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SELECTIVITY OF MONOMERIC METAPHOSPHATE REACTIONS WITH ALCOHOLS IN POLAR APROTIC SOLVENTS

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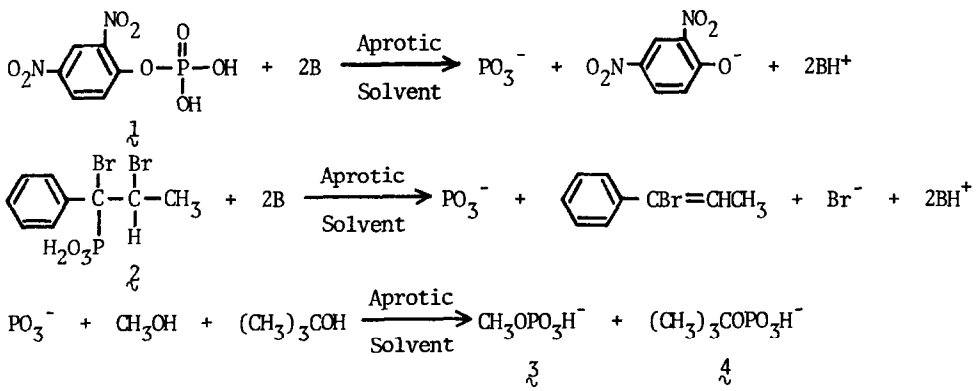
Abstract

Evidence is presented for selectivity in the reaction of metaphosphate, PO_3^-, with methanol in preference to t-butanol in acetonitrile solution. In dichloromethane solution there is also evidence for preferential nucleophilic solvation of reactant by methanol vs. t-butanol.

Following the direct observation of the monomeric metaphosphate ion, PO_3^-, in the gas phase[1], the relevant questions in this field center on the properties of "metaphosphate-like" intermediates in solution[2-7]. With the exception of work in the "three-phase" system[3], virtually all reactions in which the metaphosphate ion may have been implicated were performed in aqueous or alcoholic solutions. Recently, we have worked in aprotic solvents of different polarity[8-11], and others[12] have utilized mixtures of a ketone and a hindered secondary amine as the reaction medium.

The present study was addressed to the following question: is there selectivity in the reactions of the metaphosphate ion with different alcohols in aprotic solvents? To obtain information on this point, two sources of metaphosphate ion were utilized: 2,4-dinitrophenyl phosphate 1 and erythro-1-phenyl-1,2-dibromopropylphosphonic acid 2, both of which decompose readily at 25° C in acetonitrile solutions upon addition of two molequivalents of the hindered base diisopropylethylamine (B).



As nucleophile, an equimolar mixture of methanol and t-butanol was employed, producing a mixture of methyl phosphate 3 and t-butyl phosphate 4 as the sole products. The mole ratio of nucleophile to metaphosphate source, 5:1, was kept constant in all experiments, while the concentration of metaphosphate source (and hence of nucleophile) was increased from 0.025 M to 0.4 M. The reactions were allowed to reach completion (48 h for 1, and 10 min for 2)[13], and the solutions were analyzed by ^{31}P nmr at 145.76 MHz (Brucker WH360), utilizing a pulse delay of 2 sec to insure an accurate integration. To confirm the results, the solvent was evaporated, the residue converted to the sodium salts by ion-exchange chromatography, and the salts analyzed by ^{1}H nmr in D_2O. The results are summarized in Table I.

Table I

Product Ratios, $ROPO_3H^-/R'OPO_3H^-$ = X/1,

From Reactions of Metaphosphate Sources With Nucleophiles in Different Solvents[a]

Solvent	Concentration M	Product Ratio X	Solvent	Concentration M	Product Ratio X
Phosphate 1 + CH_3OH + $(CH_3)_3COH$			Phosphonate 2 + CH_3OH + $(CH_3)_3COH$		
CH_3CN	0.025	4.0	CH_3CN	0.025	5.0
	0.05	4.0		0.05	4.0
	0.10	4.0		0.10	3.0
	0.20	3.0		0.20	3.0
	0.40	4.0		0.40	3.0
CH_2Cl_2	0.05	7.0	CH_2Cl_2	0.05	3.0
	0.20	6.0		0.20	3.0
Phosphate 1 + CH_3OH + $[(CH_3)_2CH]_2CHOH$			Phosphonate 2 + CH_3OH + $[(CH_3)_2CH]_2CHOH$		
CH_3CN	0.20	8.0	CH_3CN	0.20	6.0
CH_2Cl_2	0.20	12.0	CH_2Cl_2	0.20	4.0
Phosphate 1 + C_2H_5OH + $(CH_3)_2CHOH$			Phosphonate 2 + C_2H_5OH + $(CH_3)_2CHOH$		
CH_3CN	0.20	1.0	CH_3CN	0.20	1.0
CH_2Cl_2	0.20	1.0	CH_2Cl_2	0.20	1.0
Phosphate 1 + $(CH_3)_3COH$ + C_6H_5OH			Phosphonate 2 + $(CH_3)_3COH$ + C_6H_5OH		
CH_3CN	0.20	5.0	CH_3CN	0.20	4.0

[a]Metaphosphate source/amine/ROH/R'OH = 1/2/5/5 moles. All reactions to completion at 25° C.

In all experiments, methyl phosphate significantly predominates over t-butyl phosphate, and the results are consistent with the following hypotheses. (a) In the more polar acetonitrile, PO_3^- is generated from phosphate 1 or phosphonate 2 in a unimolecular rate-limiting

step. The PO_3^- thus formed has a higher rate constant with methanol than with t-butanol presumably for steric reasons. It is assumed that the relatively high dipole moment (3.92 D) and dielectric constant (36.2) of acetonitrile relative to the alcohols (1.70 D and 32.6, respectively, for methanol) insures that PO_3^- is formed in an exclusive or predominant acetonitrile environment and encounters a random distribution of both alcohols. This selectivity of metaphosphate reactions in acetonitrile is consistent with the approximate constancy of the product ratios from phosphate and phosphonate, and with the approximate invariance of these ratios at different concentrations of the metaphosphate source. Since both alcohols are assumed to be present randomly around the PO_3^-, both reaction rates should decrease by about the same extent at lower concentrations. The slight trend toward higher product ratios at lower concentrations could reflect self-association of the alcohols. Self-association should be higher for methanol than for t-butanol. Thus, at lower concentrations, where there is less self-association, there should be an enhanced preference for attack by PO_3^- on methanol. As expected, the effect is observed in both reactions (from $\underset{\sim}{1}$ and $\underset{\sim}{2}$).

(b) In the less polar dichloromethane, there seems to be preferential nucleophilic solvation of phosphate $\underset{\sim}{1}$ and phosphonate $\underset{\sim}{2}$ by the smaller methanol vs. the larger t-butanol, as previously suggested[5]. However, it does not follow that such preferential solvation by alcohol must be providing assistance for the formation of PO_3^-, in the sense of converting a unimolecular into a bimolecular step. It could be that preferential solvation of the metaphosphate source by methanol simply increases the probability that PO_3^-, formed in a unimolecular step, will encounter this alcohol in the second step. Our measurements are not sufficiently refined to answer this question. However, the hypothesis of preferential nucleophilic solvation appears to be needed to account for the differences in product ratios from phosphate and phosphonate in dichloromethane at the same concentrations. Moreover, from phosphate, the product ratio is significantly higher in dichloromethane than in acetonitrile at the two concentrations where measurements were made. Models show that the phosphonic acid, $\underset{\sim}{2}$, is a very crowded molecule. This could account for the observation that, at the same concentration in dichloromethane, the ratio of methyl phosphate to t-butyl phosphate is significantly lower when the source of metaphosphate is the phosphonate $\underset{\sim}{2}$ rather than the phosphate $\underset{\sim}{1}$. The phosphonate-phosphorus should be less accessible to solvation by the alcohols than the phosphate-phosphorus. If the ratio of alkyl phosphates is dependent on the relative amounts of methanol vs. t-butanol in the inner solvation shell of the metaphosphate source, the effect should be magnified in the more accessible phosphate.

The additional data provided in Table I for different nucleophile mixtures are in accord with these hypotheses. Note in particular the preference for reaction of t-butanol over phenol in acetonitrile, which suggests the operation of an electronic effect in the reactions.

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13. The half-life for the disappearance of 1 in 0.2 M acetonitrile in the presence of amine is the same ($t_{1/2}$ = 2.5 ± 0.5 hr, 25° C) when the solution contains one, two or three molequivalents of t-butanol (no methanol present), which is consistent with an absence of nucleophilic assistance by the alcohol in the rate-limiting decomposition of phosphate to PO_3^-. Under comparable conditions $t_{1/2}$ for the disappearance of 2 is too fast to measure by our technique (ref. 10).

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