The Thermal Ring Opening of 3,3-Disubstituted Cyclobutenes

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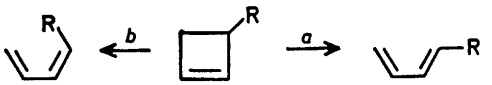
The rates of the thermal unimolecular isomerisation of 3-t-butyl-3-methylcyclobutene and 3-methyl-3-phenylcyclobutene have been measured in the gas phase over the temperature ranges 158—190° and 120—180°, respectively. They are correlated by the Arrhenius expressions $k = 10^{14.08 \pm 0.30}\exp(-150.8 \pm 2.5/RT)$ s^{-1} and $k = 10^{12.50 \pm 0.12}\exp(-126.15 \pm 0.95/RT)$ s^{-1}, respectively. The ratio of *Z*- to *E*-isomer of the butadienes formed has been measured both for these two and for the 3-methyl-3-R-cyclobutenes, where R = isopropyl, n-propyl, cyclopropyl, pentadeuterioethyl, 4-methoxyphenyl, 3-methoxyphenyl, and 4-cyanophenyl. In each case the proportion of *Z*-isomer formed is much larger than would be predicted on steric grounds. For the aryl compounds an attractive interaction during the formation of the *Z*-diene is proposed to account for its excess formation. For the alkyl substituents, a repulsive electronic interaction between the group and the developing remote double bond should be larger for methyl than for the other alkyl groups, accounting for the observed product ratios. The rates of isomerization of the 3-aryl-3-methylcyclobutenes at 161° correlate with the LUMO of the aromatic ring. The conclusions are shown to apply to results which have been reported by other authors.

THE isomerisation of cyclobutenes to butadienes has been extensively studied since the stereochemistry of the process was first demonstrated.[1] This major interest has continued in large part because the reaction is an ideal case for simplified theoretical treatments such as orbital symmetry,[2] frontier molecular orbital,[3] and the Dewar [4] and Zimmerman [5] aromaticity approaches. All these methods readily explain the observed conrotatory stereochemistry of ring opening, but rely on steric effects to account for the overwhelming preference for the formation of *trans*-alkene (1) from the pyrolysis of 3-monosubstituted cyclobutenes, where in principle both conrotatory paths [*a* and *b*, equation (1)] are equally probable. For simple cyclobutenes, the number of different substituents for which information is available is limited to R = alkyl,[6] phenyl,[7] hydroxy,[8] and acetoxy.[9]

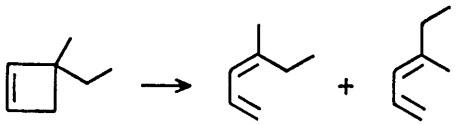


(1) (1)

Although a somewhat wider range has been reported when *trans*-3,4-disubstituted cyclobutenes are concerned,[6b,10] the additional thermodynamic instability of the *cis,cis*-diene which may be formed complicates any interpretation.

The effect of phenyl substitution on the kinetics of the reaction have been determined and shows that a potentially conjugating group at C-3 has a marked effect in reducing the activation energy for isomerisation while not affecting the stereochemistry.[7,11] The extensive kinetic studies of Frey [12–15] and his colleagues have shown the extent to which the activation energy is affected by alkyl substitution at C-1 and -3. They have observed one peculiar result, which is that the activation energy for isomerisation of 3,3-diethylcyclobutene [13] is less than that for 3,3-dimethylcyclobutene.[12] This indicates that it is easier to rotate an ethyl group inwards than a methyl group, a result borne out by their kinetic and product study on 3-ethyl-3-methylcyclobutene,[13] which gave a 68 : 32 mixture of the *Z*- and *E*-dienes (2) and (3) in which the *Z*-isomer predominates [equation (2)].

The steric argument in favour of the formation of a *trans*-double bond in the diene is essentially that repulsion between the group R and the methylene group at



(2) (2) (3)

C-4 develops during the transition stage leading to the *cis*-double bond in the necessarily *s-cis*-butadiene and hence that outward rotation of R, being larger than hydrogen is strongly favoured. In the majority of reactions where steric effects have been invoked, an ethyl group always behaves as a slightly larger group than methyl [16] and hence one would anticipate that the *E*-diene (3) should be formed preferentially. Frey and Solly [13] suggested that this unusual result was caused by an interaction between the π-electrons of the double bond in the cyclobutene and the terminal C–H bonds of the ethyl group (4), which would hold the ethyl group over the plane of the ring and hence facilitate an inward twist. Sterically such an interaction is not possible with a methyl group. An examination of the ring opening of other 3,3-disubstituted cyclobutenes should enable the validity of this hypothesis to be checked and was the impetus to the present study.

RESULTS AND DISCUSSION

Syntheses.—Cyclobutenes. Initially 3-t-butyl-3-methylcyclobutene (6a) was synthesised by a simple modification of the cyclopropylcarbene to cyclobutene rearrangement route previously used [17] and outlined in Scheme 1. Although (6a) was the major product from the decomposition of the tosylhydrazone (5), it required preparative g.l.c. separation from the other components of the mixture, and the overall yield was only 4% from methyl pivalate. The remaining cyclobutenes and (6a)

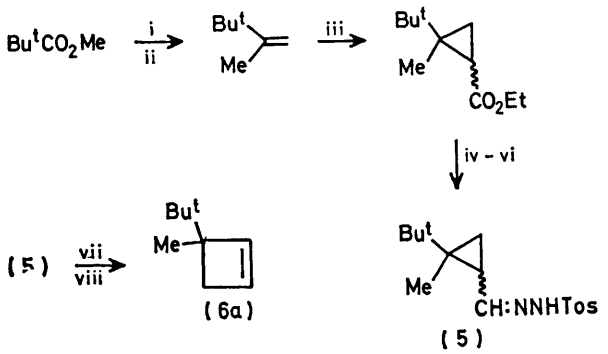
were therefore synthesised by the more efficient route shown in Scheme 2. Cyclopropyldiphenylsulphonium fluoroborate treated with the appropriate methyl ketone using solid potassium hydroxide in DMSO at room temperature to form the ylide. Work-up of the crude mixture with aqueous fluoroboric acid isomerised the oxaspiropentanes to the cyclobutanones (7) directly and extraction gave pure ketones, isolated in good-to-excellent yields.[18] The ketones were converted into the cyclobutenes using the reaction of two equivalents of methyllithium on the corresponding *p*-tolylsulphonylhydrazones.[19] The sample of (6a) prepared by this route was identical with that prepared by the route of Scheme 1.

TABLE 1

^{1}H N.m.r. spectra of 3-methyl-3-R-cyclobutenes (8). Chemical shifts in τ (coupling constants in Hz)

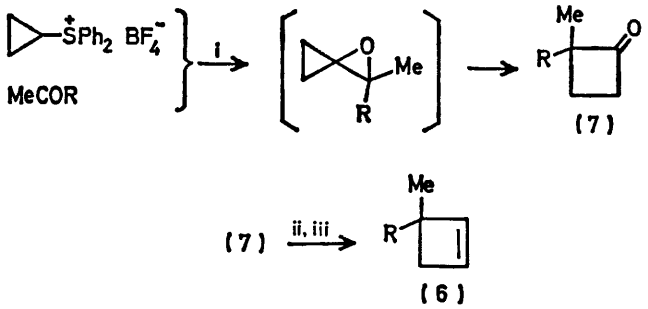
R	Me	1-H	2-H	4a-H	4b-H	Others
t-Butyl	8.80 (s) [a]	4.05br (d, 2.6)	4.01sh (d, 2.6)	7.51br (d, 13.2)	8.11sh (d, 13.2)	9.10 (Me_3C, s)
Isopropyl	8.94 (s)	4.03br (d, 2.5)	3.92sh (d, 2.5)	7.78br (d, 13.0)	7.98sh (d, 13.0)	8.34 (CH, septet, 7.5), 9.15 (Me_2, d,
n-Propyl	8.88 (s)	4.04br (d, 2.0)	3.94sh (d, 2.0)	7.78br (d, 12.0)	7.90sh (d, 12.0)	7.5) 8.5—8.8 [$(CH_2)_2$, m] 9.11 (Me, t,
Cyclopropyl	8.85 (s)	4.05br (d, 3.0)	4.26sh (d, 3.0)	7.92br (s)		7.5) 9.2—9.5 (CH, m) 9.6—10.1 [$(CH_2)_2$, m]
C_2D_5	8.87 (s)	4.03br (d, 2.8)	3.95sh (d, 2.8)	7.77sh (d, 13.0)	7.89sh (d, 13.0)	
Ethyl	8.87 (s)	4.03br (d, 2.8)	3.95sh (d, 2.8)	7.77sh (d, 13.0)	7.89sh (d, 13.0)	8.52 (CH_2, q, 7.5), 9.13 (Me, t, 7.5)
Phenyl	8.45 (s)	3.82br (d, 2.5)	3.56sh (d, 2.5)	7.35br (s)		2.77 (Ph, m)
4-Methoxyphenyl	8.50 (s)	3.85br (d, 2.8)	3.62sh (d, 2.8)	7.41br (s)		3.00 (Ar, ABq, 8.5), 6.30 (MeO, s)
3-Methoxyphenyl	8.46 (s)	3.80br (d, 2.5)	3.56sh (d, 2.5)	7.35br (s)		2.6—3.4 (Ar, m), 6.21 (MeO, s)
4-Cyanophenyl	8.44 (s)	3.72br (d, 2.5)	3.51sh (d, 2.5)	7.34br (s)		2.40 (Ar, ABq, 8.5)

[a] Multiplicity: s = singlet, d = doublet, *etc.*, sh = sharp, br = broad.



SCHEME 1 Reagents: i, MeMgI; ii, aq.NH_4Cl; iii, $N_2CHCOOEt$–$(MeO)_3P{\cdot}Cu_2Cl_2$; iv, $LiAlH_4$; v, Jones reagent; vi, *p*-$TosNHNH_2$; vii, NaH; viii, pyrolysis at 140°

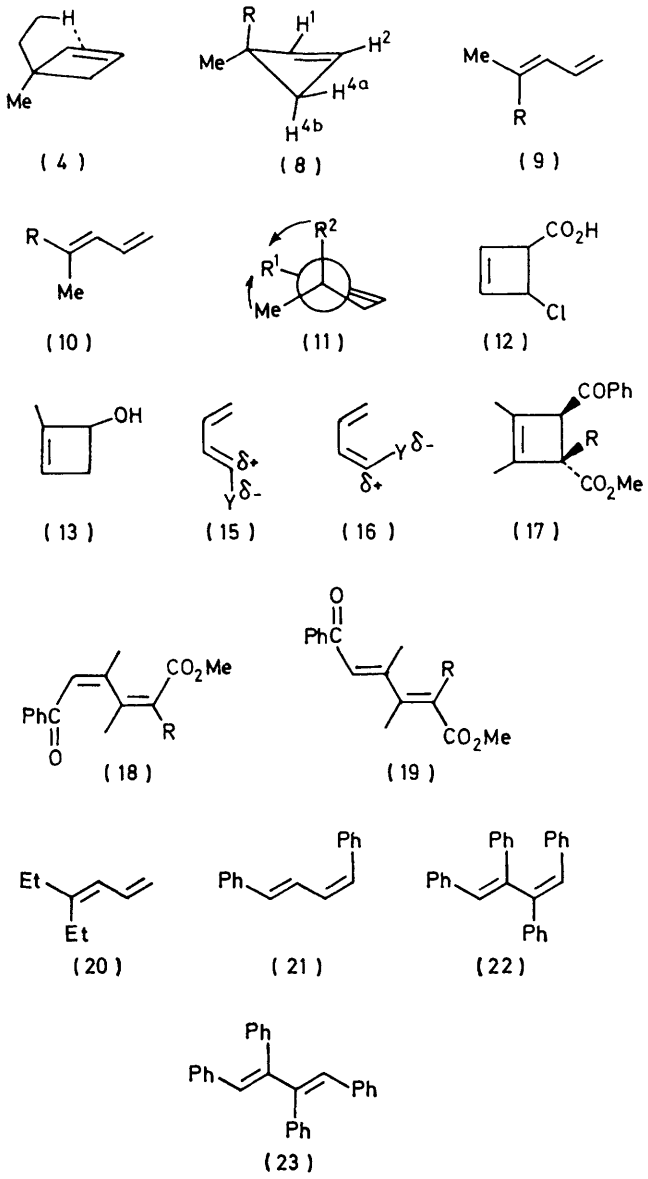
The ^{1}H n.m.r. spectra of the cyclobutenes (6a—k) are recorded in Table 1. The olefinic protons 1- and 2-H were assigned by a comparison of the spectra of (6b and d). In all the cyclobutenes one of the olefinic protons appears as a sharp doublet (half an AB quartet) and the other as a rather broader doublet, indicating an additional coupling. The sharp doublet is at lower field in all the compounds except for (6d), where it comes 0.3 p.p.m. to higher field than for (6b) and at higher field than the broad doublet. This is the behaviour to be expected from the known shielding effect of cyclopropyl [20] if the sharp doublet is that due to 2-H and the broad one to 1-H. Similarly the aryl-substituted compounds (6f—j) show a larger shift difference between the sharp and broad doublets (0.24 p.p.m.) than the alkyl ones (6a—c) (0.10 p.p.m.), as would be expected from the anisotropic effect of the ring current,[20] with both protons being deshielded but the nearer one being affected more. In the cyclobutenes (6a—c), the protons of the ring methylene are also non-equivalent and appear as a AB quartet with one half broader and shorter than the other. This corresponds to the broadening of the 1-H signal, showing that only one of the 4-H protons is coupled to it. The identity of the coupled proton was again deduced by a comparison of the spectra of (6b and d). In the former (R = Pr^i) the two signals are at τ 7.78 and 7.98, whereas in (6d) they are both at τ 7.92, showing that while one proton is unaffected, the other has experienced an upfield shift, and hence is *cis* with respect to the cyclopropane ring. The *cis* proton 4a-H is the one that shows the larger coupling to 1-H. One can account for this differential coupling by postulating that the cyclobutene ring adopts the twisted (buckled) conformation shown in (8) with the larger group pseudo-axial. In contrast with cyclobutanes, which also adopt a buckled conformation,[16] this pseudo-axial conformation is less crowded due to the absence of the pseudo-axial hydrogen at C-1. This twist of the cyclobutene places the bond between C-4 and 4b-H almost per-



a; R = Bu^t e; R = CD_2CD_3 j; R = 4-NCC_6H_4
b; R = Pr^i f; R = Ph k; R = Et
c; R = Pr^n g; R = 4-$MeOC_6H_4$
d; R = cyclopropyl h; R = 3-$MeOC_6H_4$

SCHEME 2 Reagents: i, KOH; DMSO; ii, *p*-$TosNHNH_2$; iii, 2 MeLi

pendicular to that of the bond between C-1 and 1-H, where it should show minimal coupling. The unequal coupling is seen markedly in the n-propyl, isopropyl, and t-butyl compounds, but surprisingly in the ethyl compound (6k) the two protons at C-4 are equally coupled to that at C-1, a result which was confirmed by spin decoupling and



INDOR experiments. Both in the cyclopropyl compound (6d) and in the aryl-substitued ones (6f—j), the protons at C-4 are accidentally isochronous, preventing the observation of any effect due a twisted conformation.

*Substituted Butadienes.** The synthesis and stereochemical assignment of the 1,3-dienes required for identification of the pyrolysis products has already been described,[22] except for the *Z* and *E* isomers (9 and 10; R = CD_2CD_3). These were identified by comparison of their g.l.c. retention times with those of their protio-analogues (2) and (3). Under identical conditions, analysis of the pyrolysis products of (6e) gave only two peaks of identical retention time to those obtained by pyrolysis of (6k). For the latter, the *Z*-diene (2) is eluted

TABLE 2

Products of the pyrolysis of 3,3-disubstituted cyclobutenes (6)

R in (6)	*Z*-Isomer (9)	*E*-Isomer (10)	*T* (°C)
t-Butyl	32	68	180
Isopropyl	65.5	34.5	180
n-Propyl	62	38	180
Cyclopropyl	43	57	180
Ethyl	68	32	180
C_2D_5	61	39	180
Phenyl	30	70	180
4-Methoxyphenyl	52	48	180
3-Methoxyphenyl	32	68	161
4-Cyanophenyl	45	55	161

first and hence the *Z*-stereochemistry was assigned to the diene giving the first peak from pyrolysis of (6e).

Pyrolysis of the Cyclobutenes.—Pyrolyses were performed in the gas phase in an all glass gas pipette, fitted with a Teflon Rotaflo valve, for *ca.* 1 h at 180° for R = alkyl and at 161° for R = aryl. The products were analysed by g.l.c. and the results are contained in Table 2. Control experiments established that the product composition did not vary with the time of pyrolysis, and that there was no significant surface reaction.

Kinetic Studies.—The kinetics of the isomerisation for (6a and f) were investigated over the temperature ranges 158—190° and 120—180°, respectively. The rate of disappearance of starting material was measured using

TABLE 3

Rate of thermolysis of 3-t-butyl-3-methylcyclobutene (6a)

T (°C)	158.0	180.0	190.0
$10^5/s^{-1}$	6.42	51.4	116

standard g.l.c. techniques, and plots of log (percent remaining) *versus* time gave good straight lines to over 90% reaction, showing the first-order nature of the reaction. The results are recorded in Tables 3 and 4. Use of a vessel packed with glass wool gave results in close agreement with those obtained in the unpacked gas

TABLE 4

Rate of thermolysis of 3-methyl-3-phenylcyclobutene (6f)

T (°C)	120.0	139.5	159.4	180.0
$10^5/s^{-1}$	5.56	33.7	179	928

pipette. For (6a) the rate constants are fitted by the Arrhenius equation $k = 10^{14.08 \pm 0.30}\exp(-150.8 \pm 2.5/RT)$ s^{-1} and for (6f) by $k = 10^{12.50 \pm 0.12}\exp(-126.15 \pm 0.95/RT)$ s^{-1}. Separate activation energies for the formation of the dienes (10a) and (11a) were calculated by assuming that the difference in E_a is the same as that for the ethyl compounds (2) and (3); the product ratios

* The 1,3-dienes formed by pyrolysis of the cyclobutenes (6) are all of the 4-substituted penta-1,3-diene type (9). Correct nomenclature normally includes the substituent R in the longest chain, the compound then being classified as a hexadiene, heptadiene, *etc.* In order to facilitate the discussion they will be referred to as 1,1-disubstituted butadienes. The stereochemical prefixes *Z* and *E* are designated in accord with the IUPAC rules.[21]

are the same for (6a) as for (6k) but with reversed stereochemistry. (Direct calculation was not possible because the change in product ratio over the temperature range studied was within the experimental error.) This assumption leads to the values in Table 5.

Semiquantitative studies were carried out on the other aryl substituted cyclobutenes (6g—j) and a value for the half-life ($t_{\frac{1}{2}}$) at one temperature obtained. These are shown in Table 6 together with the rate constants at 161°, the value for (6g) having been obtained by assuming

TABLE 5

Activation parameters for isomerisation of cyclobutenes

Cyclobutene	log A	E_a/kJ mol^{-1}	Product	Ref.
3,3-Dimethyl	13.93	151.04	(9; R = Me)	12
3,3-Diethyl	13.53	145.35	(20)	13
3-Ethyl-3-methyl	13.53	150.41	(3)	13
	13.50	147.35	(2)	13
3-t-Butyl-3-methyl	14.08	149.8	(10a)	This
		152.8	(9a)	work
3-Phenyl	12.4	108.8	(1; R = Ph)	7
cis-3,4-Diphenyl	13.1	102.5	(21)	11*a*
cis-1,2,3,4-Tetraphenyl	12.8	105	(22)	11*b*
trans-1,2,3,4-Tetraphenyl	11.1	88	(23)	11*b*
3-Methyl-3-phenyl	12.50	125.1	(10f)	This
		128.4	(9f)	work

the same E_a for both it and (6f), this gives a maximum value for the rate constant at 161° as it is probable that the E_a for (6g) is larger than that for (6f). Our values for the activation parameters for (6f) are in accord with those obtained on other 3-phenyl-substituted cyclobutenes (Table 5), in particular the lowering of the activation energy by 20—27 kJ mol^{-1} as a consequence of phenyl substitution.[11a]

The evidence presented in Table 2 shows that whereas medium sized alkyl groups (n-alkyl, isopropyl) rotate preferentially inwards relative to methyl, the largest groups (t-butyl and phenyl) give more of the *E*-diene (10). However, it is obvious that even here much more of the *Z*-diene is formed than might be expected as a result of the simple steric argument used to account for the formation of *trans*-alkadiene (1) with monosubstituted cyclobutenes. In attempting to estimate the magnitude of the discrepancy between the results found and those anticipated if steric size were the only criterion, we have used the conformational free-energy difference between equatorial and axial substituents on a cyclohexane ring (A value) [16a] as a simple measure of a purely steric effect and calculated an expected $Z:E$ ratio from them.* Frey's [24] results on *cis*- and *trans*-1,2,3,4-tetramethylcyclobutene enable one to estimate the energy required to twist a methyl group inwards and give a value of 15.8 kJ mol^{-1}. Using the difference in activation energy between 3-methyl- [6a] and 3,3-dimethyl-cyclobutene [12] gives the slightly larger value of 19.0 kJ mol^{-1}. These figures are between 2.2 and 2.7 times larger than the equatorial–axial energy difference for methyl and we have applied a correction factor of 2.4 to the A values for the groups R in order to calculate the expected $Z:E$ ratios. Table 7 gives the differences in A values between methyl and the group R ($A_R - A_{Me}$), the calculated $Z:E$ ratio at 180°, and the observed value. It is clear from Table 7 that in all cases the simple steric repulsion picture gives a result considerably different from that observed and that the magnitude of the discrepancy increases with the size of the group R. Thus some effect (or effects) must be operative to counterbalance any steric effects.

TABLE 6

Half-lives for isomerisation of 3-aryl-3-methylcyclobutenes (6f—j)

T (°C)	180	180	161	161	161
R in (6)	Ph	4-MeOC$_6$H$_4$	Ph	3-MeOC$_6$H$_4$	4-CNC$_6$H
$t_{\frac{1}{2}}$/s	75	600	325	450	280
10^4k at 161°/s^{-1}		2.6 [a]	21	15.5	25

[a] Extrapolated using E_a 126.4 kJ mol^{-1}, see text.

The data presented in Table 5 show that the activation energy for the formation of the *E*-diene (10; R = Me, Et, Bu^t) is remarkably constant (150.5 ± 0.5 kJ mol^{-1}) and it is evident that the energy required to twist a methyl group inwards is independent of the other alkyl substituent in (6) and therefore presumably also for R = H. Applying this E_a to predict the *cis* : *trans* ratio for 3-methylcyclobutene (6; R = H), one calculated that 0.7% of *cis*-penta-1,3-diene should be formed, well within the observable limits, but considerably greater than the observed value of <0.1%,[6a,25] indicating that here too the outward rotation of methyl is favoured by some additional factor.

The original hypothesis of Frey and Solly [13] that an interaction between the double bond and the terminal hydrogens of the ethyl group (4) are responsible for the behaviour of (6k) could account for the results of the alkyl-substituted cyclobutenes. Thus (6c) has two

TABLE 7

Calculated $Z:E$ diene ratios based on steric effects

R in (9) and (10)	Et	Pr^n	Pr^i	cyclopropyl	Bu^t	Ph	CD_2CD_3
$(A_R - A_{Me})$[a]/kJ mol^{-1}	0.5	1.7	1.7	*b*	16.4	5.9	*c*
Calc. $Z:E$ [d]	42 : 58	25 : 75	25 : 75	50 : 50	1 : 10 [4]	2 : 98	44 : 56
Obs. $Z:E$	68 : 32	62 : 38	66 : 34	43 : 57	32 : 68	30 : 70	61 : 39

[a] A Values taken from ref. 16*a*. [b] No value reported, evidence of ref. 22 suggests $A_{cyclopropyl} \doteqdot A_{Me}$ [c] This should be somewhat smaller than for C_2H_5; [35] a value of 0.4 was used. [d] Calculated using 2.4 $(A_R - A_{Me})$, see text.

* Other measures of steric size such as Taft E_s values [23] give qualitatively the same results.

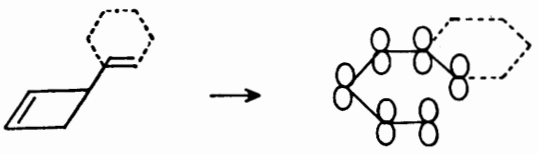
hydrogens, (6b) six hydrogens, and (6a) nine hydrogens that could interact with the double bond decreasing or increasing the probability for such an interaction. For the t-butyl compound, this would be offset by the increased size relative to ethyl producing the sort of ratios observed (Table 7). The ^{1}H n.m.r. evidence for the preferred conformations of the cyclobutenes (discussed above) with the R group pseudo-axial would tend to support this hypothesis. Indeed, the unequal coupling of the C-4 methylene group to the C-1 hydrogen in (6a) was unchanged at temperatures up to 130° as would be necessary if this twisting were to affect the product ratios. However such an interaction would appear to be contra-indicated by the results on the cyclopropyl compound (6d). Here one would anticipate an increased interaction due to the enhanced acidity of the hydrogens on the cyclopropane making an interaction with the double-bond electrons more likely, whereas a decreased percentage of *Z*-isomer (9d) is formed (Table 7). Further, the aryl-substituted cyclobutenes (6f—j) are not accommodated at all by this hypothesis as they have no hydrogens which can be suitably oriented to interact with the double bond.

The principle of least motion [26] has already been used to explain the conrotatory movement of the methylene groups in cyclobutene isomerisation.[27] Its application to the case of 3,3-disubstituted cyclobutenes would imply that during the stretching of the 3,4 bond the bulkier group would tend to lag behind and thus adopt a position more favourable for the formation of the *Z* isomer. However neither the deuterium isotope effect [(6e) *versus* (6k)], which should be inverse, nor the variation within the aryl-substituted series (Table 2) are accounted for, and nor is the absence of *cis*-penta-1,3-diene from (6; R = H).

Torsional strain has frequently been invoked in reactions where hybridisation changes from sp^3 to sp^2 (or *vice versa*) [28] and there is some evidence that it plays a role in cyclobutene isomerisation. Thus 1,3-dimethylcyclobutene has a lower energy of activation (by 1.6 kJ mol^{-1}) than the 1,4-dimethyl isomer. As has been pointed out, product formation requires the eclipsing of the methyl at C-3 against the hydrogen at C-2 for the former [shown in the Newman diagram (11; $R^1 = R^2 =$ H)], whereas for the latter, the interaction is the larger one of methyl against methyl (11; R^1 = Me, R^2 = H), accounting for the increase in activation energy.[29] Application to 3,3-disubstituted cyclobutenes (11; R^1 = H, R^2 = Et, Pr^i, *etc.*) would give a larger interaction between R^2 and R^1 than between R^1 and methyl, favouring the formation of *Z*-diene. However, this would suggest that (6a) should give a higher percentage of *Z*-butadiene than the other cyclobutenes, and the variation within the aryl compounds is left unexplained.

That the opening of the cyclobutene ring is subject to an electronic effect of the substituent is clear from the data on the phenyl compounds in Table 5, as well as from more qualitative evidence. Brauman and Archie [11a] have pointed out that substitution by a phenyl group at the 3-position stabilises the transition state by *ca.* 20 kJ mol^{-1} and have ascribed this stabilisation to delocalisation of electron density from the termini of the developing π-system onto the aromatic nucleus. Qualitatively our results on the substituted aromatic compounds (6f—j) (Table 6) would tend to confirm this hypothesis; thus as the acceptor properties of the aromatic substituent increases, the stabilisation and rate increase, and conversely a donor substituent decreases the rate. However, this is clearly too simple a picture, for a plot of log *k* against σ is markedly curved and although the use of σ$^+$ would improve the correlation, this would only be appropriate if the electron demand were inverse. Such curved Hammett plots and the absence of solvent effects [30] are typical of reactions where Frontier Orbital effects are important, such as the Diels–Alder reaction.[31] An FMO analysis of substituent effects on the cyclobutene–butadiene conversion shows that electron acceptors attached to the single bond which is breaking will depress the LUMO, thus increasing the stabilising $LUMO_{(single\ bond)}$–$HOMO_{(double\ bond)}$ interactions and similarly electron donors will also favour opening due to the increase in the $HOMO_{(single\ bond)}$–$LUMO_{(double\ bond)}$ interaction and a decrease in the corresponding HOMO–HOMO interaction. With phenyl, the acceptor properties are apparently the more important, for the rates correlate with the LUMO energies of the aromatic ring. The large drop in rate with the 4-methoxyphenyl compound (6g) is a consequence of the fact that anisole has a node at the 4-position in the LUMO and the NLUMO is considerably higher in energy. Qualitative evidence on other electron-accepting groups shows that they also accelerate the reaction; thus 3-benzoyl-1,2-dimethyl-4-methoxycarbonylcyclobutene isomerises at 110°,[10e] and 4-chlorocyclobut-2-enecarboxylic acid (12) at 60°.[10b] That electron-donating groups also increase the rate of ring opening is evident from the qualitative evidence of the ease of isomerisation of *trans*-3,4-dichlorocyclobutene,[10a] the fast isomerisation of 2-methylcyclobut-2-enol (13) at 110°,[8] and the rapid ring opening of 3-dimethylamino-1,2,3,4-tetramethylcyclobutene at 40°.[10d]

Where a conjugating substituent (*e.g.* vinyl, phenyl, carbonyl) is attached to C-3 such that on ring opening a six-centre, 6π electron Hückel system is formed as in (14) [equation (3)] then the aromatic character associated



(3)

(14)

with it will give rise to a drive towards the formation of the *Z*-diene, which is the only one where the ends are sufficiently close to allow overlap. Both donor and acceptor groups stabilise a Hückel orbital pattern and for an aryl substituent the largest interaction will occur

with the substituent group placed *para* to the breaking cyclobutene bond. That such an attractive interaction exists is supported by the fact that the difference in activation energy between *cis*- and *trans*-1,2,3,4-tetraphenylcyclobutene (Table 5) is only 16.7 kJ mol^{-1}, and that therefore the energy required to twist a phenyl group inwards is almost identical with that for a methyl group (15.8—19.0 kJ mol^{-1}), despite the marked difference in steric size.

The electronic effects which are relatively marked when a conjugating group is present will also be operative with alkyl substituents, which as electron donors will increase the rate of reaction of (6; R = H) relative to cyclobutene. However, due to the absence of π-orbitals, the stereochemistry will not be affected by this interaction. On the other hand, an analysis of the overlap independent contributions to the stereochemical preference shows that, for the bond polarity pattern shown in (15) and (16) the partial negative charge on Y will destabilise and repel the remote double bond more strongly in (16) than in (15). (All the other contributions are identical.) For alkyl groups, *ab initio* molecular orbital calculations on the σ-electron flow in monosubstituted benzenes gave the results shown in Table 8.[32]

TABLE 8

σ-Electron flow in substituted benzenes

Ph · · · H	Ph · · · Me	Ph · · · Et
←	←	←
0.063	0.007	0.013
Relative to hydrogen	→	→
	0.056	0.050

These show that, although the overall electron flow is towards the benzene ring, relative to hydrogen both methyl and ethyl are negatively charged (less positive), with ethyl less so than methyl. Similar conclusions may be drawn from the results of Hoffmann[33] on the electron distribution in propene, where the polarisation of the double bond may be considered as having arisen from a negative charge associated with the methyl group repelling the electronic charge to the remote end of the double bond. Applying these conclusions to the cyclobutene ring-opening would indicate that methyl should move outwards relative to hydrogen by more than the simple steric factor, and that methyl should move outwards relative to ethyl, the steric factor being nearly identical. Although no calculations have been done on the other alkyl substituents of Table 2, the normal σ* values of Taft[23] together with the solvolysis data on 4-alkyl[2.2.2]bicyclo-octan-1-yl *p*-bromobenzenesulphonates[34] show that electron donation increases in the order Me < Et < Pr^{i} < Bu^{t} and hence that the magnitude of the residual negative charge associated with the group is in the order Me > Et > Pr^{i} > Bu^{t}. Thus the repulsive interaction associated with (16) should decrease in this order, counterbalancing the increased steric interactions and so giving rise to the observed pattern of Table 7. Although no σ* value is available for cyclopropane, the type of bonding in it would point to its being more electron rich (and negative) than methyl in agreement with the observed greater percentage of *E*-isomer (10d).

This analysis would indicate that any electron-rich (negative) substituent Y at C-3 will preferentially form the *E*-diene (15), while an electron-poor (positive) one will not be averse to forming the *Z*-diene. The available data would bear out this contention. Thus *cis*-4-chlorocyclobut-2-enecarboxylic acid *cis*-(12) gives *Z*,*E*-4-chloropenta-2,4-dienoic acid[10b] with the negative chlorine rotating outwards and the carboxy group inwards, and the benzoylcyclobutenecarboxylate (17; R = Me) gives a 1 : 1 mixture of *Z*,*Z*-diene (18; R = Me) and *E*,*E*-diene (19; R = Me), while (17; R = H) gives a 1 : 9 mixture of the *Z*,*Z*- and *E*,*E*-dienes (18 and 19; R = H).[10c] Also 3-dimethylamino-1,2,3,4-tetramethylcyclobutene gives solely 2-dimethylamino-2,4-dimethylhexa-*E*-2,ζ-4-diene[10d,*] again with the negative group ending up away from the remote double bond.

Isotope Effect.—The pentadeuterioethylcyclobutene (6e) shows a lower proportion of *Z*-isomer (9e) than does the protio-analogue (6k). Assuming that the rate of formation of (10e) is the same as that for (3), a hypothesis in accord with our conclusion from the data in Table 5, then the isotope effect for the formation of (2) as compared with (9e), $k_{C_2H_5}/k_{C_2D_5} = 1.36 \pm 0.01$. While the direction of this effect would certainly fit with the proposal of Frey and Solly,[13] its magnitude is too small to lend any support to it, and indeed argues against it.

The exact origin of the isotope effect can not be ascribed without further work. Clearly it is not steric in origin, when one would expect it to be inverse,[35] and we suggest that it arises from the hyperconjugative interaction of the methylene group (of the ethyl) with the developing *p*-orbital on C-3 during the rehybridisation from sp^3 to sp^2. Its value (1.17 per deuterium) would then be typical of that observed for β-deuterium isotope effects in solvolytic reactions.[36]

Although we have confined our discussion to simple cyclobutenes, the conclusions are applicable also to annulated cyclobutenes (*e.g.* benzocyclobutenes) where attention has already been called to the exclusive outward rotation of oxygen functions,[37] while vinyl,[37] phenyl,[38,39] and carbonyl groups[39] may give either *Z*- or *E*-products. The effects of substituents on rate[37,38,40] are also in accord with our conclusions.

EXPERIMENTAL

General.—I.r. and u.v. spectra were recorded on Unicam SP 200 and 800 spectrometers. ^{1}H N.m.r. spectra were measured at 60 MHz on a Perkin-Elmer R12 and at 100 MHz on a Varian Associates HA100 spectrometer, with tetramethylsilane as internal reference. Mass spectra were measured on an AEI MS12 instrument. Analytical g.l.c. was carried out on a Perkin-Elmer F11 equipped with a

* Criegee[10d] does not assign a stereochemistry to this diene (nor to the starting cyclobutene), but the *E*-configuration at Δ^2 is clear from its ready isomerisation by 1,5-hydrogen shift at 210° to give 2-dimethylamino-3,4-dimethylhexa-2,4-diene.

flame ionisation detector. Peak areas were recorded using a Disc series 200 ball and disc integrator. Calibration factors were determined by standard techniques. Preparative g.l.c. was done on a Varian Aerograph A700 Autoprep, fitted with a thermal conductivity detector and using hydrogen as carrier gas. The columns used for g.l.c. were: column A, 2 m × 3 mm, 10% Carbowax 20M on Chromosorb W, and column F 2.5 m × 9 mm, 10% Carbowax 20M on Chromosorb W.

Details of the syntheses of the cyclobutene derivatives are given in Supplementary Publication No. SUP 22821 (13 pp.).*

Pyrolysis of the Cyclobutenes.—Pyrolysis were carried out in an ' aged ' glass gas pipette fitted with a Teflon Rotaflo valve and a B10 joint. A small quantity of sample was introduced into the vessel, using a 100 μl syringe, and then degassed by a freeze–pump–thaw–freeze cycle.

The vessel was immersed in an oil-bath at a suitable temperature for a known length of time (generally 180° for 1 h); it was then cooled quickly and the contents taken up in distilled n-pentane prior to g.l.c. analysis. Several g.l.c. columns and conditions were tried for each sample to ensure that maximum resolution was obtained, between the *Z*- and *E*-isomers for the alkyl compounds, and between the *Z*-diene and the cyclobutene in the aryl series. Pyrolyses were repeated to ensure reproducibility. Preliminary investigations were performed to ensure that the starting materials and products were stable under the g.l.c. conditions employed. The results are contained in Table 2.

Kinetic Runs.—A large thermostatted oil-bath (±0.05°) was used, and the time of the pyrolysis was recorded using a calibrated stop-clock. Samples were frozen in a −78° bath after pyrolysis to ensure rapid quenching of the reaction.

A plot of $\log_{10}$ (amount starting material remaining) against time gave a straight line at each temperature, from which the rate constant was obtained. Arrhenius parameters were obtained by standard least squares analysis.

[3,3,4,4,4-$^2H_5$]*Butan-2-one.*—[1,1,2,2,2-$^2H_5$]Ethyl bromide (7.30 g) was treated with magnesium (1.60 g) in dry ether to form the Grignard reagent. Acetaldehyde (2.90 g) was added slowly in dry ether, the mixture refluxed for 1 h, and then poured onto ice–water The precipitate was dissolved with dilute H_2SO_4 and the ethereal layer removed and dried ($MgSO_4$). After filtering, the solvent was removed at atmospheric pressure through a fractionating column and Perkin head. The product was purified by careful distillation, to give [3,3,4,4,4-$^2H_5$]butan-2-ol (4.15 g, 83%), b.p. 100°, $\nu_{max.}$ 3 620w, 3 340, 2 970, 2 870, 2 220, 2 080w, 1 340, 1 090, and 910 cm^{-1}; τ 6.40 (1 H, m, CHOH), 7.40br (1 H, s, OH), and 8.84 (3 H, d, *J* 6.0 Hz); *m/e* 79 (M^+).

[3,3,4,4,4-$^2H_5$]Butan-2-ol (4.15 g) was oxidised in acetone using Jones reagent. The mixture was stirred for 3 h, after which time g.l.c. analysis (column A; 80°) showed >95% conversion into the ketone. The product was extracted according to the normal Jones oxidation procedure and dried ($MgSO_4$). The solvent was removed using a fractionating column and Perkin head and the product was distilled through a Buchi fractionating column to give [3,3,4,4,4-$^2H_5$]butan-2-one (1.64 g, 40%), b.p. 80°; $\nu_{max.}$ 3 000, 2 240, 2 130, 2 080w, 1 710, 1 350, and 1 050 cm^{-1}; τ 7.90 (s); *m/e* 77 (M^+), 62, and 43.

* For details of Supplementary Publications see Notice to Authors No. 7 in *J.C.S. Perkin II*, Index issue.

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