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LIQUID CHROMATOGRAPHIC STUDY OF THE HYDROLYSIS REACTIONS OF CYCLIC AND LINEAR POLYPHOSPHATES IN AQUEOUS SOLUTION

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SUMMARY

Hydrolysis reactions of inorganic cyclic and linear tri-, tetra-, hexa- and octaphosphates were studied by liquid chromatography. The rate constants in 0.1 *M* hydrochloric acid and 0.5 *M* lithium hydroxide solutions at various temperatures were determined. The reaction mechanism is discussed on the basis of the rate constants and the activation energies.

INTRODUCTION

Condensed polyphosphates produced by the condensation of an orthophosphate are important and interesting materials as inorganic multivalent electrolytes and their chemistry has been studied from various viewpoints[1]. In particular, the chemical properties of di- and triphosphates have been extensively investigated in connection with ADP and ATP, which are biochemically important.

However, the investigation of higher linear and cyclic polyphosphates has been hindered by the difficulty involved in their preparation and isolation. We have been studying the various properties and structures of higher cyclic polyphosphates for many years[2–16]. Cyclic polyphosphates with degrees of polymerization of 3, 4, 6 and 8 have been prepared relatively easily and are very interesting materials[17,18].

In this study, the hydrolysis reactions of above four cyclic polyphosphates and the corresponding linear polyphosphates were investigated. The hydrolysis products containing linear hexa- or octaphosphate were prepared by the mild hydrolysis of cyclohexa- or cyclooctaphosphate, respectively.

To determine the hydrolysis rate accurately, it is necessary to separate and determine quantitatively each component of the hydrolysis samples and we have used anion-exchange liquid chromatography for this purpose. To analyse the hydrolysis products of cyclic polyphosphates, an isocratic elution method was successfully employed to separate the parent cyclic polymer from the other hydrolysis products.

For the determination of the hydrolysis rates of linear polymers, the linear polymer, the cyclic polymer (source material) and lower linear polymer hydrolysis products must be separated. For this purpose, a gradient elution method[19] was satisfactorily employed.

We have previously reported that the hydrolysis rates of cyclic polyphosphates are significantly affected by the presence of cations[16]. In alkaline solutions, Li^+ ion accelerates most strongly the hydrolysis rates of the cyclic polymers. This can be related to the formation of an inner-sphere complex (or ion pair) between Li^+ and the cyclic polyphosphate anion. Of both series of polyphosphates used in this study, cyclotriphosphate, $P_3O_9^{3-}$ was the least stable in both acidic and alkaline solutions. We presume that this instability results from strain in the six-membered ring in aqueous solution.

In acidic solution (0.1 M hydrochloric acid), the hydrolysis rates of the linear polyphosphates were higher than those of the corresponding cyclic polyphosphates. For both series, highly polymerized species were degraded faster. In alkaline solution, the linear polymers were more stable than the cyclic polymers. For the linear series the hydrolysis rates for the higher polymers are higher, but for the cyclic polymers even the large ring polymers were stable.

In this paper, linear and cyclic polyphosphates are abbreviated to P_n and P_{nm}, respectively, where n is the degree of polymerization.

EXPERIMENTAL

Materials

Sodium salts of cyclic polyphosphates were prepared by the usual methods[17,18]. Sodium triphosphate was obtained commercially and ammonium tetraphosphate was prepared by the method of Griffith[20]. All other chemicals used were of reagent grade.

Hydrolysis procedure

The initial concentration of each phosphate to be hydrolysed was adjusted to about $1.25 \cdot 10^{-3}$ M and the hydrolysis was performed in a water-bath, the temperature of which was maintained to within ±0.1°C. The hydrolysis reactions were stopped by rapid neutralization and cooling, and the hydrolysis products were analysed.

Chromatographic system

The anion exchanger TSK Gel SAX 10 μm was packed into a 250 mm × 4 mm I.D. column. A Hitachi 655-11 elution pump was used, and a Hitachi 655A-13 reaction pump was connected to mix the Mo^{V}–Mo^{VI} reagent with the column effluents for the spectrophotometric determination of the phosphates. A Hitachi 228A spectrophotometer with a micro flow cell was used as a detector. The flow system was similar to that shown previously[12].

Elution procedure

For the determination of the hydrolysis rates of the cyclic polyphosphates, isocratic elution with 0.4 M potassium chloride (+ 0.1% EDTA) buffered at pH 10.2 was applied and the separation of the parent cyclic polymer and the hydrolysis products was complete. On the other hand, for the analysis of the linear polymer hydrolysis reaction, elution with a gradient of potassium chloride concentration (pH 10.2) as shown in Fig. 1 was used and the cyclic polymer and all linear polymers were well separated from each other.

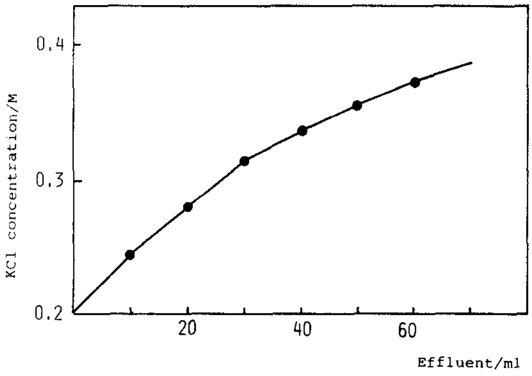

Fig. 1. Gradient elution conditions for the separation of cyclic and linear polyphosphates.

RESULTS AND DISCUSSION

The cation present significantly affect the hydrolysis rates of the cyclic polyphosphates. Complex or ion-pair formation of cyclic polyphosphate anions and the cations renders the phosphorus atom more susceptible to nucleophilic attack by OH^- or H_2O. In this study, the effect of Li^+ on the hydrolysis rates of cyclic polyphosphates in alkaline solutions was further investigated. The hydrolysis rates at various Li^+ concentrations were determined, the OH^- concentration being maintained constant. As an example, chromatograms of the hydrolysis products of cyclooctaphosphate in 0.5 *M* lithium hydroxide at 50°C are shown in Fig. 2. The separation of the cyclic polymer and its hydrolysis products by isocratic elution with 0.4 *M* potassium chloride (pH 10.2) was satisfactory. Under these conditions, the linear polymer hydrolysis products from the cyclic polymer were eluted together at an early stage of elution.

The first-order rate constants for the overall disappearance of a cyclic polymer, k_m, obtained from the analysis of the chromatograms as shown in Fig. 2 are given in Table I. The hydrolysis rates increase appreciably with increase in the Li^+concentration. The k_m value for cyclohexaphosphate hydrolysis is plotted against Li^+ concentration in Fig. 3 and a parabola was obtained. With Na^+, the graph showed a linear relationship and the slope of the line was much lower. In alkaline solutions where M^+ was used as a counter ion of OH^-, the first-order rate equation for the overall disappearance of a phosphate can be expressed as follows:

$$-\frac{dc}{dt} = k_0[OH^-][P_nO_{3n}^{n-}] + k_1[OH^-][MP_nO_{3n}^{(n-1)-}] + \\ + k_2[OH^-][M_2P_nO_{3n}^{(n-2)-}] \quad (1)$$

where the formation of a 1:1 and 2:1 ($M^+:P_nO_{3n}^{n-}$) complex (or ion pair) was assumed and k_0, k_1 and k_2 are the rate constants for the three species. If the stability constants for the 1:1 and 2:1 complexes are denoted β_1 and β_2, respectively, eqn. 1 can be written as

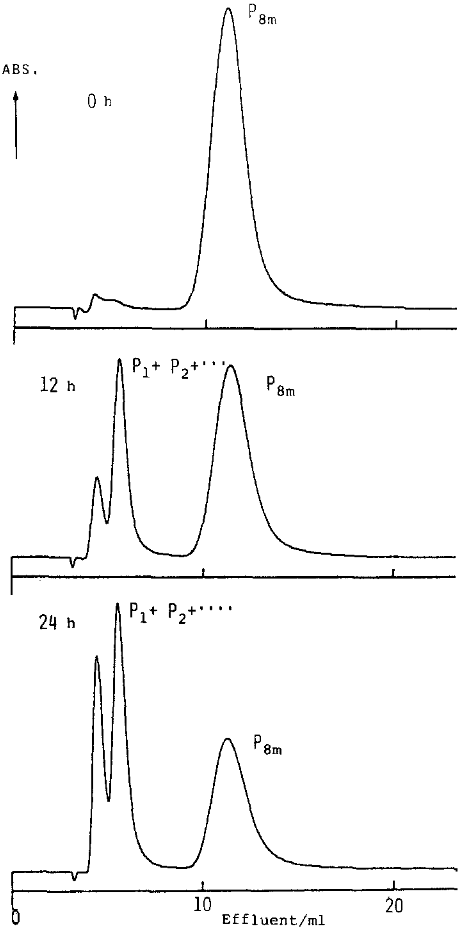

Fig. 2. Chromatograms of the hydrolysis products of cyclooctaphosphate in 0.5 *M* lithium hydroxide at 40°C.

TABLE I

RATE CONSTANTS FOR HYDROLYSIS OF CYCLIC POLYPHOSPHATES AT VARIOUS Li^+ CONCENTRATIONS

$[OH^-] = 0.5$ *M*; 50°C.

$[Li^+]$ (M)	k_m (h^{-1})			
	P_{3m}	P_{4m}	P_{6m}	P_{8m}
0.50	3.69	0.372	0.0913	0.106
0.75	5.73	0.683	0.148	0.177
1.00	7.21	1.00	0.228	0.258
1.25	10.8	1.36	0.315	0.354
1.50	14.3	1.79	0.423	0.457
1.75		2.14	0.529	0.601
2.00		2.61	0.697	0.752

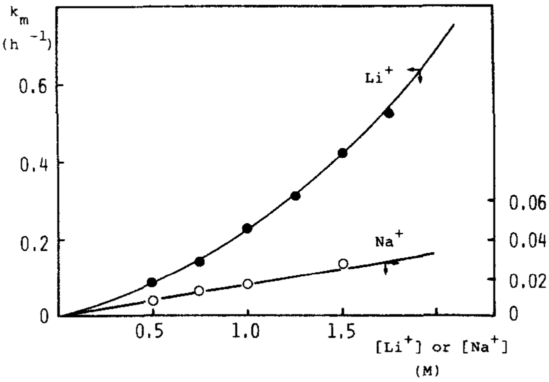

Fig. 3. The effect of lithium and sodium ions on the rate constant of cyclohexaphosphate in alkaline solution ($[OH^-] = 0.5$ *M*) at 50°C.

$$-\frac{dc}{dt} = k_0[OH^-]\,[P_nO_{3n}^{n-}] + k_1[OH^-]\,\beta_1[M^+]\,[P_nO_{3n}^{n-}] + + k_2[OH^-]\,\beta_2[M^+]^2\,[P_nO_{3n}^{n-}] \tag{2}$$

The molar fraction of the free ion, $P_nO_{3n}^{n-}$, X_0, is

$$X_0 = \frac{1}{1 + \beta_1[M^+] + \beta_2[M^+]^2}$$

and $[P_nO_{3n}^{n-}] = X_0c$. Hence eqn. 2 is rewritten as

$$-\frac{dc}{dt} = (k_0 + k_1\beta_1[M^+] + k_2\beta_2[M^+]^2)\,[OH^-]\,X_0c \tag{3}$$

$$k_m = (k_0 + k_1\beta_1[M^+] + k_2\beta_2[M^+]^2)\,[OH^-]\,X_0 \tag{4}$$

The apparent rate constant as a function of $[M^+]$ shows a quadratic relationship. For larger cyclic polymers such as P_{6m} and P_{8m}, the value of k_0 is very low and the graph of k_m *versus* $[M^+]$ is a parabola passing through the origin. The above analysis explains qualitatively the results shown in Fig. 3. The reason why Li^+ accelerates the hydrolysis rate more strongly than Na^+ is speculated as follows. As the crystal radius of Li^+ is very small compared with that of Na^+, an inner-sphere complex (or a contact ion pair) forms more easily and promotes the nucleophilic attack of OH^- on P atoms. We believe that the formation of an inner-sphere complex or contact ion pair is necessary for the acceleration of the hydrolysis rates.

As shown in the chromatograms of the hydrolysis products of P_{8m} during the half-life period, the concentration of the linear octaphosphate, which is the first hydrolysis product of cyclooctaphosphate, is relatively high. The hydrolysis reaction of cyclooctaphosphate might be utilized for the preparation of octaphosphate. We have determined the hydrolysis rates of hexa- and octaphosphate using the product obtained by the mild hydrolysis of cyclohexa- and cyclooctaphosphate, respectively. To determine the hydrolysis rates of the above linear polymers, gradient elution must be applied, the separation using a potassium chloride concentration gradient as in Fig. 1 was satisfactory.

The hydrolysis reaction of a linear phosphate may proceed by any one of at least three routes[21], the end group breaking off the chain to form orthophosphate and a phosphate that is one phosphorus atom shorter; breaking of the chain somewhere in the middle of the chain to yield two chains; or a cyclotriphosphate abstraction. In this work, the first-order rate constants for the overall disappearance of a phosphate species, k_m or k_n, were determined. For example, linear hexaphosphate degrades to linear polymers with degrees of polymerization less than 5 and cyclotriphosphate; however, new hexaphosphate is generated from cyclohexaphosphate.

The hydrolysis scheme is written as

$$P_{nm} \xrightarrow{k_m} P_n \xrightarrow{k_n} P_{n-1}, P_{n-2}, \ldots, P_{3m}$$

where k_m and k_n are the first-order rate constants for the cyclic and linear polymers, respectively. If the concentrations of cyclic and linear polyphosphates at time t are defined as x and y, respectively, the following equations can be derived:

$$-\frac{dx}{dt} = k_m x \tag{5}$$

$$-\frac{dy}{dt} = -k_m x + k_n y \tag{6}$$

These differential equations are solved by assuming that the values of x and y at time zero are a and b, respectively:

$$x = a \exp(-k_m t) \tag{7}$$

$$y = \frac{k_m a}{k_n - k_m} \exp(-k_m t) + \left(b - \frac{k_m a}{k_n - k_m}\right) \exp(-k_n t) \tag{8}$$

The values of k_m are determined by separate experiments and k_n can be calculated from the data obtained from the chromatograms shown in Fig. 4. A least-squares approximation was applied to calculate k_n and the time dependence of the octaphosphate concentration is shown in Fig. 5. The coincidence of the experimental values and those calculated from k_m and k_n by the least-squares method is satisfactory, as shown in Fig. 5.

Similarly, the rate constants in 0.1 *M* hydrochloric acid were determined. The chromatograms of the hydrolysis product in 0.1 *M* hydrochloric acid are shown in Fig. 6. All results obtained are summarized in Table II. The following conclusions might be drawn. Cyclotriphosphate with a six-membered ring structure is most rapidly

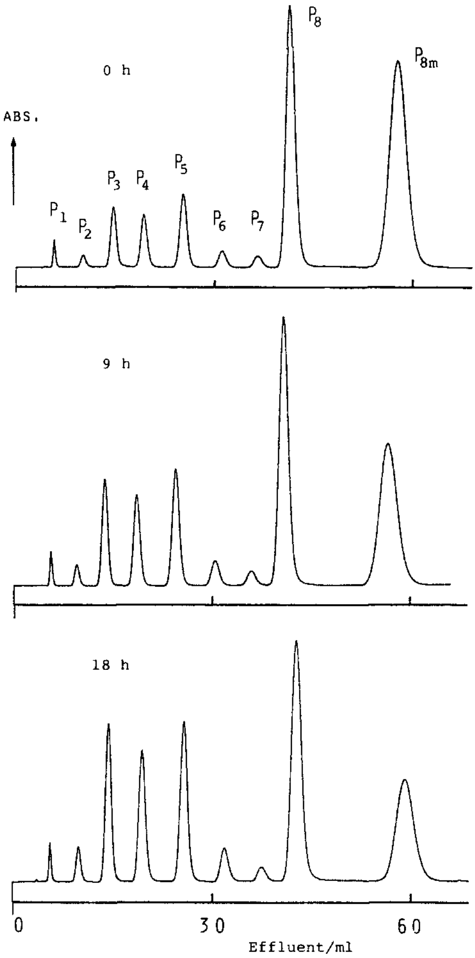

Fig. 4. Chromatograms of the hydrolysis products of octaphosphate in 0.5 *M* lithium hydroxide at 40°C.

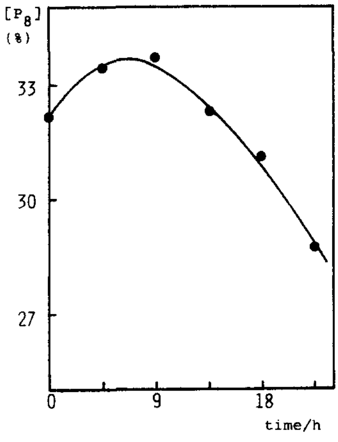

Fig. 5. Octaphosphate hydrolysis in 0.5 *M* lithium hydroxide at 40°C. Points, experimental values; solid line, calculated.

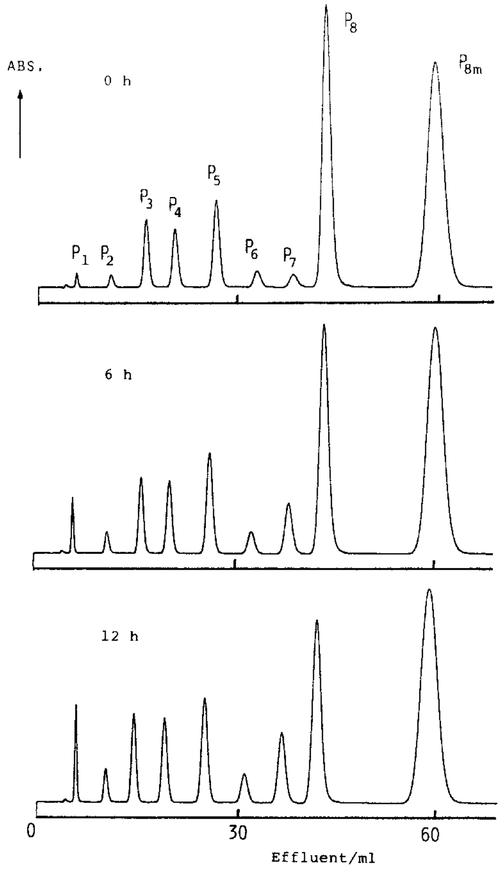

Fig. 6. Chromatograms of the hydrolysis products of octaphosphate in 0.1 *M* hydrochloric acid at 20°C.

hydrolysed in both acidic and alkaline conditions. In aqueous solutions, a six-membered ring structure is thought to be unfavourable owing to the high strain[1].

In acidic solution, linear polymers degrade rapidly compared with the cyclic polymer with same degree of polymerization. For both the cyclic and linear series, the polymers with a higher degree of polymerization degrade more rapidly under these conditions. For cyclic polyphosphates, the reason why the hydrolysis rates of larger ring compounds are higher was discussed in a previous paper[12]. Faster hydrolysis rate for longer linear polymers might be explained by the abstraction of metaphosphate resulting from the formation of a coiled structure, which is possible by neutralization of the charges on PO^- by H^+ in the acidic solution. Cleavage of the end group also occurs.

In alkaline solution, linear polyphosphates are more stable. Tri- and tetraphosphate are especially stable and for their preparation alkaline hydrolysis of cyclotri- and cyclotetraphosphate has been used[22–25]. For linear polymers, the stabilities decrease as the chain length increases. For of cyclic polymers, highly

TABLE II

THE RATE CONSTANTS OF CYCLIC AND LINEAR POLYPHOSPHATES IN 0.5 *M* LiOH AND 0.1 *M* HCl

Medium	k_m *or* k_n (h^{-1})							
0.5 *M* LiOH (50°C)	P_{3m}	4.62,	P_{4m}	0.373,	P_{6m}	0.0912,	P_{8m}	0.104
	P_3	$6.93 \cdot 10^{-4}$,	P_4	$6.19 \cdot 10^{-3}$,	P_6	0.0592,	P_8	0.135
0.1 *M* HCl (40°C)	P_{3m}	0.371,	P_{4m}	0.0430,	P_{6m}	0.0608,	P_{8m}	0.150
	P_3	0.132,	P_4	0.164,	P_6	0.348,	P_8	0.624

polymerized cyclohexa- and cyclooctaphosphate are degraded less rapidly. This tendency is marked in tetramethylammonium hydroxide solution[16].

Arrhenius plots for the hydrolysis of linear phosphates in 0.5 *M* lithium hydroxide are shown in Fig. 7. Good straight lines were obtained. The activation energies for the hydrolysis of both cyclic and linear polymers in 0.1 *M* hydrochloric acid and 0.5 *M* lithium hydroxide are shown in Table III. In 0.1 *M* hydrochloric acid, about E_a values of 20 kcal/mol for both the cyclic and linear series were obtained and they did not depend on the degree of polymerization. A similar reaction mechanism for P–O–P bond cleavage in condensed phosphates under acidic conditions can be proposed.

In 0.5 *M* lithium hydroxide solution, the activation energies of cyclic polyphosphates increase with increase in the ring size. In particular, that for cyclotriphosphate is lower than those for the other cyclic polyphosphates. This is due to the ease of nucleophilic attack on the P atom at PO_4 tetrahedra by nucleophilic reagents such as NH_3, OH^- and H_2O. A planar six-membered ring structure in aqueous

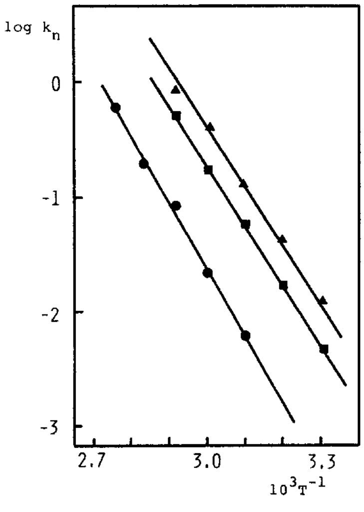

Fig. 7. Arrhenius plots for the hydrolysis reactions of tetra-, hexa- and octaphosphate in 0.5 *M* lithium hydroxide. ▲, P_8; ■, P_6; ●, P_4.

TABLE III

ACTIVATION ENERGIES OF CYCLIC AND LINEAR POLYPHOSPHATES IN 0.5 *M* LiOH AND 0.1 *M* HCl

Medium	E_a *(kcal mol^{-1})*							
0.5 *M* LiOH	P_{3m}	15.3,	P_{4m}	18.6,	P_{6m}	21.6,	P_{8m}	22.2
	P_3	–,	P_4	26.3,	P_6	24.2,	P_8	23.5
0.1 *M* HCl	P_{3m}	21.3,	P_{4m}	24.0,	P_{6m}	21.9,	P_{8m}	23.2
	P_5	20.4,	P_4	20.3,	P_6	20.9,	P_8	21.3

solution has been proposed[26]. This ring structure is unfavourable owing to the high strain. In a transition state where the P atom in the ring combines with the nucleophilic reagent, the P atom forms a trigonal bipyramidal structure using sp^3d hybrid orbitals. The stability of the intermediate and the reactivity of the phosphate with nucleophilic reagents can be explained by the above assumption.

On the other hand, for linear polymers the activation energies are generally higher than those for cyclic polymers. The values decrease with increasing chain length and seem to approach the same value for larger ring phosphates as the chain length increases. Such higher activation energies may be due to the P atom in the chain polymers being unfavourably attacked by nucleophilic reagents such as OH^-.

We can treat such complex systems easily and rapidly as many compounds are produced by the degradation of the parent compounds. This is the result of the development of high-performance liquid chromatography as an analytical tool for the condensed phosphates.

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