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STERIC EFFECTS VS SECONDARY ORBITAL INTERACTIONS IN NITRONE CYCLOADDITIONS. STERIC EFFECTS IN CYCLOREVERSIONS OF ISOXAZOLIDINES.

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Abstract - 3,4-Dihydroisoquinoline-N-oxide 1 reacted readily with both acyclic (Z)- and (E)-disubstituted alkenes bearing electron-attracting substituents (methoxycarbonyl, cyano, phenylsulphonyl and benzoyl groups) and with cyclic derivatives (e.g. maleimides) to give mixtures of the two possible diastereoisomers. Similar amounts of endo- and exo-adducts were formed in the reactions of (Z)-cyano, methoxycarbonyl and benzoyl derivatives whereas exo-addition clearly won over its endo-counterpart in the case of (Z)-(phenylsulphonyl) and cyclic derivatives. High exo-selectivity was also observed in the sluggish reactions of 1 with electron-rich alkenes [(Z)-stilbene, vinylene carbonate, acenaphthylene etc.].

Our results, which revise previous literature data, clearly show that an "endo-rule" does not hold for the reactions of 1 with (Z)-1,2-disubstituted alkenes. We conclude that in these reactions repulsive steric interactions either counteract efficiently or clearly win over stabilizing secondary orbital overlaps in controlling endo/exo-selectivity.
These reactions were found reversible under mild conditions so that relative formation rates of related pairs of (Z)- and (E)-dipolarophiles in cycloreversion processes of isoxazolidines could be determined; as a rule (E)-alkenes are extruded faster than (Z)-isomers. These results provide unambiguous experimental evidence that increase in steric compression between the substituents in (Z)-alkenes, on their way toward transition state, is not a major factor in determining their lower reactivity with respect to (E)-isomers in 1,3-dipolar cycloadditions.

INTRODUCTION

Notwithstanding several recent studies the problem of endo/exo-selectivity in 1,3-dipolar cycloadditions is far from being definitively assessed.[1] For example one can ask whether or not endo-transition states are favoured over their exo-counterparts in nitrone cycloadditions.[2] Grée and Carrié gave a definitive answer to this question in the case of (E)- and (Z)-N-alkoxy-C-cyano and-N-alkoxy-C-methoxycarbonylnitrones by showing that these 1,3-dipoles prefer to approach (Z)-1,2-disubstituted alkenes (dimethyl maleate, maleimides, maleic anhydride) with an endo-orientation.[3] However in the case of N-alkyl and N-aryl nitrones (cyclic and acyclic) this problem is still a matter of debate.[4-7] Indeed the reactions of acyclic (Z)-nitrones with maleimides and dimethyl maleate apparently exhibit a definite endo-selectivity[8,9] but the possibility of E/Z[2,10] isomerization concomitant with cycloaddition shadows the link between the geometry of the transition state and the stereochemical outcome of the reaction. Very recently

Tufariello and Puglis reported a clear-cut example of dominant exo-addition in the reaction of 1-pyrroline-N-oxide with 1-phenyl butadiene[4,11] and pointed out that cyclic nitrones, incapable of E/Z isomerization, lend themselves as better substrates to investigate the phenomenon of endo/exo-selectivity in nitrone cycloadditions.

Taking into account the above cited results we reasoned that the best way to attack this problem was to study the reaction of cyclic nitrones with electron-deficient dipolarophiles. A research in this field had necessarily to start from a report by Huisgen and coll. who disclosed possible examples of endo-specificity and endo-selectivity in the reaction of 3,4-dihydroisoquinoline-N-oxide 1 with N-phenylmaleimide (or with maleic anhydride, 100% endo-addition for both dipolarophiles) and dimethyl maleate (dominant endo-attack). Moreover the reaction of the same nitrone with dimethyl fumarate was described as diastereospecific to give quantitative yields of isolated adduct 2.[12] As the authors did not claim beyond doubt structure assignements these interesting results needed either confirmation or disproval.

Here we report on a reinvestigation of these reactions. Our study was also extended to others (Z)- and (E)-disubstituted alkenes bearing conjugating and electron-attracting substituents and to cyclic electron-rich alkenes.

RESULTS AND DISCUSSION

ENDO/EXO-SELECTIVITY

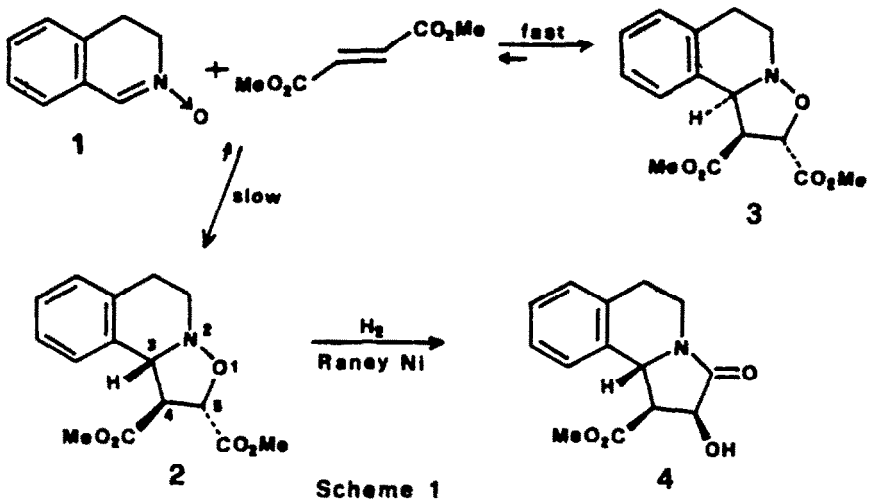
Nitrone 1 reacted readily with dimethyl fumarate (at 35°C in C_6D_6) to give almost quantitative yields of a mixture of adducts 2 and 3 (kinetic ratio, 2:3 = 0.30) which equilibrate readily even at r.t. (thermodynamic ratio, 2:3 = 13) (Scheme 1). Cycloreversion of pure 2 obeyed first order kinetics with half-life of 2.62 h at 53°C in C_6D_6. Because of its high cycloreversion rate, compound 3 could not be isolated in a pure state but it was convincingly characterized by ^{1}H-NMR spectra of the crude reaction mixture. In particular the shift to higher fields experienced by one of the methoxy groups in 3 [δ ($CDCl_3$) 3.30 and 3.80 as compared to δ 3.73 and 3.86 in 2 and δ 3.92 in 4] due to the shielding effect of the vicinal cis aromatic moiety, clearly supports the assigned structures. The lower stability of 3 than 2 concurs.

Finally catalytic hydrogenation of 2[12] under similar conditions to those used by Huisgen and coll.[12] afforded 4 whose structure was established by single crystal X-ray analysis (Figure).

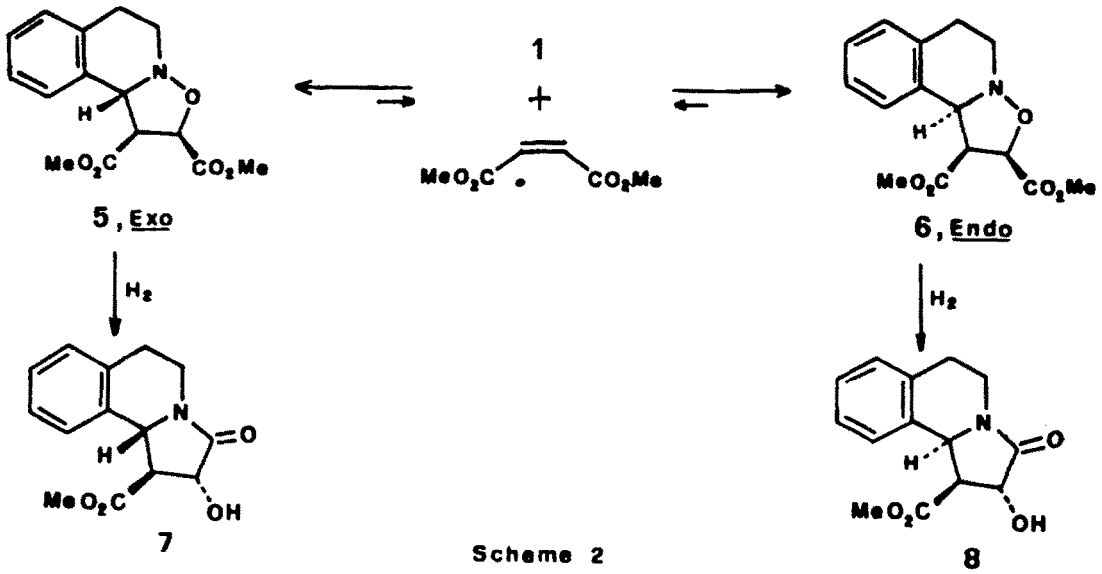
Also dimethyl maleate reacted readily with 1 (although more slowly than dimethyl fumarate) to afford a 52:48 mixture of endo-6 [δ ($CDCl_3$) 3.20 (OMe) and 3.70 (OMe)] and exo-5 [δ ($CDCl_3$) 3.80 (two OMe)] adducts (Scheme 2). Under equilibrium conditions (refluxing benzene) the exo-compound was largely dominant (exo:endo $\geq$ 20:1). The "cis" compounds 5 and 6 are definitively more stable than the related "trans" adducts 2 and 3. In fact cycloreversion reaction of the more reactive of the "cis" adducts, that is the endo-one 6, showed a half-life of ca. 28 h (at 53°C in $CDCl_3$).[13] As a result, both 5 and 6 could be isolated in a pure state and transformed by catalytic hydrogenation[12] into the lactams 7 and 8, respectively.

The structures assigned by Huisgen and coll. to the more stable adducts from the reactions of 1 with dimethyl fumarate and dimethyl maleate were 3 and 6, respectively. On the basis of the foregoing data they must be revised and reassigned as 2 and 5.

Our investigation was extended to others (Z)- and (E)-1,2-disubstituted alkenes and Table 1 gathers kinetic and thermodynamic ratios of the two diastereoisomers (9 and 10 from (Z)- and 11 and 12 from (E)-alkenes, respectively) evaluated by ^{1}H-NMR analysis of the reaction mixtures. The



Scheme 1



Scheme 2

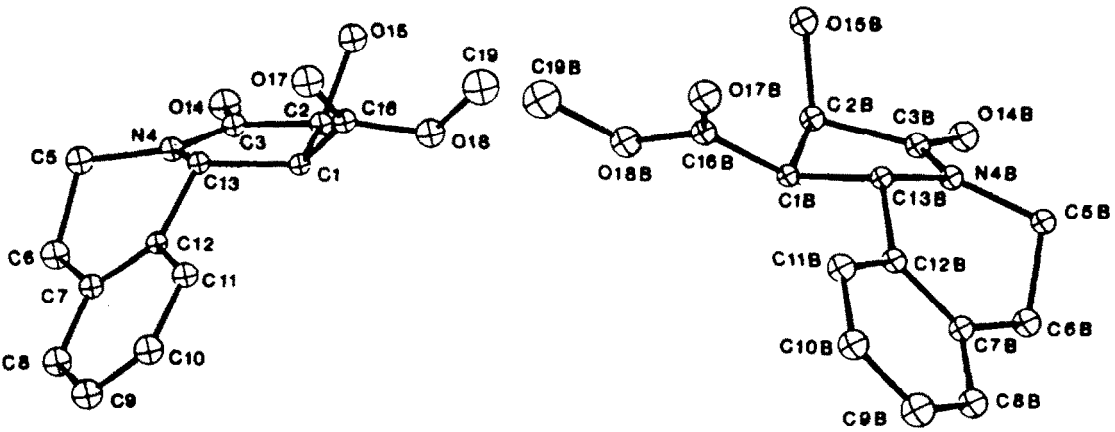
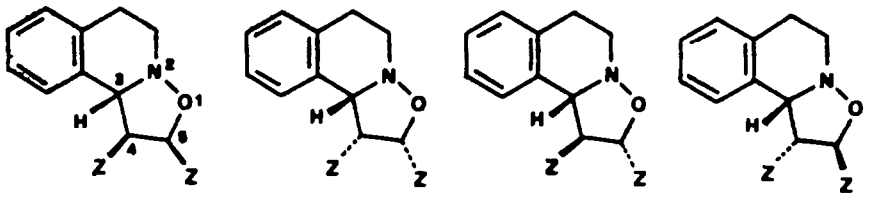


Figure. ORTEP (Johnson, 1976) perspective views of the two independent molecules of **4**, showing the atomic numbering used in the Tables 3-4.



9, Exo 10, Endo 11 12

Table 1. Kinetic (thermodynamic) ratios for the reactions of 1 with (Z)- and (E)-disubstituted alkenes.

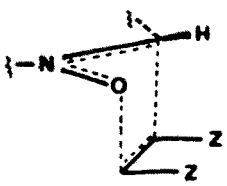
Z	9	10	11	12
a : CN[a]	50(80)	50(20)	40(85)	60(15)
b : COPh[b]	50(100)[c]	50(d)	75(≥98)	25(≤2)
c : SO_2Ph[a]	100(100)	d(d)	83(100)	17(d)
d : Ph[b]	100(100)	d(d)	≥95(100)	≤5(d)

[a] In chloroform. [b] In benzene. [c] Thermodynamic ratio in chloroform. [d] Not detected by TLC and ^{1}H-NMR analyses.

reactions of 1 with dibenzoyl and dicyano derivatives at room temperature were fast, ending up with an equilibrium which did not lie completely on the side of the adducts. (Z)- and (E)-Bis(phenylsulphonyl) derivatives reacted readily with 1 and gave rise to quantitative yields of adducts. By contrast (Z)- and (E)-stilbenes reacted very sluggisly with 1 and only after several weeks at room temperature substantial amounts of adducts could be isolated. As far as the structure of adducts reported in Table 1 is concerned it should be stressed that ^{1}H-NMR data (see Table 2) do not make it possible to discriminate between the two diastereoisomers. However we feel that taking advantage of the reversibility of all of the reactions of Table 1 and by analogy with the results of the reactions of 1 with dimethyl fumarate and dimethyl maleate one can confidently assigne structures 9 and 11 to the dominant (or to the only) detected isomer under equilibrium conditions in the reactions of (Z)- and (E)-dipolarophiles, respectively.

The most relevant feature of the reactions of 1 with (Z)- dipolarophiles (Table 1) is that exo-addition (i.e., 13) competes efficiently with endo-addition (i.e., 14) in the case of (Z)-dibenzoyl ethylene and of maleonitrile whereas the former addition mode is the only observed process in the case of (Z)-stilbene and (Z)-bis(phenylsulphonyl)ethylene. As for (E)-alkenes our findings clearly indicate that phenyl, phenylsulphonyl and benzoyl groups accomodate more easily endo-disposition, with respect to attacking 1, when they are bound to occupy position 5 in the final isoxazolidine than when they are bound to occupy position 4; that is, TS 15 is preferred over TS 16. The opposite is true for cyano and, to a higher extent, for methoxycarbonyl group (16 is favoured over 15).

We then studied cyclic dipolarophiles. The reaction of 1 with N-phenylmaleimide (NPM) took place in a few minutes (35°C, C_6D_6) to give quantitative yields of a mixture of exo-17a and endo-18a adducts (exo:endo = 96:4). Quite similar high exo-selectivities were observed in more polar solvents such as ethyl acetate (97:3), dichloromethane (95:5), acetonitrile (93:7) and nitromethane (95:5). Both endo- and exo-adducts proved stable under reaction conditions. The



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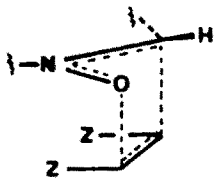

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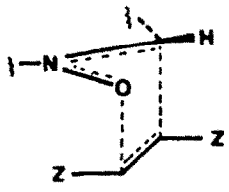

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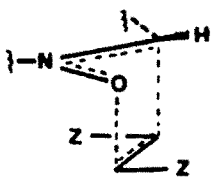

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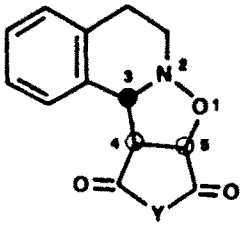

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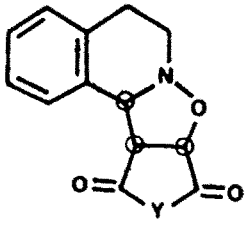

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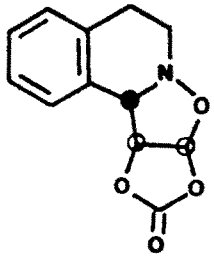

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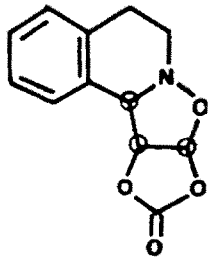

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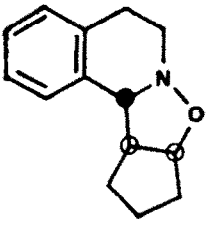
a : Y = NPh ; b : Y = NMe

c : Y = NCO_2Me ; d : Y = O



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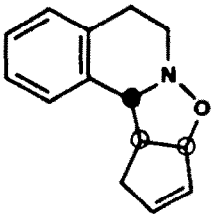

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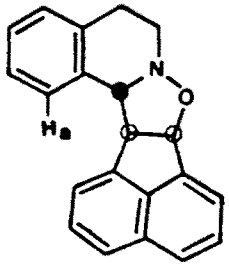

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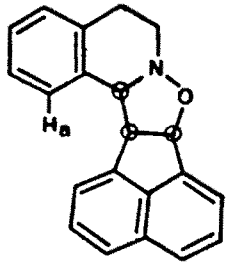

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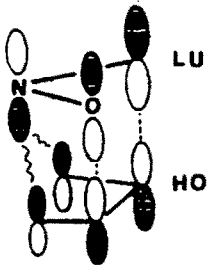

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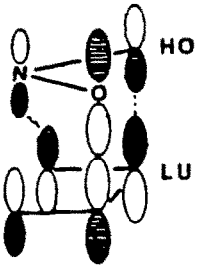

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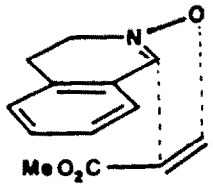

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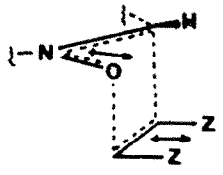

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structure of the adducts rests firmily on the ^{1}H-NMR spectra ($J_{3,4}$ = 2.0 Hz for the exo-adduct and 7.5 for the endo-derivative) and on conversion of the endo- into the exo-compound upon heating (exo:endo thermodynamic ratio = 96:4 in benzene at 80°C). Consequently the endo-structure proposed by Huisgen and coll.[12] for the adduct 1-NPM must be reassigned as exo. On passing from N-phenyl to N-methyl (exo:endo = 98:2)[14] and N-methoxycarbonylmaleimide (only the exo-adduct **17c** was detected) no relevant changes in diastereoselectivity were observed. Likewise only the exo-adduct **17d** was detected (^{1}H-NMR) in the reaction of **1** with maleic anhydride (MA). Supporting chemical evidence for this adduct ($J_{3,4}$ = 1.0 Hz) comes from its chemical correlation, carried out by Huisgen and coll.,[12] to what has now been assured to be the exo-adduct from dimethyl maleate, i.e., **5**.

Competition reactions of **1** with excess mixture of NPM and MA gave rise to an almost equimolar mixture of **17a** and **17d**, but **17d** slowly disappeared with time and only **17a** was left. This finding clearly indicates that cycloaddition rates of NPM and MA are similar whereas their extrusion rates from **17a** and **17d**, respectively, are very different. We do not have, at present, any explanation for this behaviour. However from an experimental standpoint the high reactivity of maleimides along with the surprisingly high stability of their exo-adducts makes maleimides the most suitable trapping agents for nitrones.[14] In fact all of the cycloreversions cited in this paper were carried out in the presence of excess N-methylmaleimide.

Cyclic electron-rich dipolarophiles reacted sluggishly with **1** but the diastereoselectivity scenery did not change. The reactions of **1** with cyclopentene and cyclopentadiene were found diastereopspecific whilst high exo-selectivity was observed in the reactions of **1** with vinylene carbonate (exo-**19**:endo-**20** = 95:5; $J_{3,4}$ = 0.5 Hz and 5.0 Hz for the exo- and endo-adduct, respectively) and with acenaphthylene (exo-**23**:endo-**24** ratios:kinetic = 79:21, thermodynamic = 86:14). Mass spectra of **19**, **20** and **21** showed that a cycloreversion process is the only relevant fragmentation pathway observed under electron impact.

Our results clearly show that an "endo-rule" does not hold for the reactions of 3,4-dihydroisoquinoline-N-oxide with (Z)-1,2-disubstituted alkenes. However, in some cases (e.g. reactions with dimethyl maleate and (Z)-dibenzoylethylene) kinetic exo:endo ratios are much lower than related thermodynamic ratios thus suggesting that stereoelectronic factors are actually at work during the cycloaddition process and that they favour endo-orientation. Secondary orbital interactions between the nitrogen atom of the nitrone and substituents of a (Z)-dipolarophile, are schematically depicted in **25** and **26**. These interactions have been advanced as factors responsible for endo-orientation in the case of (E) and (Z)-N-alkoxynitrones[3] and then considered important also for other types of nitrones.[2,7,8] In our opinion such interactions should not, in general, give rise to a strong stabilization owing to i) the bad geometrical alignment of the centres involved in secondary overlaps in both **25** and **26** ii) in **26** (which is the dominant F.O. interaction in the reaction of **1** with dimethyl maleate and other electron-poor dipolarophiles)[2,15] the coefficient at the nitrogen atom of the nitrone is small and one of the interactions is antibonding.

Secondary interactions can also involve substituents on the nitrone and on the dipolarophile.[7,8] The two plane orientation complex **27** and its corresponding transition state permits π-overlap between the aromatic moiety of **1** and groups such as ester groups. Experimental evidence for the attractive nature of this type of interaction has been reported.[16]

As a matter of fact the foregoing experimental data indicate that in our systems the charge transfer effects can often be overriden by steric (non bonded) interactions which can be regarded as responsible of the dominance of exo-adducts.

In this connection it should be reminded that recent MM2 and MNDO calculations have cast some doubt on the role of secondary overlaps as endo-orienting factors in Diels-Alder cycloadditions (even in the catalyzed reactions)[17a,c] and have stressed the importance of steric factors[17b,c] and of the polar term.[17a] Moreover Sustmann and Sicking, on the basis of MINDO/3 calculations, concluded that "non covalent" repulsion might well play a very important role (and, all the more interesting, it can outweigh charge transfer terms) in controlling regiochemistry in 1,3-dipolar cycloadditions of nitrile oxides and diazoalkanes.[17d] They also evidenced that contributions of the polar term are small.

Dipole-dipole interactions have previously been advanced as an important factor in controlling diasteroselectivity in nitrone cycloadditions.[9] Dipole-dipole alignement in exo TSs (e.g., 28) has been considered worse than that in endo TSs. The absence of solvent polarity effect on endo:exo ratios for the reaction of 1 with NPM and the dominance of exo-addition in the reactions of NPM and maleic anhydride with 1 seem to rule out a major role for this effect in the above described cycloadditions.

RELATIVE RATES OF CYCLOADDITION AND CYCLOREVERSION FOR (E)-AND (Z)-DIPOLAROPHILES

Steric hindrance of resonance between the carbon-carbon double bond and the conjugated (Z)-substituents should lower the reaction rate of (Z)- in comparison with related (E)-alkenes,[18] probably owing to a smaller LUMO-HOMO gap in these latter compounds. On qualitative grounds we have observed that the behaviour of methoxycarbonyl, benzoyl and sulphonyl derivatives conform to this rule (see Experimental). However the reactivity of maleonitrile was found similar to that of fumaronitrile and in the case of diphenyl derivatives we observed a reversal of reactivity. Competition experiments showed that 1 reacts with (Z)-stilbene ten times faster than (E)-stilbene. This is the second exception[14] to the rule that (E)-1,2-disubstituted ethylenes are better dipolarophiles than the related (Z)-compounds and confirms, once more, that nitrones are among the most reluctant 1,3-dipoles in following this rule.[18] Repulsive steric effects present in either one of the transition states from (E)-stilbene but not in the exo-transition state from the (Z)-stilbene can be advanced as an important factor which could lower the reactivity of the (E)-olefin.

A second reason for the lower reactivity of (Z)-dipolarophiles was advanced by Huisgen in 1962 and takes into account "the shrinking of the olefinic bond angle from ~120° to ~109° during the cycloaddition as a consequence of the rehybridization ($sp^2 \rightarrow sp^3$) which increases for cis-substituents the overlap of Van der Waals radii."[18] But the same Author more recently has stated that "one attributes minor importance to the second argument, since the early TS of concerted cycloadditions became accepted knowledge".[18] To the best of our knowledge no unambiguous experimental data have so far been reported which can shed light on the role of this steric effect. One may anticipate that, were this factor of some importance in the case of cycloadditions, it should fully display his effect in cycloreversion reactions of (Z)-derivatives (as a strong rate-enhancing factor). In fact an early TS for a cycloaddition means a late TS for the related cycloreversion with a resultant almost complete relief of steric compression for (Z)-substituents. A systematic study of the cycloreversion reaction of pairs of (Z)- and (E)-isoxazolidines (with N-methylmaleimide as trapping agent for 1) showed that adducts to (Z)-dipolarophiles underwent cycloreversion less readily than related adducts to (E)-alkenes.

Thus, (E)-dibenzoylisoxazolidine **11b** is definitively more fragile upon heating ($t_{\frac{1}{2}}$ = 1.25 h at 35°C

in $CDCl_3$) than the related (Z)-derivative (i.e., 9b; $t_{1/2}$= 7 h at 53°C in $CDCl_3$). Even in the case of isoxazolidines bearing bulky substituents, such as phenylsulphenyl groups, the (E)-isoxazolidine (i.e., 11c) fragmented ca. four times faster than the (Z)-adduct (i.e., 9c) ($t_{1/2}$=39 minutes and 2.8 h, respectively, at 80°C in $CDCl_3$). Fragmentation of diphenyl derivatives 9d and 11d took place at an acceptable rate only above 100°C but once again the (E)-derivative (i.e., 11d) entered ring cleavage more easily (ca. 3 times) than (Z)-9d. An exception is, for now, represented by cyano derivatives 10a and 12a (the only two cyano adducts isolated in a pure state) which exhibited very similar cycloreversion rate constants ($t_{1/2}$=18 and 17 minutes in $CDCl_3$ at 35°C for (E)-12a and (Z)-10a, respectively).

The foregoing results (see also preceding section for methoxycarbonyl derivatives and previous data for (E)- and (Z)-β-nitrostyrenes)[14] provide unambiguous experimental evidence that the "second reason" is not the dominant factor in promoting a cycloreversion reaction and consequently, in agreement with Huisgen's opinion, it should play a minor role in retarding cycloaddition reactions. However, it should favour cycloreversions of (Z)-dipolarophiles as indicated by the remark that relief of steric compression does indeed help increase cycloreversion rate. In fact repulsive steric interactions between the substituent at position 4 and the cis aromatic residue at position 3 allow one to easily explain why endo-adducts 6, 10a and 10b cyclorevert more readily than related exo-compounds 5,9a and 9b (as shown by a comparison of kinetic with thermodynamic ratios). The very same effect makes adducts 3 and 12a-d be less stable than related diastereoisomers 2 and 11a-d.[19,20]

Our results also suggest that the rule $k_{(E)} > k_{(Z)}$ is at least as general (or even more general) for cycloreversions as for cycloadditions. The underlying reason for this finding can be traced back to the concepts of conjugation loss (π localization energy, that is loss in π bond energy) for cycloadditions and the corresponding conjugation gain for cycloreversions.[15,21] The former effect acts as a rate-retarding factor in cycloadditions (thus partially counteracting the charge-transfer stabilization term) and it is obviously greater for (E)-alkenes (where substituents can fully display their conjugative ability) than for (Z)-derivatives. The latter effect is no doubt a prime rate-enhancing factor in cycloreversion reactions,[22] it is higher for (E)-olefins than for (Z)-isomers and overrides the "second reason". In this connection the similar reactivity observed for maleo and fumaronitrile (in both cycloadditions and cycloreversions) is consistent with the absence of steric hindrance to resonance in maleonitrile. Cycloreversion of this latter compound should be favoured by a decrease in dipole-dipole repulsion between the two cyano groups while the opposite is true for the cycloaddition reaction.

EXPERIMENTAL

Melting points are uncorrected. Elemental analyses were made on a Carlo Erba CHN analyzer mod. 1106. ^{1}H-NMR spectra were recorded on a Bruker WP80SY Spectrometer (operating at 80 MHz) equipped with an Aspect 2000 computer with TMS as internal standard. Thin layer chromatography was carried out on plates precoated with Silicagel 60 GF_{254} Merck. Spots were revealed either by spraying with 3% chromic oxide in sulphuric acid (50%) followed by heating at 120°C or under UV light (254 nm). Column chromatography was performed with Silicagel 60 (70-230 mesh) Merck eluting with cyclohexane-ethyl acetate mixtures. The reagents used were either commercially available or prepared by literature methods.

Reaction of 3,4-dihydroisoquinoline-N-oxide (1) with dimethyl fumarate. Freshly distilled 1 (40 mg, 0.27 mmol) and dimethyl fumarate (20 mg, 0.14 mmol) were dissolved in C_6D_6 (0.5 ml) and the reaction monitored by ^{1}H-NMR. After ten minutes at 35°C dimethyl fumarate had almost completely disappeared and only compounds 2 [δ 3.33 and 3.43 (two s, OMe)] and 3 [δ 3.00 and 3.43 (two s, OMe)] were detected in the reaction mixture. The 2:3 ratio changed from 0.30 after one minute to 13 after some days (at the equilibrium). Similar results were obtained in the presence of excess

Table 2. ^{1}H-NMR data of adducts 2 - 24.[a]

Comp.	Solvent	H-3	H-4	H-5	$J_{3,4}$	$J_{4,5}$
2	b	5.02	3.90	5.15	8.5	7.8
3	b	5.02	4.15	5.52	10.0	7.0
5	b	5.33	3.43	4.83	8.5	9.5
6	b	4.68	3.88	4.78	9.5	9.5
9a	c	4.93	3.72	5.24	7.0	8.5
10a	c	4.82	4.32	5.27	8.0	9.0
9b	b	5.83	4.24	5.46	7.0	8.5
10b	b	5.10	5.10	5.45	d	d
9c	c	5.52	4.50	5.05	5.0	7.0
9d	b	4.98	3.82	5.47	8.0	9.0
11a	c	4.83	3.90	5.10	9.0	7.0
12a	c	5.05	4.18	5.25	8.2	3.8
11b	b	5.60	5.60	5.60	d	d
12b	b	5.10	5.70	6.07	10.0	7.0
11c	c	5.20	4.50	5.32	3.0	5.0
12c	c	e	5.08	5.85	8.0	3.0
12d	b	4.95	3.51	5.37	8.0	9.0
17a	c	4.88[f]	3.85	4.88	2.0	7.5
18a	c	4.56[f]	4.13	5.11	7.5	7.5
17c	b	4.63	3.30	4.38	2.0	7.5
17d	b	4.50	3.82	4.30	2.0	7.8
19	c	4.76[f]	5.45	6.05	0.5	5.0
20	c	4.15[f]	5.61	6.30[g]	5.0	5.0
21	c	4.09	e	4.92[h]	7.0	7.0
22	c	4.10	e	5.42[h]	7.0	7.5
23	c	4.52	4.68	6.23	6.0	6.5
24	c	5.24	4.96	6.25	8.0	7.0

[a] Numbering refers to isoxazolidine ring. H-3 resonates either as a broad (owing to nuclear quadrupole relaxtion effects of the nitrogen atom) doublet or as a broad singlet, H-4 as a double doublet and H-5 as a doublet. [b] Deuterobenzene. [c] Deuterochloroform. [d] Not determined. [e] Buried under other signals. [f] Very broad signal. [g] Multiplet. [h] dd, J5,vinyl = 1.5 Hz.

fumarate. On a preparative scale a solution of 1 (460 mg, 3.16 mmol) and dimethyl fumarate (476 mg, 3.3 mmol) in benzene was heated under reflux for 48 h. The solvent was evaporated and the resulting residue was crystallized from cyclohexane to give pure 2 (700 mg, 77%; m.p. 89-90°C, lit.,[12] 89-90°C).

A solution of compound 2 in ethanol was hydrogenated in the presence of Raney Ni catalyst at r.t. and under atmospheric pressure. After 0.5 h the uptake of hydrogen was complete and evaporation of the solvent followed by crystallization from MeOH afforded pure 4 as prisms [88%; m.p. 190-2°C, lit.,[12] 191-3°C; δ ($CDCl_3$) 3.24 (dd), 4.63 (d, J = 7.5 Hz) and 5.49 (bd, J = 8.0 Hz) 5.60 (OH). Acetyl derivative: prisms from MeOH, m.p. 160-4°C; δ ($CDCl_3$) 2.15 (s, COMe), 3.32 (dd), 3.85 (s, OMe), 5.40 (bd, J = 7.6 Hz) and 5.70 (d, J = 8.0 Hz)].

Reaction of 1 with dimethyl maleate. A solution of 1 (40 mg) and dimethyl maleate (20 mg) in C_6D_6 (0.5 ml) at 35°C was monitored by ^{1}H-NMR and TLC. After 4 h the dipolarophile had almost completely disappeared to afford a mixture of 5 [δ 3.42 and 3.44 (two s, OMe)] and 6 [δ 3.40 and 2.95 (two s, OMe)] (48:52). On a larger scale a solution of 1 (1.00 g, 6.8 mmol) and dimethyl maleate (1.20 g, 8.3 mmol) in benzene (5 ml) was kept at r.t. for 12 h and then column chromatographed (cyclohexane:ethyl acetate 80:20) on silicagel to give in the order pure 5 (0.933 g, 47%) and 6 (0.70 g, 39%). Compound 5 (needles from MeOH, m.p. 90-2°C, lit.[12] 96-7°C) was hydrogenated in ethanol in the presence of Raney Ni to 7 [93%, needles from MeOH m.p. 160-2°C, lit.,[12] 163-4°C; δ ($CDCl_3$) 3.22 (dd), 3.98 (s, OMe), 4.84 (d,J = 9.0 Hz), 4.84 (OH), 5.08 (d,J=8.5 Hz). Acetyl derivative: prisms from MeOH, m.p. 126-9°C; δ ($CDCl_3$) 2.17 (s, COMe) 3.12 (dd), 3.94 (s, OMe), 5.13 (d,J = 8.0 Hz), 5.79 (d,J = 9.0 Hz)]. Likewise adduct 6 [needles from cyclohexane, m.p. 113-4°C. (Found:C, 61.7; H, 5.7; N, 4.50. Calc. for C15H17NO5: C, 61.85; N, 5.9; N, 4.8)] was transformed to 8 [87%, prisms from benzene-cyclohexane, m.p. 140-2°C. (Found: C,64.0; H, 5.8; N, 5.3. Calc. for C14H15NO4:C,64.4; H, 5.8; N, 5.4). δ ($CDCl_3$) 3.28 (s, OMe) 3.67 (d,J = 7.0 Hz), 4.54 (s), 5.44 (d), 6.25 (OH)]. TLC analysis showed that 5 was slightly dominant when chloroform or acetonitrile were used as reaction solvent.

The reaction of 1 with dimethyl maleate was also carried out in refluxing benzene for four days. After that time only trace amounts of 6 could be detected by TLC while compound 5 could be isolated in 80% yield.

Reaction of 1 with fumaronitrile, maleonitrile, (E)- and (Z)-dibenzoylethylene. The reaction of 1 (21 mg, 0.14 mmol) with excess fumaronitrile (30 mg, 0.38 mmol) and maleonitrile (30 mg), respectively, was carried out in $CDCl_3$ (0.5 ml) at 35°C and monitored by ^{1}H-NMR. Kinetic (evaluated after ca. 3 minutes) and thermodynamic ratios (48 h) are reported in Table 1. Both dipolarophiles reacted very readily with 1 and both reactions reached more than 60% conversion after 20 minutes. However they never went to completion and the signals of 1 were clearly apparent in the ^{1}H-NMR spectrum of the reaction mixtures even after 48 h. The reaction of maleonitrile (10 mg) in C_6D_6 (0.5 ml) in the presence of excess 1 (61 mg) led to a slight kinetic prevalence of **10a** (**9a**:**10a** ca. 45 : 55) whereas **9a** was once again dominant at the equilibrium.

In a further experiment both the foregoing reactions were conducted in benzene at r.t. After 6 h the reaction flasks were opened and solvent was kept evaporating slowly under atmospheric pressure at r.t. The low soluble adducts **10a** and **12a**, respectively, precipitated from the reaction mixtures in good yields (≥ 60%). **10a**: slightly yellow needles, m.p. 105-9°C dec. (Found: C, 69.5; H, 5.0; N, 18.5. Calc. for C13H11N3O: C, 69.3; H,4.9; N,18.7). **12a**: needles, m.p. 99-100°C, (Found: C,69.2; N, 4.8; N, 18.6). **10a** and **12a** exhibited a lower R_F (cyclohexane:ACOEt = 7:3) than **9a** and **11a**, respectively.

A competition experiment of 1 with excess mixture (1:1) of maleo and fumaronitrile qualitatively showed (^{1}H-NMR) that the former dipolarophile was slightly less reactive than the latter.

The reactions of 1 (25 mg, 0.17 mmol) with (E)- and (Z)-dibenzoylethylene (31 mg, 0.13 mmol), respectively, were carried out in C_6D_6 (0.5 ml) at 35°C. The reaction of the (E)-derivative went to completion within five minutes whereas after that time the signals of the adducts to the (Z)-dipolarophile could just be detected. Moreover only the signals of the adducts to the (E)-derivative could be detected after 5 minutes when excess mixture of (E)- and (Z)-dibenzoylethylene (1:1) was reacted with 1 under the above reported conditions.
In the reaction of (E)-dibenzoylethylene the signals of the minor isomer **12b** completely disappeared within 4 h but trace amounts of **12b** (lower RF) kept on being detectable after 48 h by TLC. Adducts **9b** [prisms, m.p. 115-7°C (Found: C, 78.5; H, 5.3; N, 3.9. Calc. for C25H21NO3 : C, 78.3; H, 5.5; N, 3.65)] and **11b** [needles, m.p. 153-5°C dec. (Found: C, 78.6; H, 5.4; N, 3.5)] slowly precipitated in a pure state from concentrated reaction mixtures. Adduct **9b** showed a higher R_F than **10b** on TLC. Transformation **10b** → **9b** was accompanied by formation of minor amounts of **11b** due to base catalyzed isomerization of **10b**. In contrast **9b** did not show appreciable isomerization to **12b** in the presence of 1 ($CDCl_3$ solution, 8 h).

Reaction of 1 with (Z)- and (E)-bis(phenylsulphonyl)ethylene. ^{1}H-NMR analysis of a solution of 1 (21 mg, 0.14 mmol) and (E)-bis(phenylsulphonyl)ethylene (23 mg, 0.075 mmol) in $CDCl_3$ showed the presence of both **11c** and **12c** (Table 1). Compound **12c** was slowly transformed into **11c** upon standing at r.t. (9 days). On a preparative scale the reaction was carried out in dichloromethane. After ten days at r.t. the solvent was removed and the crude residue triturated with little methanol to afford pure **11c** [m.p. 174-5°C (Found : C, 60.9; H, 4.4; N, 3.0. Calc. for C23H21NO5S2 : C, 60.7; H, 4.6; N, 3.1.)].

Only adduct **9c** was present (TLC and ^{1}H-NMR) in the reaction mixture of 1 with (Z)-bis (phenylsulphonyl) ethylene both in dichloromethane at r.t. and in benzene at 80°C. Evaporation of the solvent followed by treatment of the residue with MeOH yielded pure **9c** [m.p. 132-5°C (Found: C, 70.0; H, 4.8; N, 3.2].

^{1}H-NMR analysis of the reaction of 1 with an excess of a mixture of (E)- and (Z)-isomers indicated that the (E)-isomer is at least ten times more reactive than the (Z)-derivative. In fact only signals attributable to **11c** and **12c** were clearly apparent in the spectrum recorded after 15 minutes at 35°C.

Reaction of 1 with (E)- and (Z)-stilbene. A solution of 1 (0.213 mg, 1.45 mmol) and (Z)-stilbene (0.50 g, 2.77 mmol) in benzene (2 ml) was kept at r.t. for 105 days. The reaction mixture was worked up as usual to give **9d** [0.141 g, 30%; prisms from MeOH, m.p. 168-70°C. (Found:C, 84.7; H, 6.2; N, 4.5. Calc. for C23H21NO : C, 84.4; N, 6.4; N, 4.3)].

A solution of 1 (0.180 g, 1.22 mmol) with (E)-stilbene (0.180 g, 1.00 mmol) in benzene (2 ml) was left at r.t. for 2 months and then heated at reflux for five days. Usual workup led to isolation of **11d** [26 mg, 8%; needles from MeOH, m.p. 138-140°C. (Found : C, 84.6; H, 6.1; N, 4.6)]. In the reactions carried out in benzene either at 65°C (10 days) or at 35°C (60 days) compound **11d** was accompanied by minor amounts of a product that we did not manage to characterize.

Either one dipolarophile was reacted with 1 at 140°C (3.5 days) but once again **9d** and **11d**, respectively, were the only detected adducts.

Competition experiments were carried out by reacting 1 (105 mg, 0.71 mmol) with excess mixture (1:1) (270 mg, 1.5 mmol) of (E)- and (Z)-stilbene in benzene at r.t. for six months. At the end of that time the following three fractions were obtained, in the order, by column chromatography (cyclohexane:ethyl acetate = 9:1 as eluent): unreacted stilbenes, **11d** (8 mg) and **9d** (72 mg). From these data a $k_{(Z)} : k_{(E)} = 10.5$ can be evaluated.[23] Further experiments stopped at a lower conversion confirmed this finding. For example 1 (1.0 mmol) was reacted with a large excess of a mixture of (Z)- (1.54 mmol) and (E)-stilbene (2.94 mmol) at r.t. for two months (8% conversion). A **9d**: **11d** ratio of 9.5 was evaluated by ^{1}H-NMR. Both **9d** and **11d** proved stable in benzene at r.t..

Reaction of 1 with maleimides and maleic anhydride. A NMR tube containing a solution of 1 (30 mg, 0.20 mmol) and NPM (18 mg, 0.10 mmol) in C_6D_6 (0.5 ml) was placed in the NMR probe (at 35°C) and the reaction monitored at time intervals of 30 seconds. After 3 minutes the signals of NPM had completely disappeared. Then the reaction was carried out on a larger scale [190 mg (1.29 mmol) of 1 and 218 mg (1.26 mmol) of NPM in 5 ml of benzene] at r.t.. The precipitated exo-**17a** (320 mg) was filtered off and washed with benzene. The mother liquors were column chromatographed to give a further crop of **17a** (67 mg, total yield 96%; prisms from benzene, m.p. 178-9°C, lit.,[12] 178-178.5°C) and the lower R_F endo-adduct **18a** [16 mg, 4%; m.p. 130-3°C. (Found: C,71.2; H, 5.2; N, 8.8 calc. for C19H16N2O3: C, 71.25; H, 5.0; N, 8.75)]. The endo-adduct proved stable under reaction and workup conditions whilst upon heating at 53°C it was converted to the exo-adduct with a half life ≥ 32 h. The thermodynamic exo:endo ratio was obtained by heating the exo-adduct (500 mg) in benzene under reflux for 4 days. Fractional crystallization and column chromatography led to recovery of **17a** (437 mg, 87.4%) and isolation of **18a** (18 mg, 3.6%).

Under otherwise similar reaction and workup conditions 1 (190 mg, 1.29 mmol) was reacted with NPM (180 mg, 1.04 mmol) in ethyl acetate (total yield 98%, exo:endo ratio = 97:3), dichloromethane (100%, 95:5), nitromethane (100%, 95:5) and acetonitrile (98%, 93:7).[1]

The reaction of 1 with maleic anhydride in C_6D_6 was monitored by ^{1}H-NMR. Only the signals of the exo-adduct could be detected. Then an equimolar mixture of NPM (22 mg) and maleic anhydride (12 mg) was reacted with 1 (15 mg) in C_6D_6. After five minutes **17a** and **17d** were present in quite similar amounts in the reaction mixture but after 14 days (at r.t.) only the signals of **17a** were clearly apparent in the ^{1}H-NMR spectrum.

Once again ^{1}H-NMR and TLC analyses of the reaction mixture of 1 with N-methoxycarbonylmaleimide (in benzene) disclosed the presence of the sole exo-adduct. [90%; prisms from benzene, m.p. 155-6° dec. (Found: C, 59.3; H, 5.0; N, 9.0. Calc. for C15H14N2O5 : C, 59.6; H, 4.7; N, 9.3)].

Reaction of 1 with cyclopentene, cyclopentadiene, acenaphthylene, and vinylene carbonate. A mixture of 1 (305 mg, 2.08 mmol) and 6 ml of freshly distilled cyclopentene was left aside at r.t. for 6 days. Then column chromatography afforded pure **21** [380 mg, 85%; leaflets from petrol ether, m.p. 113-5°C. (Found: C, 78.4; H, 7.9; N, 6.2. Calc. for C14H17NO : C, 78.1; H, 7.9; N, 6.5). Mass spectrum: m/z, 215 ($M^{+\cdot}$, 14%), 147 ($C_9H_9NO^{+\cdot}$, 100%).]. The same adduct was isolated when this reaction was carried out at 140°C for two days.

A solution of 1 (305 mg) and freshly distilled cyclopentadiene (3 ml) in methylene chloride (3 ml) was kept at r.t. for 3 days, after which time column chromatography afforded two fractions. The first fraction consisted of a mixture of regioisomeric adducts to the dimer of cyclopentadiene[14,24] (295 mg) while the second one contained pure **22** [143 mg; leaflets from cyclohexane 98-100°C. (Found: C, 78.6; H, 7.2; N, 6.5. Calc. for C14H15NO : C, 78.9; H, 7.0; N, 6.6.)].

A solution of 1 (210 mg, 1.43 mmol) and acenaphthylene (200 mg, 1.32 mmol) in benzene (5 ml) was kept at r.t. for 1 month. At the end of that time the precipitated exo-**23** (180 mg) was filtered off and the mother liquors were column chromatographed (cyclohexane: AcOEt:CH_2Cl_2 = 70:20:10) to give a further crop of **23** (higher R_F, 75 mg, total yield 65%; needles from benzene, m.p. 187-8°C (Found:C, 84.5; H, 5.4; N, 4.8. Calc. for C21H17NO: C, 84.3; H, 5.7; N, 4.7)] and endo-**24** [(67 mg, 17%; needles from benzene, m.p. 187-8°C (Found:C, 84.1; H, 5.5; N, 4.6)]. In a further experiment the exo:endo ratio was evaluated by ^{1}H-NMR and found to be similar (4.0) to that reported above. In the endo-adduct **24** H-a proton was shifted to higher field [δ ($CDCl_3$) 6.48 (d)] in comparison with the related proton in **23** [δ 7.15]. The thermodynamic ratio was determined by heating pure **23** (60 mg) and **24**, respectively, in toluene at 115°C (sealed ampoule) for 85 h in the presence of 1 (10 mg). Usual workup led to the same exo: endo ratio (6.1) in both cases.

Finally 1 (300 mg, 3.04 mmol) and vinylene carbonate (150 mg, 1.74 mmol) were reacted in benzene (5 ml) at 35°C for 20 days. Then column chromatography (cyclohexane:AcOEt=7:3) afforded **19** [271 mg, 67%; prisms from MeOH, m.p. 142-3°C dec. (Found: C, 67.0; H, 6.5; N, 10.0. Calc. for C12H11NO4:C,67.1; H, 6.3; N, 9.8. Mass spectrum, m/z:233 ($M^{+\cdot}$, 20%), 147 ($C_9H_9NO^{+\cdot}$, 100%).] and **20** [15 mg, 3.5%; needles, m.p. 158-9°C dec. Mass spectrum, m/z : 233 (8%), 147 (100%)].

Cycloreversion reactions. Kinetic runs were carried out by dissolving 0.10 mmol of the adduct and 0.30 mmol (0.6 in the case of **10a**, **12a** and **11b**) of N-methylmaleimide in 0.5 ml of the appropriate deuterated solvent. The concentrations of the starting adducts were obtained by careful integration of H-3, H-4 and H-5 signals whilst those of the adduct to N-methylmaleimide by integration of H-3 and H-5 signals. During heating under the conditions employed for rate analyses no significant side reactions were detected. The first order rate constants for the cycloreversions were obtained by least-squares treatment of ln a/a-x (a is the initial concentration of the adduct which undergoes cycloreversion). Fragmentations of **10a**, **12a** and **11b** were carried out in the NMR probe at 35°C whereas in the other cases sealed NMR tubes were heated in a thermostat (± 0.1°C) and spectra recorded at appropriate time intervals (over two half-lives). The reported values are the average of two runs. **2** (C_6D_6, 53°C): $k_1 = 7.35 \pm 0.20 \times 10^{-5}$ sec^{-1}; **5** ($CDCl_3$, 80°C) : $k_1 = 7.40 \pm 0.15 \times 10^{-6}$ sec^{-1}; **10a** ($CDCl_3$, 35°C) : $k_1 = 6.83 \pm 0.25 \times 10^{-4}$ sec^{-1}; **12a** ($CDCl_3$, 35°C) : $6.47 \pm 0.10 \times 10^{-4}$ sec^{-1}; **11b** ($CDCl_3$, 35°C) : $k_1 = 1.54 \pm 0.05 \times 10^{-4}$ sec^{-1}; **9c** ($CDCl_3$, 80°C) : $k_1 = 6.88$

Table 3. Fractional atomic coordinates (x 10^{-4}) and equivalent B factors (A^2) for non-hydrogen atoms. E.s.d. in parentheses.

ATOM	X/A	Y/B	Z/C	B_{eq}
C1	-2134 (2)	-3169 (5)	0783 (3)	2.0 (2)
C2	-2848 (2)	-2652 (5)	0969 (3)	2.3 (2)
C3	-3242 (2)	-4137 (5)	1026 (3)	2.5 (2)
N4	-2796 (2)	-5287 (4)	1028 (2)	2.6 (1)
C5	-2970 (2)	-6904 (6)	1050 (3)	3.4 (2)
C6	-2842 (2)	-7641 (6)	0186 (3)	3.7 (2)
C7	-2147 (2)	-7137 (5)	-0026 (3)	2.7 (2)
C8	-1876 (2)	-7986 (6)	-0657 (3)	3.7 (2)
C9	-1227 (3)	-7598 (5)	-0873 (3)	4.2 (2)
C10	-0870 (2)	-6385 (6)	-0457 (3)	3.8 (2)
C11	-1141 (2)	-5513 (5)	0161 (3)	3.0 (2)
C12	-1782 (2)	-5869 (5)	0375 (3)	2.0 (2)
C13	-2080 (2)	-4886 (5)	1019 (3)	2.1 (2)
O14	-3859 (2)	-4219 (4)	1089 (2)	4.3 (1)
O15	-2779 (1)	-1814 (4)	1779 (2)	3.5 (1)
O16	-1536 (2)	-2245 (5)	1285 (3)	2.5 (2)
O17	-1078 (2)	-2737 (4)	1876 (2)	4.6 (1)
O18	-1554 (2)	-0823 (3)	0988 (2)	3.7 (1)
C19	-1039 (3)	0198 (6)	1483 (4)	5.8 (2)
C1B	0304 (2)	4576 (5)	2621 (3)	1.9 (2)
C2B	-0352 (2)	3821 (5)	2838 (3)	2.4 (2)
C3B	-0554 (2)	4957 (5)	3519 (3)	2.4 (2)
N4B	0008 (2)	5769 (4)	3873 (2)	2.2 (1)
C5B	0026 (2)	7096 (5)	4458 (3)	2.4 (2)
C6B	0177 (2)	8472 (5)	3920 (3)	3.0 (2)
C7B	0851 (2)	8193 (5)	3601 (3)	2.4 (2)
C8B	1267 (2)	9443 (5)	3514 (3)	3.3 (2)
C9B	1925 (3)	9257 (6)	3269 (3)	4.4 (2)
C10B	2145 (2)	7856 (6)	3112 (3)	3.5 (2)
C11B	1742 (2)	6570 (6)	3200 (3)	3.1 (2)
C12B	1085 (2)	6738 (5)	3428 (3)	2.3 (2)
C13B	0635 (2)	5373 (5)	3518 (3)	1.9 (2)
O14B	-1130 (1)	5064 (3)	3737 (2)	3.4 (1)
O15B	-0163 (1)	2399 (3)	3262 (2)	2.9 (1)
C16B	0759 (2)	3415 (5)	2281 (3)	2.5 (2)
O17B	1329 (2)	3014 (4)	2657 (2)	4.0 (1)
O18B	0429 (1)	2897 (4)	1461 (2)	3.6 (1)
C19B	0786 (3)	1733 (6)	1062 (3)	5.6 (2)

$\pm 0.30 \times 10^{-5}$ sec^{-1}; **11c** ($CDCl_3$, 80°C) : $k_1 = 2.98 \pm 0.06 \times 10^{-4}$ sec^{-1}; **9d** (C_6D_6, 110°C): $k_1 = 3.26 \pm 0.10 \times 10^{-6}$ sec^{-1}; **12d** (C_6D_6, 110°C) : $k_1 = 9.14 \pm 0.09 \times 10^{-6}$ sec^{-1}. Overlapping of signals prevented rate measurements in the case of **6** and **9b** whose half-life could, however, be roughly evaluated : $t_{\frac{1}{2}} \geq 2$ h and ≥ 7 h for **6** and **9b**, respectively, in $CDCl_3$ at 53°C.

Crystal data and X-ray structure refinement of compound **4**. $C_{14}H_{15}NO_4$, (colourless) crystals from MeOH, monoclinic, space group $P2_1/n$; a = 19.580 (2), b = 8.761 (1), c = 14.973 (1) A; B = 101.45 (1) °; V = 2517.3 A^3, Z = 8; D_c = 1.379 g/cm^3; F(000) = 1104; μ = 8.03 cm^{-1}. X-ray single crystal analysis and data collection performed on a Philips PW 1100 four-circle diffractometer (monochromatic CuKα radiation, λ = 1.5418 Å). Unit-cell dimensions calculated by least-squares refinement on 25 rows in the ϑ range 2-40°, 2670 reflections ($0 < h < 16$; $-7 < k < 7$; $0 \leq l < 12$) measured in the same ϑ range, merged after Lp and semi-empirical absorption correction[26] (max = 1.196), yielding 1540 unique reflections (R_{int} = 0.05). Correction for intensity variations applied (maximum variation = 4.8%). Structure solved by direct methods (MULTAN80)[27]; full-matrix least-squares refinement on F performed with a locally rewritten version of the program ORFLS[28] on the 996 reflections with $I > 3\sigma(I)$. Scattering factors for neutral atoms from International Tables for X-ray Crystallography, 1974[29]. Anisotropic thermal parameters for non-H atoms; the positions of the H atoms were calculated with the program PARST[30] and inserted with an overall isotropic B factor = 5 and not refined. At convergence, R_{all} = 0.068, R_{obs} = 0.035, S = 1.138, $(shift/e.s.d.)_{max}$ = .792 (for the scale factor), secondary extinction = 1.84×10^{-4}; the final difference Fourier map contained no peak higher than 0.29 el A^{-3}. Atomic coordinates and equivalent thermal factors for non-H atoms in Table 3; bond distances (uncorrected and corrected for riding motion[31] in Table 4 and angles in Table 5; Fig. 1a and b, drawn with ORTEPII[32] illustrates the molecular structure and

Table 4. Bond distances (Å) for non-hydrogen atoms, uncorrected and corrected for the riding motion following Busing and Levy (1984). E.s.d. in parentheses.

	UNCORRECTED DISTANCE	RIDING MOTION		UNCORRECTED DISTANCE	RIDING MOTION
C1 - C2	1.545 (6)	1.552	C1B - C2B	1.534 (6)	1.538
C1 - C13	1.544 (6)	1.547	C1B - C13B	1.538 (5)	1.541
C1 - C16	1.498 (6)	1.498	C1B - C16B	1.505 (6)	1.512
C2 - C3	1.524 (6)	1.526	C2B - C3B	1.532 (6)	1.537
C2 - O15	1.401 (5)	1.423	C2B - O15B	1.414 (5)	1.423
C3 - N4	1.332 (6)	1.337	C3B - N4B	1.329 (5)	1.332
C3 - O14	1.234 (6)	1.266	C3B - O14B	1.239 (6)	1.264
N4 - C5	1.459 (6)	1.468	N4B - C5B	1.451 (6)	1.454
N4 - C13	1.448 (5)	1.449	N4B - C13B	1.474 (5)	1.478
C5 - C6	1.511 (7)	1.512	C5B - C6B	1.510 (6)	1.516
C6 - C7	1.523 (7)	1.543	C6B - C7B	1.510 (6)	1.525
C7 - C8	1.388 (7)	1.390	C7B - C8B	1.386 (7)	1.389
C7 - C12	1.391 (6)	1.397	C7B - C12B	1.397 (6)	1.402
C8 - C9	1.413 (7)	1.422	C8B - C9B	1.418 (7)	1.421
C9 - C10	1.354 (7)	1.383	C9B - C10B	1.336 (7)	1.366
C10 - C11	1.383 (7)	1.396	C10B - C11B	1.396 (7)	1.410
C11 - C12	1.391 (6)	1.413	C11B - C12B	1.402 (6)	1.421
C12 - C13	1.496 (6)	1.502	C12B - C13B	1.507 (6)	1.516
C16 - C17	1.207 (5)	1.244	C16B - O17B	1.199 (5)	1.230
C16 - O18	1.321 (5)	1.339	C16B - O18B	1.348 (5)	1.361
O18 - C19	1.438 (6)	1.463	O18B - C19B	1.432 (6)	1.453

Table 5. Bond angles (°) for non-hydrogen atoms. E.s.d. in parentheses.

C13 - C1 - C16 113.6 (.3)	C7 - C12 - C11 119.3 (.4)	C3B - N4B - C5B 126.1 (.3)
C2 - C1 - C16 113.4 (.3)	C11 - C12 - C13 120.4 (.4)	C5B - N4B - C13B 118.9 (.3)
C2 - C1 - C13 105.5 (.3)	C7 - C12 - C13 120.3 (.4)	N4B - C5B - C6B 107.6 (.3)
C1 - C2 - O15 112.0 (.3)	N4 - C13 - C12 111.6 (.3)	C5B - C6B - C7B 108.3 (.4)
C1 - C2 - C3 104.2 (.3)	C1 - C13 - C12 115.5 (.3)	C6B - C7B - C12B 123.1 (.4)
C3 - C2 - O15 111.2 (.3)	C1 - C13 - N4 102.5 (.3)	C6B - C7B - C8B 118.0 (.4)
C2 - C3 - O14 124.7 (.4)	C1 - C16 - O18 112.0 (.4)	C8B - C7B - C12B 118.8 (.4)
C2 - C3 - N4 107.9 (.4)	C1 - C16 - O17 124.5 (.4)	C7B - C8B - C9B 121.0 (.4)
N4 - C3 - O14 127.4 (.4)	O17 - C16 - O18 123.4 (.4)	C8B - C9B - C10B 119.4 (.5)
C3 - N4 - C13 116.9 (.4)	C16 - O18 - C19 116.3 (.4)	C9B - C10B- C11B 121.2 (.4)
C3 - N4 - C5 125.3 (.4)	C13B- C1B - C16B 115.3 (.3)	C10B- C11B- C12B 120.0 (.4)
C5 - N4 - C13 117.8 (.3)	C2B - C1B - C16B 110.9 (.3)	C7B - C12B- C11B 119.5 (.1)
N4 - C5 - C6 108.4 (.4)	C2B - C1B - C13B 103.7 (.3)	C11B- C12B- C13B 121.3 (.4)
C5 - C6 - C7 111.2 (.4)	C1B - C2B - O15B 108.6 (.3)	C7B - C12B- C13B 119.2 (.4)
C6 - C7 - C12 123.1 (.4)	C1B - C2B - C3B 101.5 (.3)	N4B - C13B- C12B 112.9 (.3)
C6 - C7 - C8 117.7 (.4)	C3B - C2B - O15B 110.6 (.3)	C1B - C13B- C12B 115.8 (.3)
C8 - C7 - C12 119.2 (.4)	C2B - C3B - O14B 126.5 (.4)	C1B - C13B- N4B 100.7 (.3)
C7 - C8 - C9 120.6 (.4)	C2B - C3B - N4B 108.1 (.4)	C1B - C16B- O18B 109.1 (.4)
C8 - C9 - C10 119.3 (.5)	N4B - C3B - O14B 125.4 (.4)	C1B - C16B- O17B 126.7 (.4)
C9 - C10 - C11 120.7 (.4)	C3B - N4B - C13B 114.4 (.3)	O17B- C16B- O18B 124.2 (.4)
C10 - C11 - C12 120.9 (.4)		

atomic numbering. Lists of structure factors, anisotropic thermal parameters, H atoms parameters and torsion angles have been deposited within the Cambridge Crystallographic Data Centre.

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