A New Stereoselective Route to Trisubstituted Bromo Olefins Utilizing α-Bromoalkylides Produced by Halogen–Metal Exchange

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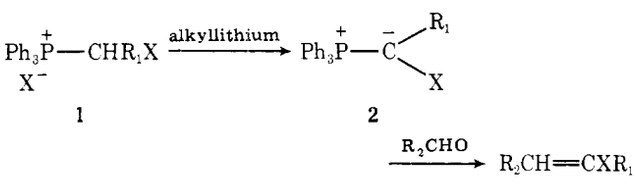
The development of general methods for the stereospecific synthesis of functionalized trisubstituted olefins has become of major importance in synthetic organic chemistry. As a new approach to the problem, the readily available triphenylphosphonium dibromomethylide has been alkylated with methyl and ethyl bromides to yield the corresponding salts **4**, which react smoothly with butyllithium at low temperature to give α-bromoalkylides **5**, formally the products of halogen–metal exchange. These ylides react with a variety of aldehydes in Wittig fashion, furnishing the corresponding trisubstituted bromo olefins **3** in yields of 30–55%. Reactions involving the ylide **5b** are usefully stereoselective, and it has been shown that in all cases it is the thermodynamically more stable isomer which predominates. In striking contrast, reactions involving the homologue **5c** are completely nonstereoselective, and this disparity appears unprecedented. Work directed toward the elucidation of the mechanisms of these processes has revealed that the detailed pathway of these reactions is determined by a number of finely balanced factors, which even a small perturbation is liable to upset. Equilibrium processes, solvent effects, and the relative thermodynamic stabilities of the resultant bromo olefins **3** all appear to exert an influence in determining reaction stereochemistry.

As synthetic intermediates, halo olefins are perhaps even more prized than their saturated counterparts. Besides being amenable to a large number of synthetic manipulations,[1] the versatile halogen grouping also permits structural elaborations in which the stereochemical relationship between other olefinic substituents often remains undisturbed.[1a-d,h,k] Consequently, a considerable effort has been devoted to the development of methods for their stereospecific synthesis.[2] In particular, the more difficult[3] stereospecific synthesis of trisubstituted halo olefins of the type RCH=CXR has aroused considerable interest (vide infra), not least because they allow ready access to a variety of trisubstituted olefins[4] which are themselves important in some areas of natural product synthesis (inter alia as intermediates in polyolefin cyclizations[5] and in insect juvenile hormone synthesis[6]).

We required a mild, unambiguous route to highly labile trisubstituted halo olefins of the above type, and an initial evaluation of existing methods pointed to the Wittig olefin synthesis[7] as a method which seemed to offer some promise. Thus, it was known that 1-bromo olefins **3a** are available from the ylide **2a**, which can be generated in the normal way from the salt **1a** as shown in Scheme I.[8] In principle therefore, the use of alkylated derivatives, e.g., **1b**, might be expected to provide an analogous route to trisubstituted bromo olefins. This hope unfortunately founders on the complete failure of standard procedures[9] for synthesizing salts such as **1b**, thus leading others[2d] to an outright dismissal of the Wittig reaction for halo olefin synthesis in which more than one carbon is required to be introduced. This impasse has, however, stimulated the development of other indirect methods based on the Wittig route. Thus, Schlosser[10] and Corey[11] have both independently shown that reaction of certain β-oxidophosphonium ylides ("betaine ylides") with various electrophilic sources of halogen does produce olefins of type **3**, although involving as it does chemical modification of a reactive intermediate, yields were fair to poor and the generality of the route seems doubtful.[12]

Scheme I



a, R_1 = H, X = Br; b, R_1 = Me, X = Br; c, R_1 = X = H

The inspiration for the present work sprang from a key observation which had been made earlier by Köbrich.[8b] He reported that when the salt **1a** was treated with phenyllithium a diversion from the expected course ensued, and a 2:3 mixture of phosphoranes **2a** and **2c** resulted, thus demonstrating that extraction of a bromine cation from this salt competes rather effectively with the usual deprotonation pathway. He also noted that the action of butyllithium produced *exclusively* **2c**, the product of a formal metal–halogen exchange.[13]

We have developed and expanded on these observations and now wish to record a new general route to α-bromoalkylides which is based on halogen–metal exchange rather than on the usual deprotonation sequence. This not only furnishes a direct highly stereoselective route to some bromo olefins **3** but also provides further information on the stereochemistry of Wittig reactions leading to trisubstituted olefins, about which little appears to be known.

Results

Reaction of the readily available triphenylphosphonium dibromomethylide[14] with hydrogen bromide and methyl and ethyl bromides produced the known **4a**[15] and the previously unreported salts **4b** and **4c** in 86, 77, and 62% yields, respectively (Scheme II). As would be anticipated, while the reaction of hydrogen bromide with the ylide at 0 °C was instantaneous, methyl bromide reacted more slowly over about a 1-h period, the progress of reaction being usefully indicated by the gradual discharge of the red ylide color. Alkylation with ethyl bromide was very much more sluggish and required a reaction period of 24–36 h.

When **4b** was suspended in THF and treated with 1 equiv of butyllithium at −40 °C, a characteristic orange coloration developed immediately, which was discharged by bubbling hydrogen bromide through the solution. Workup of this reaction led to the isolation of salt **1b** in high yield, and in addition gas chromatographic analysis of the volatile fraction revealed butyl bromide as the only constituent besides solvent residue.

Since this result appeared to demonstrate quite convincingly that the desired halogen–metal exchange was occurring cleanly, the experiment was repeated with benzaldehyde added as an ylide trap. This reaction was detectably exothermic, even below −60 °C, and resulted again in an imme-

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Table I. Products from the Reaction of Triphenylphosphonium α-Bromoalkylides with Aldehydes

Run	Ylide	Aldehyde	Product	Yield,[a] %	Isomer distribution,[b] Z:E
1	**5b**	PhCHO	**3a**	40	>95:5[c]
2		$C_6H_{13}CHO$	**3b**	55	87:13[d]
3		t-C_4H_9CHO	**3c**	16[e]	25:75
4		MeOCH=CHCHO	**3d**	30	87:13
5	**5c**	PhCHO	**3e**	48	53:47
6		$C_6H_{13}CHO$	**3f**	55	58:42
7	**5a**	PhCHO	**3g**	44	49:51
8		t-C_4H_9CHO	**3h**	~6[e]	98:2

[a] Yields refer to distilled materials and in most cases analytically pure materials. [b] The error in the Z:E ratio is ca. ±2% when determined by integration of GLC peaks and ±5% in the NMR determination. [c] NMR determination. [d] GLC determination. [e] These reactions were very clean, and the low isolated yields are probably a reflection of the unsuitability of the isolation procedure for volatile products. No further attempt was made at optimization.

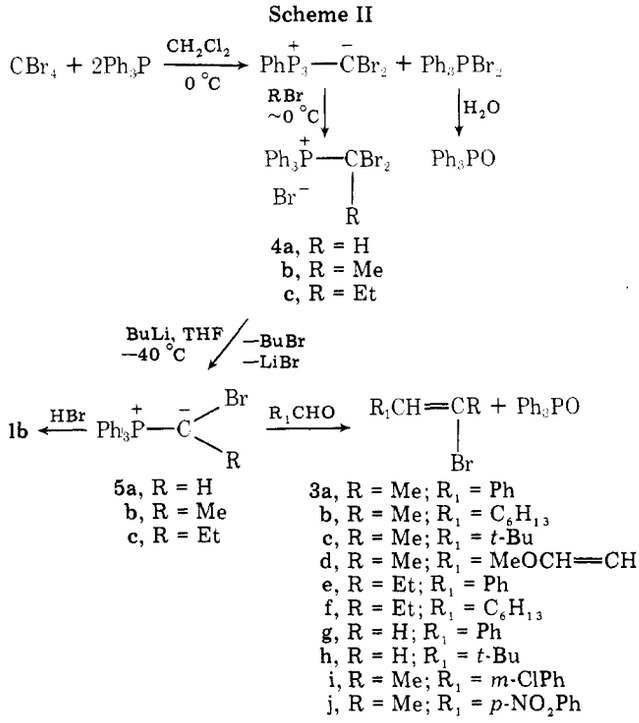
diate discharge of the color. Slow warming to room temperature followed by concentration, extraction, chromatography on silica gel, and subsequent distillation furnished pure (Z)-1-phenyl-2-bromo-1-propene in 40% yield. A similar sequence using salt **4c** produced the homologous bromo olefin in 48% yield. The scope of the new reaction was then explored using a variety of other aldehydes, and the results are summarized in Scheme II and Table I.

Configurational Assignments. The structures of the resulting bromo olefins follow from the lack of ambiguity in the synthetic method[7e] and were confimed in all cases by elemental analyses for new compounds as well as by spectral data (cf. Experimental Section). Somewhat surprisingly, a number of these simple compounds have not been previously described, and only compounds **3a**,[16] **3b**,[17] and **3g**[8] could be identified by comparison with their known spectral characteristics. For previously unknown trisubstituted bromo olefins where both isomers were clearly distinguishable in their ^1H NMR spectra, e.g., **3c, 3d,** and **3e,** a secure configurational assignment could be reached on the expectation that the vinylic proton in the E isomer, which is deshielded by the cis vicinal bromine, should resonate at lower field than in the Z isomer, where the halogen is trans. Besides the existence of another precedent which concurs with this view,[18] these assignments were confirmed in a number of cases by reduction of the bromides with sodium in liquid ammonia and subsequent gas chromatographic analysis of the derived olefins. This highly stereoselective protiodebromination reaction[19] was also used to assign configurations in cases where the NMR spectra were of little help, e.g., **3b.** Interestingly, although in the majority of cases the stereoselectivity of this reaction was around 95%, as originally claimed,[19b] with bromo diene **3d** it fell to ~85%, presumably reflecting the lesser configurational stability of pentadienylic anions vis-à-vis their allylic counterparts.

The 3-chloro- and 4-nitro-substituted derivatives **3i** and **3j** were both assigned as Z isomers on the basis of the chemical shifts of their olefinic protons, which in neither case appeared as low field as in the unsubstituted E isomer.

Since the stereochemical outcome of the new reaction has a bearing on the question of the stereochemistry and mechnism of the Wittig reaction, it was necessary to exclude the possibility of olefin stereomutation under the reaction conditions. This was ruled out by control experiments in which artificial mixtures of (Z)- and (E)-**3a** submitted to the reaction conditions were recovered unchanged and in other cases by

Scheme II



careful assay of the diastereomeric ratio at each stage of the workup procedure.

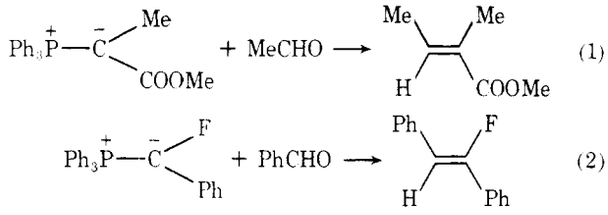
Thermodynamic Stabilities of Bromo Olefins. A prerequisite to the understanding of factors which govern the stereochemical outcome of these reactions is some information concerning the relative thermodynamic stabilities of the isomeric pairs of resultant halo olefins. In order to obtain this, each of the pairs was treated either with small amounts of HBr[20] and left to stand at room temperature for 3 weeks or refluxed with iodine in acetic acid.[21] With HBr this resulted in the pairs **3b** and **3d** becoming richer in the Z diastereomer to the extent of about 10%, while in **3c** the opposite shift occurred and the proportion of this isomer fell by a similar amount. Bromides **3a** and **3e,** each initially present in about 1:1 isomeric ratios, were not readily isomerized by acid, each mixture becoming enriched in the Z isomer by only a few per cent. However, pure (Z)-**3a** remained *completely* unaffected by this treatment and also by iodine in acetic acid. Use of the latter reagent with the pair **3c** resulted in quantitative conversion to the E isomer.

Thus, it seems reasonable to conclude that generally Z isomers are more stable, and this is in essential agreement with earlier findings for other trisubstituted halo olefins where it has been found that the lowest energy configuration is obtained in situations where the halogen and proton groupings are in a trans relationship to each other.[20] The one exception to this in the present case is the pair **3c** where the steric bulk of the *tert*-butyl group apparently reverses the normal order. Interestingly, heat of formation estimates based on additivity of group properties[22] predict that Z isomers should be favored by 1.0 kcal/mol.

Discussion

The new reaction constitutes a general procedure for the transformation of an aldehyde function to a trisubstituted bromo olefin and should be of great value in synthesis. For example, **3b,** an important intermediate in the synthesis of the fragrant components of cassia oil which was previously made from heptanal in three steps,[17] is now directly available from the same starting material. In addition, the mildness of the method makes it ideally suited for the synthesis of labile bromo olefins: **3d** fumed in moist air and would seem to be a

Scheme III



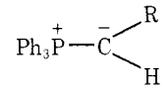
good example of a molecule whose unambiguous construction by such simple means makes the method especially attractive. The one factor which will limit the general applicability of the route is the electrophilicity of the alkylation reagent used to prepare the salts **4** (RBr in Scheme II). The practical limits of alkylating the rather stable triphenylphosphonium dibromomethylide by using simple alkyl halides as electrophiles are probably already reached at ethyl bromide. However, it is likely that other reactive halides such as allyl and benzyl[15a] derivatives might be useful in providing further extensions and possibilities.

The key halogen–metal exchange between the salts **4** and butyllithium appears to be strikingly clean, and possible complications such as competitive reaction of the alkyllithium with the α-bromoalkylide or its alkylation by the concomitantly produced butyl bromide do not seem to be a problem at −40 °C. Remarkably, the preference for bromine abstraction over deprotonation is so overwhelming that it even occurs in the salt **4a,** where the acidity of the proton must be considerably enhanced. When this salt was used as the ylide precursor and benzaldehyde as the carbonyl component, β,β-dibromostyrene was produced as an impurity to an extent of <2%, thus making this a viable alternative route for 1-bromo olefin synthesis. The origin of this effect is presumably kinetic, and parallels exist[23] in the similar behavior of some bromo alkanes and bromo olefins with butyllithium. In these cases, halogen–metal exchange proceeds several orders of magnitude faster than the corresponding proton–metal exchange and can provide a useful route to thermolabile lithium carbenoids.[23b]

The remainder of the reaction sequence, viz., reaction of α-bromoalkylides with aldehydes, is noteworthy in the provision of an unprecedented disparity between the highly stereoselective **5b** and the unselective homologue **5c.** In this case, the usual trend[7d] whereby unbranched homologues react with *greater* stereoselectivity is completely reversed.

Stereochemistry and Mechanism. The mechanism of the Wittig olefin synthesis has been the subject of a considerable body of work[24–26] which has resulted in a better understanding of the mechanism(s) of those processes which lead to 1,2-disubstituted olefins; although, there is still uncertainty over the exact nature of the intermediate(s)[27] which may or may not be involved. In turn, the pathways of unmodified[28] Wittig reactions producing trisubstituted olefins remain completely in the dark, and only a few scattered observations appear to be available. For example, the stereochemical outcome of the reactions shown in Scheme III[29] has been rationalized on the basis that steric hindrance to resonance is minimized in the products obtained. However, examples like these probably cannot be claimed as typical since the double bond is substituted by at least one strongly conjugating group, the result of which may well be to so inflate factors of thermodynamic preference that other considerations which may normally play a part are thrust into the background.

A starting point for the rationalizations collated and discussed by Schlosser to explain the stereochemical outcome of reactions leading to 1,2-disubstituted olefins was an initial classification[7d] of the ylide as "reactive", "moderated", or "stable", as determined by the nature of the substituent at the ylide carbon. This classification has very important consequences for the energetics of the initial addition step of the ylide with carbonyl compounds, directly affecting the equilibrium constant for this process which connects ylide and carbonyl starting materials with betaine or oxaphosphetane intermediates. This equilibrium constant apparently dominates the stereochemical control of the resultant olefin by its regulation of the *reversibility factor*[7d] of the initial addition, which in turn is held to be indirectly responsible for the production of largely trans olefins from stable ylides and to some extent from moderated ylides, for cis olefins from reactive ylides under conditions of kinetic control ("salt-free" conditions), and for the preponderance of trans olefins from the same ylides under equilibrium conditions. While stable ylides, e.g., **6a,** characterized by extensive delocalization of negative



6a, R = COOR
b, R = alkyl
c, R = aryl or alkenyl

charge onto a substituent, are often isolable and usually require heating to effect reaction, reactive ylides, e.g., **6b,** are labile transients invariably reacting with release of energy, and reactions are often carried out at low temperatures. In these cases, the saturated aliphatic substituent strongly increases ylide basicity and hence reactivity. Between these two extremes a third class of moderated ylides has been recognized, where, due to the relatively less effective delocalizing ability of the substituent, e.g., **6c,** the addition step is usually accompanied by rather small energy changes. Turning to the present case, although Schlosser[25b] has also exemplified the latter group by triphenylphosphonium chloromethylide,[30] a priori it is not clear how far the stabilizing features of the bromine substituent,[31] viz., its electronegativity and vacant 4d orbitals, will be opposed by the destabilizing influence of the alkyl group. In any event, the experimental observation of an energy releasing initial step immediately suggests that these phosphoranes possess some characteristics of reactive ylides.

The question of the operation of equilibria processes in these systems was probed by runs 3 and 6 in Table II. Table II also contains the results of other experiments which were carried out in an effort to gain some information in regard to factors controlling the reaction stereochemistry. These crossover experiments, essentially the classical test[25a] for the operation of the *reversibility factor,* demonstrate quite conclusively that the initial addition step is reversible for ylide **5b** and, to within the limits of experimental detection, irreversible for **5c.** This result is also consonant with the differing stabilities of their derived intermediates. While the intermediates from **5b** were observed to decompose to olefin and phosphine oxide between 5–15 °C, those originating from **5c** were much less stable, decomposing at about −25 °C. These results are significant, and taken together they suggest that important differences exist between the relative free energies of intermediates lying along the respective reaction coordinates. Stereoselectivity is often reduced by the use of more electrophilic aldehydes; run 4 shows that in this case the selectivity of **5b** remains unimpaired. Thus, although both ylides appear to be more reactive than moderated, reversibility may well be important in reactions of **5b,** particularly in the presence of salts.

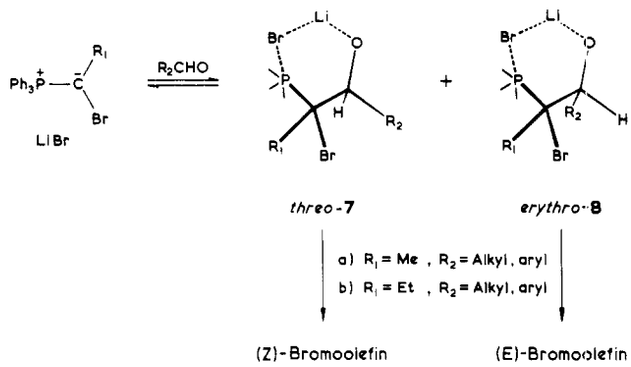
Salt effects are known to have quite dramatic consequences on the stereochemistry of Wittig reactions,[26] and indeed the lithium bromide which is generated unavoidably with these ylides appears to be intimately involved in their reactions. This can be inferred from run 5 (Table II) where DMF, which

Table II. Effect of Reaction Conditions on Bromo Olefin Stereochemistry

Run	Ylide–aldehyde	Solvent	Reaction temp,[a] time	Product	Isomer distribution, Z:E
1	**5b**–PhCHO	THF	20 °C, 5 min	**3a**[c]	>95:5[c]
2			−55 °C, 22 h	**3a**	>95:5
3			*b*	**3a** + **3i**	94:6[d]
					>95:5
4	**5b**–*p*-NO_2PhCHO	THF	Standard[g]	**3j**	>95:5[c]
5	**5b**–PhCHO	DMF[e]	−50 °C, 10 min	**3a**	57:43
6	**5c**–PhCHO	THF	As for run 3	**3e**	53:47[f] (>99%)

[a] Ylide generation was initially carried out at −40 °C in all cases except run 5, where −25 °C was used due to the sluggishness of reaction at −40 °C. [b] At −55 °C, 70 min; then add 1 equiv of *m*-ClPhCHO; −60 °C, 120 min. [c] NMR determination. [d] Combined GC–MS analysis. [e] Reaction in this solvent gave very poor yields of bromo olefin (cf. footnote *a* also); THF is the solvent of choice. [f] GLC determination. [g] See Experimental Section.

Scheme IV



is known to mimic salt-free conditions,[26] is seen to have a decisive influence on reaction stereochemistry. In this medium the stereoselectivity of **5b** is completely lost. This result appears to argue against direct oxaphosphetane formation in these systems in other solvents and points instead to the initial formation of a lithium bromide complexed betaine, as represented perhaps by **7** or **8** in Scheme IV.

Finally, the normal stereoselectivity of **5b** together with the results from the investigation of the relative thermodynamic stabilities of the resultant bromo olefins raise the question of the importance of aspects of thermodynamic control in these processes. Apparently, in cases where there is a thermodynamic preference for one particular isomer, that isomer always predominates. This is particularly emphasized by the contrast between the isomer distribution in runs 2 and 3 (Table I), where a reversal in the general trend of thermodynamic preference is nicely paralleled by a corresponding reversal in isomer distribution.

Bearing the above discussion in mind, a tentative but not unreasonable interpretation of these reactions is given in Scheme IV.

If addition occurs to give initially both the threo and erythro lithium bromide complexed betaines (Sheme IV), then a situation of thermodynamic control can be envisaged where *threo*-**7** is preferentially consumed because it leads to the more stable olefin, usually the *Z* isomer, through a lower energy transition state. In the case of ylide **5b,** as a consequence of the mobile equilibrium with starting materials, the concentration of **7a** is continually replenished at the expense of **8a** and high stereoselectivity then results. Conversely, since systems involving the homologue **5c** lack demonstrable equilibria processes, kinetic control prevails and these reactions are devoid of stereoselectivity. Of course, in salt-free reactions the energies of the uncomplexed betaines are presumably increased, and this no doubt prevents the occurrence of equilibria processes, resulting in a loss of stereospecificity. Similar results which are also in keeping with this suggestion have been obtained with other moderated ylides.[26]

Scheme IV accounts quite well for all of the major features of these reactions, but the question as to why the introduction of a small β alkyl grouping results in such a profound change is not answerable with any certainty. Clearly, the detailed pathway of these reactions is determined by a number of finely balanced factors, which even a small perturbation is liable to upset.

Experimental Section

^{1}H NMR spectra were recorded at 60 MHz with a Hitachi Perkin-Elmer R-20B instrument (tetramethylsilane as an internal standard; $CDCl_3$ solvent unless stated otherwise). IR spectra were obtained with a Beckmann IR 4240 instrument for liquid film samples. UV spectra were taken on a Varian Techtron Model 635 instrument in cyclohexane solvent unless stated otherwise. Mass spectra and combined GC–MS analyses were taken at 70 eV with an AEI MS 3074 double beam instrument fitted with a Pye Unicam Series 104 gas chromatograph unit. Analytical GLC was performed on a Varian Aerograph Series 1800 preparative instrument: column A, 5 ft × 0.25 in, 5% SE 30 on Chromosorb W; column B, 10 ft × 0.25 in, 10% SE 30 on Chromosorb W (See Table III). Elemental analyses were performed by the Australian Microanalytical Service, CSIRO, Victoria, Aust.

Materials. Triphenylphosphine was used as supplied, and carbon tetrabromide was purified[32] by passage through an alumina column using dichloromethane as solvent. Dichloromethane was purified by shaking industrial grade material successively with 5% sodium carbonate and water, followed by drying quickly over calcium chloride. Decantation onto freshly activated calcium chloride,[33] stirring overnight, decantation again, and fractionation gave a material (bp 40 °C) which was stored over 4A molecular sieves. Tetrahydrofuran was purified by initial refluxing and distillation from cuprous chloride to remove traces of peroxides, stirring overnight with 5% w/v calcium hydride,[33] and subsequent fractionation (bp 66–67 °C). It was stored over 4A molecular sieves in a dark bottle using a nitrogen atmosphere. Benzaldehyde, 3-chlorobenzaldehyde, pivalaldehyde, and heptanal were used as freshly distilled commercial samples. 3-Methoxy-2-propenal was synthesized as reported below, and 4-nitrobenzaldehyde was used as supplied.

Synthesis of Triphenylphosphonium Salts 4b and 4c. The procedure used for the synthesis of 1,1-dibromoethyltriphenylphosphonium bromide (**4b**) serves as an example. A 2-L three-neck flask equipped with a pressure equalized dropping funnel, mechanical stirrer, and low temperature thermometer was flamed and then allowed to cool while a slow current of dry oxygen-free nitrogen was passed through the apparatus, this flow being maintained throughout the preparation. When cool, the flask was charged with purified[32] carbon tetrabromide (99.6 g, 0.30 mol) in pure dry dichloromethane (300 mL) and the dropping funnel with triphenylphosphine (157.2 g, 0.60 mol) in dichloromethane (300 mL). After cooling to −5–0 °C, the solution of triphenylphosphine was added over about 10–15 min with rapid stirring. Stirring was continued for 10–15 min after the addition was complete, during which time a heavy precipitate appeared in the orange-red solution of triphenylphosphonium dibromomethylide.

The dropping funnel was then removed, and a U-shaped tube was fitted into the flask, a long arm of which was adjusted through a screw cap fitting so that it dipped below the surface of the ylide solution. The other end was fitted through an adaptor to a cold flask containing methyl bromide (38.0 g, 0.40 mol), and the nitrogen flow was then redirected to pass through the tube from the adaptor which was also

Table III. Selected Properties of Bromo Olefin Products

Compd	GLC data[a] Column [temp (°C)]	R_t, min[b] Z	E	Analytical data Found, % C	H	Br	Formula	Required, % C	H	Br
3b	A [75]	13.6	15.9				[c]			
3c	B [100]	14.5	17.5	50.87	8.31	39.1	$C_7H_{13}Br$	47.48	7.40	45.12
3d	B [140]	11.4	12.5	40.91	5.37	44.8	C_6H_9BrO	40.71	5.12	45.13
3e	A [90]	10.6	12.4	56.30	5.19	38.8	$C_{10}H_{11}Br$	56.90	5.25	37.85
3f	B [150]	23.4	25.5	54.45	8.50	36.40	$C_{10}H_{19}Br$	54.80	8.74	36.46
3g	B [130]	10.8	8.0				[d]			
3h	B [170]	12.8	10.1				[e]			
3i	A [100]	13.8		47.13	3.55	35.0	C_9H_8BrCl	46.69	3.48	34.51

[a] Nitrogen flow rates: column A, 150 mL/min; column B, 80 mL/min. [b] Related Z chloro olefins are also invariably more volatile than the E isomers; see ref 19a. [c] Previously described in ref 17. [d] Previously described in ref 8. [e] E isomer previously described in ref 36.

fitted with a gas inlet facility. With occasional dry ice cooling to keep the temperature of the ylide solution at ~0–3 °C, the methyl bromide was slowly vaporized into the gently stirred ylide solution, which decolorized completely in 60–90 min. Workup was carried out by warming to room temperature, adding 500 mL of saturated aqueous sodium bicarbonate solution (1.3 M, 0.65 mol) with vigorous stirring, separating the pale yellow organic solution, drying ($MgSO_4$), and distilling off the solvent. Removal of the last traces of solvent on a rotary evaporator gave a solid which was triturated with benzene by high speed stirring to separate the soluble triphenylphosphine oxide from the insoluble white salt. Filtration and air drying gave 141 g (89%) of the crude material, mp 191–193 °C. Purification was effected by dissolution in a minimum volume of hot dichloromethane and reprecipitation with hot acetone. Filtration followed by drying in a vacuum oven for 16 h at 80 °C gave 122 g (77%) of material, mp 198–201 °C dec. An analytical sample had mp 201–202 °C dec; ^1H NMR δ 3.02 (3 H, d, J = 15.6 Hz), 7.50–8.20 (m, 15 H). Anal. Calcd for $C_{20}H_{18}Br_3P$: C, 45.41; H, 3.43; Br, 45.32. Found: C, 45.43; H, 3.43; Br, 45.3.

1,1-Dibromopropyltriphenylphosphonium bromide was obtained similarly in 62% yield except that a fourfold molar excess of ethyl bromide over the ylide was used and a reaction period of 24–36 h at 0 °C was necessary. This reaction is not complete until the color has faded *at least* to a light yellow. The material obtained from the synthesis had mp 175–177 °C. An analytical sample melted at 196–200 °C; ^1H NMR δ 1.51 (3 H, t, J = 6.2 Hz), 2.71 (m, 2 H), 7.50–8.20 (m, 15 H). Anal. Calcd for $C_{21}H_{20}Br_3P$: C, 54.80; H, 8.74; Br, 36.46. Found: C, 54.45; H, 8.50; Br, 36.4.

1-Bromoethyltriphenylphosphonium bromide (**1b**) was obtained via the reaction of triphenylphosphonium α-bromoethylide with HBr, mp 202–204 °C. Anal. Calcd for $C_{20}H_{19}Br_2P$: C, 53.36; H, 4.25; Br, 35.50. Found: C, 53.07; H, 4.45; Br, 35.1.

3-Methoxypropenal. This previously unknown aldehyde was prepared by modification of an existing procedure.[34] 1,1,3,3-Tetraethoxypropane (44 g, 0.20 mol) was stirred rapidly at room temperature with hydrobromic acid (23 mL of ~8.8 M aqueous solution, ~0.20 mol) in water (30 mL), and after 5–10 min a yellow homogeneous solution was obtained. This was added dropwise to a cold (−40 °C) well-stirred solution of sodium methoxide (0.42 mol) in methanol (200 mL), resulting in a yellow solution which was warmed to room temperature and concentrated on a rotary evaporator at 50–60 °C. Addition of acetone (150 mL) and trituration by rapid stirring resulted in the quantitative precipitation of the sodium salt of malondialdehyde as an orange solid which was dried in a vacuum oven at 55 °C for 16 h. This salt was suspended in dry diethyl ether (100 mL) and treated with methyl chloroformate (18.9 g, 0.20 mol) with rapid stirring at room temperature for 3 h, during which time the color of the salt suspension noticeably lightened to a creamy white and the reaction vessel became warm. Filtration and removal of the volatiles on a rotary evaporator furnished the methylvinyl carbonate as a labile low melting solid, which was immediately dissolved in dry dichloromethane (~100 mL) and decomposed with ~1 g of *p*-toluenesulfonic acid. When CO_2 evolution had ceased, careful removal of dichloromethane on a rotary evaporator followed by distillation yielded 8.2 g (48%) of 3-methoxypropenal, bp 47–48 °C (5 mmHg). This aldehyde is indefinitely stable if kept in a freezer compartment well below its melting point (~25 °C), but it rapidly polymerizes on standing at room temperature: ^1H NMR δ 3.78 (3 H, s), 5.56 (1 H, dd, J = 8.4 Hz), 7.46 (1 H, d, J = 12.5 Hz), 9.36 (1 H, J = 8.4 Hz); UV λ_{max} 233 nm (ε 54 500), 312 (600); m/e 86, 85, 71, 57, 54.

Procedure for Wittig Reactions. The reaction leading to bromo diene **3d** serves as an example. The usual setup for reactions involving reactive phosphoranes was employed; i.e., a three-neck flask was fitted with a pressure equalized dropping funnel, mechanical stirrer, and low temperature thermometer and was arranged such that a slow flow of dry deoxygenated nitrogen could be maintained throughout the procedure. After flaming and cooling, the flask was charged with 1,1-dibromoethyltriphenylphosphonium bromide (16.9 g, 32.0 mmol) suspended in THF (60 mL). A convenient way of pulverizing the salts without danger of their concomitant hydration consisted of simply stirring the salt suspension gently for 20–30 min; this ensured that extremely fine particles resulted. The dropping funnel was then filled with butyllithium (25 mL of a 1.16 M solution in hexane, 29.0 mmol)[35] from a nitrogen-filled volumetric pipet, and the reaction vessel was cooled to −40 °C in a dry ice–acetone bath. Butyllithium was then added dropwise with stirring over about 10–15 min, the internal temperature being carefully regulated between −40 to −45 °C. After complete addition, the walls of the dropping funnel were rinsed with 4–5 mL of dry hexane, and stirring was continued at −40 °C for 10 min to ensure complete consumption of butyllithium, which was often indicated by a dramatic color change from blood-red to tangerine-orange, depending on the rate of addition of butyllithium (it is of the *utmost importance* to the yields obtained that the carbonyl compound *not* be added until it is certain that the color is a definite bright orange). 3-Methoxypropenal (2.5 g, 29.0 mmol) in THF (5 mL) was then added dropwise to the ylide solution at ~−60 °C, whereupon an exothermic reaction occurred and the color was discharged immediately to a creamy yellow. After stirring further for 10 min, warming to room temperature and filtration produced a yellowish-orange solution which after evaporation on a rotary evaporator, trituration with hexane (75 mL) by high speed stirring, filtration again, and concentration (~20 mL) was carefully column chromatographed on silica gel using hexane as eluent. Removal of the solvent gave a colorless oil which was distilled without delay in a semimicro apparatus fitted with a vacuum-jacketed Vigreux column to give 1-methoxy-4-bromo-1,3-pentadiene (1.54 g, 30%), bp 59–60.5 °C (5 mmHg). The diene was fairly stable if kept in the freezer compartment of a refrigerator, but it fumed in moist air with rapid darkening: ^1H NMR of (*Z*)-**3d**, δ 2.29 (3 H, m), 3.59 (3 H, s), 5.61 (1 H, dd, J = 10.1 Hz), 6.07 (1 H, dq, J = 10.1 Hz, $J_{allylic} \approx 1$ Hz), 6.67 (1 H, d, J = 12.3 Hz); ^1H NMR of (*E*)-**3d**, δ 2.23 (3 H, m), 3.63 (3 H, s), 5.22 (1 H, dd, J = 11.3 Hz), 6.53 (1 H, dq, J = 11.3 Hz, $J_{allylic} \approx 1$ Hz), 6.67 (1 H, J = 12.3 Hz); λ_{max} 245 nm (ε 36 000); ν_{max} 1610, 1650, 3025, 3075 cm^{-1}; m/e 178, 176, 163, 161, 135, 133, 97.

Similarly, the known bromo olefins **3a** and **3g** (from salt **4a**) were obtained, as well as the following.

2-Bromo-4,4-dimethyl-2-pentene (3c): Bp 65–67 °C (32 mmHg); ^1H NMR of the *Z* isomer, δ 1.17 (9 H, s), 2.22 (3 H, d, $J_{allylic}$ = 1.4 Hz), 5.73 (1 H, q, $J_{allylic}$ = 1.4 Hz); ^1H NMR of the *E* isomer, δ 1.12 (9 H, s), 2.30 (3 H, d, $J_{allylic}$ = 1.4 Hz), 5.86 (1 H, q, $J_{allylic}$ = 1.4 Hz); IR ν_{max} 1365, 1380, 1645 cm^{-1}.

1-Phenyl-2-bromo-1-butene (3e): Bp 59–62 °C (~0.2 mmHg); ^1H NMR of the *Z* isomer, δ 1.18 (3 H, t, J = 7.5 Hz), 2.58 (2 H, q, J = 7.5 Hz), 6.65 (1 H, bs), 7.1–7.6 (5 H, m). ^1H NMR of the *E* isomer, δ 1.18 (3 H, t, J = 7.5 Hz), 2.58 (2 H, q, J = 7.5 Hz), 6.88 (1 H, bs), 7.1–7.6 (5 H, m).

3-Bromo-3-decene (3f): Bp 68–70 °C (2 mmHg); ^1H NMR of the *Z* isomer, δ 0.70–1.50 (11 H, m), 1.07 (3 H, t, J = 7.5 Hz), 2.05 (2 H, m), 2.41 (2 H, bq), 5.59 (1 H, t, J = 7.2 Hz, $J_{allylic}$ = 1.1 Hz); ^1H NMR of the *E* isomer, δ 0.70–1.50 (11 H, m), 1.07 (3 H, t, J = 7.5 Hz), 2.05 (2 H, m), 2.41 (2 H, bq), 5.77 (1 H, t, J = 7.6 Hz, $J_{allylic}$ < 1.0 Hz); IR ν_{max} 1635 cm^{-1}.

(Z)-1-Bromo-3,3-dimethyl-1-butene (3h). Although the *E* isomer is known,[36] the *Z* isomers is not known: ^{1}H NMR δ 1.2 (9 H, s), 6.08 (1 H, d, J = 3.1 Hz), 6.09 (1 H, d, J = 3.1 Hz); IR ν_{max} 730, 1630 cm^{-1}.

(Z)-1-(3-Chlorophenyl)-2-bromo-1-propene (3i): Bp 76–78 °C (~0.02 mmHg); ^{1}H NMR δ 2.28 (3 H, d, J = 1.3 Hz), 6.38 (1 H, bs), 6.90–7.40 (5 H, m); IR ν_{max} 1090, 1570, 1600, 1650 cm^{-1}.

(Z)-1-(4-Nitrophenyl)-2-bromo-1-propene (3j): Mp 82–84 °C (recrystallized from hexane); ^{1}H NMR δ 2.52 (3 H, d, J = 1.3 Hz), 6.78 (1 H, bs), 7.69 (2 H, m), 8.21 (2 H, m); IR ν_{max} 1340, 1530, 1570, 1600, 1630 cm^{-1}. For other properties of the bromo olefins, see Table III.

Bromo Olefin Protiodebromination. The standard procedure previously described[19] for protiodechlorination was followed. To a well-stirred solution of sodium (1.8 g, 78 mg-atom) in liquid ammonia (ca. 30 mL) was added dropwise 1-methoxy-4-bromo-1,3-pentadiene (2.3 g, 13 mmol) as an 87:13 mixture of *E,Z* and *E,E* isomers, respectively, in hexane (5 mL). After stirring for 5 min, the excess sodium was neutralized with solid ammonium chloride, the ammonia was evaporated, and water (30 mL) and hexane (30 mL) were added. After extraction and washing with water and subsequently with 2% H_2SO_4 and dilute sodium bicarbonate, the organic layer was dried ($CaCl_2$) and the hexane carefully removed at atmospheric pressure, leaving 1-methoxy-1,3-pentadiene[37] (~0.80 g, 66%) as a 73:27 mixture of *E,E* and *E,Z* diastereomers, respectively. The major isomer was confirmed by matching its NMR and UV spectra with those of the known compound.[37]

This sequence was also successful for the assignment of (*Z*)-2-bromo-2-nonene (**3b**) but failed for those bromo olefins containing an aromatic ring, e.g., **3a**. In these cases, the derived olefins appeared to undergo further polymerization, presumably induced by sodium amide, which is a well-known process for styrenes.

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Registry No.—**1b,** 66070-22-2; (*Z*)-**3a,** 21453-89-4; (*E*)-**3a,** 54624-37-2; (*Z*)-**3b,** 24404-60-2; (*E*)-**3b,** 66070-23-3; (*Z*)-**3c,** 66070-24-4; (*E*)-**3c,** 66070-25-5; (*E,Z*)-**3d,** 66070-26-6; (*E,E*)-**3d,** 66070-27-7; (*Z*)-**3e,** 66070-28-8; (*E*)-**3e,** 66070-29-9; (*Z*)-**3f,** 66070-30-2; (*E*)-**3f,** 66070-31-3; (*Z*)-**3g,** 588-73-8; (*E*)-**3g,** 588-72-7; (*Z*)-**3h,** 66070-32-4; (*E*)-**3h,** 38203-90-6; (*Z*)-**3i,** 66070-33-5; (*E*)-**3i,** 66070-34-6; (*Z*)-**3j;** 38319-07-2; (*E*)-**3j,** 38319-08-3; **4a,** 56506-90-2; **4b,** 66070-35-7; **4c,** 66070-36-8; **5a,** 66070-37-9; **5a** uncharged isomer, 39598-55-5; **5b,** 66070-38-0; **5b** uncharged isomer, 66070-39-1; **5c,** 66070-40-4; **5c** uncharged isomer, 66070-41-5; PhCHO, 100-52-7; $C_6H_{13}CHO$, 111-71-7; *t*-C_4H_9CHO, 630-19-3; MeOCH=CHCHO, 4652-35-1; *p*-NO_2PhCHO, 555-16-8; triphenylphosphonium dibromomethylide, 66070-42-6; triphenyldibromomethylenephosphorane, 42867-45-8; 1,1,3,3-tetraethoxypropane, 122-31-6; malondialdehyde sodium salt, 24382-04-5.

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