Lewis Acid Catalysis of the Ene Addition of Chloral and Bromal to Olefins; Stereochemical and Mechanistic Studies

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The Lewis acid catalysed ene additions of chloral and bromal to alkenes are completely regiospecific, moderately regioselective, and often highly stereoselective. Diastereoselectivity in the addition to (−)-β-pinene was a function of the Lewis acid, and with $TiCl_4$ essentially quantitative asymmetric induction was observed. The stereochemical phenomena are explained satisfactorily by assuming the active enophiles possess transoid structures such as (1), that a concerted or rapid stepwise mechanism operates, and that product formation occurs predominantly through the least hindered encounter complex of the olefin and (1). In the case of 2-methylbut-2-ene, however, there is some evidence for an additional stereoelectronic contribution, the '*cis*-effect'. Stereochemical assignments are supported by *X*-ray structural data. Ketones, hydrohalogenated ene adducts, or rearrangement products are formed (mainly in the additions to olefins of moderate reactivity) indicating the participation of Friedel-Crafts type dipolar intermediates. The ene adducts themselves could be formed *via* dipolar intermediates or in competing 'concerted' reactions; the stepwise mechanism must operate in some reactions because of the observation of Wagner-Meerwein rearrangements. Olefin reactivity over the series, measured by the competitive technique, towards chloral–$AlCl_3$ showed a *ca.* 900-fold variation in rate; 'ene' reactivity decreases more steeply.

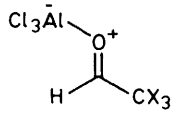
In our studies of the Lewis acid catalysed ene additions of chloral and bromal to alkenes two important features became immediately obvious. Firstly, little or no reaction occurred in the room temperature processes unless the Lewis acid dissolved in the reaction medium containing the enophile. Secondly, excepting for the most reactive olefins, thermal initiation of the reactions was generally unsuccessful. The reactive species was therefore thought to be a 1 : 1 trihalogenoacetaldehyde–Lewis acid complex such as (1) in which the Lewis acid coordinated the oxygen atom lone pair *anti* to the bulky X_3C group of the aldehyde. Since the reports [1] of our preliminary investigations in this area we have made a detailed investigation of the stereochemistry of these reactions. The mechanistic studies have largely been conducted through investigations of structure reactivity relationships and detailed analysis of the products of reaction. Full reports of this work are given here and in the accompanying papers.[2] Catalysed ene reactions have been reviewed by Snider,[3a] and several papers have appeared recently on the transition state geometry and mechanisms of ene reactions, Lewis acid catalysed ene reactions, and superene reactions.[3b-g,4]

Stereochemical and Regiochemical Studies.—The $AlCl_3$ catalysed addition of chloral and bromal to olefins is completely regiospecific in the sense that only Markownikov type adducts were observed. The reactions with olefins such as (+)-limonene and ethyl nona-3,8-dienoate were also site selective with the additions taking place at the terminal olefinic centres; however, we were unable to establish if β-caryophyllene reacted only at the strained trisubstituted *trans* double-bond.[2a]

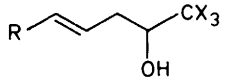
Mixtures of the *E*- and *Z*-adducts (2) and (3) should, in principle, be obtained from the ene additions to but-1-ene and higher alk-1-enes. G.l.c. analysis revealed a large bias towards formation of one isomer in the chloral–$AlCl_3$ additions to hex-1-ene (93 : 7) and oct-1-ene (92 : 8), for example, and i.r. spectra and ^1H n.m.r. signal widths for the olefinic resonances indicated that the major isomers possessed the *E*-configuration (2). Small differences in R_F values for the oct-1-ene adducts (2,3; X = Cl, R = n-C_5H_{11}) enabled the isolation of pure samples of both isomers by careful pressure column chromatography. The *E*-isomer was characterised by an appreciably larger ^1H n.m.r. signal width for the olefinic resonances than for the *Z*-isomer, respectively 46—48 Hz and 38—40 Hz.[2a] Similar stereoselectivity in favour of formation of *E*-adducts (2) was evident in all of the other additions of alk-1-enes to chloral or bromal that were investigated (R = CH_3 ⟶ n-C_5H_{11}). Assuming the products to be kinetically determined, for we were unable to find any evidence for equilibration, then the *E*-adducts can be considered to arise from interaction of (1) and the alk-1-ene in the sterically favoured topology (4) whereas the *Z*-adducts arise from the more congested arrangement (5). The co-production of ketones in all of the alk-1-ene reactions make it seem unlikely that the two σ bonds are formed concertedly in (4)/(5) (see below). In each of the above cases, therefore, the ene additions to alk-1-enes were highly regio- and stereo-selective.

In contrast, the ene additions to unsymmetrical 1,1-dialkylethylenes were found to be much less regio- and stereoselective. Reaction of chloral–$AlCl_3$ with (+)-limonene afforded the adducts (6) : (7) : (8) in a ratio 79 : 15 : 6. Since (6) is not converted into (8) on treatment with $AlCl_3$ under the reaction conditions, it appears that (8) is formed independently by way of a Friedel-Crafts type intermediate [*e.g.* (14)]. Correcting for the 3 : 1 statistical advantage of primary over tertiary allylic C-H bonds in limonene, the relative rates for the $AlCl_3$ catalysed ene transfer of primary : tertiary H is *ca.* 1.76 : 1. The comparable result for the thermal ene reaction was 1.38 : 1. The relative involatility of (6) and the complexity of its ^1H n.m.r. spectrum did not allow us to draw any firm conclusions concerning the possibility of diastereoselection in its formation. Molecular models indicated that the endocyclic double bond in (+)-limonene was too remote to influence the stereochemical outcome of tertiary allylic C–H transfer to (1); indeed ^1H n.m.r. spectra indicated that (7) consisted of a *ca.* 1 : 1 mixture of isomers.

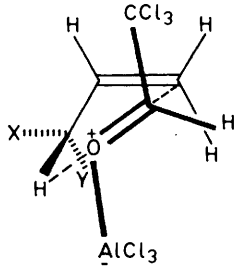
The $AlCl_3$ catalysed addition of chloral to 2-methylbut-1-ene gave a mixture (9) : *E*-(11) : *Z*-(11) of composition 47 : 44 : 9 as determined from ^1H n.m.r. intensities and capillary column g,l.c. assay. The corresponding bromal reaction afforded a *ca.* 25 : 75 mixture of (10) : (12) indicating extensive product equilibration because of the very much longer contact time. From other work [5] we have found that pure (13) is partially converted over a long period into its isomeric trisubstituted double bond isomers; traces of HCl are presum-



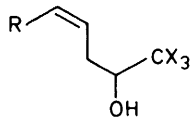
(1)



(2)



(4) X = alkyl, Y = H
(5) X = H, Y = alkyl



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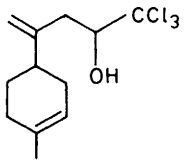

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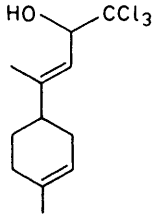

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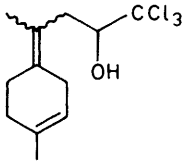

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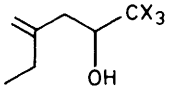

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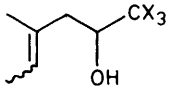
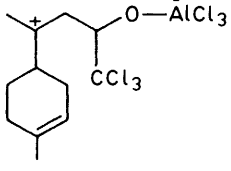
(10) X = Br



(11) X = Cl
(12) X = Br



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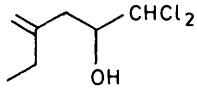

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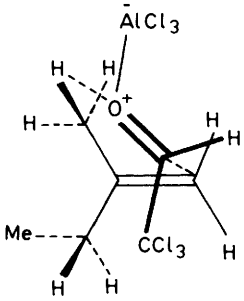

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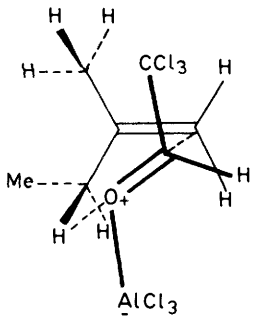


(16)

ably responsible. There was no evidence, however, for (9)/(11) equilibration in the short contact times of the chloral reaction. Correcting for the 3 : 2 statistical bias in favour of primary: secondary allylic C–H bonds in the olefin, the relative rates for ene attack at primary : secondary sites is *ca.* 1 : 1.7.

Despite the apparently high reactivity of primary allylic C–H bonds from the above results and literature precedent [3a,6] we could not find definite evidence for primary C–H transfer in the addition of chloral to 1-methylcyclohexene, even in the presence of R_2AlCl catalysts where loss of product through acid catalysed isomerisation could be ruled out.[2a,3a] The reasons for the high regioselectivity of secondary C–H transfer are not at all evident from examination of molecular models for attack of (1) on the 1-methylcyclohexene molecule, for relatively unhindered pathways appear to exist for the attack at either primary or secondary centres. On the other hand, the bias towards secondary C–H transfer in 2-methylbut-1-ene seems reasonable. For primary C–H attack the best approach geometry appears to involve confrontation of the *re* face of the olefin by the *re* face of (1), or the isoenergetic *si*/*si* confrontation, as indicated in (15). For secondary C–H attack steric interactions are minimised if the *re* face of the olefin is approached by the *si* face of (1) (or *si*/*re*) as shown in (16). The basic difference between (15) and (16) lies with the bulk of the non-reacting, and therefore freely rotating alkyl group. Since Et > Me the interaction (16) should be favoured for in (15) there is the problem of Et/Cl_3C repulsion. A similar situation pertains to the (+)-limonene chloral addition excepting here the ethyl group is replaced by the more bulky cyclohexenyl moiety. The gauche arrangement of the C–C–C skeleton of the ring inevitably forces the closer approach of non-reacting hydrogen atoms to the $AlCl_3$ moiety in (1) during reaction, whereas an unrestrained n-alkyl chain, as in 2-methylbut-1-ene, is able to adopt the more favourable *anti* conformation thereby avoiding this type of H/$AlCl_3$ compression. Thus, transfer of tertiary C–H in (+)-limonene is less favourable in the catalysed than in the thermal ene addition.

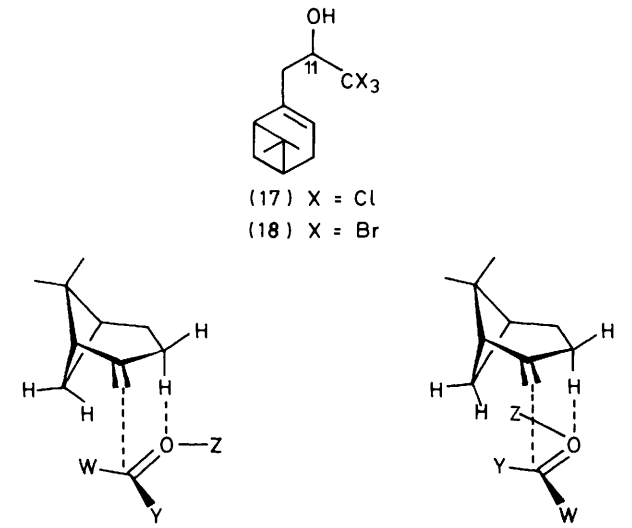
The most compelling evidence for the participation of a reactive intermediate like (1) was obtained from studies of the diastereoselectivity of the catalysed ene additions of chloral and bromal to (−)-β-pinene. This monoterpene was ideally suited to our purposes on three counts. (*a*) Only one of the two diastereotopic allylic H atoms, namely that *anti* to the bridging CMe_2 group, is reactive in the ene sense.[7] (*b*) Reaction to give ene adducts of structure (17) or (18) produces only one new chiral centre; the two diastereoisomers are both optically active. (*c*) This olefin is a very reactive ene, and it allowed the study of the addition reactions under a variety of experimental conditions, including the use of a number of Lewis acids.[2a] The results obtained are summarized in Table 1. The assignment of configuration at the new chiral centres C-11 in (17) and (18) rests on *X*-ray crystallographic evidence,[1d] and isomer ratios were determined from the appropriate ^1H n.m.r. integrals of Eu(fod)$_3$ shifted spectra and from intensities in the unshifted ^{13}C n.m.r. spectra. The analytical methods have been validated by capillary column g.l.c. analyses of the (more volatile) chemical degradation products of samples of (17) such as the methyl α-methoxycarboxylate.[2b] We were unable to detect the minor (11*R*)-isomer in the $TiCl_4$ catalysed reactions, and all of the data leads us to conclude that stereoselectivity is very *near* to 100% with this Lewis acid.

The most notable feature revealed in Table 1 is the complete inversion in the (11*R*) : (11*S*) ratios for (17) and (18) from the thermal to the catalysed ene additions. No fractionation of the isomers was detected in the isolation of these compounds by distillation, and treatment of the thermally-derived adduct (17), for example, with $AlCl_3$ did not alter the

Table 1. Diastereoisomer ratios found for the ene adducts formed in the reactions of chloral and bromal with (−)-β-pinene

Catalyst [a] (mol%)	Solvent	Adduct (17) (11*R*) : (11*S*)	Adduct (18) (11*R*) : (11*S*)	$[\alpha]_D^{24}$ for (17) (°) [d]
b	Neat	83 : 17	86 : 14	−4.6 (*c* 0.537)
BCl_3 (2—20) [c]	CCl_4	*ca.* 50 : 50		
$ZnBr_2$ (4)	Neat	25 : 75		
$AlCl_3$ (2)	CCl_4	24 : 76	25 : 75	−35.1 (*c* 0.538)
$AlCl_3$ (10)	CCl_4	25 : 75		
Et_2AlCl (100) [e]	CH_2Cl_2–hexane	22 : 78		
$BF_3{\cdot}Et_2O$ (5)	CCl_4	10 : 90		−42.4 (*c* 0.600)
$SnCl_4$ (2)	CCl_4	10 : 90	23 : 77	−42.8 (*c* 0.489)
$FeCl_3$ (2)	CCl_4	3 : 97	10 : 90	−45.9 (*c* 0.486)
$TiCl_4$ (2)	CCl_4	0 : 100	0 : 100	−48.2 (*c* 0.515)

[a] Catalysed reactions were conducted at room temperature. [b] Under N_2 in a sealed tube: 90—95 °C/10—18 h for chloral, 46 °C/8 days for bromal. [c] Ineffective catalyst; appreciable by-product formation and very low product yields. [d] Rotenone as calibration standard. (11*R*)-(17) $[\alpha]_D^{24}$ +4.5; (11*S*)-(17) $[\alpha]_D^{24}$ −47.8 by extrapolation. [e] Method 1 employed.[2a]



(17) X = Cl
(18) X = Br

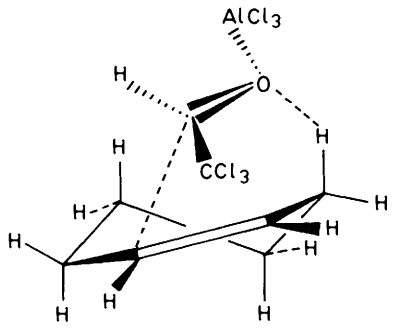
(19) W = H, Y = CX_3, Z = lone pair (21)
(20) W = CX_3, Y = H, Z = Lewis acid (22)

(23) a; *n* = 1 b; *n* = 2 c; *n* = 3 d; *n* = 4 (24)

ratio of diastereoisomers. The product balance was unaffected by an increase in $AlCl_3$ concentration, and utilisation of Et_2AlCl afforded a similar ratio of isomers to the $AlCl_3$ catalysed addition. Hence, acid-catalysed equilibration of the isomers does not occur, and the product ratios therefore appear to be kinetically determined.

In the thermal additions of chloral and bromal the favoured approach topology is shown by (19) which involves addition to the *re* face of the aldehyde, and hence leads to the formation of the (11*R*)-isomers of (17) and (18). In this approach the CX_3 group is aligned *exo* to the propenyl unit of the olefin. In the alternative confrontation (21), involving attack at the *si* face of the aldehyde, the prominent steric repulsions are between the *endo* CX_3 groups and 7α-H, making the formation of (11*S*)-(17) or -(18) unfavourable. In the Lewis acid catalysed additions, on the other hand, the interaction topology (20) should be favoured over that of (22) if it is assumed that the Lewis acid moiety Z is more sterically demanding than the aldehyde CX_3 group. The model of the reactive enophile (1) is an over-simplification since the metal atoms Al, Sn, Fe, and Ti of the Lewis acid are likely to display octahedral rather than tetrahedral co-ordination. Additionally, the CX_3 group in (20) is rather further removed from 7α-H than is the Lewis acid Z in (22). The catalysed reaction, therefore, should predominantly involve (20) and give mainly (11*S*)-(17) or -(18), as observed (Table 1). The trend to greater *S*-selectivity *roughly* parallels expectation based on the steric size of the Lewis acid moiety.

The ene additions of chloral and bromal to various other olefins possessing prochiral reaction centres, to give diastereoisomeric adducts, were also investigated by measuring product ratios by both n.m.r. and g.l.c. methods. The simplest olefins of this type, namely *cis*- and *trans*-but-2-ene, were not suitable for detailed study since the *trans*-olefin afforded very little ene adduct and the *cis*-olefin gave much polymeric material so that the ene adduct had to be purified by chromatography which could involve diastereoisomer fractionation.[2a] The cycloalkenes from cyclopentene to cyclo-octene were more amenable to study; each olefin reacted with chloral–$AlCl_3$ to give the appropriate ene adduct (23) and ketonic product (24).[2a] Only in the case of cycloheptene was the ketonic compound (24c) the major adduct (*ca.* 60%). The much lower levels of contamination (5—12%) by compounds (24,a,b,d) of the ene adducts (23a,b,d) from the other olefins of the series allowed assignment of the ^1H n.m.r. spectra of the crude unfractionated product mixtures. The strong narrow doublets (*J* 1.5—3 Hz) in the region δ 4.2—3.8 accompanied by much weaker doublets (*J* 2.5—4 Hz) *ca.* 0.1 p.p.m. downfield were assigned to atoms H_A of the major and minor diastereoisomers of (23a,b,d). Integrated intensity and peak area measurements gave the following isomer ratios: (23a) 91 : 9, (23b) 83 : 17, and (23d) 94 : 6. Assay by capillary column g.l.c. for (23a) gave closely similar results. The reproducibility of the ratios, the lack of effect of prolonged contact with $AlCl_3$ (other than to promote cyclic ether formation[2a]), and lack of evidence for isomer interconversion indicates kinetic control for the ene additions. Hydrogenation of (23a,b,d) resulted, as expected, in the collapse of the separate H_A signals to single sharp doublets (*J* 3—4.5 Hz) through removal of the chirality of the centres attaching atoms H_B. Compounds (24a,b,d) were fairly stable to the hydrogenation conditions,



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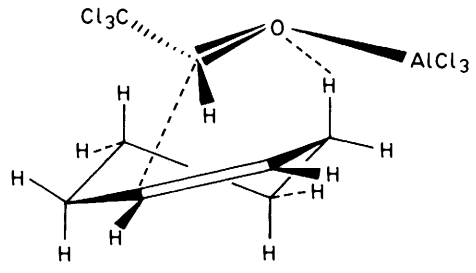

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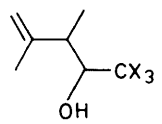
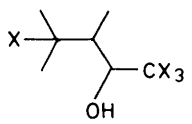


(27) X = Cl
(28) X = Br



(29) X = Cl
(30) X = Br

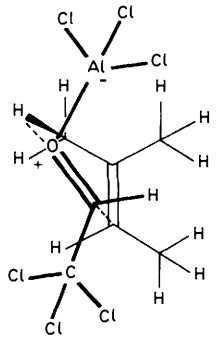
but could be removed from (23a,b,d), or their dihydro-analogues, by treatment with magnesium.[2a] Further purification of (23a,b,d) by distillation gave samples with simpler ^{1}H n.m.r. spectra which indicated no change in the ratios of diastereoisomers.

In case cycloheptene represented an inversion point for the series, the stereochemistry of the major isomers of both (23b) and (23d) were established by *X*-ray methods (see Experimental section). In both cases the crystals of the tosylate esters had centrosymmetric unit cells and in the molecular structures the chiral centres had the same relative configuration, that is (*R*,*R*) or (*S*,*S*), as shown in Figure 1. Taking cyclohexene as the model olefin, the favoured approach topology should contact the *si* face of the olefinic reaction centre with the *si* face of (1) (or *re*/*re*) to enable the bulky Cl_3C and $AlCl_3$ moieties to avoid steric conflict with the non-reacting H atoms of the alkene, as shown in (25). This topology places the Cl_3C group *endo* to the reacting propenyl unit in the olefin. The alternative *si*/*re* (or *re*/*si*) geometry, shown in (26), suffers from steric compression between the Cl_3C group and the appropriate H atoms at C-5 and C-6 of the cyclohexene molecule. Similar conclusions follow from consideration of the analogous additions to cyclopentene and cyclo-octene. In the case of cycloheptene steric problems for both modes appear to be at a maximum for the series, explaining the lower ene reactivity of this particular olefin.

Somewhat lower diastereoselectivities were found for the chloral–$AlCl_3$ additions to 1-methylcyclohexene and 1-chlorocyclohexene, respectively 75 : 25 and 57 : 43. With a substituent other than H at the non-reacting C=C terminus of model (25) there arises a new steric conflict, namely interaction between Cl_3C and the substituent. This lowers the energy difference between substituted (25) and (26) with consequent diminution of stereoselectivity. In the case of 1-chlorocyclohexene, which is of very low reactivity,[2a] the formation of much hydrochlorinated adduct also signals a change in ene/enophile interaction topology (see below).

Chloral reacted readily with 2-methylbut-2-ene in the presence of 2 mol % $AlCl_3$ to give an 85 : 15 mixture of the ene adduct diastereoisomers (27); with 10 mol % $AlCl_3$ both (27) and the hydrochlorinated adduct (29) were formed as a 55 : 45 mixture. From the corresponding reaction with bromal was isolated crystalline (28), being the major diastereoisomer. From comparisons of ^{1}H n.m.r. spectra it was clear that it possessed the same configuration as the major diastereoisomer of (27), but, unfortunately, the crystals were not suitable for *X*-ray structure analysis. Various derivatives of (27) were prepared and eventually slow crystallisation of the 3,5-dinitrobenzoate ester afforded crystals that were barely suitable for *X*-ray study. Structure determination (see Experimental section) by direct methods revealed that the chosen crystal was monoclinic with space group $P2_1$ and had two molecules in the non-centrosymmetric unit cell; the enantiomer present possessed the 2*S*,3*R*- or 2*R*,3*S*-configuration (see Figure 2), a result that was not anticipated. It was therefore necessary to prove that the selected crystal was not derived from the (spontaneously resolved) minor diastereiosomer 3,5-3,5-dinitrobenzoate. The bulk sample of recrystallized ester possessed a *ca.* 98 : 2 isomer ratio (250 MHz ^{1}H n.m.r. assay). The *very small* single crystal in ' gold label ' $CDCl_3$ was examined by 250 MHz ^{1}H n.m.r. which indicated that it was *probably* the major diastereoisomer of (27)·DNB; solvent and other impurities prevented a clear-cut decision. An *X*-ray powder photograph of the main sample of (27)·DNB was recorded and the value of 2θ determined for each of the rings observed on the *X*-ray film. With the aid of a simple computer program, standard mathematical calculations were then carried out using the unit cell dimensions and angles afforded by the single-crystal study to generate a series of theoretical 2θ values. There was excellent correlation from the two sources, and the positions and intensities of the rings on the powder photograph were exactly as predicted. It is highly unlikely that the two diastereoisomers of (27)·DNB would have identical unit cells, and the result therefore confirms that the major diastereoisomer of (27) did possess the (*R*,*S*) or (*S*,*R*) configuration.

The four possible interactions of (1) with 2-methylbut-2-ene suitable for ' concerted ' ene addition are shown in (31)—(34); the combinations (32) and (33) would both afford the (*R*,*S* + *S*,*R*) adduct, but operation of the ' *cis*-effect ' should favour (33). Distinction between (32) and (33) is possible by specific deuterium substitution, and on the basis of Stephenson's work [8] on the $^1O_2$ ene reaction the olefin (35) was selected for study. Unlike its *Z*-isomer, (35) is fairly readily prepared, and tiglic acid is a convenient starting material. The ^{1}H n.m.r. spectra of both the crude product and the chromatographically resolved diastereoisomers from the reaction of (35) with chloral–$AlCl_3$ clearly indicated that allylic C–H transfer had predominated over C–D transfer leading to (36) rather than (37). The ^{2}H n.m.r. spectra fully confirmed this conclusion, and capillary column g.l.c. assay of crude (36) indicated that it comprised an 87 : 13 mixture of diastereoisomers (*cf.* 85 : 15 for unlabelled 2-methylbut-2-ene). Although it could be argued that the failure to observe allylic D abstraction arises from a significant deuterium isotope effect, primary k.i.e.'s are known to be almost negligible ($k_H/k_D \sim 1.1$) for the Lewis acid catalysed ene additions of oxomalonic esters to olefins at 25 °C, even when intramolecular H/D competitions are available.[3f] However, if the $AlCl_3$ catalysed addition of chloral to 2-methylbut-2-ene proceeded by way of a rate-determining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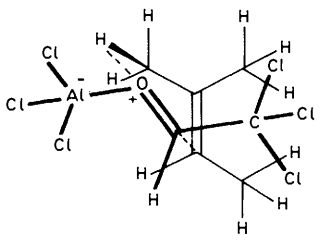
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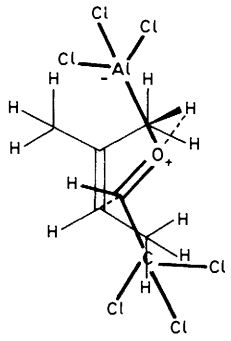
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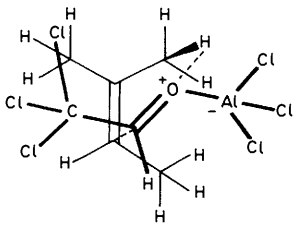
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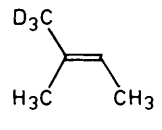
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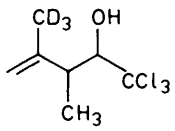
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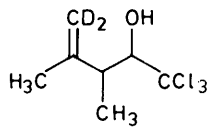
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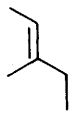
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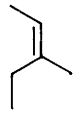
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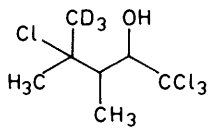
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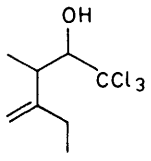
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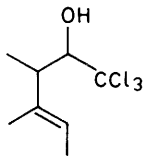
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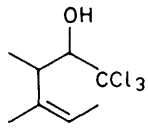
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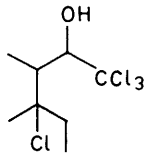
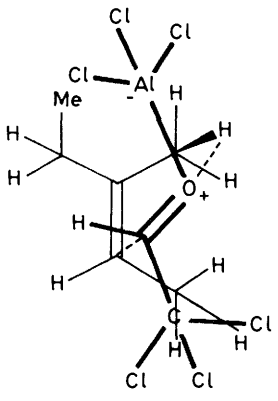

(44)

formation of a dipolar intermediate, then a product isotope effect would result unless the subsequent C–H(D) transfer occurred with zero activation energy (*cf.* the studies of Beak and Berger [9]). The stereochemistry of the addition would be determined in the rate-limiting C–C bond-forming step, and hence stereoselectivity could still arise. It does seem highly improbable that the presence of the deuterium label in (35) could result in a complete change in regioselectivity in the addition to 2-methylbut-2-ene while, at the same time, maintaining the usual diastereoisomer ratio for the ene adduct (27) or (36). Instead, we prefer the interpretation that (27) and (36) are formed stereo- and regio-selectively as a result of the operation of the '*cis*-effect'.[10] Thus, topology (33), and its enantiomer, predominates while the minor (*R,R* + *S,S*) diastereoisomer of (27) is formed by way of interaction (34).

The $AlCl_3$ catalysed reactions of both *Z*- and *E*-3-methylpent-2-ene, (39) and (40) respectively, with chloral were also examined. Both isomers afforded the four adducts (41)—(44), but the product distribution depended dramatically upon the starting material. Assay by both g.l.c. and ^1H n.m.r. methods gave the following results for the ratios (41):[(42 + (43)]:(44): from (39) 13 : 87 : trace, and from (40) 45 : 43 : 12. The results show a high preference for the operation of the '*cis* effect', but the presence of an ethyl group *syn* to the vinylic hydrogen in the *E*-isomer (40) has an appreciable perturbing influence (*cf.* the results for 2-methylbut-1-ene, above). Steric compression between the $AlCl_3$ moiety and the freely rotating ethyl group in the electronically favoured interaction topology (45) for addition to (40) [*cf.* (33)] would decrease the energy differential in its favour over the alternative interactions [*e.g.* (46)], thereby leading to a decrease in regioselectivity. It is significant that the greater steric congestion for addition to the *E*-olefin (40) resulted in the formation of appreciable quantities of the hydrochlorination product (44), indicating the incursion of a dipolar intermediate (see Mechanism, below). The experimental observations appear to rule out the possibility of proton catalysed double bond isomerization of (41) to (42) and (43) in the time scale for the addition reactions.

The diastereoselectivity of the ene addition of chloral to 2-methylbut-2-ene as a function of Lewis acid catalyst was also investigated. Typical results are summarized in Table 2, and isomer ratios were determined by capillary column g.l.c. Several Lewis acids failed to give consistent results for duplicate experiments, and with certain catalysts (notably $SnCl_4$, $TiCl_4$, and $FeCl_3$) the isomer ratio for (27) depended upon reaction time. However, the observation of an invariable diastereoisomer ratio in the reactions catalysed by $AlCl_3$ or *purified* $SnCl_4$ appears to rule out isomer interconversion, and treatment of (27) with either $AlCl_3$ or concentrated HCl failed to affect the ratio of isomers. The change in diastereoselectivities in the R_2AlCl catalysed reactions with a change in the order of addition of reagents is probably due to a parallel change in the reactive enophile from a 1 : 1 to a 2 : 1 Lewis acid : aldehyde complex.[11] Accordingly, the changes in selectivities with time for the (slower) reactions catalysed by $TiCl_4$ and $FeCl_3$ may be due to time-dependent changes in ligands and co-ordination about the metal atoms. Reaction of labelled 2-methylbut-2-ene (35) with chloral–$FeCl_3$ afforded much hydrochlorinated material [(36) + (37) : (38) = 35 : 65], indicating a substantial difference from the $AlCl_3$ catalysed process which was very much faster. The sluggish reaction of 2-methylbut-2-ene with bromal–$AlCl_3$ also gave much hydrohalogenated adduct [(28 : (30) = 75 : 25 with 2 mol% $AlCl_3$ 18 h]. Each product comprised an 85 : 15 mixture of diastereoisomers, showing a close similarity with the diastereoselectivity of the chloral addition.

Mechanistic Studies.—Most of the recent work on the mechanism of thermal and Lewis acid catalysed ene reactions has centred upon investigations of the addition of mesoxalic esters to olefins.[3c-g,12] These reactions proceed relatively



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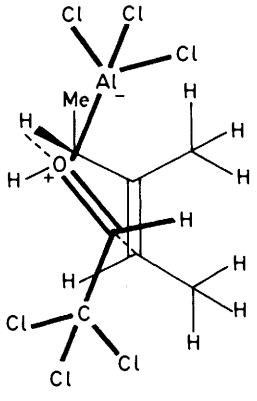

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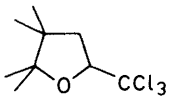

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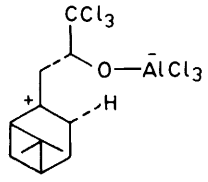
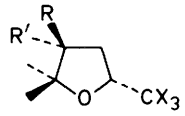
(48)



(47)

(50) R = H
(51) R = Me



(52) X = Cl, R = R′ = H
(53) X = Br, R = R′ = H
(54) X = Cl, R = CH_3, R′ = H
(55) X = Cl, R = H, R′ = CH_3
(56) X = Br, R = CH_3, R′ = H
(57) X = Br, R = H, R′ = CH_3

cleanly and in good yield [3g,12] with olefins of the more reactive types.[2a] The commonly held view of an essentially concerted reaction with H-transfer by a non-linear geometry is disputed by Kwart and Brechbiel [3c] on the basis of results from high precision measurement of kinetic deuterium isotope effects for the thermal addition of diethyl mesoxalate to allylbenzene. Instead, the finding of a temperature-independent primary k_H/k_D value of 2.557, and of inverse secondary D isotope effects of almost equal magnitude at both ends of the double bond of allylbenzene [$(k_H/k_D)_\alpha$ 0.950—0.957], led them to propose the formation of a symmetrically structured (2 + 2) charge-transfer complex in a preliminary step, followed by a rate-determining pesudopericyclic transition state similar to that proposed previously by them [3b] for the ene additions of superenophiles. In contrast, the Lewis acid catalysed process is thought to occur by the rate-limiting formation of a three-membered complex [3d,4] which, depending upon its configuration, may collapse to the ene adduct or oxetane. It is not clear, however, if oxetanes are formed with other olefins and to what extent allylbenzene may be regarded as a typical model ene. Since it is manifestly clear from the results of the preceding paper [2a] that no one olefin is a general representative of the whole class, we felt that a thorough study of structure–reactivity relationships and reaction products would provide broadly valid mechanistic information for the olefin–chloral addition reactions.

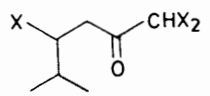
Skeletal Rearrangements.—The catalysed ene additions of chloral and bromal to β-pinene proceeded with high stereoselectivity in the presence of certain Lewis acids This together with the absence of limonyl- or bornyl-type products appears to eliminate the Friedel-Crafts intermediate [*e.g.* (47)] unless collapse to the ene adduct (17)/(18) is more rapid than rearrangement. The intramolecular H-transfer giving ene adduct could be a fast (least motion) reaction, particularly since the relevant C–H bond in (47) is essentially co-parallel with the empty p-orbital, but the results are also consistent with a ' concerted ' addition.

Table 2. Diastereoisomer ratios for the ene adduct (27) formed in the addition of chloral to 2-methylbut-2-ene

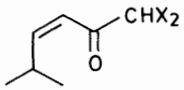
Catalyst	Mol%	(*R*,*S* + *S*,*R*) : (*R*,*R* + *S*,*S*) at time (X)
$AlCl_3$	2	85 : 15 Invariable (0—24 h)
$AlCl_3$	10	85 : 15 Invariable (0—24 h)
$SnCl_4$ [a]	2	57 : 43 (30 min); 62 : 38 (22 h)
$SnCl_4$ [a,b]	2	83 : 17 Invariable (0—24 h)
$TiCl_4$ [a]	2	67 : 33 (1 min); 78 : 22 (22 h)
$FeCl_3$	2	57 : 43 (1 min); 67 : 33 (22 h)
Me_2AlCl [c]	100	81 : 19 (2 h)
Me_2AlCl [d]	100	59 : 41 (2 h)
Et_2AlCl [c]	100	82 : 18 (2 h)
Et_2AlCl [d]	100	61 : 39 (2 h)
Thermal (130 °C) [a]		27 : 73 (24 h); 16 : 84 (72 h)

[a] Low yield (<15%). The thermal reaction afforded only *ca.* 1% adduct from a reaction conducted *in vacuo* in a tube heated to 130 °C/72 h. [b] Freshly distilled catalyst. [c] Catalyst added to reagents (Method 1).[2a] [d] Reagents added to catalyst (Method 2).[2a]

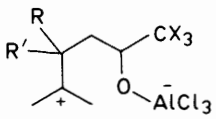
Examination of the interaction topology (15) for the addition of (1) to 2-methylbut-1-ene, with primary H-transfer, suggests that further alkyl substitution at C-3 should lead to increased steric compression of the Cl_3C group, thus causing a relative rotational displacement of the reaction partners. In these circumstances the oxygen atom may not be suitably disposed for transfer of the H atom by a concerted or rapid stepwise mechanism, thereby leading to the formation of a dipolar intermediate in which rearrangement could compete with allylic H-transfer. Indeed, reaction of 2,3,3-trimethylbut-1-ene (48) with chloral–$AlCl_3$ gave the ene adduct and the ether (49) in 2 : 1 ratio. Similarly, reaction of 3-methylbut-1-ene (50) with either chloral or bromal in the presence of 2 mol% $AlCl_3$ afforded in each case a *ca.* 60 : 40 mixture of two products in which the ene adducts could not be detected. Spectroscopic data indicated that the products were a tetrahydrofuran, (52) or (53), and a ketone, (58) or (59). Treatment with pyridine converted (58), (59) into the enones (60), (61), aiding the structural assignments as the ether–ketone mixtures could not be separated by pressure column chromatography. Surprisingly, (51) also reacted with chloral or bromal under 2 mol% $AlCl_3$ catalysis, even though the absence of an allylic H atom made the ene addition impossible, giving respectively a 50 : 50 and a 60 : 40 mixture of (54), (55) and of (56), (57). These results are consistent with the formation of an intermediate of structure (62), where R and R^1 are variously H or Me, which is transformed by a 1,2-shift of R into (63). In the case (62; X = Cl; R,R^1 = Me), formed from addition of chloral–$AlCl_3$ to (48), primary H transfer to give ene adduct successfully competes with rearrangement to (63) which suffers cyclisation to give the ether (49). Tertiary H-transfer from (62; R,R^1 = H), formed similarly from olefin (50), on the other hand, must be slow as the ene adduct could not be detected. Competition with rearrangement to (63; R,R^1 = H) and thence cyclisation to (52) or (53), is provided by intramolecular capture of halide (see below) which leads to the formation of



(58) X = Cl
(59) X = Br



(60) X = Cl
(61) X = Br



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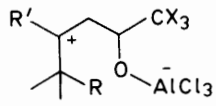

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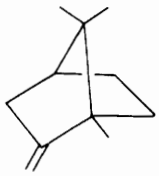

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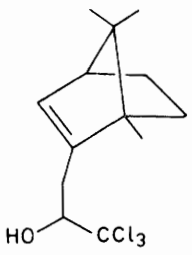

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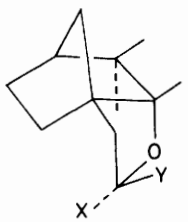
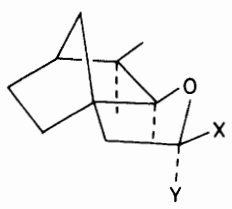
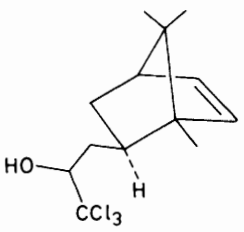


(68) X = CCl_3, Y = H
(69) X = H, Y = CCl_3



(66) X = CCl_3, Y = H
(67) X = H, Y = CCl_3



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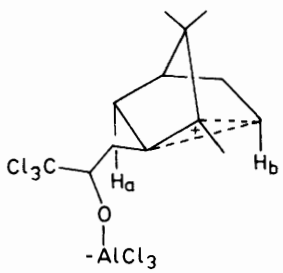

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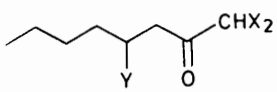


(72) X = Y = Cl
(73) X = Y = Br

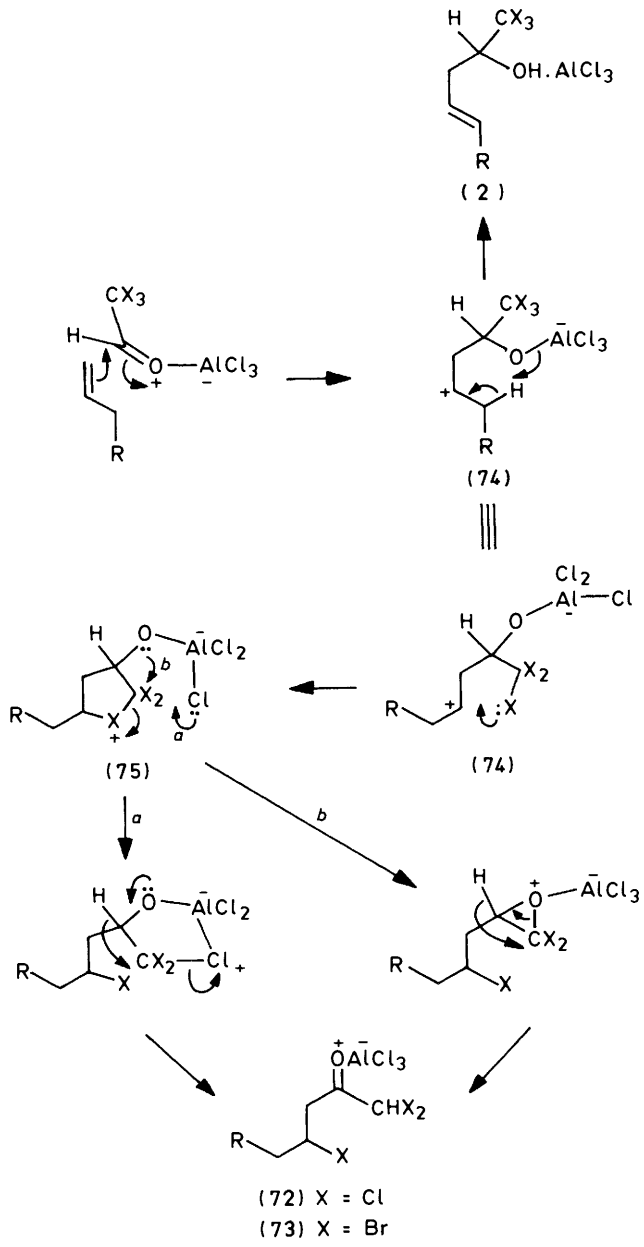
ketone (58) or (59). For the extreme case (62; R = Me, R^1 = H), where allylic H-transfer is not possible, the reaction appears to follow entirely the rearrangement–cyclisation route giving (54), (55) or (56), (57) *via* (63; R = Me, R^1 = H); we were unable to detect intramolecular halide-transfer processes which would have produced the analogues of (58) or (59).

Even more revealing results were obtained for the reaction of chloral–$AlCl_3$ with the methylene derivative of (+)-camphor (64). This olefin possesses structural features that are reminiscent of (−)-β-pinene, a highly reactive ene, and it was anticipated that an ene reaction with (1) would set the stereochemistry at the new chiral centre in the adduct (65) predominantly in the (*R*)-configuration. However, reaction afforded four products as assessed by t.l.c., and three compounds were isolated by pressure column chromatography. The major component (55%) was identified as a *ca.* 1 : 1 mixture of the *endo*-3(*S*)- and *exo*-3(*R*)-tricyclic ethers (66) and (68); steric considerations appear to rule out the alternative stereoisomers (67) and (69). The component of next highest R_F was identified as the trichloromethyl alcohol (70), and the final (minor) component proved to be the ene adduct (65), a 90 : 10 mixture of diastereoisomers. The formation of all of these products is readily rationalized in terms of the dipolar intermediate (71). Cyclisation, within this ion, to the tertiary centre would afford the ethers (66) and (68), transfer of the allylic atom H_a would give the ene adduct (65), and 1,3-hydride shift of H_b followed by deprotonation would give (70).

Formation of Ketonic Products.—It is noteworthy that ketonic by-products are a feature of the $AlCl_3$ catalysed additions of chloral and bromal to the less reactive olefins, but the presence of a substituent at C-2 of the basic propene unit of the ene completely inhibits ketone formation.[2a] Although these compounds could be regarded formally as arising from the Friedel-Crafts addition of $X_2CH{\cdot}COX$ to the alkene, we are satisfied that this process does not take place under the reaction conditions. Thus, treatment of hex-1-ene with dichloroacetyl chloride under the usual conditions for alkene–chloral addition (CCl_4 or CH_2Cl_2 solution, 2 mol% $AlCl_3$, 20 °C) afforded no (72); indeed no reaction appeared to occur. The electrophilic addition of the acid chloride required a much higher concentration of the catalyst—with 100 mol% $AlCl_3$ reaction occurred at −75 °C to give *ca.* 10% of (72) as assessed by g.l.c.

The key problem in determining the mode of formation of ketones such as (72) is the source of the halogen atom β to the C=O group, *i.e.* Y in formula (72), for it could originate from the trihalogenoacetaldehyde or from the catalyst. The formation of (73) in the addition of bromal–$AlCl_3$ to hex-1-ene appears, at first sight, to preclude the catalyst as a source of the halogen atom Y. However, halide exchange processes are likely to be prevalent (*e.g.* $RX + AlCl_3 \longrightarrow RCl + AlXCl_2$] under the reaction conditions. Unfortunately, the catalyst cannot be dispensed with as the olefins that afford ketonic by-products are insufficiently reactive to submit to the thermal ene addition of chloral or bromal. However, (72) was formed in the hex-1-ene–chloral reaction promoted by Brockmann I silica gel in hydrocarbon solvents, and replacement of $AlCl_3$ as catalyst by R_2AlCl did not, under most conditions, significantly affect ketone production.[2a] It seems highly likely, therefore, that the aldehyde CX_3 group is the source of the β halogen atom of the ketones.

Ketone formation can be rationalised, as in Scheme 1, by the formation of a dipolar intermediate (74). Allylic H-transfer within (74) leads to the ene adduct (2), but if bond rotations are relatively unrestricted or, more particularly, if the addition topology of (1) with the olefin was not ideally suited to the ene process, then (74) may interconvert into the bridged ion (75). Completion of the transfer of halide X would appear to require nucleophilic assistance, and the electron rich $OAlCl_3$ moiety is suitably placed for this purpose (paths *a* and *b*). The final step, leading to the formation of (72)/(73) in complexed form involves a 1,2-hydride shift which has close analogy with the pinacol rearrangement mechanism. A similar scheme can be written involving the $AlCl_3$ moiety as the halide donor.[1b] There is some evidence for the final step of Scheme 1 path *a*. Treatment of (76) with $AlCl_3$ in boiling

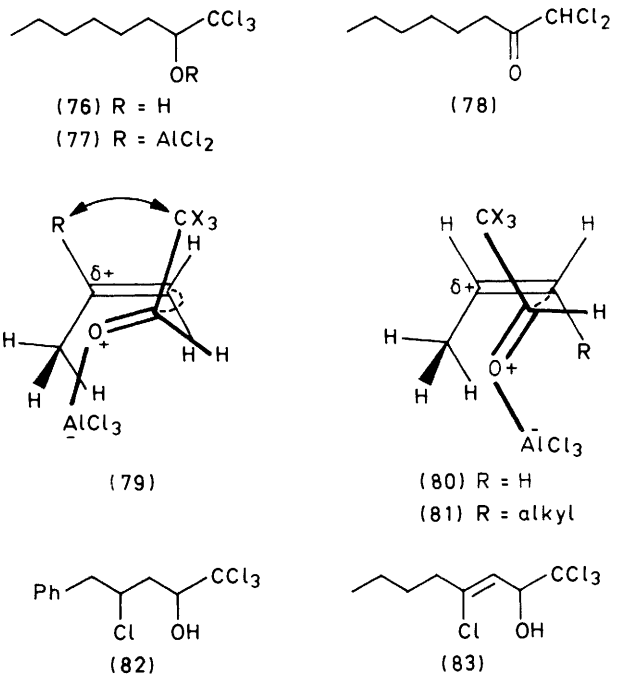


(72) X = Cl
(73) X = Br

Scheme 1.

CCl_4 led to the loss of HCl and presumably formation of (77).[13] Examination of the reaction residue, containing much resin, by t.l.c. and i.r. and ^1H n.m.r. spectroscopy showed the presence of a component with the characteristics expected [2a] of the dichloromethyl ketone (78). A more efficient route to (77) from (76) is available through reaction with $EtAlCl_2$ (ethane evolved); unfortunately (78) would be reduced rapidly by $EtAlCl_2$ to give a dichloromethyl alcohol of near identical R_F to the starting material (76).[2a]

We believe that the precise stereochemical alignment of the reaction partners in the encounter complex of olefin and (1) determines whether or not the ene adduct and/or ketone is formed. The key factor seems to be the finding that substitution of C-2 of the basic propene unit of the olefin inhibits ketone formation. In the reaction a 1,1-dialkylethylene, for example 2-methylbut-1-ene, steric interaction between the non-reacting alkyl substituent R and the X_3C group of the aldehyde leads to a relative rotational displacement of the ene



(76) R = H
(77) R = $AlCl_2$

(78)

(79)

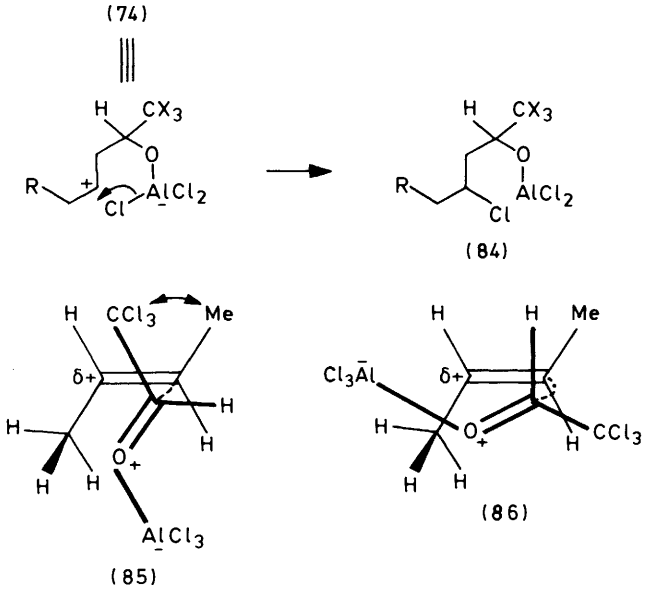
(80) R = H
(81) R = alkyl

(82)

(83)

and enophile, making (79) the preferred transition state arrangement [*cf.* (15) or (16)]. Since this geometry may not be suited to the concerted transfer of the allylic H atom, a dipolar intermediate may form in which the nucleophilic X_3C and $AlCl_3$ groups are remote from the developing carbocationic centre at C-2 of the olefin. Subsequent transfer of the proton is the predominant (least motion) reaction unless the carbocation is particularly stable and/or possesses a structure suited to rapid molecular rearrangement (*e.g.* 2-methylenebornane (64), above). In the absence of the C-2 substituent, as in the addition of (1) to an alk-1-ene, rotational displacement in the *opposite* sense should occur thus placing the X_3C group in a proper *endo*-orientation (80). The cationic centre of the dipolar intermediate formed through this geometry could be quenched by proton transfer giving ene adduct, or by halide transfer from the X_3C group (Scheme 1) giving ketone. The $AlCl_3$ moiety is too remote to quench the charge, and hence hydrohalogenated adduct is not formed (see below). A somewhat similar geometrical arrangement should pertain to the additions to *cis*-1,2-dialkylethylenes, as indicated in (81), again leading to ene adduct and ketone. It is not possible to predict, with the aid of such a simple model, the relative importance of the pathways leading to ene adduct of ketone as a function of olefin structure; indeed, it is not immediately clear why allyl bromide, for example, affords only ketone. However, with allyl bromide and allylbenzene homoallylic interaction of the C-3 substituent (Br or Ph) with a charge developing at C-2 may well be the feature responsible for diverting the reaction towards ketone production.

Formation of Hydrohalogenated Adducts.—These compounds could be regarded as the products of formal addition of HCl to the corresponding ene adducts. However, the structure of the hydrochlorinated compounds from the addition of chloral–$AlCl_3$ to allylbenzene, (82), or hex-1-yne, (83), appear to rule out this route,[2a] and in any event these compounds were formed in relatively few reactions and then only at higher (≥ 5 mol%) $AlCl_3$ concentrations. The stereochemistry of the olefin may also be important since *cis*-but-2-ene gave ene adduct and ketone on reaction with chloral–$AlCl_3$



Scheme 2.

whereas *trans*-but-2-ene afforded ketone and hydrochlorinated adduct under identical conditions.

In all cases the hydrohalogenated products could be formed by the interception of a dipolar reaction intermediate, *e.g.* (74), by X^- or an equivalent species (*e.g.* $O\bar{A}lX_3$), since in all of these products the OH group and transferred halogen atom are located on 1,3-related carbon atoms. We attempted to divert the hex-1-ene–chloral reaction towards formation of hydrochlorinated adduct by the introduction of additional Cl^- (as LiCl or HCl); in the event, reaction was inhibited (*e.g.* $AlCl_3 + Cl^- \rightleftharpoons \bar{A}lCl_4$). However, the intramolecular delivery of halide seems more likely (Scheme 2). The Lewis acidity of the Al atom is regenerated in (84) [*cf.* (77)] which could then function as a catalyst for further addition reactions. The operation of Scheme 2 requires the close approach of C-2 of the olefin and a Cl atom of the $AlCl_3$ group which would arise in the encounter complex if the $AlCl_3$ group was *endo* to the propene unit. In the addition of (1) to *trans*-but-2-ene the two geometries suitable for ene adduct production have either the Cl_3C group or $AlCl_3$ group *endo* as shown by (85) and (86), respectively. Compression between the Cl_3C and Me groups raises the energy of (85) relative to (81; R = Me) making the *trans*-olefin less reactive and allowing competition from (86) which affords ene and hydrochlorinated adducts. A very similar situation arises in the reaction of 2-methylbut-2-ene where in the preferred interaction topology (33), discussed above, the $AlCl_3$ moiety is once again in the *endo*-orientation; charge development at C-2 should afford hydrochlorinated adduct but not ketone [*i.e.* *endo*-CCl_3 in (32) or (34) is rather unfavourable], as observed. It may be coincidental, but as noted previously the diastereoisomer ratio for compound (27) was found to be the same as for (29), namely 85 : 15; however, since both compounds should be mainly formed through geometry (33), then the configurations of (27) and (29) are expected to be much the same. The formation of hydrohalogenated products in additions to other olefins can be rationalised in like fashion. Allylbenzene is atypical of the alk-1-enes in affording hydrohalogenated adduct. There are two possible reasons for this difference: allylbenzene is only weakly reactive and $\geqslant 5$ mol% $AlCl_3$ was necessary to promote reaction, and development of charge at C-2 may involve substantial interaction with the phenyl substituent.

Table 3. Relative reactivities of alkenes with chloral–$AlCl_3$

Olefin	k_A/k_B *	Olefin	k_A/k_B
β-Pinene	27.3	Hex-1-ene	1.7
(+)-Limonene	9.8	Oct-1-ene	1.0
α-Methylstyrene	9.2	Cyclohexene	0.16
1-Methylcyclohexene	2.6	Allylbenzene	0.09
		1-Chlorocyclohexene	0.03

* Oct-1-ene as standard olefin (olefin B).

Olefin Reactivity.—It was not possible in a simple way to measure ene reactivity since few olefins afford only ene adduct. However, olefin reactivity towards chloral–$AlCl_3$, which takes account only of the rate of olefin loss, by whatever mechanism, was readily determined by the competitive method. A four-fold excess of 1 : 1 olefin–oct-1-ene mixtures were treated with chloral and 2 mol% $AlCl_3$, and olefin consumption at room temperature measured relative to one of two internal standards by g.l.c. From the calibration graphs it was possible to establish alkene concentrations in the reaction solutions, allowing calculation of relative reactivities (k_A/k_B),[14] that is the relative rate constant for reaction with alkene A and alkene B (B = oct-1-ene). Since analytical accuracy was best with olefins of not too disparate g.l.c. retention times, only a limited range of olefins was investigated; results are given in Table 3 and parallel our previous qualitative results.[2a] Ene reactivity must fall more steeply than the *ca.* 900-fold change indicated since the proportion of ene adduct among the reaction products decreases along the series.

General Conclusions.—The relative orientations of ene and enophile in the collision complex appears to be important in determining the nature and stereochemistry of the addition products. The isolation variously of ketones, hydrohalogenated adducts, and rearrangement products points to the formation of Friedel-Crafts type dipolar intermediates which could also be the precursors of the ene adducts themselves. The clean stereoselective formation of ene adducts in the reactions of many 1,1-dialkylethylenes is also consistent with a ' concerted ' mechanism, and it is possible that the above by-products, obtained mainly in the reactions of the less reactive alkenes, are the result of competition from stepwise processes. Dipolar intermediates, however, should be formed more readily from the 1,1-dialkylethylenes because of the presence of the additional cation-stabilizing substituent at C-2 of the reacting propene unit, and such a mechanism would explain the very much higher reactivity of these alkenes. Stereoselectivity is largely determined in the C–C bond-forming reaction. The timing of C–H bond-breaking is not clear at present, but in some cases at least (*i.e.* observation of Wagner-Meerwein rearrangements) clearly occurs later than C–C bond-formation. These problems may well be resolved by the application of kinetic methods, but such a study should encompass a range of olefins of different structural types for there appears not to be a single ' typical ' ene. Rather, there is a general trend in behaviour which may be the outward manifestation of a change in reaction mechanism.

Experimental

Experimental procedures and instrumentation are detailed in the preceding paper; details for the preparation of compounds (2), (3), (6), (7), (9)—(12), (17), (18), (23), (24), (27)—(30), (49), (72), (73), (76), (82), and (83) are also to be found therein.[2a]

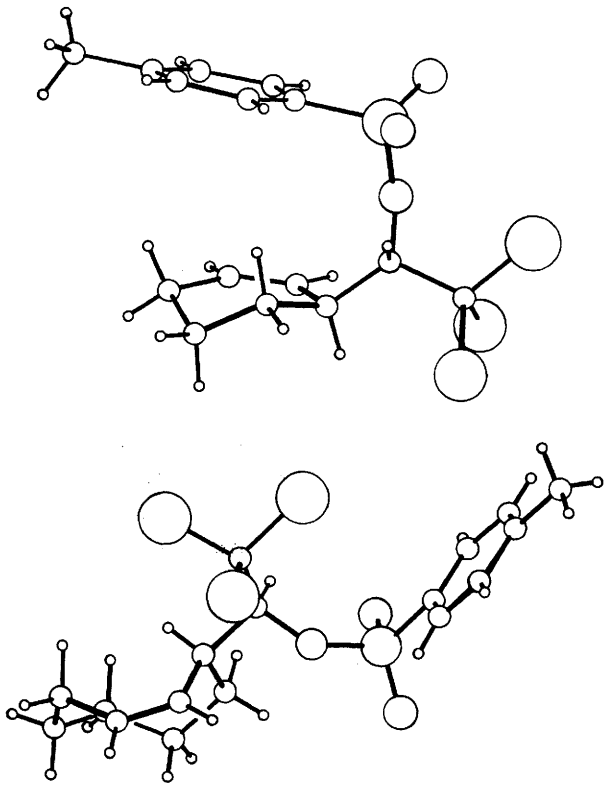


Figure 1. Molecular structures of the toluene-*p*-sulphonate esters (major diastereoisomer) of (23b) (upper) and (23d) (lower)

X-*Ray Methods and Data.*—Crystallographic methods were employed to determine the relative configuration at the chiral centres of (17), (23b), (23d), and (27). The first three compounds were converted into their toluene-*p*-sulphonate esters by way of the sodium alkoxides; details of this chemical procedure and a full account of the crystal structure of (17)-tosylate have been published elsewhere.[1d] Basic crystallographic details for the crystal structures of the toluene-*p*-sulphonate esters of 2,2,2-trichloro-1-(cyclohex-2-enyl)ethanol and of 2,2,2-trichloro-1-(cyclo-oct-2-enyl)ethanol, (23b)-tosylate and (23d)-tosylate respectively, have been reported;[1c] structural data including atom positions and structure factors were lodged with the Cambridge Data Centre at the time of the original publication. Only the molecular structure diagrams, not previously published, are given here in Figure 1. Likewise, 1,1,1-trichloro-3,4-dimethylpent-4-en-2-yl 3,5-dinitrobenzoate, (27)·DNB, was also not a structure of particular interest from the crystallographic point of view, and only brief details are therefore given here.

Compound (27)·*DNB.*—To a warm suspension of oil-free sodium hydride (0.033 g, 1.38 mmol) in dry ether (2 ml), was added a solution of 1,1,1-trichloro-3,4-dimethylpent-4-en-2-ol (27) [2a] (0.25 g, 1.15 mmol) in dry ether (2 ml). After 30 min under reflux the pale yellow solution of the alkoxide was treated with 3,5-dinitrobenzoyl chloride (0.292 g, 1.27 mmol) in dry ether (5 ml). The mixture immediately became deep red in colour and sodium chloride was precipitated. It was then stirred at room temperature for a further 30 min after which excess of sodium hydride was destroyed by addition of wet ether (5 ml) and then water (2 ml). Following dilution with ether (15 ml), washing with saturated aqueous sodium hydrogen carbonate (8 ml) and water (8 ml), and drying ($MgSO_4$), filtration and solvent removal the *product* (0.42 g, 85%) was obtained as a pale yellow solid. Recrystallization from ethanol produced fine colourless needles, m.p. 115—116 °C. Three normal crystallizations from ethanol was followed by a further recrystallization in which the rate of cooling of the hot ethanol solution was minimised by suspending the vessel in a Dewar flask filled with hot ethanol, plugging it with cotton wool, and leaving it undisturbed for 1 week. The crystals which formed were sufficiently large and regular for single crystal *X*-ray study (see below): $\nu_{max.}$ (KBr) 3 110, 2 980, 1 740, 1 635, 1 600, 1 555 1 350, 1 275, 1 170, 905, and 740 cm^{-1}; 250 MHz ^1H n.m.r. (*R,S* + *S,R*)-diastereoisomer after four recrystallizations δ 9.29 (1 H, t, *J* 2 Hz, aryl H *para* to ester group), 9.21 (2 H, d, *J* 2 Hz, aryl H *ortho* to ester group), 5.89 (1 H, d, *J* 4.5 Hz, $CHCCl_3$), 4.92 [1 H, m, $=CH(H)$], 4.89 [1 H, m, $=CH(H)$], 3.21 [1 H, qd, separations 4.5 and 7 Hz, $CH(CH_3)$], 1.88 (3 H, s, $=CCH_3$), and 1.30 [3 H, d, *J* 7 Hz, $CH(CH_3)$]; 90 MHz ^1H n.m.r. of the crude product showed the following additional signals due to the minor diastereoisomer (*R,R* + *S,S*) δ 5.79 (d, *J* 7 Hz, $CHCCl_3$), 4.90 (m, $=CH_2$), 1.40 [d, *J* 7 Hz, $CH(CH_3)$], ratio (*R,S* + *S,R*) : (*R,R* + *S,S*) was 85 : 15. Minor diastereoisomer signals were just detectable on 250 MHz spectrum of the recrystallized sample, indicating a *ca.* 2% level of the minor isomer. The 250 MHz ^1H n.m.r. of the single crystal used for the *X*-ray study showed a signal at δ 5.89 (d, *J* 4.5 Hz) thus confirming it was composed of the major diastereoisomer.

Crystallography.—Oscillation and Weissenberg photographs were taken about the *b* axis of a colourless crystal of (27)·DNB measuring *ca.* 0.7 × 0.005 × 0.005 mm and *X*-ray intensity data were obtained for the crystal mounted on an Enraf-Nonius CAD4 automatic four-circle diffractometer by use of Cu-K_α radiation. An ω scan up to the value θ 60° was employed. A total of 1 502 reflections were measured of which 834 had $I > 3\sigma(I)$ and were considered observed.

Crystal Data.—$C_{14}H_{13}Cl_3N_2O_6$, M = 411.5. Monoclinic, space group $P2_1$, a = 9.453(8), b = 6.076(4), c = 15.593(9) Å, β = 96.36(1)°, U = 895.8 Å^3, D_c = 1.525 g cm^{-3}, Z = 2, $F(000)$ = 420, Cu-K_α radiation, λ = 1.541 78 Å, μ(Cu-K_α) = 79.33 cm^{-1}.

Structure Analysis.—The multisolution program MULTAN [15] yielded a result with a high figure of merit (1.1560) which was used in the *E* map calculation. The 20 strongest peaks and 4 others of slightly lower intensity accounted for all the main atoms other than a carbon atom. Full matrix least-squares refinement on these 24 atomic positions, and with isotropic temperature factors led to convergence at *R* 0.125. The remaining C atom was readily identified from a Fourier difference synthesis, and further refinement on the 25 atoms reduced *R* to 0.0946. In subsequent refinement atomic temperature factors were allowed to vary anisotropically and after three cycles *R* converged to 0.053. A Fourier difference synthesis revealed the presence of a number of peaks from which 10 of the 13 hydrogen atom positions were readily identified. Calculated co-ordinates were used for all the hydrogen atoms other than the 3 of the vinylic CH_3 group (C-7) which could not be calculated on a simple basis; observed co-ordinates were used for the C-7 hydrogens and inclusion of the H atoms in the structure factor calculations without refinement reduced *R* to 0.0432. A weighting scheme, based on a Chebyshev polynomial, was introduced which led to an improvement in the standard deviations for bond lengths and angles while *R* increased marginally to 0.0451.

Final atomic positions are listed in Table 4, and the main bond lengths and angles are given in Table 5. Observed and calculated structure factors and thermal parameters are listed

Table 4. Atomic co-ordinates, with standard deviations in parentheses

	x/a	*y/b*	*z/c*
(*a*) Non-hydrogen atoms ($\times 10^4$)			
C(1)	360(10)	2 040(20)	1 747(6)
C(2)	1 980(10)	2 520(20)	1 919(5)
C(3)	2 570(10)	3 990(20)	1 236(5)
C(4)	3 780(10)	2 920(20)	847(7)
C(5)	3 650(10)	2 330(30)	44(7)
C(6)	2 900(10)	6 290(20)	1 563(7)
C(7)	5 100(10)	2 520(20)	1 442(7)
C(8)	2 890(10)	2 390(20)	3 403(6)
C(9)	2 870(10)	3 620(20)	4 253(6)
C(10)	2 144(9)	5 570(20)	4 309(5)
C(11)	2 085(9)	6 450(20)	5 125(7)
C(12)	2 716(9)	5 480(20)	5 872(5)
C(13)	3 380(10)	3 540(20)	5 794(6)
C(14)	3 491(9)	2 550(20)	4 985(6)
N(1)	1 313(9)	8 580(20)	5 199(6)
N(2)	3 950(10)	2 330(20)	6 567(6)
O(1)	2 173(6)	3 510(10)	2 765(4)
O(2)	3 506(7)	690(20)	3 347(4)
O(3)	728(7)	9 380(10)	4 531(4)
O(4)	1 267(7)	9 300(10)	5 921(5)
O(5)	3 707(7)	3 060(10)	7 254(4)
O(6)	4 609(8)	620(20)	6 473(4)
Cl(1)	49(3)	718(7)	744(2)
Cl(2)	−651(3)	4 505(7)	1 716(2)
Cl(3)	−167(3)	321(8)	2 549(2)
(*b*) Hydrogen atoms ($\times 10^4$)			
H(2)	2 565	1 111	1 931
H(3)	1 807	4 195	731
H(5A)	4 403	1 559	−227
H(5B)	2 699	2 647	−327
H(6A)	3 262	7 235	1 097
H(6B)	3 638	6 273	2 074
H(6C)	2 014	7 032	1 738
H(7A)	5 225	1 898	1 995
H(7B)	5 794	3 558	1 644
H(7C)	5 641	1 319	1 060
H(10)	1 667	6 287	3 780
H(12)	2 649	6 183	6 473
H(14)	4 069	1 081	4 957

in Supplementary Publication No. SUP 23794 (11 pp.).* Computation was achieved with the aid of the program CRYSTALS [16] and the molecular structure diagram (Figure 2) used the plotting program PLUTO.[17]

Effect of Lewis Acid Catalysts and Reaction Time on the Ratio of Diastereoisomers (27) *from the Ene Addition of Chloral to 2-Methylbut-2-ene.*—Standard procedures for trihalogenoacetaldehyde ene reactions [2a] were employed. Reaction times were typically 2—4 h and following the normal quenching and work-up procedures, samples of the crude products were dissolved in cyclohexane and examined by capillary column g.l.c. The two diastereoisomers of (27) were well resolved on a 50 m Carbowax 20M glass capillary column (programmed from 40 to 170 °C at 2.5 °C min^{-1}), the major stereoisomer (*R,S* + *S,R*) had R_T 51.1 min while the minor diastereoisomer (*R,R* + *S,S*) had R_T 47.6 min (N_2 inlet pressure 20 lb in^{-2}). The g.l.c. peaks were recorded at relatively high chart speed to give peaks of substantial area; the peaks due to each isomer were cut from the g.l.c. traces and the areas determined by weighing the segments of paper to within ±1 μg. All samples were analysed in duplicate, and average values are recorded in Table 2. The agreement between duplicate analyses was excellent (*ca.* ±2%).

In the study of the effects of reaction time the product ratio was monitored at various times. For the catalysed reactions the first sample was normally taken after 1 min and the final sample after *ca.* 1 day. A small quantity of the reaction solution (0.1 ml) was withdrawn by syringe and the catalyst quenched by shaking the sample with a mixture of water (0.3 ml) and cyclohexane (0.3 ml) contained in a small tube.

* For details of the Supplementary Publications Scheme see Instructions for Authors (1984), *J. Chem. Soc., Perkin Trans. 1*, 1984, Issue 1.

Table 5. Molecular geometry, with standard deviations in parentheses

(*a*) Interatomic distances (Å)

C(1)–C(2)	1.55(1)	C(9)–C(10)	1.38(1)
C(1)–Cl(1)	1.76(1)	C(9)–C(14)	1.39(1)
C(1)–Cl(2)	1.77(1)	C(10)–C(11)	1.39(1)
C(1)–Cl(3)	1.75(1)	C(11)–C(12)	1.38(1)
C(2)–C(3)	1.54(1)	C(11)–N(1)	1.50(1)
C(2)–O(1)	1.44(1)	C(12)–C(13)	1.35(1)
C(3)–C(4)	1.51(1)	C(13)–C(14)	1.41(1)
C(3)–C(6)	1.51(1)	C(13)–N(2)	1.46(1)
C(4)–C(5)	1.29(1)	N(1)–O(3)	1.22(1)
C(4)–C(7)	1.49(1)	N(1)–O(4)	1.21(1)
C(8)–C(9)	1.52(1)	N(2)–O(5)	1.21(1)
C(8)–O(1)	1.33(1)	N(2)–O(6)	1.23(1)
C(8)–O(2)	1.19(1)		

(*b*) Interatomic angles (°)

C(2)–C(1)–Cl(1)	107.6(6)	C(8)–C(9)–C(14)	116.1(10)
C(2)–C(1)–Cl(2)	111.5(7)	C(10)–C(9)–C(14)	121.3(9)
C(2)–C(1)–Cl(3)	109.9(6)	C(9)–C(10)–C(11)	117.4(9)
Cl(1)–C(1)–Cl(2)	109.1(5)	C(10)–C(11)–C(12)	123.5(9)
Cl(1)–C(1)–Cl(3)	109.4(6)	C(10)–C(11)–N(1)	118.2(10)
Cl(2)–C(1)–Cl(3)	109.3(5)	C(12)–C(11)–N(1)	118.2(10)
C(1)–C(2)–C(3)	114.4(7)	C(11)–C(12)–C(13)	117.3(9)
C(1)–C(2)–O(1)	104.9(7)	C(12)–C(13)–C(14)	122.4(9)
C(3)–C(2)–O(1)	111.7(8)	C(12)–C(13)–N(2)	119.9(9)
C(2)–C(3)–C(4)	112.0(8)	C(14)–C(13)–N(2)	117.7(10)
C(2)–C(3)–C(6)	112.6(8)	C(9)–C(14)–C(13)	117.9(9)
C(4)–C(3)–C(6)	113.4(9)	C(11)–N(1)–O(3)	116.9(9)
C(3)–C(4)–C(5)	120.7(10)	C(11)–N(1)–O(4)	116.8(10)
C(3)–C(4)–C(7)	116.1(9)	O(3)–N(1)–O(4)	126.2(9)
C(5)–C(4)–C(7)	123.1(11)	C(13)–N(2)–O(5)	117.2(10)
C(9)–C(8)–O(1)	110.1(11)	C(13)–N(2)–O(6)	118.2(10)
C(9)–C(8)–O(2)	123.0(11)	O(5)–N(2)–O(6)	124.5(10)
O(1)–C(8)–O(2)	126.9(10)	C(2)–O(1)–C(8)	118.3(8)
C(8)–C(9)–C(10)	122.3(10)		

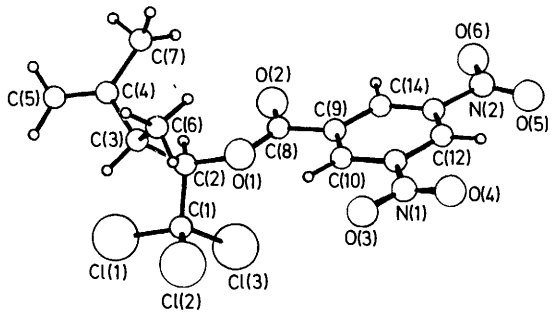


Figure 2. Molecular structure of (27)-3,5-dinitrobenzoate (major diastereoisomer)

The organic and aqueous layers were allowed to separate and the cyclohexane solution analysed by g.l.c. as above. The thermal reaction was monitored over several days owing to the slow rate of reaction.

Preparation of E-1,1,1-*Trideuterio*-2-*methylbut*-2-*ene* (35).—In order to optimize reaction conditions and handling techniques for the synthesis and use of (35), ordinary 2-methylbut-2-ene was first prepared by the same route using $LiAlH_4$ in place of $LiAlD_4$. The ^1H n.m.r. spectra of the unlabelled intermediates from the $LiAlH_4$ model series provided chemical shift data for all hydrogen atoms in these compounds and were used for comparison with the deuterium labelled intermediates to confirm that the required isotope incorporation had taken place. The preparation was effected in the following steps, (a)—(d).

(a) *Methyl tiglate* (*methyl* E-2-*methylbut*-2-*enoate*). To a solution of tiglic acid (20 g, 200 mmol) in methanol (120 ml) was added dropwise, and with swirling, concentrated sulphuric acid (0.4 ml). The mixture was boiled under reflux for 24 h, and the bulk of the excess of methanol then removed by rotary evaporation. The residue was poured into water (100 ml) and the organic products extracted into ether (2 × 20 ml). The ether solution was extracted with saturated aqueous sodium hydrogen carbonate (25 ml) and water (20 ml), dried ($MgSO_4$), and filtered. The solvent was removed under reduced pressure at about room temperature, and the crude product then distilled under reduced pressure, b.p. 54—56 °C/40 mmHg (lit.,[18] b.p. 139.4—139.6 °C/766 mmHg), giving 16 g (70%) of methyl tiglate; $\nu_{max.}$ (film) 2 950, 1 720, 1 650, 1 270, and 1 140 cm^{-1}; δ 6.87 (1 H, m, =CH), 3.73 (3 H, s, CO_2CH_3), 1.83 [3 H, br s, $=C(CH_3)CO_2CH_3$], and 1.79 (3 H, d, *J* 7 Hz, $CH_3CH=$).

(b) E-1,1-*Dideuterio*-2-*methylbut*-2-*en*-1-*ol*. To a slurry of $LiAlD_4$ (1.2 g, 28.6 mmol) in dry ether (35 ml), was added dropwise and with stirring a solution of methyl tiglate (3.6 g, 31.6 mmol) in dry ether (6 ml). When addition was complete (*ca.* 15 min) the solution was heated under reflux with vigorous stirring for 2 h, then allowed to cool to room temperature, and quenched by the cautious addition of water (5 ml). The organic solution was decanted from the white coagulated precipitate of inorganic salts which were washed thoroughly with ether (50 ml). The combined organic solutions were extracted with saturated aqueous $NaHCO_3$ (2 × 15 ml) and water (15 ml) and then dried ($MgSO_4$). Filtration and removal of solvent under reduced pressure gave the desired deuterium labelled alcohol (2.53 g, 91%). There was no over-reduction to the saturated alcohol under these reaction conditions: $\nu_{max.}$ (film) 3 330, 2 920, 2 200, 2 080, 1 660, 1 120, 1 060, and 960 cm^{-1}; δ 5.50 (1 H, m, =CH), 1.64 [3 H, br s, $=C(CH_3)CD_2OH$], 1.60 (3 H, *ca.* d, *J* 7 Hz, $CH_3CH=$), 1.40 (1 H, br s, absent on D_2O shake, OH), complete *absence* of signal at 4.04 (2 H, br s, CH_2OH) confirms complete deuterium incorporation as CD_2OH.

(c) E-1-*Bromo*-1,1-*dideuterio*-2-*methylbut*-2-*ene*. This method has been employed by Stephenson [8] for the preparation of similar allylic bromide systems. To a solution of *N*-bromosuccinimide (6.21 g, 35 mmol) in dry dichloromethane (90 ml) cooled to 0 °C, was added dropwise and with stirring dimethyl sulphide (2.52 g, 3 ml, 40.7 mmol). The pale yellow milky suspension which formed immediately was stirred at 0 °C for a further 30 min and then cooled to −20 °C prior to the dropwise addition of the deuterio alcohol from (b) (2.35 g, 26.7 mmol). The mixture was then allowed to warm up to room temperature and was stirred for a further 1 h, by which time a clear yellow solution had been formed. The solution was poured into ice (25 g), washed twice with saturated brine (2 × 25 ml), and dried ($MgSO_4$). Filtration was followed by the cautious removal of solvent at 0 °C/40 mmHg in order to minimise loss of the product. The *E*-1-bromo-1,1-dideuterio-2-methylbut-2-ene (4.0 g, 99%) was sealed in a small flask inside a tube immersed in liquid nitrogen; the bromide rapidly solidified and the low temperature prevented rearrangement and decomposition during overnight storage; δ 5.73 (1 H, *ca.* q, *J* 7 Hz, =CH), 1.70 [3 H, s, $=C(CH_3)CD_2Br$], 1.55 (3 H, d, *J* 7 Hz, $CH_3CH=$), complete *absence* of signal at 4.00 (2 H, br s, CH_2Br) confirms complete deuterium incorporation as CD_2Br.

(d) E-1,1,1-*Trideuterio*-2-*methylbut*-2-*ene* (35). The conversion of the bromoalkene from (c) into (35) is based on Stephenson's [8] method for the preparation of deuterium labelled alkenes. The diethylene glycol dimethyl ether (diglyme) solvent was initially dried over CaH_2 and then distilled from $LiAlH_4$, b.p. 62—63 °C/15 mmHg.

To a suspension of $LiAlD_4$ (0.58 g, 13.8 mmol) in diglyme (20 ml), cooled to −50 °C (solid CO_2–acetone) and under an atmosphere of nitrogen was added dropwise and with stirring the bromoalkene from (c) (4.0 g, 26.5 mmol). Stirring was continued while the solution was slowly warmed to room temperature and the product alkene (35) was then distilled directly from the reaction mixture (oil bath temperature 100 °C) and collected in a receiver cooled to −78 °C. Reaction afforded good quality olefin (35) (0.75 g, 39%) which was stored at −10 °C in a small Carius tube with a side arm and a high vacuum Teflon screw valve: b.p. 38 °C; *m/z* ($M^{+\cdot}$) 73.0973 ($C_5{}^1H_7{}^2H_3{}^{+\cdot}$ requires 73.0971); δ 5.20 (1 H, m, =CH), 1.60 [3 H, s, $=C(CH_3)CD_3$], 1.53 (3 H, d, *J* 7 Hz, $CH_3CH=$); complete *absence* of signal at 1.68 [3 H, s, $=C(CH_3)CH_3$] confirms complete deuterium incorporation as $=C(CH_3)CD_3$.

Reaction of E-1,1,1-*Trideuterio*-2-*methylbut*-2-*ene* (35) *with Chloral; Formation of* (36)—(38).—The basic standard procedure for a Lewis acid catalysed ene addition of chloral to a liquid alkene was employed.[2a] The deuterium labelled alkene (35), however, was cooled to −30 °C prior to its removal from the Carius tube storage, and all weighing procedures were conducted using cooled apparatus to minimise loss of material through evaporation. The mixture of chloral and catalyst was cooled to 0 °C in ice prior to addition of the alkene (35) *via* a gas syringe. The mixture was subsequently stirred at room temperature.

(*a*) Reaction on a 5 mmol scale in the presence of 2 mol% $AlCl_3$ in CH_2Cl_2 for 3.5 h afforded 0.7 g (64%) of the ene adduct 1,1,1-*trichloro*-4-*trideuteriomethyl*-3-*methylpent*-4-*en*-2-*ol* (36), together with small quantities of 1,1,1-*trichloro*-5,5-*dideuterio*-3,4-*dimethylpent*-4-*en*-2-*ol* (37), and 1,1,1,4-*tetrachloro*-5,5,5-*trideuterio*-3,4-*dimethylpentan*-2-*ol* (38), ratio 83 : 7 : 10. The product was subjected to pressure column chromatography ($CHCl_3$) and the two diastereoisomers of (36) were separated. The minor diastereoisomers of (36) and (37) eluted before the major diastereoisomers on g.l.c. in a 50 m Carbowax 20M glass capillary column. Diastereoisomer ratio 87 : 13.

Compound (36): Major diastereoisomer (*R,S* + *S,R*); t.l.c. R_F 0.43 ($CHCl_3$); $\nu_{max.}$ (film) 3 470, 3 070, 2 980, 2 930, 2 240, 1 640, 1 135, 905, and 810 cm^{-1}; δ 4.92 (1 H, m, 5a-H), 4.85 (1 H, m, 5b-H), 4.15 (1 H, dd, separations 3 and 6 Hz, reduced to d on D_2O shake with loss of 6 Hz splitting, 2-H) 2.94 (1 H, qd, separations 3 and 7 Hz, 3-H), 2.85 (1 H, d, *J* 6 Hz, absent on D_2O shake, OH), and 1.22 (3 H, d, *J* 7 Hz, CH_3 at C-3). The small signal at δ 1.80 [s, $D_2C=C(CH_3)$] establishes the low level of compound (37). Integration indicated that (36) : (37) was >90 : 10; 38.4 MHz ^2H n.m.r. δ 1.79 [br s, $H_2C=C(CD_3)$]; very small signal at 4.90 (m, $D_2C=$) establishes the low level of compound (37).

Compound (36): Minor diastereoisomer (*R,R* + *S,S*); t.l.c.

R_F 0.46 ($CHCl_3$); i.r. as for major isomer; δ 4.93 (2 H, m, 2 × 5-H), 3.97 (1 H, dd, separations 5.5 and 8 Hz, reduced to d on D_2O shake with loss of 8 Hz splitting 2-H), 2.90 (1 H, qd, separations 5.5 and 7 Hz, 3-H), 2.80 (1 H, d, *J* 8 Hz, absent on D_2O shake, OH), and 1.31 (3 H, d, *J* 7 Hz, CH_3 at C-3). A small signal at δ 1.80 [s, $D_2C{=}C(CH_3)$] establishes the low level of compound (37); integration indicated (36) : (37) was >90 : 10.

(*b*) Reaction on a 1.4 mmol scale in the presence of *ca.* 3 mol% $FeCl_3$ for 1 h afforded 0.09 g of a mixture of the three products (36), (37), and (38). Probable inaccuracies in the weighing of an extremely small quantity of $FeCl_3$ led to the predominance of (38). Ratio (36) + (37) : (38) was 35 : 65. Compound (38) was eluted on g.l.c. in a 25 m Carbowax 20M glass capillary column well after the minor and major diastereoisomers of (36) and (37).

Compound (36): Characteristic signals at δ 4.92 (m, 5-H) integrated as 2 H w.r.t. signals at *ca.* 4.0 (1 H, m, 2-H), confirms (36) as the principal ene adduct. Small signal at 1.80 [s, $D_2C{=}C(CH_3)$] establishes the low level of (37).

Compound (38): Mixture of diastereoisomers; δ 4.56 (1 H, d, *J* 5.5 Hz, reduced to s on D_2O shake, 2-H), 2.87 (1 H, d, *J* 5.5 Hz, absent on D_2O shake, OH), 2.60 (1 H, q, *J* 7 Hz, 3-H), 1.67 (*ca.* 1 H, s) and 1.60 (*ca.* 2 H, s) signals corresponding to $CD_3C(Cl)(CH_3)$ complicated by existence of diastereoisomers, and 1.22 (3 H, d, *J* 7 Hz, CH_3 at C-3).

Addition of E-3-*Methylpent*-2-*ene* (40) *to Chloral; Formation of* (41)—(44).—Reaction on a 10 mmol scale in the presence of 3 mol% $AlCl_3$ in CH_2Cl_2 for 2.5 h afforded 1.85 g (*ca.* 80%) of a mixture of 1,1,1-*trichloro*-3-*methyl*-4-*methylenehexan*-2-*ol* (41), E- and Z-1,1,1-*trichloro*-3,4-*dimethylhex*-4-*en*-2-*ol*, (42) and (43), and 1,1,1,4-*tetrachloro*-3,4-*dimethylhexan*-2-*ol* (44) in a ratio (41) : (42) + (43) : (44) of 45 : 43 : 12 as assessed by ^1H n.m.r. and by g.l.c. assay using a 25 m OV-17 glass capillary column. The mixture was subjected to pressure column chromatography ($CHCl_3$); (43) was isolated in a pure state but resolution of the other three products was incomplete.

Compound (41): Component of shortest retention time by g.l.c. on the above column; t.l.c. R_F 0.46 (CH_2Cl_2); $\nu_{max.}$ (film) 3 430, 3 070, 2 970, 1 640, 1 045, and 900 cm^{-1}; δ 5.00 [1 H, br s, $=CH(H)$], 4.89 [1 H, br s, $=CH(H)$], 4.17 (1 H, dd, separations 2.5 and 5.5 Hz, reduced to d on D_2O shake with loss of 5.5 Hz splitting, 2-H), 2.88 (1 H, m, 3-H), 2.87 (1 H, d, *J* 5.5 Hz, absent on D_2O shake, OH), 2.13 (2 H, q, *J* 7 Hz, 2 × 5-H), 1.24 (3 H, d, *J* 7 Hz, CH_3 at C-3), and 1.07 (3 H, t, *J* 7 Hz, 3 × 6-H).

Compound (42): t.l.c. R_F 0.46 (CH_2Cl_2); $\nu_{max.}$ (film) 3 470, 2 980, 2 930, 1 040, 820, and 745 cm^{-1}; δ 5.45 (1 H, *ca.* q, *J* 6.5 Hz, 5-H), 4.10 (1 H, dd, separations 3.5 and 6 Hz, reduced to d on D_2O shake with loss of 6 Hz splitting, 2-H), 2.90 (1 H, qd, separations 3.5 and 7 Hz, 3-H), 2.87 (1 H, d, *J* 6 Hz, absent on D_2O shake, OH), 1.67 (3 H, br s, CH_3 at C-4), 1.60 (3 H, br d, *J* 7 Hz, 3 × 6-H), and 1.20 (3 H, d, *J* 7 Hz, CH_3 at C-3).

Compound (43): t.l.c. R_F 0.50 (CH_2Cl_2); i.r. as for *E*-isomer (42); δ 5.54 (1 H, br q, *J* 6 Hz, 5-H), 3.96 (1 H, dd, separations 6 and 7.5 Hz, reduced to d on D_2O shake with loss of 7.5 Hz splitting, 2-H), 2.86 (1 H, *ca.* quintet, separations 6.5 Hz, 3-H), 2.74 (1 H, d, *J* 7.5 Hz, absent on D_2O shake, OH), 1.69 (3 H, s, CH_3 at C-4), 1.67 (3 H br d, *J* 7 Hz, 3 × 6-H), and 1.33 (3 H, d, *J* 7 Hz, CH_3 at C-3).

Compound (44): δ {by difference from (41) and (42)} characteristic signals at 4.67 (1 H, d, *J* 5.5 Hz, reduced to s on D_2O shake, 2-H), 2.72 (1 H, q, *J* 7.5 Hz, 3-H), 1.89 (2 H, *ca.* q, *J* 7 Hz, 2 × 5-H), and 1.55 (3 H, s, CH_3 at C-4).

Addition of Z-3-*Methylpent*-2-*ene* to *Chloral; Formation of* (41)—(43).—Reaction of (39) as for the *E*-olefin (40) afforded 1.8 g (78%) of a mixture of the three isomeric ene adducts (41)—(43), which were formed in a ratio (41) : (42) + (43) of 13 : 87. The *E*-adduct (42) was the major reaction product. Physical data for all three compounds are given in the preceding experiment.

Addition of 3-*Methylbut*-1-*ene* (50) *to Chloral; Formation of* (52) *and* (58).—Reaction on a 25 mmol scale in the presence of 2 mol% $AlCl_3$ in CCl_4 for 4 h followed by distillation afforded a 60 : 40 mixture of the ether 2,2-*dimethyl*-5-*trichloromethyltetrahydrofuran* (52) and the ketone 1,1,4-*trichloro*-5-*methylhexan*-2-*one* (58) (4.8 g, 88%), b.p. 70—72 °C/1.9 mmHg; t.l.c. R_F 0.62—0.67 (C_6H_6). Attempted separation by pressure column chromatography or gravity column chromatography was unsuccessful: $\nu_{max.}$ (film) 1 730 (58) 1 095, and 805 (52) cm^{-1}; δ [compound (58)] 5.90 (1 H, s, 1-H), 4.55 (1 H, m, 4-H), 3.13 (2 H, m, 2 × 3-H), 1.09 (3 H, d, *J* 5 Hz, 3 × 6-H), and 1.01 (3 H, d, *J* 5 Hz, CH_3 at C-5); δ [compound (52)] 4.29 (1 H, d of d, 5-H), 1.41 (3 H, s, *cis*-CH_3 at C-2), and 1.32 (3 H, s, *trans*-CH_3 at C-2).

Treatment of the mixture with pyridine in the usual manner [2a] followed by work-up and distillation of the residue under reduced pressure, b.p. 60—65 °C/1.4 mmHg, afforded 4.36 g of a 62 : 38 mixture of unchanged (52) and the conjugated ketone (60); t.l.c. R_F 0.62—0.69 (C_6H_6). Separation of this mixture by pressure column chromatography was unsuccessful: $\nu_{max.}$ (film) 2 920, 2 840, 1 690 (60), 1 625 (60), 1 460, 1 365, 1 150 (52), 1 120, 1 080 (52), and 800 cm^{-1}; δ 7.16 (1 H, dd, separations 6 and 16 Hz, 4-H of ketone), 6.48 (1 H, d, *J* 16 Hz, 3-H of ketone), 5.97 (1 H, s, 1-H of ketone), 4.54 (1 H, dd, separations 7 and 7 Hz, 5-H of ether), 2.76—1.76 (m, 5-H of ketone and 2 × 3-H + 2 × 4-H of ether), 1.41 (3 H, s, *syn*-CH_3 of ether), 1.31 (3 H, s, *anti*-CH_3 of ether), and 1.13 (6 H, d, *J* 7 Hz, 2 × CH_3 of ketone).

Addition of 3-*Methylbut*-1-*ene* (50) *to Bromal; Formation of* (53) *and* (59).—Reaction as with chloral for 16 h yielded after distillation a 58 : 42 mixture of 2,2-*dimethyl*-5-*tribromomethyltetrahydrofuran* (53) and 1,1,4-*tribromo*-5-*methylhexan*-2-*one* (59) in 66% yield, b.p. 40—42 °C/0.1 mmHg; t.l.c. R_F 0.63—0.68 (C_6H_6); $\nu_{max.}$ (film) 1 730 (59), 1 075 (53), and 720 cm^{-1}; δ 5.92 (1 H, s, 1-H for ketone), 4.46 (m, 4-H of ketone and 5-H of ether), 3.48 (2 H, m, 2 × 3-H of ketone), 2.50—1.80 (complex m, 5-H of ketone and 2 × 3-H + 2 × 4-H of ether), 1.44 (3 H, s, *cis*-CH_3 of ether), 1.32 (3 H, s, *trans*-CH_3 of ether), and 1.10 and 1.03 (6 H, 2 × d, *J* 5 Hz, 2 × CH_3 of ketone).

Treatment of the product mixture with pyridine in the usual manner [2a] afforded on work-up a 64 : 36 mixture of unchanged ether (53) and 1,1-*dibromo*-5-*methylhex*-3-*en*-2-*one* (61) (62%), b.p. 60—63 °C/1 mmHg; t.l.c. R_F 0.62—0.69 (C_6H_6); $\nu_{max.}$ (film) 2 920, 1 680 (61), 1 620 (61), 1 365, 1 145 (53), 1 075 (53), and 720 cm^{-1}; δ 7.09 (1 H, dd, separations 6 and 16 Hz,4-H of ketone), 6.52 (1 H, d, *J* 16 Hz, 3-H of ketone), 5.87 (1 H, s, 1-H of ketone), 4.43 (1 H, m, 5-H of ether), 2.76—1.77 (complex m, 5-H of ketone and 2 × 3-H + 2 × 4-H of ether), 1.43 (3 H, s, *cis*-CH_3 of ether), 1.31 (3 H, s, *trans*-CH_3 of ether), and 1.13 (6 H, d, *J* 6 Hz, 2 × CH_3 of ketone).

Addition of 3,3-*Dimethylbut*-1-*ene* (51) *to Chloral; Formation of* (54) *and* (55).—Reaction on a 25 mmol scale in the presence of 2 mol% $AlCl_3$ in CCl_4 afforded, after distillation under reduced pressure, b.p. 47—51 °C/0.2 mmHg, a 1 : 1 mixture of cis- and trans-2,2,3-*trimethyl*-5-*trichloromethyltetrahydrofuran* (55) and (54) as a colourless oil (64%). Separation of these compounds by pressure column chromatogra-

phy was unsuccessful as they possessed identical R_F values on t.l.c. 0.67 (C_6H_6) (Found: C, 41.25; H, 5.55. $C_8H_{13}Cl_3O$ requires C, 41.50; H, 5.66%); $\nu_{max.}$ (film) 2 960, 1 460, 1 370, 1 155, 1 075, and 795 cm^{-1}; δ 4.43 (1 H, m, 5-H), 2.5—1.8 (3 H, complex m, 3-H + 2 × 4-H), 1.32, 1.28, 1.16 and 1.09 (6 H total, 4 × s, 2 × CH_3 at C-2), and 1.02 and 0.96 (3 H, 2 × d, *J* 5 Hz, CH_3 at C-3); δ_C 102.22 and 101.05 (2 × s, CCl_3), 87.89 and 86.84 (2 × d, C-5), 86.20 and 85.79 (2 × s, C-2), 43.33 and 41.58 (2 × d, C-3), 37.43 (t, 2 × C-4 superimposed), 28.24, 26.78, 23.74, and 21.52 (4 × q, CH_3 at C-2), and 14.33 and 13.92 (2 × q, CH_3 at C-3).

Addition of 3,3-*Dimethylbut*-1-*ene* (51) *to Bromal; Formation of* (56) *and* (57).—Reaction as for the chloral addition for 7 h followed by distillation under reduced pressure, b.p. 110—120 °C/0.5 mmHg, afforded a 40 : 60 mixture of cis- and trans-2,2,3-*trimethyl*-5-*tribromomethyltetrahydrofuran* (57) and (56) as a colourless oil (60%). Separation by pressure column chromatography was unsuccessful; t.l.c. R_F 0.64 (C_6H_6) (Found: C, 26.3; H, 3.85; Br, 66.35. $C_8H_{13}Br_3O$ requires C, 26.33; H, 3.59; Br, 65.69%); $\nu_{max.}$ (film) 2 960, 1 455, 1 375, 1 155, 1 070, and 715 cm^{-1}; δ 4.40 (1 H, m, 5-H), 2.60—1.68 (3 H, complex m, 3-H + 2 × 4-H), 1.39, 1.32, 1.24, and 1.12 (6 H total, 4 × s, CH_3 at C-2), and 1.02 and 0.98 (3 H, 2 × d, *J* 6 Hz, CH_3 at C-3); δ_C [figures for major isomer (56) shown italicized] *89.82* and 86.72 (2 × s, C-2), *88.65* and 86.14 (2 × d, C-5), *51.64* and 49.18 (2 × s, CBr_3), 43.62 and *41.81* (2 × d, C-3), 39.36 and *39.12* (2 × t, C-4), 28.30, *26.78*, 24.27, and *21.58* (4 × q, CH_3 at C-2), and *14.39* and 14.09 (2 × q, CH_3 at C-3).

Addition of 2-*Methylenebornane* (64) *to Chloral; Formation of* (65), (66), (68), *and* (70).—The starting material, 2-methylenebornane (64), was prepared from (+)-camphor by a published procedure.[19] Reaction on a 3.6 mmol scale with chloral in the presence of 2 mol% $AlCl_3$ in CCl_4 solution for 4 h followed by distillation under reduced pressure, b.p. 115—120 °C/0.04 mmHg, afforded a colourless oil (56%) comprising a mixture of (65), (66), (68), and (70); t.l.c. R_F 0.57, 0.39, 0.35, and 0.25 (C_6H_6) (Found: C, 52.85; H, 6.3; Cl, 35.6. $C_{13}H_{19}Cl_3O$ requires C, 52.46; H, 6.43; Cl, 35.73%). Pressure column chromatography effected the separation of the ene adduct 1,7,7-*trimethyl*-2-(3,3,3-*trichloro*-2-*hydroxypropyl*)*bicyclo*-[2.2.1]*hept*-2-*ene* (65) and 1,7,7-*trimethyl*-6-(3,3,3-*trichloro*-2-*hydroxypropyl*)*bicyclo*[2.2.1]*hept*-2-*ene* (70), while endo-3-(S)- and exo-3-(R)-5,6,6-*trimethyl*-3-*trichloromethyl*-4-*oxatricyclo*-[5.2.1.$0^{1,5}$]*decane*, (66) and (68), were obtained as an unresolved mixture.

Compound (65): (11%), m.p. 54—58 °C; t.l.c. R_F 0.27 (C_6H_6); $\nu_{max.}$ (KBr) 3 400, 3 010, 2 930, 2 850, 1 665, 1 450, 1 390, 1 375, 1 090, 1 035, 810, and 760 cm^{-1}; δ 5.13 (1 H, m approx. to dt, separations *ca.* 1 and 9 Hz, 3-H), 4.54 (1 H, ddd, separations *ca.* 8, 6, and 1 Hz, reduced to dd on D_2O shake with loss of 6 Hz splitting, C*H*OH), 2.50 (2 H, m, reduced intensity on D_2O shake, O*H* + HC*H*CHOH), 2.1—1.5 (4 H, complex m, 4-H + *H*CHCHOH + CH_2 ring), 1.17 (2 H, m, CH_2 ring), 0.99 (3 H, s, CH_3 at C-1), 0.92 (3 H, s, *anti*-CH_3 at C-7), and 0.79 (3 H, s, *syn*-CH_3 at C-7); δ_C 160.41 (s, C-2), 111.11 (d, C-3), 103.97 (s, CCl_3), 80.47 (d, CHOH), 52.05 (s, C-1), 47.54 (s, C-7), 44.44 (d, C-4), 35.08 (t, *C*H_2CHOH), 34.39 and 27.78 (2 × t, C-5 and C-6), 19.59 (q, CH_3 at C-1), 18.71 (q, *anti*-CH_3 at C-7), and 12.51 (q, *syn*-CH_3 at C-7).

Compound (70): (12%), m.p. 48—50 °C; t.l.c. R_F 0.38 (C_6H_6); $\nu_{max.}$ (KBr) 3 400, 3 060, 2 940, 2 860, 1 650, 1 460, 1 385, 1 360, 1 105, 1 080, 885, and 810 cm^{-1}; δ 4.48 (2 H, br s, 2-H + 3-H), 4.04 (1 H, dd, separations 3 and 8 Hz, C*H*OH), 2.6—1.1 (7 H, series of m, 6 H on D_2O shake, OH + 4-H + 2 × 5-H + 6-H + CH_2), 1.04 (3 H, s, CH_3), and 0.84 (6 H, s, 2 × CH_3), δ_C 128.42 (d, C-2), 127.77 (d, C-3), 104.32 (s, CCl_3), 82.98 (d, CHOH), 72.13 (s, C-1), 44.56 (s, C-7), 42.28 (d, C-4), 35.55 (t, *C*H_2CHOH), 32.22 (t, C-5), 24.27 (d, C-6), 21.05 (q, CH_3 at C-1), 20.41 (q, *anti*-CH_3 at C-7), and 8.30 (q, *syn*-CH_3 at C-7).

Compounds (66) *and* (68): (27%), m.p. 32—34 °C; t.l.c. R_F 0.58 (C_6H_6); $\nu_{max.}$ (KBr) 2 930, 2 860, 1 450, 1 375, 1 090, 1 035, 920, 895, 805, and 685 cm^{-1}; δ 4.54 (1 H, two overlapping dd, CHO), 2.5—0.8 (9 H, series of m, ring CH + CH_2), 1.17 (3 H, s, *exo*-CH_3), 1.08 (3 H, s, *endo*-CH_3), 1.13 (3 H, s, CH_3 at C-6), 1.01 (3 H, s, CH_3 at C-6); δ_C 101.23 and 101.05 (2 × s, CCl_3), 94.32 (2 × s, superimposed, CH_3CO), 90.47 and 89.59 (2 × d, O*C*HCCl_3), 59.12 and 58.48 (2 × s, C-1), 50.17 and 48.89 (2 × d, C-7), 46.78 and 45.55 (2 × s, C-6), 40.12 and 39.06 (2 × t, CH_2), 33.16 and 32.51 (2 × t, CH_2), 27.02 and 26.08 (2 × t, CH_2), 24.62 and 24.33 (2 × t, CH_2), and 23.45, 23.27, 22.57 (two peaks superimposed), 20.76, and 16.61 (6 × q, CH_3).

Relative Reactivities of Alkenes with Chloral.—Alkenes within the range of b.p. 63—176 °C (hex-1-ene to limonene) were investigated; oct-1-ene was selected as standard alkene as it was of average b.p. and reactivity. The internal standard employed for the g.l.c. assay was cycloheptane (b.p. 118.5 °C) except for the 1-methylcyclohexene study when the internal standard was cyclohexane (b.p. 81 °C). G.l.c. analyses were conducted on a Pye 104 g.l.c. using a 5ft × ¼in glass column packed with 10% Apiezon L grease on 80—100 mesh Chromosorb W; for the 1-methylcyclohexene study a similar size column containing 15% polymetaphenyl ether on 80—100 mesh Chromosorb W was necessary to provide adequate resolution. Temperature programmed analyses were generally employed with N_2 flow rate *ca.* 20 ml min^{-1} and f.i.d. detection.

A series of standard solutions, containing known quantities of the test alkene, oct-1-ene, and internal standard were prepared. The absolute concentrations were carefully chosen to cover the ranges likely to be encountered in the test ene reactions. Using the appropriate g.l.c. analytical conditions, each calibration solution was analysed in triplicate and average values for peak height ratios calculated. Graphs of peak height (olefin/cycloheptane) *versus* weight (olefin/cycloheptane) were generally linear.

Three *identical* small-scale reactions were then carried out in ' Reactivials '. To anhydrous chloral (0.148 g, 1 mmol) dissolved in an equal volume of CH_2Cl_2, was added $AlCl_3$ (*ca.* 0.0027 g, 2 mol%). When the catalyst had dissolved a calibration solution (2 ml) containing olefin (2 mmol), oct-1-ene (2 mmol) and cycloheptane (1.5 mmol) in CH_2Cl_2 was added rapidly by means of a pipette. The solutions were stirred for a period of 1 h and then quenched by the addition of saturated $NaHCO_3$ solution. The organic layer from each reaction mixture was then analysed in triplicate using the same g.l.c. conditions as for the calibration. In each case an average value was calculated for the peak height ratio of olefin/internal standard and oct-1-ene/internal standard. By reference to the calibration graphs it was possible to establish, therefore, the alkene concentrations in the reaction solutions, and the relative reactivities of the two olefins (B = oct-1-ene) calculated according to the relationship: [14] $(k_A/k_B) = \log(A_I/A_F)/\log(B_I/B_F)$, where k_A/k_B is the relative rate constant for reaction with alkene A and alkene B, while (A_I/A_F) and (B_I/B_F) are the ratios of the initial to final alkene concentrations for A and B respectively. Results are summarized in Table 3.

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