Synthesis and Reactivity of Compounds with Cyclobutane Rings. Part III.[1] Cyclobut-1-ene-1,2-dicarboxylic Acid. *X*-Ray Crystal Structure and Exceptional Stereoselectivity in its Diels–Alder Reaction with Cyclopentadiene †

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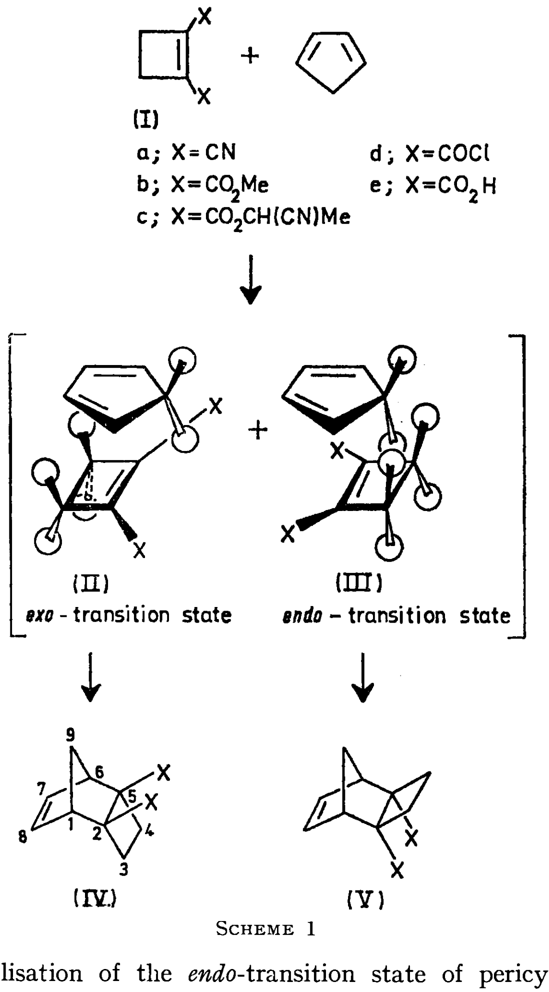
Cyclobut-1-enes with 1,2-dicyano, -bisalkoxycarbonyl, or -bischloroformyl groups react with cyclopentadiene to give predominantly [4 + 2] adducts with the electron-withdrawing groups in *exo*-positions regardless of their size. In contrast, the addition of cyclobut-1-ene-1,2-dicarboxylic acid (Ie) to cyclopentadiene yields predominantly (88 : 12) the *endo*-stereoisomer. This reversal of the stereochemical course is rationalised by the existence of an intramolecular hydrogen bond (2·625 ± 0·004 Å) in (Ie) and its influence on non-bonded interactions in the cycloaddition transition states. Compound (Ie) crystallises in the monoclinic space group *Cc* with lattice parameters $a = 5{\cdot}551 \pm 0{\cdot}002$, $b = 13{\cdot}541 \pm 0{\cdot}005$, $c = 8{\cdot}714 \pm 0{\cdot}003$ Å; $\beta = 98{\cdot}91 \pm 0{\cdot}03°$; $Z = 4$. The structure was solved by packing considerations and refined by least-squares calculations to *R* 0·041 for 975 reflections.

THE Alder rule of maximum accumulation of unsaturation,[2,3] rationalised by Woodward and Hoffmann [4] as a stabilisation of the *endo*-transition state of pericyclic $[_{\pi}4_s + {}_{\pi}2_s]$ cycloadditions (Diels–Alder reactions) by secondary orbital interactions, has proved to be of minor importance in determining the ratios of stereoisomers in Diels–Alder reactions of cyclic dienes with dienophiles containing an alkyl-substituted double bond. Due to the repulsive nonbonded interactions between the hydrogen atoms on the sp^3 hybridised carbon of cyclopentadiene and the hydrogen atoms on the alkyl groups of the dienophile in the *endo*-transition state, adducts with an electron-withdrawing group (*e.g.* CO_2R, CN, CHO) in the *exo*-position frequently prevail in products of these reactions.[5-7] Cyclobut-1-ene-1,2-dicarbonitrile (Ia), formally a 1,2-dialkyl-substituted dienophile, reacts quantitatively with cyclopentadiene to yield a 20 : 1 mixture of *exo*- (IVa) and *endo*-stereoisomers (Va).[1]



SCHEME 1

We wished to find a synthesis yielding a high proportion of *endo*-stereoisomers (V). In the case of (Ia), variations of temperature, solvent polarity, and catalysis with $AlCl_3$ did not change the *exo–endo*-stereoisomer distribution significantly.[1] In this paper, we present results of [4 + 2] cycloadditions of cyclopentadiene with some other electrophilic cyclobutenes (Ib—e). Only a slight rise in absolute yield of the *endo*-stereoisomer was achieved by changing solvent polarity in the case of (1b). The reaction with cyclobut-1-ene-1,2-dicarboxylic acid (1e), however, led to a complete reversal in the *endo–exo*-orientation and afforded the *endo*-stereoisomer (Ve) in 88% yield.

A three-dimensional *X*-ray crystal structure analysis of (Ie) established that the molecule is planar with a strong intramolecular hydrogen bridge. The preferred formation of *endo*-adducts is tentatively explained in terms of these findings.

RESULTS AND DISCUSSION

$[_{\pi}4_s + {}_{\pi}2_s]$ *Cycloadditions.*—To begin with, dimethyl cyclobut-1-ene-1,2-dicarboxylate (Ib) was allowed to react with an excess of cyclopentadiene in solvents of

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† Presented in part at the Third International Symposium on Synthesis in Organic Chemistry, Oxford, July 1973.

[1] Part II, D. Belluš, K. von Bredow, H. Sauter, and C. D. Weis, *Helv. Chim. Acta*, 1973, **56**, 3004.

[2] K. Alder and G. Stein, *Angew. Chem.*, 1937, **50**, 510.

[3] K. Alder, *Annalen*, 1951, **571**, 87.

[4] R. B. Woodward, and R. Hoffmann, *Angew. Chem. Internat. Edn.*, 1969, **8**, 781.

[5] J. A. Berson, Z. Hamlet, and W. A. Mueller, *J. Amer. Chem. Soc.*, 1962, **84**, 297.

[6] Y. Kobuke, T. Fueno, and J. Furukawa, *J. Amer. Chem. Soc.*, 1970, **92**, 6548.

[7] E. T. McBee, M. J. Keogh, R. P. Levek, and E. P. Wesseler, *J. Org. Chem.*, 1973, **38**, 632.

different polarity. The proportion of the *endo*-adduct (Vb) formed showed a clear tendency to increase with increasing solvent polarity. This trend is in accord with the observation [5] that a polar solvent favours the formation of *endo*-adducts. Berson [5] derived a linear relationship between the solvent polarity parameter Ω and differences in free energies of activation for *endo*- and *exo*-additions, which in turn are linearly related to the logarithms of ratios of *endo*–*exo*-stereoisomers, *i.e.* log(*endo*/*exo*). Figure 1 shows that the cycloadditions of (Ib) with cyclopentadiene obey this relationship.

However, even in methanol the absolute amount (7·1%) of *endo*-isomer (Vb) was of no practical use. Thus, in subsequent experiments, electrophilic cyclobutenes with various electron-withdrawing groups at C-1 and -2 of the cyclobutene were used in order to examine their controlling influence on the stereochemistry of [4 + 2] cycloadditions with cyclopentadiene.

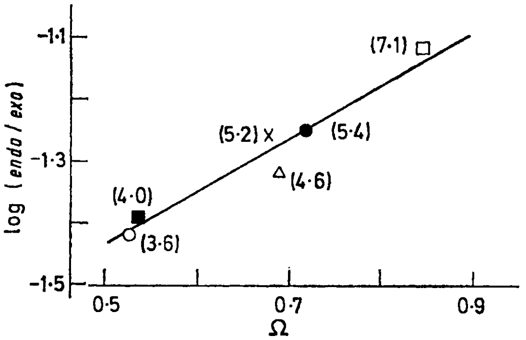

FIGURE 1 Cyclopentadiene–(Ib) adducts: *exo* : *endo* ratio *versus* solvent polarity (% *endo*-adduct in parentheses): ○ n-hexane; ■ 1,2-dimethoxyethane; △ acetonitrile; × nitromethane; ● ethanol; □ methanol

The average bond angle of the functional groups X is considerably larger (*ca.* 133°) than normally found for simple substituted double bonds. From the schematic illustration of the transition state (II) wherein the reactants lie in parallel planes, it is apparent that the cyclopentadiene out-of-plane hydrogen atom is easily inserted between the straight and narrow cyano-groups of (Ia) or between the methoxycarbonyl groups of (Ib) if both of them are in the *s-cis*-conformation. Thus, *exo*-adducts (IVa) and (IVb) are formed predominantly *via* the sterically less hindered *exo*-transition state (II). Nevertheless, the groups X are conformationally free and will hardly exist only in the *s-cis* conformation but will rotate around the single bond. For that reason it was hoped that with increasing size of the X groups their repulsive influence would compete with the repulsive influence of the cyclobutene methylene hydrogen atoms in their ability to control the steric approach to cyclopentadiene. The results for the series of cyclobutenes (Ia—d) (Table 1) showed, however, no evident relationship between the content of *endo*-isomer and size of the X groups.

The desired synthetic goal, *i.e.* high yields of *endo*-stereoisomer (V) was unexpectedly achieved by cycloaddition of cyclobut-1-ene-1,2-dicarboxylic acid (Ie) to cyclopentadiene. There was no precedent in the literature for such a complete reversal in the cycloaddition stereoselectivity of a carboxylic acid compared with that of the corresponding esters. For example, methyl methacrylate yielded on cycloaddition with cyclopentadiene at 25° 30·1% of the *endo*-isomer while methacrylic acid gave 29·2%,[6] s-butyl (*Z*)-crotonate 79·6% and (*Z*)-crotonic acid 83·7%,[6] ethyl (*E*)-4,4,4-trifluoromethylcrotonate 22·1% and (*E*)-4,4,4-trifluoromethylcrotonic acid 26·3%.[7] Hence, the preferred *endo*-addition of (Ie) could not be explained by some kind of specific electronic effect of the carboxy-groups operating in the transition state. Unfortunately, no cycloadditions of unsaturated (*Z*)-1,2-dicarboxylic acids with cyclopentadiene have hitherto been reported, thus not allowing a more pertinent comparison.

TABLE 1

Results of isomer distributions and product yields in the cycloaddition of electrophilic cyclobutenes (Ia—e) to cyclopentadiene (25 ± 0·4°; 1,2-dimethoxyethane; 24 h)

Cyclobutene	Overall yield of cycloadducts	Distribution of isomers (%) *	
		exo (IV)	*endo* (V)
(Ia)	100%	94	6
(Ib)	100%	96	4
(Ic)	100%	93·5	6·5
(Id)	100%	84·5	15·5
(Ie)	100%	12	88

* Average values of two parallel runs.

Cyclobut-1-ene-1,2-dicarboxylic acid (Ie) has been reported [8,9] to possess an extremely low first dissociation constant, $\mathrm{p}K_1$ 1·12, and a very high second dissociation constant, $\mathrm{p}K_2$ 7·63, due to a strong intramolecular hydrogen bond with a predicted O–H · · · O length of 2·61 Å. This last value is somewhat longer than the O–H · · · O distance of 2·45 Å quoted as an optimum distance for a strong intramolecular hydrogen bond in sp^2 unsaturated (*Z*)-1,2-dicarboxylic acids, thus enabling the hydrogen bond in (Ie) to lie in the plane of the molecule. It is now suggested that the high dienophilicity of (Ie) is a consequence of its molecular planarity, which allows maximum conjugation between the electronegative carboxy-group and the cyclobutene double bond.

Examination of Dreiding models of the possible *exo*-transition state (IIe) reveals that a considerable repulsive non-bonding interaction between the out-of-plane hydrogens of cyclopentadiene and the hydrogen atom involved in the intramolecular hydrogen bond can be assumed. The methylene hydrogens of cyclopentadiene can, in (IIe), no longer insert between the functional groups in the cyclobutene molecule as was possible with the cyano or even the ester groups. Furthermore, the fixation of one carboxy-group of (Ie) in the *s-trans*-conformation by the hydrogen bond

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[8] L. L. McCoy, *J. Amer. Chem. Soc.*, 1967, **89**, 1673.

[9] E. M. Eyring, L. D. Rich, L. L. McCoy, R. C. Graham, and N. Taylor, *Adv. Chem. Phys.*, 1971, **21**, 237.

provides unfavourable geometry for secondary orbital interactions between the lone electron pairs of the hydroxylic oxygen of this group and the π-electrons of cyclopentadiene in the *endo*-transition state (IIIe). In (IIIa—d), however, owing to the conformational freedom of the electron-withdrawing groups X as well as to the increased bond angles between X and the cyclobutene bond, the secondary orbital interaction may be assumed to be considerably less pronounced. As a consequence, the activation energy of *exo*-addition of (Ie) may become higher than that of *endo*-addition. The experimental results [88% of the *endo*-isomer (Ve)] support this explanation and underline the unique parallel action of both steric and electronic factors in the [4 + 2] cycloaddition of (Ie) with cyclopentadiene, thus distinguishing this diacid clearly from the electrophilic cyclobutenes (Ia—d).*

To obtain further evidence for the considerations outlined above concerning the structure and *endo*-directing ability of (Ie), the molecular structure of (Ie) was established by *X*-ray analysis.

Stereochemical Assignments.—Cycloadducts (IVa, d, and e) and (Va, d, and e) were identified by direct comparison with or by conversion into authentic samples (see Experimental section). Unequivocal structural proof for the new cycloadducts (IVb) and (IVc) is furnished by their alkaline hydrolysis to the dicarboxylic acid (IVe), which was identical (m.p., i.r., n.m.r.) with an authentic sample of (IVe).[1] As judged by n.m.r., there was no *exo–endo*-isomerisation as a result of hydrolysis.

TABLE 2

(a) Fractional atomic co-ordinates ($\times 10^5$) and their estimated standard deviations in parentheses

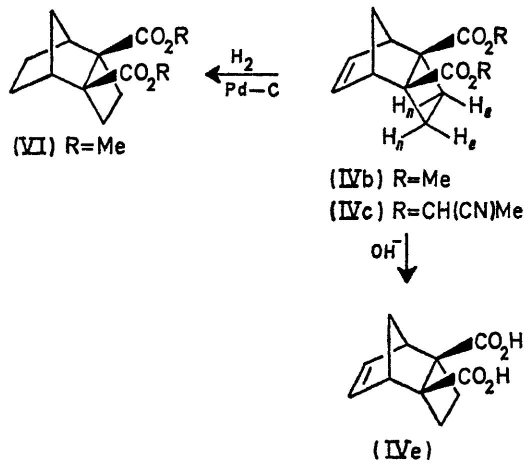
Atom	*x*/*a*	*y*/*b*	*z*/*c*	Atom	*x*/*a*	*y*/*b*	*z*/*c*
O(1)	19099(33)	54006(10)	17037(20)	C(5)	22568(48)	44690(15)	14133(34)
O(2)	38274(39)	42163(12)	6516(29)	C(6)	−21714(43)	46153(15)	36084(33)
O(3)	−15343(33)	54688(10)	34535(20)	H[O(1)]	08000(450)	54660(170)	22380(290)
O(4)	−38877(39)	43490(14)	44182(30)	H[O(4)	−44920(410)	48240(160)	47870(260)
C(1)	6935(44)	37241(14)	20042(33)	H(31)	−31860(640)	25170(240)	21410(390)
C(2)	−10909(42)	37784(13)	28938(35)	H(32)	−11860(470)	23540(230)	37770(340)
C(3)	−15897(66)	26806(17)	28150(47)	H(41)	−50(470)	24460(200)	6770(340)
C(4)	4848(61)	26229(16)	17849(48)	H(42)	20070(540)	22840(250)	22470(380

(b) Thermal parameters ($\times 10^5$) and their estimated standard deviations in parentheses

Atom	b_{11}	b_{22}	b_{33}	b_{12}	b_{23}	b_{31}	Atom	*B*/Å
O(1)	3810(60)	366(9)	1671(31)	−433(36)	−76(24)	2650(60)	H[O(1)]	2·7(6)
O(2)	3090(50)	604(10)	1333(26)	−92(35)	16(25)	2250(60)	H[O(4)]	1·6(5)
O(3)	3370(60)	403(9)	1403(27)	43(32)	−89(21)	1830(60)	H(31)	6·9(9)
O(4)	3330(50)	507(9)	1432(28)	164(32)	−69(23)	2720(60)	H(32)	4·2(7)
C(1)	2750(60)	337(10)	1135(31)	57(38)	96(27)	1670(70)	H(41)	4·4(7)
C(2)	2720(60)	340(10)	1145(30)	34(38)	141(28)	1540(70)	H(42)	5·6(9)
C(3)	5220(120)	381(12)	2505(53)	−125(57)	132(42)	4730(140)		
C(4)	5370(110)	366(12)	2678(57)	98(62)	155(42)	4870(130)		
C(5)	2560(60)	427(10)	928(29)	−158(42)	16(27)	990(60)		
C(6)	2250(60)	519(14)	877(28)	176(42)	−50(30)	1130(70)		

The anisotropic temperature factor is defined by $B = \exp -(h^2b_{11} + k^2b_{22} + l^2b_{33} + hkb_{12} + klb_{23} + lhb_{31})$.

The n.m.r. spectra of this stereoisomeric pair agree perfectly with the assignment. The *endo*-hydrogens 3-H$_n$ and 4-H$_n$ are shifted upfield due to the shielding effect of the double bond and appear at δ 1·34 in (IVb) and at 1·38 in (IVc). The difference $\Delta\delta$ between chemical shifts of AA′BB′ multiplets of 3(4)-H$_n$ and 3(4)-H$_e$ is higher in the *exo*-stereoisomers [0·97 for (IVb) and 0·93 p.p.m. for (IVc)] than in the *endo*-isomers [0·77 for (Vb) and 0·75 p.p.m. for (Vc)]. More importantly, hydrogenation of the double bond in (IVb) brings about a large downfield shift of 0·70 p.p.m. for 3(4)-H$_n$ while the 3(4)-H$_e$ protons were *de facto* unaffected (Δ −0·02 p.p.m.). All these facts are known as characteristic features of n.m.r. spectra of related tricyclo[4.2.1.0^{2,5}]non-7-enes.[1] The *endo*-structures were assigned to by-products (Vb and c).



SCHEME 2

*Crystal Structure Determination of Cyclobut-*1-*ene*-1,2-*dicarboxylic Acid* (Ie).—Crystallographic details and discussion of the solution of the crystal structure are contained in the Experimental section. The structure was refined to *R* 0·041 including hydrogen atoms.

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* From both steric and electronic considerations one would expect the anhydride of (Ie) to exhibit even more pronounced *endo*-stereoselectivity on reaction with cyclopentadiene. However, our attempts, as well as those reported in the literature (*cf.* F. B. Kipping and J. J. Wren, *J. Chem. Soc.*, 1957, 1733), to prepare the anhydride failed. Apparently, cyclisation to the anhydride and formation of the highly strained 3-oxabicyclo-[3.2.0]hept-1(5)-ene ring system are prevented by the large bond angles C(1)-C(2)-C(6) and C(2)-C(1)-C(5) in (Ie) (Figure 2).

Final atomic co-ordinates and thermal parameters with their standard deviation are given in Table 2. Bond lengths and angles are shown in Tables 3 and 4, and torsion angles in Table 5. The molecular structure is illustrated in Figure 2. The drawing plane is approximately parallel to the crystallographic (102) plane with the *b* axis vertical. The two molecules shown are part of an infinite chain of molecules related by a glide plane and linked by intramolecular hydrogen bonds O(4)–H(O4) · · · O(2′) 2·638 ± 0·003 Å long. It is evident from the bond lengths and angles in Figure 2 that the geometry is very favourable both for intermolecular and intramolecular hydrogen bonds. The latter, O(1)–H(O1) · · · O(3), is 2·625 ± 0·004 Å long and nearly linear.

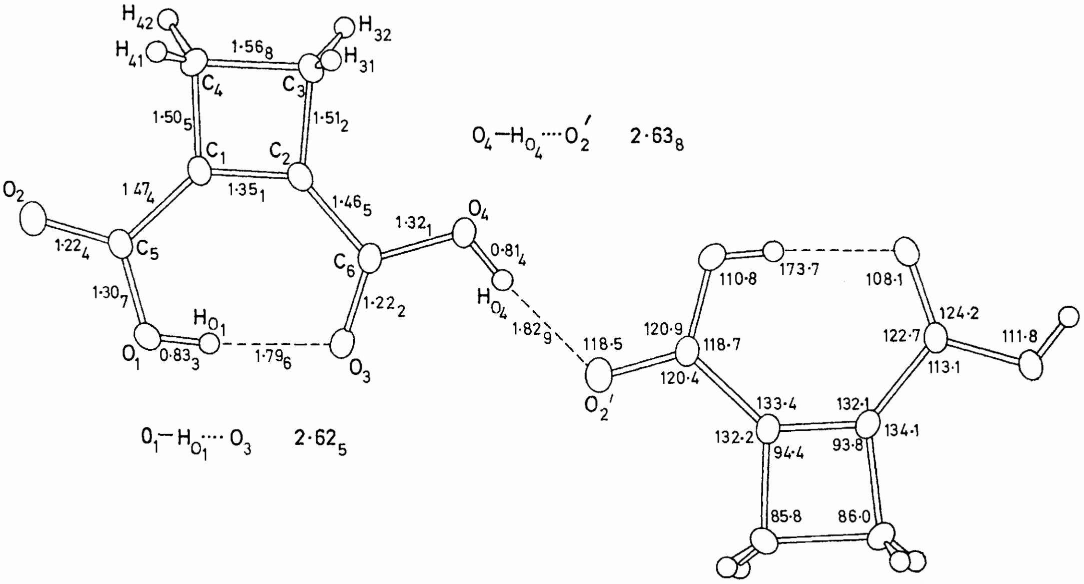

FIGURE 2 Cyclobut-1-ene-1,2-dicarboxylic acid: atomic numbering scheme, bond lengths (Å) and angles (°)

TABLE 3

Bond lengths (Å) and their estimated standard deviations in parentheses

C(5)–O(1)	1·307(3)	C(6)–O(4)	1·321(3)
C(5)–O(2)	1·224(4)	C(6)–O(3)	1·222(3)
C(1)–C(5)	1·474(3)	C(2)–C(6)	1·465(3)
C(1)–C(4)	1·505(3)	C(2)–C(3)	1·512(3)
C(1)–C(2)	1·351(4)	C(3)–C(4)	1·568(5)
O(1)–H[O(1)]	0·833(25)	O(4)–H[O(4)]	0·814(22)
C(4)–H(41)	0·991(35)	C(3)–H(31)	1·009(28)
C(4)–H(42)	0·991(29)	C(3)–H(32)	0·944(33)
H[O(1)] · · · O(3)	1·796(25)	H[O(4)] · · · O(2′)	1·829(22)
O(1) O(3)	2·625(4)	O(4) O(2′)	2·638(3)

TABLE 4

Angles (°) and their estimated standard deviations in parentheses

C(5)–O(1)–H[O(1)]	110·8(16)	C(6)–O(4)–H[O(4)]	111·8(16)
C(4)–C(1)–C(5)	132·2(3)	C(3)–C(2)–C(6)	134·1(3)
C(4)–C(1)–C(2)	94·4(2)	C(3)–C(2)–C(1)	93·8(2)
C(5)–C(1)–C(2)	133·4(2)	C(1)–C(2)–C(6)	132·1(2)
C(1)–C(4)–C(3)	85·8(2)	C(2)–C(3)–C(4)	86·0(2)
C(1)–C(4)–H(41)	111·6(18)	C(2)–C(3)–H(31)	112·4(16)
C(1)–C(4)–H(42)	111·3(20)	C(2)–C(3)–H(32)	113·9(21)
C(3)–C(4)–H(41)	117·1(15)	C(4)–C(3)–H(31)	108·2(17)
C(3)–C(4)–H(42)	116·5(20)	C(4)–C(3)–H(32)	113·0(19)
H(41)–C(4)–H(42)	111·8(25)	H(31)–C(3)–H(32)	118·7(25)
O(1)–C(5)–O(2)	120·9(2)	O(3)–C(6)–O(4)	124·2(2)
O(1)–C(5)–C(1)	118·7(2)	O(4)–C(6)–C(2)	113·1(2)
O(2)–C(5)–C(1)	120·4(2)	O(3)–C(6)–C(2)	122·7(2)
O(1)–H[O(1)]–O(3)	174(3)	O(4)–H[O(4)]–O(2′)	173(3)

The four-membered ring, C(1)—(4), is planar with all torsion angles smaller than ±0·1°. Its geometry may be compared with that of the highly symmetric planar cyclobutene molecule, C(1)–C(2) 1·342, C(2)–C(3) 1·517, C(3)–C(4) 1·566, C(3)–H 1·094 Å, C(1)–C(2)–C(3) 94·2°, determined by microwave spectroscopy.[10] The differences are small and not significant. Figure 3 shows selected torsion angles and distances of atoms from the best plane through all non-hydrogen atoms in one

TABLE 5

Torsion angles (°)

C(2)–C(6)–O(4)–H[O(4)]	178	C(1)–C(5)–O(1)–H[O(1)]	−1
O(3)–C(6)–O(4)–H[O(4)]	−1	O(2)–C(5)–O(1)–H[O(1)]	179
C(1)–C(2)–C(6)–O(3)	−1	C(2)–C(1)–C(5)–O(1)	3
C(1)–C(2)–C(6)–O(4)	179	C(2)–C(1)–C(5)–O(2)	−178
C(3)–C(2)–C(6)–O(3)	176	C(4)–C(1)–C(5)–O(1)	−175
C(3)–C(2)–C(6)–O(4)	−4	C(4)–C(1)–C(5)–O(2)	4
C(6)–C(2)–C(3)–C(4)	−178	C(5)–C(1)–C(4)–C(3)	179
C(6)–C(2)–C(3)–H(31)	−70	C(5)–C(1)–C(4)–H(41)	61
C(6)–C(2)–C(3)–H(32)	69	C(5)–C(1)–C(4)–H(42)	−65
C(1)–C(2)–C(3)–C(4)	0	C(2)–C(1)–C(4)–C(3)	0
C(1)–C(2)–C(3)–H(31)	108	C(2)–C(1)–C(4)–H(41)	−118
C(1)–C(2)–C(3)–H(32)	−113	C(2)–C(1)–C(4)–H(42)	117
C(1)–C(4)–C(3)–C(2)	0	C(4)–C(1)–C(2)–C(3)	0
C(1)–C(4)–C(3)–H(31)	−112	C(4)–C(1)–C(2)–C(6)	178
C(1)–C(4)–C(3)–H(32)	114	C(5)–C(1)–C(2)–C(3)	−179
H(41)–C(4)–C(3)–C(2)	112	C(5)–C(1)–C(2)–C(6)	−1
H(41)–C(4)–C(3)–H(31)	0		
H(41)–C(4)–C(3)–H(32)	−134		
H(42)–C(4)–C(3)–C(2)	−112		
H(42)–C(4)–C(3)–H(31)	136		
H(42)–C(4)–C(3)–H(32)	3		

[10] B. Bak, J. J. Led, L. Nygaard, J. Rastrup-Andersen, and G. O. Sørensen, *J. Mol. Structure*, 1969, **3**, 369.

molecule. Equation (1) describes the plane in crystal co-ordinates.

$$-3{\cdot}0908x + 1{\cdot}4852y - 6{\cdot}3369z + 0{\cdot}9024 = 0 \quad (1)$$

The molecule as a whole is significantly non-planar. The two carboxy carbon atoms are displaced 0·029 [C(5)] and 0·037 Å [C(6)] to the same side of the cyclobutene ring. The carboxy-groups are twisted in a disrotatory sense, 4° around C(1)–C(5) and 2·7° in the other direction around C(2)–C(6). The resultant distances from the cyclobutene ring plane are 0·125 for O(1) and 0·096 Å for O(3). The length of the intramolecular hydrogen bond is obviously not affected by a small disrotatory displacement of this type. We feel that the deviations of the molecular shape from planarity, statistically significant in the crystal structure, are probably caused by non-bonded interactions resulting from the molecular packing in the crystal.

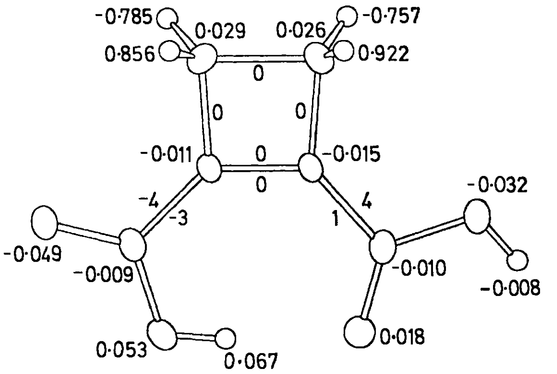

FIGURE 3 Cyclobut-1-ene-1,2-dicarboxylic acid: selected torsion angles (°) and distances (Å) from the best plane through the ten non-hydrogen atoms. The molecule in the drawing is the mirror-image of the reference molecule described in Tables 2—5

In solution we would expect to find a planar average structure stabilised by the intramolecular hydrogen bond. This view is supported by the very high second dissociation constant, pK_2 7·63.[8] The ability of the molecule to adopt the slightly non-planar shape found in the crystal may be of advantage in the initial approach of the cyclopentadiene molecule to the π electrons of (1e).

EXPERIMENTAL

N.m.r. spectra were determined using a Varian HA 100 spectrometer. Compounds (Ia, b, d, and e) were prepared as described.[1]

Bis-1-*cyanoethyl Cyclobutene*-1,2-*dicarboxylate* (Ic).—To a cold (0°) solution of (Id) (8·9 g, 50 mmol) in benzene (100 ml) a solution of freshly distilled 1-cyanoethanol (7·1 g, 0·1 mol) and triethylamine (10·1 g, 0·1 mol) in benzene (100 ml) was added. Removal of the solid ammonium salt and evaporation of the benzene under reduced pressure afforded an oil, distillation of which at 110° and 10^{-3} mmHg yielded the *ester* (Ic) (11·0 g, 93%) (Found: C, 57·8; H, 5·0; N, 11·4. $C_{12}H_{12}N_2O_4$ requires C, 58·0; H, 4·9; N, 11·3%), $\nu_{max.}$ ($CHCl_3$) 1742, 1645, 1280, 1123, and 1096 cm^{-1}, $\lambda_{max.}$ (MeOH) 232 nm (log ε 3·96), δ ($CDCl_3$) 1·72 (6H, d, *J* 7 Hz, 2 × CH_3), 2·79 (4H, s, CH_2CH_2), and 5·50 (2H, q, *J* 7 Hz, 2 × OCH).

exo- *and* endo-*Dimethyl Tricyclo*[4.2.1.$0^{2,5}$]*non*-7-*ene*-2,5-*dicarboxylates* (IVb) *and* (Vb).—A solution of compound (Ib) (6·05 g, 35·6 mmol) in freshly distilled cyclopentadiene (120 ml) and 1,2-dimethoxyethane (300 ml) was stirred for 24 h until all the starting material had reacted as judged by t.l.c. The solvent was evaporated and the crude mixture of stereoisomers (IVb) and (Vb) was chromatographed on silica gel (800 g). Elution with benzene–ethyl acetate (9 : 1) gave three fractions. Fraction (a) consisted of the pure exo-*stereoisomer* (IVb) (5·6 g, 66·5%) as an oil, b.p. 90—93° at 5 × 10^{-2} mmHg, which crystallised from hexane at −70° as needles, m.p. 46·5—47°, R_F 0·73 (Found: C, 66·0; H, 6·8. $C_{13}H_{16}O_4$ requires C, 66·1; H, 6·8%), $\nu_{max.}$ ($CHCl_3$) 1727, 1430, 1333, 1284, 1250, 1144, 1115, and 712 cm^{-1}; δ [$(CD_3)_2CO$] 1·34 (2H, m, 3-H_{endo} and 4-H_{endo}), 1·59 and 2·01 (2H, 2 × m, 9-H_2), 2·31 (2H, m, 3-H_{exo} and 4-H_{exo}), 3·04 (2H, m, 1- and 6-H), 3·64 (6H, s, 2 × OCH_3), 6·54 (2H, t, *J* 2 Hz, 7- and 8-H). Fraction (b) was a mixture of (IVb) and (Vb) (2·43 g, 28%). Fraction (c) consisted of the *endo*-isomer (Vb) (0·14 g, 1·7%) as an oil, R_F 0·67. The crude diester was purified by preparative g.l.c. (15% Carbowax 20 M; 10 ft × 1/4 in; 210°). The *diester* had M^+ 236 ($C_{13}H_{16}O_4$ requires *M*, 236), $\nu_{max.}$ ($CHCl_3$) 1727, 1432, 1286, 1252, 1244, 1119, and 700 cm^{-1}, δ [$(CD_3)CO$] 1·41 and 2·04 (2H, 2 × m, 9-CH_2), 1·75 (2H, m, 3- and 4-H *syn* to 9-CH_2 by analogy with similar derivatives[1]), 2·52 (2H, m, 3- and 4-H *cis* to esters), 2·84 (2H, m, 1- and 6-H), 3·56 (6H, s, 2 × CH_3), and 6·10br (2H, s, 7- and 8-H).

exo- *and* endo-*Bis*-1-*cyanoethyl Tricyclo*[4.2.1.$0^{2,5}$]*non*-7-*ene*-2,5-*dicarboxylates* (IVc) *and* (Vc).—These stereoisomers were prepared in the same way as (IVb) and (Vb). After chromatographic isolation, the fraction with R_F 0·70 contained (IVc), an *oil*, M^+ 314 ($C_{17}H_{18}N_2O_4$ requires *M*, 314), δ [$(CD_3)_2CO$] 1·38 (2H, m, 3- and 4-H_{endo}), 2·31 (2H, m, 3- and 4-H_{exo}), 3·08 (2H, m, 1- and 6-H), and 6·44 (2H, ' t,' 7- and 8-H) and the fraction with R_F 0·63 contained (Vc), an *oil*, M^+ 314, δ [$(CD_3)_2CO$] 1·80 (2H, m, 3- and 4-H_{endo}), 2·55 (2H, m, 3- and 4-H_{exo}), 2·92 (2H, m, 1- and 6-H), and 6·11 (2H, m, 7- and 8-H).

exo-*Tricyclo*[4.2.1.$0^{2,5}$]*non*-7-*ene*-2,5-*dicarboxylic Acid* (IVe).—Compound (IVb) (1 g) in one experiment and (IVc) (1 g) in another were hydrolysed for 6 h at room temperature with an excess of methanolic potassium hydroxide. After addition of water (20 ml), methanol was evaporated and diacid (IVe) was precipitated with 1N-hydrochloric acid to pH 5. In both experiments, the yield of (IVe) was quantitative, m.p. 237—238°; the i.r. and n.m.r. spectra were superimposable on those of an authentic sample, m.p. 236—238°.[1]

exo-*Dimethyl Tricyclo*[4.2.1.$0^{2,5}$]*nonane*-2,5-*dicarboxylate* (VI).—Hydrogenation of (IVb) (0·7 g) over 5% Pd–C (0·1 g) in methanol (30 ml) afforded a quantitative yield of *diester* (VI) as an oil, b.p. 92—96° at 3 × 10^{-3} mmHg (Found: C, 65·3; H, 7·6. $C_{13}H_{18}O_4$ requires C, 65·5; H, 7·6%), $\nu_{max.}$ ($CHCl_3$) 1728, 1430, 1268, 1141, 1123, 1052, 1000, and 924 cm^{-1}, δ [$(CD_3)_2CO$] 1·35—2·1 and 2·4—2·6 (8H, m), 2·14 (2H, m, 3- and 4-H_{endo}), and 2·29 (2H, m, 3- and 4-H_{exo}).

Cycloaddition of Dimethyl Cyclobut-1-*ene*-1,2-*dicarboxylate* (Ib) *with Cyclopentadiene in Various Solvents*.—Diester (Ib) (0·1 g) was stirred for 24 h with cyclopentadiene (2 ml) and solvent (30 ml) at 25° in a constant temperature bath. After this time, no (Ib) was present in any solvent. Direct analysis of the reaction mixture by g.l.c. (see below) indicated 3·6% of the *endo*-isomer (Vb) in n-hexane, 4·0%

in 1,2-dimethoxyethane, 4·6% in acetonitrile, 5·2% in nitromethane, 5·4% in ethanol, and 7·1% in methanol, each value being an average of two runs (Figure 1).

Comparative Cycloadditions of Cyclobutenes (Ia—e) *with Cyclopentadiene in* 1,2-*Dimethoxyethane.—General procedure.* Freshly distilled cyclopentadiene (10 ml) was added to a stirred solution of each cyclobutene (10 mmol) in 1,2-dimethoxyethane (30 ml; dried over molecular sieve 4 A) and allowed to react for 24 h at 25 ± 0·4°. Two parallel experiments were always run. After this time, no cyclobutene was present in any case (t.l.c. or i.r.). The *exo–endo*-stereoisomeric distribution was then determined. Results are given in Table 1.

Quantitative analyses of cycloadducts. (IVa) and (Va). After evaporation of solvent and the excess of cyclopentadiene, the stereoisomeric content in the crystalline residue were determined by means of n.m.r. in $CDCl_3$. Integrated intensities of well separated multiplets at δ 3·34 and 6·48 for (IVa) and at 3·16 and 6·36 for (Va) were used.

(IVb) and (Vb). These were determined directly in the reaction solution by g.l.c. A 10 ft × 1/4 in stainless steel column with 3% Carbowax 20 M on 80—100 Varaport 30 at 205° with helium as carrier gas was used. The retention time of (Vb) was 3·2 min, of (IVb) 3·9 min.

(IVc) and (Vc). After evaporation of solvent and the excess of cyclopentadiene the distribution of stereoisomers in the oily residue was determined by means of quantitative n.m.r. Integrals of multiplets at δ 3·08 and 6·44 for (IVc) and at 2·92 and 6·11 for (Vc) were used.

(IVd) and (Vd). A solution of triethylamine (2·1 g, 21 mmol) in dry methanol (10 ml) was added to the reaction mixture in order to convert the primary cycloadducts (IVd) and (Vd) quantitatively into the methyl esters (IVb) and (Vb).

(IVe) and (Ve). The excess of cyclopentadiene was evaporated, acetic anhydride (15 ml) was added, and the solution was heated at 80° for 2·5 h in order to convert the primary cycloadducts (IVe) and (Ve) quantitatively into their anhydrides. After cooling, the crude mixtures were analysed for anhydride content by means of g.l.c. under the same conditions as for (IVb) and (Vb). The retention time of the anhydride of (IVe) was 5·6 min, of that of (Ve) was 6·7 min. Authentic anhydrides were prepared in a different way.[1]

Crystal Structure Determination.—Acicular crystals of cyclobut-1-ene-1,2-dicarboxylic acid (Ie) were grown from acetonitrile solution. Preliminary unit cell and space group data were determined from Weissenberg and precession photographs taken with Cu-K_α radiation; cell constants were refined by least-squares methods from 2θ values for 10 reflections measured on a diffractometer with Mo-K_α radiation.

Crystal data. $C_6H_6O_4$, M = 142·11. Monoclinic, a = 5·551(2), b = 13·541(5), c = 8·714(3) Å, β = 98·91(3)°, U = 647·1 Å^3, Z = 4, D_c = 1·46 g cm^{-3}, $F(000)$ = 296. Mo-K_α radiation, λ = 0·71069 Å, μ(Mo-K_α) = 1·5 cm^{-1}. Space group Cc (#9) [11] from systematic absences, intensity statistics, and structure analysis.

Crystallographic measurements. A Picker-FACS-I automatic diffractometer was used for data collection with Mo-K_α radiation and a graphite monochromator. The intensities of 1396 independent reflections with $\theta \leqslant 35^\circ$ were measured by a continuous θ—2θ scan with background counts at the extrema; the 977 reflections with $I \geqslant 2\sigma(I)$ were considered observed. Data reduction included correction for Lorentz and polarisation factors, but not for absorption.*

Structure analysis. Structure analysis was not entirely straightforward because of difficulties due to the space group ambiguity. The systematic absences $(hkl): h + k = 2n$, $(h0l): l = 2n$, are compatible with both the centrosymmetric space group $C2/c$ (#15) and the non-centrosymmetric space group Cc (#9).[11] E Value statistics [12] ($\langle E\rangle$ = 0·854, $\langle E^2 - 1\rangle$ = 0·828, $\langle E^2\rangle$ = 1·000) imply an acentric electron density distribution with an appreciable degree of centricity. This implication was, however, ignored and the analysis attempted in the centrosymmetric space group.

Packing considerations and the symmetry requirements of space group $C2/c$ with $Z = 4$ were used to place a model of molecular symmetry C_2 in the $h0l$ projection. The orientation of the model was confirmed from a Patterson synthesis. A trial and error procedure was used to find a set of y-co-ordinates; the model was shifted along b and the $R\,(= \Sigma||F_o| - |F_c||/\Sigma|F_o|)$ index was plotted as a function of the shifts. The model corresponding to the lowest R index (0·30) was refined by block diagonal least-squares. Refinement with anisotropic temperature parameters in space group $C2/c$ converged at R 0·142. The high value of R and an odd molecular geometry indicated some severe error in the model.

It appeared obvious that the error was due to a wrong choice of space group. The non-centrosymmetric space group Cc with only four general positions requires no molecular symmetry with $Z = 4$. Our model in space group $C2/c$ with molecular symmetry C_2, on the other hand, consisted of only one half of the molecule. The parameter set was therefore expanded over the questionable two-fold axis and refinement of the expanded model in space group Cc by block diagonal least-squares was attempted. No improvement in either R or the sum of weighted residual squares was achieved. The reason is that the centre of symmetry had not been removed from the model. Ermer and Dunitz have discussed this type of problem.[13]

Inspection of a list of observed and calculated structure factors and application of a criterion recommended by Dunitz [14] proved the absence of a centre of symmetry. The ' symmetry deadlock ' was then broken by arbitrarily increasing the y-co-ordinates of one half of the molecule and refining with isotropic temperature factors. As an additional precaution full-matrix, rather than block diagonal, least-squares were used in order to avoid problems from correlation between the pseudo-symmetric halves of the molecule.

Thereafter, refinement proceeded smoothly. After the introduction of anisotropic thermal parameters the hydrogen atoms were located from a difference Fourier synthesis and included in the refinement with isotropic thermal parameters. The x- and z-co-ordinates of one atom [O(1)] were held constant. The final full-matrix, least-squares cycle refined positional and anisotropic thermal parameters for the ten heavy atoms, positional and isotropic thermal

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* All calculations were performed on an IBM/370–155 computer using our own program system (H.-C. M. and G. R.).

[11] ' International Tables for X-Ray Crystallography,' Kynoch Press, Birmingham, 1952, vol. I.

[12] I. L. Karle, K. S. Dragonette, and S. A. Brenner, *Acta Cryst.*, 1965, **19**, 713.

[13] O. Ermer, and J. D. Dunitz, *Acta Cryst.*, 1970, **A26**, 163.

[14] J. D. Dunitz, personal communication.

parameters for the six hydrogen atoms, and a scale factor. No parameter shift was larger than half the estimated standard deviation obtained by matrix inversion. The quantity refined was $\Sigma w^*(|F_o| - |F_c|)^2$ with weights $w = 1/\sigma(F_o)$ based on counting statistics. The 419 unobserved reflections and two reflections most severely affected by extinction (112) and (020) were given zero weight.

Final values of the R index are 0·0411 for the 975 observed reflections, 0·0606 for all 1394 reflections measured [excluding (112) and (020)], and 0·0347 for the 878 most reliable ones with $F_o \geqslant 2\sigma(F_o)$.*

A list of the observed and calculated structure factors is given in Supplementary Publication SUP No. 20974 (7 pp.).†

We thank Professor J. D. Dunitz for suggestions on crystallographic problems, Dr. H. Sauter for help with n.m.r. problems, and Dr. C. D. Weis for discussions on chemical topics.

[3/2551 *Received*, 14*th December*, 1973]

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* Estimated values of F_{obs} for the unobserved reflections were computed from counting statistics by the data-reduction routine.

† For details of Supplementary Publications see Notice to Authors No. 7 in *J.C.S. Perkin II*, 1973, Index issue.