

# Circular dichroism and exciton effect of syndiotactic methacrylic polymers with chiral diacyl hydrazide side chains:

## 3. Poly[methacrylic acid- $N^\beta$ (L-seryl)hydrazide] and poly[methacrylic acid- $N^\beta$ (L-alanyl)hydrazide] and their *N*-*t*-butyloxycarbonyl protected derivatives\*

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The phenomenon of exciton coupling, which is very well known from circular dichroism (c.d.) spectroscopy studies of biopolymers, has now also been found for syndiotactic vinyl polymers in solution. The syndiotactic polymers were prepared by reacting poly(methacrylic acid hydrazide) with the *N*-protected amino acids L-(+)-serine and L-(+)-alanine, yielding poly[methacrylic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)L-seryl)hydrazide] and poly[methacrylic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)L-alanyl)hydrazide]. On removal of the *N*-*t*-butyloxycarbonyl group, the corresponding deprotected polymers were also obtained. All four polymers possess functional and optically active lateral chains which are capable of mutual interactions by hydrogen bonding, dipolar and electrostatic forces. At strongly alkaline pH, the diacyl hydrazide moiety is deprotonated to confer polyelectrolyte character to the macromolecule. The interactions between lateral chains lead in the deprotonated state to spatial and conformational order between the side chains, causing sizeable excitation effects in the c.d. spectra. The presence of exciton effects was supported by the c.d. spectroscopic behaviour of the polymers at different pH and by that of copolymers, the latter being obtained by different degrees of conversion of the poly(methacrylic acid hydrazide). The degree of order is strongly influenced by changing temperature and the addition of methanol and salts. By comparison with previously studied polymers derived from syndiotactic poly(methacrylic acid hydrazide) and L-(+)-lactic acid or D-(-)-lactic acid, the structural features necessary for exciton coupling are discussed. A model for the main-chain conformation which was proposed earlier was found to be compatible also with the results obtained for the present polymers.

**(Keywords: tactic vinyl polymers; circular dichroism; exciton effect; conformational order)**

### INTRODUCTION

Few attempts have been undertaken up to now to utilize a tactic polymer chain with functional lateral chains, capable of hydrogen bonding and other interactions, to obtain conformational order in a polymer<sup>1</sup>. One example relates to the circular dichroism (c.d.) study of isotactic poly(alkyl vinyl ether) down to 140 nm. No ordered conformation was found, however<sup>2</sup>. Moreover, exciton effects are rarely observed in the c.d. spectra of synthetic polymers<sup>3</sup>. In one additional instance, where polyethyleneimine with optically active, thymine-containing pendants had been prepared, an exciton effect caused by stacking of thymine rings was postulated<sup>4</sup>.

In our previous work<sup>3,5</sup> syndiotactic poly(methacrylic acid hydrazide) (s-PMH) has been condensed with L-(+)-

lactic acid to yield syndiotactic poly[methacrylic acid- $N^\beta$ (L-lactoyl)hydrazide]. This polymer was found to be capable of assuming conformational order in aqueous solutions over a wide range of pH. Different conformations existed under neutral and acidic conditions from those in alkaline conditions. The c.d. spectra showed very strong Cotton effects and sizeable exciton effects which were interpreted as a manifestation of conformational order.

The approach of linking a highly functional, optically pure and conformationally restricted lateral moiety to a highly tactic backbone, for the purpose of inducing conformational order in the polymer in solution, has been continued in the present work. To this end, the simple amino acids L-(+)-alanine and L-(+)-serine in their *N*-*t*-butyloxycarbonyl (Boc) protected form were condensed with s-PMH. By consecutively removing the Boc group in the two polymers, four different polymers in all were obtained whose conformational behaviour was studied by c.d., u.v. and potentiometry.

\* Dedicated to Professor Dr H. J. Cantow on the occasion of his 65th birthday

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## EXPERIMENTAL

## Materials

*Syndiotactic poly(methacrylic acid hydrazide) (s-PMH).* This was prepared by hydrazinolysis of syndiotactic poly(methyl methacrylate) (s-PMMA) of  $M_n = 160\,000 \pm 10\,000$ , containing 92% syndiotactic triads<sup>6,7</sup>.

*Syndiotactic poly[methacrylic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)-*L*-seryl)hydrazide] (L-s-PMHBocS).* To a solution of 200 mg (2 mmol) s-PMH in 20 ml H<sub>2</sub>O are added 710 mg (4 mmol) *N*-Boc-*L*-serine dissolved in 10 ml H<sub>2</sub>O. The mixture is cooled to 0°C under N<sub>2</sub> and 770 mg (4 mmol) *N*-ethyl-*N'*(3-dimethylaminopropyl)carbodiimide hydrochloride (EAPC) is added as a powder. After 2 h at 0°C under N<sub>2</sub> with stirring, the polymer is precipitated in a mixture of methanol and diethyl ether (2:1 v/v). If the s-PMH is of higher molecular weight, or if the solution is more concentrated, the polymer may precipitate during preparation. After redissolving in H<sub>2</sub>O, reprecipitating in acetone and drying at room temperature *in vacuo*, a yield of about 50% is obtained.

*Syndiotactic poly[methacrylic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)-*L*-alanyl)hydrazide] (L-s-PMHBocA).* To 1.13 g (6 mmol) *N*-Boc-*L*-alanine dissolved in a mixture of H<sub>2</sub>O and dioxane (2:1 v/v) are added 423 mg (4.23 mmol) s-PMH dissolved in 20 ml H<sub>2</sub>O. It is cooled to 3–4°C under N<sub>2</sub> and 1.38 g (7.2 mmol) EAPC in 2 ml H<sub>2</sub>O added. After 1 h at this temperature with stirring, the precipitated polymer is separated by centrifugation and decantation. For purification, the polymer is suspended in water, stirred overnight, filtered, dissolved in dimethylsulphoxide (DMSO) and reprecipitated by adding the solution dropwise to H<sub>2</sub>O. After another reprecipitation and drying at room temperature *in vacuo*, a yield of about 70% is obtained.

*Cosyndiotactic (methacrylic acid hydrazide)-*s*-co-[methacrylic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)-*L*-seryl)hydrazide] copolymers ((MH)-*s*-co-(L-MHBocS)).* The procedure for preparing the homopolymer is followed, except that the amounts of both *N*-Boc-*L*-serine and EAPC are reduced evenly to the extent required for the desired copolymer composition.

*Pivalic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)-*L*-seryl)hydrazide (L-PivHBocS).* To a solution of 200 mg (1.75 mmol) pivalic acid hydrazide in 5 ml tetrahydrofuran (THF) are added 410 mg (2 mmol) *N*-Boc-*L*-serine in 10 ml THF and 600 mg (3 mmol) dicyclohexylcarbodiimide (DCC) in 10 ml THF. It is left stirring for 2 days at room temperature. The precipitated dicyclohexylurea is removed and the solution evaporated to dryness *in vacuo*. The residue is dissolved in 50 ml diethyl ether and extracted twice with 30 ml each of H<sub>2</sub>O. The combined water extracts are evaporated *in vacuo* to yield a syrupy residue. The product is crystallized from a mixture of ethyl acetate/*n*-hexane at room temperature to a yield of 60%.

*Pivalic acid- $N^\beta$ (*N*(*t*-butyloxycarbonyl)-*L*-alanyl)hydrazide (L-PivHBocA).* To a solution of 490 mg (2.6 mmol) *N*-Boc-*L*-alanine in dioxane/H<sub>2</sub>O (1:4 v/v) an aqueous solution of 300 mg (2.6 mmol) pivalic acid hydrazide is added slowly. Then 1 g (5.2 mmol) EAPC is

added and left stirring for 24 h at room temperature. The product precipitates quantitatively. It is filtered, washed with H<sub>2</sub>O and dried *in vacuo* at room temperature.

## Methods

Removal of the *N*-protecting Boc group from the homopolymers, copolymers and model compounds yields free  $\alpha$ -NH<sub>2</sub> groups. The deprotection may be carried out by a solution of HBr in glacial acetic acid<sup>8</sup>. The polymers are consecutively precipitated as the hydrobromides in a mixture of methanol and diethyl ether. Because Cl<sup>-</sup> shows less of u.v. absorption above 190 nm than Br<sup>-</sup>, a different procedure was, however, followed in most cases. The polymer is dissolved in 0.1 N HCl and kept at 50°C for 24 h. The L-s-PMHBocA is not sufficiently soluble in the acidic region, but goes into solution as the reaction proceeds. Because only isobutene and CO<sub>2</sub> are evolved during deprotection, freeze-drying yields the pure compounds.

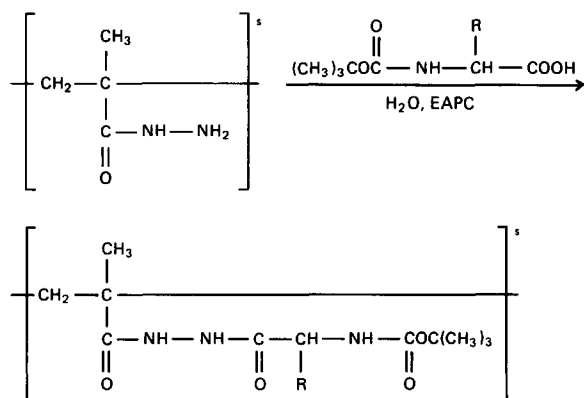
The <sup>1</sup>H and <sup>13</sup>C n.m.r. spectra for the characterization of polymers and model compounds were obtained as described elsewhere<sup>6</sup>. The composition of the copolymers (MH)-*s*-co-(L-MHBocS) was determined from the <sup>1</sup>H spectra by:

$$P(A) = \frac{5I_{\text{Boc}}}{9(I_{\alpha\text{-CH}_3} + I_{\beta\text{-CH}_2})} \quad (1)$$

where  $P(A)$  is the probability for the L-MHBocS monomeric unit and  $I$  are the integral intensities of the resonances identified by their subscript. Thus Boc refers to the nine protons of the *t*-butyloxycarbonyl group and  $\alpha$ -CH<sub>3</sub> and  $\beta$ -CH<sub>2</sub> to the protons of these groups in the main chain. The c.d. and u.v. spectra<sup>5</sup> and the potentiometric titrations<sup>6</sup> have been obtained as previously described. The concentration for the u.v. spectra was chosen to lead to an absorbance between 1.5 and 2.0. The same concentration range yielded the best signal-to-noise ratio for the c.d. spectra. The i.r. spectra were recorded using the conventional KBr press technique.

## RESULTS AND DISCUSSION

The polymers studied by c.d. have been derived by reacting syndiotactic poly(methacrylic acid hydrazide) (s-PMH) with *t*-butyloxycarbonyl-*L*-serine or *t*-butyloxycarbonyl-*L*-alanine in aqueous solution in the presence of *N*-ethyl-*N'*(3-dimethylaminopropyl)carbodiimide hydrochloride (EAPC) as the condensing agent:



$R = \text{CH}_2\text{OH}$  (syndiotactic poly[methacrylic acid- $N^\beta(N(t\text{-butyloxycarbonyl})L\text{-seryl})$  hydrazide] (L-s-PMHBocS))

$R = \text{CH}_3$  (syndiotactic poly[methacrylic acid- $N^\beta(N(t\text{-butyloxycarbonyl})L\text{-alanyl})$  hydrazide] (L-s-PMHBocA))

s = syndiotactic enchainment of repeat units

By partial acylation of s-PMH with *t*-butyloxycarbonyl-*L*-serine, the corresponding cosyndiotactic (methacrylic acid hydrazide)-*s-co*-[methacrylic acid- $N^\beta(N(t\text{-butyloxycarbonyl})L\text{-seryl})$  hydrazide] ((MH)-*s-co*-(L-MHBocS)) copolymers have been obtained. In addition, the deprotected polymers were prepared by removing the *t*-butyloxycarbonyl (Boc) protecting group to yield syndiotactic poly[methacrylic acid- $N^\beta(L\text{-seryl})$  hydrazide] (L-s-PMHS), poly[methacrylic acid- $N^\beta(L\text{-alanyl})$  hydrazide] (L-s-PMHA) and (methacrylic acid hydrazide)-*s-co*-[methacrylic acid- $N^\beta(L\text{-seryl})$  hydrazide] ((MH)-*s-co*-(L-MHS)) cosyndiotactic copolymers.

For spectroscopic comparisons, the low-molecular-weight model compounds pivalic acid- $N^\beta(N(t\text{-butyloxycarbonyl})L\text{-seryl})$  hydrazide (L-PivHBocS), pivalic acid- $N^\beta(N(t\text{-butyloxycarbonyl})L\text{-alanyl})$  hydrazide (L-PivHBocA), pivalic acid- $N^\beta(L\text{-seryl})$  hydrazide (L-PivHS) and pivalic acid- $N^\beta(L\text{-alanyl})$  hydrazide (L-PivHA) have also been prepared. The polymers and model compounds were characterized by  $^1\text{H}$  and  $^{13}\text{C}$  n.m.r. and by potentiometry.

All polymers and model compounds possess diacyl hydrazide moieties with two carbonamide groups, which, at acid and neutral pH, behave spectroscopically as two separate chromophores. At alkaline pH, a diacyl hydrazide anion is formed from the two carbonamide groups, which behaves as a single chromophore.

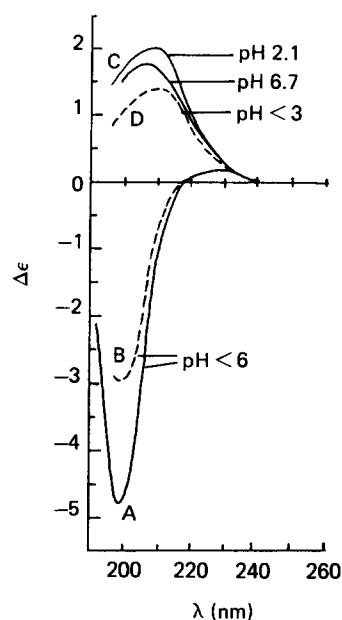
These two types of chromophores are responsible for the c.d. and u.v. spectra above 190 nm, no other chromophores being present which absorb significantly in this range. It might be suspected that the urethane group in the *N*-protected polymers and model compounds might interfere above 190 nm. Therefore, the  $\text{NH}_2$  group of optically active *L*-2-amino-1-propanol was Boc-protected to serve as a model. No u.v. and c.d. absorptions were found over the relevant range of pH and also no buffer plateaux were observed in the potentiometric titration curves up to pH 13. Such plateaux might have indicated deprotonation of the urethane group leading to the appearance of a chromophore absorbing at longer wavelength.

The potentiometric acid-base behaviour was employed to determine the solubility behaviour of the polymers in aqueous solution. Good solubility was found in the alkaline region for all polymers, on account of their polyelectrolyte character, and also in the acidic range for the deprotected polymers. The protected polymers L-s-PMHBocS and L-s-PMHBocA showed only a small solubility in the acidic range which, however, was sufficient for u.v. and c.d. measurements. The L-s-PMBocS showed, in addition, a considerable increase in solubility at  $\text{pH} < 3.5$  which was apparently not due to cleavage of the Boc group or to protonation, and which may, therefore, be caused by a specific interaction between protons and polymer.

#### C.d. in the neutral and acidic region

The *N*-protected *L*-alanine derivatives L-s-PMHBocA and L-PivHBocA show c.d. spectra which are approximately independent of pH in the neutral and acidic region. In Figure 1 a negative Cotton effect is seen at 198 nm, whereby the polymer has a molar dichroic absorption coefficient  $\Delta\epsilon$  that is only about 30% more negative in comparison to the model. The comparable magnitude of the Cotton effects indicates that the side chains of the polymer have a conformational population which is not very different from the low-molecular-weight model. This, in turn, makes it very likely that a strongly preferred conformation for the side chains is not present. For the polymer, an additional Cotton effect, small and positive, is seen at 228 nm.

After cleavage of the Boc protecting group to yield L-s-PMHA and L-PivHA, the negative Cotton effect of the protected compounds disappears, to be replaced by a positive Cotton effect at 210 nm. Again, polymer and model do not differ greatly in their  $\Delta\epsilon$ . Interestingly, protonation of the  $\alpha\text{-NH}_2$  group of the polymer does not lead to a large difference either, as can be seen by comparing L-s-PMHA at pH 2.1 and pH 6.7. The lack of a difference between polymer and model, and the lack of effect of pH for the polymer, again points to a disordered conformation. There appears to exist no ordered conformation for the polymer the effect of which would be absent in the model or which could be disrupted by electrostatic repulsion. A third corroborative finding is the lack of change in  $\Delta\epsilon$  when methanol or trifluoroethanol are added to the polymer solution. If the polymer were on the verge of assuming an ordered conformation, then the alcohols would probably encourage this ordering, by analogy with the example of the deprotected polymer derived from *L*-serine, discussed below.



**Figure 1** C.d. spectra of the *N*-protected *L*-alanine derived polymer, L-s-PMHBocA (curve A), and its model, L-PivHBocA (curve B), as well as the c.d. spectra of the corresponding deprotected compounds L-s-PMHA (curves C) and L-PivHA (curve D). Spectra were recorded in aqueous solution at ambient temperature, using HCl to adjust the pH

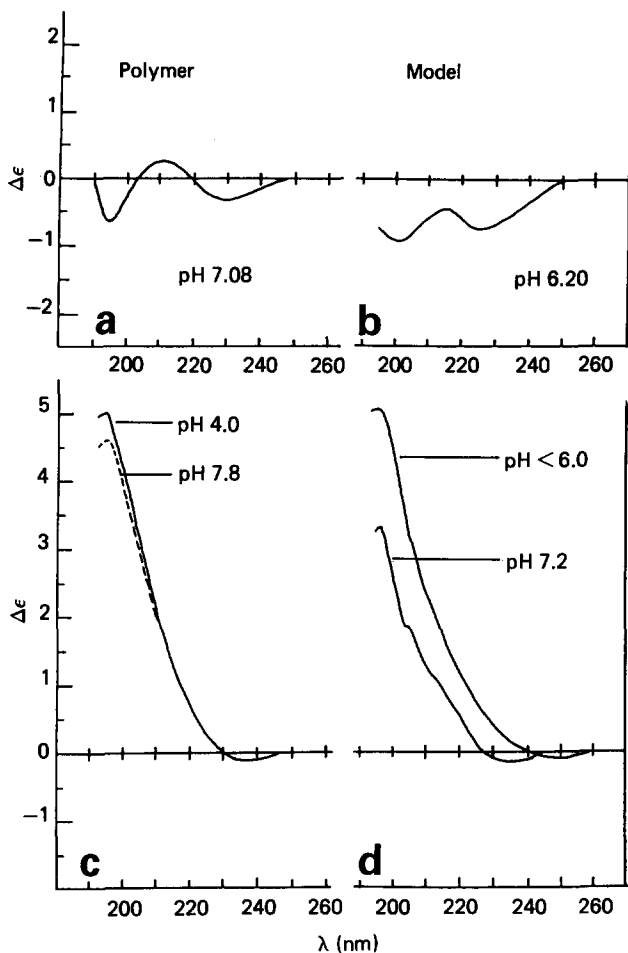


Figure 2 C.d. spectra of (a) the *N*-protected polymer L-s-PMHBocS, (b) its model compound L-PivHBocS, (c) the deprotected polymer L-s-PMHS and (d) its model compound L-PivHS. Spectra were recorded from aqueous solution at different pH

The c.d. spectra of the *N*-protected and *N*-deprotected L-serine derivatives are given, Figure 2, for both the polymers and the models. The *N*-protected polymer L-s-PMHBocS and its model L-PivBocS show similar c.d. curves with three extrema, with the spectral trace of the polymer displaced as a whole towards more positive  $\Delta\epsilon$  and shorter wavelengths. Apparently, at least three Cotton effects are superimposed on each other with the two outer bands having a negative  $\Delta\epsilon$  and the middle band a positive  $\Delta\epsilon$ . The two longer-wavelength bands of the polymer at 230 and 211 nm may be ascribed to an  $n \rightarrow \pi^*$  carbonamide transition in two conformers and the lowest-wavelength band at 195 nm to a  $\pi \rightarrow \pi^*$  transition. The difference found in the c.d. spectra between polymer and model may then be caused by a change in the population of the two conformers. The *N*-deprotected polymer L-s-PMHS and its model L-PivHS show a relatively strong positive Cotton effect at 195 nm ( $\pi \rightarrow \pi^*$ ) and a much smaller negative band at  $\sim 234$  nm ( $n \rightarrow \pi^*$ ). The spectral trace of the polymer does not depend greatly on the degree of protonation of the  $\alpha$ -NH<sub>2</sub> group.

The similarity in the spectra of the serine derived polymer and its model, both protected and unprotected, and the lack of a large effect for the protonation of the unprotected polymer, again indicate the absence of an ordered conformation for the side chains. This is analogous to the conclusions reached for the L-alanine

derived polymers. It must be remembered, however, that it is primarily the N-CH bond in the side chain, and the substituents on its asymmetric centre, which transports the chiral induction to the neighbouring, inherently symmetric, carbonamide chromophore. Therefore, it is primarily the conformation about this bond which may be seen in the c.d. spectra.

The effect of adding methanol to the aqueous solution of the protected polymer L-s-PMHBocS is seen in Figure 3. With increasing methanol concentration, a positive Cotton effect grows below 200 nm, which probably belongs to the  $\pi \rightarrow \pi^*$  transition. No such effect of methanol is observed for the corresponding model compound. The 230 nm Cotton effect of the  $n \rightarrow \pi^*$  transition of the polymer does not change much, except for being shifted to somewhat longer wavelength. In view of the unchanged 230 nm band, and the probably also unchanged 211 nm band, a factor other than conformation appears to influence the optical activity. This factor may be connected to an exciton coupling of the  $\pi \rightarrow \pi^*$  transitions of carbonamide chromophores which are adjacent within the same diacyl hydrazide moiety.

Adding methanol to the aqueous solution of the deprotected polymer L-s-PMHS leads to an increase in the  $\Delta\epsilon$  of its positive band at 195 nm, while addition of LiClO<sub>4</sub> diminishes its intensity. Again, no effect is observed for the model compound. Methanol is known to support ordered conformations in polypeptides by favouring hydrogen bonding and polar interactions as compared to H<sub>2</sub>O, while LiClO<sub>4</sub> tends to diminish ordered conformations by inhibiting such hydrogen bonding and polar interactions. It may be concluded, therefore, that a significant tendency to form an ordered conformation is present, both for L-s-PMHBocS and L-s-PMHS. This is of interest in the light of the observation that these two polymers form ordered conformations under alkaline conditions as described below.

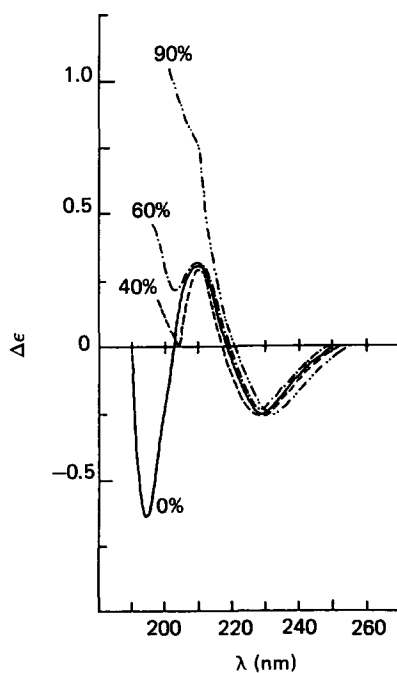


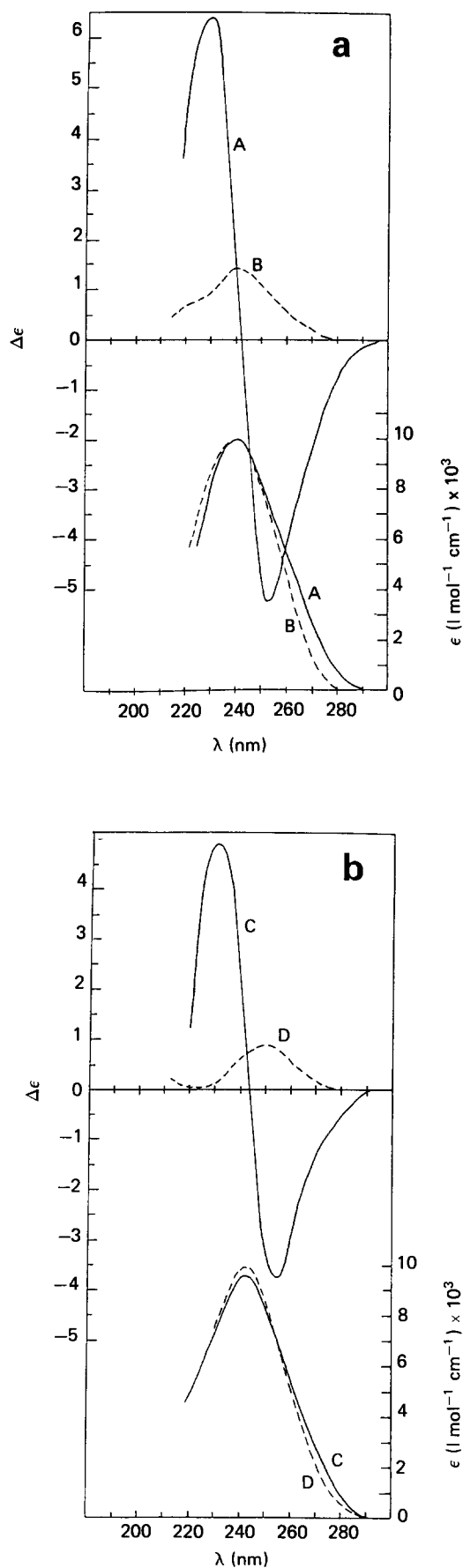
Figure 3 C.d. spectra of L-s-PMHBocS in neutral aqueous solution on addition of methanol (amount of MeOH added shown next to curves)

Because it has been found that the protected polymer L-s-PMHBocS shows increased solubility in the strongly acidic range below pH 3.5, it may be suspected that this solubility increase is associated with a conformational change, since the polymer does not contain groups that can be protonated at this pH. That this is a reasonable assumption can be seen from the c.d. spectra, which show that the two  $n \rightarrow \pi^*$  transitions, which previously have been associated with two different conformations, change their relative intensities greatly going to pH 2, whereby the band at 230 nm decreases and that at 211 nm increases in intensity.

#### C.d. in the alkaline region

Adding KOH to the aqueous solutions of the polymers and model compounds leads to deprotonation of the diacyl hydrazide moiety. I.r. spectra show the appearance of a strong new band at  $1550 \text{ cm}^{-1}$ , in addition to the strong bands at  $1700 \text{ cm}^{-1}$  [amide I (sec. urethane)],  $1670 \text{ cm}^{-1}$  [amide I (sec. amide,  $\nu(\text{C}=\text{O})$ )] and  $1515 \text{ cm}^{-1}$  [amide II (sec. amide,  $\nu(\text{C}-\text{N}) + \delta(\text{C}-\text{N}-\text{H})$ )] which are already present in the neutral, uncharged polymer. The homopolymers derived from L-alanine, i.e. L-s-PMHBocA and L-s-PMHA, and their models L-PivHBocA and L-PivHA, show in their deprotonated state simple c.d. and u.v. bands at wavelengths around 240 nm which do not appear in the neutral and acidic region. The cumulative partial double-bond system, extending over the whole diacyl hydrazide anion chromophore, leads to transitions located at relatively long wavelengths, as compared to the two independent carbonamide chromophores which make up the uncharged diacyl hydrazide group. Comparing the polymer to its model, about the same  $\lambda_{\text{max}}$  is found for the positive Cotton effect in the c.d. spectra of the N-protected compounds, i.e. 241 nm for L-s-PMHBocA and 242 nm for L-s-PivHBocA. This is also the same wavelength as the  $\lambda_{\text{max}}$  of the u.v. spectra of these compounds at 241–242 nm. For the deprotected compounds there is a discrepancy. The c.d.  $\lambda_{\text{max}}$  of L-s-PMHA is at 250 nm and for L-PivAH at 246 nm, while the u.v.  $\lambda_{\text{max}}$  is unchanged at 241–242 nm. Possibly a small negative Cotton effect seen at lower wavelength of  $\sim 225 \text{ nm}$  leads to an apparent shift of the maximum of the positive band to longer wavelength. The  $\Delta\epsilon$  and the area of the positive Cotton effect of the polymer L-s-PMHBocA is less than half of the model L-PivHBocA, while they approach each other for L-s-PMHA and L-PivHA. One may conclude that an ordered conformation is probably not present in the polymers derived from L-alanine in the alkaline range.

However, the results for the L-serine derived polymers in the alkaline region are greatly different from the L-alanine derived compounds. The Cotton effects are split and more intense, pointing to an ordered conformation. In Figure 4, the c.d. and u.v. spectra of the L-serine derived compounds in their deprotonated state are shown. The u.v. spectra of the polymers and models are very similar in shape and intensity to the L-alanine derived compounds and their  $\lambda_{\text{max}}$  are also approximately the same at 240–243 nm. The c.d. spectra of the L-serine derived models are still similar in general shape and position to the L-alanine derived models. For instance, the  $\lambda_{\text{max}}$  at 241 and 249 nm for L-PivHBocS and L-PivHS, respectively, are at nearly the same positions as for L-PivHBocA and L-



**Figure 4** C.d. and u.v. spectra of L-serine derived polymers and models: (a) the N-protected polymer L-s-PMHBocS (curve A) and the model L-PivHBocS (curve B); (b) the deprotected polymer L-s-PMHS (curve C) and the model L-PivHS (curve D). The compounds were fully deprotonated by raising the pH to 13.3 or 13.4 for the polymers and to 12.2 or 12.3 for the models

PivHA. However, the c.d. spectra of the polymers are greatly different. An S-shaped double band of higher intensity appears for L-s-PMHBocS and L-s-PMHS, showing a crossover at the u.v.  $\lambda_{\max}$ . The two c.d. bands of the doublet are of about the same size and their  $\lambda_{\max}$  are about equidistant from the crossover. This type of S-shaped double band has already been found for L-lactic acid derived polymers<sup>3,5</sup>.

According to exciton theory<sup>9</sup>, S-shaped c.d. double bands of opposite sign, equal  $\Delta\epsilon$  and area, and coincident crossover with u.v.  $\lambda_{\max}$  appear when at least two conditions are met. First, identical or at least similar chromophores with strong  $\pi \rightarrow \pi^*$  transitions must be in close spatial proximity to each other. Secondly, the electric dipole transition moments of the chromophores must be in a fixed spatial and chiral orientation to each other. Provided such an exciton effect is present, the order of the signs of the two bands of the doublet, as counted from long to short wavelengths, is related to the sense of spiralling of the relative orientation of the transition moments. Because in Figure 4 the order of signs is (-)(+), a left-handed spiralling is indicated. Since the direction of the electric transition moments is likely not to deviate greatly from the long axis of the diacyl hydrazide anion moiety, the left-handed spiralling also applies to the orientation of the diacyl hydrazide anions themselves. Low-molecular-weight model compounds cannot fulfil the second conditions for an exciton effect on account of their high molecular mobility in solution. Also, in dilute solution, they are too far apart, on average. However, the second condition can be met by the present polymers at least in principle. There may exist a fixed spatial and chiral orientation, provided, the diacyl hydrazide anion moieties in the lateral chains are held in a fixed orientation to each other by interactions between these chains. Such interactions appear to be possible with the L-serine derived polymers because not only does the diacyl hydrazide anion moiety possess a charge and hydrogen-bonding ability, but also the lateral chain possesses an -OH group and an -NH<sub>2</sub> urethane group. Because the diacyl hydrazide anion and the -NH<sub>2</sub> or urethane group are also present in the L-alanine derived polymers, the -OH group in the L-serine derived polymers apparently has a vital function in the interactions and the resulting fixed spatial orientation of the lateral chains towards each other.

The presence of an exciton effect can be supported by c.d. spectra, recorded at different pH of the deprotected, L-serine derived polymer L-s-PMHS. At different pH, the polymer is deprotonated to different degrees and a correlation between pH and degree of deprotonation  $\alpha$  can be obtained by u.v. titration<sup>3</sup>. Both the c.d. and u.v. spectra are shown at four different pH values in Figure 5. Because  $\epsilon$  and  $\Delta\epsilon$  are molar quantities and are based on the total concentration of monomeric units which contain diacyl hydrazide groups, and not on deprotonated diacyl hydrazide units only, there is a strong rise in intensity for both the u.v. and the c.d. spectra with increasing pH. Moreover, the c.d. spectra of the polymer develop gradually into a double band, starting from the single band that is typical for the model compound and for the L-alanine derived polymers and models. At pH 10.8, the u.v. absorbance  $\epsilon$  is about 40% ( $\alpha \sim 0.4$ ) of the maximum obtainable with complete deprotonation at pH > 13.0. The c.d.  $\lambda_{\max}$  nearly coincides with the u.v.  $\lambda_{\max}$ , as is

required for this non-exciton Cotton effect. Raising the pH to 11.3 increases  $\epsilon$  to 56% ( $\alpha \sim 0.56$ ) of the maximum obtainable and the exciton double band starts to develop. It is now the crossover in the c.d. spectra (c.d.  $\lambda_0$ ) that nearly coincides with the u.v.  $\lambda_{\max}$ . At pH 11.7 the exciton effect has developed further and at pH > 13.3 reaches its limiting size. Obviously, the rise in  $\Delta\epsilon$  does not correspond to the rise in  $\epsilon$ . While  $\epsilon$  rises linearly with deprotonation to a first approximation,  $\Delta\epsilon$  starts to rise strongly only at  $\alpha \sim 0.5$  and then rises more strongly than  $\epsilon$  (ref. 3). This may be rationalized by taking into consideration the electrostatic repulsion between like charges on the polymer chain. At  $\alpha = 0.5$ , negatively charged monomeric units might alternate with uncharged monomeric units on a time average. The condition of spatial proximity is, therefore, not fulfilled to an extent which would be given, for example, by a Bernoullian distribution. Thus an exciton effect cannot arise to a larger extent. Every additional deprotonated monomeric unit, however, which is being added by raising the pH, necessarily leads to greater proximity of the diacyl hydrazide anions and therefore to a large non-linear increase in the exciton effect.

The number of diacyl hydrazide anions and their distribution along the chain can be changed not only by varying the pH but also by preparing copolymers via partial acylation of s-PMH. It may therefore be assumed that the partial acylation reaction proceeds at random on the polymer chain. On exposing the resulting copolymers to a high enough pH, all diacyl hydrazide monomeric

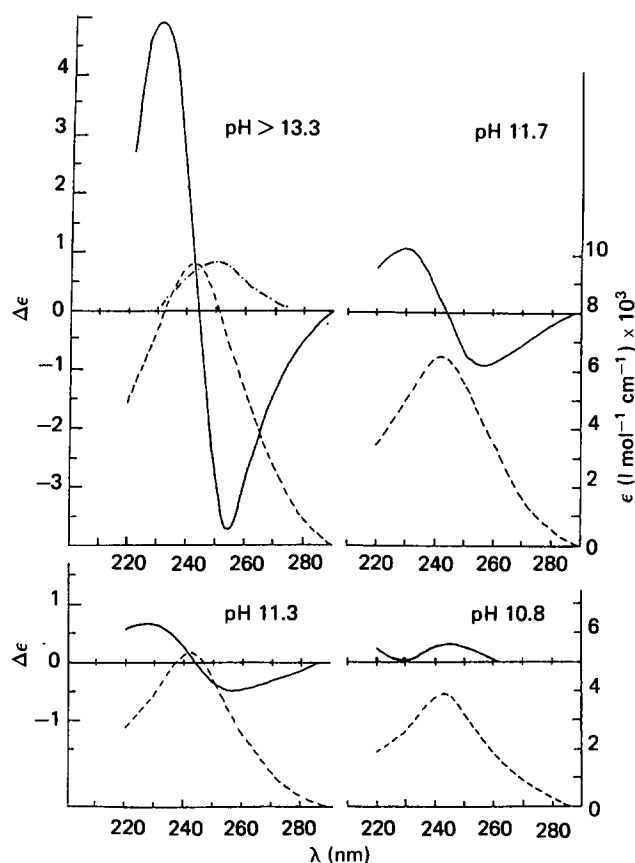
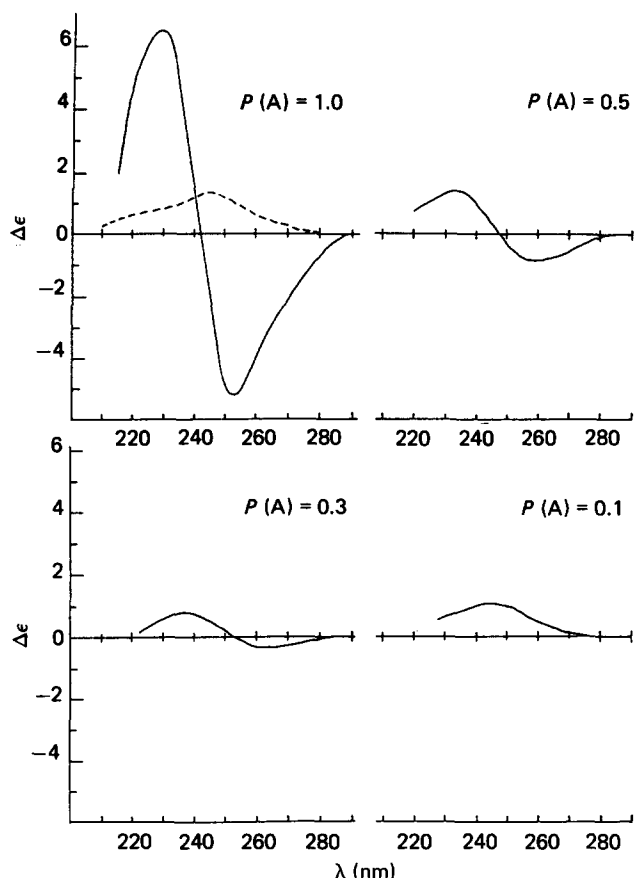


Figure 5 C.d. spectra of L-s-PMHS at different pH (—), u.v. spectra of L-s-PMHS at different pH (---) and the c.d. spectrum of L-PivHS (— · —) at pH = 13.3

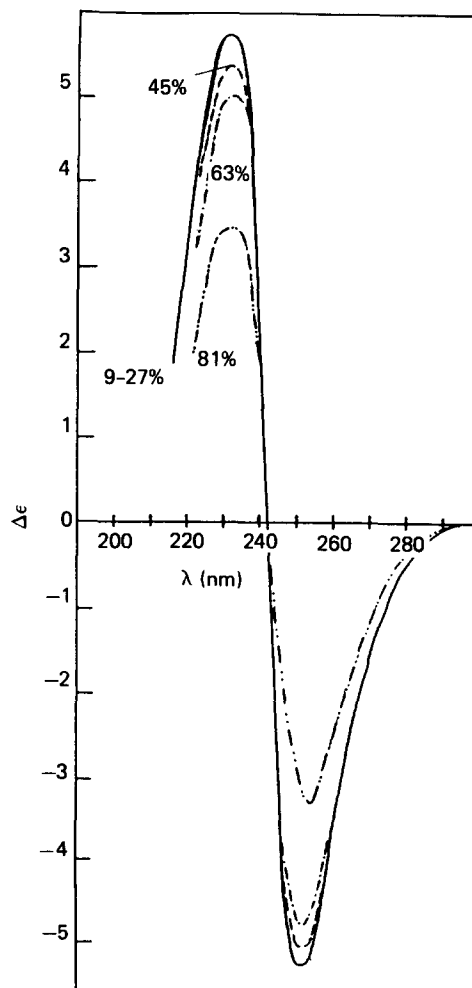


**Figure 6** C.d. spectra of (MH)-s-co-(L-MHBocS) copolymers of different  $P(A)$  and the homopolymer L-s-PMHBocS ( $P(A)=1.0$ ) (—), as well as the model compound L-PivHBocS (---). All polymer spectra were recorded at pH 13, the model at pH 12.5

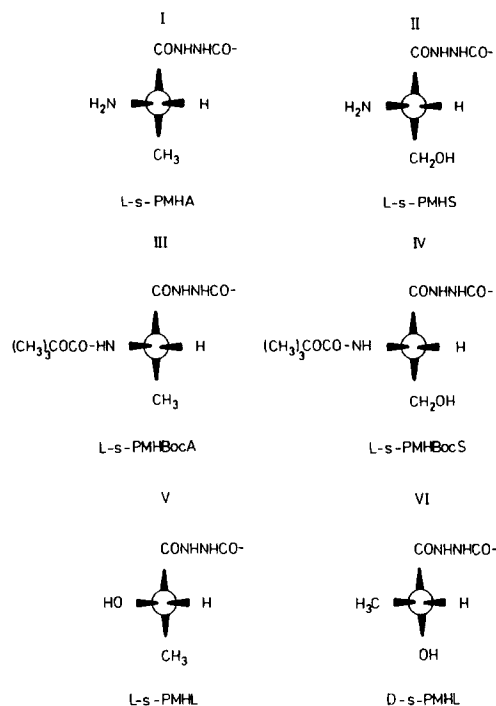
units, which are distributed at random between the monoacyl hydrazide monomeric units, will be in their anionic state. When the probability of finding a diacyl hydrazide anion unit,  $P(A)$ , is increased, the number of adjacent diacyl hydrazide anions, i.e. anion pairs, will also rise and the possibility of an exciton effect arises. In *Figure 6* a series of three (MH)-s-co-(L-MHBocS) copolymers of  $P(A)=0.1, 0.3$  and  $0.5$ , together with the homopolymer ( $P(A)=1.0$ ), are presented. At  $P(A)=0.1$  (acylation of 10%) a broad positive Cotton effect is seen, which is similar in location and shape to that of the model compound (as also shown in *Figure 6*). It follows that the polymeric nature of the copolymer as such does not yet lead to an exciton effect. With  $P(A)=0.3$ , some adjacent diacyl hydrazide anions exist and an exciton doublet starts to develop in place of the single Cotton effect. The doublet becomes stronger at  $P(A)=0.52$  and, with  $P(A)$  increasing further, develops to its final state at  $P(A)=1.0$ . The steep rise of the exciton doublet above  $P(A)=0.5$  corresponds to the marked increase in the number of adjacent diacyl hydrazide anions which gains momentum at  $P(A)$  values greater than  $0.5$ . The c.d. data shown in *Figure 6* lead to two more observations which are of direct bearing on the question whether an exciton doublet is really present. First, the two bands that form the doublet are not of the same  $\Delta\epsilon$  nor of the same area. The positive band is always larger in absolute magnitude than the negative band. The lower the  $P(A)$ , the larger this inequality becomes. Secondly,  $\lambda_0$  is displaced more from the expected value of 242 nm to higher wavelengths, the

lower is  $P(A)$ . Simultaneously,  $\lambda_{\max}$  are displaced in the same direction. The common reason for these two observations is the superposition of the exciton doublet with the simple Cotton effect of diacyl hydrazide anions whose transitions are not coupled. The lower the  $P(A)$ , the more anions are isolated on the polymer chain, i.e. are without adjacent anions, and the larger is the simple Cotton effect. No coupling of the transition moments is possible and these anions behave in a spectroscopically similar manner to the deprotonated model compound. An analogous observation is made for the change of pH in *Figure 5*. Here, the superposition of the exciton doublet with the non-excitonic Cotton effect also leads to a larger positive band, while  $\lambda_0$  and  $\lambda_{\max}$  are not affected to the same extent in this case.

The addition of water-miscible solvents and of salts to the aqueous alkaline solution may yield some information about the nature of the interactions between the lateral chains which lead to fixation of their relative positions in space and of their conformation. The effect of the addition of methanol on the c.d. spectra of L-s-PMHBocS is seen in *Figure 7*. Obviously, the doublet progressively decreases in intensity. The degree of deprotonation is not diminished during addition of methanol, as the u.v. spectra show. Hydrogen bonding and dipolar interactions between lateral chains which favour order are expected to increase with the amount of methanol. However, the decrease in dielectric constant



**Figure 7** C.d. spectra of L-s-PMHBocS as a function of the addition of methanol (9 to 81% v/v) to the alkaline aqueous solution of pH 13.0 (amount of MeOH added shown next to curves)



**Figure 8** Structure of the lateral chain for all polymers studied (not a Newman projection): L-s-PMHL, syndiotactic poly[methacrylic acid-*N*<sup>β</sup>(L-lactoyl) hydrazide]; D-s-PMHL, syndiotactic poly[methacrylic acid-*N*<sup>β</sup>(D-lactoyl) hydrazide]. The circle in the centre represents the asymmetric carbon

and the resulting increase in electrostatic repulsion nevertheless appear to disrupt the spatial and conformational order of the side chains. In contrast, the c.d. spectra of the L-alanine derived polymers and of all model compounds show no significant effect of methanol, as they possess no order that could be disrupted. An increase in temperature leads also to a loss of intensity for the exciton doublet of L-s-PMHBocS, which is to be expected because of the higher kinetic energy available.

The electrostatic charge repulsions are diminished by the action of salt, and the same also applies to the interactions between dipolar partial charges, as well as to hydrogen bonding. While a moderate reduction of the charge repulsion may conceivably stabilize the order of lateral chains, the concurrent decrease in the hydrogen bonding is probably always detrimental to the order. Apparently the net effect here is a reduction in order. Again, the addition of salt to L-alanine derived polymers and all model compounds is without significant effect on the c.d. spectra. Related to the influence of salt is the action of the type of base employed for deprotonating the diacyl hydrazide moieties. The exciton doublet contracts to some extent, when the bases NaOH or LiOH are employed instead of KOH. This is probably connected to a reduction in the ionic radii (crystal radii<sup>9</sup>: K<sup>+</sup>, 1.44; Na<sup>+</sup>, 1.12; Li, 0.86 Å). A delicate balance apparently prevails between the electrostatic interactions of the charges and the attractive interactions, particularly hydrogen bonding. Of interest also is the observation that on removal of a 'disturbance', e.g. the removal of methanol or salt, the original c.d. spectra are obtained again. Moreover, the presence of artefacts by chemical degradation of the polymers in the alkaline range has been excluded by bringing the pH to neutral after the spectroscopic measurements, thereby again obtaining the original u.v., c.d. and n.m.r. spectra.

The postulate of a delicate balance between repulsive and attractive interactions is strengthened by a comparison of the conformational behaviour of the polymers studied so far. The polymers in the present work are derived from L-serine and L-alanine, both protected and unprotected. In a previous study, polymers derived from s-PMH and L-lactic acid or D-lactic acid have been reported<sup>3,5</sup>. The only structural and configurational difference between all the polymers studied so far is seen in two of the three substituents on the asymmetric centre at the end of the lateral chain. In Figure 8, the structures and configurations of the asymmetric centres are seen. Polymers II, IV, V and VI showed an exciton effect in the alkaline region, while I and III did not. Comparing I and V, the only difference is an -NH<sub>2</sub> in I which is replaced by an -OH in V. An -OH group is apparently favouring an exciton effect, while -NH<sub>2</sub> in I or (CH<sub>3</sub>)<sub>3</sub>COCONH- in III do not. Similarly, if the -CH<sub>3</sub> in I is replaced by -CH<sub>2</sub>OH in II, an exciton effect is observed again. It may, therefore, be assumed that the hydrogen bonding provided by the -OH groups is instrumental in stabilizing side-chain order. On the other hand, neither -NH<sub>2</sub> (II) nor (CH<sub>3</sub>)<sub>3</sub>COCONH- (IV) prevent the appearance of an exciton effect, if a -CH<sub>2</sub>OH group is also present.

In view of the ordered spiralling of neighbouring diacyl hydrazide anions, an ordered spatial arrangement of the side chains as a whole is also probable. This is because the hydrogen bonding of -OH at the end of the lateral chain appears to be instrumental in exciton coupling. Thus a conformational order of the whole side chain is indicated. Carrying the reasoning one step further, perfect spatial and conformational order of the side chain is, moreover, not possible without an ordered conformation of the main chain. A 4<sub>2</sub>-helix of the main chain with spiralling of the side chains has already been proposed as a possible conformation for this type of polymer<sup>5</sup>. This model may also apply to the present polymers derived from L-serine.

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