Syn-Anti Isomerism in the 1,3-Dipolar Cycloaddition to Cis 3,4-Disubstituted Cyclobutenes. 5. Diastereoselectivity in the Reaction with Diazoalkanes[1]

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The 1,3-dipolar cycloaddition of diazomethane, diazoethane, phenyldiazomethane, and 2-diazopropane with several cyclobutenes, with open and cyclic cis 3,4-disubstitution, has been investigated. The cycloaddition proceeds in good yield to give syn and/or anti adducts. The structure of the adducts was established by spectroscopic data. The reactions of diazomethane cover the complete range of facial selectivity from 100% syn diastereoselectivity (e.g., with bis(mesyloxy)cyclobutene) to 100% anti diastereoselectivity (e.g., with bicyclo[3.2.0]hept-6-ene) through mixtures of various syn:anti ratios [e.g., syn:anti = 60:40 with bis(methoxycarbonyl)cyclobutene]. In particular electron-attracting substituents containing heteroatoms favor syn attack whereas in the case of cyclic disubstitution, even with heteroatoms, there is a shift toward anti adducts. The face selectivity data of the reactions of diazoethane and phenyldiazomethane are very similar to those of diazomethane. In the case of the bulky 2-diazopropane there is a significant shift toward anti addition, but the observed diastereoselectivity roughly parallels that of diazomethane. Nonplanarity of the double bond (as disclosed by ab initio calculations) and the related energy asymmetry of the out-of-plane bending of the olefinic hydrogens are advanced as the inherent facial bias of cyclobutenes which tends to govern facial selectivity.

Introduction

Facial selectivity in nucleophilic, electrophilic, and radical as well as cycloadditive attacks on the diastereotopic faces of a double bond has recently grown into one of the most investigated fields of organic chemistry, owing to its relevance to both synthetic strategies and mechanistic studies. In particular the way in which the allylic substituent effectively controls or directs π-facial selectivity in cycloadditions has been the subject of a great deal of experimental and theoretical work.[2]

Cis 3,4-disubstituted cyclobutenes represent very appealing substrates to study this problem in the field of 1,3-dipolar cycloadditions. In fact, Franck-Neumann et al.[3] and our group[4] demonstrated, in the 1970s, that 1,3-dipoles (diazoalkanes, nitrile oxides, nitrones, benzonitrile phenylimide, and azomethine imides)[3,4] can exhibit a remarkable contrasteric syn[5] preference in the reaction with these dipolarophiles. Moreover these researches made clearly apparent that syn attack is highly favored by the presence of heteroatoms as substituents in the allylic positions. In the light of these data, some years ago we undertook a systematic investigation, directed toward the goal of finding out the underlying reason of this interesting and peculiar stereochemical outcome.[1,6] Some very recent preliminary communications dealing with the reaction of diazoalkanes with cis 3,4-disubstituted cyclobutenes[7b-d] prompt us to report the full account of our own data on this reaction. As far as theory is concerned, we have already reported in preliminary communications[1] that the nonplanarity of the olefinic moiety of the cyclobutene induced intramolecularly by the allylic substituent (through a σ-π conjugation) and the consequent energy asymmetry of out-of-plane bending of the olefinic hydrogens nicely parallels the observed facial selectivity of 1,3-

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Table I. Syn:Anti Ratios, Evaluated by Column Chromatography, for the Reactions of Cyclobutenes 1 with Diazomethane and 2-Diazopropane

	relative yield			relative yield		
X	2, %	3, %	total yield, %	4, %	5, %	total yield, %
a: OCOMe	100[a]	–	95	70[a]	30[a]	79
b: OSO_2Me	100[a]	–	97	87[a]	13[a]	84
c: OMe	100[a-c]	–	*d*	80[a-c]	20[a-c]	*d*
d: OCH_2Ph	100[a]	–	75	87[a]	13[a]	83
e: Cl	96	4	90	28[e]	72[e]	78
f: COOMe	60[b]	40[b]	90	<5[e]	>95[e]	85
X-X						
g: -OSOO-	60[f] (64)	40[g] (36)	68	10[c,h] (18)	90[c,i] (82)	83
h: -OCSO-	57	43	72	20[a]	80[a]	72
i: -OCOO-	36	64	83[j]	9	91	89
j: $-OCM_2O-$	40	60	82[j]	–	100[a,c]	71[k]
k: $-OCH_2O-$	–	100	65[j]	–	–	–
l: $-(CH_2)_3-$	–	100	70[j]	–	100	62
m: $-(CH_2)_4-$	4[a,c]	96[a,c]	71	–	–	–

[a] Syn:anti ratio confirmed by ^1H NMR analysis of the crude reaction product. [b] Similar results for the reactions of **1c** and **1f** with diazomethane and of **1c** with 2-diazopropane has been reported in a preliminary communication by Martin et al.[7d] [c] Syn:anti ratio confirmed by GC analysis of the crude reaction product. [d] Total yield not reported because compound **1c** was used as an ethereal solution of unknown concentration. [e] Reference 3. These results have been confirmed by us. [f] Relative yield of the two syn diastereoisomers: **2g′**:**2g″** = 6:4. [g] Relative yield of the two anti diastereoisomers: **3g′**:**3g″** = 1:1 (^1H NMR ratio). [h] Only one syn diastereoisomer, i.e. **4g′**, was detected. [i] Relative yield of the two anti diastereoisomers: **5g′**:**5g″** = 1:1 (^1H NMR ratio). [j] Reference 6a. [k] Total yield from *cis*-3,4-dihydroxycyclobutene, precursor of **1j**.

dipolar cycloadditions to these dipolarophiles. In the present work we will show, on the basis of ab initio optimized geometry of several cyclobutenes,[6] that this is specifically true for the reaction of diazomethane, a 1,3-dipole characterized by a low dipole moment and a low steric demand.

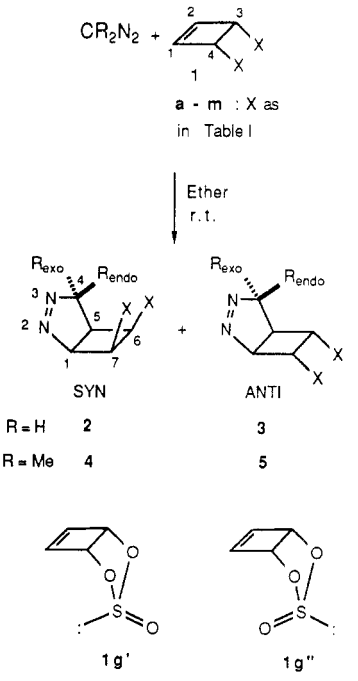
The intrinsic stereochemical demand of cyclobutenes can be modulated by various intermolecular effects, such as dipole–dipole and steric interactions, involving a direct "through space" interaction between the attacking 1,3-dipole and the substituent. Indeed, the results of 2-diazopropane cycloadditions, reported below, do well illustrate the role of steric effects. Moreover, we will show that a yet unexplored intermolecular "Coulombic effect" may be invoked as a factor which also favors syn attack of diazomethane in the case of cyclobutenes bearing allylic substituents containing heteroatoms.

As far as other theories are concerned, the relevance of Houk's staggered model,[8] of Hehre's electrostatic model,[9] of Cieplak's rule,[10] and of Fukui's "nonequivalent orbital extension" model[11] to the diastereoselectivity under study will be briefly commented.

Results

The complete list of cis 3,4-disubstituted cyclobutenes **1** under study is reported in Table I together with the experimental syn:anti ratios (determined by column chromatography) for their 1,3-dipolar cycloadditions with diazomethane (DZM) and 2-diazopropane (DZP) (see also Scheme I). Compounds **1a–e** and **1g–k** reacted readily (≤24 h) at room temperature with excess diazomethane

Scheme I



(ether solution) to give good to excellent yields of adducts, i.e., syn adducts **2** and anti adducts **3** (Scheme I and Table I). More sluggish were found the reactions of DZM with **11** (≥3 days), **1f** (≥15 days), and **1m** (>15 days). In the case of sulfinyldioxycyclobutene **1g** (actually a 1:1 mixture of **1g′** and **1g″**), the anti adduct consisted of a 1:1 mixture of the two diastereoisomers **3g′** and **3g″** while the two syn adducts, i.e. **2g′** and **2g″** (**2g′**:**2g″** ≃ 6:4), could be separated in a pure state. It is quite evident that, in order to compare on the same foot (at least as far as it is possible) the electronic effect of the sulfinyldioxy group with that of the other groups studied, we must consider the syn:anti ratio of the reaction of **1g′** (with the oxygen on the sulfur exo with respect to the cyclobutene ring). This value is given in parentheses in Table I and is based on ^1H NMR data (see Experimental Section) and on the reasonable assumption that the dominant syn adduct should be the less congested adduct, namely **2g′**.

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Table II. Syn:Anti Ratios for the Reactions of Ciclobutenenes 1 with Diazoethane and Phenyldiazomethane[a]

	relative yield				relative yield			
X	6, %	7, %	8, %	total yield, %	9, %	10, %	11, %	total yield, %
a: -OCOMe	100	–	–	90	100	–	–	62
e: -Cl[b]	94	4.5	1.5	88	≥95	≤5		80
f: -COOMe	54	33	13	75	55	45		68
i: -OCOO-	25	55	20	71	22	55	23	65
l: $-(CH_2)_3$	–	64	36	47				

[a] Ratios of adducts were evaluated by column chromatography. **7e:8e**, **7f:8f**, **7i:8i**, and **10i:11i** ratios by ^{1}H NMR. [b] 100% syn selectivity has been reported in refs 3b and 7b for the reaction of diazoethane with **1e**.

Table III. ^{1}H NMR Data [δ and J (Hz)] for Some Adducts of Diazomethane (Compounds 2 and 3) and of Phenyldiazomethane (Compounds 9–11) to Cyclobutenes 1[a-c] [$\Delta\delta = \delta(CDCl_3) - \delta(C_6D_6)$]

compd	solv	H-1	H-4-endo	H-4-exo	H-5	H-6	H-7	$J_{1,7}$	$J_{5,6}$	$J_{1,6}$	$J_{5,7}$
2c	C_6D_6	4.94	4.80	4.27	2.14	3.48	3.90	6.0	6.0	1.0	3.2
	$\Delta\delta$	0.47	0.09	0.44	0.57	0.53	0.52				
2d	C_6D_6	4.88	4.98	4.35	2.00	3.61	4.05	6.5	6.5	1.2	3.2
	$\Delta\delta$	0.48	−0.04	0.27	0.66	0.53	0.45				
2f	$CDCl_3$	5.51	5.14	4.80	2.69	3.52	4.03	9.5	10.0	1.0	1.5
	$\Delta\delta$	0.51	−0.05	0.29	0.64	0.52	0.37				
3f	$CDCl_3$	5.40	4.63		3.11	2.78	3.40	3.0	6.0	1.0	1.0
	$\Delta\delta$	0.21	0.61		0.41	0.48	0.25				
2h	$CDCl_3$	5.72	5.25	4.68	3.06	5.25	5.65	6.3	5.8	2.7	3.0
	$\Delta\delta$	1.35	0.69	1.06	1.80	1.64	1.56				
3h	$CDCl_3$	5.75	4.83		3.08	4.73	5.15	1.0	1.5	–	–
	$\Delta\delta$	1.00	1.28		1.35	1.44	1.12				
9i[d]	$CDCl_3$	5.94	6.26	–	2.98	5.18	5.54	6.0	6.0	3.0	2.0
	$\Delta\delta$	1.03	0.33		1.05	1.31	1.24				
10i[d]	$CDCl_3$	5.86	5.86	–	2.97	4.69	5.01	1.0	2.0	–	1.0
	$\Delta\delta$	1.06	0.92		1.13	1.41	1.02				
11i[e]	$CDCl_3$	5.70	–	6.01	3.32	4.26	4.93	1.0	2.0	–	1.0
	$\Delta\delta$	0.92	–	1.01	1.14	0.94	1.03				

[a] $J_{6,7}$ are in the range of 5.5–6.5 Hz for all of the adducts in this table but **2f** and **3f** ($J_{6,7}$ = 10.0 Hz), $J_{4\text{-exo},4\text{-endo}}$ are in the range of 18.0–19.0 Hz, and $J_{1,5}$ are in the range of 6.0–7.0 Hz. [b] $J_{1,4\text{-endo}} \simeq 2.5$ Hz and $J_{1,4\text{-exo}} \leq 1.0$ Hz in **2c,d,f,h**. [c] $J_{4\text{-endo},5} = 4.5$ Hz in **2c** and **2d**, 5.0 Hz in **2f**, and 2.9 Hz in **2h** while $J_{4\text{-exo},5} = 9.0$ Hz in **2c,d,f** and 9.5 Hz in **2h**. [d] $J_{1,4} = J_{4,5} = 2.6$ Hz in both **9i** and **10i** (for **10i** calculated from the spectrum in C_6D_6). [e] $J_{4,5} = 9.5$ Hz and $J_{1,4} = 1.5$ Hz.

As for diastereoselectivity the reaction of DZM covers the whole range of facial selectivity from 100% syn diastereoselectivity (with **1a–d**) to 100% anti diastereoselectivity (with **1k** and **1l**) through mixtures of various syn:anti ratios (with **1e–j** and **1m**). Both Franck-Neumann et al.[3b] and, very recently, Martin et al.[7b] have stated that the reaction of DZM with *cis*-3,4-dichlorocyclobutene (**1e**) affords exclusively the syn adduct **2e**. By contrast we managed to isolate and characterize small amounts (≃4%) of the anti adduct **3e**. Isolation of **3e** is noteworthy because it suggests that in the case of **1a–d** just less anti adduct than we could detect (1–2%) is formed. That is, the difference in energy between the transition states leading to syn and anti adducts in the case of **1a–d**, most probably, does not exceed ≃3.0 kcal/mol. At this point one can ask whether there is a parallelism between reaction rates and syn:anti ratios. The dominance of syn attack in the case of bis(methoxycarbonyl)cyclobutene (**1f**) and the 100% anti selectivity in the case of (methylenedioxy)cyclobutene (**1k**) clearly show that a favored syn attack is not always associated with a fast reaction and vice versa.[12]

2-Diazopropane is less stable but more reactive than diazomethane, and high yields of adducts (i.e., **4** and **5**, Scheme I) could also be isolated (Table I). The tendency to enter syn attack is significantly lower for DZP than for DZM, and, as a result, no examples of 100% syn selectivity were found for the former 1,3-dipole. Nevertheless, OAc, OSO_2Me, OMe, and OCH_2Ph groups promote a remarkably high syn selectivity. Noteworthy, the diastereoselectivity observed for DZP (as a whole) parallels that of DZM.

To support the assumption (see Discussion) that the differing facial selectivity observed for DZP in comparison with DZM is steric in origin, we extended our study to the reactions of diazoethane and phenyldiazomethane with cyclobutenes **1a,e,f,i,l** (Scheme II and Table II). The diastereoisomer analysis was somewhat complicated by the fact that anti attack can occur according to two orientations, exo (which is dominant) and endo, leading to anti-exo (**7** and **10**) and anti-endo (**8** and **11**) adducts, respectively. However, inspection of Table II clearly reveals that the behavior of diazoethane and phenyldiazomethane is very similar to that of DZM, thus ruling out any relevant electronic effect on facial selectivity by the substituent on the diazoalkane.

The structure of compounds **2–11** was assigned on the basis of analytical and spectroscopic data (IR and ^{1}H NMR) as well as of their behavior on TLC. The absence of isomerization from 1-pyrazoline to 2-pyrazoline was easily established by IR spectra; the weak absorption of the azo group at ≃1540 cm^{-1} was observed in all of the adducts, whereas, consistently, no N–H stretching absorption could be detected.

A fast easy distinction between syn and anti adducts was allowed by TLC analysis. In fact, in agreement with the expected dipole moment for syn adducts, which are significantly higher than those of the corresponding anti adducts,[13] the former compounds showed, as a rule, a lower R_f value (silica gel and cyclohexane/ethyl acetate mixtures as eluant) on TLC than the latter. Although apparently

(12) In this connection it may be of interest that Martin et al. were not able to find out any relationship between π^* energy of the cyclobutene ($LU_{cyclobutene}$ – HO_{DZM} MO interaction certainly plays a dominant role in controlling the rate of the reaction of cyclobutenes with DZM) and syn:anti ratios.[7d]

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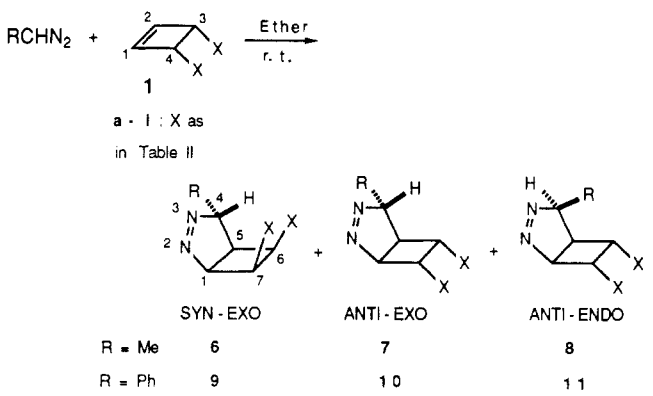
Table IV. ^{1}H NMR Data [δ and J (Hz)] for Some Adducts of 2-Diazopropane to Cyclobutenes 1 [$\Delta\delta = \delta(CDCl_3) - \delta(C_6D_6)$][a]

compd	solv	H-1	H-5	H-6	H-7	Me-4-endo	Me-4-exo	$J_{1,7}$	$J_{5,6}$	$J_{1,6}$	$J_{5,7}$
4a	C_6D_6	4.90	1.63	5.03	5.32	1.60	0.74	6.4	7.3	2.6	2.2
	$\Delta\delta$	0.52	0.87	0.23	0.20	0.11	0.36				
5a	$CDCl_3$	5.38	2.50	4.90	5.08	1.63	1.22	2.4	4.5	1.0	1.0
	$\Delta\delta$	0.31	0.42	0.08	−0.05	0.24	0.38				
4b	$CDCl_3$	5.30	2.63	5.46	5.51	1.83	1.18	6.2[b]	7.2	2.6	2.2
	$\Delta\delta$	0.83	1.18	0.74	0.67	0.12	0.53				
5b	$CDCl_3$	5.49	2.89	4.75	5.10	1.69	1.23	1.0	5.0	1.0	1.0
	$\Delta\delta$	0.58	0.59	0.36	0.29	0.34	0.60				
4g′	$CDCl_3$	5.72	2.56	5.30	5.48	1.85	1.08	6.0	6.0	2.0	2.0
	$\Delta\delta$	0.94	1.24	0.95	1.01	0.28	0.56				
5g′	C_6D_6	4.70	1.62	4.36	4.70	0.98	0.60	1.5[c]	2.0	–	1.0
	$\Delta\delta$	0.73	0.86	0.70	0.55	0.67	0.65				
5g″	C_6D_6	5.45	2.60	4.12	4.45	1.02	0.60	1.5	2.5	–	1.0
	$\Delta\delta$	0.30	0.35	0.82	0.68	0.63	0.65				

[a] $J_{1,5}$ in anti adducts are higher than in syn adducts (e.g., $J_{1,5}$ = 7.5 Hz in **5a** and **5b** vs 5.5 Hz in **4a** and **4b**) whereas the opposite is true for $J_{6,7}$ (e.g., $J_{6,7} \simeq 6.7$ Hz in **4a** and **4b** vs $\simeq$ 5.5 Hz in **5a** and **5b**). [b] J evaluated from the spectrum in C_6D_6. [c] J evaluated from the spectrum in $CDCl_3$.

Scheme II



very rough this method is actually very reliable; as a matter of fact it works well for all of the couples of syn/anti adducts reported in Table I and II but **4c** and **5c**. Even in this latter case there is not an inversion of R_f, but the two diastereoisomers move together on TLC. In the case of adducts derived from diazoethane and phenyldiazomethane the two anti adducts exhibit the same or a very similar R_f value which is significantly higher than that of the syn adduct.

In Tables III and IV a collection of ^{1}H NMR data is reported which illustrates the diagnostic features used for definitive structural assignments. When a pair of syn and anti adducts is considered, both $J_{1,7}$ and $J_{5,6}$ in the syn adduct are always larger than the related coupling constants in the anti adduct in accord with a cis relationship between the protons involved in these couplings in the former adduct and a trans relationship in the latter one. In particular, the values of $J_{1,7}$ ($\leq$3.0 Hz) in anti adducts (which are always lower than $J_{5,6}$ as a result of the electronegativity effect of the azo group or as a consequence of some puckering of the cyclobutane ring) lie well outside the range of possible values for cis coupling constants in cyclobutanes ($\geq$5.0 Hz).[14] Likewise $^4J_{1,6}$ and $^4J_{5,7}$ are, as a rule, higher in syn adducts than in the related anti adducts. Particularly informative were also found the chemical shifts of protons at position 4 in pyrazolines **2** and **3**. In fact H-4-endo and H-4-exo in anti adducts **3** absorb at very similar fields in $CDCl_3$ and on passing from $CDCl_3$ to C_6D_6 experience very similar upfield shifts. Moreover their upfield shifts either compare well with or are even higher than the upfield shifts of the other ring protons (i.e., H-1, H-5, H-6, and H-7). In contrast, the corresponding hydrogens in syn adducts **2** give rise to two well-separated signals in $CDCl_3$ solutions, owing to the fact that syn substituents make the two protons at position 4 feel a significantly different chemical environment. On changing C_6D_6 for $CDCl_3$ H-4-exo moves to higher field in a comparable way to the other ring protons while the chemical shift of H-4-endo is either practically unaffected (entries 1–3 of Table III) or when it experiences a significant upfield shift (entries 5 and 7 of Table III) its shift is definitively the lowest of all ring protons. Syn substituents should, and actually do, shield the 4-endo proton in adducts **2** from efficient solvation. In a similar way one can argue about the ^{1}H NMR behavior of Me-4-exo and Me-4-endo in adducts **4** vs that of the same groups in adducts **5** even if the difference is less dramatic.

Protons at position 4 of the adducts of diazomethane to cyclobutenes exhibit very different coupling constants (see footnotes in Table III) not only with H-5 ($J_{cis} \simeq 9.0$ Hz and $J_{trans} \simeq 4.5$ Hz) but also with H-1 ($J_{cis} \leq 1.0$, $J_{trans} \simeq 2.5$ Hz). The values of these coupling constants disclosed the possibility of an easy choice between the two anti diastereoisomers obtained in the reactions of diazoethane and phenyldiazomethane with cyclobutenes **1**. Actually the dominant isomer was that one with lower $J_{4,5}$ and higher $J_{1,4}$ (that is with H-4 trans with respect to H-1 and H-5) deriving from the less crowded exo-TS. Likewise this very same criterion, along with the aromatic solvent-induced effect illustrated above, allowed a safe structural assignment (with H-4 in the endo position) to the only syn adduct detected in the reactions of these two diazoalkanes.

Discussion

Starting from the reaction of diazomethane with "acyclic" cis 3,4-disubstituted cyclobutenes **1a–f** (top half of Table I), the higher contrasteric syn selectivity found for X = OAc, OMe, OSO_2Me, Cl, OCH_2Ph no doubt provides compelling evidence of the dominance of electronic factors over steric repulsions. But the question arises of how important is the steric hindrance, which tends to impede the syn attack of diazomethane on the cyclobutenes **1a–e**. Calculated (ab initio) structural data for cyclobutenes 1[6] disclose that the dihedral angle β (see Figure 2 for definition) between the cyclobutene ring and the plane defined by C–X bonds is quite large (i.e., in cyclobutenes with acyclic substituents its value is $\geq$114°).[6b] Moreover the direction of approach of a 1,3-dipole to compounds **1** is likely to resemble that depicted in Figure 1. As a result steric effects in the 1,3-dipolar addition to

(14) Gamba, A.; Mondelli, R. *Tetrahedron Lett.* **1971**, 2133; *Org. Magn. Reson.* **1973**, *5*, 101.

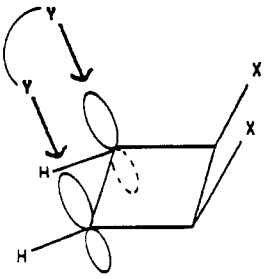


Figure 1.

cyclobutenes may well be somewhat less important than one could at first sight expect. It should also be stressed that the most stable conformation of substituents in cyclobutenes **1a–d** leaves the syn face rather free from steric congestion as shown by their ab initio structures.[15] Consequently electronic syn orienting effects, which are relatively strong owing to the cooperation of the two substituents at positions 3 and 4, are not overshadowed by repulsive factors (steric and dipole–dipole interactions) and clearly emerge in the reaction of diazomethane with **1a–e**. Passing to cyclobutene **1f**, steric hindrance on the syn face slightly increases but syn attack is still dominant, leading to the conclusion that dominance of syn attack can also be observed for substituents connected to cyclobutene ring through a carbon atom. No examples of 100% anti selectivity have so far been reported for cyclobutenes with acyclic substituents; an example of dominant anti addition is provided by the reaction of diazomethane with *cis*-3,4-dimethylcyclobutene (syn:anti = 30:70).[16]

The bottom half of Table I shows how cyclic disubstitution on cyclobutenes brings about a remarkable decrease in the tendency of diazomethane to attack the syn face of these dipolarophiles. Specifically, examples of 100% anti selectivity were found for both carbocyclic disubstitution (entry l) and heterocyclic disubstitution (entry k). However, there are also noteworthy examples of syn selectivity as in the case of (sulfinyldioxy)- and (thiocarbonyldioxy)cyclobutenes (entries g and h).

Steric interactions are certainly a factor of prime importance in disfavoring syn attack in the case of bulky 1,3-dipoles such as DZP, and the decrease in syn selectivity observed for this 1,3-dipole (Table I) can confidently be ascribed to its high steric demand. As far as acyclic substituents are concerned, steric repulsions are particularly effective in the case of dichloro- and bis(methoxycarbonyl)cyclobutenes so that they cause reversal of facial selectivity with respect to diazomethane. However, the high syn selectivity observed for **1a–d** once more testifies to the strength of the electronic syn orienting effects. But, what about these effects? The results reported in this paper for the four diazoalkanes studied as well as our results for other 1,3-dipoles (such as nitrones, nitrile oxides, nitrile imides and azomethine imides)[1,4,6] make it evident that, whatever the 1,3-dipole, cyclobutenes tend to impose their own stereochemical demand, that is, some intrinsic

(15) (a) Actually our ab initio (4-31G and STO-3G basis sets) calculations were carried out with imposed C_s symmetry.[6b] In the case of *cis*-3,4-dichlorocyclobutene optimization without symmetry constraints led to almost identical results in particular for the out-of-plane bending of olefinic hydrogens [i.e., $\alpha_1(H_1C_1C_2C_3) = -2.05°$ and $\alpha_2(H_2C_2C_1C_4) = -2.23°$ to be compared with $-2.24°$ (see Table V); $\beta_1(C_1C_4C_3Cl) = 115.61°$ and $\beta_2(C_2C_3C_4Cl) = 116.03°$ vs $\beta = 115.82°$]. (b) The X-ray structure of *cis*-3,4-bis(mesyloxy)cyclobutene (**1b**) [$\beta_1(C_1C_4C_3O) = 112.6°$ and $\beta_2(C_2C_3C_4O) = 115.0°$] fully confirms this statement and shows that deviation from C_s symmetry is actually small; methanesulfonyl groups are located exo with respect to the cyclobutene ring. Gatti, G. Università di Pavia, private communication.

(16) Keppel, R. A.; Bergman, R. G. *J. Am. Chem. Soc.* **1972**, *94*, 1350.

Table V. Olefinic Hydrogens Out-of-Plane Bending (α, deg) for Ground-State Cyclobutenes and Energy Asymmetry [$\Delta E_{\pm 20°} = E_{+20°} - E_{-20°}$, kcal/mol] of Distorted Cyclobutenes[a,b]

cyclobutene	α	$\Delta E_{\pm 20°}$
1a	−2.6[c]	2.7[g]
1b	−1.6[c]	1.15[g]
1c	−1.43[d]	1.48[h]
1e	−2.24[d]	2.14[h]
dimethylcyclobutene	−0.90[d]	0.69[h]
1f	−0.40[e]	0.27[g]
1h	0.1[d]	−0.52[h]
1i	0.51[d]	−1.0[h]
1j	−0.17[d]	−0.51[h]
1k	0.20[d]	−0.90[h]
1l	0.96[d]	−0.95[h]
1m	−0.50[f]	+0.43[g]
bicyclo[2.2.0]hex-2-ene	3.91[d]	−3.35[h]
bicyclo[2.1.0]pent-2-ene	7.08[d]	−5.36[h]

[a] A negative value of the bending angle α (or a positive value of $\Delta E_{\pm 20°}$) means a predicted syn selectivity. [b] The experimental syn:anti ratios are shown in Table I (for compounds **1a–m**) and in Figure 2 (for dimethylcyclobutene, bicyclohexene, and bicyclopentene). [c] STO-3G optimization with imposed C_s symmetry (see also ref 6b). [d] 4-31G optimization (C_s symmetry; refs 6a and 6b). [e] STO-3G optimization (C_s symmetry). The geometry of COOMe groups was fixed to the values obtained by full geometry AM1 optimization of **1f**. In this latter structure deviation from C_s symmetry is small and the oxygen atoms of the two carbonyl groups are located above the cyclobutene ring. [f] STO-3G optimization (C_s symmetry) of the most stable boat-endo form. [g] STO-3G calculations on STO-3G structures. [h] STO-3G calculations on 4-31G structures.

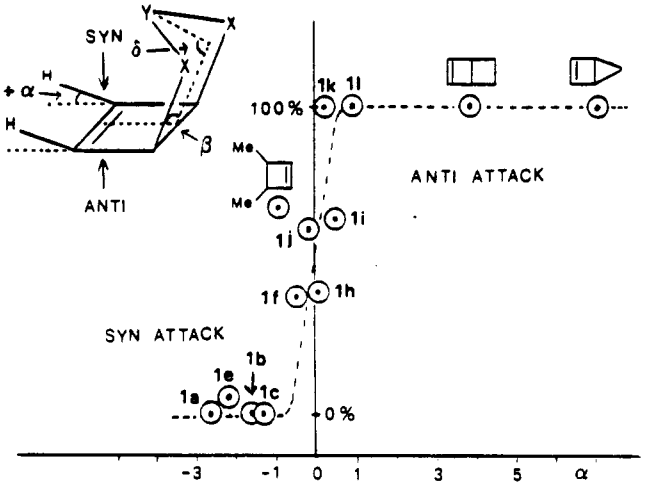


Figure 2. Anti addition (%) for the reaction of diazomethane with cyclobutenes 1 vs α.

feature of cyclobutenes tend to guide facial selectivity. A clue to this "stereoelectronic" factor is provided by our ab initio MO calculations[1,6] which have revealed that: (i) the double bond in cis 3,4-disubstituted cyclobutenes is pyramidalized, (ii) the extent and direction of their ground-state pyramidalization depend on the type of substituents and on whether these substituents are part of a ring condensed onto the cyclobutene moiety. Thus, electron-withdrawing substituents such as Cl, OMe, etc. induce an out-of-plane anti ($\alpha < 0$) bending of the olefinic hydrogens whereas cyclobutenes condensed onto small carbocyclic ring exhibit high syn ($\alpha > 0$) bending (see Table V and Figure 2). In particular, ring closure, namely on passing from acyclic to related cyclic substituents, favors syn bending and, as a result, there is a flattening of the double bond on passing from **1a** and **1c** to **1i** and **1k**, respectively, and an inversion of out-of-plane distortion on passing from *cis*-3,4-dimethylcyclobutene ($\alpha = -0.90°$) to bicycloheptene

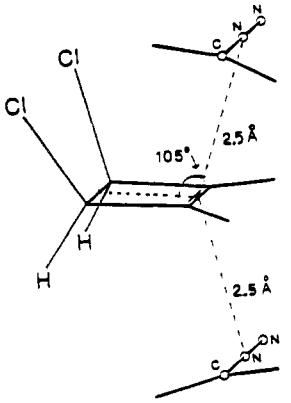


Figure 3.

11 (α = 0.96°). The plot of syn:anti ratios of diazomethane cycloadditions vs α [Figure 2;[17] $\alpha(H_1C_1C_2C_3)$ in symmetrical cyclobutenes is the dihedral angle between the plane of the two olefinic C–H bonds and the cyclobutene plane] makes it apparent that there is a qualitatively good parallelism between nonplanarity of the cyclobutene double bond and facial selectivity in these reactions.[20] Cyclobutenes with $|\alpha| < \sim 1.0°$ are candidates for mixtures whereas $|\alpha| > \sim 1.0°$ should tend to promote high (either anti or syn) facial selectivity. In particular, it is gratifying that the prediction based on α values of a lessening of the tendency to afford syn adducts on passing from acyclic to cyclic disubstitution (i.e., from **1a**, **1c**, and dimethylcyclobutene to **1i**, **1k**, and **1l**) is borne out by the experimental findings reported in Table I. Moreover ground-state nonplanarity of the double bond suggests that there should be a related energy asymmetry of the out-of-plane bending of the olefinic hydrogens on their way toward TS. For example, syn bent cyclobutenes should resist the anti bending of olefinic hydrogens induced by a syn attack of diazomethane more strongly than the further syn bending required by an anti attack of the 1,3-dipole. In fact when a prefixed deformation of olefinic hydrogens of +20° (syn) and −20° (anti), respectively, was imposed to cyclobutenes, the energy differences of the resulting syn and anti bent form [i.e., $\Delta E_{\pm 20°} = E_{+20°} - E_{-20°}$] (Table V) well correlate with the α values and, consequently, with the observed facial selectivity. Finally, we have also shown that the adduct favored by an easier double bond distortion takes also advantage of a higher charge-transfer interaction between occupied and unoccupied MOs of the partner reactants.[1c] We can conclude that ground-state π-bond pyramidalization and the related bending asymmetry lends itself as a reasonable candidate for the intrinsic "electronic"

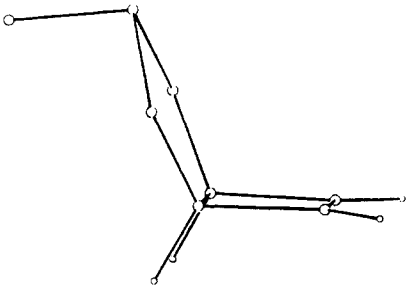


Figure 4. AM1 structure of the more stable conformer of **1g'**.

facial bias of cyclobutenes which is a major controlling factor of facial selectivity.

What is the underlying reason which guides double-bond distortion in cyclobutenes? A detailed analysis of intramolecular interactions, using a hybrid atomic orbital basis, has led us to propose that the nonplanarity of the double bond occurs in the direction of increasing hyperconjugative interactions between the hybrid atomic orbital involved in the σ-allylic bonds and in the π-bond.[1,6] Double bond nonplanarity in cyclobutenes can also be explained by the PMO theory based on the bond orbital approach: in this model bending was attributed to a tendency to minimize σ_{CH}/π and maximize σ^*_{CX}/π interactions.[2g]

A further effect, which tends to differentiate CT energies of the two orientation complexes leading to the syn and anti adduct, respectively, could be at work with cyclobutenes containing heteroatoms in the substituents. Both semiempirical and ab initio calculations show that when reactants, in the geometrical structures of their isolated molecules, are approached according to Figure 3 the energy gap of the FO interactions undergo significant changes.[21] In the case of dimethylcyclobutene the energy gaps of the dominant FO interaction are practically the same for both the anti ($\epsilon_{LU,cyclobutene} - \epsilon_{HO,DZM}$ = 13.78 eV) and the syn (13.89 eV) attack. In the case of dichlorocyclobutene the energy gap of the highly dominant FO interaction is substantially, even if not dramatically, lower for the syn (12.05 eV) than for the anti approach (12.76 eV). This effect is not due to delocalizing interactions between the reagents (e.g., orbital mixing between the system of the 1,3-dipole and the heteroatom lone pairs) but it is electrostatic in nature and can be classified as a Coulombic or field effect.[21] Anyway, this effect, which certainly warrants further systematic studies in order to assess its role in this and other kinds of selectivity, favors the syn approach by enhancing its charge-transfer stabilization in the case of substituents containing heteroatoms.[22]

(17) In Figure 2, aside from cyclobutenes investigated in this work, bicyclo[2.1.0]pent-2-ene,[18] bicyclo[2.2.0]hex-2-ene[19] (only anti adducts were detected in their 1,3-dipolar cycloadditions), and dimethylcyclobutene,[16] whose reactions have been investigated by other authors, are reported.

(18) Adam, W.; Beinhauer, A.; De Lucchi, O.; Rosenthal, R. J. *Tetrahedron Lett.* **1983**, *24*, 5727.

(19) Christl, M.; Mattauch, B. *Chem. Ber.* **1985**, *118*, 4203.

(20) (a) In particular in range in which out-of-plane bending does not impose a clear-cut facial choice (i.e., when $|\alpha| < \sim 1.0°$) the presence of other factors does not leave room for a quantitative relationship between α values and syn:anti ratios. Thus, for example, in the case of dimethylcyclobutene (α = −0.90°) the "wrong" dominance of the anti attack can confidently be ascribed to steric factors. (b) The relationship between nonplanarity of cyclobutene double bond and facial selectivity had briefly been suggested by Houk et al.[2g] and then, repeatedly, stressed by us.[1,6] More recently this relationship has also been noted by Martin et al.[7d] (c) Gleiter had previously suggested that ease of deformation of the double bond may be a rate and diastereoselectivity determining factor in norbornene reactions: Spanget-Larsen, J.; Gleiter, R. *Tetrahedron* **1983**, *39*, 3350.

(21) INDO and ab initio (3-21G) (reported values are from 3-21G calculations) model calculations have been made on supermolecules in their syn and anti approaches. The frontier orbital energy shifts with respect to the isolated molecules can produce different energy gaps for the two approaches, so that syn and anti attacks can be compared in the qualitative frontier orbital model. In the presence of Cl and OMe substituents both approximations give lower energy gaps ($\epsilon_{LU,cyclobutene} - \epsilon_{HO,DZM}$) for the syn than for the anti attack. Further calculations (INDO, ab initio 3-21G) on the same systems, carried out in the absence of delocalizing interactions between the reactants, show that the difference of FO energy gaps survives and underline its electrostatic origin. The explanation has been checked in other systems (e.g. syn/anti attack of diazomethane to methoxyallene) and found it to be of general value. The finding that with *cis*-3,4-dimethylcyclobutene the energy gaps of syn and anti approaches are not discriminated corroborates our explanation of the effect. An extended report of these results is in preparation.

(22) This effect helps counteract repulsive interactions between the substituents and the incoming DZM. However it should be stressed that, as a whole, the direct through space interaction between the substituents and the 1,3-dipole is destabilizing as shown by the high anti selectivity found for the reaction of diazomethane with cis,endo-5,6-disubstituted bicyclo[2.2.2]oct-2-enes. Burdisso, M.; Gandolfi, R.; Rastelli, A., to be published. See also Burdisso, M.; Gandolfi, R.; Pevarello, P.; Rastelli, A. *Tetrahedron Lett.* **1987**, *28*, 1225.

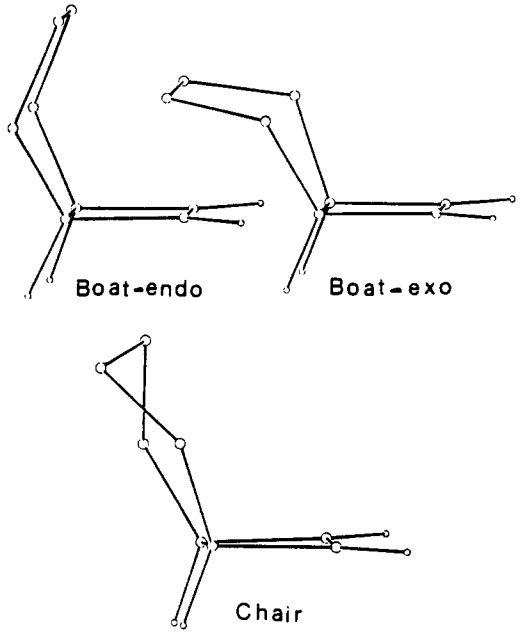


Figure 5.

This latter factor might fully reconcile with theory the prevalent formation of the syn adduct in the reactions of DZM with **1f** and **1h**. In these cases, on the basis of α values and taking into account steric effects, a slight prevalence of the anti adduct seemed a priori more reasonable. On the other hand the anticipated preference for anti addition in the case of bicycloheptene **1l** and, even more, in the case of its dioxa derivative **1k** does require some help to reach the observed 100% anti selectivity in their reaction with DZM. We have recently shown that compounds **1l** and **1k** prefer a boatlike conformation [i.e., dihedral angle δ (see Figure 2 for definition) = 143.9° and 152.8°, respectively][6a] in which a severe steric hindrance is present on the syn face leading to anti specificity. However other bicyclic derivatives show a very flat conformation for the cyclopentane ring (e.g., $\delta \simeq 174°$ for **1h**,[6b,23a] **1i**,[6] and **1g'**; see the fully optimized AM1 geometry[23b] reported in Figure 4 for the latter compound),[23c] leaving room for electronic control. In this connection particularly interesting is the case of bicyclo[4.2.0]oct-7-ene (**1m**). In fact MM2 calculations[24a] reveal that the most stable conformation of **1m** is a boat–endo structure but also that the boat–exo form and, to a lesser extent, the chair form (see Figure 5) should be appreciably populated [relative energies (kcal/mol): 0.0, 0.45, and 0.78],[24b] thus allowing for some syn attack.

Other Models

Further effects advanced by other authors in different contexts, but pertinent to the chemistry reported here, must be mentioned: Houk's staggering effect,[2j,k,8] Hehre's electrostatic model,[9] Cieplak's σ (allylic bond)–σ^* (forming bond) interaction,[10] and Fukui's "nonequivalent orbital extenstion".[11]

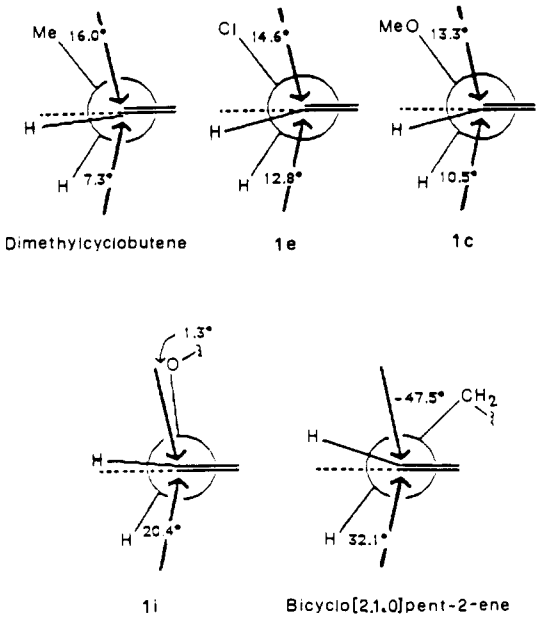


Figure 6. Newman projections along the C_1C_4 bond of some cyclobutenes showing the dihedral angles formed between the forming bond (bold arrows) and the allylic CX (syn attack) and CH (anti attack) bonds.

The tendency of the forming bond to be as staggered as possible with respect to the allylic bonds (Houk's staggered model) warrants a particular mention due to its wide applicability and success. In particular, it gives a very satisfactory explanation of the facial selectivity observed in 1,3-dipolar cycloadditions of nitrile oxides with open chain alkenes and norbornene. However, it does not seem to give an unambiguous account of the whole trend of the results with cis 3,4-disubstituted cyclobutenes. If we assume an angle between the forming bonds and the double bond of 104°,[25] we obtain the dihedral angles between the forming bonds and the allylic C–X and C–H bonds reported in Figure 6 for some cyclobutenes. This leads to the prediction of anti attack for **1i**, a dominant syn attack for bicyclopentene and mixtures for dimethylcyclobutene, **1c**, and **1e** but with a higher percentage of syn attack in the former dipolarophile than in the latter two in striking contrast with experimental data. In particular, it is not possible on the basis of the staggering effect to explain the 100% syn selectivity observed for **1a–d**. However, this effect should play some role, and, for example, the increase in syn attack on passing from **1i** to **1c** is, inter alia, favored by the outward rotation of the oxygen atoms and inward rotation of the hydrogen atoms in the latter compound with respect to the former.

The reactivity model by Hehre[9] predicts that nucleophiles (electrophiles) will attack double bonds anti (syn) with respect to lone pair containing allylic substituents; if this general rule is applied to the cycloadditions of diazomethane to cyclobutenes, predictions follow which are in disagreement with experimental findings, at least if diazomethane is considered as a nucleophile. It is well known that DZM is classified as an "electron rich" 1,3-dipole.[26] Cieplak's model predicts that an attack on a

(23) (a) A single-crystal X-ray analysis showed that thiocarbonyldioxycyclobutene (**1h**) has C_s symmetry with $\beta = 114.2°$ and $\delta = 177.1°$ (Gatti, G. Università di Pavia, private communication) in agreement with the calculated values. (b) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902. (c) $\beta_1(C_1C_4C_3O) = 116.7°$, $\beta_2 2(C_2C_3C_4O) = 114.9°$, and $\delta \simeq 173.9°$. A slightly less stable conformer (by 0.14 kcal mol^{-1}) exhibits the following angles: $\beta_1 = 115.0°$, $\beta_2 = 115.1°$, and $\delta \simeq 185.7°$.

(24) (a) Allinger, N. L. *J. Am. Chem. Soc.* **1977**, *99*, 8127. (b) Boat-endo, boat-exo and chair form (MM2 calculations) exhibit the following α and β values: $\alpha_1(H_1C_1C_2C_3) = -0.2°$, $-0.4°$, and $-1.8°$, respectively; $\alpha_2(H_2C_2C_1C_4) = -0.4°$, $-0.6°$, and $0.4°$, respectively; $\beta_1(C_1C_4C_3C) = 115.4°$, $115.3°$, and $120.2°$, respectively; $\beta_2(C_2C_3C_4C) = 116.4°$, $116.6°$, and $108.5°$, respectively. $\delta = 131.4°$ and $235°$ for the boat-endo and the boat-exo form, respectively.

(25) Mc Douall, J. J. W.; Robb, M. A.; Niazi, U.; Bernardi, F.; Schlegel, H. B. *J. Am. Chem. Soc.* **1987**, *109*, 4642.

(26) *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984.

double bond should occur as anti with respect to the more electron-rich σ allylic bond,[10,27a] thus easily explaining the high syn selectivity observed for cyclobutenes with electron-attracting substituents. Cieplak, on qualitative grounds, has suggested that face selectivity is controlled by a stabilizing hyperconjugative interaction between the σ^* orbital of the forming bond and the anti σ allylic bond. However, the theoretical foundation of this theory, in particular the importance of the σ^* orbital, has been questioned.[27b] In this connection one should be reminded that a major role in dictating selectivity in cyclobutenes has recently been assigned to a stabilizing interaction between the σ^* orbital of the syn allylic bond and the σ orbital of the partially formed bond[7b] and that a stabilizing σ^* (of the allylic substituents)–π interaction in the activated complex favoring syn attack has been advanced, several years ago, by Franck-Neumann.[3c]

Finally, predictions based on the "nonequivalent orbital extension" model are in contrast with our experimental findings. For example, in the case of cyclobutenes **1a–e** the π^* (π) orbital mixes into itself the σ^* (σ) orbital of the C_1–C_2 bond through the interaction with the $n_-(n_+)$ combination of the heteroatom lone pairs. As a result, according to Fukui's rules,[11] the perturbed π^* (π) orbital should be more developed on the anti (syn) face leading to the wrong prediction of anti dominant attack for the reaction of the electron-rich DZM with the electron-deficient cyclobutenes **1a–e**.

Conclusions

Cis 3,4-disubstituted cyclobutenes bearing open-chain electron-attracting substituents, containing heteroatoms, are anti bent (i.e., with the olefinic hydrogens bent on the opposite side with respect to substituents) in their ground-state structure as shown by MO calculations. They react with diazomethane, diazoethane, and phenyldiazomethane to afford syn adducts in ≥95% yield. Ground-state syn bent cyclobutenes (in particular with cyclic cis 3,4-disubstitution) exhibit a 100% anti selectivity whereas planar or almost planar cyclobutenes tend to afford mixtures of syn and anti adducts in the reactions with the same 1,3-dipoles. Thus, a relationship between nonplanarity of the double bond moiety in cis 3,4-disubstituted cyclobutenes and the facial selectivity of their reactions with diazoalkanes clearly emerges from theoretical and experimental data. We suggest that nonplanarity and the related energy asymmetry of out-of-plane bending of olefinic hydrogens in cyclobutenes not only parallel but actually play a relevant role in determining the facial selectivity observed in their reactions with diazoalkanes. This intrinsic stereochemical demand is modulated by various other effects such as steric effects (as shown by the reactions with 2-diazopropane), charge-transfer effects, staggering effects, etc.

Experimental Section

Melting points were uncorrected. Elemental analyses were made on a Carlo Erba CHN analyser, Model 1106. Infrared spectra were recorded on a Perkin-Elmer 157 spectrophotometer. NMR spectra were recorded either on a Bruker WP80SY or on a Varian Gemini 300 RT instrument with tetramethylsilane as internal standard. Protons were correlated by decoupling experiments. For most adducts also the aromatic solvent induced shift [(ASIS, $\Delta\delta = \delta(CDCl_3) - \delta(C_6D_6)$] was determined. ^{1}H NMR spectra were evaluated as first-order spectra. Mass spectra were measured on a Finnigan MATT 8222 using electron-impact (EI) and chemical-ionization (CI) modes. GC analyses were carried out with a Dani 6500, PTV injector, RSL 200 PB (25 m) and CP-Sil-19 CB (25 m) capillary columns, and carrier H_2. Thin-layer chromatograms were done on plates precoated with silica gel 60 GF_{254} (Merck). Spots were visualized either by spraying with 3% chromic oxide in sulfuric acid (50%) followed by heating at 120 °C or under UV light. Column chromatography was performed with silica gel 60 (70–230 mesh) (Merck), eluting with cyclohexane–ethyl acetate mixtures.

Cyclobutenes 1. Dichlorocyclobutene is commercially available. Cyclobutenes **1a**,[4d] **1c**,[28] **1f**,[29] **1i**,[30] **1j**,[6a], **1k**,[6a] **1l**,[31] and **1m**[32] were prepared according to literature procedures. Cyclobutenes **1b,d,g** and **1h** were prepared from *cis*-3,4-dihydroxycyclobutene[4c] by standard methods. Thus treatment of dihydroxycyclobutene (300 mg) (i) with methanesulfonyl chloride (2.0 molar equiv) and triethylammine (3.0 molar equiv) in dichloromethane at 0 °C led to **1b** (66%, purified by column chromatography), (ii) with thiocarbonyldiimidazole (2.0 molar equiv) in refluxing benzene for 15 h afforded **1h** (50% after column chromatography), (iii) with excess thionyl chloride (2.0 mL) in the presence of pyridine (0.5 mL) in refluxing chloroform for 2 h produced a ≃1:1 mixture of **1g′** and **1g″** (82%; this mixture was purified by column chromatography but we did not manage to separate the individual components). The preparation of **1d** was performed under phase-transfer conditions by vigorously stirring a mixture of dihydroxycyclobutene (200 mg), benzyl chloride (5 mL), sodium hydroxide (50%, 10 mL), and tetraethylammonium bromide (93 mg) for 24 h at room temperature. Then the organic layer was separated, and the aqueous phase was extracted (3 × 30 mL) with ether. The combined extracts were washed with water and dried. The solvent and most of the excess benzyl chloride were removed under reduced pressure, and the residue was column chromatographed to give pure **1d** (52%). **1b**: colorless prisms; mp 85–86 °C; ^{1}H NMR ($CDCl_3$) δ 3.17 (s, 6 H), 5.75 (m, H-3 and H-4), 6.62 (m, H-1 and H-2). **1d**: slightly yellow oil; ^{1}H NMR ($CDCl_3$) δ 4.72 (m, 6 H), 6.39 (m, 2 H). **1g**: slightly yellow oil; ^{1}H NMR ($CDCl_3$) δ 5.80 (m, 4 H), 6.55 and 6.75 (two multiplets, vinyl protons of **1g′** and **1g″**; **1g′**:**1g″** = 1.0); IR 1200 cm^{-1}. **1h**: slightly yellow prisms; mp 56–58 °C; ^{1}H NMR ($CDCl_3$) δ 5.70 (m, 2 H), 6.85 (m, 2 H).

Reaction of Diazoalkanes with Cyclobutenes 1. The cycloaddition reactions of cyclobutenes **1** (300 mg) with diazomethane were carried out in ether by using a large excess of the 1,3-dipole. The reaction mixture was kept at room temperature (≃21 °C) and after ≤24 h 100% conversion (TLC and GC analyses) was achieved in the case of **1a–e** and **1g–k**. High yields were also obtained after shorter reaction times and, for example, total yields reported in Table I for **1g–k** were achieved after 2 h in the case of **1g** and 5 h in the case of **1h–k**. Compound **1f** was reported as unreactive by Franck-Neumann.[3b] In our hands after 15 days at room temperature **1f** had almost disappeared. The yield reported in Table I for **1l** and **1m** are for a reaction time of 70 h and 15 days, respectively. In the case of **1m**, after that time GC analysis still showed the presence of significant amounts of the starting cyclobutene. After the appropriate time the solvent was evaporated, and diastereoisomer ratios were evaluated by column chromatography. These ratios were further qualitatively secured by TLC analysis (yet from the beginning of the reaction) and quantitatively by ^{1}H NMR analysis of the

(27) (a) For successful rationalizations, based on Cieplak's rule, of facial selectivity data, see: Chung, W.-S.; Turro, N. J.; Srivastava, S.; Li, H.; Le Noble, W. J. *J. Am. Chem. Soc.* **1988**, *110*, 7882 and references cited therein. Naperstkow, A. M.; Macaulay, J. B.; Newlands, M. J.; Fallis, A. G. *Tetrahedron Lett.* **1989**, *30*, 5077. (b) Wu. Y.-D.; Houk, K. N. *J. Am. Chem. Soc.* **1987**, *109*, 908. Wu, Y.-D.; Houk, K. N. In *Stereochemistry of Organic and Bioorganic Transformations*; Bartmann, W., Sharpless, K. B., Eds.; VCH: Deerfield Beach, 1987; p 247. (c) For a very recent experimental finding which does not follow the "Cieplak's rule", see: Meyers, A. I.; Wallace, R. N. *J. Org. Chem.* **1989**, *54*, 2509.

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crude reaction product. In some cases (see Table I) also GC allowed an evaluation of the diastereoisomer ratio yet from the very beginning of the reaction.

In the case of 2-diazopropane, diazoethane, and phenyldiazomethane the reactions were carried out under similar conditions (ether, room temperature, and excess 1,3-dipole), and diastereoisomer ratios were evaluated as described above for diazomethane. Diazoethane and 2-diazopropane reacted faster and phenyldiazomethane more slowly than diazomethane. As for the reliability of syn:anti ratios, it should be emphasized that acids, bases (even in trace amounts), heat, etc. can trigger decomposition (or isomerization) of 1-pyrazolines and sometimes we observed fast "unexpected" spontaneous decomposition of syn and/or anti adducts. Nevertheless, reproducible results could be obtained by operating with pure starting products under carefully controlled reaction and workup conditions. In particular, we observe neither syn ⇄ anti nor cis ⇄ trans isomerizations.

2a: colorless crystals from ether; mp 64–65 °C; IR 1740 and 1540 cm^{-1}; ^1H NMR (C_6D_6) δ 1.58 (s, COMe), 1.61 (s, COMe) 1.95 (m, H-5), 3.95 (ddd, H-4-exo, $J_{4\text{-endo},4\text{-exo}}$ = 18.0 Hz, $J_{1,4\text{-exo}}$ = 1.0 Hz, $J_{4\text{-exo},5}$ = 9.0 Hz), 4.55 (ddd, H-4-endo, $J_{4\text{-endo},5}$ = $J_{1,4\text{-endo}}$ = 3.0 Hz), 4.85 (ddd, H-6, $J_{5,6}$ = $J_{6,7}$ = 6.5 Hz and $J_{1,6}$ = 1.8 Hz), 4.93 (m, H-1), 5.30 (ddd, H-7, $J_{1,7}$ = 6.5 Hz and $J_{5,7}$ = 2.5 Hz). $\Delta\delta$: 0.40 (COMe), 0.41 (COMe), 0.97 (H-5), 0.65 (H-4-exo), 0.32 (H-4-endo), 0.43 (H-6), 0.64 (H-1), 0.30 (H-7); ^{13}C NMR ($CDCl_3$) δ 20.3 (q, Me), 33.15 (d, C-5), 68.55 (d, C-6), 69.1 (d, C-7), 78.7 (t, C-4), 88.2 (d, C-1), 169.5 (s, CO). Anal. Calcd for $C_9H_{12}N_2O_4$: C, 50.94; H, 5.70; N, 13.20. Found: C, 50.97; H, 5.70; N, 13.28.

2b: colorless crystals from ether; mp 81–83 °C dec; IR 1540, 1370, and 1180 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.00 (m, H-5), 3.10 (s, $MeSO_2$), 3.20 (s, $MeSO_2$), 4.76 (ddd, H-4-exo, $J_{4\text{-exo},4\text{-endo}}$ = 19.0 Hz, $J_{1,4\text{-exo}}$ = 1.0 Hz, $J_{4\text{-exo},5}$ = 9.0 Hz), 5.17 (ddd, H-4-endo, $J_{4\text{-endo},5}$ = $J_{4\text{-endo},1}$ = 3.0 Hz) 5.34 (m, H-6), 5.60 (m, H-1 and H-7). $\Delta\delta$: 0.77 ($MeSO_2$), 0.80 ($MeSO_2$), 1.32 (H-5), 0.86 (H-4-exo), ≤0.50 (H-4-endo), ≥0.70 (H-6, H-7, and H-1). Anal. Calcd for $C_7H_{12}N_2O_6S_2$: C, 29.58; H, 4.23; N, 9.86. Found: C, 29.77; H, 4.36; N, 9.66.

2c: colorless oil; IR 1540 cm^{-1}. Anal. Calcd for $C_7H_{12}N_2O_2$: C, 53.83; H, 7.74; N, 17.94. Found: C, 54.10; N, 8.05; N, 17.85.

2d: slightly yellow oil; IR 1540 cm^{-1}. Anal. Calcd for $C_{19}H_{20}N_2O_2$: C, 74.00; H, 6.54; N, 9.09. Found: C, 74.20; H, 6.73; N, 8.95.

The reaction of excess diazomethane with *cis*-3,4-dichlorocyclobutene (**1e**) went to completion within 4 h. Evaporation of the solvent led to a colorless solid residue, which was column chromatographed (cyclohexane/AcOEt, 7:3, as eluant) to afford pure **3e** (higher R_f) and **2e** as colorless solids. Compounds **2e** and **3e** on standing at room temperature either neat or in cyclohexane/ethyl acetate solution suffered a fast decomposition to give a brown-reddish product. **2e**: mp 70 °C dec; IR 1533 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.08 (m, H-5), 4.65 (ddd, H-4-exo, $J_{4\text{-exo},4\text{-endo}}$ = 19.0 Hz, $J_{1,4\text{-exo}}$ = 1.0 Hz, and $J_{4\text{-exo},5}$ = 9.0 Hz), 4.88 (ddd, H-6, $J_{5,6}$ = $J_{6,7}$ = 7.0 Hz and $J_{1,6}$ = 1.8 Hz), 5.13 (ddd, H-4-endo, $J_{4\text{-endo},5}$ = $J_{1,4\text{-endo}}$ = 2.5 Hz), 5.13 (ddd, H-7, $J_{1,7}$ = 6.0 Hz and $J_{5,7}$ = 2.5 Hz), 5.55 (m, H-1). $\Delta\delta$ 1.13 (H-5), 0.63 (H-4-exo), 0.83 (H-6), 0.31 (H-4-endo), 0.75 (H-7), 0.85 (H-1). **3e**: mp ≃55 °C dec; ^1H NMR (C_6D_6) δ 2.08 (m, H-5), 2.94 (ddd, H-6, $J_{5,6}$ = 6.3, $J_{6,7}$ = 6.0, and $J_{1,6}$ = 1.0 Hz), 3.50 (ddd, H-4-exo, $J_{4\text{-exo},5}$ = 7.0 Hz, $J_{4\text{-exo},4\text{-endo}}$ = 18.0 Hz, and $J_{1,4\text{-exo}}$ = 1.5 Hz), 3.75 (ddd, H-4-endo, $J_{4\text{-endo},5}$ = $J_{1,4\text{-endo}}$ = 2.8 Hz), 3.86 (ddd, H-7, $J_{1,7}$ = 3.0 Hz and $J_{5,7}$ = 1.0 Hz), 4.73 (m, H-1). $\Delta\delta$ 0.99 (H-5), 1.04 (H-6), 1.05 (H-4-exo), 1.02 (H-4-endo), 0.70 (H-7), 0.67 (H-1); IR 1532 cm^{-1}. Anal. Calcd for $C_5H_6N_2Cl_2$: C, 36.36; H, 3.60; N, 16.97. Found: C, 36.75; H, 3.66; N, 17.12.

2f: colorless prisms from benzene–petroleum ether; mp 89.5–90.5 °C (lit.[7d] no mp); IR 1750, 1540 cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 31.0 (d), 38.1 (d), 45.6 (d), 51.6 (q), 52.0 (q), 80.5 (t), 83.3 (d), 169.3 (s), 170.6 (s). **3f**: slightly yellow needles from benzene-petrol ether; mp 94.5–96 °C (lit.[7d] no mp); IR 1750, 1540 cm^{-1}; ^{13}C NMR ($CDCl_3$) δ 31.5 (d), 44.4 (d), 44.9 (d), 52.2 (q), 52.4 (q), 83.8 (t), 87.1 (d), 170.9 (s), 171.5 (s).

2g′: colorless crystals from cyclohexane; mp 87–88 °C; IR 1540, 1200 cm^{-1}; CI (isobutane) mass spectrum, m/e 175 (MH^+); ^1H NMR (C_6D_6) δ 1.38 (m, H-5), 3.70 (ddd, H-4-exo, $J_{4\text{-exo}}$ = 1.5 Hz, $J_{4\text{-exo},5}$ = 9.0 Hz, and $J_{4\text{-exo},4\text{-endo}}$ = 19.0 Hz), 4.36 (ddd, H-4-endo, $J_{1,4\text{-endo}}$ = $J_{4\text{-endo},5}$ = 3.0 Hz), 4.40 (m, H-1 and H-6), 4.80 (ddd, H-7, $J_{1,7}$ = $J_{6,7}$ = 5.5 Hz and $J_{5,7}$ = 3.0 Hz). **2g″**: colorless crystals from cyclohexane; mp 98–99 °C; IR 1540, 1200 cm^{-1}; CI (isobutane) mass spectrum, m/e 175 (MH^+); ^1H NMR (C_6D_6) δ 1.42 (m, H-5), 3.97 (ddd, H-6, $J_{1,6}$ = 2.0 Hz and $J_{5,6}$ = $J_{6,7}$ = 6.0 Hz), 4.03 (dd, H-4-exo, $J_{4\text{-exo},5}$ = 9.5 Hz and $J_{4\text{-exo},4\text{-endo}}$ = 18.0 Hz), 4.30 (ddd, H-7, $J_{1,7}$ = 6.0 Hz, $J_{5,7}$ = 3.0 Hz), 4.45 (m, H-1), 4.90 (ddd, H-4-endo, $J_{1,4\text{-endo}}$ = $J_{4\text{-endo},5}$ = 3.0 Hz). The shift to lower fields experienced by H-4-endo proton in **2g″** as compared to the same proton in **2g′** can easily be rationalized as a result of the deshielding effect of the oxygen atom of the sulfoxide group which in **2g″** faces this proton; **3g′** and **3g″** were obtained as a mixture (colorless solid): IR 1540 and 1200 cm^{-1}; CI (isobutane) mass spectrum, m/e 175 (MH^+). **3g′**: ^1H NMR (C_6D_6) δ 1.61 (m, H-5), 3.60 (m, H-4-endo and H-4-exo), 3.79 (dd, H-6, $J_{5,6}$ = 2.0 Hz and $J_{6,7}$ = 5.0 Hz), 4.54 (bd, H-7, $J_{1,7}$ and $J_{5,7}$ < 1.0 Hz), 4.68 (m, H-1). **3g″**: ^1H NMR (C_6D_6) δ 2.42 (m, H-5), 3.55 (dd, H-6, $J_{5,6}$ = 2.5 Hz and $J_{6,7}$ = 5.5 Hz), 3.60 (m, H-4-endo and H-4-exo), 4.32 (ddd, H-7, $J_{1,7}$ = $J_{5,7}$ = 1.0 Hz), 5.37 (m, H-1). Here again the deshielding effect of the oxygen atom of the sulfoxide group brings about a shift to lower field of H-5 and H-1 in **3g″** and H-6 and H-7 in **3g′** with respect to the chemical shift of the same protons in **3g′** and **3g″**, respectively.

2h: colorless needles from cyclohexane; mp 161–163 °C dec; IR 1540 cm^{-1}. Anal. Calcd for $C_6H_6N_2O_2S$: C, 42.35; H, 3.53; N, 16.47. Found: C, 42.34; H, 3.65; N, 16.35. **3h**: colorless needles from cyclohexane; mp 127–128 °C; IR 1540 cm^{-1}. Anal. Found: C, 42.42; H, 3.56; N, 16.3.

2m and **3m** were isolated as a mixture [slightly yellow oil; **2m** exhibited a slightly higher retention time than **3m** on GC (CP-Sil-19 CB column)]: IR 1540 cm^{-1}; the mass spectrum (GC/MS) of both **2m** and **3m** displayed a peak at m/e 151 (MH^+) under chemical-ionization mode (isobutane) while under electron-impact mode the mass spectrum of **2m** almost exactly matched that of **3m** with the most significant peaks of m/e (relative intensity) 79 (100), 93 (65), 107 (35), and 122 ($[M - N_2]^{\cdot+}$, 38). The molecular ion could not be detected under these latter conditions. **2m**: ^1H NMR ($CDCl_3$) δ 2.72 (m, H-5, $J_{1,5}$ = 5.5 Hz, $J_{5,6}$ = 9.0 Hz, and $J_{5,7}$ = 2.0 Hz), 3.01 (m, H-7, $J_{1,7}$ = $J_{6,7}$ = 9.0 Hz), 4.26 (ddd, H-4-exo, $J_{4\text{-exo},4\text{-endo}}$ = 18.0 Hz, $J_{4\text{-exo},5}$ = 9.0 Hz, and $J_{1,4\text{-exo}}$ = 2.0 Hz), 4.68 (ddd, H-4-endo, $J_{1,4\text{-endo}}$ = 3.0 Hz, $J_{4\text{-exo},5}$ = 2.0 Hz), 5.17 (m, H-1). The signals of all other protons of **2m** are buried under the signals of **3m** with the exception of two multiplets at δ 0.90 (1 H) and 1.12 (1 H). **3m**: ^1H NMR ($CDCl_3$) δ 1.20–1.80 (overlapping multiplets, 8 H), 1.90 (m, H-6), 2.37 (m, H-5 and H-7), 4.38 (ddd, H-4-exo, $J_{4\text{-exo},4\text{-endo}}$ = 18.0 Hz, $J_{1,4\text{-exo}}$ = 2.0 Hz, and $J_{4\text{-exo},5}$ = 7.0 Hz), 4.46 (ddd, H-4-endo, $J_{1,4\text{-endo}}$ = $J_{4\text{-endo},5}$ = 3.2 Hz), 4.87 (m, H-1, $J_{1,5}$ ≃ 6.0 Hz and $J_{1,7}$ ≃ 2.5 Hz).

4a: colorless needles from benzene–petroleum ether; mp 57–58 °C; IR 1740, 1535 cm^{-1}. Anal. Calcd for $C_{11}H_{16}N_2O_4$: C, 54.99; H, 6.71; N, 11.66. Found: C, 54.82; H, 6.65; N, 11.45. **5a**: colorless needles from cyclohexane; mp 78–79 °C; IR 1740, 1540 cm^{-1}. Anal. Found: C, 54.84; H, 6.61; N, 11.60.

4b: slightly yellow crystals; mp 142–144 °C dec; IR 1540, 1350, 1180 cm^{-1}. Anal. Calcd for $C_9H_{16}N_2S_2O_6$: C, 34.62; H, 5.13; N, 8.97. Found: C, 34.47; H, 5.06; N, 8.80. **5b**: colorless needles from benzene; mp 100–102 °C; IR 1540, 1350, 1180 cm^{-1}. CI (methane) mass spectrum, m/e (relative intensity) 63 (11), 72 (12), 83 (14), 93 (92), 147 (100), 189 (36), 207 (12), 313 ([MH^+], 62).

4c and **5c** were obtained as a mixture [colorless oil; **5c** showed a lower retention time than **4c** on GC (RSL 200 BP column)]: IR 1535 cm^{-1}; GC EI mass spectrum, m/e 156 ($[M - N_2]^{\cdot+}$) for both **4c** and **5c**. **4c**: ^1H NMR ($CDCl_3$) δ 1.22 (s, Me-exo), 1.75 (s, Me-endo), 2.37 (ddd, H-5, $J_{1,5}$ = 6.0 Hz, $J_{5,6}$ = 7.5 Hz and $J_{5,7}$ = 2.6 Hz), 3.32 (s, OMe), 3.50 (s, OMe), 4.01 (ddd, H-6, $J_{6,7}$ = 6.0 Hz and $J_{1,6}$ = 2.0 Hz), 4.41 (ddd, H-7, $J_{1,7}$ = 6.0 Hz), 5.35 (ddd, H-1). $\Delta\delta$ 0.15 (Me-exo), –0.12 (Me-endo), 0.51 (H-5), 0.29 (OMe), 0.22 (OMe), 0.51 (H-6), 0.51 (H-7), 0.45 (H-1). **5c**: ^1H NMR (CD_3COCD_3) δ 1.52 (s, Me), 3.28 (s, OMe), 3.48 (s, OMe), 5.18 (ddd, H-1, $J_{1,5}$ = 7.5 Hz, $J_{1,7}$ = 2.0 Hz, and $J_{1,6}$ = 1.0 Hz). The other signals of the protons of **5c** either were buried under those of **4c** or could not reliably be assigned.

4d: slightly brown solid; mp 26–27 °C; IR 1535 cm^{-1}; ^1H NMR (C_6D_6) δ 1.07 (s, Me-exo), 1.85 (ddd, H-5, $J_{1,5}$ = 6.5 Hz, $J_{5,6}$ = 8.0 Hz, and $J_{5,7}$ = 2.6 Hz), 1.95 (s, Me-endo), 3.72 (ddd, H-6, $J_{1,6}$ = 2.0 Hz and $J_{6,7}$ = 6.5 Hz), 4.10 (ddd, H-7, $J_{1,7}$ = 6.0 Hz), 4.88 (dd, H-1), 4.35 and 4.48 (AB system, J = 8.0 Hz, CH_2), 4.12 and 4.81

(AB system, J = 11.0 Hz, CH_2); δ 0.18 (Me-exo), –0.11 (Me-endo), 0.53 (H-5), 0.46 (H-6), 0.45 (H-7), 0.47 (H-1). Anal. Calcd for $C_{21}H_{24}N_2O_2$: C, 75.00; H, 7.14; N, 8.33. Found: C, 75.30; H, 7.27; N, 8.16. **5d**: slightly yellow oil; IR 1535 cm^{-1}; ^1H NMR (C_6D_6) δ 0.82 (s, Me-exo), 1.30 (s, Me-endo), 2.32 (ddd, H-5, $J_{1,5}$ = 7.5 Hz, $J_{5,6}$ = 5.0 Hz and $J_{5,7} \leq$ 1.0 Hz), 3.50 (ddd, H-6, $J_{1,6} \leq$ 1.0 Hz and $J_{6,7}$ = 5.5 Hz), 3.98 (ddd, H-7, $J_{1,7}$ = 2.0 Hz), 4.19 and 4.46 (AB system, J = 11.5 Hz, CH_2), 4.54 (bs, 2 H, CH_2), 5.12 (ddd, H-1). $\Delta\delta$ 0.32 (Me-exo), 0.19 (Me-endo), 0.22 (H-5), 0.23 (H-6), 0.12 (H-7), 0.16 (H-1).

4e: colorless needles, mp 83–85 °C (lit.[3a,b,d] no mp); ^1H NMR ($CDCl_3$) δ 1.15 (s, Me), 1.92 (s, Me), 2.70 (ddd, H-5, $J_{1,5}$ = 5.5 Hz, $J_{5,6}$ = 7.5 Hz and $J_{5,7}$ = 1.8 Hz), 4.80 (ddd, H-6, $J_{1,6}$ = 2.5 Hz and $J_{6,7}$ = 7.0 Hz), 5.10 (ddd, H-7, $J_{1,7}$ = 7.0 Hz), 5.45 (ddd, H-1). $\Delta\delta$ 0.47 (Me-exo), 0.17 Me-endo), 1.10 (H-5), 0.85 (H-6), 0.83 (H-7), 0.85 (H-1). **5e**: colorless solid; mp 73–74 °C (lit.[3a,b,d] no mp); ^1H NMR ($CDCl_3$) δ 1.15 (s, Me), 1.65 (s, Me), 2.82 (ddd, H-5, $J_{1,5}$ = 7.0 Hz, $J_{5,6}$ = 6.5 Hz, and $J_{5,7}$ = 1.0 Hz), 4.09 (ddd, H-6, $J_{1,6}$ = 1.5 Hz and $J_{6,7}$ = 6.5 Hz), 4.63 (ddd, H-7, $J_{1,7}$ = 1.5 Hz), 5.29 (ddd, H-1). $\Delta\delta$ 0.60 (Me-exo), 0.49 (Me-endo), 0.57 (H-5), 0.63 (H-6), 0.53 (H-7), 0.52 (H-1).

5f: colorless oil which solidifies on standing in colorless prisms; mp 35–36 °C (lit.[3b] no mp); ^1H NMR ($CDCl_3$) δ 1.15 (s, Me), 1.58 (s, Me), 2.92 (m, H-5 and H-6), 3.38 (m, H-7), 3.70 (s, OMe), 3.78 (s, OMe), 5.25 (m, H-1). $\Delta\delta$ 0.38 (Me-exo), 0.28 (Me-endo), ≃0.25 (H-6), ≃0.12 (H-5), 0.03 (H-7), 0.32 (OMe), 0.32 (OMe), 0.18 (H-1). Aside from **5f** we isolated small amounts (≃5%) of a lower R_f oily product which, however, we did not manage to fully characterize.

4g′: slightly yellow oil; IR 1540, 1205 cm^{-1}; EI mass spectrum, m/e (relative intensity) 41 (77), 67 (42), 83 (21), 95 (100), 132 (18), 149 (8); CI (methane) mass spectrum 203 ([MH^+], 0.2), 111 (0.8), 41 (100). **5g′** and **5g″** were isolated as a mixture (slightly yellow oil): IR 1540, 1205 cm^{-1}; EI mass spectrum, m/e (relative intensity) 41 (68), 53 (23), 67 (42), 83 (18), 95 (100), 132 (12); CI (methane) mass spectrum 203 ([MH^+], 0.2), 111 (11), 41 (100).

4h: colorless needles from benzene; mp 135–137 °C; IR 1540 cm^{-1}; EI mass spectrum, m/e (relative intensity) 198 ($M^{\bullet+}$, 2.8), 170 ([$M - N_2$]$^{\bullet+}$, 1.8), 115 (52), 95 (100), 83 (38), 67 (51), 53 (34), 41 (92); ^1H NMR ($CDCl_3$) δ 1.13 (s, Me-exo), 1.92 (s, Me-endo), 2.72 (m, H-5), 5.20 (m, H-6), 5.67 (m, H-1 and H-7). $\Delta\delta$ 0.61 (Me-exo), 0.30 (Me-endo), 1.40 (H-5), 1.29 (H-7), 1.19 (H-1 and H-7). **5h**: colorless needles from benzene/cyclohexane; mp 111–112 °C; IR 1540 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.20 (s, Me), 1.60 (s, Me), 2.75 (dd, H-5, $J_{1,5}$ = 6.5 Hz and $J_{5,6}$ = 2.0 Hz), 4.92 (dd, H-6, $J_{6,7}$ = 5.0 Hz), 5.13 (bd, H-7, $J_{1,7} \leq$ 1.0 Hz), 5.66 (bd, H-1). $\Delta\delta$ 0.63 (Me-exo), 0.65 (Me-endo), 0.97 (H-5), 1.02 (H-6), 0.88 (H-7), 0.88 (H-1). Anal. Calcd for $C_8H_{10}N_2O_2S$: C, 48.48; H, 5.05; N, 14.14. Found: C, 48.36; H, 5.07; N, 14.04.

4i: colorless needles from benzene/cyclohexane; mp 135–138 °C; IR 1800 and 1540 cm^{-1}; ^1H NMR (C_6D_6) δ 0.45 (s, Me), 1.28 (ddd, H-5, $J_{1,5}$ = 6.0 Hz, $J_{5,6}$ = 6.0 Hz, and $J_{5,7}$ = 1.8 Hz), 1.55 (s, Me), 3.62 (ddd, H-6, $J_{6,7}$ = 6.0 Hz and $J_{1,6}$ = 3.5 Hz), 4.11 (ddd, H-7, $J_{1,7}$ = 6.0 Hz), 4.43 (ddd, H-1). $\Delta\delta$ 0.65 (Me-exo), 0.35 (Me-endo), 1.40 (H-5), 1.33 (H-6), 1.32 (H-7), 1.15 (H-1). Anal. Calcd for $C_8H_{10}N_2O_3$: C, 52.75; H, 5.49; N, 15.38. Found: C, 52.59; H, 5.47; N, 15.19. **5i**: colorless needles from benzene/cyclohexane; mp 101 °C; IR 1810 and 1540 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.21 (s, Me-exo), 1.62 (s, Me-endo), 2.71 (ddd, H-5, $J_{1,5}$ = 6.3 Hz, $J_{5,6}$ = 2.0 Hz, and $J_{5,7} \leq$ 1.0 Hz), 4.77 (dd, H-6, $J_{6,7}$ = 5.5 Hz), 4.93 (ddd, H-7, $J_{1,7}$ = 1.0 Hz), 5.61 (dd, H-1). $\Delta\delta$ 0.52 (Me-exo), 0.57 (Me-endo), 0.84 (H-5), 0.85 (H-6), 0.71 (H-7), 0.71 (H-1). Anal. Found: C, 52.60; H, 5.50; N, 15.20.

5j: colorless needles from cyclohexane; mp 72–73 °C; IR 1540 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.16 (s, Me), 1.27 (s, Me-exo), 1.55 (s, 6 H, Me-endo and Me), 2.27 (dd, H-5, $J_{1,5}$ = 6.5 Hz and $J_{5,6}$ = 2.0 Hz), 4.38 (dd, H-6, $J_{6,7}$ = 6.0 Hz), 4.52 (bd, H-7), 5.30 (dd, H-1, $J_{1,7}$ = 1.0 Hz). $\Delta\delta$ 0.36 (Me), 0.12 (Me-exo), 0.30 (Me), 0.05 (Me-endo), 0.27 (H-5), 0.33 (H-6), 0.14 (H-7), 0.15 (H-1). Anal. Calcd for $C_{10}H_{16}N_2O_2$: C, 61.22; H, 8.16; N, 14.29. Found: C, 61.03; H, 8.24; N, 14.22.

5l: colorless oil; IR 1540 cm^{-1}; CI (isobutane) mass spectrum (relative intensity) 165 ([MH^+], 70), 137 ([$M - N_2$]$^+$, 12); ^1H NMR (C_6D_6) δ 0.92 (s, Me-exo), 1.42 (s, Me-endo), 1.00–1.80 (m, 7 H), 2.20 (m, H-6), 2.48 (m, H-7), 4.48 (dd, H-1, $J_{1,5}$ = 6.0 Hz and $J_{1,7}$ = 2.0 Hz). $\Delta\delta$ 0.18 (Me-exo), 0.13 (Me-endo), 0.22 (H-1). The exact value of the chemical shift of H-5, H-6, and H-7 in the spectrum recorded for the $CDCl_3$ solution could not be evaluated. ^{13}C NMR ($CDCl_3$) δ 20.4 (q), 25.3 (t), 27.1 (q), 31.3 (t), 32.9 (t), 37.3 (d), 42.1 (d), 43.8 (d), 90.7 (s), 91.4 (d).

6a: colorless prisms from petrol ether; mp 45–46 °C; IR 1750 and 1540 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.35 (d, Me, $J_{4,Me}$ = 7.2 Hz), 2.00 (s, COMe) and 2.05 (s, COMe), 2.47 (m, H-5), 4.96 (m, H-4, $J_{4,5} = J_{1,4}$ = 2.0 Hz), 5.27 (ddd, H-6, $J_{5,6} = J_{6,7}$ = 7.0 Hz and $J_{1,6}$ = 4.5 Hz), 5.57 (m, H-1 and H-7). $\Delta\delta$ 0.37 (Me), 0.42 (COMe), 0.45 (COMe), 0.87 (H-5), 0.21 (H-4), 0.47 (H-6), 0.52 (H-1), 0.22 (H-7). Anal. Calcd for $C_{10}H_{14}N_2O_4$: C, 53.09; H, 6.24; N, 12.38. Found: C, 52.89; H, 6.11; N, 12.33. A slightly higher R_f oily product (≃5%) was detected, but its ^1H NMR was not consistent with that of an adduct or a mixture of adducts.

The reaction of diazoethane with **1e** reached 100% conversion in ≤2 h, and TLC analysis of the reaction mixture clearly revealed the presence of two spots. The colorless residue obtained after evaporation of the solvent was column chromatographed (cyclohexane/AcOEt, 7:3, as eluant) to give **7e** + **8e** (higher R_f) and **6e**. No decomposition was observed during column chromatography. **6e**: colorless solid; mp 84–86 °C (lit.[7b] mp 85 °C); IR 1535 cm^{-1}; ^1H NMR (C_6D_6) δ 0.90 (d, Me, $J_{4,Me}$ = 7.2 Hz), 1.55 (m, H-5), 3.99 (ddd, H-6, $J_{1,6}$ = 2.0 Hz and $J_{5,6} = J_{6,7}$ = 7.2 Hz), 4.27 (ddd, H-7, $J_{1,7}$ = 7.2 Hz and $J_{5,7}$ = 2.5 Hz), 4.77 (m, H-1), 5.00 (m, H-4, $J_{1,4} = J_{4,5}$ = 2.5 Hz). $\Delta\delta$ 0.48 (Me), 1.23 (H-5), 0.89 (H-6), 0.83 (H-7), 0.83 (H-1), 0.25 (H-4). Compounds **7e** and **8e** were obtained as an oily mixture which rapidly became brown-reddish on standing at room temperature either neat or in $CDCl_3$ solution: IR 1535 cm^{-1}. **7e**: ^1H NMR ($CDCl_3$) δ 1.30 (d, Me, $J_{4,Me}$ = 7.0 Hz), 2.68 (ddd, H-5, $J_{5,6}$ = 6.0 Hz, $J_{1,5}$ = 7.0 Hz, $J_{4,5}$ = 2.0 Hz, and $J_{5,7}$ = 1.0 Hz), 3.97 (ddd, H-6, $J_{1,6}$ = 1.0 Hz and $J_{6,7}$ = 6.0 Hz), 4.54 (ddd, H-7, $J_{1,7}$ = 2.0 Hz), 4.88 (m, H-4, $J_{4,5}$ = 2.0 Hz and $J_{1,4}$ = 3.0 Hz), 5.40 (m, H-1). $\Delta\delta$ 0.70 (Me), 0.72 (H-5), 0.89 (H-6), 0.61 (H-7), 0.83 (H-4), 0.54 (H-1). **8e**: ^1H NMR ($CDCl_3$) δ 1.68 (d, Me, $J_{4,Me}$ = 7.0 Hz). $\Delta\delta$ = 0.58. The other signals either could not be assigned or were buried under those of **7e**.

6f: colorless needles from benzene; mp 110–111 °C; IR 1732, 1720, 1542 cm^{-1}; ^1H NMR (C_6D_6) δ 1.35 (d, Me, $J_{4,Me}$ = 7.2 Hz), 1.57 (m, H-5, $J_{1,5}$ = 7.0 Hz, $J_{4,5}$ = 4.5 Hz, $J_{5,6}$ = 9.0 Hz, and $J_{5,7}$ = 1.8 Hz), 2.87 (dd, H-6, $J_{6,7}$ = 9.5 Hz), 3.25 (s, OMe), 3.35 (s, OMe), 3.59 (ddd, H-7, $J_{1,7}$ = 9.0 Hz), 4.97 (ddd, H-1, $J_{1,4}$ = 2.5 Hz), 5.38 (m, H-4). $\Delta\delta$ 0.15 (Me), 0.67 (H-5), 0.67 (H-6), 0.38 (OMe), 0.31 (OMe), 0.44 (H-7), 0.58 (H-1), –0.22 (H-4). Anal. Calcd for $C_{10}H_{14}N_2O_4$: C, 53.09; H, 6.24; N, 12.38. Found: C, 53.08; H, 6.26; N, 12.46. Adducts **7f** and **8f** were separated by fractional crystallization from cyclohexane/benzene. **7f**: colorless prisms; mp 70–72 °C; IR 1735, 1540 cm^{-1}; ^1H NMR (C_6D_6) δ 0.80 (d, Me, $J_{4,Me}$ = 7.3 Hz), 2.29 (dd, H-6, $J_{5,6}$ = 6.0 Hz, $J_{6,7}$ = 9.0 Hz, and $J_{1,6}$ < 1.0 Hz), 2.50 (m, H-5, $J_{1,5}$ = 6.0 Hz, $J_{4,5}$ = 1.5 Hz, and $J_{5,7}$ = 1.0 Hz), 3.17 (ddd, H-7, $J_{1,7}$ = 3.0 Hz), 3.38 (s, OMe), 3.42 (s, OMe), 4.28 (m, H-4, $J_{1,4}$ = 3.0 Hz), 5.25 (m, H-1). $\Delta\delta$ 0.44 (Me), ≃0.43 (H-6), ≃0.22 (H-5), 0.19 (H-7), 0.29 (OMe), 0.33 (OMe), 0.49 (H-4), 0.15 (H-1). Anal. Found: C, 52.80; H, 6.31; N, 12.43. **8f**: colorless prisms; mp 115–117 °C; IR 1720, 1738, 1530 cm^{-1}; ^1H NMR (C_6D_6) δ 1.20 (d, Me, $J_{4,Me}$ = 7.3 Hz), 2.54 (dd, H-6, $J_{5,6}$ = 6.8 Hz, $J_{6,7}$ = 9.5 Hz, and $J_{1,6}$ < 1.0 Hz), 2.89 (ddd, H-5, $J_{1,5} = J_{4,5}$ = 6.8 Hz and $J_{5,7}$ < 1.0 Hz), 3.21 (dd, H-7, $J_{1,7}$ = 2.8 Hz), 3.27 (s, OMe), 3.39 (s, OMe), 3.88 (m, H-4, $J_{1,4}$ = 2.0 Hz), 4.92 (m, H-1). $\Delta\delta$ 0.43 (Me), 0.41 (H-6), 0.36 (H-5), 0.21 (H-7), 0.43 (OMe), 0.41 (OMe), 0.66 (H-4), 0.28 (H-1). Anal. Found: C, 53.21; H, 6.15; N, 12.44.

6i: colorless leaflets from benzene; mp 94–95 °C; IR 1790, 1530 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.35 (d, Me, $J_{4,Me}$ = 7.2 Hz), 2.61 (m, H-5), 5.07 (ddd, H-6, $J_{5,6} = J_{6,7}$ = 6.0 Hz and $J_{1,6}$ = 2.5 Hz), 5.28 (m, H-4, $J_{1,4}$ = 2.5 Hz and $J_{4,5}$ = 2.5 Hz), 5.48 (ddd, H-7, $J_{1,7}$ = 6.0 Hz and $J_{5,7}$ = 2.5 Hz), 5.75 (m, H-1, $J_{1,5}$ = 6.0 Hz). $\Delta\delta$ 0.58 (Me), 1.21 (H-5), 1.17 (H-6), 1.08 (H-7), ≃0.43 (H-4), ≃0.90 (H-1). Anal. Calcd for $C_7H_8N_2O_3$: C, 50.00; H, 4.80; N, 16.66. Found: C, 49.80; H, 5.00; N, 16.55. Compounds **7i** and **8i** were obtained as a mixture by column chromatography. Adduct **7i** could be separated in a pure state by fractional crystallization from benzene. **7i**: slightly yellow prisms; mp 143–145 °C dec; IR 1800, 1530 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.38 (d, Me, $J_{4,Me}$ = 7.2 Hz), 2.60 (ddd, H-5, $J_{1,5}$ = 6.7 Hz, $J_{5,6}$ = 2.0 Hz, and $J_{4,5}$ = 2.5 Hz), 4.58 (dd, H-6, $J_{6,7}$ = 6.0 Hz), 4.88 (m, H-4 and H-7), 5.70 (ddd, H-1, $J_{1,7}$ = 1.0 Hz, $J_{1,4}$ = 3.0 Hz). Anal. Found: C, 49.75; H, 5.05; N, 16.75. Com-

pound **8i** could not be isolated in a pure state but its presence could safely be inferred by the presence of a doublet at δ 1.70 (Me, $J_{4,Me}$ = 7.9 Hz) and of a ddd at δ 3.07 (H-5, J = 2.0, 7.0, and 8.5 Hz), in the ^1H NMR spectrum ($CDCl_3$) of the **7i** + **8i** mixture.

7l: slightly brown oil with a higher R_f than **8l** (cyclohexane-/AcOEt, 9:1, as eluant); IR 1540 cm^{-1}; ^1H NMR (C_6D_6) δ 0.98 (d, Me, $J_{4,Me}$ = 7.0 Hz), 0.90–1.90 (m, 8 H), 2.45 (m, H-7), 4.38 (m, H-4, $J_{1,4} = J_{4,5}$ = 2.5 Hz), 4.48 (ddd, H-1, $J_{1,5}$ = 6.0 Hz and $J_{1,7}$ = 2.5 Hz). Δδ 0.24 (Me), 0.17 (H-7), 0.27 (H-4), 0.27 (H-1). **8l**: slightly brown oil; IR 1540 cm^{-1}; ^1H NMR (C_6D_6) 1.36 (d, Me, $J_{4,Me}$ = 7.0 Hz), 0.88–1.80 (m, 7 H), 2.10 (m, H-6), 2.42 (m, H-7), 4.15 (m, H-4, $J_{4,5}$ = 7.5 Hz and $J_{1,4} \leq$ 1.0 Hz), 4.30 (dd, H-1, $J_{1,5}$ = 6.0 Hz and $J_{1,7}$ = 2.0 Hz). Δδ 0.26 (Me), 0.42 (H-6), 0.10 (H-7), 0.37 (H-4), 0.34 (H-1).

9a: colorless needles from cyclohexane; mp 60–63 °C; IR 1740, 1540 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.02 (s, OAc), 2.10 (s, OAc), 2.84 (m, H-5), 5.38 (ddd, H-6, $J_{5,6} = J_{6,7}$ = 6.9 Hz and $J_{1,6}$ = 2.4 Hz), 5.62 (ddd, H-7, $J_{1,7}$ = 6.9 Hz and $J_{5,7}$ = 2.4 Hz), 5.65 (m, H-1), 5.98 (dd, H-4, $J_{1,4} = J_{4,5}$ = 2.7 Hz). Δδ 0.38 (OAc), 0.46 (OAc), 0.66 (H-5), 0.38 (H-6), 0.27 (H-7), 0.40 (H-1), 0.03 (H-4). Anal. Calcd for $C_{15}H_{16}N_2O_4$: C, 62.49; H, 5.59; N, 9.72. Found: C, 62.35; H, 5.65; N, 9.85.

9e: colorless needles from benzene; mp 115–116 °C dec (lit.[7b] mp 116–117 °C); IR 1540 cm^{-1}; ^1H NMR (C_6D_6) δ 2.02 (m, H-5), 4.04 (ddd, H-6, $J_{5,6} = J_{6,7}$ = 7.5 Hz, and $J_{1,6}$ = 2.1 Hz), 4.24 (ddd, H-7, $J_{1,7}$ = 7.3 Hz and $J_{5,7}$ = 2.5 Hz), 4.90 (m, H-1), 6.15 (dd, H-4, $J_{1,4} \simeq J_{4,5}$ = 2.8 Hz). Δδ 0.93 (H-5), 0.91 (H-6), 0.88 (H-7), 0.86 (H-1), 0.10 (H-4). Anal. Calcd for $C_{11}H_{10}Cl_2N_2$: C, 54.77; H, 4.15; N, 11.61. Found: C, 54.90; H, 4.18; N, 11.81. We were able to isolate a higher R_f product (≃3%), but its fast decomposition to give a reddish product has made it impossible, to date, to characterize it.

9f: colorless platelets from methanol: mp 120–122 °C; IR 1733, 1538 cm^{-1}; ^1H NMR (C_6D_6) δ 1.96 (m, H-5) 2.84 (dd, H-6, $J_{5,6} = J_{6,7}$ = 9.5 Hz), 3.24 (s, OMe), 3.36 (s, OMe), 3.56 (ddd, H-7, $J_{1,7}$ = 9.0 Hz and $J_{5,7}$ = 2.5 Hz), 5.02 (ddd, H-1, $J_{1,5}$ = 7.2 Hz and $J_{1,4}$ = 2.6 Hz), 6.60 (dd, H-4, $J_{4,5}$ = 5.0 Hz). Δδ 0.60 (H-5), 0.79 (H-6), 0.43 (OMe), 0.35 (OMe), 0.51 (H-7), 0.68 (H-1), –0.33 (H-4). Anal. Calcd for $C_{15}H_{16}N_2O_4$: C, 62.49; H, 5.59; N, 9.72. Found: C, 62.33; H, 5.59; N, 9.73. **10f** and **11f** were isolated as a mixture (slightly yellow oil). The ^1H NMR spectrum of this mixture displayed four singlets at δ (C_6D_6) 3.20 and 3.35 (methoxy groups in **11f**) and at δ 3.42 and 3.46 (methoxy groups in **10f**) thus clearly disclosing the presence of two adducts: IR 1738, 1535 cm^{-1}. Anal. Found: C, 62.60; H, 5.45; N, 9.65.

9i: colorless needles from benzene; mp 133–135 °C dec; IR 1800, 1540 cm^{-1}. Anal. Calcd for $C_{12}H_{10}N_2O_3$: C, 62.60; H, 4.38; N, 12.17. Found: C, 62.66; H, 4.38; N, 12.14. Adducts **10i** and **11i** were obtained as a mixture from column chromatography and separated by fractional crystallization. **10i**: colorless leaflets from benzene; mp 166–168 °C dec; IR 1800, 1540 cm^{-1}. Anal. Found: C, 62.70; H, 4.50; N, 12.10. **11i**: colorless prisms from chloroform; mp 140–142 °C dec; IR 1800, 1540 cm^{-1}. Anal. Found: C, 62.76; H, 4.24; N, 12.22.

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Registry No. **1a**, 71348-58-8; **1b**, 126036-72-4; **1c**, 67520-63-2; **1d**, 126036-73-5; **1e**, 2957-95-1; **1f**, 42577-15-1; **1g′**, 126036-74-6; **1g″**, 126108-41-6; **1h**, 126036-75-7; **1i**, 33186-71-9; **1j**, 115977-19-0; **1k**, 61253-93-8; **1l**, 4927-03-1; **1m**, 616-10-4; **2a**, 101219-81-2; **2b**, 126036-76-8; **2c**, 121399-69-7; **2d**, 126036-77-9; **2e**, 121829-49-0; **2f**, 121399-74-4; **2g′**, 126036-78-0; **2g″**, 126108-42-7; **2h**, 126036-79-1; **2m**, 126036-81-5; **3e**, 126108-21-2; **3f**, 121468-35-7; **3g′**, 126108-27-8; **3g″**, 126108-43-8; **3h**, 126108-28-9; **3m**, 126108-29-0; **4a**, 113749-60-3; **4b**, 126036-82-6; **4c**, 121399-72-2; **4d**, 126036-83-7; **4e**, 19877-63-5; **4g′**, 126109-24-8; **4h**, 126036-84-8; **4i**, 113749-65-8; **5a**, 113829-20-2; **5b**, 126108-30-3; **5c**, 121468-34-6; **5d**, 126108-31-4; **5e**, 19877-62-4; **5f**, 22160-73-2; **5g′**, 126036-85-9; **5g″**, 126108-44-9; **5h**, 126108-32-5; **5i**, 113829-26-8; **5j**, 126036-86-0; **5l**, 113749-71-6; **6a**, 126108-22-3; **6e**, 121829-50-3; **6f**, 126036-87-1; **6i**, 126108-33-6; **7e**, 126108-23-4; **7f**, 126108-34-7; **7i**, 126108-35-8; **7l**, 126108-36-9; **8e**, 126108-24-5; **8f**, 126108-37-0; **8i**, 126108-38-1; **8l**, 126108-39-2; **9a**, 126036-70-2; **9e**, 121829-53-6; **9f**, 126108-40-5; **9i**, 126187-26-6; **10f**, 126036-80-4; **10i**, 126036-71-3; **11f**, 126108-26-7; **11i**, 126108-25-6; *cis*-3,4-dihydroxycyclobutene, 60090-87-1; benzyl chloride, 100-44-7; diazomethane, 334-88-3; 2-diazopropane, 2684-60-8; diazoethane, 1117-96-0; phenyldiazomethane, 766-91-6.

On the Mechanism of the Radical Chain Transformation of Nitroalkanes to Alkanes Using Triaryl- or Trialkyltin Hydrides[1]

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The standard potentials, $E°$, for the oxidations and reductions of triphenyl- and tributylstannyl radicals in THF containing 0.1 M tetrabutylammonium perchlorate (TBAP) have been estimated by a combination of electrochemical and kinetic measurements. Lower limits of $E°$ for the oxidations are >–0.42 V and >–0.43 V (vs SCE) respectively for the triphenylstannyl radical and the tributylstannyl radical. The oxidation potentials of the stannyl radicals were combined with the reduction potentials of nitroalkanes to define the thermochemistry for the electron-transfer reaction between these species. It was found that the electron-transfer reaction was not a feasible propagation step in the reactions of stannyl radicals with simple nitroalkanes and that an addition/elimination sequence must apply.

Nitroalkanes can be converted to their corresponding alkanes by using tributyltin hydride[2,3] or nicotinamide derivatives[4] as reducing agents. Initially,[2,3a] the tin hydride reaction mechanism was thought to invoke an electron transfer between the stannyl radical and the nitroalkane as one of the propagation steps, eqs 1–3. However, an

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