

Figure 3: TEM micrographs of samples of 4 wt% PS2M in *r*-BMA. a) film sample quenched to -80°C, b) bulk sample quenched to -40°C.

Good luck with your research

DESIGN, PREPARATION, AND CHARACTERIZATION OF HYDROGEN BONDED SUPRAMOLECULAR AGGREGATES BASED ON THE CYANURIC ACID-MELAMINE LATTICE

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Abstract: Molecular self-assembly is described as a strategy for synthesizing large hydrogen-bonded supramolecular aggregates that are based on the planar lattice formed of equimolar portions of cyanuric acid and melamine. The aggregates described in this paper contain four to ten individual molecules, and have molecular networks of 18 to 54 hydrogen bonds, and have molecular weights in the range 2.7 to 6.5 kDa. Each of these aggregates has been characterized using ¹H NMR, spectroscopy, gel permeation chromatography, and vapor pressure osmometry. Physical-organic chemistry is used to (i) improve our criteria for the design of self-assembling structures and (ii) develop techniques for characterizing non-covalently bound aggregates in organic solution.

INTRODUCTION

Molecular self-assembly is the spontaneous association of molecules under equilibrium conditions into stable, structurally well-defined aggregates in which the individual components are joined by networks of non-covalent bonds (Ref. 1). In this paper, we present the design, preparation, and characterization of a series of self-assembling supramolecular aggregates. These structures are based on the planar triad hydrogen bonded motifs that are believed to characterize the lattice (CA-M) (Fig. 1) formed between equimolar proportions of cyanuric acid (CA) and melamine (M). The strategy we have adopted for the formation of hydrogen-bonded supramolecular aggregates in organic solution is based on the synthesis of discrete, soluble portions of this hydrogen-bonded CA-M lattice. The motif we have used as a template around which to build self-assembling structures is the cyclic CA₃M₃ unit (bold) that characterizes this lattice. The CA-M lattice fulfills two

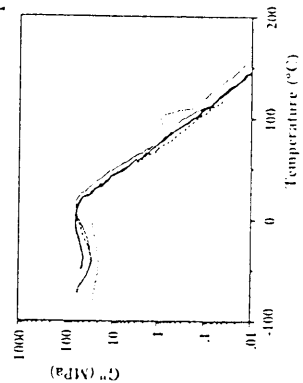


Figure 4: Mechanical loss spectra of semi-IPN's with 4 wt% PS2M in 2-ethylhexylmethacrylate. Morphologies depicted in figure 2. a) pure poly-cross-EHMA b) as fig. 2a and 2b c) as fig. 2c d) as fig. 2d

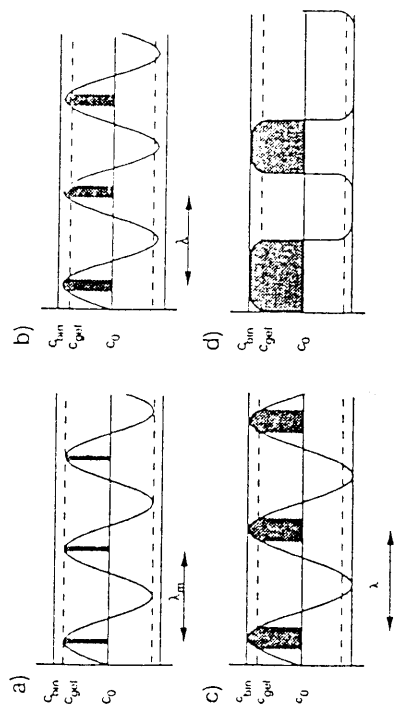


Figure 5: Schematic representation of the development of concentration fluctuations during spinodal demixing. a)-d) structure depicted in figs. 2a-2d respectively.

key requirements to serve as the basis of self-assembling structures. First, the cyclic CA_3M_3 unit is a highly symmetrical motif. This factor aids in the design and characterization of these supramolecular aggregates, especially

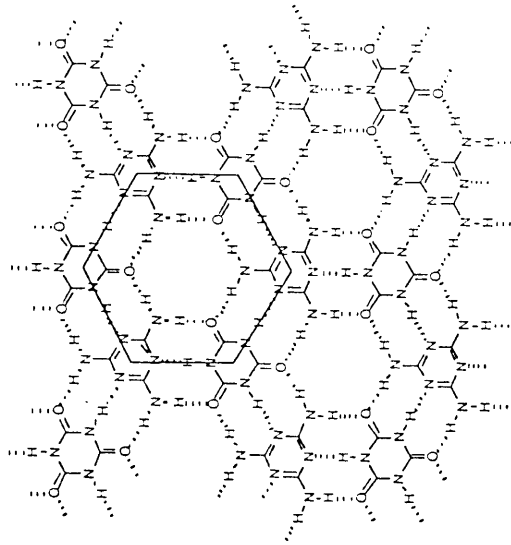


Fig. 1. The hydrogen-bonded CA-M lattice we are using as a conceptual template for the design of self-assembled supramolecular aggregates.

by NMR spectroscopy. Second, the high density of hydrogen bonds in CA-M provides a strong enthalpic driving force for self-assembly.

A major intellectual impetus for the development of self-assembly as a technique in organic chemistry is the range of self-assembled structures found in living organisms (Ref. 2). Examples of these structures include (i) telomers, whose structures are stabilized by stacked, cyclic hydrogen bond networks between G residues (Ref. 3), and (ii) fRNA molecules, whose structures are dictated by series of hydrogen bonds between A:U and G:C residues (Ref. 4).

We are using physical-organic chemistry to study a series of hydrogen bonded supramolecular aggregates that are based on networks of hydrogen bonds and to examine issues crucial to the application of self-assembly as a strategy for synthesis in organic chemistry. These issues include:

1. Considerations in Design. Preorganization of constituent molecules has

emerged as a key consideration in the design of self-assembling structures. We wish to determine where the balance lies between the rigidity and flexibility of constituent molecules, the ease of their synthesis, and the stabilities of complexes derived from them.

2. Techniques for Characterization. The characterization of large molecular structures is difficult. We wish to identify and exploit the analytical methods that provide the most useful data for the characterization of non-covalently bound supramolecular aggregates in organic solution.
3. An Understanding of Thermodynamics. Enthalpy forms the thermodynamic basis of synthesis using covalent bonds. As a consequence, the intuition of chemists concerning structure, enthalpy, and stability is strong. The corresponding intuition regarding the relations involving entropy is significantly weaker. In self-assembly, understanding the interplay between enthalpy and entropy is a central feature in the design of structures. We wish to understand this interplay in sufficient detail to be able to predict the stabilities of new supramolecular aggregates.

RESULTS AND DISCUSSION

Mixing equimolar portions of most isocyanurates and melamines in chloroform at room temperature results in their association to form random oligomers, with no evidence for the existence of a stable cyclic CA_3M_3 unit in solution. We have, therefore, used a hub and spoke architecture to preorganize the melamine particles for self-assembly with the isocyanurate moieties into the desired supramolecular aggregates (Refs. 5-9). This feature reduces the unfavorable entropy of translation associated with the association of multiple particles into a single aggregate. The design of the spoke was also conceived to minimize the effects of freezing rotations about flexible bonds on complexation (*i.e.* minimizing losses in conformational entropy on assembly). The self-assembly of three types of supramolecular aggregates based on this approach is shown in Fig. 2. The trimelamine derivative $hubM_3$ self-assembles with three equivalents of $neohex(CA)$ $neohexylisocyanurate$ to form aggregates of type A [$hub(M)_3:3neohex(CA)$] (Refs. 5,7). The solubility of $neohexylisocyanurate$ in chloroform is low (<0.5 mM). On complexation with $hub(M)_3$, the $neohexylisocyanurate$ dissolves. The ability of one equivalent of $hub(M)_3$ to solubilize three equivalents of $neohexylisocyanurate$ provides qualitative evidence for the stoichiometry of the resulting supramolecular aggregate. The hexamelamine derivative $hub(MM)_3$ forms aggregates of type B [$hub(MM)_3:6neohex(CA)$] with six equivalents of $neohexylisocyanurate$ that are based on two adjacent layers

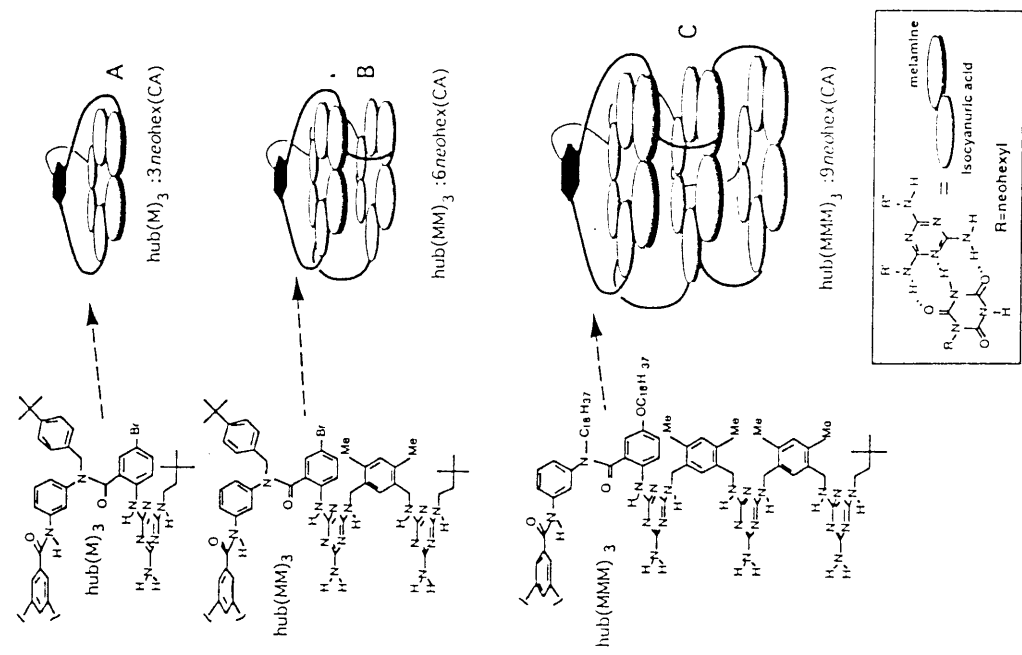


Fig. 2. Structures of the hydrogen-bonded self-assembled aggregates.

of the cyclic C₃M₃ unit. This series is completed by the nonamelamine derivative hub(MMM)₃ which undergoes self-assembly with nine equivalents of neoHexylisocyanurate to give a ten-particle aggregate of type C [hub(MMM)₃:9neoHex(CA)] that is stabilized by 54 hydrogen bonds in three adjacent layers of the CA-M lattice.

These supramolecular aggregates have been characterized by ¹H NMR spectroscopy in CDCl₃ (to probe the local structure of the aggregates), gel permeation chromatography in CH₂Cl₂/CHCl₃ (to assess the global structures and relative sizes of the aggregates), and vapor pressure osmometry (to obtain molecular weights for the aggregates in chloroform solution).

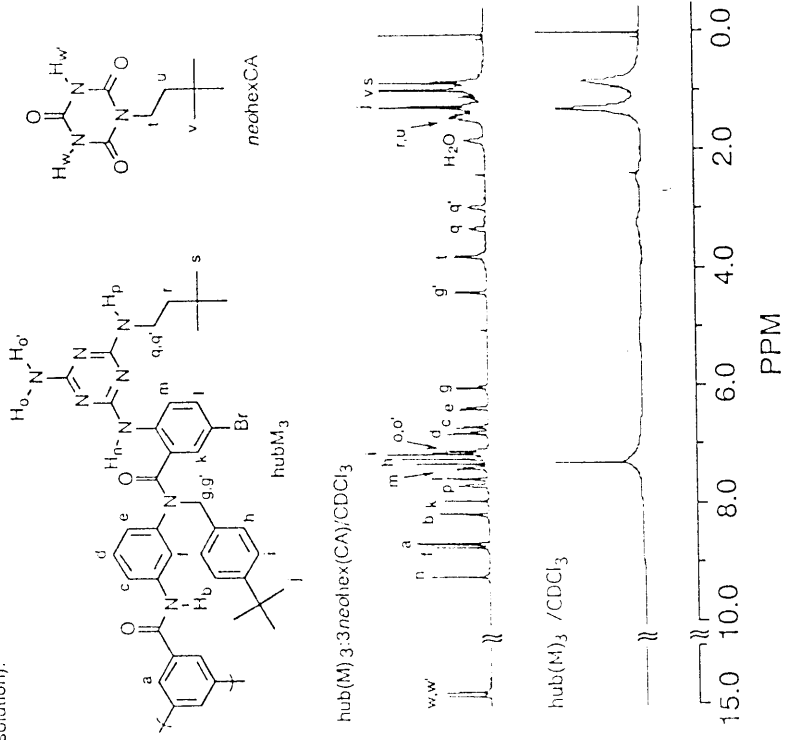


Fig. 3. Changes in the ¹H NMR spectra on formation of hub(M)₃:3neoHex(CA).

The changes in the ^1H NMR spectrum on going from uncomplexed $\text{hub}(\text{M})_3$ (bottom) to the self-assembled aggregate $\text{hub}(\text{M})_3\cdot 3\text{neohex}(\text{CA})$ are illustrated in Fig. 3 (Refs. 5,7). Free $\text{hub}(\text{M})_3$ gives a broad, featureless spectrum in CDCl_3 as a consequence of self-association in solution and hindered rotation about its many amide bonds. In contrast, the aggregate $\text{hub}(\text{M})_3\cdot 3\text{neohex}(\text{CA})$ gives a sharp spectrum in CDCl_3 which can be assigned completely to the single supramolecular aggregate as shown. This sharpening in the ^1H NMR spectra indicates a significant increase in the order of the structure on formation of the rigid, well-defined supramolecular aggregate from its individual components.

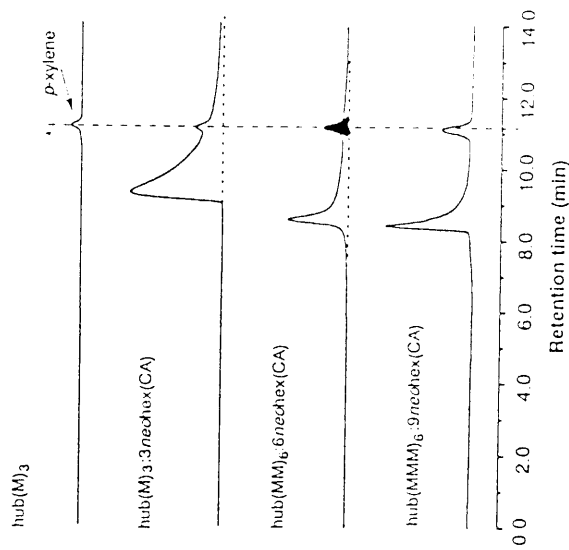


Fig. 4. GPC traces of supramolecular aggregates with CH_2Cl_2 . *Pure*-xylene functions as an internal standard.

Gel permeation chromatography (GPC) allows us to assess the degree of homogeneity of these aggregates and obtain a qualitative idea of their size, relative to each other and a series of polystyrene standards. The separation in GPC does not rely on any competitive adsorption processes and this

technique is, therefore, ideal for the analysis of non-covalently bound aggregates. Fig. 4 shows GPC traces (eluted with CH_2Cl_2) for uncomplexed $\text{hub}(\text{M})_3$, $\text{hub}(\text{M})_3\cdot 3\text{neohex}(\text{CA})$, $\text{hub}(\text{MM})_6\cdot 6\text{neohex}(\text{CA})$, and $\text{hub}(\text{MMM})_9\cdot 9\text{neohex}(\text{CA})$. The traces for the aggregates show a progression from a peak that is associated with a significant degree of tailing for $\text{hub}(\text{M})_3\cdot 3\text{neohex}(\text{CA})$ to one in which the degree of tailing is substantially reduced for $\text{hub}(\text{MMM})_9\cdot 9\text{neohex}(\text{CA})$. We believe that the tailing in these GPC traces indicates that disassembly of the aggregates is occurring during the GPC analysis, resulting in the elution of a population of smaller structures along with the initial aggregate (Refs. 5,8). The decrease in tailing from $\text{hub}(\text{M})_3\cdot 3\text{neohex}(\text{CA})$ to $\text{hub}(\text{MMM})_9\cdot 9\text{neohex}(\text{CA})$ suggests an increase in kinetic stability on this progression.

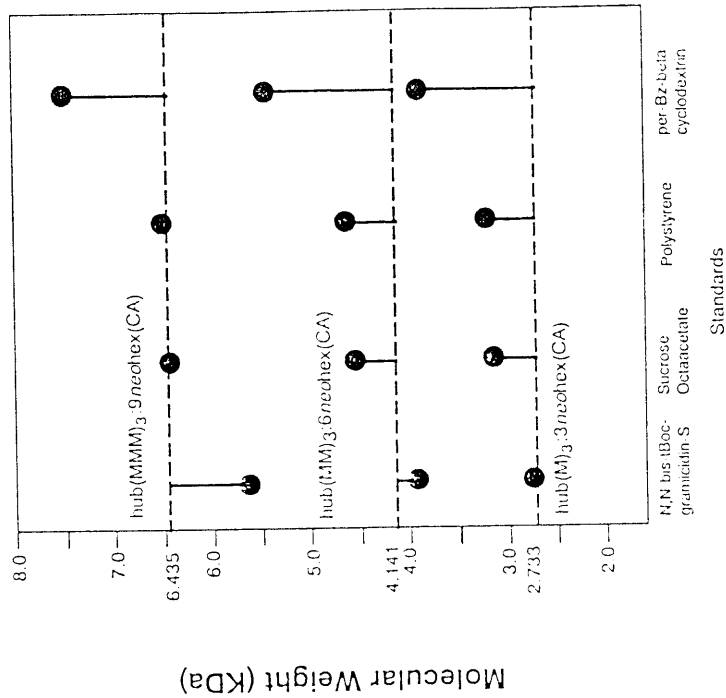


Fig. 5. Experimental molecular weights of aggregates determined by VPO, using four different molecular weight standards.

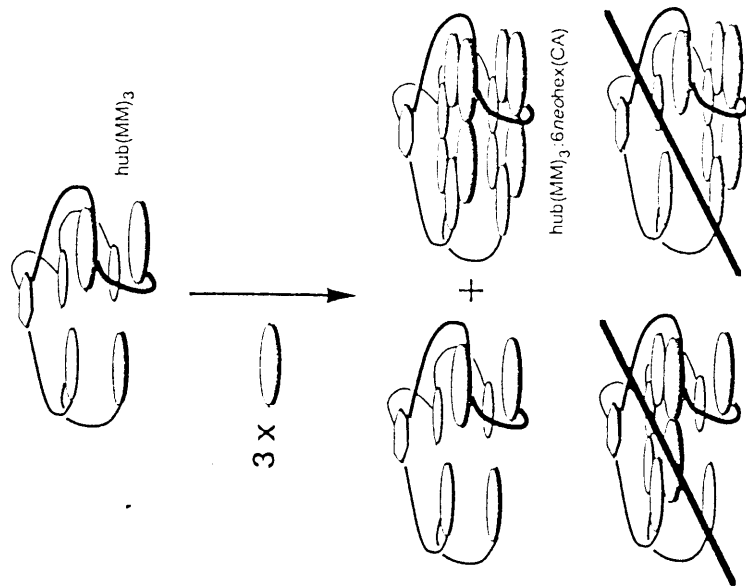


Fig. 6. Operation of positive cooperativity in the formation of $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$.

$\text{hub}(\text{MMM})_3:9\text{neoex}(\text{CA})$. These observations suggest that structures that are based on multiple layer self-assembling motifs will be a stable series of hydrogen-bonded supramolecular aggregates. We are now in a position to (i) assess critically our criteria for design; (ii) apply molecular modeling to assist our design and to correlate structural information; (iii) prepare structures with increasing stabilities, and consequently; (iv) prepare structures of increasing size. These fundamental demonstrations of the ability to position molecules within aggregates with a high degree of precision offer rich possibilities for the preparation of functioning.

The third technique we are using to characterize these hydrogen-bonded aggregates is vapor pressure osmometry (VPO). The data obtained for the molecular weights of the three self-assembled aggregates $\text{hub}(\text{M})_3:3\text{neoex}(\text{CA})$, $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$, and $\text{hub}(\text{MMM})_3:9\text{neoex}(\text{CA})$ in CHCl_3 solution VPO is illustrated in Fig. 5. In each case, correlation of the data from solution was made against four independent standards of known molecular weight [N,N'-bis(Boc-gramicidin-S (MW 1342), sucrose octaacetate (MW 679), polystyrene (MW 5050), and perbenzoyl b-cyclodextrin (MW 3321)]. This procedure reduces the effects of non-ideal behavior by both the aggregates and the standard and, therefore, provides a stronger basis with which to interpret the data from VPO. The observed molecular weights for $\text{hub}(\text{M})_3:3\text{neoex}(\text{CA})$ [calc. 2733], $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$ [calc. 4141], and $\text{hub}(\text{MMM})_3:9\text{neoex}(\text{CA})$ [calc. 6435] in solution are within 15% of the calculated molecular weights. This level of agreement is close to that obtained for many of these self-assembled aggregates by VPO.

In the progression from $\text{hub}(\text{M})_3:3\text{neoex}(\text{CA})$ to $\text{hub}(\text{MM})_3:9\text{neoex}(\text{CA})$ we have been able to demonstrate the operation of positive cooperativity in the formation of these multilayer aggregates. Addition of only three equivalents of $\text{neoex}(\text{CA})$ to a single equivalent of $\text{hub}(\text{MM})_3$ leads to formation of only the complete $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$ aggregate (Fig. 6). The excess $\text{hub}(\text{MM})_3$ remains uncomplexed. Unlike the self-assembly of $\text{hub}(\text{M})_3:3\text{neoex}(\text{CA})$, the assembly of $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$ could generate other aggregates (shown in Fig. 6-bottom) that we would expect to have well-defined structures. We should, therefore, be able to detect these intermediates by ^1H NMR if they were present in solution. The absence of intermediates along the assembly pathway suggests strongly that the assembly of $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$ displays positive cooperativity. This trend is repeated in the self-assembly of the triple layer aggregate $\text{hub}(\text{MMM})_3:9\text{neoex}(\text{CA})$.

CONCLUSIONS

The preparation and characterization of these three types of supramolecular aggregates demonstrates the increased versatility of CA-M as a basis for the design of stable, self-assembling hydrogen-bonded structures. These molecules are characterized by 18-54 hydrogen bonds, 4-10 constituent pieces, molecular weights in the range 2.7-6.5 kDa, various levels of preorganization, and a range of stabilities. We have illustrated the operation of positive cooperativity in the formation of $\text{hub}(\text{MM})_3:6\text{neoex}(\text{CA})$ and

nanostuctures, using a bottom-up principle rather than the process of continuing miniaturization that is being used currently in the techniques of microfabrication.

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SUPRAMOLECULAR MEMBRANES FOR OPTICAL RESOLUTIONS AND MOLECULAR RECOGNITIONS

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Abstract: Poly(L-glutamate) having amphiphilic side chains was designed as membrane materials for optical resolution of α -amino acids. Solvent-cast films of the poly(L-glutamate) had a self-ordered structure containing α -helix of the poly(L-glutamate). Optical resolutions of various amino acids were carried out through the thin membranes of the amphiphilic poly(L-glutamate).

Racemic mixtures of Tryptophan were completely separated through the membrane. Mechanism of the optical resolutions was investigated in terms of molecular recognitions of racemic Tryptophan by the ordered structure of the membrane.

INTRODUCTION

Membrane separation processes have marked advantages in industrial applications because of ease of handling, instrumental simplicity and efficiency in energy as compared to chromatographic separation process. However, an ideal membrane which can separate optical isomers has not yet appeared except in a form of liquid membrane.

Normally, optical isomers have the same chemical and physical properties so that the separation of these optical isomers is very difficult by conventional separation methods such as distillation or recrystallization. The permeation of substrates through a membrane is determined by partitioning behaviors of the permeating substrate with respect to the membrane and by their diffusibilities or mobilities in the membrane. However, the complete optical resolution requires another factor, that is, molecular recognition which can distinguish one isomer from another isomer. Thus, for improving the enantioselectivity of the membrane, considerable efforts should be made to optimize the combination of these factors.

Poly(α -amino acids) are known to form a stable helical structure which is either right-hand or left-hand helixoids based on enantiometric structures of α -amino acids. It is strongly expected that the helical structure of poly(α -amino acids) may have a good enantioselectivity owing to some stereospecific interactions.

According to these concept, poly(L-glutamate) derivatives having amphiphilic side chains of hydrophilic and hydrophobic groups were designed as membrane materials. Following structure was selected for the membrane materials:¹⁾