[CONTRIBUTION FROM THE GEORGE HERBERT JONES LABORATORY, UNIVERSITY OF CHICAGO, AND THE GENERAL ELECTRIC RESEARCH LABORATORY]

THE REACTION OF TRIETHYL PHOSPHITE WITH α-TRICHLOROMETHYL CARBONYL COMPOUNDS

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The observation that amines and alcohols are phosphorylated by dibenzyl phosphonate, in the presence of polyhalomethanes such as carbon tetrachloride or bromotrichloromethane (1), led to our investigation (1948–1950) of the reaction of α-trichloromethyl carbonyl compounds with trialkyl phosphites. This paper deals with the reactions of chloral, ω,ω,ω-trichloroacetophenone, and ethyl trichloroacetate with triethyl phosphite. These reactions are described in the doctoral thesis of one of us (I. S. B.) (2); their publication is prompted by Werner Perkow's recent description of the chloral-triethyl phosphite reaction (3).

The reaction of trialkyl phosphites with alkyl halides (Arbuzov reaction) proceeds by the following reaction path to yield a dialkyl alkylphosphonate.

$$(RO)_3P{:} + R'X \rightarrow [R'P(OR)_3]^+X^- \rightarrow R'P(O)(OR)_2 + RX \qquad (A)$$

The alkyl halide undergoes a nucleophilic displacement to yield the nonisolable alkyl trialkoxyl phosphonium halide. The halide ion can then attack an alkoxyl group to give the phosphonate ester and the alkyl halide (4).

Chloral. The first interpretation of the reaction of chloral with triethyl phosphite was that it proceeded by the above-described Arbuzov reaction to yield the expected diethyl dichloroformylmethylphosphonate, $(CH_3CH_2O)_2(O)PCCl_2CHO$ (I), (2). This interpretation was also advanced by subsequent investigators (5).

The identity of the chloral-triethyl phosphite reaction product as I was based upon the following observations and assumptions.

(a) It is the product expected from the Arbuzov reaction.

(b) Phosphorus and chlorine analyses are in correct agreement.

(c) The immediate production of a silver mirror is observed on treatment with Tollens' reagent.

(d) Prolonged treatment with a strongly acidic solution of 2,4-dinitrophenylhydrazine produced the *bis*-2,4-dinitrophenylhydrazone of glyoxal. This derivative can arise from I, if the cleavage, of the normally hydrolytically stable carbon-phosphorus bond, is facilitated by the presence of the chlorines adjacent to the phosphorus atom. Kamaĭ and Egorova had indeed reported that a carbon-phosphorus bond cleavage occurs during the acidic hydrolysis of diethyl trichloromethylphosphonate, $CCl_3P(O)(OCH_2CH_3)_2$ (6). This observation, however, has since been demonstrated to be incorrect; no carbon-phosphorus bond cleavage is observed (7).

Besides the above-mentioned evidence which substantiates the structure of the triethyl phosphite-chloral reaction product as I, the following non-corroborative observations were made.

(e) The product behaves as if the carbonyl group is absent. Attempts to obtain a color test for, or a derivative of, the aldehydic group failed. Besides the positive Tollens' test, the reaction with 2,4-dinitrophenylhydrazine was extremely slow and the yield of derivative was small.

(f) Although an appreciable quantity of heat must be applied before the usual Arbuzov reaction proceeds, the triethyl phosphite-chloral reaction, in contrast, proceeds violently by simply mixing the reagents together. The reaction must be moderated by cooling in an ice-water bath. The yields are quantitative (95% or better).

Observations (e) and (f) created some doubts as to the validity of structure I. Recently, Werner Perkow (3) has demonstrated that triethyl phosphite reacts with chloral to give the phosphate ester, diethyl β,β-dichlorovinyl phosphate, $(CH_3CH_2O)_2(O)POCH{=}CCl_2$ (II), and not the expected isomeric phosphonate ester (I).

Thus, Perkow showed that the reaction product was unsaturated; it readily absorbed one mole of chlorine or bromine. It gave no qualitative tests for the aldehyde group, although Tollens' reagent was not employed. Hydrolysis with conc'd hydrochloric acid, in a sealed tube, yielded phosphoric acid; the organic fragments were not identified. It did not react with 2,4-dinitrophenylhydrazine, in contrast to our observation (e).

After this manuscript was completed, three independent papers dealing with the synthesis of the dimethyl homolog of II have been published (8). The reaction involves the dehydrochlorination of dimethyl 2,2,2-dichloro-1-hydroxyethyl phosphonate.

$$(CH_3O)_2(O)PCHOHCCl_3 + {}^{-}OH \rightarrow \underset{\text{III}}{(CH_3O)_2(O)POCH{=}CCl_2} + H_2O + Cl^{-} \qquad \text{(B)}$$

Mattson, Spillane, and Pearce (8a) corroborate our observation, in that III does give glyoxal dinitrophenylosazone. Barthel, Alexander, Giang, and Hall (8c), however, claim that neither II nor III reacts with 2,4-dinitrophenylhydrazine, but that III gives glyoxal *p*-nitrophenylosazone.

Perkow's observations motivated the preparation of a new sample of the triethyl phosphite-chloral product and its infrared spectrum was examined. The spectrum (Fig. 1) confirms Perkow's conclusion that the product is II, and not I.

The pertinent absorptions occur in the 3.26 and 6.06μ regions. Both clearly indicate olefinic unsaturation; in contrast, the strong absorption in the 5.80μ region due to an aldehydic carbonyl group, to be expected of structure I, is absent. The characteristic absorption frequencies due to the various phosphorus-oxygen linkages are in accord with previous investigations (9). Similar interpretations of the infrared spectra of these compounds have recently been advanced (8a, b, c). In addition, the reaction of triethyl phosphite with dichloroacetaldehyde proceeds in the same fashion to give diethyl β-chlorovinyl phosphate. The latter reveals similar 3.26 and 6.06μ absorption bands with no carbonyl absorption (10).

The confirmation of II as the correct product structure requires the explana-

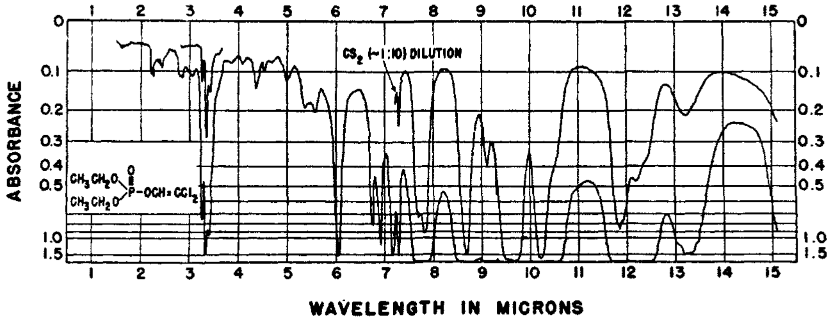


FIG. 1. INFRARED SPECTRA OF DIETHYL β,β-DICHLOROVINYL PHOSPHATE. Lower curve, pure liquid. Upper curve, *ca.* 1:10 CS_2 solution. (Instrument, Perkin-Elmer model 21; cell thickness, 0.0541 mm.)

tion of (a) its reaction with Tollens' reagent, (b) its reaction with 2,4-dinitrophenylhydrazine, and (c) the reaction path of its formation.

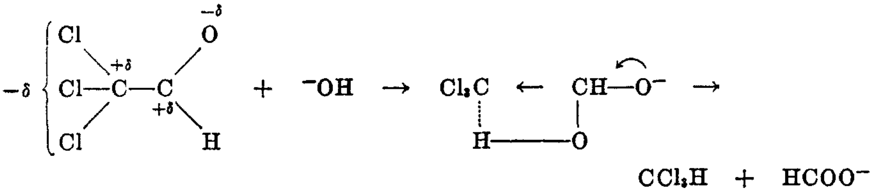
(a) Tollens' reagent, being strongly basic, can hydrolyze the vinyl ester to the corresponding aldehyde which can then reduce the complex cation to metallic silver:

$$\begin{aligned}&(CH_3CH_2O)_2(O)POCH{=}CCl_2 + {}^{-}OH\\&\quad\rightarrow (CH_3CH_2O)_2(O)PO^- + [CCl_2{=}CHOH \rightarrow HCCl_2CHO]\end{aligned}\qquad (C)$$

Freshly distilled vinyl acetate, for example, gives an immediately positive Tollens' test.

(b) Acidic hydrolysis of II again can produce dichloroacetaldehyde as in (a) above. Prolonged treatment of dichloroacetaldehyde with 2,4-dinitrophenylhydrazine is known to give the *bis*-glyoxal derivative. This reaction has been corroborated by Mattson, Spillane, and Pearce (8a).

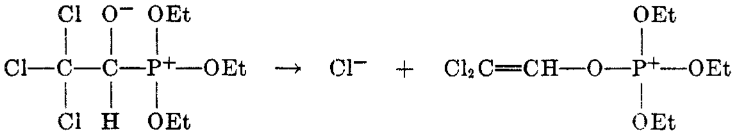
(c) Any suggested reaction path must consider that triethyl phosphite does not react with non-chlorinated aldehydes. The instant reaction, therefore, must be intimately connected with the strong inductive effects of the chlorine atoms in chloral. These effects, which produce an over-all formal charge distribution as represented by IV, lead to a hydrolytic instability of the carbon-carbon bond. Thus,



(D)

IV

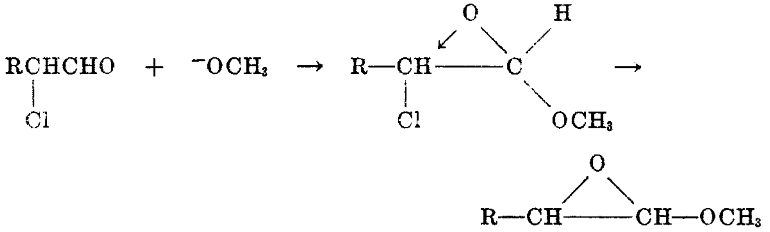
Triethyl phosphite, a Lewis base, can attack the relatively unhindered carbonyl carbon atom to give the intermediate, V. The neighboring negatively charged oxygen atom can readily link with the positively charged phosphorus atom (3-membered ring formation) with the concomitant cleavage of the carbon-phosphorus bond and the release of a chloride ion to give VI.



$$\mathrm{Cl{-}\overset{Cl}{\underset{Cl}{C}}{-}\overset{O^-}{\underset{H}{C}}{-}\overset{OEt}{\underset{OEt}{P^+}}{-}OEt \rightarrow Cl^- + Cl_2C{=}CH{-}O{-}\overset{OEt}{\underset{OEt}{P^+}}{-}OEt} \qquad \text{(E)}$$

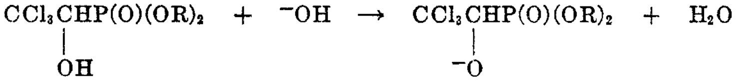
V VI

The reaction of α-chloroaldehydes and other bases, for example, methoxide ions, leads to a similar neighborly attack by the carbonyl oxygen atom. Thus, Stevens, Farkas, and Gillis (11) have observed the following:



(F)

The fact that the triethyl phosphite-chloral reaction proceeds exothermically favors, but does not establish, the Lewis acid-base neutralization reaction as the primary reaction step. Further indication that the above-proposed mechanism is correct is that it can readily explain the dehydrochlorination rearrangement reaction (as represented by Eqn. B) observed by the subsequent three groups of investigators (8). The first step is the removal of a proton from the hydroxyl group to give VII; the latter contains a negatively charged oxygen atom in the same relationship to a formally positively charged phosphorus atom as in V. The rearrangement can then occur as in the chloral-triethyl phosphite case.



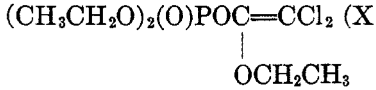
$$\mathrm{CCl_3\underset{OH}{C}HP(O)(OR)_2 + {}^-OH \rightarrow CCl_3\underset{^-O}{C}HP(O)(OR)_2 + H_2O} \qquad \text{(G)}$$

VII

ω,ω,ω-Trichloroacetophenone. Triethyl phosphite reacts vigorously with ω,ω,ω-trichloroacetophenone to give an almost quantitative yield of product. In the light of Perkow's work and the present spectral findings, the product is diethyl α-phenyl-β,β-dichlorovinyl phosphate, $(CH_3CH_2O)_2(O)POC(C_6H_5){=}CCl_2$ (VIII).

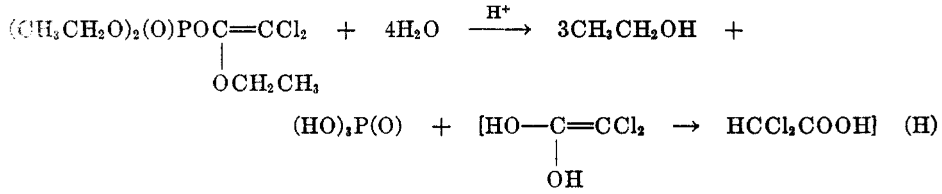
Hydrolysis of the reaction product with hydrochloric acid yields an oil. The elementary analysis of the latter material is in agreement with that of ω,ω-dichloroacetophenone.

Ethyl trichloroacetate. In contrast to the two strongly exothermic and near-quantitative reactions above, a mixture of ethyl trichloroacetate and triethyl phosphite must be heated to 140° before evolution of ethyl chloride begins; the yields are only fair. This suggests that the product is either the material expected from the normal Arbuzov reaction, diethyl dichlorocarbethoxymethylphosphonate, $(CH_3CH_2O)_2(O)PCCl_2COOCH_2CH_3$ (IX) (12) or is a mixture of IX and diethyl α-ethoxy-β,β-dichlorovinyl phosphate,



$$(CH_3CH_2O)_2(O)PO\underset{\displaystyle OCH_2CH_3}{\underset{|}{C}}{=}CCl_2 \text{ (X).}$$

An indication that X is the major reaction product is provided by its acidic hydrolytic behavior. The compound yields both phosphoric and dichloroacetic acids.



$$(CH_3CH_2O)_2(O)PO\underset{\displaystyle OCH_2CH_3}{\underset{|}{C}}{=}CCl_2 + 4H_2O \xrightarrow{H^+} 3CH_3CH_2OH +$$

$$(HO)_3P(O) + [HO{-}\underset{\displaystyle OH}{\underset{|}{C}}{=}CCl_2 \rightarrow HCCl_2COOH] \text{ (H)}$$

Carbon tetrachloride. Prior to the performance of the above-described reactions, the reaction of carbon tetrachloride with triethyl phosphite was investigated to determine whether there was any free-radical contribution to the reaction path. Suitable vacuum line techniques disclosed that the yield of diethyl trichloromethylphosphonate $(CCl_3P(O)(OCH_2CH_3)_2$, (13) was not greatly affected by the presence of inhibitory amounts of oxygen.

EXPERIMENTAL

The preparation of triethyl phosphite. The original method of the preparation of triethyl phosphite by the interaction of phosphorus trichloride, absolute ethanol, and pyridine in ether solution (14) was modified by the use of quinoline instead of pyridine. Dimethylaniline (15) and diethylaniline (16a, b) have also been used. Triethyl phosphite is a clear, mobile liquid with a sickening odor (b.p. 51–53°/13 mm., n_D^{20} 1.4138, 72% yield). It is now available commercially.

Apparatus. The reactions were conducted in a 125-ml. two-necked round-bottomed flask equipped with a gas inlet tube and a ₸ 24/40 joint. The latter was attached to an all-glass Claisen distillation assembly. The distillation assembly was fitted with a ₸ 19/38 joint to accommodate a dropping-funnel. A stream of nitrogen removed the ethyl halide, formed during the reaction, from the reaction mixture.

Triethyl phosphite was reacted with the following halides: *Carbon tetrachloride in the absence of air.* Commercial carbon tetrachloride was distilled through a vacuum-jacketed tantalum wire column (b.p. 75°).

Triethyl phosphite (10 g., 0.06 mole) and carbon tetrachloride (9.27 g., 0.06 mole) were placed in a tube and the latter was evacuated. Three degassing operations removed the dissolved air. The tube was sealed, heated for four hours at 100°, opened, and the reaction mixture was distilled at reduced pressure. The fraction boiling at 118°/10 mm. was diethyl trichloromethylphosphonate, n_D^{20} 1.4618, 31% yield.

Anal. Calc'd for $C_5H_{10}Cl_3O_3P$: P, 12.1; Mol. wt., 255.

Found: P, 12.1; Mol. wt., 258 (cryoscopic; benzene).

Carbon tetrachloride in the presence of oxygen. The reaction was performed as above, except that 15 mm. of oxygen was introduced into the reaction tube before it was sealed. Distillation of the reaction mixture at 100°/3 mm. gave diethyl trichloromethylphosphonate (23% yield; n_D^{20} 1.4600).

Chloral. Chloral (b.p. 96–97°) was obtained by its distillation from a mixture of chloral hydrate and sulfuric acid.

Triethyl phosphite (14.4 g., 0.0865 mole) was added dropwise to chloral (12.7 g., 0.0865 mole). The reaction is extremely vigorous and was moderated by cooling in an ice-water bath. Both Perkow (3) and Barthel, *et al.* (8c) moderate the reaction by using ether or benzene as a solvent. The diethyl β,β-dichlorovinyl phosphate formed in the reaction was recovered by distillation (b.p. 69–71°/0.5 mm., n_D^{20} 1.4498, 98% yield).

Anal. Calc'd for $C_6H_{11}Cl_2O_4P$: P, 12.5; Cl, 28.5; Ag equiv., 124.5.

Found: P, 12.5; Cl, 28.3; Ag equiv., 123.9.

This reaction has also been conducted by cautiously adding triethyl phosphite to an equimolar amount of chloral which is stabilized with hydroquinone. The product was obtained in 95% yield (b.p. 146°/20 mm.; n_D^{20} 1.4491).

The ester gives a positive test with Tollens' reagent, but does not react with thiosemicarbazide. With 2,4-dinitrophenylhydrazine hydrochloride, the 2,4-dinitrophenylosazone of glyoxal (m.p. 326°) is obtained.

ω,ω,ω-Trichloroacetophenone. Trichloroacetophenone (b.p. 113–115°/8 mm.) was prepared by the Friedel-Crafts method (17) by the use of aluminum chloride, benzene, and trichloroacetyl chloride (18). A 2,4-dinitrophenylhydrazone derivative of the ω,ω,ω,-trichloroacetophenone melted at 113–115° with decomposition.

Triethyl phosphite (15 g., 0.09 mole) was slowly added to ω,ω,ω-trichloroacetophenone (20 g., 0.09 mole) in order to moderate the violence of the reaction. The product, diethyl α-phenyl-β,β-dichlorovinyl phosphate, was recovered by distillation (b.p. 105–110°/10^{-3} mm., n_D^{20} 1.5195, 91% yield).

Anal. Calc'd for $C_{12}H_{15}Cl_2O_4P$: P, 9.6; Cl, 21.8; Ag equiv., 162.

Found: P, 9.5; Cl, 21.8; Ag equiv., 160.

The ester was heated with 18% aqueous hydrochloric acid in a sealed tube for six hours at 160° to give a material which correctly analyzed for ω,ω-dichloroacetophenone.

Anal. Calc'd for $C_8H_6Cl_2O$: Cl, 37.5; Ag equiv., 94.5.

Found: Cl, 38.0; Ag equiv., 95.4.

Ethyl trichloroacetate. Ethyl trichloroacetate (b.p. 61–63°/12 mm. n_D^{20} 1.4505) was prepared in 81% yield by passing anhydrous hydrogen chloride into a solution of trichloroacetic acid in anhydrous ethanol (19).

A mixture of triethyl phosphite (33.2 g., 0.2 mole) and ethyl trichloroacetate (38.3 g., 0.2 mole) was heated for four hours at 140–150°. A smooth evolution of ethyl chloride took place.

The reaction mixture was distilled to give the following fractions.

Fraction 1: Ethyl trichloroacetate (b.p. 62–70°/12 mm., n_D^{20} 1.4460, 33.3% of the starting ester).

Fraction 2: The reaction product is diethyl α-ethoxy-β,β-dichlorovinyl phosphate (b.p. 103°/0.5 mm., n_D^{20} 1.4284, 40% yield).

Anal. Calc'd for $C_8H_{15}Cl_2O_5P$: P, 10.6. Found: P, 10.6.

Fraction 3: An impure liquid (schlieren). This material is presumably the product obtained by the replacement of two of the chlorine atoms of ethyl trichloroacetate by two diethyl phosphono groups (b.p. 114–120°/0.5 mm., 8% yield).

Anal. Calc'd for $C_{12}H_{25}ClO_8P$; P, 15.7. Found: P, 16.3.

Fraction 4: A small amount of a residue (2.6 g.) which did not distill.

Hydrolysis of the reaction product with 18% aqueous hydrochloric acid yielded phosphoric acid (identified as the aniline salt, m.p. and mixture m.p. 178.5–179°), and dichloroacetic acid (identified as the S-benzylthiuronium salt, m.p. and mixture m.p. 174–175°).

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SUMMARY

The reactions of triethyl phosphite with chloral, ω,ω,ω-trichloroacetophenone, and ethyl trichloroacetate are described. The infrared spectrum of the triethyl phosphite-chloral reaction product corroborates Werner Perkow's conclusion that it is not the Arbuzov reaction expected phosphonate ester, $(C_2H_5O)_2(O)PCCl_2CHO$ (I), but is the isomeric phosphate ester, $(C_2H_5O)_2(O)PCH{=}CCl_2$ (II). The mechanism proposed to explain this rearrangement can also apply to the recently reported rearrangement of $(RO)_2(O)PCHOHCCl_3$ to II when the former compound is dehydrochlorinated with base.

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REFERENCES

(1) (a) ATHERTON, OPENSHAW, AND TODD, *J. Chem. Soc.*, 382 (1945); 660 (1945); (b) ATHERTON AND TODD, *J. Chem. Soc.*, 674 (1947).
(2) IRVING S. BENGELSDORF, Ph.D. dissertation, University of Chicago, 1951.
(3) PERKOW, *Chem. Ber.*, **87**, 755 (1954).
(4) GERRARD AND GREEN, *J. Chem. Soc.*, 2550 (1951).
(5) (a) ARBUZOV AND ALIMOV, *Izvest. Akad. Nauk. S.S.S.R., Otdel. Khim. Nauk*, 530 (1951); (b) LADD AND HARVEY, U.S. Patent 2,597,938; *Chem. Abstr.*, **47**, 1182b (1953).
(6) KAMAĬ AND EGOROVA, *Zhur. Obshcheĭ Khim.* (*J. Gen. Chem. U.S.S.R.*), **16**, 1521 (1946).
(7) (a) YAKUBOVICH, GINSBURG, AND MAKAROV, *Doklady Akad. Nauk. S.S.S.R.*, **71**, 303 (1950); (b) YAKUBOVICH AND GINSBURG, *Doklady Akad. Nauk. S.S.S.R.*, **82**, 273 (1952); (c) CROFTS AND KOSOLAPOFF, *J. Am. Chem. Soc.*, **75**, 5738 (1953); (d) BENGELSDORF AND BARRON, *J. Am. Chem. Soc.*, in press.
(8) (a) MATTSON, SPILLANE, AND PEARCE, *J. Agr. Food Chem.*, **3**, 319 (1955); (b) LORENZ, HENGLEIN, AND SCHRADER, *J. Am. Chem. Soc.*, **77**, 2554 (1955); (c) BARTHEL, ALEXANDER, GIANG, AND HALL, *J. Am. Chem. Soc.*, 2424 (1955).
(9) DAASCH AND SMITH, *Anal. Chem.*, **23**, 853 (1951); (b) BELLAMY AND BEECHER, *J. Chem. Soc.*, 728 (1953).
(10) (a) BENGELSDORF, unpublished results; (b) BARTHEL, *et al.*, ref. 8c.
(11) STEVENS, FARKAS, AND GILLIS, *J. Am. Chem. Soc.*, **76**, 2695 (1954).
(12) HARMAN AND THORPE, U.S. Patent 2,599,761; *Chem. Abstr.*, **46**, 10608 (1952).
(13) (a) KAMAĬ AND EGOROVA (ref. 6); (b) KOSOLAPOFF, *J. Am. Chem. Soc.*, **69**, 1002 (1947).
(14) MILOBEDZKI AND SACHNOWSKI, *Chem. Polski*, **15**, 34 (1917); *Chem. Abstr.*, **13**, 2865 (1919).
(15) MCCOMBIE, SAUNDERS, AND STACEY, *J. Chem. Soc.*, 380 (1945).
(16) (a) FORD-MOORE AND WILLIAMS, *J. Chem. Soc.*, 1465 (1947); (b) FORD-MOORE AND PERRY, *Org. Syntheses*, **31**, 111 (1951).
(17) BILTZ, *et al.*, *J. prakt. Chem.*, **142**, 193 (1935).
(18) DELACRE, *Bull. acad. roy. Belg.*, 189 (1902); *Chem. Zentr.*, [1], **73**, 1197 (1902).
(19) SPIEGEL AND SPIEGEL, *Ber.*, **40**, 1730 (1907).