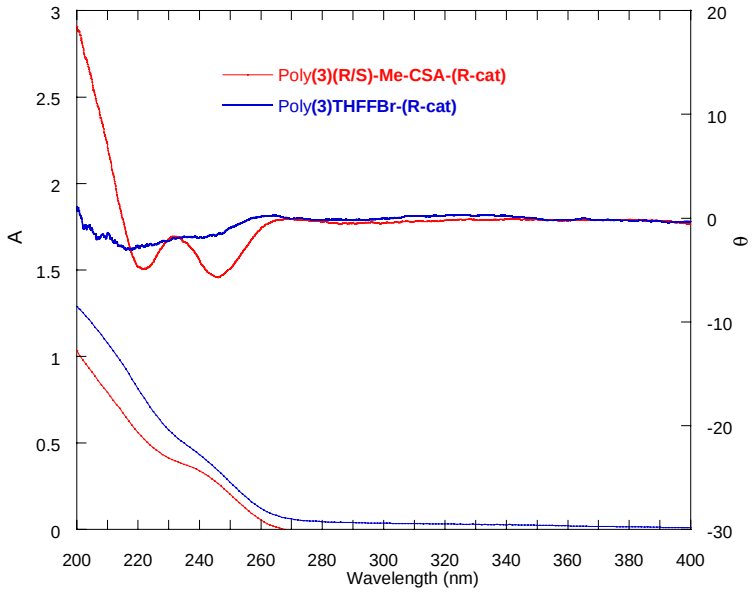


Figure 2.41 The CD spectra of poly**(3)(R/S)-Me-CSA-(R-cat)** and poly**(3)THFFBr-(R-cat)**.

As can be seen in Figure 2.40**,** poly**(1)(R/S)-Me-CSA-(R-cat)** and

Poly**(1)THFFBr-(R-cat)** show same Cotton effects in their CD spectra, which suggest that the introduction of bulky groups do not change the structure of its backbone. However, the spectra for poly**(3)(R/S)-Me-CSA-(R-cat)** and poly**(3)THFFBr-(R-cat)** showed different features (Figure 2.41). Both the polymer and the counter ions of the ionic polymer contribute to the UV spectra. Bromide anions only have active UV absorbance up to 220 nm, and this means, from 220 nm to higher wavelength, the UV absorbance bands are exclusively due to the polymer. Within this wavelength range, with their UV absorbance bands at almost same intensity, the tetrahydrofurfurylated polymer shows much weaker Cotton effects than the methylated one, but has an absorbance band from 260 nm to 210 nm. Since the intensity of the peak in CD spectra reflects how regular the screw sense is, the weakened Cotton suggests a decrease of helical sense for the polymer. The single-handed helical structure of poly**(3)-(R-cat)** results from the chirality of the catalysts, the bulky group may play a positive role in enhancing the enantioselectivity of the reaction. But when the pendant groups were enlarged after the polymerization, the conformation of single handed helical polymers may be diminished due to the new sterics of the bulky pendant groups.

2.8 Summary

Different hydrophilic polycarbodiimides were prepared by employing monomers bearing hydrophilic tertiary amino groups. The reaction between these polymer and methylating reagents yielded ionic polymers with good water solubility. Three different approaches were used toward the goal of preparing single-handed helical polycarbodiimides.

Ionic polycarbodiimides with chiral counter ions were prepared and investigated for induced helicity. During annealing, no change in specific optical rotation was found for ionic

nonfluxional polycarbodiimides with chiral counter ions. Weak induced specific optical rotation was observed and calculated for fluxional polycarbodiimides in room temperature when mixed acid of camphorsulfonic acid and methylsulfonic acid was applied. Through the annealing behavior of same optical active cationic polycarbodiimides bearing enantiomeric or racemic counter camphorsulfonic acid, their inversion barrier can be determined through Arrhenius analysis of the kinetic data. The enantiomeric or racemic camphorsulfonic acid does not change the inversion barriers of the polymers.

Hydrophilic chiral monomers were prepared and polymerized to yield the water soluble polymers. Their annealing behavior was investigated and CD spectra of their aqueous solutions were measured. Single handed water soluble helical polycarbodiimides was also prepared through the polymerization of achiral monomers using chiral titanium complexes. The CD spectra of the resulting polymers were measured for both the neutral and ionic polymers. Based on these data, polycarbodiimides bearing symmetric pendant group suitable for use as peptide mimics were found. Compared with neutral polycarbodiimides bearing tertiary amines, the corresponding ionic polycarbodiimides show higher inversion barriers. Compared with single-handed configurational polymers prepared from chiral monomers, the single-handed conformational polymers have higher order helicity. When the conformational single-handed helical polycarbodiimides were alkylated, some of their helical bias was lost.

2.9 Experiment section

Instruments

Anhydrous solvents were passed through columns packed with Q5 catalysts and molecular sieves prior to use. Polymerization was performed in a MBRAUN UNILAB dry box. ^{1}H NMR and ^{13}C NMR spectra were obtained on Mercury 300 or Mercury 400 spectrometers. Chemical shifts were reported in δ (ppm) relative to tetramethylsilane as internal standard. All infrared spectra were obtained from a JASCO FT/IR-410 spectrometer and wavenumbers in cm^{-1} are reported for characteristic peaks. UV-vis/CD spectra were obtained from JASCO J-600 spectropolarimeter. UV-vis spectra was recorded on a JASCO V-550 spectrophotometer. Optical rotation measurements were taken on a JASCO P-1010 polarimeter at 589 nm. A 100 mm long cell was used for standard optical rotation measurement and a 50 mm long sealed cell with water jacket was used for kinetic optical rotation measurement. A NESLAB RTE-210 circulating water bath was used to control the varying temperatures of the samples for kinetic optical rotation measurement and CD spectrum. Solutions for kinetic optical rotation were 0.2 g/100 mL prepared at room temperature (concentration of 0.2 g/10 mL were adopted for annealing experiments of ionic polycarbodiimides bearing symmetric pendant groups). Element analysis was performed in Atlantic Microlab, Inc.

Helical induction experiments for poly[N-methyl-N'-(N,N-dimethylethylene) carbodiimide] and poly[N-methyl-N'-(2-morpholinoethyl)carbodiimide]

To aqueous solution of poly[N-methyl-N'-(N,N-dimethylethylene) carbodiimide] or poly[N-methyl-N'-(2-morpholinoethyl)carbodiimide] (0.20 g/100 mL, 1.0 mL) in a vial, an

aqueous solution of methylsulfonic acid (0.092 mmol/mL) and (S)-camphorsulfonic acid (0.092 mmol/mL) were added. Then the solution was transferred to a volumetric flask, more water was added to prepare a 10.0 mL solutions. Specific optical rotation measurements were run under specific optical rotation mode, the weigh for all samples was set as 0.020g. The amount of acids, the amount of polymer and specific optical rotation value were recorded in Table 2.2 and Table 2.3.

Helical induction experiments for poly[N-methyl-N'-(2-morpholinopheyl)-carbodiimide]

Aqueous solution of camphorsulfonic acid (0.092 mmol/mL) and methylsulfonic acid (0.092 mmol/mL) were added to vials charged with poly[N-methyl-N'-(2-morpholinopheyl)-carbodiimide] (0.020 g). Overnight stirring of the reaction yields homogeneous solutions. Then the solutions were transferred to volumetric flasks, more water was added to prepared standard solutions (10.0 mL). The solutions were filtrated. Specific optical rotations were run under specific optical rotation mode, the weigh for all samples was set as 0.020g. The amount of acids, the amount of polymers and specific optical rotation values were recorded in Table 2.4.

Effect of the pendant group size on the backbone

Aqueous solution of poly**(1)THFFBr-(R-cat)** (0.000052 mmol/L) and poly**(3)THFFBr-(R-cat)** (0.000063 mmol/L) were prepared and run for their CD spectrum.

(2,2,2-Trifluoroethoxy)trichlorotitanium(IV).

Under nitrogen atmosphere, Titanium(IV) chloride (71.13 mmol, 7.80 mL) was dissolved in anhydrous methylene chloride (60 mL), 2,2,2-trifluoroethanol (59.28 mmol, 4.32

mL) was added dropwise. After it was stirred for 5 hours, solvent was removed under reduced pressure. Anhydrous hexane (20 mL) was added to wash the solid. Then hexane was removed by filtration. The recrystallization of the white powder in benzene yielded the product (2.24 g, 15%). ^{1}H NMR (300MHz, $CDCl_3$) 4.88(m, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 76.83, 117.14, 120.84, 124.53, 128.24.

N,N-dimethylaminoethyleneisothiocyanate.

To a solution of N,N'-dicyclohexylcarbodiimide (116.32 mmol, 24.00g) in ether (250 mL) cooled by ice bath under stirring, N,N-dimethylethylenediamine (116.32 mmol, 13.35 mL) was added. Solution of carbon disulfide (116.32 mmol, 7.00 mL) in ether (100 mL) was added dropwise from a sep funnel equipped in the flask. When the addition was complete, the ice bath was removed and the mixture was stirred for 2 hours. The white precipitate was separated by filtration. The solution was concentrated by rotavep. A gas phase transfer yielded the product (13.00 g, 83%) Mp: 35-38 ^{0}C. IR (neat) 2941(m) 2825(m) 2773(m) 2193(m) 2103(s) 1456(m) ^{1}H NMR (300MHz, $CDCl_3$) 2.30(s, 6H) 2.61(t, 2H) 3.60(t, 3H). ^{13}C NMR (75MHz, $CDCl_3$): δ 43.66, 45.40, 45.56, 58.70.

N,N'-Di(N,N-dimethylaminoethylene)carbodiimide

N,N-dimethylethylenediamine(50.54 mmol, 5.80 mL) was added to a solution of N,N-dimethylaminoethyleneisothiocyanate (50.54 mmol, 6.57 g) in methylene chloride (120 mL) cooled by ice bath. The reaction was allowed to warm up to room temperature naturally. 12 hours later, sodium sulfate (105.63 mmol, 15.00 g) and mercury(II) oxide (76.04 mmol, 16.50 g) were added. The mixture was stirred at room temperature for 10 hours. The slurry solid was removed by filtration. The product solution was concentrated by rotavep. A vacuum

distillation (0.11 mmHg, 70-80°C) yielded product (6.08, 65%). IR (neat) 2125(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.27(s, 6H) 2.46(t, 2H) 3.28(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 45.02, 45.75, 60.07.

3-N,N-dimethylaminopropylisothiocynate

To 120 mL of a DCC (9.92 g, 47.60 mmol) solution in ether at 0°C, N, N-dimethylpropylamine (6.00 mL, 47.60 mmol) was added dropwise. A white precipitate was formed. After the addition was complete, the mixture was allowed to warm to room temperature and was stirred for two hours. The solid was removed by filtration. The solvent was removed by rotavep. A vacuum distillation (0.5 torr, 30-40°C) produced the N,N-dimethyl-3-amino-propylisothiocynate (4.27 g, 62%). IR 2975(s) 2944(s) 2822(s) 2774(s) 2190(s) 2106(s) 1457(s) 1345(s) ^{1}H NMR (400MHz, $CDCl_3$) 1.86(m, 2H), 2.23(s, 6H), 2.38(t, 2H), 3,59(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 28.36, 43.36, 45.78, 56.37

N,N'-di(3-N,N-dimethylaminopropyl)carbodiimide

To a solution of 3-N,N-dimethylaminopropylisothiocynate (1.17 g, 8.13 mmol) in methylene chloride (15 mL), which was cooled to 0°C, N, N-dimethylpropylamine (1.00 mL, 8.13 mmol) was added in one portion. After it was stirred for 24 hours, HgO (2.65 g, 12.2 mmol) was added to give a yellow mixture, which turned to black gradually. The next day, $MgSO_4$ was added to dry the solution. After filtration and the removal of the solvent, a distillation (60 mpa, 60-70°C) yielded the product (1.30 g, 75%). IR (neat) 2128(s) ^{1}H NMR (400MHz, $CDCl_3$) 1.72(m, 2H), 2.22(s, 6H), 2.33(t, 2H), 3.26(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 29.71, 45.13, 45.84, 57.22.

N,N'-di(2-morpholinoethyl)carbodiimide

Sodium phosphate (60.96 mmol, 10.00g), triethylbenzylammonium chloride (3.05 mmol, 0.69 g), 2-morpholinoethylamine (60.96 mmol, 8.00 mL) and mathylene chloride (100 mL) were added to a flask. The mixture was cooled to 0 ^{0}C by an ice bath. Thiophosgene (30.42 mmol, 2.32 mL) was added in one portion. The reaction was allowed to warm up to room temperature naturally. The mixture was stirred for two days before the solid was filtrated off to give the thiourea solution.

Mercury(II) oxide and sodium sulfate were added to the thiourea solution for dehydration. The orange solution turned black gradually. The reaction was stirred overnight at room temperature. The black solid was filtrated off and solvent was removed by rotavep. A vacuum distillation (0.17 torr, 132 ^{0}C) yielded 4.80 g product. Yield: 59%. IR (neat) 2125(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.48(t, 2H) 2.54(t, 4H) 3.27(t, 2H) 3.71(t, 4H). ^{13}C NMR (75MHz, $CDCl_3$): δ 43.74, 53.81, 59.36, 67.13.

3-(2-N,N-dimethylaminoethoxyl)propyl carboxylamide

N,N-dimethylethylene alcohol (1.29 mol, 130 mL) and acrylamide (1.27 mol, 90.0 g) were mixed together in a flask. The mixture was heated at 60 ^{0}C. Dowex monosphere 550A(OH) anion exchange resin (CAS: 69011-18-3) (100 g) was added when a homogeneous solution was produced. The reaction was stirred over night at this temperature. The resin was filtrated off. A vacuum distillation (0.08 torr, 120 ^{0}C) yielded 63.0 g product. Yield: 31%. IR (neat) 3357(br, s) 3203(s) 2945(m) 2870(m) 1669(s) 1455(m) 1405(m) 1115(m). ^{1}H NMR (300MHz, $CDCl_3$) 2.24(s, 6H) 2.48(t, 4H) 3.55(t, 2H) 3.68(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 36.70, 45.69, 58.69, 66.72, 68.39, 174.70.

2-(2-N,N-dimethylaminoethoxyl)ethyl amine

At 0 ^{0}C, to a thoroughly stirred aqueous solution (0.8 L) of potassium hydroxide (3.94 mol, 221g), bromine (0.79 mol, 40.40 mL) was added dropwise over a period of 30 minutes. The yellow solution was allowed to set for another 30 minutes when the addition was complete. Still at 0 ^{0}C, 3-(2-N,N-dimethylaminoethoxyl)propyl carboxylamide was added dropwise to the solution. The reaction was allowed to warm up to room temperature after the addition was complete. 5 hours later, temperature for the reaction was increased and the reaction was heated at 80 ^{0}C over night.

The reaction was cooled down to room temperature and mathylene chloride was added to extract the product (5×200 mL). All methylene chloride fractions were combined together and dried by magnesium sulfate. Then it was filtrated and concentrated by rotavep. A vacuum distillation (3.3 mmHg, 90 ^{0}C) yielded 12.79 g product. Yield: 25%. IR (neat) 3397(br, s) 2952(s) 2872(s) 2832(s) 2783(s) 1651 (m) 1576(s) 1472(s) 1312(m) 1118(s) ^{1}H NMR (300MHz, $CDCl_3$) 1.63(br, 2H) 2.26(s, 6H) 2.50(t, 2H) 2.85(t, 2H) 3.47(t, 2H) 3.54(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 41.74, 45.84, 58.87, 69.01, 73.29.

N,N'-di((2-N,N-dimethylaminoethoxyl) ethyl)urea

To solution of di(4-nitrophenyl) carbonate (42.11 mmol, 12.81 g) in chloroform (160 mL), 2-(2-(N,N-dimethylamino)ethoxyl) ethyl amine (84.24 mmol, 11.12 g) was added in one portion. The reaction was stirred for 10 hours. Aqueous solution (200 mL) of sodium hydroxide (0.4 mol, 16 g) was added to the reaction. Organic phase was separated from the aqueous one. More chloroform was added to the aqueous solution to extract the product (4×150 mL). All chloroform fractions were combined together and dried by magnesium

sulfate. The solid then was filtrated off and the solution was concentrated to give 12.25 g pure product. Yield: 100%. IR (KBr film) 3409(br, s) 2982(br, s) 1735(s) 1656(s) 1554(s) 1461(s) 1127(s). ^{1}H NMR (300MHz, $CDCl_3$) 2.22(s, 12H) 2.45(t, 4H) 3.35(m, 4H) 3.49(m, 8H). ^{13}C NMR (75MHz, $CDCl_3$): δ 40.34, 46.00, 59.21, 68.71, 70.69, 158.87.

N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide

N,N'-di[(2-(N,N-dimethylamino)ethoxyl) ethyl] urea (42.24 mmol, 12.25 g) was dissolved in benzene (450 mL), p-toluenesulfonyl chloride (42.48 mmol, 8.10 g), sodium phosphate (168.96 mmol, 27.65 mmol) and triethylbenzylammonium chloride (4.22 mmol, 0.96 g) were added. The mixture was heated and refluxed for two days. The solid was removed by filtration and the solution was concentrated by rotavep. A vacuum distillation (0.085 torr, 110 ^{0}C) yielded 5.72 g product. Yield: 50%. IR (neat) 2133(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.25(s, 12H) 2.50(t, 4H) 3.38(t, 4H) 3.56(t, 8H) ^{13}C NMR (75MHz, $CDCl_3$): δ 46.16, 46.46, 59.07, 69.45, 70.92, 204.77.

N-methyl-N'-(N,N-dimethylaminoethylene)carbodiimide

To solution of methylisothiocyanate (73.74 mmol, 5.55g) in methylene chloride (50 mL) cooled by ice bath, N,N-dimethylaminoethyleneamine (73.75 mmol, 8.48 mL) was added in one portion. The reaction was allowed to warm up to room temperature naturally and the solution was stirred overnight. Mercury(II) oxide (73.74 mmol, 16.00g) and calcium sulfate (110.61 mmol, 15.06 g) were added for dehydration. Two hours later, solid was removed by filtration and the solution was concentrated by rotavep. A vacuum distillation (0.3 torr, 40-50 ^{0}C) yielded 3.55 g product. Yield: 38%. IR (neat) 2134(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.27(s, 3H) 2.45(t, 2H) 2.94(s, 3H) 3.27(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 33.25, 44.82, 45.63,

60.00.

N-methyl-N'-2-morpholinoethylcarbodiimide

Same procedure similar to above was employed. Methylisothiocyanate (91.68 mmol, 6.90 g), 2-morpholinoethylamine (91.68 mmol, 12.00 mL), mercury(II) oxide (110.02 mmol, 23.83 g), sodium sulfate (137.52 mmol, 19.53 g) and methylene chloride (100 mL) were used to yield 1.84 g product. Yeild: 12%. (0.24 torr, 70 ^{0}C). IR (neat) 2124 (s). ^{1}H NMR (400MHz, $CDCl_3$) 2.51(m, 6H) 2.97(m, 3H) 3.26(m, 2H) 3.72(m, 4H). ^{13}C NMR (100MHz, $CDCl_3$): δ 33.29, 43.44, 53.69, 59.29, 67.14.

N-methyl-N'-4-morpholinophenylcarbodiimide

To solution of 4-morpholinophenylamine (16.33 mmol, 3.00g) in methylene chloride (35 mL) cooled by ice bath, methylisothiocyanate (16.34 mmol, 1.23 g) was added in one portion. The reaction was allowed to warm up to room temperature naturally and the solution was stirred overnight to give rise to a thiourea.

The next day, DMAP (0.41 mmol, 50 mg) and triethylamine (48.99 mmol, 6.80 mL) were added and the solution was cooled again by ice bath. Methylsulfonyl chloride (32.66 mmol, 2.50 mL) was added dropwise over a period of 20 minutes. The reaction was warmed up to room temperature. 3 hours later, solid in the reaction mixture was filtrated off and solvent was removed by rotavep. Purification of the slurry residue by column chromatography yielded 0.97 g product. Yield: 27%. IR (neat) 2133(s) ^{1}H NMR (300MHz, $CDCl_3$) 3.09(m, 7H) 3.84(t, 4H) 6.83(d, 2H) 6.99(d, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 33.03, 49.93, 67.10, 116.92, 124.50, 132.46, 148.86.

1-nitro-4-(4-methylpiperizino)benzene

1-fluoro-4-nitrobenzene (193.27 mmol, 27.27 g) and 1-methylpiperizine (193.27 mmol, 15.00 mL) were dissolved in acetonitrile (300 mL). Triethylamine (503.45 mmol, 70.0 mL) was added. The reaction was refluxed for 18 hours. Then the solvent was removed by rotavep and aqueous solution (200 mL) of sodium hydroxide (400.0 mmol, 16.0 g) was added to dissolve the residue. The product was extracted by methylene chloride (5×100 mL). All methylene chloride fractions were combined and dried by sodium sulfate. The removal of solid and solvent by filtration and rotavep respectively yielded 44.10 g product. Yield: 100% mp 104-105 ^{0}C. IR (KBr film) 2939(s) 2850(s) 2808(s) 1596(s)1494(s) 1331(s) 1243(s) 1114(s) 1006(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.36(s, 3H) 2.55(t, 4H) 3.43(t, 4H) 6.81(d, 2H) 8.10(d, 2H). ^{13}C NMR (75MHz, $CDCl_3$): δ 46.42, 47.31, 54.85, 112.86, 126.13, 138.56, 154.96.

4-(4-methylpiperizino)aniline

In an autoclave, 1-nitro-4-(4-methylpiperizino)benzene (198.84 mmol, 44.00 g) was dissolved in THF (200 mL). Raney Ni (slurry in water, 2800) (4.50 g) was added. The autoclave was sealed and the reaction was held under hydrogen of pressure (80 psi). After being stirred for two days, the catalyst was filtrated off and solvent was removed by rotavep. A sublimation (0.13 torr, 150 ^{0}C) yielded 24.20 g product. Yield: 64%. Mp 88-90 ^{0}C. IR (KBr film) 3359(s) 3194(s) 2931(m) 2805(s) 1646(m) 1512(s) 1457(m) 1277(s) 1231(s) 822(s). ^{1}H NMR (300MHz, $CDCl_3$) 2.35(s, 3H) 2.58(t, 4H) 3.07(t, 4H) 6.64(d, 2H) 6.81(d, 2H). ^{13}C NMR (75MHz, $CDCl_3$) δ 46.50, 51.18, 55.65, 116.40, 118.73, 140.24, 144.64.

Methoxyethyleneisothiocyanate

Methylene chloride (100 mL) was added to a flask charged with aqueous solution (200 mL) of sodium bicarbonate (0.36 mol, 30 g), followed by the addition of methoxyethyleneamine (113.77 mmol, 10.00 mL). The mixture was cooled by ice bath and thiophosgene (120.20 mmol, 9.50 mL) was added. The reaction was allowed to warm up to room temperature and the mixture was stirred for 5 hours. Organic layer was separated from the aqueous one and dried by sodium sulfate. Then the solid was removed by filtration and the solution was concentrated by rotavep. A vacuum distillation (28 mmHg, 93 ^{0}C) yielded 12.31 g product. Yield: 87%. IR (neat) 2933(m) 2892(m) 2197(s) 2114(s) 1344(m) 1125(m). ^{1}H NMR (300MHz, $CDCl_3$) 3.41(s, 3H) 3,57(t, 2H) 3.66(t, 2H) ^{13}C NMR (75MHz, $CDCl_3$) δ 45.31, 59.25, 70.70.

N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide

To solution of methoxyethyleneisothiocyanate (27.58 mmol, 3.23g) in chloroform (50 mL) cooled by ice bath, 4-(4-methylpiperizino)aniline (27.58 mmol, 5.28 g) was added in one portion. The reaction was allowed to warm up to room temperature and the solution was stirred for two days. Then triethylamine (82.74 mmol, 11.50 mL) and DMAP (0.74 mmol, 90 mg) was added. The reaction was cooled again by ice bath and methylsulfonyl chloride (55.16 mmol, 4.30 mL) was added dropwise over a period of 20 minutes. Ice bath was removed when the addition was complete. Two and half hours later, the mixture was poured to hexane (300 mL) and was stirred thoroughly for another 20 minutes. The solid was removed by filtration. The hexane solution was washed by water (3×150 mL) to remove the water soluble byproduct. The aqueous phase was then separated and the organic phase was

dried by sodium sulfate. The removal of solid and solvent through filtration and rotavep respectively yielded 1.75 g product. Yield: 23%. IR (neat) 2127(s) ^{1}H NMR (300MHz, $CDCl_3$) 2.36(s, 3H) 2.58(t, 4H) 3.17(t, 4H) 3.39(s, 3H) 3.52(t, 2H) 3.59(t, 2H) 6.85(d, 2H) 7.03(d, 2H). ^{13}C NMR (75MHz, $CDCl_3$) δ 46.48, 47.07, 49.79, 55.41, 59.06, 72.16, 117.14, 124.56, 148.83.

N-(N,N-dimethylaminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide

To a solution of N,N-dimethylethyleneisothiocyanate (27.15 mmol, 3.53 g) in methylene chloride (60 mL) cooled by ice bath, (S)-1-Methoxy-2-propylamine (27.15 mmol, 2.90 mL) was added in one portion. Ice bath was removed when the addition was complete and the reaction was stirred overnight. Mercury(II) oxide (29.87 mmol, 6.45 g) and sodium sulfate (40.72 mmol, 5.78 mmol) were added to the reaction. The color of the mixture turned black from orange gradually. Ten hours later, solid in the mixture was filtrated off and the solution was concentrated. A vacuum distillation (0.15 torr, 80 ^{0}C) yielded 2.95 g product. Yield: 59% $[\alpha]_D$=15.96 ($CHCl_3$ c=0.50) IR (neat) 2124(s) ^{1}H NMR (300MHz, $CDCl_3$) 1.18(d, 3H) 2.24(s, 6H) 2.46(t, 2H) 3.29(m, 4H) 3.37 (s, 3H) 3.60(m, 1H) ^{13}C NMR (75MHz, $CDCl_3$) δ 19.14, 44.86, 45.62, 52.76, 59.17, 60.01.

3-(N-methyl-N-(N,N-dimethylaminoethylene)amino)propyl carboxylamide

N,N,N'-trimethylethylenediamine (224.21 mmol, 22.91g) and acylamide (224.21 mmol, 15.94g) were added to a flask. As little methanol as possible was added to dissolve the mixture. The solution was set for two days even without being stirred. The removal of the solvent yielded 38.00 g product. Yield: 98% IR (neat) 3700-3050(br, s) 2949(s) 2819(s) 2778(s) 1670(s) 1462(s) 1404(s) 1263(m) 1025(s). ^{1}H NMR (300MHz, $CDCl_3$) 2.21(s, 6H)

2.27(s, 3H) 2.40(m, 4H) 2.50(t, 2H) 2.60(t, 2H). ^{13}C NMR (75MHz, $CDCl_3$) δ 33.33, 42.13, 45.77, 53.10, 55.41, 57.20.

N-methyl-N-(N,N-dimethylaminoethylene)aminoethyleneamine

To a stirred aqueous solution (180 mL) of potassium hydroxide (1.93 mol, 108.0g) cooled by ice bath, bromine (385.54 mmol, 19.80 mL) was added dropwise over a period of 20 minutes. The reaction was stirred for another 30 minutes when the addition was complete. Then the solution was cooled again by ice bath, aqueous solution (150 mL) of 3-(N-methyl-N-(N,N-dimethylaminoethylene)amino)propyl carboxylamide (192.77 mmol, 33.40 g) was added dropwise. The key point to achieve high yield is slow addition of the amide solution to avoid heat. After the addition was complete, the reaction was allowed to warm up to room temperature naturally and stirred overnight. Then it was heated at 100 ^{0}C for half an hour and cooled down to room temperature. Chloroform was added to extract the product (3×200 + 2×150). All chloroform fractions were combined and dried by sodium sulfate. The solid was filtrated off and the crude product was concentrated through rotavep. A vacuum distillation (25 mmHg, 95 ^{0}C) yielded 13.49 g product. Yield: 48%. IR (neat) 3700-3050(s) 2945(s) 2817(s) 2775(s) 1576(s) 1463(s) 1308(s) 1027(s). ^{1}H NMR (300MHz, $CDCl_3$) 2.34(s, 9H) 2.43(m, 6H) 2.76(t, 2H) ^{13}C NMR (75MHz, $CDCl_3$) δ 39.90, 42.94, 46.18, 56.29, 57.80, 61.34.

(S)-1-Methoxy-2-propylisothiocyanate

(S)-(+)-1-Methoxy-2-propylamine (98.16 mmol, 8.75g), sodium bicarbonate (368.10 mmol, 30.92 g), water (200 mL) and methylene chloride (100 mL) were added to a flask. To this stirred mixture, thiophosgene (122.70 mmol, 9.40 mL) was added dropwise. After the

addition was complete, the reaction was stirred for four hours. The aqueous layer was separated and organic layer was dried by sodium sulfate. Solid was removed and the solution was concentrated by rotavep. A vacuum distillation (31 mmHg 93 ^{0}C) yielded 11.47 g product. Yield: 95%. $[\alpha]_D$=40.62 ($CHCl_3$ c=0.35) IR (neat) 2985(m) 2931(m) 2100(s) 2080(s) 1338(m) 1109(m). ^{1}H NMR (300MHz, $CDCl_3$) 1.35(d, 3H) 3.42(m, 5H) 3.94(m, 1H) ^{13}C NMR (75MHz, $CDCl_3$) δ 18.68, 53.55, 59.50, 76.00.

N-(N-methyl-N-(N,N-dimethylaminoethylene)aminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide

To a solution of (S)-1-Methoxy-2-propylisothiocyanate (48.17 mmol, 6.32 g) in methylene chloride (60 mL) cooled by ice bath, N-methyl-N-(N,N-dimethylaminoethylene)-aminoethyleneamine was added in one portion. Ice bath was removed and the reaction was stirred overnight. Mercury(II) oxide and sodium sulfate were added to the reaction. The color of the mixture turned black from orange gradually. Ten hours later, solid in the mixture was filtrated off and the solution was concentrated. A vacuum distillation (0.11 torr, 90 ^{0}C) yielded 4.79 g product. Yield: 41%. $[\alpha]_D$=6.91 ($CHCl_3$ c=0.40) IR (neat) 2124(s) ^{1}H NMR (300MHz, $CDCl_3$) 1.20(d, 3H) 2.24(s, 6H) 2.29(s, 3H) 2.39(m, 2H) 3.30(m, 4H) 3.38(s, 3H) 3.62(m, 1H) ^{13}C NMR (75MHz, $CDCl_3$) δ 19.21, 42.77, 44.74, 46.12, 52.71, 56.01, 57.57, 58.68, 59.17.

N-((S)-1-methoxy-2-propyl)-N'-4-(4-methylpiperizino)phenylcarbodiimide

To a stirred solution of (S)-1-Methoxy-2-propylisothiocyanate (14.45 mmol, 1.90 g) in chloroform (50 mL) cooled by ice bath, 4-(4-methylpiperizino)aniline (15.21 mmol, 2.91 g) was added in one portion. Ice bath was removed and the reaction was stirred overnight. Then

triethylamine (45.63 mmol, 6.34 mL) and DMAP was added. The reaction was cooled again by ice bath and methylsulfonyl chloride (29.66 mmol, 2.30 mL) was added dropwise over a period of 20 minutes. Ice bath was removed when the addition was complete. Two and half hours later, the mixture was poured to hexane (200 mL) and was stirred thoroughly for another 20 minutes. The solid was removed by filtration. The hexane solution was washed by water (3×100 mL) to remove the water soluble byproduct. The organic phase was then separated and dried by sodium sulfate. The removal of solid and solvent through filtration and rotavep respectively yielded 2.13 g product. Yield: 51%. $[\alpha]_D$=5.25 ($CHCl_3$ c=0.24) IR (neat) 2120(s) ^{1}H NMR (300MHz, $CDCl_3$) 1.28(d, 3H) 2.35(s, 3H) 2.57(t, 4H) 3.17(t, 4H) 3.40(m, 5H) 3.80(m, 1H) ^{13}C NMR (75MHz, $CDCl_3$) δ 19.54, 46.47, 49.80, 53.88, 55.41, 59.26, 117.16, 124.44, 132.11, 148.81.

(1R)-10-Camphorsulfonyl chloride

(1R)-10-Camphorsulfonic acid (51.65 mmol, 12.00 g) and thionyl chloride (150.8, 11.0 mL) were added to a flask. The solid was dissolved when the reaction was heated. After 6 hours reflux, the solution was poured to a ice water mixture (300 mL) and stirred vigorously for 20 minutes. The liquid was filtrated off and the solid was dried under vacuum to give 12.11 g product. Mp 64-66 ^{0}C $[\alpha]_D$=30.40 ($CHCl_3$ c=0.42) Yield: 93%. ^{1}H NMR (300MHz, $CDCl_3$) 0.94(s, 3H) 1.15(s, 3H) 1.50(m, 1H) 1.78(m, 1H) 1.98-2.19(m, 3H) 2.48(m, 2H) 4.02(dd, AB, 2H) ^{13}C NMR (75MHz, $CDCl_3$) δ 20.04, 20.16, 25.65, 27.25, 42.67, 43.14, 48.51, 60.02, 64.55, 213.00.

10-Camphorsulfonyl chloride

Similar procedure to above was employed. 10-Camphorsulfonic acid (86.09 mmol, 20.00

g) and thionyl chloride (246.8 mmol, 18.0 mL) were used to yield 20.19 g product. Yield: 93%. Mp 80-82 ^{0}C. IR (KBr film) 2981(s), 2965(s) 2934(m) 2894(w) 1744(s) 1374 (s) 1180(s) 552(s) 505(s) ^{1}H NMR (300MHz, $CDCl_3$) 0.92(s, 3H) 1.14(s, 3H) 1.49(m, 1H) 1.77(m, 1H) 1.96-2.18(m, 3H) 2.44(m, 2H) 4.02(dd, AB, 2H) ^{13}C NMR (75MHz, $CDCl_3$) δ 20.02, 20.14, 25.65, 27.24, 42.65, 43.12, 48.52, 60.00, 64.56, 218.80.

(1R)-10-Camphorsulfonic acid methyl ester

To solution of (1R)-10-camphorsulfonyl chloride (47.46 mmol, 11.90 g) in methylene chloride (110 mL) cooled by ice bath, solution of sodium methoxide (74.07 mmol, 3.10 g) in methanol (40 mL) was added dropwise over a period of 40 minutes. Ice bath was removed when the addition was complete. 30 minutes later, water (150 mL) was added. The two layers were separated and aqueous layer was washed by methylene chloride (100 mL). All methylene chloride fractions were combined and dried by sodium sulfate. Then the solid was filtrated off and the solution was concentrated by rotavep. Ether (25 mL) was added and the mixture was heated to reflux to dissolve the residue. The solution was set in the refrigerator overnight. Then solid was collected through filtration and dried under vacuum to yield 7.50 g product. Yield: 68%. Mp: 57-59 ^{0}C $[\alpha]_D$=-44.43 ($CHCl_3$ c=0.22). IR (KBr film) 2973(s) 2912(m) 1742(s) 1356(s) 1172(s) 992(s) 809(s) 749(s) ^{1}H NMR (300MHz, $CDCl_3$) 0.89(s, 3H) 1.11(s, 3H) 1.45(m, 1H) 1.66(m, 1H) 1.93-2.16(m, 3H) 2.42(m, 2H) 3.29(dd, AB, 2H) 3.95(s, 3H). ^{13}C NMR (75MHz, $CDCl_3$) δ 20.05, 20.13, 25.20, 27.23, 42.86, 43.08, 46.35, 48.35, 56.46, 58.17, 214.57.

10-Camphorsulfonic acid methyl ester

Similar procedure to above was employed. 1-(R/S)-10-camphorsulfonyl chloride (80.52

mmol, 20.19 g), sodium methoxide (92.60 mmol, 5.00 g), methylene chloride (200 mL) and methanol (60 mL) were used to yield 14.20 g product. Yield: 76% Mp: 53-55 ^{0}C. IR (KBr film) 2966(s) 2887(m) 1748(s) 1354(s) 1169(s) 980(s) 834(s) 676(s) ^{1}H NMR (300MHz, $CDCl_3$) 0.88(s, 3H) 1.14(s, 3H) 1.45(m, 1H) 1.65(m, 1H) 1.93-2.16(m, 3H) 2.42(m, 2H) 3.29(dd, AB, 2H) 3.94(s, 3H). ^{13}C NMR (75MHz, $CDCl_3$) δ 20.04, 20.12, 25.20, 27.23, 42.85, 43.08, 46.35, 48.34, 56.45, 58.17, 214.56.

(1S)-10-Camphorsulfonic acid methyl ester

(1S)-10-camphorsulfonyl chloride (58.66 mmol, 14.71 g), sodium methoxide (74.07 mmol, 4.00 g), methylene chloride (130 mL) and methanol (50 mL) were used to yield 12.02 g product. Yield: 88% Mp: 55-57 ^{0}C $[\alpha]_D$=45.45 ($CHCl_3$ c=0.20) IR (KBr film) 2972(s) 1735(s) 1354(s) 1172(s) 991(s) 810(s) 749(s) ^{1}H NMR (400MHz, $CDCl_3$) 0.89(s, 3H) 1.12(s, 3H) 1.44(m, 1H) 1.66(m, 1H) 1.98-2.14(m, 3H) 2.45(m, 2H) 3.29(dd, AB, 2H) 3.96(s, 3H). ^{13}C NMR (100MHz, $CDCl_3$) δ 20.07, 20.14, 25.19, 27.24, 42.86, 43.08, 46.35, 48.36, 56.46, 58.18, 214.60.

General procedure for polymerization

Unless noted, the following is a general procedure for the preparation of neutral polycarbodiimides. All manipulations were performed in a MBRAUN UNILAB dry box. Catalysts and monomers were added to a vial, when necessary, solvent is also added to the reaction. All polymerization was performed in room temperature unless otherwise noted. During the polymerization, the color of the living species, the amidinate group serves as an indicator. A persistent dark red solution indicates an active living species for polymerization while the white or colorless is a sign for deactivated living species. The consumption of the

monomers was monitored by IR and the time span for polymerization varies from a couple hours to several days, depending on the structure of monomers.

When the polymerizations were complete, concentrated solutions of the polymer solution in chloroform were prepared. The solutions were usually poured to an empty beaker, the viscous solution was swirled so that it can cover the bottom and lower part of the wall of the beaker, then acetonitrile as precipitant was added gently. The polymer layer sticks to the wall of beaker was broken into flakes. After being soaked for one to three days, polymers and acetonitrile were separated by centrifugation or filtration and the polymers were dried under vacuum. For precipitation, high concentration of polymer is the key point in obtaining the high yield, because dilute polymer solutions give rise to suspensions when precipitant was added so as to make it hard to collect.

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide]

N,N'-Di(N,N-dimethylaminoethylene)carbodiimide (4.35 mmol, 0.80 g) and (2,2,2-trifluoroethoxy)-trichlorotitanium(IV) (0.022mmol, 5.5 mg) were used to yield 0.59 g product. Yield: 74%. ^{1}H NMR (300MHz, $CDCl_3$) 2.21(br, s) 2.95-3.10(br, w) 3.50(br, w) ^{13}C NMR (75MHz, $CDCl_3$) δ 46.35(br, s) 58.91(br, w) 61.51(br, w) 147.78(br, w).

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide]-(R-cat)

N,N'-Di(N,N-dimethylaminoethylene)carbodiimide (5.43 mmol, 1.00 g) and (R)-BINOL-Ti (0.027 mmol, 12 mg) were used to yield 0.73 g product. Yield: 73%. $[\alpha]_D$=43.54 (H_2O c=0.20) ^{1}H NMR (300MHz, $CDCl_3$) 2.21(br, s) 2.95-3.11(br, w) 3.53(br, w) 4.18-4.43(br, w) ^{13}C NMR (75MHz, $CDCl_3$) δ 46.35(br, s) 59.01(br, w) 61.50(br, w) 147.83(br, w).

Poly[N,N'-di(3-N,N-diimethylaminopropyl)carbodiimide]

N,N'-di(3-N,N-diimethylaminopropyl)carbodiimide (2.38 mmol, 0.50 g) and (2,2,2-trifluoroethoxy)-trichlorotitanium(IV) (0.012mmol, 3.0 mg) were used to yield 0.50 g product. Yield: 100%. ^{1}H NMR (400MHz, $CDCl_3$) 2.16(br, m) 2.20-2.80(br, s) 2.80-3.05(br, w) 3.10-4.80(br, s). ^{13}C NMR (100MHz, $CDCl_3$) δ 46.81(br, m) 54.62(br, s) 58.12(br, w) 67.00(br, s).

Poly[N,N'-di(3-N,N-diimethylaminopropyl)carbodiimide]-(R-cat)

N,N'-di(3-N,N-diimethylaminopropyl)carbodiimide (2.83 mmol, 0.60 g) and (R)-BINOL-Ti (0.014mmol, 6.3 mg) were used to yield 0.53 g product. Yield: 88%. $[\alpha]_D$=25.24 ($CHCl_3$ c=0.20). ^{1}H NMR (300MHz, $CDCl_3$) 2.07(br, m) 2.10-2.81(br, s) 2,81-3.03(br, w) 3.10-4.80(br, s). ^{13}C NMR (75MHz, $CDCl_3$) δ 54.71(s) 67.19(s) 148.00(w).

Poly[N,N'-di(2-morpholinoethyl)carbodiimide]

N,N'-di(2-morpholinoethyl)carbodiimide (2.38 mmol, 0.64 g) and (2,2,2-trifluoroethoxy)-trichlorotitanium(IV) (0.012mmol, 3.0 mg) were used to yield 0.51 g product. Yield: 80%. ^{1}H NMR (400MHz, $CDCl_3$) 1.65(br, m) 2,17(br, s) 2.85-3.40 (br, w) 3.77(br, m). ^{13}C NMR (100MHz, $CDCl_3$) δ 30.26(br, w) 45.87(br, s) 58.84(br, w) 148.10(br, w).

Poly[N,N'-di(2-morpholinoethyl)carbodiimide]-(R-cat)

N,N'-di(2-morpholinoethyl)carbodiimide (2.24 mmol, 0.60 g) and (R)-BINOL-Ti(IV) (0.011mmol, 5.0 mg) were used to yield 0.51 g product. Yield: 85%. $[\alpha]_D$=5.15 ($CHCl_3$ c=0.40) ^{1}H NMR (400MHz, $CDCl_3$) 1.61(br, m) 2,15(br, s) 2.95-3.37 (br, w) 3.84(br, m). ^{13}C

NMR (100MHz, $CDCl_3$) δ 30.09(br, w) 45.76(br, s) 58.77(br, w) 147.90(br, w).

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide]

N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide (1.65 mmol, 0.45 g) and (2,2,2-trifluoroethoxy)-trichlorotitanium(IV) (0.008mmol, 2.0 mg) were used to yield 0.45 g product. Yield: 100%. ^{1}H NMR (400MHz, $CDCl_3$) 2.23(br, s) 2.47(br, m) 3.41(br, m) 3.50(br, m) ^{13}C NMR (100MHz, $CDCl_3$) δ 46.36(s) 48.06(w) 59.08(m) 59.35(m) 69.86(m) 72.16(w) 149.09(w).

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide]-(R-cat)

N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide (2.21 mmol, 0.60 g) and (R)-BINOL-Ti(IV) (0.011mmol, 5.0 mg) were used to yield 0.37 g product. Yield: 62% $[\alpha]_D$=9.97 ($CHCl_3$ c=0.21). ^{1}H NMR (400MHz, $CDCl_3$) 2.22(br, s) 2.45(br, m) 3.40(br, m) 3.48 (br, m) ^{13}C NMR (100MHz, $CDCl_3$) δ 46.27(s) 47.87(w) 68.98(m) 59.24(m) 69.81(m) 72.10(w) 149.10(w).

Poly[N-methyl-N'-(N,N-dimethylaminoethylene)carbodiimide]

N-methyl-N'-(N,N-dimethylaminoethylene)carbodiimide (7.87 mmol, 1.00g) was added to a vial charged with Dichloro-η^5-cyclopentadienyl-dimethylamido titanium(IV) (0.04 mmol, 9.0 mg). The solution was stirred until a firm block was produced. No more purification was performed. ^{1}H NMR (300MHz, $CDCl_3$) 2.24(br, s) 2.27(br, s) 2.75(br, w) 3.15(br, w) 3.39(br, w) ^{13}C NMR (75MHz, $CDCl_3$) δ 46.29(s) 47.90(w) 60.11(w) 62.08(m).

Poly[N-methyl-N'-2-morpholinoethylcarbodiimide]

N-methyl-N'-2-morpholinoethylcarbodiimide (5.91 mmol, 1.00g) was added to a vial charged with Dichloro-η^5-cyclopentadienyl-dimethylamido titanium(IV) (0.03 mmol, 6.7

mg). The solution was stirred until a firm block was produced. No more purification was performed. ^{1}H NMR (300MHz, $CDCl_3$) 2.27(br, s) 2.53(s) 2.89- 3.37(br, s) 3.37-3.49(br, m) 3.49-3.95(br, s) ^{13}C NMR (75MHz, $CDCl_3$) δ 34.40(br, w) 45.90(br, w) 54.45(br, s) 60.52(br, m) 61.21(w) 67.20(br, s).

Poly[N-methyl-N'-4-morpholinophenylcarbodiimide]

N-methyl-N'-4-morpholinophenylcarbodiimide (4.46 mmol, 0.97 g) was dissolved by chloroform (2.5 mL). The solution was added to a vial charged with (2,2,2-trifluoroethoxy)-trichlorotitanium(IV) (0.02mmol, 5.0 mg). Polymer produced in the reaction precipitated gradually. After being stirred overnight, acetone (15 mL) was added to the vial. Then all liquid was removed after the polymer was soaked for two days. It was dried under vacuum to yield 0.91 g product. Yield: 94%. No NMR spectrum was run due to the poor solubility of the polymer in any solvents.

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(R-cat)

N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide (3.28 mmol, 0.90 g) and (R)-BINOL-Ti(IV) (0.022mmol, 9.8 mg) were used to yield 0.32 g product. Yield: 36%. $[\alpha]_D$=645.68 (DMF c=0.22). ^{1}H NMR (300MHz, $CDCl_3$) 2.15(br, m) 2.31(br, s) 2.33-2.65(br, s) 2.65-90(br, s) 5.95-7.30(br, s) ^{13}C NMR (75MHz, $CDCl_3$) δ 46.45 50.08(br, m) 55.60(br, m) 58.41(br, s) 117.12(br, w) 123.34(br, w) 146.72(br, w).

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide] -(S-cat)

N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide (0.73 mmol, 0.20 g) and (S)-BINOL-Ti(IV) (0.005mmol, 2.2 mg) were used to yield 0.056 g product. Yield: 28%. $[\alpha]_D$=-678.68 (DMF c=0.15).

Poly[N-(N,N-dimethylaminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide]

N-(N,N-dimethylaminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide (8.10 mmol, 1.50 g) and chloroform (1.0 mL) was added to a vial charged with (2,2,2-trifluoroethoxy)trichlorotitanium(IV) (0.054mmol, 13.0 mg). The reaction was stirred for two weeks in room temperature. Then acetone (15 mL) was added to the vial to precipitate the product. Two days later, the liquid was removed through filtration and the polymer was dried under vacuum to yield 1.12 g product. Yield: 75%. $[\alpha]_D$=-22.32 ($CHCl_3$ c=0.22). ^{1}H NMR (300MHz, $CDCl_3$) 0.94-1.28(br, s) 2.24(br, s) 2.42-2.89(br, m) 3.08-3.70(br, s) 3.80-4.08(br, w) 4.30-4.80(br, w) 4.96(br, w) ^{13}C NMR (75MHz, $CDCl_3$) δ 19.56(br, m) 46.02(br, s) 59.20(br, m) 149.00(br, w).

Poly[N-(N-methyl-N-(N,N-dimethylaminoethylene)aminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide]

N-(N-methyl-N-(N,N-dimethylaminoethylene)aminoethylene)-N'-((S)-1-methoxy-2-propyl)carbodiimide (4.76 mmol, 1.15 g) was added to a Schlenk tube charged with (2,2,2-trifluoroethoxy)trichlorotitanium(IV) (0.024mmol, 6.0 mg). The reaction was stirred at 65 ^{0}C for one week. Then acetonitrile was added to precipitate the product. Two days later, solvent was removed by filtration and the polymer was dried under vacuum. 0.17 g product was obtained. Yield: 15%. $[\alpha]_D$=2.64 (H_2O c=0.18). ^{1}H NMR (300MHz, $CDCl_3$) 0.91-1.26(br, s) 2.21(br, s) 2.36-2.85(br, s) 3.02-3.53(br, s) 3.98(br, w) 4.42(br, w) ^{13}C NMR (75MHz, $CDCl_3$) δ 19.32(br, m) 42.78(br, m) 44.87(w) 46.20(s) 53.41(w) 57.58(br, m) 58.71(w).

General procedure for the preparation of the ionic polycarbodiimides

Since the polycarbodiimides bear tertiary amino pendant groups, they can react with

alkylating reagents, such as methyl iodide, camphorsulfonic acid methyl ester and 2-tetrahydrofurfuryl bromide to give ionic polycarbodiimides. The following is the typical procedure for these reactions. Unless otherwise noted, the neutral polycarbodiimides were dissolved in chloroform and methylating reagents were added in one portion, the reactions were stirred for two days at room temperature. For the reaction of poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]s, the ionic polymers precipitated during the alkylation, so the products were collected through filtration. For the rest reactions, their products are soluble in chloroform, so they were worked up by being precipitated in ether. After being soaked for 1-2 days, ether was removed by filtration and polymers were dried under vacuum.

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide](S)-Me-CSA

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide] (0.26 g), (S)-camphorsulfonic acid methyl ester (2.83 mmol, 0.70 g) and chloroform (5.0 mL) were used to yield 0.65 g product. $[\alpha]_D$=13.64 (H_2O c=2.00). ^{1}H NMR (400MHz, $CDCl_3$) 0.78(br, s) 1.02(br, s) 1.37(br, w) 1.63(br, w) 1.72-2.16(br, s) 2.16-2.85(br, s) 2.85-4.40(br, s) ^{13}C NMR (100MHz, $CDCl_3$) δ 20.21(s) 24.91(br, m) 27.27(br, m) 43.25(br, s) 48.27(br, m) 54.21(br, s) 58.74 (br, w)

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide](R/S)-Me-CSA-(R-cat)

Poly[N,N'-Di(N,N-dimethylaminoethylene)carbodiimide]-**(**R-cat**)** (0.020 g), (R/S)-camphorsulfonic acid methyl ester (0.23 mmol, 0.057 g) and chloroform (1.0 mL) were used to yield 0.055 g product. $[\alpha]_D$=13.09 ($CHCl_3$ c=0.20) ^{1}H NMR (400MHz, $CDCl_3$) 0.75(br, s) 1.00(br, s) 1.41(br, w) 1.63(br, w) 1.70-2.19(br, s) 2.19-2.91(br, s) 2.91-4.60(br, s)

^{13}C NMR (100MHz, $CDCl_3$) δ 20.08(s) 25.03(br, m) 27.08(br, m) 42.73(br, s) 47.00(br, s) 54.24(br, s) 58.64 (br, w)

Poly[N,N'-di(3-N,N-dimethylaminopropyl)carbodiimide](S)-Me-CSA

Poly[N,N'-di(3-N,N-dimethylaminopropyl)carbodiimide] (0.50 g), (S)-camphorsulfonic acid methyl ester (4.76 mmol, 1.17 g) and chloroform (3.0 mL) were used to yield 0.85 g product. $[\alpha]_D$=20.67 (H_2O c=2.00) ^{1}H NMR (400MHz, $CDCl_3$) 0.77(br, s) 1.00(br, s) 1.36(br, w) 1.58(br, m) 1.84(br, s) 1.97(br, s) 2.23(br, s) 2.50(br, s) 2.83-4.19(br, s) 4.19-4.69(br, s) ^{13}C NMR (100MHz, $CDCl_3$) δ 20.00(s) 25.04(br, m) 27.08(br, m) 42.95(br, s) 48.16(br, m) 53.77(br, s) 58.61(m) 62.49(br, w).

Poly[N,N'-di(3-N,N-dimethylaminopropyl)carbodiimide](R/S)-Me-CSA-(R-cat)

Poly[N,N'-di(3-N,N-diimethylaminopropyl)carbodiimide]-(R-cat) (0.20 g), (R/S)-camphorsulfonic acid methyl ester (1.87 mmol, 0.46 g) and chloroform (3.0 mL) were used to yield 0.22 g product. $[\alpha]_D$=25.24 ($CHCl_3$ c=0.20) ^{1}H NMR (300MHz, $CDCl_3$) 0.79(br, s) 1.02(br, s) 1.42(br, w) 1.50-2.12(br, s) 2.12-2.90(br, s) 2.90-5.20(br, s) ^{13}C NMR (75MHz, $CDCl_3$) δ 20.11(m) 25.22(br, w) 27.22(br, w) 42.84(br, m) 54.71(br, m) 61.13(br, w) 66.97(br, m) 149.20(br, w).

Poly[N,N'-di(2-morpholinoethyl)carbodiimide](S)-Me-CSA

Poly[N,N'-di(2-morpholinoethyl)carbodiimide] (0.14 g), (S)-camphorsulfonic acid methyl ester (1.03 mmol, 0.25 g) and chloroform (5.0 mL) were used to yield 0.16 g product. $[\alpha]_D$=1.32 (H_2O c=2.00) ^{1}H NMR (300MHz, $CDCl_3$) 0.80(br, m) 1.03(br, m) 1.38(br, w) 1.67(br, w) 2.04(br, m) 2.11-2.86(br, s) 3.14(br, w) 3.26-4.40(br, s) ^{13}C NMR (75MHz, $CDCl_3$) δ 20.14(w) 26.00(br, w) 42.85(br, w) 54.75(br, s) 58.70(br, w) 60.49(br, w)

67.05(br, s) 148.50(br, w).

Poly[N,N'-di(2-morpholinoethyl)carbodiimide](R/S)-Me-CSA-(R-cat)

Poly[N,N'-di(2-morpholinoethyl)carbodiimide]-(R-cat) (0.11 g), (R/S)-camphorsulfonic acid methyl ester (0.81 mmol, 0.20 g) and chloroform (2.0 mL) were used to yield 182 mg product. $[\alpha]_D$=24.47 ($CHCl_3$ c=0.22) ^{1}H NMR (300MHz, $CDCl_3$) 0.80(br, m) 1.04(br, m) 1.36(br, w) 1.48-3.05(br, s) 3.13(br, w) 3.26-4.60(br, s) ^{13}C NMR (75MHz, $CDCl_3$) δ 20.15(w) 24.90(br, w) 27.30(br, w) 43.33(br, w) 54.74(br, s) 58.71(br, w) 61.12(br, w) 67.05(br, s) 148.43(br, w).

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide](S)-Me-CSA

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide] (0.84 g), (S)-camphorsulfonic acid methyl ester (3.31 mmol, 0.81 g) and chloroform (5.0 mL) were used to yield 0.84 g product. $[\alpha]_D$=13.09 (H_2O c=2.00) ^{1}H NMR (300MHz, $CDCl_3$) 0.77(br, s) 1.03(br, s) 1.33(br, m) 1.58(br, m) 1.79(br, m) 1.85(br, m) 1.98(br, s) 2.20(br, m) 2.26(br, m) 2.61(br, s) 3.09(br, m) 3.34(br, s) 3.47(br, m) 3.83(br, m) 4.02(br, m). ^{13}C NMR (75MHz, $CDCl_3$) δ 20.33(s) 24.88(m) 27.38(w) 42.95(br, m) 47.69(m) 48.12(m) 53.86(m) 54.44(s) 58.77(s) 65.24(br, m) 149.35(br, w).

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide](R/S)-Me-CSA-(R-cat)

Poly[N,N'-di((2-N,N-dimethylaminoethoxyl)ethyl)carbodiimide]-(R-cat) **(**0.14 g**),** (R/S)-camphorsulfonic acid methyl ester (1.03 mmol, 0.25 mg) and chloroform (2.0 mL) were used to yield 0.15 g product. $[\alpha]_D$=9.97 ($CHCl_3$ c=0.21) ^{1}H NMR (300MHz, $CDCl_3$) 0.78(br, s) 1.03(br, s) 1.35(br, m) 1.60(br, m) 1.81(br, m) 1.87(br, m) 1.99(br, s) 2.21(br, m) 2.27(br, m) 2.59(br, s) 3.10(br, m) 3.32(br, s) 3.51(br, s) 3.82(br, m) 4.01(br, m). ^{13}C NMR

(75MHz, $CDCl_3$) δ 20.23(s) 24.88(m) 27.36(w) 43.18(m) 47.68(br, m) 53.99(br, s) 58.75(s) 65.49(br, m) 149.22(br, w).

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]MeI-(R-cat)

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(R-cat) (0.20 g), methyl iodide (2.19 mmol, 0.14 mL) and chloroform (3.0 mL) were used to yield 0.25 g product. $[\alpha]_D$=387.27 (DMF c=0.20) ^{1}H NMR (300MHz, D_2O) 2.75(br, m) 3.14(br, s) 3.24-4.40(br, s) 6.20-7.36(br, m) ^{13}C NMR (75MHz, D_2O) δ 44.40(br, s) 51.88(br, s) 58.75(br, m) 61.60(br, m) 122.20(br, w). Anal Calcd. For $C_{16}H_{25}ON_4I$: I, 29.58%. Found I, 28.52%.

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]MeI-(S-cat)

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(S-cat) (0.040 g), methyl iodide (0.44 mmol, 27.0 μL) and chloroform (0.5 mL) were used to yield 0.066 g product. $[\alpha]_D$=-384.39 (DMF c=0.13) ^{1}H NMR (400MHz, D_2O) 2.75(br, m) 3.10(br, s) 3.39(br, m) 3.46(br, m) 6.69-7.20(br, m) ^{13}C NMR (100MHz, D_2O) δ 44.02 (br, s) 51.69(br, s) 58.50(br, m) 61.30(br, m). Anal Calcd. For $C_{16}H_{25}ON_4I$: I, 29.58%. Found I, 28.73%.

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide](S)-Me-CSA-(R-cat)

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(R-cat) (0.20 g), (S)-camphorsulfonic acid methyl ester (1.46 mmol, 0.36 g) and chloroform (3.0 mL) were used to yield 0.36 g product. $[\alpha]_D$=236.52 (DMF c=0.20) ^{1}H NMR (300MHz, D_2O) 0.57(s) 0.82(s) 1.17 (br, m) 1.44(br, m) 1.69(w) 1.75(br, m) 1.86(br, m) 2.05-2.36(br, m) 2.61(m)

2.66(m) 3.06(br, s) 3.11(br, s) 2.50-3.70(br, m) 6.75-7.10(br, m) ^{13}C NMR (75MHz, D_2O) δ 19.08(s) 24.63(m) 26.42(m) 42.33(s) 42.67(s) 44.00(br, s) 47.18(s) 48.17(s) 51.40(br, m) 58.20(br, s) 58.52(m) 61.30(br, m).

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide](R)-Me-CSA-(R-cat)

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(R-cat) (0.20 g), (R)-camphorsulfonic acid methyl ester (1.46 mmol, 0.36 g) and chloroform (3.0 mL) were used to yield 0.33 g product. $[\alpha]_D$=209.51 (DMF c=0.20) ^{1}H NMR (400MHz, D_2O) 0.54(s) 0.79(s) 1.14 (br, m) 1.40(br, m) 1.67(w) 1.72(br, m) 1.84(br, m) 2.05-2.30(br, m) 2.56(m) 2.59(m) 3.03(s) 3.07(s) 2.40-3.60(br, m) 6.73-7.12(br, m) ^{13}C NMR (100MHz, D_2O) δ 19.07(s) 24.63(m) 26.42(m) 42.32(s) 42.67(s) 44.00(br, s) 47.18(s) 48.17(s) 51.41(br, m) 58.20(br, s) 58.52(m) 61.46(br, m).

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide](R/S)-Me-CSA-(R-cat)

Poly[N-methoxyethylene-N'-4-(4-methylpiperizino)phenylcarbodiimide]-(R-cat) (0.16 g), (R/S)-camphorsulfonic acid methyl ester (1.17 mmol, 0.29 g) and chloroform (2.0 mL) were used to yield 0.22 g product. $[\alpha]_D$=248.29 (DMF c=0.20) ^{1}H NMR (300MHz, D_2O) 0.58(s) 0.83(s) 1.18 (br, m) 1.45(br, m) 1.70(w) 1.76(br, m) 1.87(br, m) 2.10-2.35(br, m) 2.62(m) 2.67(m) 3.07(br, s) 3.12(br, s) 2.70-3.80(br, m) 6.75-7.15(br, m) ^{13}C NMR (75MHz, D_2O) δ 19.36(s) 24.89(s) 26.65(s) 42.56(s) 42.87(s) 44.30(br, s) 47.38(s) 48.32(s) 51.62(m) 58.20(br, m) 58.72(m) 60.90(br, m) 117.70(br, w) 123.00(br, w).

Poly[N-(N,N-dimethylaminoethylene)-N'-((S)-1-methoxy-2-propyl) carbodiimide]MeI

Methyl iodide (8.64 mmol, 0.54 mL) and methanol (3.0 mL) were added to a vial charged with Poly[N-(N,N-dimethylaminoethylene)-N'-((S)-1-methoxy-2-propyl) carbodiimide] (0.80 g). The reaction was stirred for two days. Then the polymer was precipitated in acetone and dried under vacuum to yield 0.96 g product. $[\alpha]_D$=5.80 (DMF c=1.00) ^{1}H NMR (300MHz, DMSO, D6) 0.80-1.30(br, w) 2.22(br, m) 3.35(br, s) 3.03-3.60(br, s) ^{13}C NMR (75MHz, DMSO, D6) δ 19.51(br, w) 45.44(br, s) 54.32(br, s) 59.00(br, w) 78.10(br, w).

Poly[N,N'-di(N,N-dimethylaminoethylene)carbodiimide]THFFBr-(R-cat)

Poly[N,N'-di(N,N-dimethylaminoethylene)carbodiimide]-(R-cat) (0.15 g), 2-tetrahydrofurfuryl bromide (1.96 mmol, 0.25 mL) and chloroform (2.0 mL) were used to yield 0.095 g product. $[\alpha]_D$=36.93 ($CHCl_3$ c=0.20) ^{1}H NMR (400MHz, $CDCl_3$) 2.21(br, s) 2.49(br, m) 2.99(br, w) 3.10-3.93(br, m) 4.31(br, w) ^{13}C NMR (100MHz, $CDCl_3$) δ 46.21(br, s) 58.78(br, w) 61.33(br, w) 147.90(br, w).

Poly[N,N'-di(2-morpholinoethyl)carbodiimide]THFFBr-(R-cat)

Poly[N,N'-di(2-morpholinoethyl)carbodiimide]-(R-cat) (0.15 g), 2-tetrahydrofurfuryl bromide (1.34 mmol, 0.17 mL) and chloroform (2.0 mL) were used to yield 0.046 g product. $[\alpha]_D$=3.98 ($CHCl_3$ c=0.20) ^{1}H NMR (400MHz, $CDCl_3$) 1.64(br, m) 2.17(br, s) 3.08(br, w) 3.29(br, w) 3.75(br, w) ^{13}C NMR (100MHz, $CDCl_3$) δ 27.88(br, w) 30.12(br, m) 45.84(br, s) 47.12(br, w) 57.77(br, w) 58.70(br, m) 147.83(br, w).

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