Chemical Reviews

THE RUPE AND MEYER–SCHUSTER REARRANGEMENTS

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Contents

I. Introduction

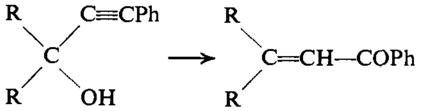
A. DEFINITION

The Rupe rearrangement is the acid-catalyzed rearrangement of tertiary α-acetylenic alcohols leading to the formation, predominantly, of α,β-unsaturated ketones.

The Meyer–Schuster rearrangement is the isomerization, by a 1,3 shift, of secondary and tertiary α-acetylenic alcohols to α,β-unsaturated carbonyl compounds. When the acetylenic group is terminal, the products are aldehydes; otherwise, they are ketones.

B. BACKGROUND

Meyer and Schuster[1] reported the first example of a Meyer–Schuster rearrangement when they obtained the ketones **2** and **4** by treating the carbinols **1** and **3** with a variety of acidic catalysts like acetic acid–concentrated sulfuric acid, ether saturated with dry hydrogen chloride, acetic anhydride, and acetyl chloride. An attempt[2] at converting compound **1** to its ethyl ether with concentrated sulfuric acid and ethanol also gave the α,β-unsaturated ketone **2**. Rupe and colleagues then effected the acid-catalyzed isomerization of a large number of α-acetylenic alcohols.[3–15] The color tests answered by the (presumably impure) products led them to conclude that they were aldehydes.[4,6–8] Repetition of these experiments later[16–20] showed that the main products of Rupe rearrangements are ketones and that the aldehydes reported were probably impurities. More recently, carefully performed experiments by Chanley[21] and others[22–25] have confirmed the observation that aldehydes are at best only minor products in Rupe rearrangements.



1 R = Ph **2**
3 R = p-ClC$_6$H$_4$ **4**

II. Scope of This Review

A search of the literature shows that two reviews[26,27] on the Meyer–Schuster and Rupe rearrangements have appeared

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(1) K. H. Meyer and K. Schuster, *Chem. Ber.*, **55**, 819 (1922).

(2) C. Moureu, C. Dufraisse, and C. Mackall, *Bull. Soc. Chim. Fr.*, 934 (1923).

(3) H. Rupe and K. Glenz, *Justus Liebigs Ann. Chem.*, **436**, 195 (1924).

(4) H. Rupe and E. Kambli, *Helv. Chim. Acta*, **9**, 672 (1926).

(5) H. Rupe and E. Kambli, *Justus Liebigs Ann. Chem.*, **459**, 215 (1927).

(6) H. Rupe and L. Giesler, *Helv. Chim. Acta*, **11**, 656 (1928).

(7) H. Rupe, W. Messner, and E. Kambli, *ibid.*, **11**, 449 (1928).

(8) H. Rupe, A. Wirz, and P. Lotter, *ibid.*, **11**, 965 (1928).

(9) H. Rupe and A. Gassmann, *ibid.*, **12**, 193 (1929).

(10) H. Rupe and H. Hirschmann, *ibid.*, **14**, 687 (1931).

(11) H. Rupe and F. Kuenzy, *ibid.*, **14**, 701 (1931).

(12) H. Rupe and F. Kuenzy, *ibid.*, **14**, 708 (1931).

(13) H. Rupe, R. Haecker, E. Kambli, and N. Wassieleff, *ibid.*, **16**, 685 (1933).

(14) H. Rupe and A. Gassmann, *ibid.*, **17**, 283 (1934).

(15) H. Rupe and H. Werdenberg, *ibid.*, **18**, 542 (1935).

(16) F. G. Fischer and K. Lowenberg, *Justus Liebigs Ann. Chem.*, **475**, 184, 199, 203 (1929).

(17) C. D. Hurd and R. E. Christ, *J. Amer. Chem. Soc.*, **59**, 118 (1937).

(18) C. D. Hurd and R. N. Jones, *ibid.*, **56**, 1924 (1934).

(19) C. D. Hurd and W. D. McPhee, *ibid.*, **71**, 398 (1949).

(20) C. C. Price and S. L. Meisel, *ibid.*, **69**, 1497 (1947).

(21) J. D. Chanley, *ibid.*, 70, 244 (1948).

(22) H. B. Henbest and G. Woods, *J. Chem. Soc.*, 1150 (1952).

(23) K. Suga and S. Watanabe, *Chiba Daigaku Kogakubu Kenkyu Hokoku*, **9**, 67 (1958); *Chem. Abstr.*, **54**, 5432 (1960).

(24) T. Takeshima, *J. Sci. Res. Inst., Tokyo*, **45**, 103 (1951); *Chem. Abstr.*, **46**, 4477 (1952).

(25) T. Takeshima, *J. Amer. Chem. Soc.*, **75**, 3309 (1953).

(26) R. Heilmann and R. Glenat, *Ann. Chim. (Paris)*, **8**, 178 (1963).

(27) G. Kugatova-Shemyakina, H. Laumenskase, G. K. Krasil'nikova, V. Mezolis, and V. Kaloelite, *Vop. Khim. Terpenov Terpenoidov, Akad. Nauk Lit. SSR, Tr. Vses. Soveshch.*, *Vilnyus*, 65 (1959).

recently, both of them relatively short. These isomerizations are also discussed briefly[28] in a review on rearrangements of acetylenic compounds involving π electrons of the triple bond.

This review therefore covers in detail the literature appearing in *Chemical Abstracts* up to the end of June 1968 and in about 20 selected journals up to the end of June 1970. Base-catalyzed and vapor-phase transformations of acetylenic alcohols have also been included, but the reactions of acetylenic glycols have been left out.

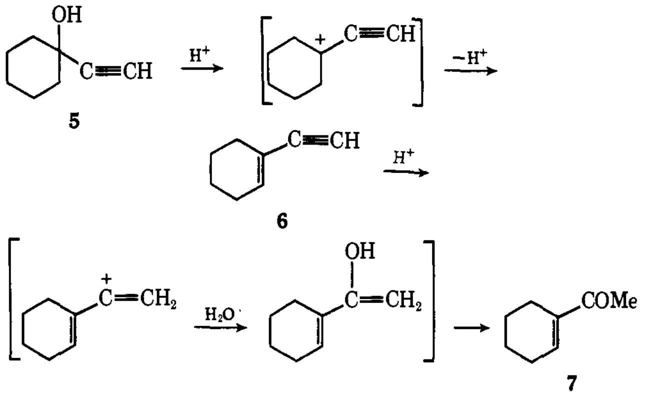
III. Liquid-Phase Acid-Catalyzed Rearrangements

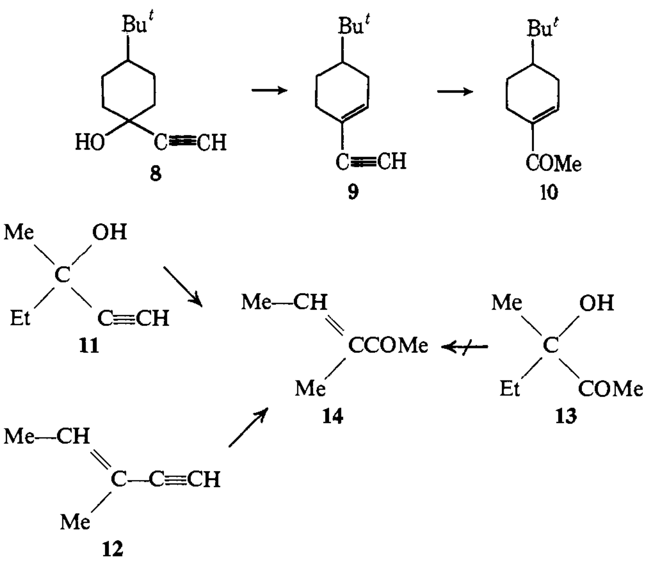
A. MECHANISM

1. The Rupe Rearrangement

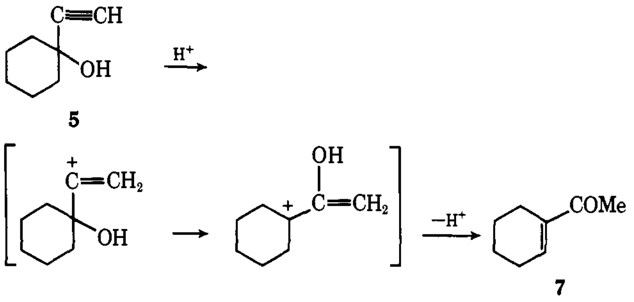
It is now generally agreed that the Rupe rearrangement of tertiary α-acetylenic alcohols to α,β-unsaturated ketones proceeds through a dehydration–hydration sequence, with enynes as intermediates.

Electrophilic attack by protons from the catalyst results in the formation of a tertiary carbonium ion which then expels a proton from an adjacent carbon atom, giving a vinylacetylene like **6**. Further electrophilic attack gives a secondary carbonium ion, which on work-up furnishes eventually the α,β-unsaturated ketone **7**. Such enyne intermediates have been detected spectroscopically[29] and even isolated[18,30–34] on several occasions. The quicker conversion[35] under identical conditions of the vinylacetylene **9** than the ethynyl carbinol **8** to the product **10** has been interpreted as evidence favoring the intermediacy of **9** in the rearrangement of **8** to **10**. The observation[36] that compounds **11** and **12** are converted by formic acid to **14**, while the alcohol **13** is not, rules out a hydration–dehydration sequence for the Rupe rearrangement.





It was observed that ethynylcyclohexene (**6**) was transformed much slower than ethynylcyclohexanol (**5**) to acetylcyclohexene (**7**) by the acid form of the cation-exchange resin Dowex 50 in acetic acid, and therefore a mechanism not invoking an enyne as intermediate was proposed.[37] This mechanism was accepted by Ansell, Hancock, and Hickinbottom[30] who were attempting hydration of terminal vinylacetylenes with formic acid. The need for such a mechanism has recently been questioned by Apparu and Glenat[38] who observed enynes as well as ketonic products during the isomerization of a few ethynyl carbinols with Dowex 50 in acetic acid. Contrary to earlier reports,[30,37] they were able to effect quick and complete hydration of vinylacetylenes with Dowex 50 in acetic acid. They also observed that enynes with terminal vinyl groups were hydrated much slower and that sulfuric acid in acetic acid brought about isomerization faster.



2. The Meyer–Schuster Rearrangement

In the acid-catalyzed rearrangement of an acetylenic alcohol of the general formula **15**, the intermediate alkynyl cation **16a** cannot expel a proton from an adjacent carbon atom and therefore isomerizes to the allenyl cation **16b** which on work-up furnishes the carbonyl compound **18**. When R‴ = H, the product is an aldehyde. In effect, the hydroxyl group undergoes a 1,3 or "propargylic"[39] shift across the triple bond. Such isomerizations occur when R′, R″ = Me also.

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(29) W. E. Parham, E. L. Wheeler, R. M. Dodson, and S. W. Fenton, *J. Amer. Chem. Soc.*, **76**, 5380 (1954).

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(35) M. S. Newman and P. H. Goble, *ibid.*, **82**, 4098 (1960).

(36) G. F. Hennion, R. B. Davis, and D. E. Maloney, *ibid.*, **71**, 2813 (1949).

(37) M. S. Newman, *ibid.*, **75**, 4740 (1953).

(38) M. Apparu and R. Glenat, *Bull. Soc. Chim. Fr.*, 1113 (1968).

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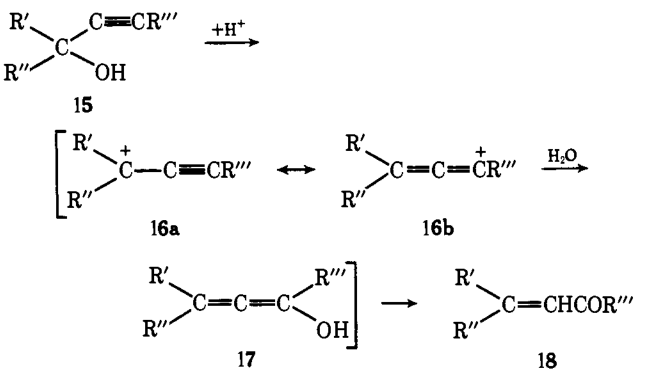

R′,R″ = *tert*-Bu or Ar; R‴ = H, alkyl, or aryl

Alkynyl cations like **16a** have been recently detected[40] by nmr and uv spectroscopy. The formation[38] of allenyl acetates in some reactions performed in acetic acid is evidence for the (transient) existence of allenyl cations like **16b**. The isolation[1] of 4,4′-dichlorobenzophenone from the acid-catalyzed isomerization of **3** and oxidative degradation is another item of evidence corroborating the above mechanism.

The driving force for both the Rupe and the Meyer–Schuster rearrangements appears to be the irreversible processes involved in the formation of unsaturated carbonyl compounds from the intermediate carbonium ions.

B. SUBSTRATES

The types of products obtained by the action of acidic catalysts on a variety of ethynyl carbinols are indicated in Table I.

C. CATALYSTS

A wide variety of acidic materials catalyzes the Rupe and the Meyer–Schuster rearrangements. The commonest of these is formic acid, in concentrations from 70[9] to 97%[78] for periods ranging from 3 min[78] to 100 hr[29] at different temperatures. Formic acid usually serves as the solvent also,[79] but in some instances it has been used in methanol solution.[80] It has been claimed that formic acid is not strong enough an acid to bring about rearrangements of all acetylenic carbinols, while stronger mineral acids are generally not miscible with the carbinols used. Better results have therefore been reported[81] with a mixture of sulfuric acid and acetic acid as catalyst, or, alternatively, a cation exchanger like Dowex 50 in acetic acid. Aqueous sulfuric acid of various strengths,[2,32,43,45,55,59] sulfuric acid diluted with solvents like ethanol,[9,82–84] 2-propanol,[3] *n*-butyl ether,[85] and acetic acid,[1,86–88] and phosphoric acid diluted with acetic acid[89,90] also bring about isomerization. Improved yields of aldehydes are claimed when some hydroquinone is added[54,91] to the catalyst and when a mixture of water and a miscible nonhydroxylic solvent like dioxane or acetic acid is used.[44] Phenol, malic, maleic, malonic, chloracetic, trichloracetic, and benzenesulfonic acids and zinc chloride have also been observed[89] to catalyze the isomerization; the evidence indicates that the rearrangement is appreciable with acids stronger than formic acid and that the nature

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(40) H. G. Richey, Jr., J. C. Philips, and L. E. Rennick, *J. Amer. Chem. Soc.*, 87, 1381 (1965).

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(49) Y. Okajima, *Yakugaku Zasshi*, 79, 1288 (1959); *Chem. Abstr.*, **54**, 4475 (1960).

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(61) J. Cymerman, I. M. Heilbron, and E. R. H. Jones, *ibid.*, 90 (1945).

(62) N. A. Preobrazhenskii and I. A. Rubtsov, *Zh. Obshch. Khim.*, **18**, 1719 (1948).

(63) I. Heilbron, E. R. H. Jones, M. Julia, and B. C. L. Weedon, *J. Chem. Soc.*, 1823 (1949).

(64) M. N. Shchukina and I. A. Rubtsov, *Zh. Obshch. Khim.*, **18**, 645 (1948).

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(69) J. Rauss-Godineau, J. Barralis, W. Chodkiwiecz, and P. Cadiot, *Bull. Soc. Chim. Fr.*, 193 (1968).

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(80) E. Hofstetter and A. E. W. Smith, *Helv. Chim. Acta*, **36**, 1949 (1953).

(81) M. Apparu and R. Glenat, *Bull. Soc. Chim. Fr.*, 1106 (1968).

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(90) T. Takeshima, *J. Amer. Chem. Soc.*, **75**, 4107 (1953).

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Table I

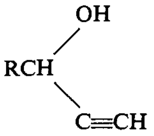
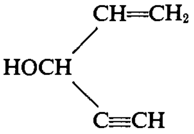
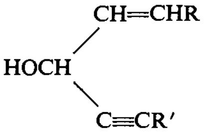
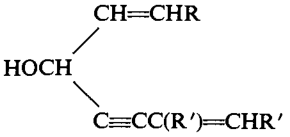
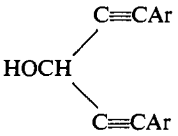
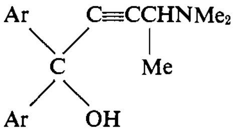
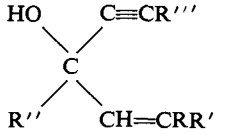
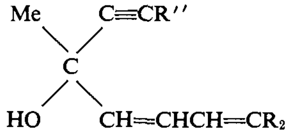
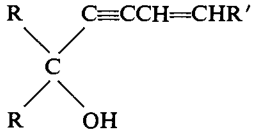
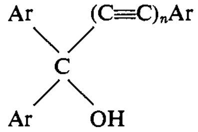
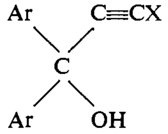
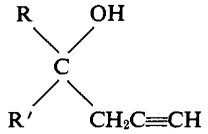
Substrates	*Remarks*	*Ref*
1. α-Acetylenic alcohols		
(a) Primary $CH\equiv CCH_2OH$	They undergo no rearrangement, giving only formates with 99% formic acid	41
(b) Secondary	They take part in Meyer–Schuster rearrangements	34, 42–45
(i) Saturated aliphatic	Conflicting claims have appeared on their ability to undergo Rupe rearrangements	
	Reactions in formic acid and acetic acid have been claimed to yield only formates and acetates, respectively	42
R = saturated alkyl	Loss of acetylene to give starting aldehydes and their self-condensation products has been reported.	46
	Hot, concentrated sulfuric acid has been reported to yield Rupe-type products	47
(ii) α′-Vinyl 	It is unaffected by 25% sulfuric acid	48
(iii) Substituted α′-vinyl 	When R = R′ = Cl	50
	R = R′ = Ph	51
	R = Ph, R′ = H or Me propargylic shifts to Meyer–Schuster products take place	43, 49, 51
	In other cases, products arising from allylic shifts of OH group are obtained	48, 52
(iv) α′,γ-Divinyl 	The OH group undergoes a 1,3 allylic shift; this is accompanied at times by dehydration	42, 49, 53
(v) α′-Acetylenic 	They rearrange to Meyer–Schuster products	54
(c) Tertiary	They undergo Rupe or Meyer–Schuster rearrangement, depending on whether a proton can be ejected or not from an α-carbon atom	
	Ethynylcyclopropanol, however, is unaffected by aqueous hydrochloric acid	55
(i) Acetates of	Rupe rearrangement products are obtained	56, 57
	Pyrolysis gives allenyl acetates	58
(ii) ω-Dialkylaminoalkyl 	Meyer–Schuster products are formed	59

Table I (Continued)

Substrates	*Remarks*	*Ref*
(iii) α′-Substituted vinyl 	The OH group undergoes an allylic shift; this is accompanied by dehydration sometimes	43, 48, 52, 53, 60, 61
	When R‴ = OEt, the Meyer–Schuster product is an ester	62
(iv) α′-Butadienyl. 	The OH group migrates to the end of the butadienyl system.	65
(v) γ-Vinyl 	Meyer–Schuster products are formed.	66
	Formation of ethers (by loss of water from 2 mol of carbinol) has also been noted	67
	Dehydration to dienynes occurs at times	32
	When R′ = OMe, the OH group migrates across the triple and then the double bond to yield $R_2C{=}C{=}C{=}CHCHO$	68
(vi) Conjugated polyacetylenic 	They undergo Meyer–Schuster rearrangements, but more slowly	66, 69
(vii) Miscellaneous[a] 	When X = Br or Cl, acid chlorides or carboxylic acids are obtained by Meyer–Schuster isomerizations	66, 69
	When X = OEt or SEt, the corresponding α,β unsaturated esters are formed by Meyer–Schuster rearrangements	63, 64, 70–73
2. β-Acetylenic tertiary alcohols 	When R, R′ = Me, *tert*-Bu, or Ar, α,β-unsaturated ketones are formed by a dehydration–hydration sequence	74, 75
	When R, R′ = other aliphatic groups, both α,β- and β,γ-unsaturated ketones are formed, the former in larger amounts	75
	When R, R′ = part of an alicyclic ring, the mixture of α,β- and β,γ-unsaturated ketones is richer in the latter	75
	By using different catalysts, the cis and trans forms of the α,β-unsaturated ketone have been obtained separately	76, 77

[a] A few other examples are given in ref 28.

of the acidic catalyst does not affect the course of the rearrangement.

Other effective catalysts are cation exchangers like Dowex 50 in formic acid[92] and acetic acid,[37,93] anhydrous oxalic acid,[94,95] hydrochloric acid in 2-propanol,[96] hydrochloric acid and mer[illegible]ic chloride,[97] dry ether saturated with hydrogen chloride,[1] *p*-toluenesulfonic acid,[80] phosphorus pentoxide in dry benzene,[30,98] potassium bisulfate,[43] sodium or magnesium sulfate under vacuum,[76] sulfuric acid and mercuric

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(93) R. Heilmann and R. Glenat, *C. R. Acad. Sci.*, **240**, 2317 (1955).

(94) R. Ya. Levina and E. I. Vinogradova, *J. Appl. Chem. USSR*, **9**, 1299 (1936); *Chem. Abstr.*, **31**, 2587 (1937).

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sulfate,[99–102] ethanol and mercuric sulfate,[77] phosphorus oxychloride-pyridine,[80] acetyl chloride,[1] acetic anhydride-acetyl chloride,[80] acetic anhydride-sodium acetate,[80] acetyl chloride-pyridine,[80] acetic anhydride,[1,7,103] 2,4-dinitrophenylhydrazine reagent,[101,104–106] and thionyl chloride.[1,107]

Phosphorus and thionyl halides generally convert ethynyl alcohols to mixtures of acetylenic and allenic products. These mixtures arise from "acetylene-allene" or "propargylic"[39] rearrangements, which have been reviewed[28,39,108,109] recently. The types of products obtained by reaction of ethynyl carbinols with these reagents are outlined in Table II. R represents the propargyl ($-C\equiv CC<$) group, R′ the isomeric allenyl ($>C=C=C<$) group, and R′′ the alkynyl group ($>CC\equiv C-$) obtained from R′.

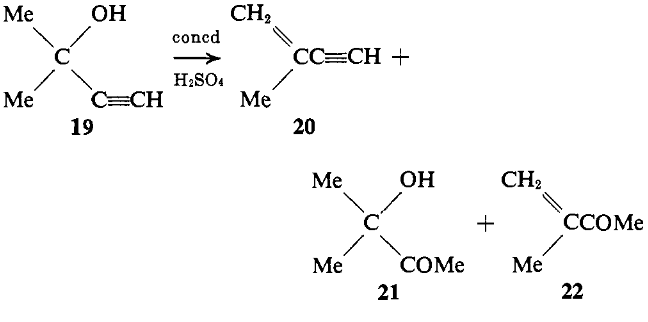
D. REACTION PRODUCTS

The separation and identification of the reaction products and the minor modifications observed in them are discussed here.

Mixtures of aldehydes and ketones are separated from each other through bisulfite addition compounds,[10,15] column chromatography,[29,78] distillation through a fractionating column,[139] or by fractional crystallization of the semicarbazones.[6,13]

The structures of the products are established by ozonolysis[13,15,19] oxidative degradation,[1] hydration of the appropriate enynes[95] (prepared from the starting ethynyl carbinols by treatment with phosphorus oxychloride and pyridine[32]), comparison of melting points of reaction products and their derivatives with those of authentic specimens,[10,11,16,25,35] air oxidation,[140] reduction to saturated alcohols and reoxidation to acids and ketones,[80] and spectroscopically.[29,35,78]

Cis–trans isomerism in the reaction products has been detected only in a few instances,[76,141–143] although it would be expected to be more prevalent. Polymorphic modifications of reactions products[144,145] have been reported. In addition to α,β-unsaturated ketones, β,γ-unsaturated ketones are also formed at times.[13,25,31,75,146] The sulfuric acid catalyzed rearrangement of the carbinol **19** yields the enyne **20**, the keto alcohol **21**, and the Rupe product **22**, but none of the expected aldehyde.



19 **20** **21** **22**

Even carbinols which can undergo Rupe rearrangement quite often give[25,30] low yields of Meyer-Schuster products (α,β-unsaturated aldehydes). The low yields have been attributed to their easy oxidation and self-condensation. Attempts to inhibit polymerization by adding hydroquinone[54,91] have not been very successful. Other attempts to improve the yields of aldehydes (by trapping them[26,106] with carbonyl reagents as soon as they are formed and by sweeping the reaction products away from the catalyst, as by steam distillation[45] or passage over a catalyst in the vapor phase[139,147–148]) have been more successful.

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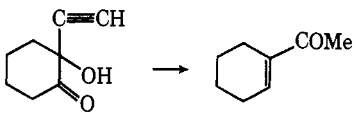
Table II

Halide	*Reaction conditions*	*Products*	*Ref*
PBr_3[a]	Py, 0°, *i*-Pr_2O	$(RO)_3P + (RO)_2POR'$	110
PBr_3[a]	Py, higher temp	$(R'Br)_2$	110
PBr_3[a]	0°, Py or no Py	RBr	111
PBr_3[a]	No Py	RBr + the two products from addition of HBr to each of the two double bonds in R'Br	112
PBr_3[a]	No Py	R'Br	113
PBr_3[a]	No Py, HOAc	R'Br + product from addition of HBr to R'Br	114
PBr_3[a] excess	No Py	$(R'POBr_2)_2$ + (the product from addition of HBr to $R'Br)_2$	110
PBr_5[b]	0°, Et_2O, no Py	RBr + R'Br + ROEt + product from addition of HBr to R'Br	115
PBr_5[b]	Et_2O, 0°, Py	RBr + R'Br + products from addition of bromine to ROH, RBr, and R'Br	115
$SOBr_2$[c]	Et_2O, no Py	R'Br + products formed by addition of HBr to R'Br and addition of bromine to R'Br	115
$SOBr_2$[c]	No Py, pentane	RBr	111
$SOBr_2$[c]	Py, 0°	R'Br	115
HBr aq		No reaction; incomplete formation of R'Br	116, 117
		RBr	118
HBr aq	$NH_4Br + Cu_2Br_2$	R'Br	117, 119, 120
PCl_3	Py, low temp	$(RO)_3P + (RO)_2POR'$	110
PCl_3	Py, low temp	$(RO)_2POR'$	121–123
PCl_3	Py, higher temp	RCl	110
PCl_3 excess	Et_3N, Et_2O, −20°	$(RO)_2POR'$	122
PCl_3 excess	No Py	$R'POCl_2 \rightarrow R''POCl_2$	124–126
PCl_3 excess	No Py	RCl + addition product of HCl to R'Cl + (addition product of HCl to $R'POCl_2$) + $R'POCl_2$	110, 113
PCl_5	No Py, 0°, ether	RCl	112
PCl_5	0°, no Py, Et_2O	ROEt + R'Cl	116
$SOCl_2$	Py	RCl (with primary and secondary carbinols) + R'Cl	112, 127
$SOCl_2$	Py	R'Cl	128, 129
$SOCl_2$	Py	R'Cl + $(RO)_3S$	116
$SOCl_2$	No Py	RCl	112
$SOCl_2$	No Py	R'Cl	113, 116
HCl	$CaCl_2$	RCl	130
HCl aq	CuCl + NH_4Cl	RCl + R'Cl	131–133
HCl aq	CuCl + NH_4Cl	RCl + R'Cl + conjugated chlorodienes	19, 99, 134, 135
SF_4[d]		R'F	135

[a] The products of these reactions were earlier thought to be propargyl bromides, but later[113,119,136–138] it was recognized that many of them were partly, if not wholly, allenic bromides. [b] The decomposition $PBr_5 \rightarrow PBr_3 + Br_2$ accounts for the presence of free bromine and consequent reactions. [c] The reaction $2SOBr_2 \rightarrow S + SO_2 + 2Br_2$ liberates free bromine. [d] The alcohols used were tertiary and liberally substituted with chlorine and fluorine.

E. ABNORMAL PRODUCTS

Deoxygenation has been observed, the keto carbinol **23** giving **24**.[92]



23 **24**

The isomerization of the alcohol **25** gives the normal product **26** and the abnormal product **27**.[149]

Dismutation of ethynyl carbinols to starting aldehydes or ketones followed by self-condensation or rearrangement and oxidation are also known (eq a and b).[46,150]

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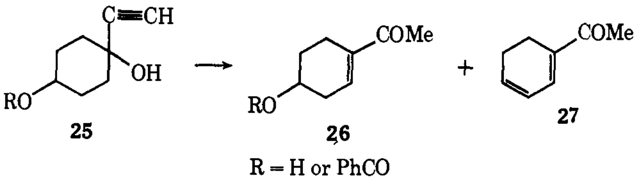
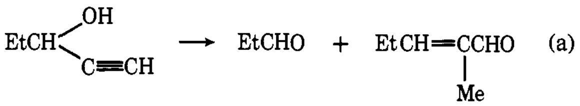
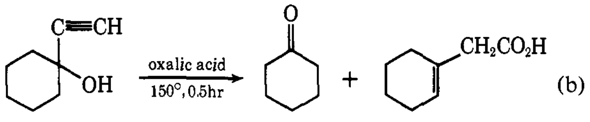
(149) E. R. H. Jones and F. Sondheimer, *J. Chem. Soc.*, 615 (1949).

(150) E. Bergmann and F. Bergmann, *J. Amer. Chem. Soc.*, **59**, 1449 (1937).

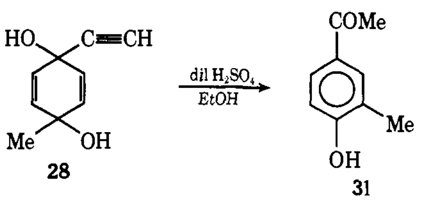

25 26 27

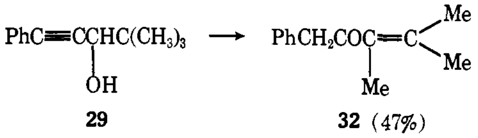
R = H or PhCO


$\mathrm{EtCH(OH)C{\equiv}CH \longrightarrow EtCHO + EtCH{=}C(Me)CHO}$ (a)

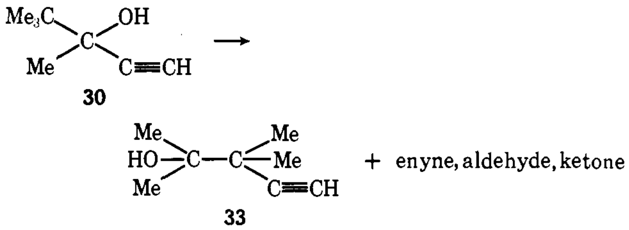


Methyl group migrations, with[34,151] or without[81] subsequent ejection of a proton, explain the formation of compounds **31**, **32**, and **33** from **28**, **29**, and **30**, respectively.


28 31

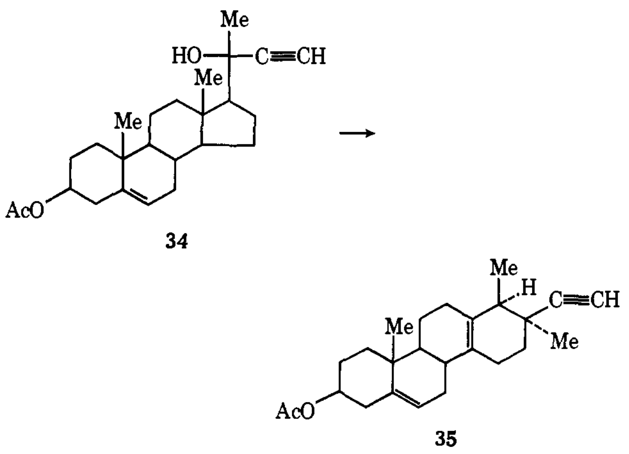

$\mathrm{PhC{\equiv}CCH(OH)C(CH_3)_3 \longrightarrow PhCH_2COC(Me){=}C(Me)_2}$

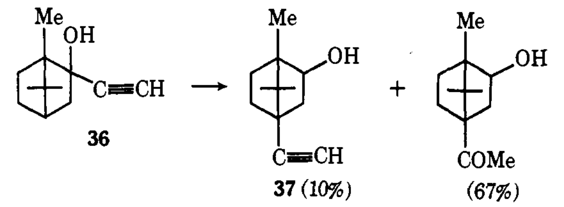
29 32 (47%)


$\mathrm{Me_3C{-}C(Me)(OH){-}C{\equiv}CH \longrightarrow Me_2C(OH){-}C(Me)_2{-}C{\equiv}CH}$ + enyne, aldehyde, ketone

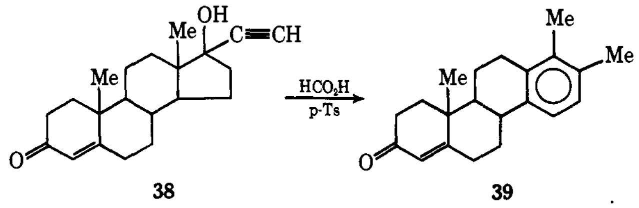
30 33

A Wagner-Meerwein rearrangement[78] converts the ethynyl alcohol **34** to **35** and a Wagner-Nametkin rearrangement[152] converts the carbinol **36** to **37**.

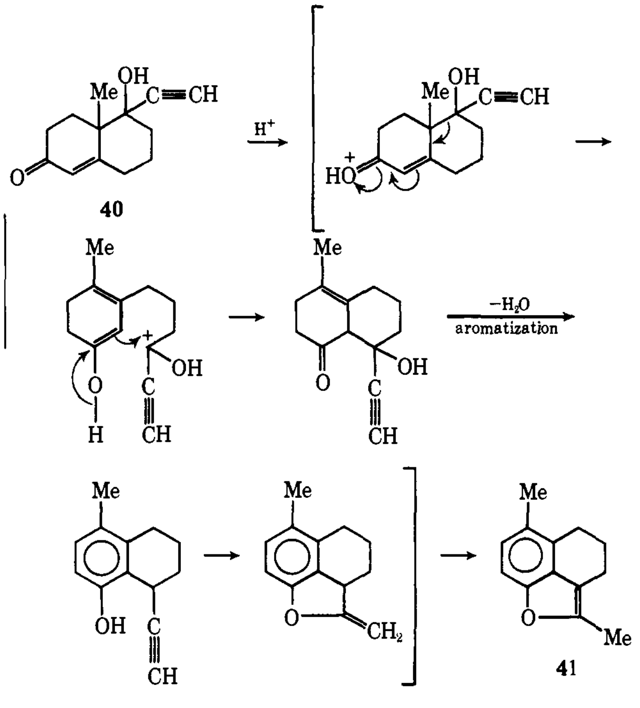

34 35


36 37 (10%) (67%)

The transformation of 17-ethynyltestosterone **38** to the ring D homo aromatic product **39** is explained by a Wagner-Meerwein shift and internal Prins rearrangement, followed by isomerization.[153-156]


38 39

The δ-hydroxy-δ-ethynyl α,β-enone **40** is rearranged to the benzofuran **41** by the mechanism shown below when refluxed with *p*-toluenesulfonic acid in chloroform for 2 hr.[157]


40 41

The thionyl chloride-pyridine catalyzed reaction[158] of the ethynyl alcohol **1** leads to the tetracyclic compound **42** in addition to the expected product **2**. The corresponding reaction with compound **43** gave three compounds assigned[158] structures **44-46**.

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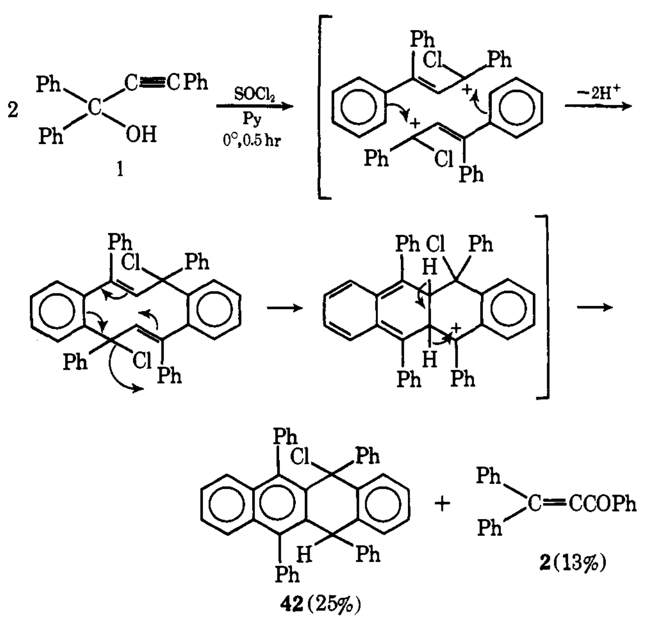
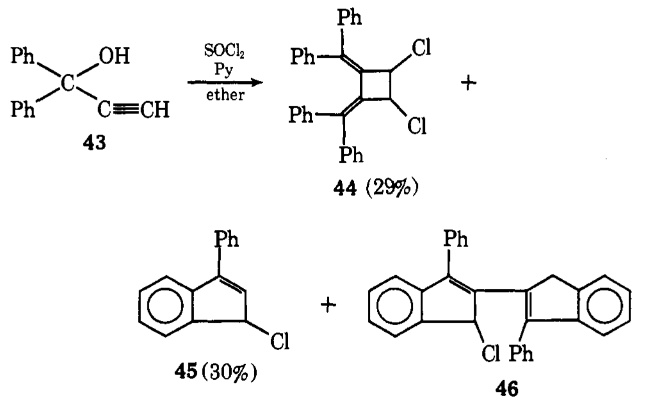


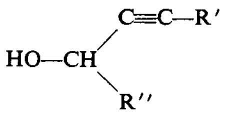


IV. Liquid-Phase Base-Catalyzed Rearrangements

The literature on this aspect of the Rupe and Meyer-Schuster rearrangements is meager, but, nevertheless, some generalizations can be made.

A. MECHANISM

The base-catalyzed rearrangements of α-acetylenic carbinols like[159,160]



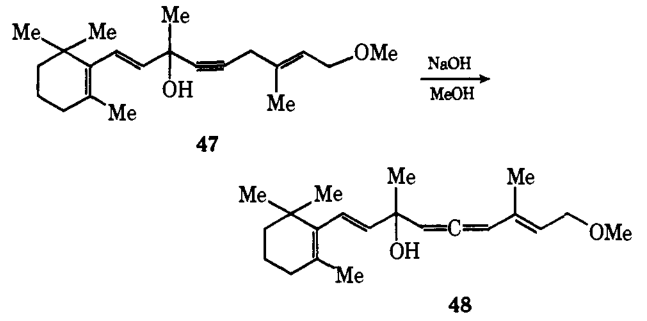
$$HO-CH(C\equiv C-R')(R'')$$

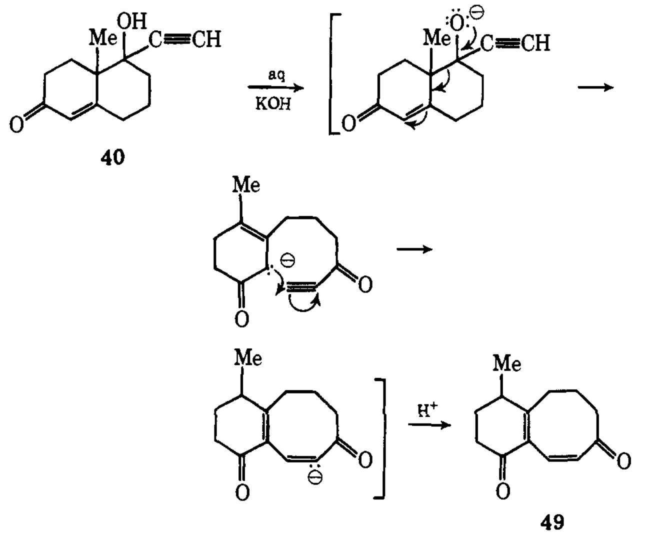
(R' or R'' = Ar)

lead to products of the Meyer-Schuster type. Isomerizations to Rupe-type products seem to be unknown. The base-catalyzed isomerizations appear to proceed with propargylic shift of the α-acetylenic hydrogen.

B. SUBSTRATES

Secondary α-acetylenic alcohols like the one above isomerize as expected, but tertiary alcohols appear to yield other products.[161–164] Thus the alcohol **47** is isomerized[165] to **48** while **40** is rearranged[166] to **49**.





C. CATALYSTS

Alkalis like aqueous alcoholic potassium hydroxide[159,165,167,168] and organic bases (amines) like pyridine,[159] diethylamine, and triethylamine[160] have been employed. The more potent inorganic catalysts degrade the rearrangement products further unless they are trapped with carbonyl reagents like hydrazine.[168] It is not known definitely whether pyridine causes rearrangements.[159]

Sodium and potassium amides in liquid ammonia react with terminal α-acetylenic carbinols replacing the hydroxylic and acetylenic hydrogens and subsequently forming *C*- and *O*-monoalkyl and *C*,*O*-dialkyl compounds with alkyl halides.[169–171] Lithium amide in liquid ammonia also forms

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(159) G. R. Lappin, *J. Org. Chem.*, **16**, 419 (1951).

(160) A. W. Nineham and R. A. Raphael, *J. Chem. Soc.*, 118 (1949).

(161) P. Rona and P. Crabbe, *J. Amer. Chem. Soc.*, **91**, 3289 (1969).

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(165) S. Swaminathan, K. G. Srinivasan, and P. S. Venkataramani, *Tetrahedron*, **26**, 1453 (1970).

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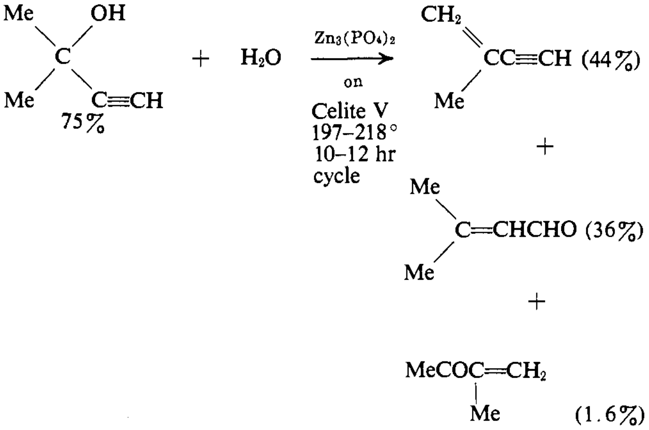
(171) M. D. d'Engenieres, M. Miocque, and J. A. Gautier, *ibid.*, 2480 (1964).

C,O-dilithio compounds, but only C-alkylation occurs with alkyl halides.[170–172] Alkylating agents like 1-bromo-3-chloropropane are extensively dehydrohalogenated by sodium and potassium amides.[171] The allylethynyl compounds thus formed are rearranged to propenylethynyl compounds *via* vinylallenyl intermediates.[173] Methylacetylenic alcohols are isomerized to terminal acetylenic alcohols[174] by potassium amide in liquid ammonia.

V. Vapor-Phase Rearrangements

Reactions of ethynyl alcohols with catalysts in the vapor phase are primarily processes[175–177] for preparing vinylacetylenes.[80,139,147,148,178] In addition, Rupe as well as Meyer–Schuster types of products[147,148] are also obtained; since the aldehydes formed are swept away from the catalyst continuously, self-condensation is not possible and so they are isolated in significantly higher yields than in the liquid phase.[179,180]



The thermolysis of α-ethynyl-α′-allyl[181] and α′-propargyl-α-vinyl[182,183] carbinols results in products arising from an oxy-Cope rearrangement.

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