the equilibrium condition to coincide with the statistically random condition, it must be assumed that the heats and entropies of mixing are zero, which appears unlikely.

Furthermore, there does not appear to be any real reason why the process of reconstitution (as in coconut oil) should result in a more random placement of the fatty acids than the process of catalytic rearrangement (as in butterfat), as the former is unlikely to be limited to esterifications involving only simple fatty acid esters and glycerol since intra- and inter-glyceride trans-esterifications should also be taking place. Therefore, both processes should lead to essentially the same end products as a result of the same directive influences. It is difficult to imagine that any interesterification reaction with such diverse mixtures of fatty acids could ever be carried out free of any selective physico-chemical influences, which would be an obligatory condition for insuring randomness.

Like the studies on the native and rearranged butterfats, the work with the coconut oils was limited to the available materials. Despite the lack of comprehensiveness it has revealed hitherto unavailable information. These results indicate the need for more exhaustive and systematic analysis of interesterified fat mixtures before the glyceride arrangements produced by the common present-day industrial processes may be pronounced as truly random.

ACKNOWLEDGMENTS

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REFERENCES

1. Bailey, A. E., "Industrial Oil and Fat Products," 2nd ed., Interscience Publishers, Inc., New York, 1951, chap. 19.
2. Eckey, E. W., JAOCS *33*, 575 (1956).
3. Bhattacharya, R., and T. P. Hilditch, Proc. Roy. Soc. London, A *129*, 468 (1930).
4. Naudet, M., and P. Desnuelle, Bull. soc. chim. *14*, 323 (1947).
5. Mattson, F. H., and L. W. Beck, J. Biol. Chem. *219*, 735 (1956).
6. Ast, H. J., and R. J. VanderWal, JAOCS *38*, 67 (1961).
7. Kuksis, A., M. J. McCarthy, and J. M. R. Beveridge, *Ibid.*, *40*, 530 (1963).
8. Skrabal, A., "Chemical Kinetics," International Critical Tables, Vol. 7, McGraw-Hill, Inc., New York, 1930, p. 138.
9. Van Lohuizen, O. E., and P. E. Verkade, Rec. trav. chim. *79*, 133 (1960).
10. Brandner, J. D., and R. L. Birkmeier, JAOCS *37*, 390 (1960).
11. Kuksis, A., and M. J. McCarthy, Can. J. Biochem. Physiol. *40*, 679 (1962).
12. McCarthy, M. J., A. Kuksis, and J. M. R. Beveridge, *Ibid.*, *40*, 1693 (1962).
13. Jensen, R. G., G. W. Gander, and J. A. Sampugna, J. Dairy Sci. *45*, 329 (1962).
14. McCarthy, M. J., and A. Kuksis, unpublished observations.

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Long Chain *a*-Phosphono Fatty Acids, Salts and Esters[1]

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Abstract

A series of α-phosphono fatty acids and their salts and esters was prepared from pelargonic, capric, lauric, myristic, palmitic, and stearic acids. In comparison to corresponding α-sulfo fatty acids the α-phosphono fatty acids are white solids of higher melting point, weaker acids, less hygroscopic, have a lower critical micelle concentration and are less resistant to hard water. Methyl, isopropyl, and amyl esters $RCH[PO(OH)_2]CO_2R'$, were prepared from the α-phosphono fatty acids; a sulfuric acid catalyst was required in the case of lower boiling alcohols. Hydrolysis studies with sodium methyl α-phosphonomyristate showed the α-phosphono ester to be 50 times as stable towards alkali as the corresponding α-sulfo ester, but only one-tenth as stable toward acid hydrolysis. Wetting, foaming, detergent, and other surface active properties of the α-phosphono fatty acids, salts, and esters were measured and compared with those of analogous α-sulfo compounds.

Introduction

THE SYNTHESIS and properties of α-sulfo fatty acids and their derivatives has been reported by this laboratory (6). It is of interest to determine the effect of an α-phosphono group in place of an α-sulfo group in the fatty acid chain. Related work by others has concerned mainly the synthesis of trialkyl esters of α-phosphono fatty acids and their properties as plasticizers and lubricants (1,9–12). This paper describes the preparation of α-phosphono fatty acids and their salts and esters from pelargonic, capric, lauric, myristic, palmitic, and stearic acids in the reaction sequence shown in Figure 1.

Methyl, isopropyl, and amyl esters, $RCH[PO(OH)_2]CO_2R'$, containing 14–19 carbon atoms, were prepared from the α-phosphono fatty acids. α-Phosphono fatty acids are weaker acids than the α-sulfo fatty acids and it was necessary to add a sulfuric acid catalyst in the case of the lower boiling alcohols. The acids, esters, and their salts were examined for solubility, critical micelle concentration, surface and interfacial tension, Ca^{++} stability, wetting properties, detergency, foam height, and lime soap dispersing properties. Hydrolysis rate constants were also determined for the α-phosphono fatty acid esters.

Experimental

α-Phosphono Fatty Acids. The synthesis of α-phosphonopalmitic acid illustrates the general procedure.

Palmitic acid was α-brominated in the usual manner by the Hell-Volhard-Zelinskii reaction, followed by reaction of α-bromopalmitoyl bromide with absolute ethanol. Ethyl α-diethylphosphonopalmitate was prepared as described by Ackerman et al. (1) by heating

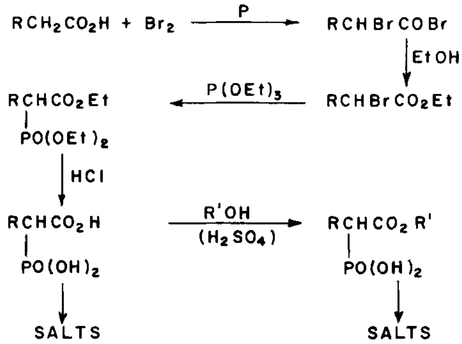

FIG. 1.

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[1] Presented at the AOCS meeting, Atlanta, 1963.

[2] E. Utiliz. Res. Dev. Div., ARS, USDA.

TABLE I

α-Phosphono Fatty Acids $RCH[PO(OH)_2]CO_2H$

Total number of C atoms	Melting point[a] °C	Analysis, found/theory %		
		C	H	P (Carius Method)
9	130–1	45.57/45.37	8.22/ 8.04	12.90/13.00
10	131.2;162–4	47.66/47.61	8.42/ 8.39	11.88/12.28
12	131.4;162	51.47/51.42	8.99/ 8.99	10.67/11.05
14	131.8;153–6	54.31/54.17	9.52/10.07	9.63/ 9.98
16	131.6;156–65	57.27/57.12	9.87/ 9.89	9.56/ 9.21
18	131.0;157–65	58.95/59.30	10.19/10.23	8.52/ 8.50

[a] α-Phosphonopelargonic acid has a sharp mp, but the higher homologs proceed to a glassy state at about 131C and finally to a liquid state at the temp listed.

the α-bromo ester with 100% excess of triethyl phosphite. Excess triethyl phosphite and any unreacted ethyl α-bromopalmitate was removed by distillation at 0.1 mm to a pot temp of 185C. The crude triethyl ester was hydrolyzed by refluxing with a large excess of 20–35% HCl for 40-50 hr. Considerable gelling and foaming accompanied hydrolysis. The reaction mixture was transferred to an evaporating dish, evaporated to dryness, dissolved in ether, washed to remove HCl, and again evaporated. Color was removed from the dark residue by extraction with $CHCl_3$ in a Soxhlet extractor. After drying to constant weight the light gray residue was crystallized from toluene, 15:1, at room temp. In the case of α-phosphonopelargonic acid, which was insoluble, low melting impurities were extracted by toluene. The white, powdery acid was dried to constant weight in a vacuum oven at 60C. The α-phosphono fatty acids gave the following % yields: pelargonic 58; capric 91; lauric 75; myristic 79; palmitic 67; stearic 65. Yields are based on the ethyl α-bromo esters. Melting points and analyses are in Table I.

Sodium Amyl α-Phosphonopelargonate. A solution of 0.105 mole (25 g) of α-phosphonopelargonic acid in 140 ml of n-amyl alcohol was refluxed 7 hr with azeotropic removal of water. Excess alcohol was removed at 0.1 mm to a pot 110C temp, giving a crude brown liquid, neutralized to pH 6.5 in 2500 ml of 50% EtOH with alcoholic NaOH. Solvent was removed under vacuum using a rotary evaporator to a volume of about 75 ml. After adjusting the volume to 150 ml with absolute ethanol, product was crystallized at —20C. One additional crystallization from 98% ethanol gave a white product in 42% yield.

Sodium Amyl α-Phosphonocaprate was similarly prepared in 69% yield.

Sodium Isopropyl α-Phosphonolaurate. A solution of 0.089 mole (25 g) α-phosphonolauric acid in 135 ml isopropanol was heated at reflux with 2 g 100% H_2SO_4 for 24 hr. Toluene, 200 ml, was then added, and excess alcohol and water removed by distillation to 110C pot temp, adding toluene continuously to maintain the initial volume.

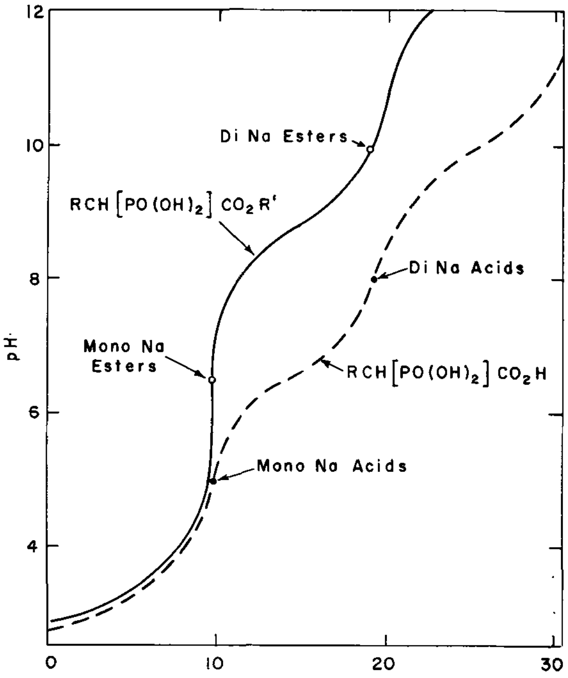


FIG. 2.

After cooling to room temp the solution was diluted with an equal volume of ether, transferred to a separatory funnel, and washed free of mineral acid. (Without the ether a stable emulsion forms, making washing very difficult.) The crude viscous product was neutralized to pH 6.5 in 2500 ml 50% ethanol with alcoholic NaOH. Nearly all the solvent was removed in a rotary evaporator under vacuum. The viscous residue was dissolved in 150 ml 95% ethanol, filtered, and crystallized at —20C. A second crystallization from 95% ethanol gave a white product in 66% yield.

Sodium Isopropyl α-Phosphonopalmitate was prepared similarly in 55% yield.

Methyl α-Phosphonomyristate. α-Phosphonomyristic acid, 0.081 mole (25 g), was heated at reflux with 85 ml of absolute methanol and 1.5 g of 100% H_2SO_4 for 24 hr. The solution was cooled, toluene was added, and alcohol and water removed by distillation as in the case of the isopropyl esters. Ether was added to the toluene solution which was then washed free of mineral acid. After removal of half the solvent under vacuum the volume was adjusted to 300 ml with toluene. Crystallization at —20C and vacuum drying

TABLE II

Properties of $RCH[PO(OH)_2]CO_2H$

Total number of C atoms	Aqueous solubility 25C %	Surface & interfacial tension 0.1%, 25C dynes/cm		Critical micelle concentration[a]		Detergency Terg-O-Tometer 0.25%, 60C ΔR[b]	Foam height[c] 0.25%, 60C mm	Ca^{++} stability[d] ppm $CaCO_3$
		S.T.	I.T.	%	mmoles/l.			
9	>20	51.0	17.4	0.72	30.23	9.2	0	1150
10	>20	43.8	17.5	0.34	13.48	11.4	180	460
12	>5	29.2	3.6	0.07	2.50	23.4	220	160
14	0.5	30.7	3.6	0.018	.58	27.6	240	55
16	<0.1	......	......	0.003	.09	15.7	too viscous	......
18	<0.1	......	......	......	......	32.5	too viscous	......
$RCH(SO_3H)CO_2H$								
16	25	41.5	13.3	.02	.60	28.0	......	670
18	13	43.5	11.5	.005	.14	31.2	......	275

[a] Surface tension method.
[b] ΔR = increase in reflection after washing 10 swatches of standard soiled cotton in 1 liter distilled water solutions, 10 swaches/liter.
[c] Stable foams in the Ross-Miles test (5).
[d] Modified Hart method (14).

TABLE III

Surface Active Properties of $\mathrm{RCH[\underset{ONa}{P}O(OH)]CO_2R'}$ and $\mathrm{RCH(SO_3Na)CO_2R'}$

α-Phosphono ester	Σ Carbon atoms	Aqueous solubility, 25C %	Critical micelle concn[a]		Wetting time, sec, 0.1%, 25C[b]		Detergency 0.25%, 60C ΔR	Foam[c] height 0.25%, 60C mm.	Ca++ stability ppm $CaCO_3$	Lime soap dispersing power[d] %
			%	mmoles per liter	Distilled water	300 ppm				
Sodium amyl α-phosphonopelargonate	14	3	0.60	18.2	5.8	8.4	15.4	165	270	30
Sodium amyl α-phosphonocaprate	15	2	0.31	9.0	3.1	17.2	19.1	230	90	30
Sodium isopropyl α-phosphonolaurate	15	10	0.23	6.68	3.9	12.0	22.8	210	840	20
Sodium methyl α-phosphonomyristate	15	0.7	0.25	7.26	11.1	300	21.5	190	155	>100
Sodium isoproypl α-phosphonopalmitate	19	5	0.013	0.32	31	>300	25.7	205	110	60
Sodium methyl α-phosphonostearate	19	< 0.1[e]	0.012	0.29	>300	>300	27.5	210	......	......
Sodium amyl α-sulfopelargonate	14	>10	0.52	15.6	12.1	5.3	15.0	80	630	>100
Sodium propyl α-sulfolaurate	15	>10	0.18	5.3	3.2	2.0	24.7	205	>1800	40
Sodium methyl α-sulfomyristate	15	>10	0.096	2.8	12.5	6.5	32.0	205	>1800	9
Sodium methyl α-sulfostearate	19	10	0.003	0.08	47	91	31.0	205	800	9

[a] Visual Pinacyanole Chloride method.
[b] Draves test (3).
[c] Immediate values; foams were unstable.
[d] Borghetty method (2).
[e] Thick, clear gel, hot.

at 60C gave the acid ester, $C_{12}H_{25}CH\ [PO(OH)_2]\ CO_2CH_3$. Yield 68%.

Sodium Methyl α-Phosphonomyristate. Neutralization of the acid ester to pH 6.5 gave the monosodium salt, $C_{12}H_{25}CH[PO(ONa)OH]CO_2CH_3$, as a white crystalline product. Yield 63%.

Methyl α-Phosphonostearate and Monosodium Salt. These were prepared similarly in yields of 89% and 84%. Methyl α-phosphonostearate can be crystallized directly from the reaction mixture at —20C. One additional crystallization at the same temp gave the pure acid ester.

Methyl α-Phosphonopalmitate was prepared in 48% yield, following the same procedure used for methyl α-phosphonostearate.

Discussion

α-Phosphono Fatty Acids

Physical and Chemical Properties. The α-phosphono fatty acids are higher melting, less hygroscopic, and less acidic than the corresponding α-sulfo fatty acids. Comparison of the pH of 0.01 molar aqueous α-phosphonolauric acid with that of 0.01 molar aqueous α-sulfolauric acid indicates 20% and 100% inonization respectively.

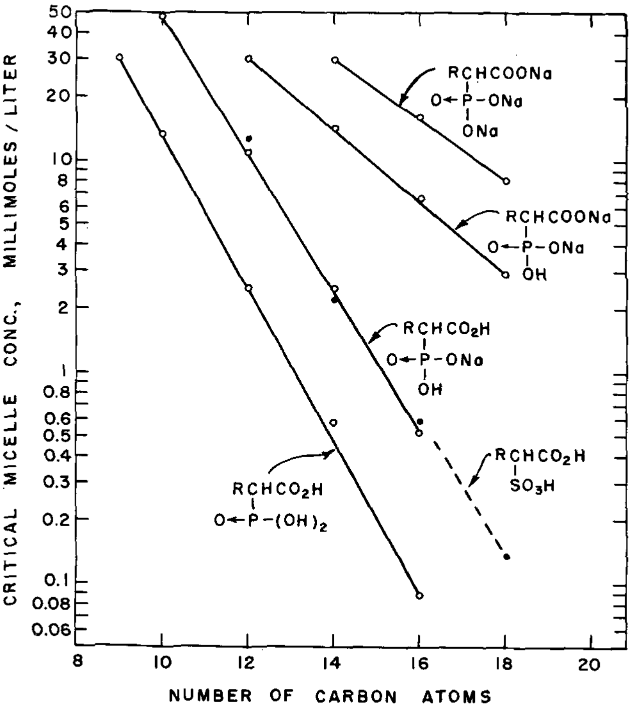


FIG. 3.

A composite potentiometric titration with NaOH in 50% ethanol shows the α-phosphono fatty acids have equivalence points at pH 5.0 [neutralization of the first acidic hydrogen of the $—PO(OH)_2$ group], pH 8.0 (neutralization of the carboxylic hydrogen) and pH 10.9 [neutralization of the acidic hydrogen of $—PO(OH)O^-$]. This is shown in Figure 2 where comparison is made with the similar plot of the α-phosphono fatty acid esters. The esters have equivalence points at pH 6.5 [neutralization of the first acidic hydrogen of the $—PO(OH)_2$ group] and pH 10 [neutralization of $—PO(OH)O^-$].

Surface Active and Related Properties. Surface active and related properties of α-phosphono fatty acids are compared with analogous α-sulfo acids in Table II. The α-phosphono fatty acids are much less soluble than corresponding α-sulfo acids, tend to form gels and viscous solutions, and are less resistant to hard water. On successive neutralization of α-phosphonopalmitic acid with NaOH solubility at 25C increases from<0.1% to 0.1% to 1%. This difference in solubility is also true of salts of the other alkali metals, and of salts with ammonia, amines, and alkanolamines.

The lower detergency of α-phosphonopalmitic acid is apparently due to greater viscosity of the aqueous solution and less efficient agitation under the washing conditions. At a lower concentration of 0.1%, detergency was increased to a △R value equal to that for 0.25% sodium dodecyl sulfate (25.7).

Certain of the compounds in Table II have excel-

TABLE IV

Hydrolysis Rate Constants for α-Substituted Esters

Esters	First order rate constant $N/3\ H_2SO_4$ 100C[a] min^{-1}	Second order rate constant[b] $N/10$ NaOH, 100C 1/mole/min
Na Methyl α-phosphonomyristate	0.04	0.003
Na Methyl α-sulfostearate............	0.005	0.14

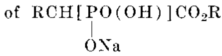
[a] $k_1\ (\text{first order}) = \frac{1}{t} \ln \frac{a}{a - x}$

[b] $k_2\ (\text{second order}) = \frac{1}{t} \frac{x}{a(a - x)}$

Because of the viscous nature of the acid solution these values should be regarded as approximate.

TABLE V

Comparison of Analytical Methods for Determination of Sodium and Phosphorus of RCH[PO(OH)]CO₂R′



$$\mathrm{RCH[\underset{\displaystyle \overset{|}{ONa}}{PO}(OH)]CO_2R'}$$

α-Phosphono fattay acid ester	% Sodium			% Phosphorus		
	Theory	Found		Theory	Found	
		Ash[a]	HBr[b] titration		Ash[a]	Carius method
Sodium amyl α-phosphonopelargonate	6.96	6.88	6.87	9.38	9.26	9.13
Sodium amyl α-phosphonocaprate	6.68	6.56	6.52	8.99	8.84	8.81
Sodium isoproypl α-phosphonolaurate	6.68	6.61	6.60	8.99	8.90	8.66
Sodium methyl α-phosphonomyristate	6.68	6.68	7.01	8.99	8.99	8.78
Sodium isopropl α-phosphonopalmitate	5.74	5.64	5.57	7.73	7.60	7.62
Sodium methl α-phosphonostearate	5.74	5.66	5.69	7.73	7.62	7.64

[a] $NaPO_3$ ash, 800C. Pt crucibles.
[b] Method of Haeberer and Maerker (4).

lent foaming properties. α-Phosphonolauric acid, α-phosphonomyristic acid, the disodium and ditriethanolammonium salts of α-phosphonostearic acid give rich stable foams in soft water.

Critical Micelle Concentration. The α-phosphono fatty acids have a lower cmc than corresponding α-sulfo acids (Table II). All the salts were prepared *in situ.* Figure 3 shows the relation of cmc to chain length and salt formation. The critical micelle concentrations of α-sulfo fatty acids fall on the same line as the cmc of the monosodium salts of the α-phosphono acids, presumably because in each case there is the uni-univalent electrolyte, $RCH(SO_3^-)CO_2H$ or $RCH[PO(OH)O^-]CO_2H$. Increase in the length of the fatty acid chain of these compounds results in a decrease in cmc in the usual logarithmic relationship shown for α-sulfo homologs (13).

This relationship appears to hold true for the di- and tri-basic α-phosphono acid salts. At 16-carbon atoms, increasing degree of ionization from α-phosphopalmitic acid to mono, to di- and to tri-sodium salts increases the cmc from 0.09 to 0.5 to 7.0 to 16 mmoles per liter.

Acid Esters. The methyl esters of α-phosphonomyristic, palmitic, and stearic acids were isolated in a pure state as white fluffy solids meltting at 72–73.6C, 76–78C, and 83–85C. Analytical values follow:

Compound	% Carbon Found/Theory	% Hydrogen Found/Theory	% (Carius) Phosphorus Found/Theory
Myristate	55.52/55.88	9.54/ 9.69	9.36/9.61
Palmitate	58.80/58.26	10.12/10.07	8.63/8.84
Stearate	60.22/60.29	10.39/10.39	8.01/8.18

These acid esters are sparingly soluble in water; the α-phosphonomyristate forms a gel at 0.2%.

Mono Sodium Salts of Esters. Table III lists surface active and related properties for comparison with sodium salts of α-sulfo esters. The monosodium salts of the α-phosphono fatty acid esters are less soluble and less resistant to hard water than the corresponding sodium salts of α-sulfo fatty acid esters (7). As in the case of α-sulfo esters, esters of shorter chain acids such as sodium amyl α-phosphonopelargonate, $C_7H_{15}CH[PO(OH)ONa]CO_2C_5H_{11}$, with the hydrophilic portion at or near the middle of the chain, have good wetting properties.

Infrared Examination. IR analysis verifies the presence of $-COOR'$ group at 1740 cm^{-1}, the absence of $-COOH$ at 1700 cm^{-1}, and the absence of $-COO^-$ at 1580 cm^{-1}.

Stability to Hydrolysis. The α-sulfo fatty acid esters have been shown to have greater stability toward acid and alkaline hydrolysis than simple esters (8). It is believed that the rather bulky sulfo group α to the carboxylate group confers stability to hydrolysis through steric hindrance. This was found to be true also for α-phosphono esters.

Hydrolysis kinetics were determined in the manner described in (8). Sodium methyl α-phosphonomyristate, 0.01 mole, and 200 ml of 0.2*N* NaOH were heated at 100C. This allowed for neutralization of the remaining acidity of the phosphono group and left an excess of 0.1*N* base available for saponification as in the measurements with α-sulfo esters. The phosphono ester appears to be ca. 50 times as stable toward alkaline hydrolysis as the α-sulfo ester.

Acid hydrolysis kinetics were studied in a similar manner by stirring 0.01 mole of sodium methyl α-phosphonomyristate in 100 ml of $N/3$ H_2SO_4, withdrawing 10 ml samples for titration at intervals. Because of the viscous nature of the phosphono acid produced and difficulty in obtaining a sharp end point, these values should be regarded as approximate, but the acid stability of the phosphono ester appears to be about 1/10th that of the α-sulfo ester. Results are compared in Table IV.

Analysis

Sodium salts of α-phosphono fatty acid esters were analyzed by ashing dry aliquots in platinum crucibles at 800C. Presumably the course of reaction for the monosodium salt proceeds to the metaphosphate:

$$RCH[PO(OH)ONa]CO_2R' \xrightarrow{800C} NaPO_3 + CO_2 + H_2O$$

Results in Table V show good agreement for sodium determined by an independent titrimetric method (4) and for phosphorus by the Carius method.

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Ashing procedure for sodium α-phosphono fatty acid esters by C. L. Ogg. Microanalyses for C.H. and P by Ruth B. Kelly and Judith A. DeMorjian. Analyses for Na by HBr titration by Elizabeth T. Haeberer.

REFERENCES

1. Ackerman, B., R. M. Chladek, and Daniel Swern, J. Am. Chem. Soc., *79*, 6524–6526 (1957).
2. Borghetty, H. C., and C. A. Bergman, JAOCS, *27*, 88–90 (1950).
3. Draves, C. Z., and O. L. Sherburne, Am. Dyestuff Reptr., *39*, 771–772 (1950).
4. Haeberer, E. T., and G. Maerker, JAOCS *40*, 274–275 (1963).
5. Ross, J., and G. D. Miles, Oil & Soap, *18*, 99–102 (1941). Am. Soc. Testing Mater., Book of ASTM Standards, ASTM Designation D 1173–53, Part 10, 878–880 (1958).
6 Stirton, A. J., JAOCS, *39*, 490–496 (1962).
7. Stirton, A. J., R. G. Bistline, Jr., J. K. Weil, W. C. Ault, and E. W. Maurer, *Ibid.*, *39*, 128–131 (1962).
8. Stirton, A. J., R. G. Bistline, Jr., J. K. Weil, and W. C. Ault, *Ibid.*, *39*, 55–58 (1962).
9. Swern, D. (to the Secretary of Agriculture), U.S. 2,973,380 (1961).
10. Swern, D. (to the Secretary of Agriculture), U. S. 2,963,458 (1960).
11. Swern, D., W. E. Palm, B. Ackerman, and L. P. Witnauer, Chem. Eng. Data Series, *3*, 346–349 (1958).
12. Swern, D., W. E. Palm, R. Sasin, and L. P. Witnauer, J. Chem. Eng. Data, *5*, 486–488 (1960).
13. Weil, J. K., and A. J. Stirton, J. Phys. Chem., *60*, 899–901 (1956).
14. Wilkes, B. G., and J. N. Wickert, Ind. Eng. Chem., *29*, 1234–1239 (1937).

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