

**Crystal and Molecular Structure of
Pentaaquohexa(diphenyl phosphato)trimagnesium(II),
[(C₆H₅O)₂P(O)O]₆Mg₃(H₂O)₅, a Hydrated Magnesium Phosphodiester Salt
with Penta- and Hexacoordinate Metal Ions**

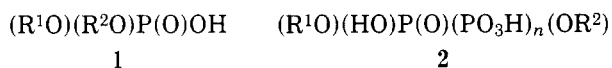
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Anhydrous magnesium diphenyl phosphate is prepared by the reaction of diphenyl methyl phosphate with tris(tetrahydrofuran)magnesium(II) bromide. A solution of the salt in benzene and moist ether deposits triclinic crystals of pentaaquohexa(diphenyl phosphato)trimagnesium(II), space group *PI*, with two formula units, [(C₆H₅O)₂P(O)O]₆Mg₃(H₂O)₅, in the unit cell (*Z* = 2λ) of dimensions: *a* = 15.173 (23); *b* = 23.625 (17); *c* = 12.896 (9) Å; α = 104.85 (6); β = 112.56 (10); γ = 86.23 (10)°. Reflections were collected on a *PI* diffractometer (Mo Kα) by ω step scan mode. The structure was solved by Patterson superposition methods and by iterative Fourier maps, and refined by full-matrix least-squares methods to a final *R* factor of 8.3% for 8126 reflections. Average interatomic distances (Å) are: 2.154, 2.111 for Mg–W (water); 2.042, 1.987 for Mg–O (phosphoryl) for coordination numbers 6 and 5, respectively; and 4.702 for Mg–Mg. The compound can be formulated as [(ArO)₂P(O)O]₂Mg(W)₂·[(ArO)₂P(O)O]₂Mg(W)·[(ArO)₂P(O)O]₂Mg(W)₂, where Ar = C₆H₅ and W = H₂O. The structure consists of infinite chains of phosphodiester molecules linked through Mg²⁺ ions and oriented along the *z* axis. The chains are joined together by the Mg²⁺ ions to give a sequence of eight-membered rings fused in a spiro configuration at the metal, each ring with two Mg, two P, and four O atoms. There are two types of magnesium ions, coordination number 6 and coordination number 5. There are two of the former and one of the latter in the asymmetric unit. Each magnesium ion is coordinated to four oxygen atoms from four different phosphate groups and by one or two water molecules. The geometry about the CN6 Mg atoms is nearly octahedral, but that of the CN5 Mg atom is neither regular trigonal bipyramidal (TBP) nor regular tetragonal pyramidal (TP). The structure suggests models for some possible interactions which may contribute to the conformation of hydrated metal salts of some polynucleotides.

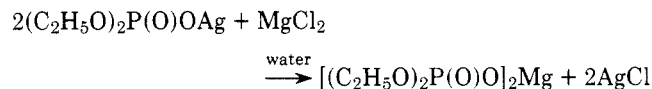
Research on the crystal and molecular structure of esters of phosphoric and polyphosphoric acids, **1** and **2**, has been pursued intensively with the goal of arriving at information on the conformations of such molecules, which are of great importance in biochemistry.



The structures of simple calcium,² sodium,^{3,4} and potassium⁵ phosphomonoesters (1, R² = H), and of barium,^{6,7} and silver⁸ phosphodiesters (1), all as hydrates, have been solved by x-ray diffraction analysis. More complicated structures of type 1 (R² = H) have been elucidated, namely, calcium thymidine 5'-phosphate hexahydrate,⁹ barium adenosine 5'-phosphate heptahydrate,¹⁰ and the cadmium,¹¹ cobalt,¹¹ and manganese¹² salts of cytidine 5'-phosphate hydrates. The following salts of phosphodiesters (1) are also known: sodium adenylyl-3',5'-uridine hexahydrate,¹³ and the calcium¹⁴ and sodium¹⁵ salts of guanylyl-3',5'-cytidine nonahydrate. Sodium guanosine 3',5'-cyclic phosphate tetrahydrate¹⁶ has been reported. Among ammonium salts triethylammonium uridine 3'-*O*-thiophosphate methyl ester¹⁷ and triethylammonium uridine 2',3'-*O*,*O*-cyclophosphorothioate,¹⁸ as well as the model compound bis(dicyclohexylammonium) α,β-(2-naphthyl) dipolyphosphate,¹⁹ are known. The structures of two metal ion salts of condensed polyphosphate monoesters (2, R² = H) have been fully described: rubidium adenosine 5'-dipolyphosphate monohydrate,^{20a} and disodium adenosine 5'-tripolyphosphate hexahydrate.^{20b}

A number of structures based on formulas 1 (R² = H), **1**, and **2** (*n* = 1), but without any metal ion constituent, have been solved and are referenced in recent articles.^{21–23} The structures of three diesters (1) in the phospholipid field, L-α-glycerophosphorylcholine²⁴ and its cadmium chloride trihydrate complex,²⁵ and 1,2-dilauroyl-DL-phosphatidylethanolamine,²⁶ are known.

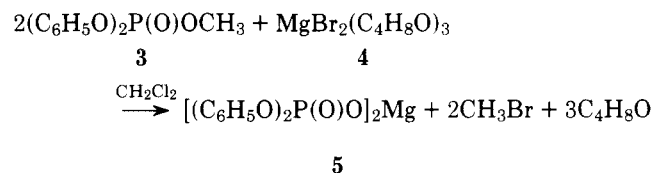
In spite of the essential role played by magnesium in the biochemistry of phosphorus, only two structures of organic phosphate salts of this metal have, to our knowledge, been reported. Ezra and Collin²⁷ prepared magnesium diethyl phosphate as follows:



The monoclinic crystals obtained from 95% ethanol and ethyl acetate consist of a polymer of the formula unit [(C₂H₅O)₂P(O)O]₂Mg, in which Mg atoms are coordinated to four phosphoryl oxygens in a nearly regular tetrahedral arrangement. In contrast, Schwalbe, Goody, and Saenger²⁸ observed discrete molecules of tetrapyridinebis(diethylphosphorothioato)magnesium(II), with Mg atoms in octahedral coordination.

The structures of several *inorganic* magnesium phosphates are known, and the coordination number (CN)²⁹ of their metal atoms varies as follows: 6 in Mg(HPO₄)(H₂O),³⁰ 4, 5, and 6 in Mg₃(PO₄)₂,³¹ 6 in Mg(NH₄)₂(HPO₄)₂(H₂O)₄,³² 6 in Mg₂(PO₄)Cl,³³ 5 and 6 in α-Mg₂P₂O₇,³⁴ and 6 in Mg₂P₄O₁₂³⁵ (tetrametaphosphate).

The present investigation focuses on the synthesis of anhydrous magnesium diphenyl phosphate (MDP) by the new reaction:³⁶



Both the reagent, tris(tetrahydrofuran)magnesium bromide (**4**),³⁶ and the reaction product, MDP (**5**), are relatively soluble in dichloromethane (3.0 and 0.02 M solutions at 25 °C, re-

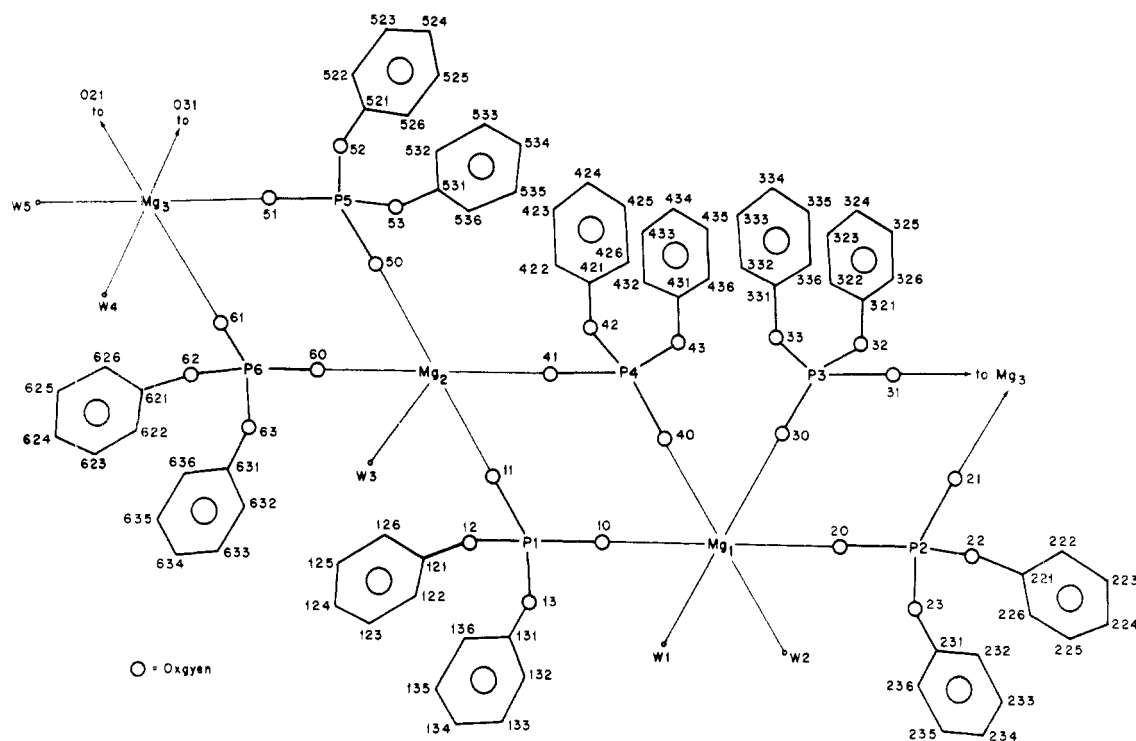


Figure 1. Numbering system for the atoms in the formula unit of 6.

spectively). The salt 5 prepared in this manner has also a finite solubility in benzene (0.002 M at 25 °C). This method, therefore, permits the introduction of known amounts of aprotic and protic donor molecules into a strictly anhydrous magnesium phosphodiester solution for the purpose of studying the coordination chemistry of these biochemically important complexes.

Experimental Section

Preparation of Magnesium Diphenyl Phosphate (5). A solution of diphenyl methyl phosphate³⁷ (2.43 g, 9.12 mmol) in anhydrous dichloromethane (3 mL) was added dropwise to a solution of $MgBr_2(C_4H_9O)_3$ (4; 1.83 g, 4.56 mmol) in dichloromethane (25 mL) at 25 °C under Ar. The clear solution was stirred for 4 h at 25 °C; no solid phase was observed at this point. The solution was evaporated at 30 °C (30 mm), and the residue was extracted with anhydrous diethyl ether (2 × 10 mL). The resulting powder was dried for 45 min at 25 °C (0.1 mm): yield 2.01 g or 85% of the theory based on formula $[(C_6H_5O)_2P(O)]_2Mg$. For elemental analysis, the sample was washed successively with small volumes of benzene and ether, and was dried as above. Calcd for $C_{24}H_{20}O_8P_2Mg$ (mol wt 522): C, 55.2; H, 3.8; P, 11.8; Mg, 4.6. Found: C, 55.2; H, 4.0; P, 11.8; Mg, 4.5. ³¹P NMR δ +18.6 ppm in $CDCl_3$ and +9.1 ppm in D_2O (sharp singlets in both cases), from $H_3PO_4 = 0$. Compound 5 is crystalline according to x-ray powder photographs.

Crystallization of Pentaquoehexa(diphenyl phosphato)trimagnesium(II). (6). A solution of MDP (5) in benzene was diluted with moist diethyl ether (5:1, v/v) and kept for several days at 25 °C to allow the slow growth of satisfactory small plates. The crystals, once harvested, were very sensitive to atmospheric moisture; they were handled under a constant flow of Ar in a glove box, and sealed in glass capillaries with a trace of silicon grease to prevent the crystals from slipping. Crystal data: triclinic; space group $P1$; $a = 15.173$ (23); $b = 23.625$ (17); $c = 12.896$ (9) Å; $\alpha = 104.85$ (6); $\beta = 112.56$ (10); $\gamma = 86.23$ (10)°; $V = 4124$ Å³; $Z = 2$ (one formula unit $C_{72}H_{70}O_{28}P_6Mg_3$ per asymmetric unit). $\rho_{calcd} = 1.34$ g cm⁻³; $\rho_{obsd} = 1.37$ g cm⁻³ (floatation in carbon tetrachloride/hexane). Intensity data were collected on a $P1$ diffractometer employing Mo $K\alpha$ radiation by ω step scan mode. Out of 13 459 unique reflections collected below $2\theta = 52^\circ$, 8126 reflections with their intensities 2.33 σ above the background were considered to be observed reflections. Lorentz and polarization corrections were applied to the intensity data, but no absorption corrections were applied.

Solution and Refinement. The structure was solved by Patterson superposition methods and by iterative Fourier maps. Sixteen of the

peaks selected from the superposition maps performed on the four prominent sharpened Patterson peaks could be judiciously assigned to be atomic peaks, from the criterion that phosphorus has tetrahedral and magnesium octahedral ligands. The first Fourier map calculated with seven of these peaks revealed four other peaks of the 16 selected peaks and from the subsequent Fourier maps all the 110 nonhydrogen atoms were located.

Refinements on observed reflections were by full-matrix least squares, minimizing $\sum w(\Delta F)^2$ with weights $w = 1/\sigma^2(F)$. In the isotropic refinements the structure was refined in two blocks and in anisotropic refinements it was divided into six blocks and the three magnesium atoms were included in every block. The positions of the hydrogen atoms belonging to phenyl groups were calculated (at 1.0-Å distance) from the molecular geometry. Their parameters were included in the refinements, but they were not refined. Their thermal parameters were the final isotropic terminal parameters of carbon atoms to which they are attached. During the anisotropic refinements those reflections of $\Delta F > 10 \sigma$ were not included in refinements. In the final difference Fourier map a number of peaks were found around the water oxygen atoms. Seven of these peaks were assumed to be hydrogen atoms belonging to water oxygen atoms, due to their reasonable hydrogen-bond geometries. These were also included in the final structure factor calculation.

After termination of the refinements the positions of the phenyl hydrogen atoms were recalculated from the final coordinates and their thermal parameters were readjusted, respectively. The final structure factor calculated (177 atoms) with all the observed 8126 reflections gave an R value of 0.083 and $R_w = 0.128$. The scattering factors for nonhydrogen atoms were from International Tables for X-Ray Crystallography,³⁸ and for H atoms from Stewart et al.³⁹ The positional and thermal parameters of the atoms with their esd's are given in Table V. Table V is given as supplementary material; see paragraph at end of paper. For consultation of structure factors see also paragraph at end of paper.

Results and Discussion

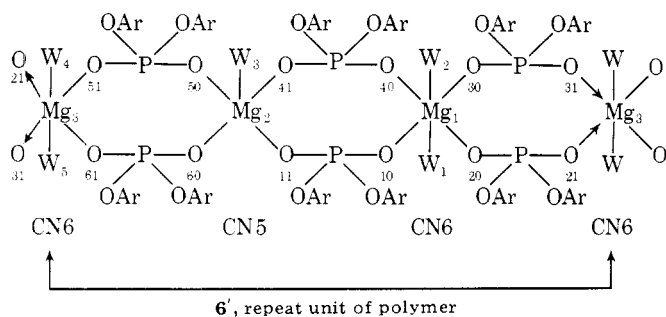
Molecular Structure of Pentaquoehexa(diphenyl phosphato)trimagnesium(II) (6). The atoms are numbered as shown in Figure 1, and one isolated formula unit is illustrated in Figure 2. Tables I and II give the most significant interatomic distances and angles, respectively. Several equations of least-squares planes, the deviations of certain atoms from those planes, and a few dihedral angles between planes related to the geometry about the magnesium are

Table I. Main Interatomic Distances (Å) in 6 and Their Standard Deviations^a

Metal–Oxygen					
Mg(1)–O(10)	2.056 (4)	Mg(2)–O(11)	1.987 (3)	Mg(3) ← O(21) ^b	2.073 (4)
Mg(1)–O(20)	2.033 (4)	Mg(2)–O(41)	1.985 (4)	Mg(3) ← O(31) ^b	2.033 (4)
Mg(1)–O(30)	2.075 (3)	Mg(2)–O(50)	1.964 (5)	Mg(3)–O(51)	2.023 (4)
Mg(1)–O(40)	2.019 (4)	Mg(2)–O(60)	2.012 (3)	Mg(3)–O(61)	2.023 (4)
Mg(1)–W(1)	2.176 (4)	Mg(2)–W(3)	2.111 (5)	Mg(3)–W(4)	2.141 (5)
Mg(1)–W(2)	2.129 (4)			Mg(3)–W(5)	2.166 (4)
Phosphorus–Oxygen					
P(1)–O(10)	1.471 (5)	P(2)–O(20)	1.466 (5)	P(3)–O(30)	1.483 (4)
P(1)–O(11)	1.473 (4)	P(2)–O(21)	1.476 (4)	P(3)–O(31)	1.469 (4)
P(1)–O(12)	1.599 (3)	P(2)–O(22)	1.603 (4)	P(3)–O(32)	1.604 (4)
P(1)–O(13)	1.596 (4)	P(2)–O(23)	1.603 (4)	P(3)–O(33)	1.590 (4)
P(4)–O(40)	1.471 (4)	P(5)–O(50)	1.473 (5)	P(6)–O(60)	1.477 (3)
P(4)–O(41)	1.486 (4)	P(5)–O(51)	1.489 (4)	P(6)–O(61)	1.471 (5)
P(4)–O(42)	1.589 (4)	P(5)–O(52)	1.599 (4)	P(6)–O(62)	1.590 (4)
P(4)–O(43)	1.585 (4)	P(5)–O(53)	1.597 (4)	P(6)–O(63)	1.609 (4)
Benzene Ring ^c					
Average values		C–C 1.362 (14)		C–O 1.398 (9)	
Metal–Metal					
Mg(1)···Mg(2)	4.720 (3)	Mg(2)···Mg(3)	4.636 (2)	Mg(3)···Mg(1) ^b	4.751 (3)
Metal–Phosphorus					
Mg(1)···P(1)	3.404 (3)	Mg(2)···P(1)	3.254 (2)	Mg(3)···P(2) ^b	3.311 (2)
Mg(1)···P(2)	3.332 (3)	Mg(2)···P(4)	3.145 (2)	Mg(3)···P(3) ^b	3.471 (2)
Mg(1)···P(3)	3.291 (2)	Mg(2)···P(5)	3.410 (3)	Mg(3)···P(5)	3.264 (2)
Mg(1)···P(4)	3.440 (3)	Mg(2)···P(6)	3.366 (2)	Mg(3)···P(6)	3.303 (2)
Oxygen(water)–Oxygen(phosphoryl)					
W(1)···O(20)	2.932 (6)	W(2)···O(10)	2.675 (6)	W(3)···O(60)	2.629 (5)
W(1)···O(40)	3.012 (5)	W(2)···O(51)	2.808 (6) ^d	W(3)···O(30)	2.791 (6)
W(1)···O(10)	3.041 (6)	W(2)···O(30)	3.019 (6)	W(3)···O(11)	2.856 (5)
		W(2)···O(20)	3.072 (5)	W(3)···O(41)	3.130 (5)
		W(2)···O(31)	3.131 (6)		
W(4)···O(21)	2.644 (6) ^b	W(5)···O(22)	2.836 (5) ^b		
W(4)···O(41)	2.818 (6)	W(5)···O(31)	2.883 (6) ^b		
W(4)···O(61)	3.020 (5)	W(5)···O(21)	2.908 (5) ^b		
W(4)···O(51)	3.058 (6)	W(5)···O(61)	2.912 (5)		
Oxygen(water)–Oxygen(water)					
W(1)···W(2)	2.890 (6)	W(4)···W(5)	2.984 (5)		
Oxygen(phosphoryl)–Oxygen(phosphoryl)					
O(11)···O(50)	2.826 (5)	O(11)···O(41)	3.019 (5)		
O(31)···O(51) ^d	2.891 (4)	O(60)···O(41)	3.049 (5)		
O(50)···O(60)	2.904 (5)	O(50)···O(41)	3.095 (5)		
O(10)···O(30)	2.913 (5)	O(11)···O(60)	3.933 (5)		
O(21)···O(51) ^d	2.942 (5)	O(61)···O(21) ^b	4.078 (5)		
O(31)···O(61) ^d	2.964 (5)	O(10)···O(20)	4.084 (5)		

^a Numbers in parentheses are esd's in the least significant digits. ^b Atoms related by $z + 1$. ^c Average values; esd's in parentheses are the larger of an individual deviation. ^d Atoms related by $z - 1$.

gathered in Table VI, submitted as Supplementary Material.



Compound 6 can be formulated as $[(\text{ArO})_2\text{P}(\text{O})]_2\text{Mg}(\text{W})_2 \cdot [(\text{ArO})_2\text{P}(\text{O})\text{O}]_2\text{Mg}(\text{W}) \cdot [(\text{ArO})_2\text{P}(\text{O})\text{O}]_2\text{Mg}(\text{W})_2$. This

is best seen in the partial formula 6'. The structure consists of infinite chains of phosphodiester molecules linked through Mg ions and oriented along the z axis. The chains are joined together by the Mg ions to give a sequence of eight-membered rings fused in a spiro configuration at the metal, each ring with two Mg, two P, and four O atoms. The six phosphodiester molecules in the formula unit of the compound, which is also the asymmetric unit of the crystal, occur as three dimers, one of them bonded by CN5 Mg, and two by CN6 Mg.^{40,41} Both types of coordination spheres in the triplet of dimers have four O atoms from four different phosphoryl groups, and the coordination is completed by one or two water molecules, respectively. The geometry about both CN6 atoms is nearly octahedral, but that of the CN5 atoms is neither trigonal bipyramidal (TBP)²⁹ nor tetragonal pyramidal (TP),²⁹ although it is closer to the latter; this question is discussed below.

No information is available on the structure of anhydrous

Table II. Main Angles (deg) in 6 and Their Standard Deviations

Mg(1)---Mg(2)---Mg(3)	143.7 (2)	Mg(2)---Mg(1)---Mg(3) ^a	135.6 (2)	Mg(2)---Mg(3)---Mg(1) ^b	137.8 (2)
Mg(1)–O(10)–P(1)	149.2 (2)	Mg(2)–O(11)–P(1)	139.8 (2)	Mg(3)–O(51)–P(5)	136.2 (2)
Mg(1)–O(20)–P(2)	144.0 (2)	Mg(2)–O(41)–P(4)	129.3 (2)	Mg(3)–O(61)–P(6)	141.4 (2)
Mg(1)–O(30)–P(3)	134.7 (2)	Mg(2)–O(50)–P(5)	165.5 (2)	Mg(3) ← O(21)–P(2) ^b	137.2 (2)
Mg(1)–O(40)–P(4)	160.5 (2)	Mg(2)–O(60)–P(6)	149.1 (2)	Mg(3) ← O(32)–P(3) ^b	164.5 (2)
O(11)–Mg(2)–O(60)	159.3 (2)	O(50)–Mg(2)–W(3)	157.0 (2)	O(41)–Mg(2)–O(50)	103.2 (2)
O(41)–Mg(2)–W(3)	99.6 (2)	O(11)–Mg(2)–O(41)	98.9 (1)	O(50)–Mg(2)–O(60)	93.8 (2)
O(10)–Mg(1)–O(20)	174.5 (2)	O(30)–Mg(1)–W(1)	175.5 (2)	O(40)–Mg(1)–W(2)	172.6 (2)
O(10)–Mg(1)–O(30)	89.7 (2)	O(10)–Mg(1)–W(2)	79.5 (2)	O(20)–Mg(1)–O(40)	91.0 (2)
O(20)–Mg(1)–W(1)	88.3 (2)	O(30)–Mg(1)–W(2)	91.8 (2)	O(40)–Mg(1)–W(1)	91.7 (2)
O(51)–Mg(3)–W(5)	177.0 (2)	O(61)–Mg(3)–O(21)	169.4 (2)	O(31)–Mg(3)–W(4)	171.0 (2)
O(51)–Mg(3)–O(21)	91.8 (1)	O(51)–Mg(3)–W(4)	94.5 (2)	O(61)–Mg(3)–W(5)	88.0 (2)
O(61)–Mg(3)–O(31)	93.9 (2)	W(5)–Mg(3)–O(31)	86.7 (2)	O(21)–Mg(3)–W(4)	77.7 (2)
O(metal)–P–O(metal) ^c	120.1 (3)	O(phenyl)–P–O(phenyl) ^c	104.0 (3)		
O(i)(metal)–P(j)–O(i + 2)(phenyl) ^c	111.2 (3)	i = 10, 11, 20, 21, ... 60, 61; j = 1, 2, ... 6; k = 1 or 3			
O(i)(metal)–P(j)–O(i + k)(phenyl)	104.7 (2)				
C–C–C ^c	119.8 (9)	C–O–P ^c	124.1 (4)		
O(ij)–C(ij)–C(ij2)	121.0 (7)	i = 1, 2, ... 6; j = 2 or 3			
O(ij)–C(ij)–C(ij6)	117.0 (7)				

^a Atoms related by $z - 1$. ^b Atoms related by $z + 1$. ^c Average quantities.

MDP (5). However, little ion-pair dissociation is expected in a benzene solution of 5, and we speculate that the limited amount of water introduced into the benzene/ether solvent allows the partial hydration, and the reorganization of the hydrated ion pairs into the "triplets" present in the formula unit and the polymer crystal.

The distances between phosphoryl oxygens and magnesium are shorter than those between water oxygens and the metal, and any Mg–O distance is shorter when the metal has CN5 than when it has CN6. A decrease in interatomic distance should accompany a decrease in CN, since nonbonded repulsions between ligands should be lower in the lower CN state.⁴²

The average Mg(CN5)–O(phosphoryl) distance (1.987 Å) is less than the average Mg(CN6)–O(phosphoryl) distance (2.042 Å); likewise the average Mg(CN5)–W (2.111 Å) is less than the average Mg(CN6)–W (2.154 Å). The average Mg–W (water) distance is larger in the partially hydrated aquo-MDP (6) (2.132 Å) than in the completely hydrated octahedral MgX₂(H₂O)₆ (X = Cl, Br)⁴³ and in several other salts^{44–47} (~2.08 Å), and it is closer to the value found in diaquobis(acetylacetonato)magnesium(II) (2.148 Å).⁴⁸ The Mg–O(phosphoryl) distances in 6 are in the range reported for other Mg–O distances (1.990–2.161 Å).^{44–48} An exceptionally long Mg–O distance has been recorded (2.40 Å).³³ In compound 6, Mg–O(phosphoryl) < Mg–W, but the reverse is true in some other structures, e.g., magnesium formate dihydrate.⁴⁶ Apparently the phosphoryl oxygen in combination with water molecules tends to occupy the coordination sites associated with stronger bonds.

The P–O bonds bridged by Mg atoms are shorter (average distance 1.475 Å) than those leading to the phenyl rings (average distance 1.597 Å). Resonance delocalization of unshared oxygen electrons into the benzene ring would decrease the extent of p–d π bonding involving those oxygen unshared electrons and the phosphorus, accounting for the observed differences. The distances between consecutive Mg atoms in the formula unit average 4.678 Å, while the distance between metal atoms across formula units is 4.751 Å, indicative of the polymeric nature of the crystal; note also the Mg...P distances, e.g., Mg(3)---P(2) [$z + 1$] which are similar to, or shorter than, related distances within the formula unit.

With respect to the distances between water oxygens and phosphoryl oxygens, it is noteworthy that, in some instances, e.g., W(3)---O(30) and W(4)---O(41), a water coordinated to one magnesium atom is relatively close to a phosphoryl oxygen

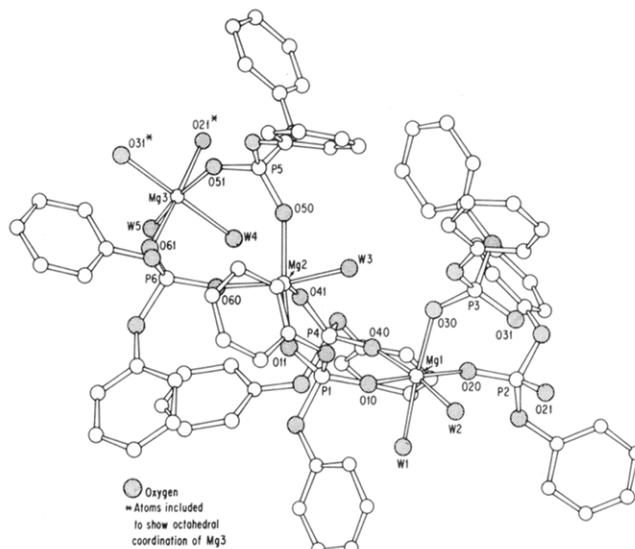


Figure 2. Compound 6 showing the different coordinations for magnesium.

bonded to another Mg atom within the same formula unit. The same is true across formula units, e.g., W(2)---O(51) [$z - 1$], W(4)---O(21) [$z + 1$], and W(5)---O(31) [$z + 1$]. In one instance, the water approaches close to one of the ester oxygens in the adjacent formula unit, W(5)---O(22) [$z + 1$] = 2.83 Å. These data suggest significant stabilization of the structure through hydrogen bonding involving water and phosphate oxygens within and across formula units. These phenomena are of interest in connection with models by which hydrated metal ions can contribute to the structure and configuration of hydrated metal salts of polynucleotides.

The three magnesium atoms in the formula unit define an angle of 143.7°, while the related angles involving one Mg atom of the adjacent formula units are 135.6 and 137.8°, respectively. The Mg–O–P angles vary from a minimum of 129.3° to a maximum of 165.5°, and within a formula unit this extreme range is found about CN5 Mg. The O–P–O angles are wider (av 120.1°) when both oxygens are coordinated to the metal than when they are covalently bonded to the phenyl rings (av 104.0°). The phosphate groups are distorted tetrahedra.⁴⁹

The skeletal geometry about the two CN6 Mg atoms is that of a distorted octahedron. The maximum deviation from 180°

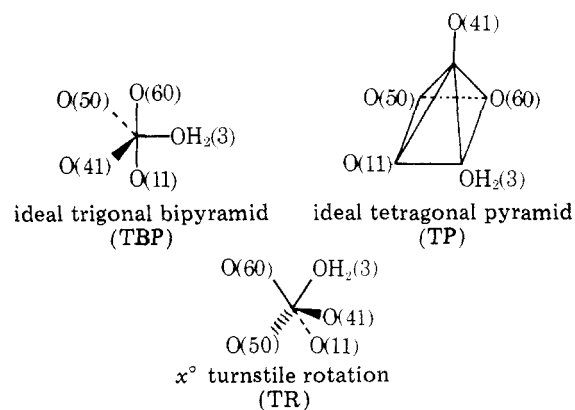
Table III. Deviations from Ideal Trigonal Bipyramid (TBP) and Tetragonal Pyramid (TP) in the Skeletal Geometry of 5-Coordinate Magnesium in 6

Angle	From TBP		From TP	
	Deviation from, deg	Deviation, deg	Deviation from, deg	Deviation, deg
O(11)-Mg-O(60)	180	-20.7	150	+9.3
O(50)-Mg-H ₂ O(3)	120	+37.0	150	+7.0
O(41)-Mg-O(50)	120	-16.8	105	-1.8
O(41)-Mg-H ₂ O(3)	120	-20.4	105	-5.4
O(41)-Mg-O(60)	90	+9.4	105	-5.6
O(11)-Mg-O(41)	90	+8.9	105	-6.1
O(50)-Mg-O(60)	90	+3.8	86	+7.8
O(11)-Mg-O(50)	90	+1.3	86	+5.3
O(11)-Mg-H ₂ O(3)	90	-1.7	86	+2.3
H ₂ O(3)-Mg-O(60)	90	-10.8	86	-6.8

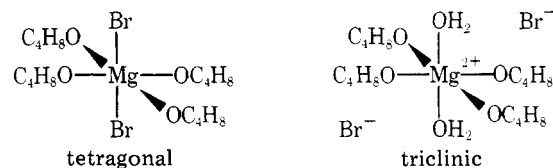
is found in one angle each of Mg(1) (-8°) and Mg(3) (-10°); the maximum deviation from 90° is found in one angle of Mg(1) (-11°) and one of Mg(3) (-12°). The remaining angles are close to the ideal values.

The skeletal geometry about CN5 Mg can be analyzed as follows. (i) The ten bond angles about the metal are considered in the order of their decreasing values, and the deviations from the values to be expected if those ligands are placed on the ideal trigonal bipyramid skeleton are noted. The results are shown in Table III. (ii) The same set of ligands are then placed on the hypothetical ideal trigonal pyramid skeleton which would result from the performance of a permutational isomerization of the TBP structure according to the Berry pseudorotation mechanism;⁵⁰ in doing so, the ligand that seems to be closer to being "flagpole" in the resulting TP is chosen as the "pivot" of the pseudorotation. The deviations between observed and ideal TP angles are listed in Table III. (iii) Several significant least-squares planes based on the ideal TBP and TP are calculated (Table VI), and the dihedral angles formed by some of these planes are calculated. (iv) From these considerations it is concluded that the actual geometry about the CN5 Mg deviates sufficiently from the regular TBP and TP geometries so that another more general description of the skeletal geometry is desirable. For reasons previously given,⁵¹⁻⁵³ the description chosen is that of an x° turnstile rotation (x° -TR) configuration. This geometry is derived from the motions of the five ligands during the permutational isomerization of a TBP phosphorane by the TR mechanism.⁵⁴ The x° -TR is not an ideal geometry; it represents the accommodation of all bond angles and distances in the actual structure to the electronic and steric demands of all the ligands. The x° -TR configuration deviates from the ideal 30°-TR configuration⁵⁴ (C_s point group), which is the geometry of the ideal barrier to be traversed in the TR mechanism of isomerization. The direction, but not the magnitude, of the deviations from the ideal TBP found in the actual x° -TR can be surmised from the TR mechanism. The value of x° in x° -TR is estimated from the dihedral angle between planes 6 and 7 in Table VI, namely 17°. The ligand "pair" of the TR mechanism is H₂O(3), O(60), and the angle H₂O(3)-Mg(2)-O(60) is quite small, 79.2°. Ligands O(11), O(50), and O(41) constitute the TR "trio".⁵⁴

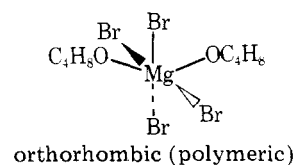
CN6 is commonly found^{28,30-35,41,43-48,55-59} in Mg compounds, however CN4 Mg is not rare.^{27,42,60-63} CN5 Mg has also been encountered, either as the only type in the formula unit,⁶⁴⁻⁶⁶ or in combination with other CN types, e.g., 6,^{34,41} or 4 and 6.³¹ Formula units containing Mg atoms in CN6 and 7,⁶⁷ or even 8,^{68,69} have been described. In most cases, the less common mixed coordination states are represented in structures where there is sharing between corners or edges of the respective polyhedra. It should be noted that such sharing is not required to stabilize the aquo-MDP structures (6).



The structures mentioned above include anhydrous as well as fully and partially hydrated complexes; in some of them, the crystal is polymeric, but in others, the crystal contains discrete molecules. A series of Mg complexes have been described^{36,55,57,59} in which the same counteranion (bromide) and the same donor (tetrahydrofuran) generate an anhydrous



complex (tetragonal)^{55,57} or a partially hydrated complex (triclinic),⁵⁹ both as molecular crystals, depending on experimental conditions. In addition, a related anhydrous complex (orthorhombic)⁵⁹ can also be obtained as a polymeric crystal. A fourth member of the series, namely the reagent 4 utilized in the present work, has been isolated only as microcrystalline



powder. From the work of Vallino^{65,70} on the related compound, monoclinic CH₃MgBr(C₄H₈O)₃, it is possible that MgBr₂(C₄H₈O)₃ represents another complex with CN5 Mg.

The lower coordination states of magnesium may simply result from steric interference in the attainment of the pre-

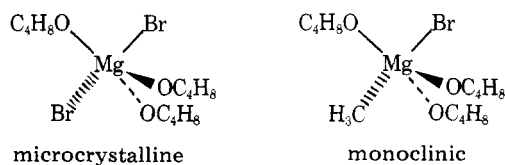


Table IV. Solubility [M] of Magnesium Diphenyl Phosphate (5) and Pentaquo-hexa(diphenyl phosphato)trimagnesium(II) (6) in Aprotic Organic Solvents at 25 °C

Solvent	5	6
Dichloromethane	0.02	0.2
Carbon tetrachloride	i ^a	i
Tetrahydrofuran	0.07	0.14
Diethyl ether	i	i
Benzene	0.002	0.003
Cyclohexane	i	i

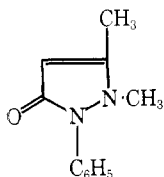
^a i = <0.001 M.

ferred 6-coordination. For example, CN4 is observed in $C_2H_5MgBr[O(C_2H_5)_2]_2$ ⁶¹ and $C_6H_5MgBr[O(C_2H_5)_2]_2$,⁶⁰ while a reduction of the size of the halogen and of the steric hindrance due to the ether, as in $[(C_2H_5)Mg_2Cl_3(C_4H_8O)_3]_2$,⁴⁰ leads to a structure with one CN5 and one CN6 Mg atom in the formula unit.⁴⁰ A smaller alkyl group and ether donor, but a large halogen, as in $CH_3MgBr(C_4H_8O)_3$,⁶⁵ leads to CN5 Mg. The diethyl ether complex $MgBr_2[O(C_2H_5)_2]_2$ ⁶² has CN4 Mg, but the tetrahydrofuran analogue $MgBr_2(C_4H_8O)_2$ ⁵⁹ has CN6 Mg. The steric control of magnesium coordination may play an important role in the structure and conformation, and hence in the biochemical properties of hydrated nucleotide-magnesium complexes.

A comparison between the magnesium phosphodiester salt (6) and the calcium phosphomonoester salt prepared by Li and Caughlan² discloses that in both cases two formula units, $[(ArO)_2P(O)O]_6Mg_3(H_2O)_5$ vs. $[(ArO)(HO)P(O)O]_2Ca(H_2O)_3$, compose the unit cell (one formula per asymmetric unit in space group *P1*). The degree of hydration per metal ion is higher in the calcium salt, which contains three water molecules in the pentagonal bipyramidal heptacoordinate sphere, as compared to the two and one water molecules coordinated to the two types of Mg atoms in 6. In both structures, the coordination sphere of the metal is completed by four oxygen atoms from four different phosphoryl groups. The Ca-O(water) and Ca-O(phosphoryl) distances are about 12% longer than the corresponding Mg-O distances.

Some Properties of MDP (5) and Aquo-MDP (6). The solubility of MDP and of aquo-MDP in aprotic organic solvents of relatively low polarity is given in Table IV. The hydrated complex is significantly more soluble than the anhydrous salt in both dichloromethane and tetrahydrofuran, suggesting weaker intermolecular forces in the triclinic crystals (6) than in the powder (5). Both solids are more soluble in benzene than in diethyl ether.

Anhydrous MDP exhibits very little tendency to form stable complexes with ethers, unlike other magnesium salts. This phenomenon is perhaps related to the strong tendency of phosphoryl oxygens to coordinate with Mg atoms. This is manifested not only in the organic and the inorganic phosphates, but also in tris(octamethylpyrophosphoramido)magnesium(II),⁵⁸ which is not a salt, and in which both phosphoryl oxygens of the same phosphoramido molecule contribute to the 6-coordination sphere of the metal. Carbonyl oxygen also shows a strong tendency to coordinate with Mg ions, which is manifested in the structure of magnesium hexaantipyrine perchlorate,⁵⁶ where six molecules of the



heterocycle are octahedrally coordinated to the metal with oxygens as the ligands. This phenomenon is particularly important in some nucleotide salts.¹²

The ³¹P NMR signal of MDP appears at significantly higher magnetic field in deuteriochloroform (+18.6 ppm) than in D₂O (+9.1 ppm, both from H₃PO₄ = 0), which reflects a more effective shielding of the phosphorus nucleus by electrons for the salt in the organic solvent relative to water.

Conclusions

The data presented in this paper, in conjunction with those contained in the cited references, reveal that magnesium possesses a combination of properties which undoubtedly contributes to the special role that this metal plays in the chemistry and biochemistry of phosphates. Among these properties are: (1) the tendency to form strong electrostatic and coordinative bonds with phosphoryl oxygens; (2) the tendency to form relatively stable complexes in all its coordination states (CN4, 5, 6, 7, and 8); (3) the particular relationship that exists between the Mg-O(phosphoryl) and Mg-O(water) bond distances, which relates to the ability of the hydrated magnesium phosphates to form hydrogen bridges connecting the metal ion with the phosphate oxygens; and (4) the acid-enhancing tendency of Mg ions, as in $Mg-O^+-H_2 \leftrightarrow Mg-O-H H^+$, which may also relate to the strength of its hydrogen bonds.

The present findings that the magnesium ion can achieve stable 5- and 6-coordinate states in an organic phosphate crystal which does not involve the sharing of corners or edges of the polyhedra, and that the difference in coordination number results exclusively from differences in the number of water molecules in the coordination spheres, are new and significant. Previous examples of variable metal coordination in magnesium phosphates had been observed among inorganic crystals, i.e., $Mg_3(PO_4)_2$ ³¹ and $\alpha-Mg_2P_2O_7$,³⁴ where polyhedron sharing contributes to the stability of the crystals.

Differences in CN are associated with differences in geometry, and it is evident that the conformation of a simple phosphodiester molecule, $(R^1O)(R^2O)P(O)OH$, can be altered significantly depending on the state of hydration of the magnesium ion with which the diester forms the electrostatic (salt) and the coordinative oxygen-metal bonds. The differences in geometry between a more or less regular octahedron on one hand, and a highly distorted TBP or TP (i.e., the *x*^o-TR geometry) on the other hand, are quite significant; this point must be considered in any attempt to derive possible conformations for a polymeric crystal made up of phosphodiester units and magnesium ions. The state of hydration of the magnesium ion, and hence the resulting CN and geometry about the metal, is probably dependent on the availability of sufficient space near the metal to accommodate the water. Hence, steric effects associated with the R¹ and R² groups of the phosphodiester may contribute to the overall geometry of the salt through the operation of this effect.

Finally, we speculate that some of the features present in the aquo-MDP crystals may apply also to the structure and conformation of a more complex hydrated magnesium dinucleotide salt, $[(nucleoside-3')(nucleoside-5')P(O)O]_2Mg \cdot (H_2O)_x$. Since the latter is derived from the polyfunctional nucleoside molecule, it is obvious that the possible competition between the additional nitrogen- and oxygen-containing functions of the nucleosides^{9-18,20-23,71-77} on one hand, and the two phosphoryl oxygens of the phosphate group and the water molecules on the other hand, for the available magnesium coordination sites, must be taken into consideration. However, models of a formula unit analogous to that present in the aquo-MDP salt (6, cf. 6') can be built in which each pair of ArO groups attached to a phosphate can be replaced by a pair of nucleosides connected by the usual 3' → 5'-internu-

cleotide bonds to give rise to a polynucleotide chain. An assessment of the possible biochemical significance of this model requires further studies on actual hydrated magnesium dinucleotides and small polynucleotides, none of which are available at present.

The phosphate groups in aquo-MDP occupy two different types of positions in the metal coordination polyhedra: *distal* and *vicinal* positions. The distal positions correspond to the collinear arrangement in an ideal octahedron, or to the trans-basal arrangement in an ideal tetragonal pyramid. The vicinal positions correspond to the orthogonal arrangement in an ideal octahedron, or to the cis-basal and basal-flagpole arrangements in the ideal tetragonal pyramid. These two types of phosphate-metal coordination geometries are reflected in significantly different O (phosphoryl)···O (phosphoryl) distances, e.g., O(10)···O(20) = 4.084 Å and O(21)···O(61) = 4.078 Å, which correspond to CN6 Mg distal configuration, and O(11)···O(60) = 3.933 Å, which corresponds to CN5 Mg distal configuration, on one hand, and O(10)···O(30) = 2.913 Å etc. and O(11)···O(41) = 3.019 Å etc., which correspond to CN6 and CN5 Mg vicinal configurations, respectively.

The above data concerning the observed O···O interatomic distances between phosphate groups in our simple hydrated magnesium phosphodiester complex may be compared with the recent crystallographic study of metal binding to yeast phenylalanine tRNA by Jack et al.⁷⁸ These authors found three *strong* binding sites for magnesium, and inferred the metal coordination from the refined atomic coordinates of the macromolecule. They concluded that the magnesium ions in two of the sites link "close phosphate groups"; it is possible that these O···O distances correspond to our vicinal inner sphere coordination O···O distances. Jack et al. characterized the magnesium in the third binding site as having "a rather special environment linking single-stranded regions of the dihydrouridine and the T-ψ-C loops". They speculated that: "this site is probably involved in the first stage of melting of the tRNA molecule, and may be critical for stabilizing the tertiary structure". The only acceptable binding at magnesium site no. 3 (ref 78, Table 2) is that of the phosphoryl oxygen G19-OR. On the other hand, *distal* type coordinations are actually found at samarium sites no. 3 and 5 (ref 78, Table 1). *Vicinal* type coordinations are found at samarium sites no. 1 and 2, just as they are at magnesium sites no. 1 and 2, as pointed out by Jack et al.

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Registry No.—4, 63866-80-8; 5, 19015-72-6; 6, 63865-88-3; diphenyl methyl phosphate, 115-89-9.

Supplementary Material Available: Table V, positional and thermal parameters; Table VI, some least-squares planes and dihedral angles between planes; and Figure 3, computer-generated stereo drawing of one formula unit of compound 6 (5 pages). Ordering information is given on any current masthead page. (The structure factors, 40 pages, can be obtained by writing to the senior author.)

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Specificity in the Micellar Catalysis of a Hofmann Elimination^{1,2}

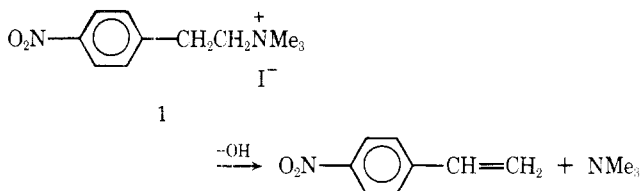
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The E2 elimination of trimethylamine from *p*-nitrophenethyltrimethylammonium iodide in 0.1 M NaOH is inhibited by anionic micelles of sodium dodecyl sulfate. Cationic micelles of hexadecyltrimethylammonium bromide and zwitterionic micelles of *N,N*-dimethyl-*N*-dodecylglycine have little effect on the reaction rate. However, micelles of *N,N*-dimethyl-*N*-hexadecyl-*N*-(2-hydroxyethyl)ammonium bromide and *N,N*-dimethyl-*N*-hexadecyl-*N*-(3-hydroxypropyl)ammonium bromide are catalytic at high alkali concentrations (pH >12.0), where the surfactants are converted into proteophilic zwitterions which participate as bases in the elimination. This is a significant exception to the general observation that all surfactants of the same charge type cause the same type of reactivity change.

Surfactants affect the reactivity of molecules hydrophobic enough to be taken into micelles and, in the last few years, considerable attention has been directed to the catalysis observed in many cases.³⁻⁵ We recently reported that cationic micelles of hexadecyltrimethylammonium bromide (CTABr) markedly increase the acidity of carbon acids.⁶ We have since examined the catalytic effectiveness of CTABr and other surfactants toward the hydroxide-catalyzed elimination reaction of 4-nitrophenethyltrimethylammonium iodide (1).



This reaction received some attention by Hughes and Ingold⁷ and more recently by Hodnett⁸ but this is the first reported examination of the rate of 4-nitrostyrene formation as a function of pH, temperature, and surfactant concentration. This is the first reported study of the effect of micelles on the synthetically important Hofmann elimination reaction.

Experimental Section

Materials. Sodium dodecyl sulfate (Aldrich) and CTABr (Matheson) were purified by the methods of Grunwald.⁹ *N,N*-Dimethyl-*N*-hexadecyl-*N*-(2-hydroxyethyl)ammonium bromide (2) was prepared by quaternizing *N,N*-dimethylethanolamine (Aldrich) with 1-bromohexadecane (Eastman) in refluxing 2-propanol and was purified by recrystallization from EtOH: mp 194-204 °C (lit.¹⁰ 208-210

°C); NMR (D₂O) δ 3.10 (s, NCH₃), 1.26 [s, C(CH₂)_n], 0.86 (t, CCH₃). *N,N*-Dimethyl-*N*-dodecylglycine¹¹ (3) was prepared by quaternizing *N,N*-dimethylglycine with 1-bromododecane (Aldrich) in 2-propanol and was purified by recrystallization from EtOH-Et₂O: mp 200-205 °C (lit.¹¹ 183 °C); NMR (D₂O) δ 3.29 (s, NCH₃), 1.31 1s, C(CH₂)_n], 0.85 (t, CCH₃). The *N,N*-dimethylglycine was prepared by reductive methylation¹² and was purified by recrystallization from EtOH-Et₂O. *N,N*-Dimethyl-*N*-hexadecyl-*N*-(3-hydroxypropyl)ammonium bromide (4) was prepared by quaternizing *N,N*-dimethylpropylamine (Aldrich) with 1-bromohexadecane (Eastman) in refluxing 2-propanol and was purified by recrystallization from EtOH: mp 84-89 °C; NMR (D₂O) δ 3.12 (s, NCH₃), 1.32 [s, C(CH₂)_n], 0.89 (t, CCH₃). *n*-Octylamine was distilled under reduced pressure and stored over NaOH.

4-Nitrophenethyltrimethylammonium Iodide (1). Phenethylamine (22 g, 0.18 mol) was slowly added to 100 mL of rapidly stirred red fuming nitric acid at 5 °C. After 3 h the reaction mixture was poured onto ice and made alkaline with NaOH solution. The product was extracted with ether; the extract was dried (Na₂SO₄) and evaporated to dryness. The crude 4-nitrophenethylamine (22 g, 0.13 mol) was combined with 100 mL of 2-propanol, 16 g of K₂CO₃, and 137 g (60 mL, 0.91 mol) of iodomethane and heated at reflux for 60 h. When cool the reaction mixture solidified. Part of the solid was soluble in hot EtOH, and this solution yielded yellow crystals of product which were recrystallized twice: mp 195-196 °C (lit.⁷ 199 °C); NMR (Me₂SO-*d*₆) δ 3.40 (s, NCH₃), 3.53 (s, NCH₂), 3.84 (m, ArCH₂), 8.00 and 8.55 (AA'BB' pattern, ArH). Anal. Calcd for C₁₁H₁₇N₂O₂: C, 39.30; H, 5.10; N, 8.33; I, 37.75. Found: C, 39.27; H, 5.17; N, 8.49; I, 37.82.

Kinetics. The reactions were followed spectrophotometrically at 320 nm using a Beckman Model DB spectrophotometer with a water-jacketed cell compartment. The temperature was maintained within 0.1 °C by a Lauda K2/R constant temperature water circulator. All surfactant solutions were prepared on the day of use from carbonate-free NaOH solution and stored in tightly stoppered flasks. The NaOH stock solutions were prepared from freshly boiled, N₂ satu-