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ANIONIC OLIGOMERIZATION OF ACRYLAMIDE BY ALKALI METAL METHOXIDES

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Abstract—The anionic oligomerization of acrylamide by methanolic alkali metal methoxides was studied in methanol and in aprotic solvents. Oligomer yield increased with increasing initiator concentration, the dielectric constant of the solvent, the electropositivity of the alkali metal and with decrease in methanol concentration. Initiation occurred by addition of methoxide to the double bond. Simultaneous monitoring of the reactants and products showed that β-methoxypropionamide, first formed in up to 70% yield, undergoes a base-catalysed reversible reaction generating acrylamide which participates in propagation. Acid hydrolysis of the oligomers showed that propagation had proceeded through 1,2-addition (30–50%) leading to an acrylamide structure, and 1,4-addition (50–70%) leading to a β-alanine structure in the polymers.

INTRODUCTION

The anionic polymerization of acrylamide in aprotic solvents was found to lead to the formation of poly-β-alanine having quite high molecular weight [1, 2] through a hydrogen transfer mechanism; in methanol no polymerization occurred [3]. This result indicated termination by the protic solvent and it seemed that, on using low methanol concentration and appropriate molar ratios of [monomer]/[methanol], it should be possible to control the anionic polymerization of acrylamide in an aprotic dipolar solvent, so that oligomers are formed.

The oligomerization was studied using methanolic alkali metal methoxides as initiators; factors affecting the reaction, such as solvent, concentrations of methanol, monomer and initiator and type of the alkali metal, were investigated. The proportions of 1,4- and 1,2-repeat units in the oligomers were determined.

RESULTS AND DISCUSSION

Effect of methanol

The effect of methanol concentration was investigated. On using methanol as solvent for the reaction catalysed by sodium methoxide there was no oligomerization of the acrylamide and only β-methoxypropionamide [1, 3] was isolated. Reaction in DMSO or DMF using methanolic sodium methoxide, where the methanol molar concentration was not more than 20% of that of the monomer, led to solid polymers soluble in DMSO, DMF and water, partially soluble in methanol and insoluble in common organic solvents. The fractions soluble in methanol melted at 75–80° and the insoluble fractions at 105–110°. These results showed that, by regulating the concentration of methanol, which acts as terminator, it is possible to regulate the molecular weights of the oligomers. NMR and i.r. spectra of the polymers showed the absence of double bonds but the presence of methoxy groups (δ = 3.4 ppm and 1130 cm^{-1} absorption) indicating that initiation is by addition of methoxide to the double bond of acrylamide.

A series of reactions carried out in DMSO in which the amount of methanol was varied (Table 1A) showed that for a relatively high methanol concentration, viz. [monomer]/[methanol] = 0.58, no oligomer was formed and only I was obtained. At [monomer]/[methanol] ratios between 1 and 3, the yield of oligomer decreased, and that of I and of unreacted monomer increased, on increasing the methanol concentration.

Effect of initiator

The effect of the initiator concentration on the oligomerization was investigated in DMSO at 25° at a [monomer]/[methanol] ratio = 0.95 (Table 1B). On increasing the concentration of sodium methoxide, the yield of oligomers increased, and those of I and of unreacted monomer decreased. At the lowest initiator concentration investigated ([acrylamide]/[sodium methoxide] = 28.4), no oligomerization occurred and only I was formed. Similar results were obtained in the anionic polymerization of acrylamide [4] and in the anionic oligomerization of methacrylonitrile [5] and methylmethacrylate [6] in which $\overline{DP}$ increased with increasing initiator concentration. Increasing the initiator concentration also increased the rate of conversion (polymerization in DMF) (Fig. 1).

To obtain more information concerning the initiation, the reaction was carried out in methanol, where initiation occurs but there is no propagation. The rate of reaction increased with increase of the methoxide concentration (Fig. 2). The effect of catalyst concentration on the amount of I formed and unreacted monomer is given in Table 1C. It is seen that the yield of I is maximal (100%) when [acrylamide]/[methoxide] = 1, decreases sharply to 10% at a ratio of 2, and then increases with further decrease in initiator concentration. The yields of the products after 2 hr remained unchanged after 12 hr, indicating that the systems have attained equilibrium.

These results suggest that a reversible reaction connected with I occurs and that it may be dependent on the methoxide concentration. Hence experiments

Table 1. Effect of methanol and initiator concentration on the oligomerization*

Exp. no.	[Methanol], (mole/l)	[$NaOCH_3$], (mole/l)	Unreacted monomer, %	I. yield, %	Oligomer yield, %
		(A) Effect of methanol (solvent-DMSO)†			
	1.6		7	16	74
	3.2		13	41	50
	4.8		23	57	15
	8.0		16	74	0
		(B) Effect of initiator (solvent—DMSO)‡			
	5.7	0.19	15	85	0
	5.7	0.38	23	57	17
	5.7	0.57	20	52	25
	5.7	1.04	8	32	51
		(C) Effect of initiator (solvent–methanol)§			
9		4.24	5	90	
10		2.80	0	100	
11		1.40	90	10	
12		0.60	20	81	
13		0.28	10	88	
14		0.20	8	95	

* Experimental conditions: methanolic sodium methoxide (5N) was added to a solution of acrylamide (5g. 0.07 mole) in DMSO (10 ml) or methanol: reaction time 15 hr, temp. 25° (except for C).
† Acrylamide, 4.66 mole/l and 1 ml of $NaOCH_3$ were used.
‡ Acrylamide, 5.7 mole/l was used.
§ Acrylamide, 2.8 mole/l; methanol final volume (25 ml); reaction temp. 60°, time 2 hr (and checked after 12 hr).

were carried out (Table 2) in which a methanolic solution of I was reacted with various concentrations of sodium methoxide. From exp. 16 it is seen that a quantitative acid-base reaction occurs between the sodium methoxide and I leading to the formation of the anion of I. This is easily followed by gas chromatography. The anion is not volatile, but after acidification I is liberated.

$$CH_3OCH_2CH_2CONH_2 + NaOCH_3 \longrightarrow [CH_3OCH_2CH_2CONH]^-Na^+ \xrightarrow{HCl} CH_3OCH_2CH_2CONH_2 \quad (I)$$

The fact that when $[I]/[CH_3O^-] = 1$ no acrylamide was formed indicates that the anion of I is rather stable and that it is I itself which decomposes to acrylamide. This is also seen both in the results of exp. 17–19, carried out at $[I]/[CH_3O^-]$ ratios > 1 where the amount of acrylamide formed in the reversible reaction decreased with increase of the methoxide concentration, i.e. the concentration of I anion. However, in the presence of excess sodium methoxide, which is a stronger base than that of the anion of I (exp. 15), even this anion decomposes to give acryl-

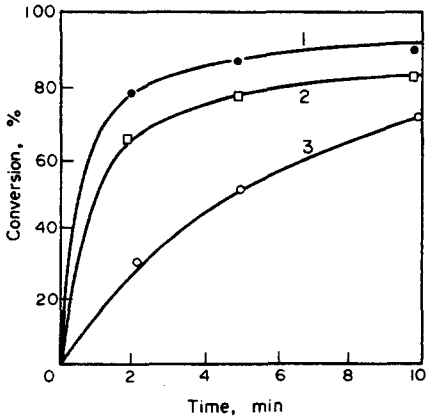


Fig. 1. Effect of sodium methoxide concentration on %-conversion for reaction in DMF. [$NaOCH_3$], mole/l: (●), 1.2; (□), 0.6; (○), 0.2.

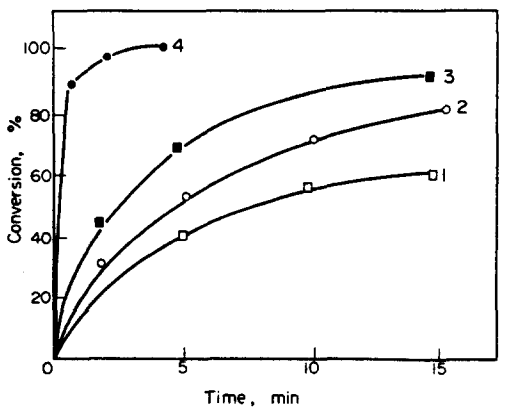


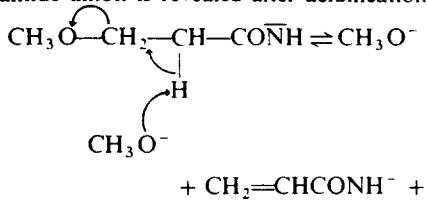
Fig. 2. Effect of sodium methoxide concentration on %-conversion for reaction in methanol. [Acrylamide] [$NaOCH_3$]: (□), 15; (○), 6; (■), 3; (●), 1.

Table 2. Effect of initiator concentration on the reversibility of addition of methoxide to acrylamide*

Exp. no.	$[NaOCH_3]$ (mole/l.)	$\frac{[I]}{[NaOCH_3]}$	Acrylamide formed, %	I	
				remaining†, %	after acidification, %
15	2.0	0.5	0	0	89‡
16	1.0	1.0	0	0	100
17	0.66	1.53	5	15	95
18	0.33	3.0	22	36	80
19	0.20	5.0	30	60	—

* Experimental conditions: methanolic sodium methoxide (5N) was added to a solution of I (β-methoxypropionamide) (1.03g, 0.01 mole, 1.0 mole l) in methanol (final volume, 10 ml) at 60°; reaction time 2 hr (and checked after 12 hr).
† The amount of I was determined in the reaction mixture both directly and after acidification.
‡ Acidification showed the presence of 7% acrylamide metallated by sodium methoxide.

amide, which itself suffers metallation, and the acrylamide anion is revealed after acidification.



$$+ CH_2{=}CHCONH^- + CH_3OH.$$

All these results indicate that the anion of I is stable to decomposition catalysed by itself but is decomposed by stronger bases such as methoxide. The anion of I itself catalyses the decomposition of free I (the acidity of the α-hydrogen of I is greater than that of I anion) (exp. 17–19) by a mechanism similar to that depicted for methoxide.

These findings help to explain some of the results in Table 1. Comparison of exp. 9 and 10 shows that, with a ratio of $[acrylamide]/[CH_3O^-] = 1$, a 100% yield of I was formed. Actually a 100% yield of the respective anion is obtained, and due to the absence of free methoxide, it does not decompose. In exp. 9 where excess methoxide was used, the yield of I was smaller and acrylamide was still found; this is due to the decomposition of I anion to acrylamide catalysed by methoxide.

To obtain more information on the reversibility of formation of I, the reaction was carried out in DMF(10 ml) so that the amount of methanol liberated could be followed by gas chromatography. The reaction was carried out at 25° using I (20 mmole) and 0.5 ml of 5N methanolic sodium methoxide (2.5 mmole). After 5 min, acrylamide (5.6 mmole) was formed and methanol (6 mmole) was liberated (in addition to the initial amount of methanol). This result clearly indicates that the formation of acrylamide from I is due to elimination of methanol. Actually, methoxide ion was liberated but because it metallated I, it was transformed to methanol. These concentrations did not change after 2 hr indicating that an equilibrium was established. During the reaction, a white precipitate was formed; it was identified as the sodium salt of I on acidification.

Similar to the formation of I from acrylamide, the reversible reaction was also dependent on the catalyst concentration. In exp. 16 (Table 2) where $[I]/[CH_3O^-] = 1$, equilibrium was established in seconds; in exp. 17 where the ratio was 1.5, equilibrium was attained after 2 min, and in exp. 19 where the ratio was 5 it was reached only after 2 hr.

Effect of solvent

Both the rate of reaction and the formation of oligomers were found to depend strongly on the solvent. Comparable reactions were run in DMF, DMSO, dioxane and methanol (20 ml solvent) using optimal reaction conditions for oligomerization (acrylamide, 3.5 mole/l, sodium methoxide, 0.5 mole/l, and methanol 2.5 mole/l). The reactions were carried out at 45°, and the rate of conversion of monomer was in the order DMSO > DMF > dioxane > methanol (Fig. 3).

Reactions carried out in DMF with various concentrations of methanol showed that increasing the methanol concentration decreased the rate of reaction (Fig. 4) probably due to lowering the possibility of propagation by causing termination and decreasing the activity of the anions by increasing their solvation with methanol. On using the more dipolar aprotic solvents, it was possible to achieve oligomerization even at relatively low [sodium methoxide]/[acrylamide] ratios and relatively high methanol concentrations. DMSO ($\epsilon = 46.4$) [7] being more effective than DMF ($\epsilon = 37.6$) [7]. Thus while with DMSO at a ratio of $[methoxide]/[acrylamide] = 0.036$ oligomerization still occurred up to a ratio of $[methanol]/[acrylamide] = 1.5$, with DMF using even a

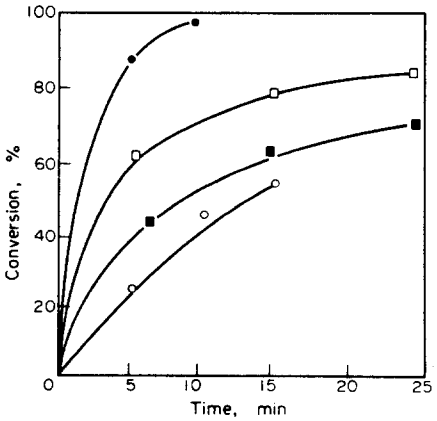


Fig. 3. Effect of solvent on %-conversion. (●). DMSO; (□). DMF; (■). dioxane; (○). methanol.

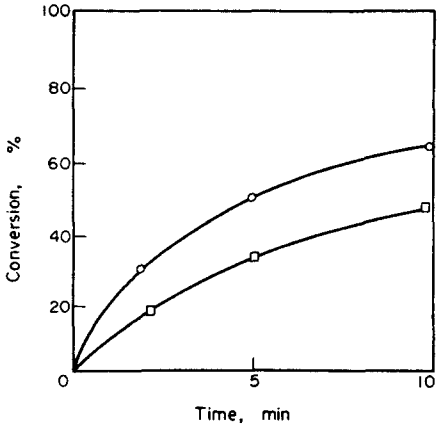


Fig. 4. Effect of methanol concentration on %-conversion. [Methanol], mole/l: (○), 4.1; (□), 8.2.

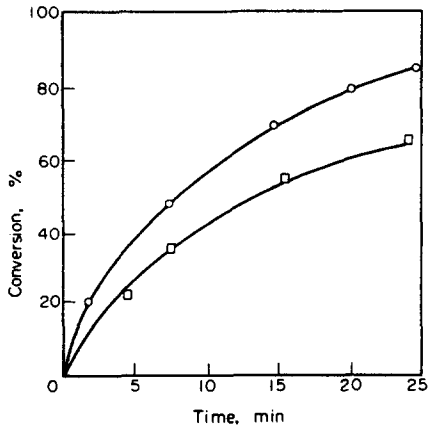


Fig. 6. Effect of alkali metal on rate of conversion–oligomerization in DMF. (○), K; (□), Na.

higher [initiator]/[monomer] ratio (0.065), the reaction did not proceed beyond the initiation stage even at a [methanol]/[monomer] ratio = 1.3.

These results may be explained thus: in protic solvents anions undergo solvation through the acidic hydrogens of the solvent [8], and in aprotic solvents their solvation is much less since it is mainly a result of ion–dipole interactions [9]. Aprotic solvents with high dielectric constants also undergo strong association with methanol through hydrogen bonding [9, 10] and thus lower its effective concentration, and this in turn also leads to a decrease in the degree of solvation of the anions. The greater rates observed in the aprotic solvents are mainly due to this lowering of the degree of solvation of the anions and making them more reactive. This activity enhances the nucleophilic addition of β-methoxy-acrylamide anions to the double bond of the monomer and thus increases propagation.

Effect of the alkali metal counter-ion

This effect was investigated in both methanol (where termination occurs at the initiation stage and there is only addition of methanol to the double bond) and in aprotic solvent (DMF) where propagation occurs. In methanol there was no effect of the alkali metal (Fig. 5). while in DMF the rate of conversion of monomer increased in the order K > Na (Fig. 6).

The effect of the alkali metal on the formation of the addition product, I, and its disappearance was studied in DMF (Fig. 7). The reaction starts by addition of methoxide to acrylamide, and I or its anion is formed, according to the amounts of methanol and initiator present. With sodium methoxide it was found that there is quantitative conversion of all the consumed acrylamide into I, until the amount of I reached a maximum, and then the concentration of I started to fall off. With potassium methoxide, the maximal amount of I formed is smaller (1.75 compared to 3.75 mole/l. for Na under the same conditions), and the maximum is attained sooner (15 min compared to 25 min). With lithium methoxide the reaction is much slower, and 1.75 mole/l of I are formed after 100 min. However, after 15 hr the concentration of I present in the reaction mixtures was 0.29, 1.27 and 1.74 mole/l. with K, Na and Li respectively (starting concentration of acrylamide 5.83 mole/l). This is in conformity with the fact that the reversible reaction ($I \rightleftharpoons CH_2{=}CHCONH_2 + CH_3OH$) is base catalysed, and it is expected to be slower with the less basic lithium catalyst.

Comparison of Figs. 6 and 7 shows that, with potassium methoxide, the rate of disappearance of

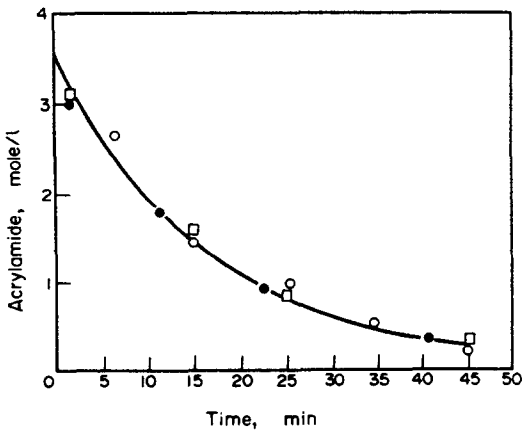


Fig. 5. Effect of alkali metal on rate–oligomerization in methanol. (○), K; (●), Na; Li, (□).

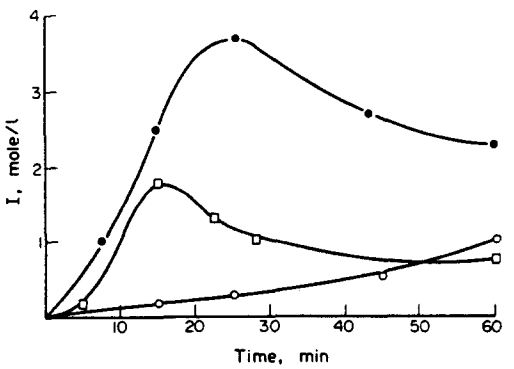


Fig. 7. Effect of alkali metal on formation of β-methoxy propionamide–and on its decomposition. (●), Na; (○), Li, K, (□).

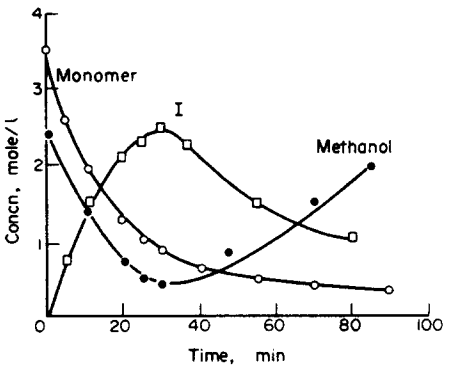


Fig. 8. Simultaneous follow-up of reactants and products. (○), monomer; (□), β-methoxy propionamide (I); (●), methanol.

monomer is greater than the rate of formation of I (up to the maximum concentration of I attained), in contrast to what was found with sodium methoxide. Thus after 15 min, almost 70% of the monomer disappeared, while the yield of I was only 30%. Obviously during this time monomer has disappeared in the formation of higher oligomers. This indicates the greater nucleophility of the anion of I having the potassium gegen ion ($\sim\overline{CONH}K^+$) over the corresponding sodium derivative in adding to the double bond of acrylamide.

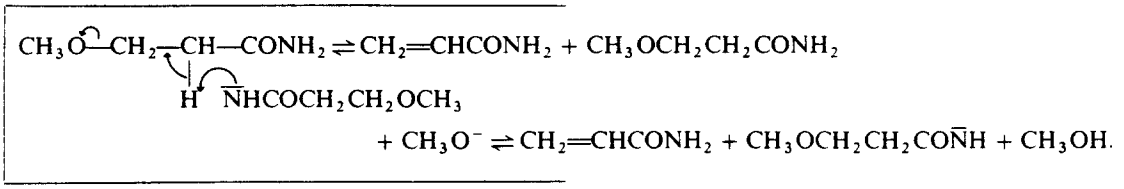
The reactivities of the alkali metal methoxides were further compared from study of the maximum amount of methanol that can be added to a constant ratio of [methoxide]/[acrylamide] in DMF without stopping propagation. Thus at a ratio of [methoxide]/[acrylamide] = 0.1, this amount of methanol was given by the ratio of [methanol]/[acrylamide] = 1.8 in the case of sodium and only 0.71 in the case of lithium.

Simultaneous follow-up of reactants and products

To obtain more information concerning the oligomerization, an experiment was carried out in which the disappearance of the reactants and the formation of I were followed simultaneously. The reaction was carried out at 28° in an aprotic solvent (DMF) and in the presence of such a concentration of methanol that will allow propagation. The results in Fig. 8 and Table 3 show that acrylamide is consumed continuously, and concurrently I is formed. After 70% of the acrylamide had been converted to I and the concentration of the latter reached a maximum, I started to disappear more quickly than the monomer. The methanol concentration went down from an initial 2.5–0.45 mole/l when the maximum amount of I was formed. Concurrently with the disappearance of I, the concentration of methanol started to increase up to 2 mole/l, and then decreased to 1.1 mole/l after 6 hr, when the system reached equilibrium (the concentrations of acrylamide and I were 0.2 and 0.75 mole/l respectively).

The reactants were determined quantitatively by gas chromatography. Methanol was determined in the reaction mixture before acidification (so that methoxide ion was not converted to methanol; acrylamide and I were determined in the reaction mixture, after neutralization by HCl, so that both I and its anion were determined together. The results (Table 3) indicate that not all the I formed was free, but part of it (equal to the amount of the sodium methoxide used) was in the form of I anion. This can be seen from the fact that at the maximum where 2.5 mole/l of I were formed, not all the methanol was consumed although its initial concentration was also 2.5 mole/l. Actually the concentration of methanol that remained (0.45 mol/l) is approximately equal to that of the initial concentration of sodium methoxide, indicating that an amount of I equal to the methoxide remained in the form of an anion without undergoing termination by methanol, and also showing that no free methoxide was present in the reaction mixture. This confirms the previous result (Table 2).

The decrease in the concentration of I after the maximum is paralleled exactly by the increase of methanol concentration. This clearly indicates that there is a reversible reaction, base-catalysed by the anion of I, in which I is decomposed to acrylamide and methanol.



It is possible that the methoxide formed may abstract a hydrogen not from I but from acrylamide, forming acrylamide anion. However, lack of olefinic double bonds in the oligomers, indicates that, even if such

Table 3. Variation in concentration of reactants with time*

Time, min	[Acrylamide] (mole/l)	[I] (mole/l)	[Methanol] (mole/l)	[Methanol reacted + $NaOCH_3$] (mole/l)
0	3.5	0	2.50	0.5
11	2.0	1.5	1.50	1.5
20	1.25	2.1	0.75	2.25
25	1.0	2.35	0.50	2.50
30	0.8	2.5	0.45	2.55

* Experimental conditions: sodium methoxide (2 ml of 5N solution) (0.5 mole/l) was added to acrylamide (5g, 3.5 mole/l) in DMF; total volume of reaction mixture, 20 ml; reaction carried out at 28° for 6 hr.

an anion is formed, it disappears by reaction with methanol.

The fact that after the maximum, where I started to decompose to monomer + methanol, the concentration of acrylamide continued to decrease instead of increasing indicates that propagation of the oligomerization occurs so consuming the monomer. Propagation can be by addition of the anion of I to acrylamide:

$$CH_3OCH_2CH_2C\bar{O}NH + CH_2{=}CHCONH_2 \rightarrow CH_3OCH_2CH_2CONHCH_2\bar{C}HCONH_2$$

(A)

$$CH_3OCH_2CH_2CONHCH_2CH_2C\bar{O}NH$$

(B)

$$(A) + CH_2{=}CHCONH_2 \rightarrow CH_3OCH_2CH_2CONHCH_2\underset{\displaystyle CONH_2}{\underset{|}{C}}HCH_2C\bar{H}CONH_2$$

$$(B) + CH_2{=}CHCONH_2 \rightarrow CH_3OCH_2CH_2CONHCH_2CH_2CONHCH_2\bar{C}HCONH_2.$$

To verify further that I is a source of the acrylamide consumed in the propagation reaction, an experiment was carried out in which the conditions were the same as those prevailing when the concentration of I was at the maximum (Table 3) namely [I] = 2.0 mole/l [I anion] = 0.5 mole/l [methanol] = 0.5 mole/l in DMF at 28 . The result was that I disappeared and an oligomer was formed. The amount of I remaining after 6 hr was the same as that which remained in the previous reaction (0.75 mole/l).

In the early stages of the reaction all the acrylamide that reacted was converted to I, and only later when the reversible reaction of I started to reduce its concentration did propagation become noticeable. As mentioned, methanol can lead to termination, and this should be prominent at relatively high methanol concentrations. Besides, methanol leads to solvation of the β-methoxy-acrylamide anions, and the solvated anions are less reactive than the unsolvated ions especially towards nucleophilic addition. This means that, on reducing the methanol concentration, there are less chances of termination, and the β-methoxy-acrylamide anions become less solvated and thus more likely to add to acrylamide leading to propagation. When a large part of I has decomposed, the concentration of methanol increases once more and can stop propagation.

From the findings about the mechanism of the reaction, it is possible to explain the fact that increasing the methoxide concentration led to increase in the oligomer yield and degree of polymerization. The higher initiator concentration leads to higher concentration of $\sim C\bar{O}NH$ anions of I or of growing ends. There is in turn an enhanced possibility that these anions will catalyse the reversible reaction in which methanol is split out from methoxy end groups leading to the formation of olefinic double bonds which will be available for nucleophilic addition by $\sim C\bar{O}NH$ anions in the course of propagation.

$$\sim C\bar{O}NH + CH_3OCH_2CH_2CONH\sim \rightarrow \sim C\bar{O}NH + CH_3OH + CH_2{=}CHCONH\sim$$

$$\sim C\bar{O}NH + CH_2{=}CHCONH\sim \rightarrow \sim CONHCH_2\bar{C}HCONH\sim.$$

Structure of the oligomers

Since there are two possible modes of propagation, 1,2-addition leading to a $\sim CONH_2$ amide group in the polymer, and 1,4-addition leading to a β-alanine structure, the polymers were subjected to hydrolysis of the amide bonds by 6N HCl for 16 hr under reflux. As can be seen from the following scheme, cleavage by the acid can lead to the formation of ammonia besides amino acids such as β-alanine (A), β-aminodicarboxylic acid (B) (2-aminomethyl glutaric acid) and β-amino-tricarboxylic acid (C)

$$\sim NHCH_2CH_2CO\left\{NHCH_2\underset{\displaystyle CONH_2}{\underset{|}{C}}H{-}CH_2CH_2CO\right\}\left\{NHCH_2\underset{\displaystyle CONH_2}{\underset{|}{C}}HCH_2\underset{\displaystyle CONH_2}{\underset{|}{C}}HCH_2CH_2CO\right\}NH\sim$$

$$NH_2CH_2CH_2COOH \qquad NH_2CH_2\underset{\displaystyle COOH}{\underset{|}{C}}H{-}CH_2CH_2\underset{\displaystyle COOH}{\underset{|}{C}}H \qquad NH_2CH_2{-}\underset{\displaystyle COOH}{\underset{|}{C}}HCH_2\underset{\displaystyle COOH}{\underset{|}{C}}HCH_2CH_2{-}COOH$$

(A) (B) (C)

If propagation is only through 1,4-addition, then only β-alanine will be formed. The amount of β-alanine was determined quantitatively by ninhydrin after separation from the acid hydrolysate on paper chromatography. The maximum amount of β-alanine found in the different hydrolysates was between 48–71% based on acrylamide, so that about 30–50% of the propagation must have proceeded through 1,2-addition. The primary amide groups were separately determined by subjecting the oligomers to hydrolysis with 10% NaOH at 95° and distilling the ammonia formed onto 0.1N HCl. Blank experiments

in which β-alanine was heated with alkali under the same conditions did not lead to ammonia. The results indicated that between 25–43% of the starting acrylamide was present as primary amide groups in the oligomers resulting from 1,2-addition. In all cases the sum of the percentages of β-alanine and of acrylamide units in the oligomer was about 90%, showing that other compounds besides β-alanine were present in the hydrolysate. From the hydrolysate scheme shown before, it is seen that an amino dicarboxylic acid or an amino tricarboxylic acid may be present. The possibility of formation of the latter must be small since it requires two consecutive 1,2-additions following a 1,4-addition; since the former is less frequent, the amount of the aminotricarboxylic acid will be very small. Actually paper chromatography of the hydrolysate using 80% phenol showed a weak spot at Rf 0.38 in addition to the strong spot of β-alanine at Rf 0.66; no spot having a lower Rf was detected. This spot could be due to the β-amino dicarboxylic acid (B). Glutamic acid, which is an α-amino dicarboxylic acid quite similar in structure, has an Rf 0.31 under the same conditions (α-amino acids show Rf lower than β-amino acids; α-alanine has Rf 0.60).

The presence of amino di-carboxylic acid in the hydrolysate was confirmed by high voltage (4500 V) electrophoresis at pH7. The hydrolysate contained β-alanine which moved 4.5 cm in the direction of the cathode, and another amino acid which moved 16.8 cm in the direction of the anode. Glutamic acid moved 17.2 cm under the same conditions in the direction of the anode. Since a β-amino acid is less acidic than an α-amino acid of similar structure, it is quite probable that the β-amino dicarboxylic acid (B) was actually present. No higher spot in the direction of the anode was noticed, indicating that no amino tricarboxylic acid in detectable amount was present in the hydrolysate.

The presence of the amino-dicarboxylic acid proves that there were 1,2- and 1,4-additions, and that the oligomer was a copolymer of acrylamide and β-alanine. To confirm this point and to exclude the possibility of the presence of a mixture of two homopolymers of acrylamide and of β-alanine, the crude oligomer was subjected to mild basic hydrolysis (0.1N NaOH for 10 min) so that about 10% of the primary amide groups were hydrolysed (checked by titration of liberated ammonia). The hydrolysate was passed over a strongly basic ion-exchange resin, Amberlite 410, to hold acidic fractions. As an example, out of 0.850 g oligomer which was partially hydrolysed, 0.095 g was held by the ion-exchange resin. The rest of the oligomer contained 62% β-alanine compared with 60% in the starting oligomer. The fraction held on the resin was eluted by dilute HCl and found to contain 50% β-alanine. These results show that there was no significant fraction of homopolyacrylamide, since the chance of its suffering hydrolysis and subsequently being held on the resin should have been greater than that of acrylamide-β-alanine copolymers and there should have been a drastic lowering in the β-alanine content of the oligomer that was held on the ion-exchange resin.

All the oligomers melted between 75–110°. They were completely soluble in water, and large parts of them also in methanol. Their molecular weights by cryoscopy (camphor) were between 550 and 850 (DP = 8 – 12), confirmed by methoxyl end group analysis; in contrast, the high polymers obtained in the absence of protic solvents were insoluble in methanol (part of them also in water) and were high melting (325–340°) [1, 4, 11]. The low melting points of the products and their solubility are due to the very low molecular weights of the oligomers, and to them being random copolymers of acrylamide and β-alanine, which do not allow any special conformation of the product and also interfere with hydrogen bonding between the —CONH-groups.

EXPERIMENTAL

Materials

Acrylamide (Fluka) was recrystallized from methanol. Methanol was dried over magnesium. Dimethyl sulphoxide (DMSO) and dimethyl formamide (DMF) were dried by azeotropic distillation with benzene and fractionally distilled *in vacuo*. Dioxane was dried over sodium and distilled. Biphenyl (BDH) was used. 5N sodium methoxide was prepared by dissolving the required amount of sodium in dry methanol.

Oligomerization procedure

The reactions were carried out in three-necked flasks with a mechanical stirrer, thermometer and an opening fitted with a self-sealing rubber cap through which the reagents were added by syringe. For reactions above 45°, a reflux condenser fitted with a calcium chloride guard tube was attached. The flask was dried by flaming *in vacuo*. All the reactions were carried out under nitrogen. Acrylamide was added followed by the solvent and biphenyl (0.1g) used as internal standard. The flask was held at the required temperature and methoxide was added. When the reaction was complete, aqueous HCl was added to neutralize the reaction mixture. The precipitate of biphenyl was filtered and the solution was evaporated to dryness *in vacuo*. Acetone was added to the residue to dissolve acrylamide and β-methoxy propionamide (I); the insoluble oligomer was dissolved in water and alkalimetal ion removed by passing over Amberlite IRC-50. The pure oligomer was recovered on evaporation of the aqueous solution to dryness *in vacuo*.

β-Methoxy propionamide (I)

Sodium methoxide solution (5N, 20 ml, 0.1 mole) was added to a solution of acrylamide (7.1g, 0.1 mole) in dry methanol (50 ml). The solution was boiled under reflux for 1 hr, cooled and neutralized with HCl. The precipitated sodium chloride was filtered, and the filtrate was evaporated to dryness *in vacuo*. The residue was distilled *in vacuo*, and β-methoxy propionamide was collected at 100°/1mm; yield 8.1g (80%), m.p. 46° [3]. Infra-red (Nujol, cm^{-1}) 2820 ($—CH_2—CH_2$) 1670 (amide I), 1615 (amide II), 1110 (ether); NMR (D_2O, δ), 3.4 (s, 3, OCH_3), 3.6 (*t*, 2, OCH_2), 2.6 (*t*, 2, $—CH_2CO$). Anal. calcd for $C_4H_9NO_2$: C, 46.40; H, 8.63; N, 13.58. Found: C, 46.21; H, 8.73; N, 13.45.

Determination of β-alanine in the oligomers

Oligomer (100 mg) was dissolved in water (10 ml) and conc. HCl (10 ml) and heated under reflux for 10 hr. The solution was evaporated to dryness *in vacuo*; the residue was taken up in water (5 ml) and aliquot portions were taken for quantitative paper chromatography [12]. A reference solution containing β-alanine (20 mg) in 0.1N HCl (5 ml) was used, and the developing solvent was *n*-butanol–water (1:1) to which acetic acid was added to bring the mixture into one phase.

Gas chromatography

Gas chromatography was used to monitor quantitatively the monomer, I and methanol. Biphenyl was used as an internal standard. The analysis was carried out using a Packard 7400 Gas Chromatograph. For determination of monomer and I, the column was packed with 3% diethylene glycol succinate on chromosorb W. Injector and detector temperatures were 160°, and the column was held at 140°. For determination of methanol the column was packed with 3% SE 30, the column temperature was 50° and the detector and injector temperatures were 100°. Only methanol, biphenyl, and DMF are detected on this column.

REFERENCES

1. D. S. Breslow, G. E. Hulse and A. S. Matlack, *J. Am. chem. Soc.* **79**, 3760 (1957).
2. J. P. Kennedy and T. Otsu, *J. Macromol. Sci.-Revs. Macromol. Chem.* **C6** (2), 237 (1972).
3. H. Tani, N. Oguni and T. Araki, *Makromolek. Chem.* **76**, 82 (1964).
4. N. Ogata, *Bull. chem. Soc. Japan* **33**, 906 (1960).
5. G. Teichman and A. Zilkha, *Europ. Polym. J.* **3**, 283 (1967).
6. S. Freireich and A. Zilkha, *J. Macromol. Sci.-Chem.* **A6**, 1383 (1972).
7. B. A. Feit, J. Sinnreich and A. Zilkha, *J. org. Chem.* **32**, 2570 (1967).
8. E. A. S. Cavell and J. A. Speed, *J. chem. Soc.* 226 (1961).
9. A. J. Parker, *Q. Rev.* **16**, 163 (1962).
10. E. Tommila and N. L. Murto, *Acta chem. scand.* **17**, 1947 (1965).
11. N. Ogata, *Makromolek. Chem.* **40**, 55 (1960).
12. J. P. Greenstein and M. Winitz, *Chemistry of the Amino Acids*, p. 1309. John Wiley, New York (1961).