The Stereochemistry of the Phosphonate Modification of the Wittig Reaction

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A number of olefins prepared by the phosphonate carbanion modification of the Wittig reaction were shown to have *trans* configurations. Vapor phase chromatography of the intact reaction mixtures showed, at most, only trace amounts of *cis* isomers. To determine the degree of stereospecificity of the reaction under adverse circumstances, several experiments were devised with systems which, based on the generally accepted reaction mechanism,[1,2] should be more favorable for the preparation of *cis* olefins. In only one case, however, was a significant amount of a *cis* isomer formed [6.4% *cis*-1,2-(1,1′-dinaphthyl)ethylene in a 1:10 *cis–trans* mixture], demonstrating the great stereospecific tendency of the reaction. Possible interpretations of the observed differences in stereospecificity of olefin formation from phosphonate carbanions and phosphorus ylids are discussed.

The preparation of olefins by a convenient, general procedure has long been of interest. The Wittig reaction has proved to be quite versatile in this respect. The phosphonate modification of the Wittig reaction has proved to be useful in preparing sensitive olefins not preparable by standard Wittig synthesis.[1,3–5] In addition, it is not particularly sensitive to atmospheric oxygen, thus allowing simpler experimental procedures, is, in general, less expensive, and furnishes the *trans* isomers stereospecifically. This paper is concerned with demonstrating the extent of stereospecificity of the reaction and in determining whether reaction systems can be found that will result in the formation of *cis* olefins.

Discussion

Several recent papers have described the influence of reactants and reaction conditions on the stereochemistry of the Wittig reaction.[5–9] Although stable ylids furnish predominantly *trans* olefins, mixtures of isomers are often obtained from more transient phosphoranes. Phosphonate carbanions, on the other hand, have been reported to invariably furnish a great preponderance of *trans* olefin.[10] A variety of substituted olefins prepared in our laboratories by the phosphonate method with both aromatic and aliphatic aldehydes have in evey case been a *trans* configuration.

Patai and Schwartz[11] describe the preparation of a mixture of *cis*- and *trans*-ethyl *p*-nitrocinnamate from a condensation of *p*-nitrobenzaldehyde and O,O-diethyl carbethoxymethylphosphonate. Since only *trans*-ethyl *p*-nitrocinnamate could be isolated, the authors concluded that originally a *cis–trans* mixture of isomers was obtained which subsequently isomerized upon heating or recrystallization. Repetition of this work showed that the crude product was in fact a 10:90% mixture of *trans*-*p*-nitrocinnamate and *p*-nitrobenzaldehyde. Products were identified by gas chromatography and isolated by column chromatography. A 90:10% sample mixture of *p*-nitrobenzaldehyde (m.p. 106.5°) and *trans*-ethyl *p*-nitrocinnamate (m.p. 137°) melts at 80–85°, corresponding roughly to the melting point of the "*cis–trans*" mixture of Patai and Schwartz.

A number of stilbene analogs, distyrylbenzene, ethyl cinnamate, β-styrylacrylic acid, and cinnamic acid were prepared by using the phosphonate modification of the Wittig reaction. Only *trans* products could be isolated, although vapor phase chromatography indicated the presence of trace amounts of *cis* isomers.

Wadsworth and Emmons[1] have postulated a nonstereospecific reaction, with subsequent equilibration of the mixture to the more stable *trans* isomer.

To determine the importance of olefin equilibration on the nature of the product, 1,2-(1,1′-dinaphthyl)ethylene (**1**), 2-styrylpyridine (**2**), and ethyl crotonate (**3**) were prepared from reactions enriched with measured amounts of the *cis* isomer and compared by gas chromatography with the products formed from standard preparations.

$$\mathrm{RCHO} + (\mathrm{C_2H_5O})_2\mathrm{P(O)CH_2R'} \xrightarrow{\text{base}} \mathrm{RCH{=}CHR'} + \mathrm{HOP(O)(OC_2H_5)_2} \quad (1)$$

1, R = R′ = 1-naphthyl
2, R = 2-pyridyl; R′ = Ph
3, R = Me; R′ = acetoxy

All of the olefin–product mixtures contained sufficient *cis* isomer to account for the amount normally formed during reaction plus the amount added beforehand. This established the stability of the *cis* isomers toward the reaction conditions and illustrated the stereospecific nature of the reaction. In the preparation of ethyl crotonate, equilibration studies showed that equilibrium in a simulated reaction medium lay far to the side of the *trans* isomer, however (99.6:0.4), illustrating that the small amount of *cis* product formed during the reaction does not arise from equilibration of the *trans* isomer (see Experimental for details).

From the reaction path proposed by Wadsworth and Emmons,[1] several schemes which might increase the amount of product having a *cis* configuration can be devised[8] (see eq. 2).

With starting materials containing large groups (L), enhancement of the yield of *cis* olefin from the sterically favored **4** might be realized. On using 1-naphthal-

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(1) W. S. Wadsworth and W. D. Emmons, *J. Am. Chem. Soc.*, **83**, 1732 (1960).

(2) L. Horner, H. Hoffmann, W. Klink, H. Ertel, and V. Toscano, *Chem. Ber.*, **95**, 581 (1962).

(3) G. Wittig and W. Haag, *ibid.*, **88**, 1654 (1955).

(4) H. Pommer, *Angew. Chem.*, **72**, 911 (1960).

(5) R. Ketcham, D. Jambotkar, and L. Martinelli, *J. Org. Chem.*, **27**, 4666 (1962).

(6) L. D. Bergelson, V. A. Vaver, L. I. Barsukov, and M. M. Shemyakin, *Dokl. Akad. Nauk SSSR, Chem. Sect.* (Eng. Transl.), **143**, 148 (1962).

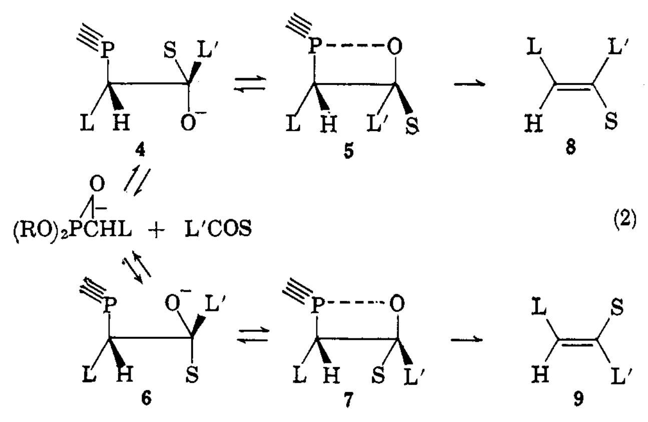
(7) M. M. Shemyakin, L. D. Bergelson, and V. A. Vaver, *Chem. Eng. News*, **40**, 36 (1962).

(8) A. J. Speziale and K. W. Ratts, *J. Am. Chem. Soc.*, **85**, 2790 (1963).

(9) J. Bestmann and O. Kratzer, *Chem. Ber.*, **95**, 1894 (1962).

(10) L. Horner, H. Hoffmann, H. Whippel, and G. Klabre, *Chem. Ber.*, **92**, 2499 (1959).

(11) S. Patai and A. Schwartz, *J. Org. Chem.*, **25**, 1232 (1960).

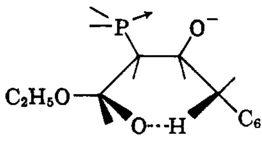


(2)

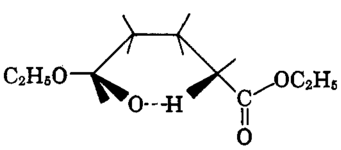
L′ and L = large group
S = small group

dehyde and dimethyl 1-naphthylmethylphosphonate, products containing 7–9% *cis*-1,2-(1,1′-dinaphthyl)-ethylene were obtained. Although the reaction still produced predominantly *trans*-dinaphthylethylene, six to seven times as much sterically less-favored *cis*-dinaphthylethylene as *cis*-stilbene was formed under similar reaction conditions.[12]

A second scheme for increasing the proportion of *cis* olefin involved attempts to make structure **5** (eq. 2) more favorable than **7** by providing an intramolecular attraction between L and L′. Diethyl carbethoxymethylphosphonate was condensed with both phenylacetaldehyde and ethyl acetoacetate to see if internal hydrogen bonding as shown in structures **10** and **11** would provide such an attraction.



10



11

In the preparation of ethyl γ-phenylcrotonate (**12**, successor of **10**) initial attempts in alcohol gave only ethyl styrylacetate (**13**). In toluene solution at −20° a good yield of the desired product was obtained. V.p.c. indicated the formation of only one product, which was shown to be the *trans* isomer by infrared, n.m.r., and ultraviolet spectra, and mass-spectrometric data. (See footnotes *q* and *r* to Table I for a similar reaction with *n*-butyraldehyde.)

The temperature necessary to bring about the condensation of ethyl acetoacetate with diethyl carbethoxymethylphosphonate was sufficiently high to cause equilibration of the product to a 48:52 mixture of *cis*- and *trans*-ethyl carbethoxymethylcrotonates. (For a similar reaction with 2-heptanone, see Table I.)

Two attempts, similar to those used successfully with the Wittig reaction,[5] were made to alter the *cis*/*trans* ratio of products by changing the relative rates of the steps of the proposed[1] reaction path (eq. 2). Such a situation would result if formation of **4** and **6** could be made the rate-determining step. The reaction of *p*-methoxybenzaldehyde and diethyl benzylphosphonate or diethyl *p*-nitrobenzylphosphonate, compounds which might fulfill this kinetic requirement, gave only small amounts of *cis*-stilbenes (Table I).

Complete kinetic control of the stereochemistry of the product would result from an irreversible formation of **4** and **6**.[5] With *p*-nitrobenzaldehyde and diethyl *p*-methoxybenzylphosphonate, however, only *trans*-4-methoxy-4′-nitrostilbene was obtained. With 2,4-dinitrobenzaldehyde, none of the substituted stilbene was detected by v.p.c.

According to Shemyakin, *et al.*,[6,7] Wittig reactions can be made stereospecifically *cis* by the addition of certain halogen salts to the reaction. Although no apparent theoretical basis existed for predicting an effect on the *trans* nature of phosphonate reactions, lithium iodide and sodium iodide were added to the reaction mixture in the preparation of 2-pyridinealdehyde and diethyl benzylphosphonate; addition of lithium iodide resulted in a complete repression of the reaction, with no product apparent (v.p.c.) after 1 hr. With sodium iodide as an additive, a 14% yield of exclusively *trans*-2-styrylpyridine resulted.

In contrast to the Wittig reaction,[5,8] the use of sterically and electronically different starting materials has produced only minor changes in the stereospecific nature of the phosphonate carbanion modification of the Wittig reaction. Other factors also altering the steric nature of the products from Wittig reactions,[6,7] such as reaction media and Lewis-base additives, have been ineffective in changing the tendency of the aldehyde–phosphonate condensation to produce *trans* olefins. The vastly different behavior of Wittig reactions and phosphonate reactions with respect to factors influencing the steric nature of the product might be interpreted as evidence either for a different reaction mechanism, or for large differences in the rate ratio of $k_{\text{intermediate decomp}}/k_{\text{intermediate formation}}$. Although such factors as the nature of the solvent, Lewis-base additives, or substituents may significantly alter the rate ratio in Wittig reactions, an extremely rapid formation or a relatively slow decomposition of the intermediates could cause such factors to be ineffective in phosphonate reactions.

Experimental

Preparation of Intermediates.—Phosphonates were prepared by a Michaelis–Arbuzov reaction with the corresponding bromides or chlorides and trimethyl or triethyl phosphite.[13] Halides were prepared by standard procedures or used as received from Eastman Kodak Co. Products were purified by distillation or v.p.c. and purities were determined by v.p.c.

Preparation of Various Disubstituted Ethylenes. Method I.—A mixture of equimolar amounts of an appropriate phosphonate with an aldehyde or ketone was added dropwise to a solution of an equivalent amount of sodium alkoxide in the corresponding alcohol. After the mixture had been refluxed for several hours, the resulting reaction mixture was diluted with an equal volume of water if solid products were expected and the resulting solid was purified by crystallization. If liquid products were formed, the crude product mixtures were purified by gas chromatography.

Method II.—A suspension of sodium methoxide or sodium ethoxide in N,N-dimethylformamide was treated with an equimolar amount of a mixture of the appropriate phosphonate and carbonyl compound, and the resulting reaction mixture was stirred at room temperature for 1–2 hr. The product was precipitated by

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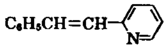
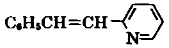
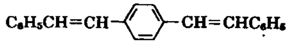
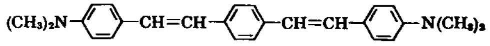
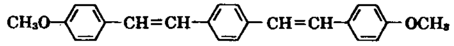
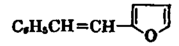
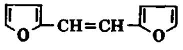
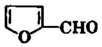
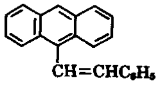
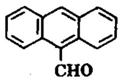
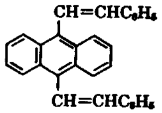
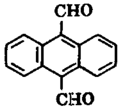
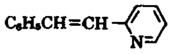
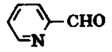
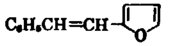
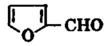
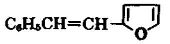
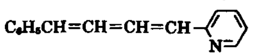
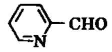
[12] A referee has suggested that, since the maximum $\Delta\Delta F$ which can be calculated for the two over-all reactions is only of the order of 1.5 kcal./mole (assuming the yields of products are proportional to the k_{cis} and k_{trans}), effects other than steric ones may be the factors contributing to the observed ratio of products.

[13] G. M. Kosolapoff, "Organo Phosphorus Compounds," 1st Ed., John Wiley and Sons, Inc., New York, N. Y., 1950, p. 121.

TABLE I

PREPARATION OF DISUBSTITUTED ETHYLENES

Olefin	Phosphonate[a]	Aldehyde or ketone	Method[b]	Base	M.p. or b.p., °C. (recrystn. solvent)	% yield cis	% yield trans	Ref.
$C_6H_5CH{=}CHC_6H_5$	A	C_6H_5CHO	III	$NaOCH_3$	. . .	1.2	86.9	*c–e*
						0.9	97.9	
$C_6H_5CH{=}CH(p\text{-}O_2NC_6H_4)$	A	$p\text{-}O_2NC_6H_5CHO$	III	$NaOCH_3$	154–155 (C_2H_5OH)	0.8	36.3	*c, f, g*
$C_6H_5CH{=}CH(p\text{-}O_2NC_6H_4)$	D	C_6H_5CHO	III	$NaOCH_3$	154–155 (C_2H_5OH)	1.9	74.5	*c, f–h*
$C_6H_5CH{=}CH(p\text{-}CH_3OC_6H_4)$	A	$p\text{-}CH_3OC_6H_5CHO$	III	$NaOCH_3$	135–136 (C_2H_5OH)	0	100	*c, f, i*
$C_6H_5CH{=}CH(p\text{-}C_2H_5OCOC_6H_4)$	C	C_6H_5CHO	III		102–102.5	0	76.3	*c, f, j*
			I	$NaOC_2H_5$	($CH_3OH–H_2O$)	. .	78.5	
$C_6H_5CH{=}CH(p\text{-}CH_3OCOC_6H_4)$	C	C_6H_5CHO	I	$NaOC_2H_5$	159.5–160 (CH_3COCH_3)	. .	36.7	*c, f, k*
$p\text{-}NO_2C_6H_4CH{=}CH(p\text{-}C_2H_5OCOC_6H$	C	$p\text{-}NO_2C_6H_4CHO$	III	$NaOC_2H_5$	165.5–166.5	1.9	63.5	*c, f, g, j*
$p\text{-}CH_3C_6H_4CH{=}CH(p\text{-}C_2H_5OCOC_6H_4)$	C	$p\text{-}CH_3C_6H_4CHO$	III	$NaOC_2H_5$	134–135	0	64.8	*c, j*
$4\text{-}CH_3OC_6H_4CH{=}CH(p\text{-}NO_2C_6H_4)$	D	$p\text{-}CH_3OC_6H_4CHO$	II	$NaOCH_3$	130–131 (CH_3OH)	0	15.8	*j*
$1\text{-}C_{10}H_7CH{=}CH(1\text{-}C_{10}H_7)$	F	$1\text{-}C_{10}H_7CHO$	II	$NaOCH_3$	164–165	6.4	66.7	*c, e g*
$C_6H_5(CH{=}CH)_2(C_2H_5OCOC_6H_4)$	C	$C_6H_5CH{=}CHCHO$	III	$NaOC_2H_5$	129.5–130.5	0	85.1	*c, j*
$C_6H_5CH{=}CHCH_2COOC_2H_5$	B	$C_6H_5CH_2CHO$	I	$NaOC_2H_5$	. . .	0	93.4	*l, m*
$C_6H_5CH_2CH{=}CHCOOC_2H_5$	B	$C_6H_5CH_2CHO$	IV	NaH	. . .	0	. . .	. . .
$CH_3CH{=}CHCOOC_2H_5$	B	CH_3CHO	IV	NaH	. . .	. .	. . .	*n*
$CH_3(COOC_2H_5)C{=}CHCOOC_2H_5$	B	$CH_3COCH_2COOC_2H_5$	I	$NaOC_2H_5$	. . .	16.3	17.9	*c, o, p*
$n\text{-}C_3H_7CH{=}CHCOOC_2H_5$	B	$n\text{-}C_3H_7CHO$	I	$NaOC_2H_5$	. . .	0	66.5	*c, q, r*
$n\text{-}C_5H_{11}(CH_3)C{=}CHCOOC_2H_5$	B		I	$NaOC_2H_5$	. . .	19.0	40.6	*c, s*
	A	C_5H_5NCHO	III	$NaOCH_3$	92.5–93	0	75	*t, u*
	A	C_5H_5NCHO	III	$NaOCH_3$	. . .	0	14	*v*
	A	$1,4\text{-}(HCO)_2C_6H_5$	II	$NaOCH_3$	265–266 (lit. 258)	. .	74	. . .
	E	$p\text{-}(CH_3)_2NC_6H_4CHO$	III	$NaOCH_3$	318–325 dec.	. .	77.5	*w*
	E	$p\text{-}CH_3OC_6H_4CHO$	II	$NaOCH_3$	272–275	. .	41	*x*
	I	C_6H_5CHO	II	$NaOCH_3$	117–119 (lit. 120.2)	. .	44.6	. . .

	G	C_6H_5CHO	II	$NaOCH_3$	49–52 (lit. 54–55)	..	73	...
	G		II	$NaOCH_3$	96–98 (lit. 100)	..	42	...
$3,4\text{-}(CH_3O)_2C_6H_3CH{=}CHC_6H_5$	A	$3,4\text{-}(CH_3O)_2C_6H_3CHO$	III	$NaOCH_3$	110–110.5 (lit. 111)	..	92	y
$p\text{-}(CH_3)_2NC_6H_4CH{=}CHC_6H_5$	A	$p\text{-}(CH_3)_2NC_6H_4CHO$	II	$NaOCH_3$	150–153 (lit. 147–148)	..	80	...
	A		II	$NaOCH_3$	133–134.5	..	58.5	...
	A		II	$NaOCH_3$	275.5–277.5 (lit. 276–279.5)	..	78.5	z, aa
$C_6H_5CH{=}CHCH{=}CHC_6H_5$	A	$C_6H_5CH{=}CHCHO$	II	$NaOCH_3$	152.5–153.5	..	76	...
$3,4\text{-}(CH_3O)_2C_6H_3CH{=}CH{=}CH{=}CHC_6H_5$	H	$3,4\text{-}(CH_3O)_2C_6H_3CHO$	II	$NaOCH_3$	142–143	..	37	bb
$C_6H_5CH{=}CHC_6H_5$	A	C_6H_5CHO	II	$NaOCH_3$	126–127	..	85	t
	A		II	$NaOCH_3$	92.5–93	..	75	t
	A		II	$NaOCH_3$	54–55	..	84	t
	G	C_6H_5CHO	II	$NaOCH_3$	49–52	..	77	t
	H		II	$NaOCH_3$	122.5–123.5	..	Poor	...

[a] A = diethyl benzylphosphonate; B = diethyl carbethoxymethylphosphonate; C = diethyl *p*-carbethoxybenzylphosphonate; D = diethyl *p*-nitrobenzylphosphonate; E = tetraethyl *p*-xylylenediphosphonate; F = dimethyl 1-naphthylmethylphosphonate; G = diethyl 2-furylmethylphosphonate; H = diethyl styrylmethylphosphonate; and I = tetraethyl *o*-xylylenediphosphonate. [b] See Experimental. [c] Yields determined by chromatographic comparison with a weighed amount of *n*-octadecane. [d] The 97.9% yield came from a run containing 2 equiv. of sodium methoxide. [e] *cis* olefins were identified by chromatographic comparison with an authentic sample. [f] The identity of *cis* olefins was not established; however, the chromatographic zone attributed to *cis* occupied a reasonable position for that compound. [g] All physical constants are of *trans* olefin. [h] *Anal.* Calcd. for $C_{14}H_{11}NO_2$: C, 74.7; H, 4.9; N, 6.2. Found: C, 73.9; H, 4.5; N, 6.2. [i] *Anal.* Calcd. for $C_{15}H_{14}O$: C, 85.7; H, 6.7. Found: C, 85.3; H, 7.1. [j] Reaction mixtures were heated on the steam bath for 1 hr. [k] Ester interchange occurred during the reaction in methanol with sodium methoxide as a base. [l] Reaction mixture was kept at room temperature, or below at all times. [m] Reaction mixture was processed as soon as addition of reactants to base was complete. [n] Tetrahydrofuran used as reaction medium instead of toluene. [o] Yield based on method I. [p] Reaction was neutralized with a slight excess of glacial acetic acid. [q] If the reaction mixture was refluxed after addition, the major product was found to be ethyl 3-ethoxyhexanoate resulting from a base-catalyzed conjugate addition of ethanol to the desired product. [r] A minor component in the reaction mixture appeared to be an isomeric ethyl hexenoate. *Anal.* Calcd. for $C_8H_{14}O_2$: C, 67.6; H, 9.9. Found: C, 67.6; H, 10.2. Mass-spectrometric analysis gave parent peak at 142. Infrared analysis indicated an unconjugated, nonterminal double bond. The compound probably arose from a base-catalyzed isomerization of the expected product. [s] An additional 22.5% of product had been altered by the influence of the basic medium to furnish both *cis*- and *trans*-ethyl 3-methyl-3-octenoate in an 11:14 ratio, respectively. The structures of the products were determined by mass-spectrometric and infrared analysis. [t] See E. J. Seus and C. V. Wilson, *J. Org. Chem.*, **26**, 5243 (1961). [u] The yield figures are for the isolated product. The area % ratio from the reaction mixture of *trans*- to *cis*-2-styrylpyridine was 63:2. [v] Sodium bromide was added to the reaction mixture. [w] *Anal.* Calcd. for $C_{28}H_{28}N_2$: C, 84.7; H, 7.6; N, 7.0. Found: C, 84.2; H, 7.4; N, 7.2. [x] *Anal.* Calcd. for $C_{24}H_{22}O_2$: C, 77.6; H, 6.5. Found: C, 77.6; H, 6.6. [y] Heated to 90°. [z] 10% excess phosphonate. [aa] *Anal.* Calcd. for $C_{30}H_{22}$: C, 94.2; H, 5.8. Found: C, 93.8; H, 5.6. [bb] *Anal.* Calcd. for $C_{18}H_{18}O_2$: C, 81.2; H, 6.8. Found: C, 81.2; H, 6.6.

the addition of an equal volume of water and purified by crystallization from an appropriate solvent.

Method III.—Equivalent amounts of a phosphonate and a carbonyl compound were dissolved in N,N-dimethylformamide (0.005 mole/10 ml.) and the solution was treated with either dry sodium methoxide or sodium ethoxide. After the reaction had subsided (several minutes), the reaction mixtures were examined by v.p.c. and product yields were calculated by comparing them with an *n*-octadecane internal standard.

Method IV.—A suspension of sodium hydride in toluene was treated with an equivalent amount of diethyl carbethoxymethylphosphonate, the resulting carbanion forming a homogeneous solution. After the solution had been cooled to −20°, distilled phenylacetaldehyde was added dropwise, while the temperature was maintained at 0 to −20°. Upon completion of the addition, the cold reaction mixture was examined by v.p.c.

Preparation of Ethyl Crotonate.—A mixture of 8.96 g. (0.040 mole) of O,O-diethyl carbethoxymethylphosphonate, 1.92 g. (0.040 mole) of sodium hydride (50% dispersion in mineral oil), and 50 ml. of dry tetrahydrofuran was cooled to −20° and treated dropwise with 1.76 g. (0.040 mole) of acetaldehyde. The mixture was stirred for 1.25 hr. after completion of addition and filtered. Gas chromatography of the filtrate showed the condensation product to be 98 area % ethyl crotonate and 2 area % ethyl isocrotonate.

In a similar experiment, ethyl isocrotonate (obtained as a mixture of 19 area % ethyl isocrotonate and 87 area % ethyl crotonate) was added to the phosphonate carbanion along with the acetaldehyde in order to determine whether a significant amount of isomerization occurred under the reaction conditions. Gas chromatography of the resulting product showed 8 area % ethyl isocrotonate and 92 area % ethyl crotonate (theory for the mixture, assuming quantitative yield and no isomerization of the additive, is 9.5 area % ethyl isocrotonate and 90.5 area % ethyl crotonate).

Equilibration of Ethyl Crotonate.—A solution of 0.46 g. (0.0040 mole) of pure (v.p.c.) ethyl crotonate in 4.14 g. of dry tetrahydrofuran, containing a trace of sodium hydride, was stirred at room temperature. Samples withdrawn and subjected to v.p.c. analysis after 1, 24, 48, and 72 hr. gave 0.3, 0.3, 0.4, and 0.4 area %, respectively, ethyl isocrotonate.

The Vapor Phase Chromatographic Method.—Reaction mixtures containing an accurately weighed amount of *n*-octadecane were chromatographed on an appropriate column and area % data were calculated for the olefin products and hydrocarbon standard. By assuming identical thermal-response characteristics for *cis* and *trans* olefins, and by applying a factor obtained by comparison of the thermal responses of *n*-octadecane with the isolated *trans* olefins, both *cis*/*trans* ratios and yield data were obtainable from the chromatograms. Product zones were identified by comparison of retention times with those of authentic samples, or were trapped and examined by mass and/or infrared spectroscopy. Several zones were assigned to *cis* olefins without verification when they were present in insufficient quantity to trap and when no authentic samples were available for retention-time comparison. These unconfirmed products were present in insufficient quantities to be of theoretical significance. Table II lists starting materials and products examined by v.p.c.; their thermal response ratios compared with those of *n*-octadecane (v.p.c. area of sample/v.p.c. area of C_{18})/(wt. of sample/wt. of C_{18}); and their retention times relative to those of *n*-undecane and *n*-tetradecane.

Although the accuracy of the chromatographic method of determining the yield is somewhat dependent on the characteristic shapes of the graphic areas in question, the method gave good precision and appears to be accurate to within ±5%. Where isolated *cis* isomers were available, no instance was observed, even with α-carbonyl olefins, of any *cis*–*trans* isomerism on the chromatographic columns.

TABLE II

THERMAL-RESPONSE CHARACTERISTICS AND RELATIVE RETENTION TIMES OF SEVERAL SUBSTITUTED OLEFINS AND THEIR PHOSPHONATE AND ALDEHYDE PRECURSORS[a]

Compd.	Column temp., °C.	Thermal-response ratio[b]	Retention time c	Retention time *cis*[d]	Retention time *trans*[e]
Diethyl carbethoxymethylphosphonate	213	..	2.50	...	...
	250	0.76	0.94	...	...
Diethyl benzylphosphonate	213	..	5.21	...	...
	250	0.85	1.75	...	...
Dimethyl 1-naphthylmethylphosphonate	250	0.50	6.00	...	...
Diethyl *p*-nitrobenzylphosphonate	250	0.47	6.13	...	...
Diethyl *p*-methoxybenzylphosphonate	250	0.84	3.39	...	...
Benzaldehyde	213	..	0.60	...	...
Anisaldehyde	250	..	0.73	...	...
p-Nitrobenzaldehyde	250	..	0.83	...	...
Cinnamaldehyde	213	..	..	...	1.94
2-Pyridinealdehyde	..	..	0.50 0.82	...	...
n-Octadecane	250	..	3.12	...	...
Ethyl 3-methyl-3-octenoate	177	..	..	1.63	1.81
Ethyl 3-methyl-2-octenoate	177	..	..	1.89	2.30
Ethyl 3-ethoxy-3-methyloctanoate	177	..	3.52	...	...
Diethyl 3-methyl-2-pentenedioate	213	..	..	1.98	2.11
Ethyl cinnamate	213	..	..	...	3.37
Ethyl *p*-nitrocinnamate	213	..	..	...	14.5
Stilbene	213	1.00	..	4.56	8.32
p-Methoxystilbene	250	0.84	..	...	5.90
p-Nitrostilbene	250	0.73	..	5.87	10.5 12.4
p-Carbethoxystilbene	250	0.68	..	...	...
p-Methoxy-*p*′-nitrostilbene	250	0.68	..	...	22.4
p-Carbethoxy-*p*′-methylstilbene	250	..	..	...	17.2
p-Carbethoxy-*p*′-nitrostilbene	250	..	..	...	46.9
2-Styrylpyridine	213	..	..	5.68	10.4
4-Carbethoxy-1,4-diphenylbutadiene	250	0.46	..	...	28.9
1,2-Di(1-naphthyl)ethylene	250	..	..	26.5	...

[a] Data were obtained from 4-mm.-i.d. glass columns with thermal conductivity cell detectors. Column packings were composed of 25% Dow–Corning silicone fluid 200 on 80–100-mesh acid- and base-washed Celite 545. [b] See Experimental. [c] Relative to *n*-undecane at 177°, 8-ft. column, 36 cc./min. flow rate. [d] Relative to *n*-undecane at 213°, 8-ft. column, 75 cc./min. flow rate. [e] Relative to *n*-tetradecane at 250°, 4-ft. column, 104 cc./min. flow rate.

Structure Analysis of Ethyl Styrylacetate (13) and Ethyl γ-Phenylcrotonate (12).—Mass-spectrographic analyses of **12** and **13** gave parent peaks at mass 190. The remainder of the spectra were very similar, and could not justify the ethyl styrylacetate structure, based upon simple fragmentation. Examination of a known sample of styrylacetic acid also showed an analogous fragmentation pattern, suggesting rearrangements in the electron beam. Compound **13** gave a typical ultraviolet spectrum of a substituted styrene with a λ_{max} at 248 mμ (ε 16,000) and end absorption at 200 mμ. Infrared analysis showed maxima at 5.78 (s), 6.03 (w), and 10.40 μ (m), characteristic of an isolated ester carbonyl and a *trans* olefin conjugated to an aromatic ring. N.m.r. spectra were obtained at 60 Mc./sec. with a Varian Dual Purpose V-4302 n.m.r. spectrometer equipped with a field homogeneity control unit. Calibration of spectra was done by the side-band modulation technique,[14] with 3–6% by volume of tetramethylsilane (TMS) as an internal reference in all samples. The Hewlett–Packard wide range oscillator, Model 200 CD, was checked at all times against a Hewlett–Packard electronic counter, Model 521C. Spectra were run at 22°. A comparison of the n.m.r. spectrum of compound **13** with several model compounds (isosafrol and anethol, Varian spectra no. 252 and 258, respectively) indicated a structure compatible with that of

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(14) V. J. Kowalewski and D. G. de Kowalewski, *J. Chem. Phys.*, **33**, 1794 (1960).

TABLE III

trans-ETHYL STYRYLACETATE

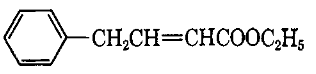
$C_6H_5CH{=}CHCH_2CO_2CH_2CH_3$

Multiplet centers, c.p.s.	Multiplicity	Assignment	Remarks
-73.6[a]	Triplet	CH_3	
-186.7	"Doublet"	$C{=}C{-}CH_2$	1. Principal splitting is 5 c.p.s.
-191.7			2. Additional second-order structure is evident
-246.5[a]	Quartet	CO_2CH_2	$J_{\text{methyl,methylene}} = 7$ c.p.s.
-365 to -385	Multiplet	$CH{=}CH$	1. Highly asymmetric, with peaks at -371.3, -377.0, -379.8, and -381.0 2. Band contour is very similar to that of the styryl protons in *trans*-propenyl benzene, (3-chloropropenyl) benzene, and cinnamyl alcohol 3. Band center at ~ -377 4. Second-order structure only
-433.8[a]	Broad "singlet"	C_6H_5	

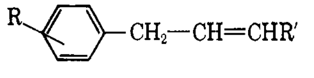
[a] True chemical shifts.

trans-ethyl styrylacetate., Table III summarizes the n.m.r. data for compound **13**.

Infrared analysis of **12** gave a carbonyl absorption at 5.84 and a strong absorption at 6.05 μ characteristic of a double bond conjugated with a carbonyl. The absorption band at 10.16 μ, probably indicative of *trans*-hydrogen atoms on the double bond, is of a sufficiently low wave length (ethyl crotonate, 10.3 μ) that assignment of a *trans* structure on the basis of infrared evidence is at best tentative. Ultraviolet analysis gave a spectrum very similar to that of ethyl crotonate, with a maximum at shorter wave lengths showing end absorption at 200 mμ. The geometric configuration was elucidated by n.m.r. To substantiate the infrared data which indicated the position of the double bond, it was necessary to compare the chemical shift positions of the methylene protons and the styryl hydrogens of the unknowns with those of several model compounds. If a deshielding effect on the methylene is assumed in the proposed structure, by the conjugated carbethoxy, an upper limit for the



resonance position could be established by examining compounds of the type where R and R′ are substituents which would not

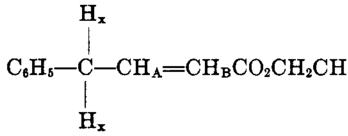


affect the chemical shift of the methylene protons. Eugenol, N-acetoxy-6-allyl-4,8-dimethyl coumarin, and allyl benzene show methylene resonance positions at -198 c.p.s. With these values as an upper limit, it is apparent that **12**, with methylene proton resonance at -205 and -212, lies well within the limits, whereas **13**, with methylene resonance positions at -187 -192 c.p.s., lies above a reasonable upper limit. This result is in accord with assignment of structure based on infrared analysis.

A comparison of the coupling constants $J_{\text{H,H(ethylene)}}$ of **12** with several model compounds indicates a *trans* configuration. In *cis*- and *trans*-ethyl crotonate, ethyl 4-bromocrotonate, crotonitrile, crotonic acid, methyl crotonate, and *trans*-crotonaldehyde $J_{\text{H,H}(trans)}$ averages 15.3, but $J_{\text{H,H}(cis)}$ averages 11.4 c.p.s.[14,15] The value of 15.5 for **12** clearly labels it as having the *trans* configuration. Table IV summarizes the n.m.r. data for compound **12**.

TABLE IV

N.M.R. ANALYSIS OF *trans*-ETHYL γ-PHENYLCROTONATE



$$C_6H_5{-}\overset{\displaystyle H_x}{\underset{\displaystyle H_x}{C}}{-}CH_A{=}CH_BCO_2CH_2CH_3$$

Line positions, c.p.s.	Multiplicity	Assignment	Remarks
-75.8[a]	Triplet	CH_3	
-203.9			Chemical shift, -208.35
-205.5	Quartet	$C_6H_5C(H_X)_2$	$J_{AX} = \sim 7.3$ c.p.s.
-211.2			$J_{BX} = \sim -1.6$ c.p.s.
-212.8			
-247.5[a]	Quartet	OCH_2	$J_{\text{methyl,methylene}} = 7$ c.p.s.
-334.1			Line no. 10[b]
-335.4	Triplet	$C{=}CH_B$	Line no. 11
-337.3			Line no. 12
			Chemical shift, -344.7
-349.6			Line no. 7
-350.9	Triplet	$C{=}CH_B$	Line no. 8
-352.8			Line no. 9
-406.5			Line no. 6
-412.9	Multiplet	$C{=}CH_A$	Line no. 5
-421.6			Line no. 4
			Chemical shift, ~ -422
			Three other lines of this multiplet hidden under C_6H_5
-426.2	Multiplet	C_6H_5	$J_{HA\text{-}HB} = \sim 15.5$ c.p.s.

[a] Multiplet centers, chemical shift for assigned group. [b] Lines are numbered after P. G. de Kowalewski and V. J. Kowalewski [*J. Phys. Radium*, **22**, 129 (1961)]. The part of the spectrum of this compound arising from the propenylene group has been analyzed as an ABX_2 group following the method of de Kowalewski and Kowalewski. The lines have been numbered in accordance with their Figure 2b. Calculation of D_{47}, D_{58}, and D_{69} as given by the Kowalewskis indicates that the data are consistent with the lines as numbered. More accurate calculation of J_{AX} and J_{BX} is not possible because three of the six A-group lines are under the lines from the phenyl protons. The contour of the two triplets at -335 and -351 c.p.s. also indicates that J_{AX} and J_{BX} have opposite signs. We have arbitrarily taken J_{AX} to be positive.

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[15] P. J. Yajko and R. J. Kurland, private communication.