^{1}H NMR Detection. A solution of ketenimine **1n** (0.158 mmol) and thiobenzophenone (**2a**, 0.22 mmol) in CCl_4 (0.6 mL) in a freeze–thaw-degassed, sealed NMR tube was examined at intervals, following the disappearance of the peak at 1.68 ppm (s, 2 Me of **1n**) and the formation of two peaks at 1.84 and 1.58 ppm, respectively, which equally increased up to 45–55% of conversion of the reagents. After reaching a maximum, the two peaks slowly disappeared and were replaced by the benzothiazine signals.

IR Detection. Thiobenzophenone (**2a**, 2.46 mmol) was reacted with ketenimine **1o** (2.0 mmol) in CCl_4 (6 mL) under an argon atmosphere at room temperature. The reaction course was followed at intervals in a NaCl cell (0.5 mm) previously purged with argon. Bands in the 3370–3430-cm^{-1} region (NH) were observed immediately, which increased with time. After reaching a maximum, the bands slowly disappeared.

Reaction of *N*-Phenylmethylketenimine (1t) with Thiobenzophenone (2a). Thiobenzophenone **2a** (1.47 mmol) was reacted with ketenimine **1t** (1.30 mmol) in CCl_4 (10 mL) at 25 °C for 30 h. After evaporation of the solvent in vacuo, chromatographic workup of the reaction mixture on a preparative plate (silica, 1:2 CH_2Cl_2–petroleum ether) gave the following.

(a) 2-Ethyl-4,4-diphenyl-4*H*-3,1-benzothiazine (**6t**): 0.517 mmol; mp 126–128 °C (from methanol); ^{1}H NMR (CCl_4–C_6D_6, 0.4–0.15 mL) δ 1.00 (t, Me), 2.4 (g, CH_2, $J_{CH_2CH_3}$ = 7.57 Hz), 6.5–7.8 (m, 14 H, arom); mass spectrum, *m/e* 329 (M^+), 300, 166. Anal. Calcd. for $C_{22}H_{19}NS$: C, 80.20; H, 5.81; N, 4.25. Found: C, 80.13; H, 5.78; N, 4.29.

(b) 2-(Phenylimino)-3-methyl-4,4-diphenylthietane (**3t**): oil, 0.608 mmol; IR (CCl_4) 1685 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.15 (d, 1 H), 5.04 (q, Me, J_{H-CH_3} = 7.3 Hz), 6.9–7.7 (m, 15 H, arom); mass spectrum, *m/e* 329 (M^+), 252, 194, 135, 131. The iminothietane **3t** was heated at 100–110 °C for 30 min in a sealed tube to give the thioamide **4t** *only*: 0.577 mmol; mp 210–213 °C (from methanol); IR (CCl_4) 3395 cm^{-1} (NH); ^{1}H NMR ($CDCl_3$, 80 MHz) δ 1.52 (br), 2.27 and 2.31 (Me), 6.58–7.5 (m, 5 H, arom), 8.44 and 9.06 (br, NH); ^{1}H NMR ($CDCl_3$, 100 MHz at 5 and 58 °C) the two sharp signals at δ 2.28 and 2.33 (0.31:1) of Me collapse in a broad signal at 2.30 ppm; mass spectrum, *m/e* 329 (M^+), 296, 252, 237, 193. Anal. Calcd. for $C_{22}H_{19}NS$: C, 80.20; H, 5.81; N, 4.25. Found: C, 80.24; H, 5.77; N, 4.23.

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Registry No. 1a, 13911-54-1; **1b**, 63086-85-1; **1c**, 52199-13-0; **1d**, 74331-60-5; **1e**, 50743-09-4; **1f**, 74331-61-6; **1g**, 45813-90-9; **1h**, 14181-75-0; **1j**, 22731-54-0; **1k**, 5110-45-2; **1m**, 17205-60-6; **1n**, 14016-34-3; **1o**, 18779-86-7; **1p**, 14016-32-1; **1q**, 74331-62-7; **1t**, 22752-55-2; **2a**, 1450-31-3; **2b**, 1141-08-8; **2c**, 3705-95-1; **3a**, 66276-00-4; **3b**, 63086-84-0; **3c**, 74366-17-9; **3d**, 74366-18-0; **3e**, 74366-19-1; **3f**, 74366-20-4; **3g**, 74366-21-5; **3h**, 74366-22-6; **3t**, 74366-23-7; **4e**, 67684-90-6; **4f**, 74366-24-8; **4g**, 74366-25-9; **4h**, 74366-26-0; **4t**, 74366-27-1; **6j**, 63119-39-1; **6k**, 63086-81-7; **6l**, 63086-82-8; **6m**, 74366-28-2; **6n**, 63086-83-9; **6o**, 74366-29-3; **6p**, 74366-30-6; **6q**, 74366-31-7; **6q′**, 74366-32-8; **6r**, 74366-33-9; **6s**, 74366-34-0; **6t**, 74366-35-1; **7p**, 74366-36-2; **7q′**, 74366-37-3.

Supplementary Material Available: Figures 1 (for **1p** and **2a**), 2 (for **1o** and **2a**), and 4 (for **1t** and **2a**) showing the time dependence of the NMR spectra of reaction mixtures and Table III listing the ^{1}H NMR and IR data of ketenimines **1a–k,m–q,t** (4 pages). Ordering information is given on any current masthead page.

Selectivity in Ketenimine–Thioketone Cycloadditions. 2. Kinetic and Theoretical Studies of the Mechanism of the 1,2- and 1,4-Cycloadditions[1]

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The kinetics of the thermal 1,2- and 1,4-cycloadditions of thiobenzophenones to ketenimines to give four-membered adducts, 2-iminothietanes, and six-membered adducts, 4*H*-3,1-benzothiazines, respectively, has been studied with respect to changes of solvents and substituents as well as at different temperatures. Both reactions show the typical features of concerted processes, viz., little change of rate with the polarity of the solvent, small activation energies, and large and negative activation entropies, but have some substantial differences. The results are consistent with a scheme where the products are formed from two site-selective additions of the reactants through independent pathways, very likely by concerted mechanisms. The formation of intermediates such as an open-chain zwitterion or a four-membered cycloadduct involving the C=N bond of the cumulene appears unlikely for both processes. Perturbational molecular reasonings coupled with SCF–MO computations indicate as most probable a [$_\pi 2_s + {}_\pi 2_a$] pericyclic process between the C=S bond of the thione and the C=C of the cumulene for the 1,2-cycloaddition and a [$_\pi 4_s + {}_\pi 2_s$] process between the C=S bond of the thione and the heterodiene system which consists of the C=N bond of the ketenimine and the C=C of the *N*-phenyl ring for the 1,4-cycloaddition.

In a previous article[3] we have described two different reaction modes which take place in the thermal cycloadditions of thioketones to ketenimines, namely, a 1,2-cycloaddition of the C=S bond of the thione across the C=C bond of the cumulene and a 1,4-cycloaddition across the conjugated system consisting of the C=N bond of the cumulene and the C=C of the *N*-aryl group (Scheme I). The extent of substitution at the terminal carbon of the cumulene and the nature of the group R on nitrogen turned out to be the structural factors directing the site of attack by the thione group. However, the intimate electronic factors which determine the outcome of these reactions, namely, their stereochemical course and mechanism(s), remained obscure. The clarification of these

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(2) (a) University of Ferrara. (b) CNR Laboratory. (c) University of Bologna.
(3) A. Dondoni, A. Battaglia, and P. Giorgianni, *J. Org. Chem.*, accompanying paper in this issue.

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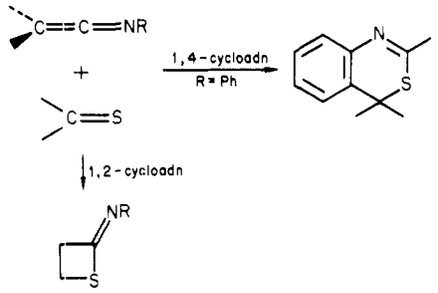
Scheme I



facets is of considerable importance for a better understanding of the mechanisms and synthetic applications of the reactions between ketenimines and thioketones and also for obtaining information on the cycloadditions of heterocumulenes in general. In fact, despite various theoretical and experimental studies,[4] the stereochemistry (regioselectivity and site selectivity) and mechanism of these reactions constitute a problem which has not been completely clarified. The ketenimine–thioketone cycloadditions offer just one example of this problem and of the difficulties which are encountered for its solution.

A set of mechanistic possibilities which may be considered for the 1,2- and 1,4-cycloadditions of *N*-phenylketenimines 1 (R = Ph, Me, H) is shown in Scheme II. These include the following: (i) the formation[5] of the 2-iminothietane **3** and 3,1-benzothiazine **6** by two independent pathways, viz., a $[{}_{\pi}2_s + {}_{\pi}2_a]$ pericyclic reaction[6] for **3** (path A) and a $[{}_{\pi}4_s + {}_{\pi}2_s]$ pericyclic reaction leading to the azapolyene **8** (path B) as the primary precursor of **6**; (ii) the rate-determining formation of the open-chain zwitterion **10** (path C) followed by 1,6 ring closure to **8** or/and 1,4 ring closure to **3**, depending on the substitution at the various sites of the ketenimine; (iii) the initial formation of the 1,3-thiazetidine **11** by a $[{}_{\pi}2 + {}_{\pi}2]$ cycloaddition (path D) and subsequent rearrangement to the four-membered adduct **3** or/and the six-membered adduct **8**. Of course, other combinations of the pathways outlined in Scheme II are equally possible, such as the formation of **3** by a multistep process and **8** by a concerted mechanism or vice versa as well as the reversible formation of the 1,3-thiazetidine **11** from the zwitterion **10**.

Since the choice of the various reaction pathways of Scheme II appeared very difficult, we have examined this problem by combining experimental and theoretical approaches, the former based on a kinetic study and the latter on perturbational molecular orbital (PMO) reasonings coupled with SCF–MO computations.

Results and Discussion

(A) Kinetics of the 1,2-Cycloaddition. A suitable pair of reactants for the study of this reaction was *N*-mesityldimethylketenimine (**1d**) and thiobenzophenone (**2a**), which gave the corresponding 2-iminothietane **3d** almost quantitatively by clean second-order kinetics and at a convenient rate for NMR monitoring. From rate measurements under different conditions (Table I), the reaction between ketenimine **1d** and thioketone **2a** was revealed to take place at comparable rates in three solvents of different polarities[7] and to have a modest activation energy (E_a = 14.8 kcal mol^{-1}) and a large negative activation entropy ($\Delta S^{\ddagger}$ = −32 eu). These characteristics are those expected for a pericyclic process rather than for a multistep reaction occurring through an open-chain dipolar intermediate.[8] On the other hand, substantial changes in reactivity were determined by the extent of substitution and the nature of the groups in the cumulene. The reactions of C-monosubstituted ketenimines **1h**, **1f**, and **1g** with thioketone **2a** were much faster than those of C,C-disubstituted derivatives **1d** and **1b**. Among the former compounds, the *N*-phenyl derivative **1h** was more reactive than the *N*-mesityl and *N*-methyl derivatives **1f** and **1g**, this indicating that an electron-donor group flanking nitrogen decreases the rate of the reaction. Finally, the *C,C*-diphenylketenimine **1b** was less reactive than the corresponding *C,C*-dimethyl derivative **1d**. These observations indicate that the reaction is sensitive to the steric effects of substituents at the terminal carbon of the cumulene and that the ketenimine plays the role of the acceptor partner in the cycloaddition.

Table I. Kinetics[a] of the 1,2-Cycloaddition between Ketenimines[b] 1 ($R^1R^2C{=}C{=}NR^3$) and Thiobenzophenone[b] (2a)

	R^1	R^2	R^3	T, °C	solvent	10^4k,[c] M^{-1} s^{-1}
1d	CH_3	CH_3	mesityl	55	CCl_4	0.718[d]
				30	CCl_4	0.110[d]
				26	CCl_4	0.0756[e]
				22	CCl_4	0.0575[d]
				55	CD_2Cl_2	0.372
				55	$CDCl_3$	0.327
1b	Ph	Ph	mesityl	26	CCl_4	$\ll 0.1$[f]
1h	H	Ph	Ph	26	CCl_4	145
1f	H	Ph	mesityl	26	CCl_4	18.8
1g	H	Ph	CH_3	26	CCl_4	1.98

[a] Reaction followed by NMR (see Experimental Section). [b] The initial concentrations of **1** and **2a** were 0.3–0.6 M. [c] Average of at least two runs with a standard error of ±2%. [d] The activation parameters calculated from these rate constants were E_a = 14.8 ± 0.3 kcal mol^{-1}, log A (22 °C) = 5.75 s^{-1}, $\Delta S^{\ddagger}$ (22 °C) = −34 ± 2 cal deg^{-1} mol^{-1}, $\Delta H^{\ddagger}$ (22 °C) = 14.2 ± 0.3 kcal mol^{-1}, and $\Delta G^{\ddagger}$ (22 °C) = 24.3 ± 0.5 kcal mol^{-1}. [e] Calculated from the activation parameters by the Arrhenius equation. [f] Too slow to be measured with accuracy because of the concomitant decomposition of the reactants.

It is worth noting that the exclusive formation of 2-iminothietane **3h** takes place from *N*-phenylphenylketenimine (**1h**), although both 1,2- and 1,4-cycloaddition pathways are in principle available. Moreover, this reaction is the most rapid among those so far examined. In view of the results[3] indicating kinetic control of the product distribution of these reactions, it may be deduced that the 1,4-cycloaddition of thioketone **2a** to ketenimine **1h** is a higher energy process than the 1,2-cycloaddition. This, however, does not apply in general since *N*-phenylmethylketenimine (**1t**) gives[3] the corresponding 2-iminothietane **3t** and 3,1-benzothiazine (**6t**) in ca. a 1:1 ratio, which indicates that in this case the two reaction pathways have similar energy requirements.

(4) (a) L. Ghosez and M. J. O'Donnell in "Pericyclic Reactions", Vol. II, A. P. Marchand and R. E. Lehr, Eds., Academic Press, New York, 1977, Chapter 2; (b) K. N. Houk, *ibid.*, Chapter 4.

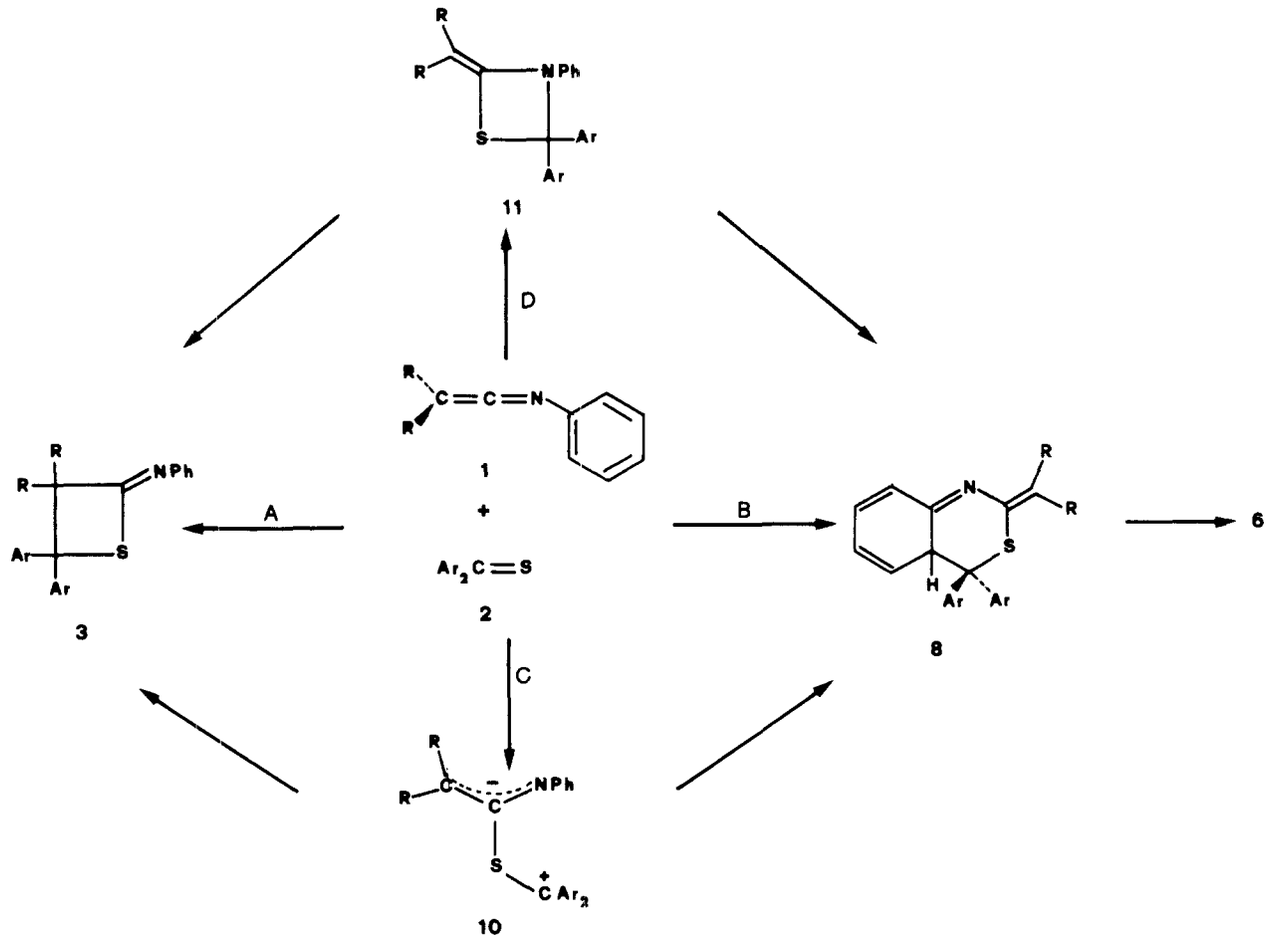
(5) The same notation of compounds as in the preceeding paper[3] has been maintained throughout this article.

(6) As is shown in section D, the orbital interaction scheme of this cycloaddition is more complex than that for a typical $[{}_{\pi}2_s + {}_{\pi}2_a]$ interaction between two ethylene molecules (R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry", Verlag Chemie, Weinheim/Bergstr., Germany, 1970, p 68), although the geometry of approach of the reactants is orthogonal in both cases.

(7) C. Reichardt, *Angew. Chem., Int. Ed. Engl.*, 18, 98 (1979); C. Reichardt, "Solvent Effects in Organic Chemistry", Verlag Chemie, New York, 1979.

(8) R. E. Lehr and A. P. Marchand in "Pericyclic Reactions", Vol. I, A. P. Marchand and R. E. Lehr, Eds., Academic Press, New York, Chapter 1.

Scheme II



(B) Kinetics of the 1,4-Cycloaddition. The kinetics of this reaction were also studied with respect to changes of solvents, substituents in both reactants, and temperature (Table II). In all cases, the reactions were followed by UV spectroscopy and were found to be second-order processes up to 80–90% conversion of the reactants. The reactions of *N*-arylketenimines **1n–q** with thiobenzophenone (**2a**) and those of ketenimine **1o** with the aryl-substituted thioketones **2a–c** showed that the aryl substitution exerted a small effect on the rate of the cycloaddition. Nevertheless, the variations of rate in the two sets of reactions followed regular trends, which indicates that the ketenimine acts as the *donor* and the thioketone as the *acceptor* partner in the cycloaddition. Also, the variation of the substituents at the terminal carbon of the cumulene produced only small effects on the reactivity, since a ratio of ca. 10 can be roughly estimated between the rates of *C,C*-dimethyl- and *C,C*-diphenylketenimines.[9]

Variations of the polarity of the solvent[7] were not accompanied by similar changes of the reaction rates, which, in fact, were almost equal in carbon tetrachloride and in acetonitrile. Finally, the reaction was characterized by a small activation energy (E_a = 7.6 kcal mol^{-1}) and a very large and negative activation entropy ($\Delta S^{\ddagger}$ = −49 eu). Also in this case, the whole set of kinetic results points uniformly to a concerted rather than a multistep mechanism.[8]

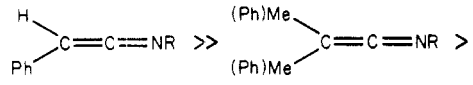
(C) Mechanisms of the 1,2- and 1,4-Cycloadditions. The results in Tables I and II provide a clear sequence of reactivity for substituted ketenimines in the two types of cycloadditions with thiobenzophenone (**2a**). This gives a quantitative value to the effect[3] which C and N substituents in the ketenimine have on the reactivity and site selectivity toward thiobenzophenones (see relationship 1). The kinetics of both 1,2- and 1,4-cycloadditions show the features expected for concerted processes,[8] viz., a small dependence of rate on the changes of the polarity of the solvent, small activation energies, and large negative activation entropies. These results make the stepwise mechanism C (Scheme II) involving the zwitterion **10** quite

Table II. Kinetics[a] of the 1,4-Cycloaddition between *N*-Aryldimethylketenimines 1 [$(CH_3)_2C{=}C{=}NR^3$] and Thiobenzophenones 2 ($Ar_2C{=}S$)

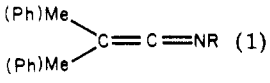
ketenimine,[b] R^3	thione,[c] Ar	T, °C	solvent	10^4k,[d] M^{-1} s^{-1}
1n, Ph	2a, Ph	22	CH_2Cl_2	5.33
1o, 4-CH_3Ph	2a, Ph	22	CH_2Cl_2	8.38
		0	CCl_4	3.39[e]
		22	CCl_4	9.57[e]
		40	CCl_4	19.2[e]
		22	CH_3CN	12.7
		22	$(CH_3)_2CO$	5.13
1p, 4-CH_3OPh	2a, Ph	22	CH_2Cl_2	10.67
1q, 3-CH_3OPh	2a, Ph	22	CH_2Cl_2	9.79
1o, 4-CH_3Ph	2b, 4-CH_3Ph	22	CH_2Cl_2	3.43
1o, 4-CH_3Ph	2c, 4-ClPh	22	CH_2Cl_2	14.7

[a] Reactions followed by UV (see Experimental Section). [b] Initial concentrations of 1 were 0.03–0.14 M. [c] Initial concentrations of 2 were 0.003–0.006 M. [d] Average of at least two runs with a standard error of ±2%. [e] The activation parameters calculated from these rate constants were E_a = 7.6 ± 0.3 kcal mol^{-1}, log A (22 °C) = 2.6 s^{-1}, $\Delta S^{\ddagger}$ (22 °C) = −49 ± 2 cal deg^{-1} mol^{-1}, $\Delta H^{\ddagger}$ (22 °C) = 7.0 ± 0.3 kcal mol^{-1}, and $\Delta G^{\ddagger}$ (22 °C) = 21.3 ± 0.5 kcal mol^{-1}.

(9) The rate constant for *N*-(*p*-chlorophenyl)diphenylketenimine (1m) in CCl_4 at 40 °C was 1.26 × 10^{-4} M^{-1} s^{-1}.



1,2-cycloaddition (R = Ph, Me, mesityl) 1,4-cycloaddition (R = Ph)



1,2-cycloaddition (R = mesityl)

improbable in both cases. However, there are some specific differences between the two processes: (i) the rate of the 1,2-cycloaddition depends largely (more than a factor of 1000) on the substitution at the terminal carbon of the ketenimine, whereas the rate of the 1,4-cycloaddition is only slightly affected by similar changes (ca. a factor of 10); (ii) the rate of the 1,2-cycloaddition is decreased by electron-donor groups bonded to the cumulene nitrogen, whereas that of the 1,4-cycloaddition is increased; (iii) the activation energy, E_a, of the 1,4-addition is half that of the 1,2-addition, but $\Delta S^{\ddagger}$ is much smaller. These observations suggest that the 1,2- and 1,4-cycloadditions take place through two independent pathways, very likely by concerted mechanisms, rather than through multistep processes involving the rate-determining formation of a common intermediate. Pathways A and B of Scheme II are consistent with these conclusions. On the other hand, pathway D leading to the 1,3-thiazetidine 11 as a primary adduct which subsequently rearranges to product 3 *or* 6 appears less probable. In fact, the considerable effect on the rate of the 1,2-cycloaddition by substitution at the terminal carbon of the cumulene (Table I) is more consistent with a direct addition across the C=C bond than across the C=N bond which is distant from the site of substitution. Moreover, the very small activation entropy (−48 eu) of the 1,4-cycloaddition, which indicates a high degree of order in the transition state, is well in line with the concerted pathway B where the formation of 8 requires both a cisoid conformation of the heterodiene system C=N—C=C and the coplanarity of the *N*-aryl ring with the C=N bond. In addition to these arguments, it is worth noting that adduct 11 has not been observed even in reactions which were followed at intervals by NMR spectroscopy,[3] whereas four-membered-ring adducts from 1,2-cycloadditions of ketene acetals[10] and ynamines[11] across the C=N bond of ketenimines have been isolated along with the six-membered-ring products from 1,4-cycloaddition. In the latter case, a stepwise mechanism via a dipolar intermediate has been proposed,[11] whereas this appears quite unlikely for the ketenimine–thioketone reactions under study.

(D) Theoretical Study of the 1,2- and 1,4-Cycloadditions. In order to verify whether concerted mechanisms were allowed on theoretical grounds and to give some insight on the electronic factors which determine the reactivity and control the stereoselectivity in ketenimine–thioketone reactions, we carried out a theoretical study of the system by means of PMO reasonings[12] and SCF-MO computations.[13] These have been carried out at the ab initio SCF-MO STO-3G level[14] for the model systems $H_2C{=}C{=}NH$ and $H_2C{=}S$ (Figure 1) and their combina-

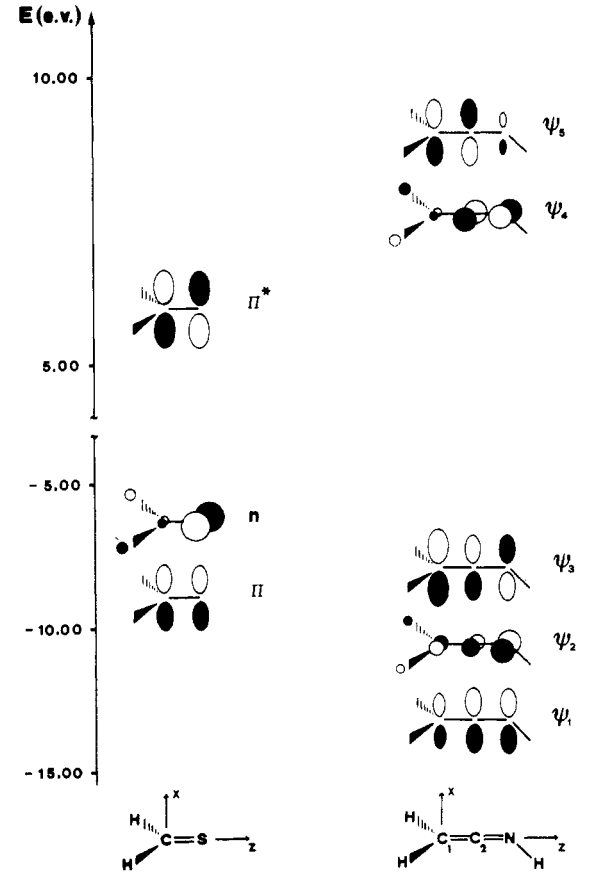


Figure 1. Relevant MO's of thioformaldehyde ($H_2C{=}S$) and ketenimine ($H_2C{=}C{=}NH$) computed at the SCF-MO ab initio level with an STO-3G basis set.

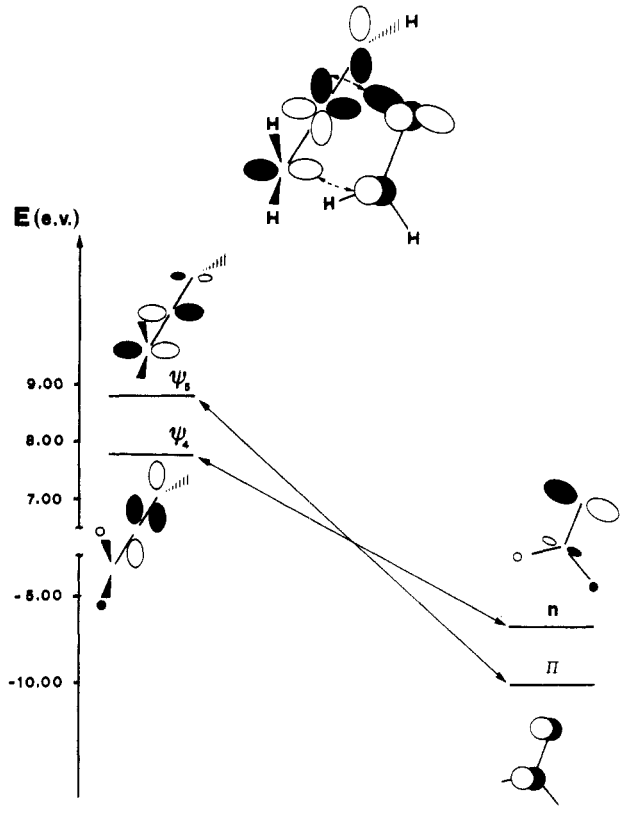


Figure 2. Dominant orbital interactions in the $[{}_{\pi}2_s + {}_{\pi}2_s]$ approach of the C=S of the thione to the C=C bond of the ketenimine.

(10) N. P. Gambaryan, *Russ. Chem. Rev. (Engl. Transl.)*, **45**, 630 (1976).
(11) L. Ghosez and C. de Perez, *Angew. Chem., Int. Ed. Engl.*, **10**, 184 (1971).
(12) The fundamentals of perturbation theory may be found in any quantum mechanics text. Applications to quantum chemistry are particularly well represented in E. Heilbronner and H. Bock, "The HMO Model and Its Application", Verlag Chemie, Weinheim/Bergstr., Germany, 1976.

tions and at the CNDO/2 level[13] for substituted ketenimines.

On treatment of the 1,2-cycloaddition as a [2 + 2] pericyclic process between the C=S of the thione and the C=C of the cumulene (route A), the most favorable mode of approach is that where the two reactants are situated almost orthogonally to each other (Figure 2) in order to maximize the overall stabilizing effect associated with the two-orbital, two-electron interactions between the occupied n and π MO's of the thioketone and the vacant ψ_4 and ψ_5 MO's of the ketenimine. In this arrangement, the sulfur lone pair (n) of the C=S unit interacts mainly with the atomic component of the ψ_4 MO of the cumulene centered at C_2, and the atomic component at the carbon of the π MO of C=S interacts with that of the cumulene ψ_5 MO centered at C_1. Therefore, this almost orthogonal mode of approach of the reactants is similar to that occurring in a $[{}_\pi 2_s + {}_\pi 2_a]$ process between two ethylene molecules,[6] but since it involves both π systems of the cumulene and of the thioketone, the interaction scheme is more complex. The important difference is that in the present case the steric repulsions are significantly reduced, and the $[{}_\pi 2_s + {}_\pi 2_a]$ cycloaddition can proceed relatively easily. These orbital interactions also account for the regiochemistry of the 1,2-cycloaddition, which, in fact, leads exclusively to 2-iminothietane derivative **3**, since the orbital coefficient values of Figure 1 indicate that the largest stabilization is obtained when bonding occurs between the sulfur atom of the thione and the central carbon of the cumulene. Furthermore, according to the interaction diagram of Figure 2, the ketenimine appears to act as the acceptor partner in the pericyclic process, a role which is in line with the indications from the kinetic studies (section A). In agreement with this conclusion, the energies of the LUMO's, obtained by CNDO/2 computations, for two model ketenimines with the formula $H_2C{=}C{=}NR$ indicate that the *N*-phenyl derivative (R = Ph, E_{LUMO} = 2.91 eV) is a better electron acceptor than the *N*-methyl derivative (R = Me, E_{LUMO} = 4.27 eV), a trend which parallels that of the reactivity of compounds **1h** and **1g** with thiobenzophenone (**2a**) (Table I). Hence, theoretical considerations fit the experimental data quite well and reinforce the conclusions in favor of mechanism A.

Also, pathway B, which involves the initial formation of the 1,4-cycloadduct 8 by a $[{}_\pi 4_s + {}_\pi 2_s]$ pericyclic process between the C=S bond of the thione and the heterodiene C=N—C=C system of the ketenimine, appeared to be allowed on the basis of PMO reasonings. In this case, the most effective interactions are ψ_2–π^* and π–ψ_4 (Figure 3). In fact, CNDO/2 computations indicate that the coefficients of the NHOMO, ψ_2, and the LUMO, ψ_4, of the ketenimine have the correct symmetry for a 1,4-interaction with the π and π^* MO's of the thioketone; furthermore, the sizes of the coefficients of these MO's predict a significant stabilization. However, since the charge transfers associated with these two interactions appear to be of comparable magnitudes and in opposite directions, the overall effect may be predicted to be small, This is in agreement with the small substituent effect deduced from the kinetic study (Table II). However, on consideration of the fact that the reaction is highly regioselective, whereas

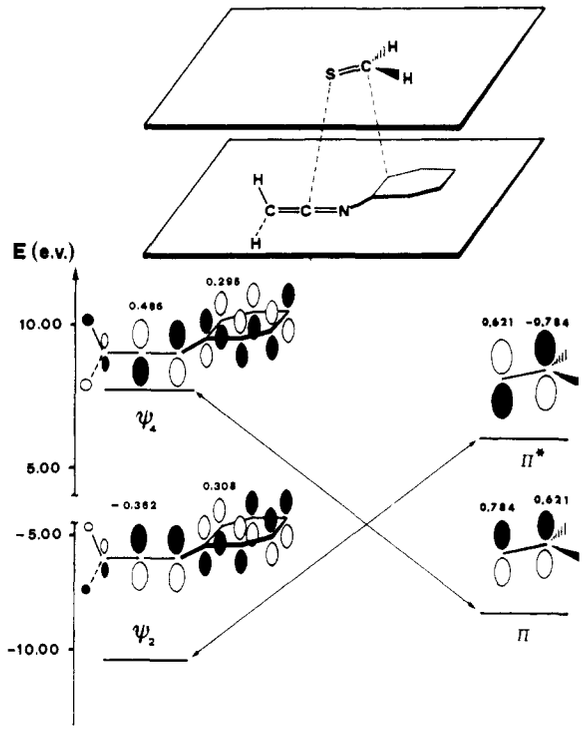


Figure 3. Dominant orbital interactions in the $[{}_\pi 4_s + {}_\pi 2_s]$ approach (orbital coefficients computed at the CNDO/2 level) between thioformaldehyde and *N*-phenylketenimine.

the two orbital interactions ψ_2–π^* and π–ψ_4 predict opposite orientations of the reactants in the cycloaddition, the regiochemistry of the reaction appears to be controlled by the latter interaction.

Conclusions

The variations of rate and the accompanying changes of site selectivity which have been observed in the cycloadditions of thiobenzophenones **2** to ketenimines **1** can be interpreted in terms of a competition between two pericyclic processes whose relative extents depend on a balance of steric and electronic effects. In C-monosubstituted ketenimines where the C=S bond of the thione can easily reach the C=C bond of the ketenimine by approaching the cumulene from the unsubstituted side, the electronic effects determine a high reactivity and the exclusive 1,2-cycloaddition across the C=C bond. This reaction can be viewed as a $[{}_\pi 2_s + {}_\pi 2_a]$ process. However, in C,C-disubstituted derivatives where the substituents inhibit the approach of the thione from both sides of the C=C bond of the cumulene, the 1,2-cycloaddition becomes a high-energy process which is overcome by the 1,4-cycloaddition across the heterodiene system consisting of the C=N of the cumulene and the C=C bond of the *N*-aryl group. This reaction can be viewed as a $[{}_\pi 4_s + {}_\pi 2_s]$ process. When the reaction across this heterodiene system is also inhibited by ortho substituents in the *N*-aryl group, the 1,2-cycloaddition across the C=C bond of the cumulene takes place again but at a very low rate. The balance of these effects may lead to the occurrence of both 1,2- and 1,4-cycloadditions as observed for *N*-phenylmethylketenimine.[3]

Experimental Section

Reagents and Solvents. The preparation of ketenimines **1** and thiobenzophenones **2** has been already described.[3] Stable compounds were purified by crystallization or distillation just before use. C-Monosubstituted ketenimines **1h**, **1f**, and **1g**, whose tendency to polymerize on distillation prevented their isolation and purification, were generated in situ and their purities determined by ^{1}H NMR from the intensities of the olefinic proton

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of the cumulene and the aromatic protons. The solutions of all ketenimines 1 were stable under the conditions of the kinetic experiments.

Solvents were purified by standard methods[16] and stored under an argon atmosphere.

Kinetic Measurements. (a) UV Method. This method was employed for the study of the 1,4-cycloaddition reactions. Exact amounts (2–3 mL) of ketenimine and thioketone solutions were mixed in a Pyrex ampule whose path length (ca. 1.4 cm) had been precisely determined by standard solutions of thiobenzophenone (**2a**). The solution was quickly frozen and then degassed by the freeze–thaw technique under vacuum (0.001 mmHg). Finally, the ampule was sealed and positioned in the thermostated (±0.2 °C) cell compartment of a Perkin-Elmer Model 402 UV spectrophotometer. The kinetics were followed by monitoring the thioketone through its absorbance in the visible region (590–650 nm). Reactions were followed to at least 2 half-lives, and rate constants were calculated from the second-order rate equation.

(b) ^{1}H NMR Method. This method was employed for the study of the 1,2-cycloaddition reactions. The solution (0.5 mL) of the ketenimine was added to a weighed amount of thioketone in a NMR tube, and the mixture was frozen and degassed by the usual freeze–thaw technique. The NMR tube was sealed and then positioned in the thermostated (±0.3 °C) probe of a JEOLCO-60 NMR spectrometer. The reactions were followed up to 70–80% of their extent by measurement at intervals of the intensities of appropriate signals of the ketenimine, I_k, and cycloadduct, I_c, and the percentages of unreacted ketenimine were calculated from the relationship $[I_k/(I_k + I_c)]100$. The analytical peaks were those corresponding to the olefinic proton for the reactions of **1h**, **1f**, and **1g** and the methyl of the cumulene for the reaction of **1d**. The measurement of the intensity of each signal was repeated three or four times, and the values were averaged. From the percentages of unreacted ketenimine determined at different intervals and the initial amounts of the two reactants, their molar concentrations were obtained. The rate constants were calculated from the second-order rate equation.

The activation parameters were calculated by standard methods:[17] E_a from the linear plot of log A vs. $1/T$, log A from E_a through the Arrhenius equation, $\Delta S^{\ddagger}$ from log A by the equation $\Delta S^{\ddagger} = 4.576(\log A - 13.23)$, $\Delta H^{\ddagger}$ from the approximation $\Delta H^{\ddagger} = (E_a - RT)$, and $\Delta G^{\ddagger}$ ($\Delta H^{\ddagger} - T\Delta S^{\ddagger}$).

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Registry No. 1b, 63086-85-1; **1d**, 74331-60-5; **1f**, 74331-61-6; **1g**, 45813-90-9; **1h**, 14181-75-0; **1n**, 14016-34-3; **1o**, 18779-86-7; **1p**, 14016-32-1; **1q**, 74331-62-7; **2a**, 1450-31-3; **2b**, 1141-08-8; **2c**, 3705-95-1; thioformaldehyde, 865-36-1; ketenimine, 17619-22-6.

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Metal-Catalyzed Organic Photoreactions. Titanium(IV) Chloride Catalyzed Photoreaction of Saturated Ketones with Methanol and Its Application to the Synthesis of Frontalin[1]

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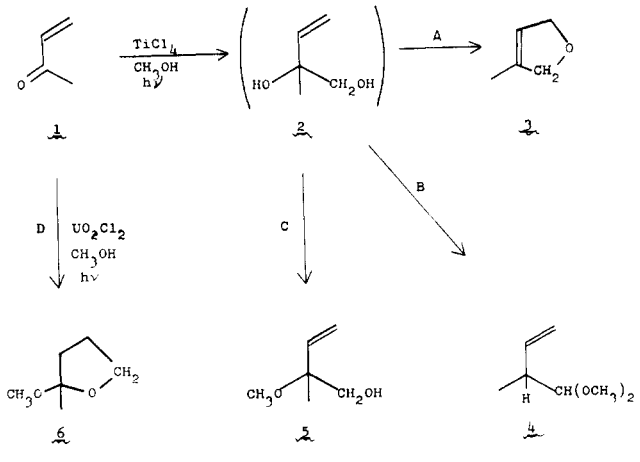
Photoreaction of acyclic and cyclic saturated ketones in methanol in the presence of $TiCl_4$ afforded 1,2-diols as the main products. The effect of the substituents on the stereochemical course of the photoreaction was examined with substituted cyclohexanones. Further, the present reaction was applied for the synthesis of a pheromone, frontalin.

We reported[2] that α,β-enones, when irradiated in alcohols in the presence of $TiCl_4$ or UO_2Cl_2, undergo novel types of reaction with the formation of a C–C bond between the substrate and alcohol. As a typical example, the $TiCl_4$- and UO_2Cl_2-catalyzed reactions of α,β-enones **1** with methanol are shown in Scheme I. Depending upon the types of the substrates, the $TiCl_4$-catalyzed photoreaction gave three types of product: dihydrofurans **3** (type A), acetals **4** (type B), and 1,2-diol monomethyl ethers **5** (type C). All the products are considered to be derived from a common intermediate, 1,2-diol **2**, which is formed through the 1,2-addition of methanol to the carbonyl group. When UO_2Cl_2 was used as catalyst, on the other hand, the products were cyclic acetals **6** (type D), derived through 1,4-addition of methanol to the enones.

All the reactions (types A–D) can be shown schematically to involve a step of the formal coupling of the hydroxymethyl radical with the carbonyl carbon (1,2 type) or the olefinic β-carbon (1,4 type) of the enones. However, the present reaction is characteristic in several features.[2] (1) 1,2-Addition of methanol to enones as observed in the

Scheme I



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