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2,2,6,6-Tetramethylcyclohexanethione *S*-methylide, a highly hindered thiocarbonyl ylide: two-step cycloadditions☆

Rolf Huisgen,* Henry Giera† and Kurt Polborn

Department Chemie und Biochemie der Ludwig-Maximilians-Universität München, Butenandtstr. 5-13, D-81377 München, Germany

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Dedicated to Johann Mulzer, University of Vienna, on the occasion of his 60th birthday

Abstract—The switching from the concerted 1,3-dipolar cycloaddition to a two-step pathway via zwitterionic intermediates requires a major energy difference between HOMO–LUMO energies of 1,3-dipole and dipolarophile, as well as sterically demanding reactants. In contrast to previously studied models, the title compound **1C**, a thiocarbonyl ylide prepared by N_2 extrusion from dihydrothiadiazole **7C** at 80 °C, combined with 2,3-bis(trifluoromethyl)fumaronitrile (**11**) to give a zwitterion (*gauche*-**10**); the latter failed to close the thiolane ring by 1,5-cyclization, but formed the seven-membered ketene imine **9C** by 1,7-cyclization. X-ray analysis of **9C** revealed an angle-deformed cumulated bond system and a *transoid* relation of the CF_3 groups. The relatively stable **9C** allowed ^{19}F NMR recordings from −90 to +90 °C; temperature-dependent line broadening resulted from equilibration with ≤1% of an unknown isomer. Among various possible angle-strained rate processes, an inversion *transoid* **19** ⇌ *cisoid* **20** is preferred which involves a topomerization at the C=N bond; lateral inversion and rotation are discussed. At 80 °C in solution, ketene imine **9C** slowly suffered fragmentation to give *trans*- and *cis*-1,2-bis(trifluoromethyl)cyclopropane-1,2-dicarbonitrile (**13**) + thioketone **6C** by intramolecular substitution. The reaction of **1C** with ethenetetracarbonitrile furnished a tetracyanothiolane **3C**, whereas **1C** and dimethyl 2,3-dicyanofumarate ((*E*)-**26**) afforded thiolanes of the same *trans*,*cis*-ratio as **1C** with dimethyl 2,3-dicyanomaleate ((*Z*)-**26**); a preceding (*E*,*Z*)-equilibration of **26** thwarts mechanistic conclusions. When the solvent contained water or methanol, short-lived ketene imines **4C** and **31** were intercepted.

1. Introduction

Like the related Diels–Alder reactions,[3] 1,3-dipolar cycloadditions can be achieved by several mechanistic pathways.[4] The wide-spread 'normal' type fulfils the expectations for the concerted course.[5] When highly nucleophilic thiocarbonyl ylides **1** were reacted with ethenetetracarbonitrile (TCNE)[6] or benzylidenemalononitrile,[7] competing 1,5- and 1,7-cyclizations—the latter involving a nitrile group—revealed a mechanism via 1,5-zwitterionic intermediates. Due to rotation in the zwitterion, (*E*,*Z*)-isomeric dipolarophiles, like dimethyl 2,3-dicyanofumarate and dimethyl 2,3-dicyanomaleate, did not retain their configuration during the cycloaddition.[8,9] A second structural requirement must be fulfilled for the two-step pathway to occur: steric hindrance at least at one terminus of the thiocarbonyl ylide **1**. Voluminous substituents are likely to raise the activation barrier of the concerted cycloaddition; to a far lesser degree they impede formation of a zwitterionic intermediate.

In the reaction of 2,2,4,4-tetramethyl-3-thioxocyclobutanone *S*-methylide (**1A**) with TCNE, the zwitterion **2A** provided thiolane **3A** and the seven-membered cyclic ketene imine **4A** in the ratio 35:65. The strained **4A** was neither isolable nor detectable by IR or ^1H NMR spectroscopy, but was in situ intercepted by methanol to give **5A** when the solvent THF contained 1.2 equiv of methanol. If not captured, **4A** returns to the zwitterion and is again distributed by k_5 and k_7, until all the material arrives at the favored thiolane **3A** (Scheme 1).[6] A recent quantum-chemical calculation (B3LYP/6-31G*) of TSs and intermediates by Domingo and Picher[10] fully confirmed the experimentally established reaction course.

When TCNE was replaced by 2,3-bis(trifluoromethyl)-fumaronitrile (**11**), the reactions with thiocarbonyl ylides **1A** and **1B** furnished the crystalline spirocyclic imines **9A** and **9B**. They were isolable here despite substantial angle strain (Scheme 2).[11–14]

☆ See Ref. 1.

Keywords: 1,3-Dipolar cycloadditions; Thiocarbonyl ylides; Cyclic ketene imines; Dynamic ^{19}F NMR.
* Corresponding author. Tel.: +49 89 2180 77712; fax: +49 89 2180 77717; e-mail: rolf.huisgen@cup.uni-muenchen.de
† Present address: Fachhochschule München, Fachbereich 05, Lothstr. 34, D-80334 München, Germany.

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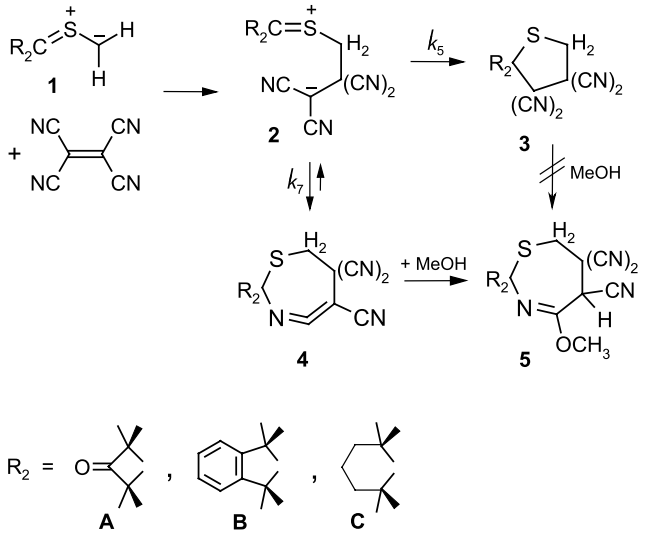
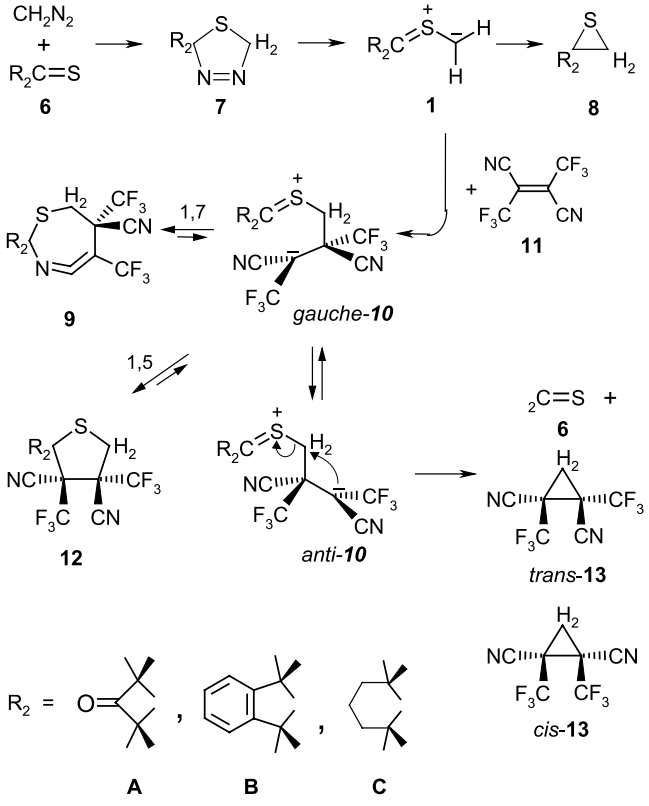


Scheme 1.

In the four-membered cyclobutanone ring of **1A**, the pairs of *gem*-dimethyl groups are bent back as a result of bond angles. This phenomenon reduces the hindrance at the *tertiary* terminal of the 1,3-dipole, an effect that disappears in the five- and six-membered ring of thiocarbonyl ylides **1B** and **1C**. Our expectation of increasing steric hindrance in the sequence **1A**<**1B**<**1C** found support in the experiments described in this paper. In particular, the top member, 2,2,6,6-tetramethylcyclohexanethione *S*-methylide (**1C**), revealed noteworthy changes in reactivity, and the relatively stable spiroketene imine **9C** allowed to study NMR phenomena over a range of 180 °C.



Scheme 2.

2. Results and discussion

2.1. Preparation and properties of the cyclic ketene imine 9C

Thiocarbonyl ylide **1C** was conveniently accessible by the cycloaddition of diazomethane to thioketone **6C** and thermolysis of the isolated 2,5-dihydrospiro-1,3,4-thiadiazole **7C** (Scheme 2).[2] The N_2 extrusion from **7C** proceeded with a half-life of 15.6 min in xylene at 100 °C, that is, substantially slower than that of the tetramethylindan derivative **7B**.[15] This is probably a consequence of further weakening of the allylanionic resonance in **1C**. Recent calculations ((U)B3LYP/6-31G*) of related examples by Sustmann et al. showed that the local C_s of the thiocarbonyl ylide is preserved with a widened angle C–S–C reflecting the strain.[16] The elusive **1C** underwent complete electrocyclization to thiirane **8C** if not intercepted in situ by an electron-deficient dipolarophile.

When **7C** was refluxed in benzene for 15 h in the presence of 1.1 equiv of 2,3-bis(trifluoromethyl)fumaronitrile (**11**), the crystalline spirocyclic ketene imine **9C**, a pale-yellow substance, was isolated. The N_2 elimination from **7C** and the subsequent fragmentation of **9C**, affording 1,2-bis(trifluoromethyl)cyclopropane-1,2-dicarbonitrile (**13**, *trans*/*cis*=95:5) and thioketone **6C**, were monitored by ^{19}F NMR analysis in the presence of a weight standard. The first-order thermolysis of **7C** is the slow step ($t_{1/2}$=5.1 h, C_6D_6, 80 °C) which was measured via the formation of (**9C**+**13**). The concentration of **9C** rose, went through a shallow maximum (73% after ~15–16 h), and then fell off, as is typical of the intermediate in a kinetic system of two consecutive first-order reactions. An induction period was observed for the formation of the final product **13** (+**6C**). In a separate experiment, the first-order conversion of **9C** to **13** took place with $t_{1/2}$=38.5 h, that is, slower by a factor of 7.5, than its formation from **7C**. By-the-way, the true rate of cycloaddition, **1C**+**11**→**9C**, is rather high, but is kinetically hidden behind the preceding slow N_2 expulsion from **7C**.

In consecutive first order reactions, both time of occurrence and percentage of the maximal concentration of the intermediate are functions of the two rate constants.[17] Applied to our example,

$$\%(\mathbf{9C})_{\max} = 100(k_1/k_2)^{k_2/(k_2-k_1)} = 74 \quad (1)$$

$$t_{\max} = \frac{1}{k_2 - k_1}\ln(k_2/k_1) = 17.1\ \text{h} \quad (2)$$

the agreement with observation is fair when the modest precision of the rate measurements is taken into consideration.

The role of thiolane **12** in Scheme 2 highly depends on the cycloaliphatic residue R_2. Ketene imine **9A** was quantitatively converted to **12A** at 60 °C in a first-order reaction; its rate constant was increased by 10^3 with rising solvent polarity.[12] As for ketene imine **9B**, the reversible formation of **12B** and the irreversible generation of cyclopropane **13**+thione **6B** took place in the ratio of about 4:1 ($CDCl_3$,

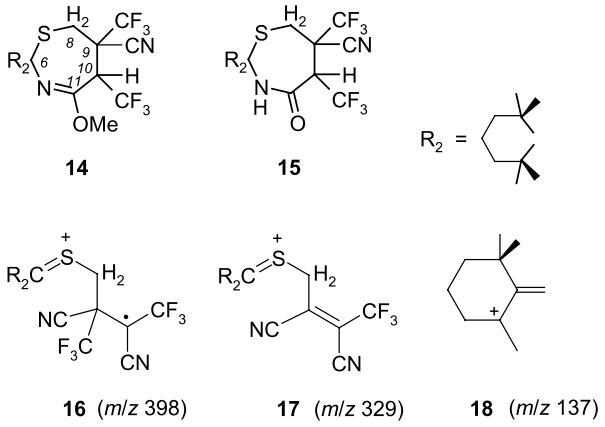
40 °C).[14] Thiolane **12C**, however, was not observed in the thermolysis of **9C** (C_6D_6, 80 °C).

When we invoke the 1,5-zwitterion **10** as short-lived mediator for the reactions of Scheme 2, the increasing steric requirements of R_2 in the sequence **A**<**B**<**C** explain the change in product composition. The *gauche* conformation of **10** is favored by its Coulomb potential over *anti*-**10** in which the distance of charge centers is nearly doubled. The *tert*-carbanion and the N-atom of the nitrile group compete in *gauche*-**10** for reaction with the thiocarbonylium function. The 1,5-cyclization (→**12**) will be more severely hampered than the 1,7-ring closure (→**9**) with growing size of R_2. As a consequence, the tetramethylcyclohexylidenesulfonium ion in *gauche*-**10C** refuses to combine with the *tert*-carbanion, while still allowing for combination with the linear nitrile group.

On the other hand, the high steric demand of R_2 increases the van der Waals strain in *gauche*-**10C**, and diminishes the energetic disadvantage of *anti*-**10C**. The latter offers the structural prerequisites for an intramolecular nucleophilic substitution with thione **6C** as leaving group. Without and with rotation about the former double bond of **11**, *gauche*-**10C** furnishes *trans*-**13** and *cis*-**13** (95:5); the 'forbidden' front-side attack, *gauche*-**10**→**13**+**6**, is avoided, as previously stated.[14]

On addition of methanol or water, ketene imine **9C** followed the pattern of **9A**[11,12] and **9B**.[15] The structures of the lactim ether **14** and the lactam **15** were confirmed by the spectra; the H,F and C,F couplings helped in assigning the NMR signals.

The mass spectra of **9C**, **14**, and **15** show common features, as briefly discussed for **9C** (Scheme 3). The formulation of $\mathbf{9C}^+$ as distonic radical cation **16** (*m*/*z* 398, 5%) suggests that the strain loss now shifts the balance in favor of the open-chain structure. Elimination of CF_3 leads to sulfonium ion **17** (*m*/*z* 329, 17%) which, in turn, could be the precursor of thioketone radical cation $\mathbf{6C}^+$ ($C_{10}H_{18}S^+$, *m*/*z* 170, 31%). It has been reported that the MS of thioketones—those with blocked α-positions included—generally show strong peaks for $[M^+ - SH]$.[18,19] In our example, the base peak $C_{10}H_{17}^+$ (*m*/*z* 137, 100%) results. It can be formulated cyclically (e.g., **18**) or as open-chain dienyl cation. A cascade of $C_nH_{2n-3}^+$ fragments, down to $C_5H_7^+$ (*m*/*z* 67, 18%), was observed, then replaced by the sequence $C_nH_{2n-1}^+$: $C_5H_9^+$ (52%), $C_4H_7^+$ (39%), $C_3H_5^+$ (61%). High resolution secured the molecular formulae; however, the structures are tentative.



Scheme 3.

2.2. Structure and dynamics of cyclic ketene imine 9C

The X-ray structure of ketene imine **9B** was described in 1990; **9B** was the first isolated cumulated bond system ever observed in a seven-membered ring.[13] The stereochemical aspects appeared somewhat improbable, and thus made a second example all the more desirable. The monocrystal diffraction of ketene imine **9C** furnished a structure which is shown in Figure 1 from two perspectives. Bond lengths and angles of the seven-membered ring are rather similar to those of **9B** (Table 1). The bending of the cumulated system to 163.2° (163.8° for **9B**) and the dihedral angle C6–N12⋯C10–C9 (90° in allene) of 57.8° for both **9B** and **9C** demonstrate the ring strain. The conformation of the seven-membered ring resembles a deformed twist-chair (Fig. 1a). The spiro-annellated cyclohexane chair shows local C_s symmetry (Fig. 1b), and the average intracyclic torsion angle (53.9°) exhibits nearly the same flattening as observed for cyclohexane itself (54.9°, gas).[20]

Our cyclic ketene imines share the short C═N bond

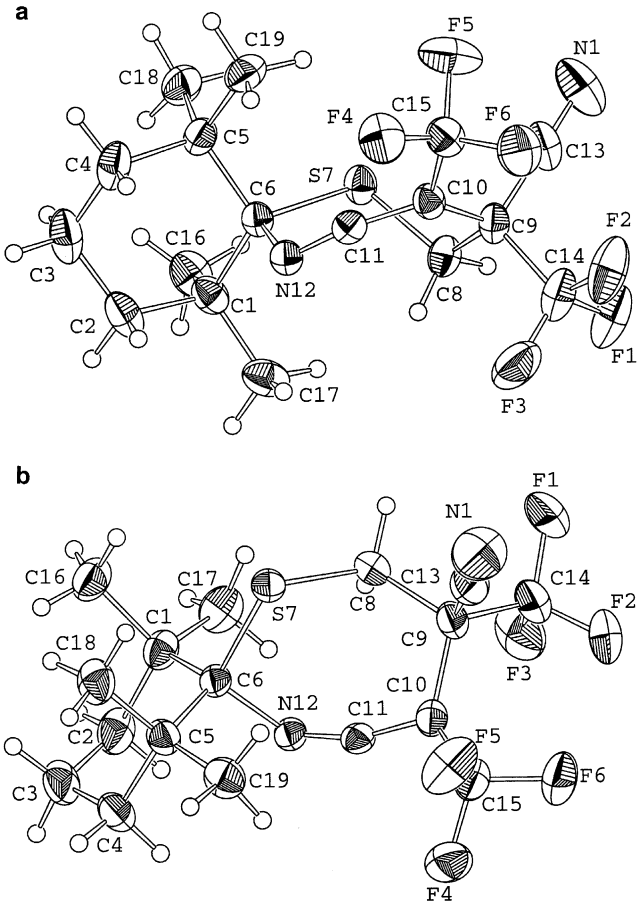


Figure 1. X-ray structure of 1,1,5,5-tetramethyl-9,10-bis(trifluoromethyl)-10,11-didehydro-7-thia-12-azaspiro [5.6]dodecane-9-carbonitrile (**9C**); ZORTEP plot from two perspectives (thermal ellipsoids represent 30% probability).

Table 1. X-ray structure of ketene imine **9C**: selected bond lengths and angles

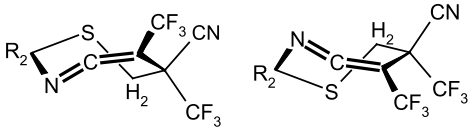
Bond lengths (Å)			
S7–C8	1.812(3)	N12–C6	1.504(3)
C8–C9	1.557(4)	C6–S7	1.877(2)
C9–C10	1.526(4)	C9–CF_3	1.540(5)
C10–C11	1.318(4)	C10–CF_3	1.475(4)
C11–N12	1.201(3)	C1–C6	1.568(4)
Bond angles (°)			
C6–S7–C8	105.1(1)	C10–C11–N2	163.2(3)
S7–C8–C9	115.7(2)	C11–N12–C6	118.5(2)
C8–C9–C10	110.4(2)	N12–C6–S7	105.9(1)
C9–C10–C1	112.5(2)	C11–C10–C15	120.8(2)
Intracyclic torsion angles (°)			
C6–S7	27.2(2)	C10–C11	−0.91(1.0)
S7–C8	−90.3(2)	C11–N12	−61.6(1.0)
C8–C9	54.4(3)	N12–C6	34.4(3)
C9–C10	9.7(3)	(C10–N12)	57.8

(1.195 Å for **9B** and 1.201 Å for **9C**) with open-chain ketene *N*-arylimines,[21–23] which suggests partial nitrilium salt character. If C10 holds a partial anionic charge, a certain pyramidalization would be expected. Indeed, C10 is located by 0.13 Å above the plane defined by C9, C11, C15, and the three angles at C10 add up to 357.8° in **9C**. The ^{13}C chemical shift at the terminus C10 (61.7 ppm in **9B**, 60.6 ppm in **9C**) is also in accordance with a partial ylide character.[24]

An even shorter C═N bond (1.172 Å) was reported for the nine-membered cyclic ketene imine **21** which likewise bears electron-attracting substituents;[25] as expected, the bending of C═C═N (172.2°) is smaller than in **9B** and **9C**.

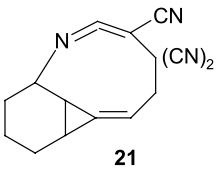
Pivotal in our context is the *transoid* configuration **19** with respect to the CF_3 groups in the crystals of both **9B** and **9C** (Scheme 4). The cumulated bond system is a stereogenic element which—together with the adjacent center of tetrahedral asymmetry—should give rise to a pair of diastereomers, **19** and **20**. At first glance, one set of NMR parameters (^1H, ^{13}C, ^{19}F) is in conformity with one frozen structure in solution. However, the varying sharpness of the two quadruplets in the ^{19}F NMR spectra of **9A**–**9C** rather points to a dynamic phenomenon.

The superior thermal stability of **9C** ($t_{½}$ = 38.5 h in C_6D_6 at 80 °C), compared with **9A**[12] and **9B**,[14] allowed ^{19}F NMR recording (376 MHz) from +90 to −90 °C in [D_8] toluene (Fig. 2). The two CF_3 groups of **9C** couple with $^5J(F,F)$ = 5.8 Hz. The quadruplet at δ −55.3 ° (30 °C), tentatively assigned to the CF_3 group in 10-position, gains in sharpness and height on stepwise raising of the temperature to 90 °C. On cooling, line broadening occurs, and a maximum half-width is passed at about −30 °C; below that temperature, distinct resharpening takes place. The 9-CF_3 signal at −73.2, on the other hand, shows maximal broadening at +30 °C and sharpens on both rise and fall of the temperature. The quadruplet shape of the signal is just discernible at +90 °C, but fully developed at −20 °C.



transoid **19**

cisoid **20**



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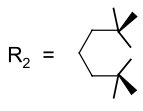


Scheme 4.

For the case of equal exchange partners A and B, the Gutowsky–Holm equation relates the rate constant at coalescence temperature (T_c) with the chemical shift difference $|\nu_A-\nu_B|$.[26] Anet and Basus calculated the exchange broadening for very unequal populations (mole fraction $p \ll 1$ for the minor component).[27] The maximal half-width of a Lorentzian line is approximated by (Eq. 3), and the corresponding rate constant by (Eq. 4).

$$\Delta_{1/2}^{\max} = p|\nu_A - \nu_B| \tag{3}$$

$$k = 2\pi|\nu_A - \nu_B| \tag{4}$$

Inserting the latter into the Eyring equation leads to (Eq. 5) for the free energy of activation.

$$\Delta G^{\#} = RT_c\left(23.76 + \ln\frac{T_c}{2\pi|\nu_A - \nu_B|}\right) \tag{5}$$

Since we are dealing with a pair of quadruplets instead of a single line, both line broadenings in Figure 2 refer to the same rate process with $\Delta G^{\#}$. A larger value of $2\pi|\nu_A-\nu_B|$ must be compensated for by a higher T_c (see Eq. 5). At −70 °C (and lower) small signals without fine structure are visible in Figure 2: one on the right side of the left quadruplet, at a distance of 154 Hz, and another 87 Hz left of the right quadruplet. The T_c of the 10-CF_3 signal is lower than that of the 9-CF_3, and a smaller $|\nu_A-\nu_B|$ is expected. The tiny companions show the opposite relation and hence cannot be the signals of the minor equilibrium partners. Plotting the δ values of the two CF_3 resonances against temperature yields curvilinear functions which do not reveal a discontinuity in the region of coalescence. No asymmetry of the signals is discernible (Fig. 2). Both phenomena support a small population ($\leq$1%) of the minor partner.

Several possibilities for the exchange process—none of them completely satisfactory—will be briefly discussed. The first is an equilibrium of ketene imine **9C** with a tiny concentration of the open-chain zwitterion **10C**. It was shown for the isomerization of **9A** to thiolane **12A** (see above) that the ring-opening is the rate-determining step. Given that the conversion **9C**→**13C**+**6C** has a half-reaction time of 38.5 h in C_6D_6 at 80 °C, it is, however, barely imaginable that the rate of ring-opening equilibration, **9C**⇌**10C**, should reach the NMR time scale in the nonpolar medium toluene at a temperature as low as −30 °C (Fig. 2).

Less readily assailable is a variant which assumes an ionization equilibrium of ketene imines **9** with an intramolecular contact ion pair via a modest barrier. The subsequent dissociation to afford the zwitterions *gauche*-**10**

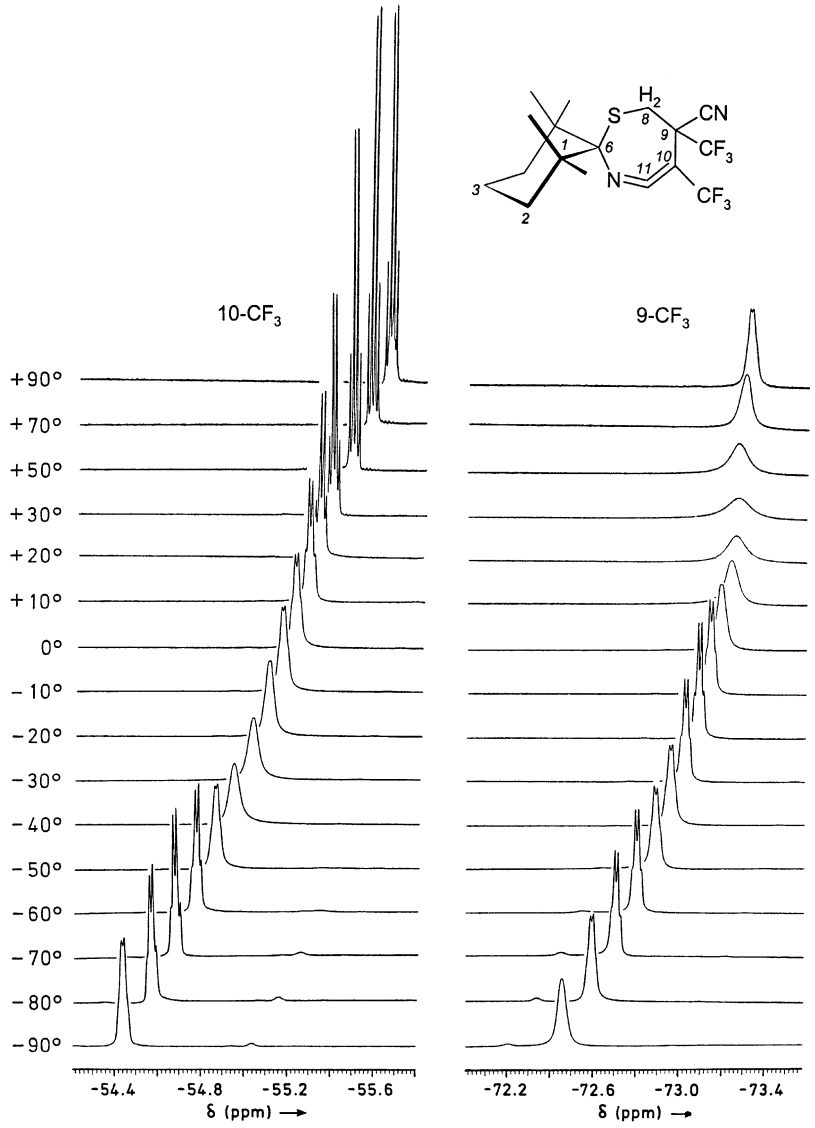


Figure 2. Temperature-dependent ^{19}F NMR spectra of cyclic ketene imine **9C** in [D_8]toluene.

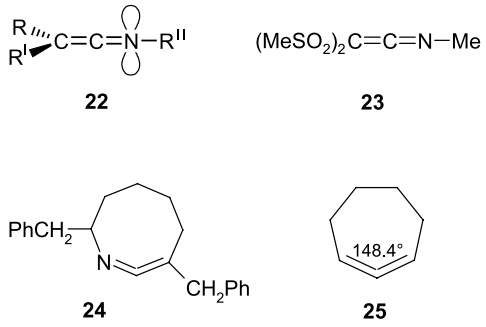
and *anti*-**10** would have to overcome a larger barrier, that is, the ionization equilibrium is established at a temperature which still does not allow dissociation. Yet, this time, it is difficult to explain why our scenario leading from **9** to **10** (namely, structural changes in the course of delocalization of ionic charges, relief of ring strain, build-up of the Coulombic term) should necessitate a two-barrier process.

Among processes without ring opening, an inversion of the tetramethylcyclohexane chair of **9C** has to be considered. The spiro-C-atom (6-position) constitutes a further stereoelement. The size of the inversion barrier of such a hexasubstituted cyclohexane is hard to predict. We need to consider that, in the ^{19}F NMR spectrum of **9A**, line broadening was observed as well.[12] At any rate, for the 'soft' inversion of the tetramethylcyclobutanone ring (spiro partner in **9A**), a substantial barrier is not probable.

Thus, we are left with the equilibration of *transoid* **19** with a small population of *cisoid* **20** by ring inversion as reason for the line broadening observed in **9C**. This process involves a *E*,*Z* isomerization at the C=N double bond. Kinetic studies with open-chain ketene imines are in harmony with a lateral inversion through a linear TS **22**.[21–23,28] Trialkylketene imines show barriers of about 15 kcal mol^{-1}. The topomerization of ketene *N*-phenylimine was calculated (SCF/STO-3G) by Jochims et al., and barriers of 12.5 kcal mol^{-1} for the lateral inversion (linear TS) and 34.9 kcal mol^{-1} for the rotation about the C=N bond (planar bent TS) resulted.[23] Interestingly, like TS **22**, bis(sulfonyl)ketene imine **23** is linear in the ground state, reflecting the stabilization of the nitrilium ylide resonance contributor (Scheme 5).[29]

Firl et al. prepared the cyclic eight-membered ketene imine **24** (not obtained pure) and observed two diastereomers; a barrier of 19 kcal mol^{-1} was evaluated from a slight broadening of ^{13}C NMR signals and ascribed to an inversion at the C=N bond.[30]

The step from the eight-membered ring **24** to the seven-membered ketene imine **9C** is accompanied by a drastic



Scheme 5.

increase in strain. Only three ring members of **9C** are disposable to span the termini of a quasi-linear TS of type **22**. The S-atom in the bridge offers some alleviation, but it is doubtful whether such a high-energy TS can reasonably be assigned to a rate process with $T_c = -30\,^{\circ}C$. On the other hand, the shrinking of the allene-type torsion angle from 90 to 57.8° in **9C** presents a ketene imine on the way to the quasi-planar TS of C=N rotation.

Cyclohepta-1,2-diene (**25**) and cyclohexa-1,2-diene make fleeting appearances, but can be intercepted by Diels–Alder reactions with diphenylisobenzofuran.[31] According to calculations (B3LYP/TZP//B3LYP/DZP),[32] the allene subunit is still chiral (C_2), but the bending of C=C=C to 148.4° in the seven-membered ring and to 132.8° in the six-membered ring signals increasing strain. The topomerization of allene itself by rotation via a planar biradical (angle C–C–C 143°) requires 44.6 kcal mol^{-1} (B3LYP/TZP).[33] For cyclohexa-1,2-diene, the calculated barrier shrinks to 14.1 kcal mol^{-1} (MR-CI+Q/ANO-1//DFT).[34]

In view of these data, a diastereomerization of **9C** (*transoid* **19** ⇆ *cisoid* **20**) by rotation about the C=N bond, rather than inversion, ought to be considered as an alternate possibility.

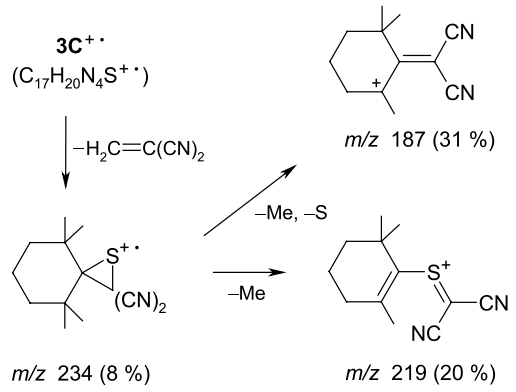
2.3. Reactions of 1C with further tetra-acceptor-substituted ethylenes

The reaction of dihydrothiadiazole **7C** with TCNE in benzene (80 °C, 20 h) exclusively furnished the tetracyanothiolane **3C** (Scheme 1). When the medium contained some methanol, the ^{1}H NMR analysis indicated the presence of the seven-membered lactim ether **5C** and thiolane **3C** in a ratio of about 84:16. Thus, the 1,7-cyclization of zwitterion **2C** prevailed over the 1,5-cyclization, as it did for **2A** (**5A**/**3A** = 68:32)[6] and **2B** (**5B**/**3B** = 97:3).[15] The short-lived ketene imine **4C**, lacking the stabilization by the 'perfluoroalkyl effect',[35] quickly isomerizes via **2C** to the thiolane **3C**, but can be intercepted by methanol.

As reported above, the reaction of **1C** with 2,3-bis(trifluoromethyl)fumaronitrile (**11**) gave rise to ketene imine **9C** and fragmentation products **13**+**6C**, but no thiolane **12C** was detected (Scheme 2). Probably, steric hindrance thwarts the 1,5-cyclization of the zwitterion *gauche*-**10C**.

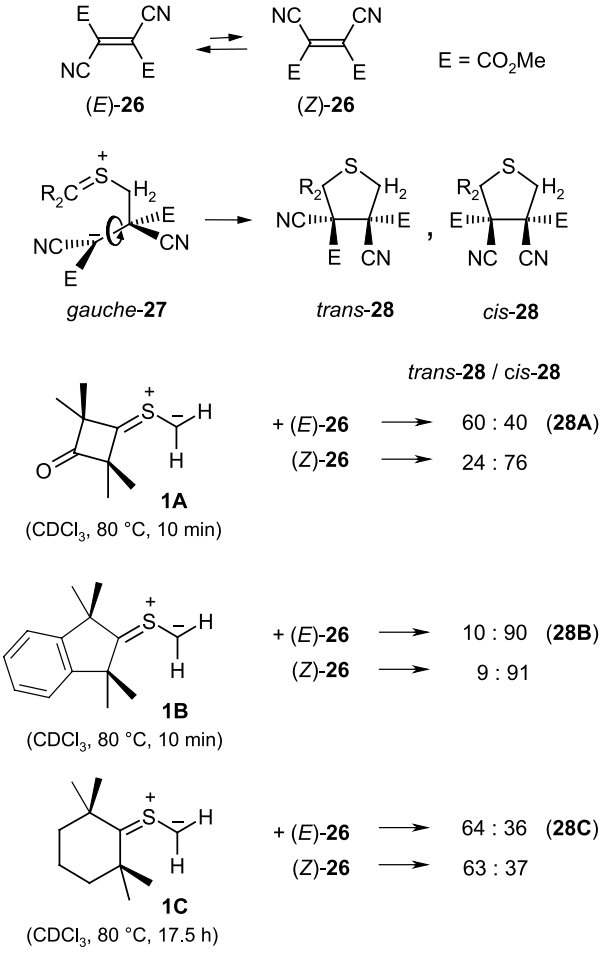
As radical cations, many cycloadducts break up into their original building blocks. Not so **3C**$^+$ which eliminates methylenemalononitrile with subsequent loss of Me and S, as suggested by Scheme 6. The molecular formulae were confirmed by high resolution and isotope peaks, but the proposed structures are speculative.

The isomer pair of dimethyl 2,3-dicyanofumarate ((*E*)-**26**)



Scheme 6.

and dimethyl 2,3-dicyanomaleate ((*Z*)-**26**) had provided first evidence for non-retentive cycloadditions of thiocarbonyl ylides (Scheme 7).[8] The different *trans*,*cis* ratios of thiolanes **28A**, which were observed in reactions of **1A** with (*E*)-**26** and (*Z*)-**26**, indicated a keen competition of rotation and 1,5-cyclization governing the zwitterion



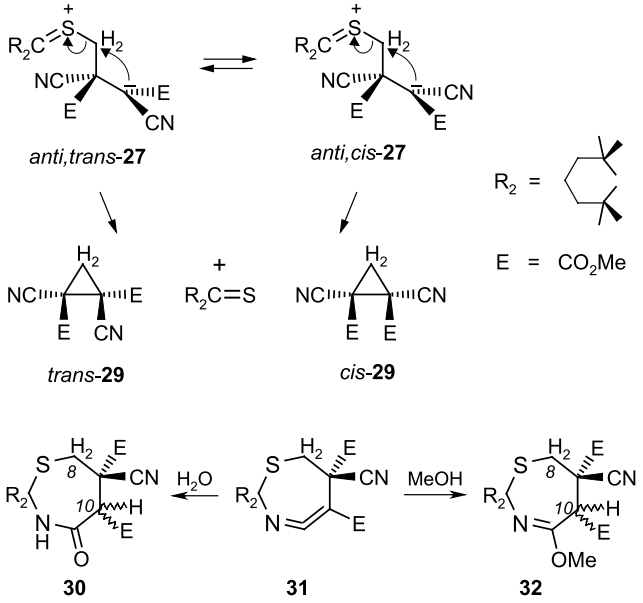
Scheme 7.

gauche-**27A**.[9] Growing steric screening in **27B** reduces the rate of 1,5-cyclization and allows the rotational equilibrium to be established before cyclization takes place: the same ratio of thiolanes **28B** was obtained from reactions with (*E*)-**26** and (*Z*)-**26**.[15]

The cycloadditions of **1C** likewise produced virtually identical ratios of thiolanes **28C** with (*E*)-**26** and (*Z*)-**26** (Scheme 7), but, regrettably, the results are mechanistically insignificant for several reasons: (a) after the reactions with (*E*)-**26** or (*Z*)-**26** ($CDCl_3$, 80 °C, 17.5 h), 16% of the dihydrothiadiazole **7C** were still unconsumed. That suggests $t_{½} \approx 6.7$ h for the first-order N_2 expulsion from **7C** versus $t_{½} = 3.0$ min for **7B**.[15] Thus, the liberation of thiocarbonyl ylide **1C** is slower by a factor of about 135 than that of **1B**, and the long time gives subsequent reactions an increased chance. (b) Among the dihydrothiadiazoles **7**, spiro-compound **7C** belongs to the most active catalysts for the *E*,*Z* isomerization of **26**. The precautions we took to curb it in the reactions of **7A** and **7B**[8] were ineffective here. After the reaction with **7C**, the excess of **26** revealed an established equilibrium at (*E*)/(*Z*)= 87:13. This did not permit us to draw any conclusion concerning the steric course of cycloaddition.

The *trans*,*cis*-isomeric thiolanes **28C** were separated and obtained in crystalline form. The stereochemical assignment was based on the value of $\Delta\delta_H$ of the diastereotopic protons 2-H_2: 0.19 ppm for *trans*-**28C** and 0.39 ppm for *cis*-**28C**. This empirical criterion, $\Delta\delta_H$ *trans*<*cis*,[9] was found to be valid for all tested thiolane pairs **28**,[15] and the structures were confirmed by several X-ray analyses.[15]

The reactions of **7C** with (*E*)-**26** under the above conditions furnished 41% of the thiolanes **28** (*trans*/*cis*=64:36) and 47% of dimethyl 1,2-dicyanocyclopropane-1,2-dicarboxylate (**29**, *trans*/*cis*=57:43). The zwitterions *gauche*-**27** undergo cyclization, and the conformers *anti*-**27** are responsible for the intramolecular substitution (Scheme 8), a process described above for zwitterions **10**. The fragmentation products, **29**+**6C**, are thermodynamically favored. When the pure thiolanes, *trans*-**28** and *cis*-**28**, were heated to 100 °C for 3 h in $CDCl_3$, complete conversion to **29** (*trans*/*cis*=50:50) was observed.



Scheme 8.

The intervention of ketene imine **31** was demonstrated by reactions of **1C** with (*E*)-**26** in the presence of water or methanol. The resulting pairs of diastereomeric lactams **30** and lactim methyl ethers **32** differ in their configurations at C-10; one of the lactams was isolated in pure state. The value of ^2J(H,H) of the ring—CH_2 group offers a diagnostic tool for five-membered versus seven-membered rings, for example, 12.6 Hz (*trans*-**28C**), 12.8 Hz (*cis*-**28C**), and 12.7 Hz (*trans*-**28B**) versus 15.4 Hz (**9C** and **14**), 16.5 Hz (**15**), and 15.2 Hz (**30**).

3. Experimental

3.1. Instruments and procedures[2]

The NMR solvent was $CDCl_3$, if not stated otherwise. As weight standards in the quantitative ^{1}H NMR analysis (±5% relative) were used: *sym*-tetrachloroethane (δ 5.92), the *as*-isomer (4.28), trichloroethene (6.70), or dibenzyl (2.92); standard in ^{19}F NMR analysis: (1,1-dichloro-2,2,2-trifluoroethyl)benzene (δ −78.2), abbrev. DICHLO. Multiplicities of ^{13}C NMR (20.2 MHz) signals were determined by comparison of ^{1}H decoupled and off-resonance spectra. The MS are EI spectra with 70 eV; intensities of isotope peaks are reported as, for example, ^{13}C% calcd/% found. Several MS made use of the program CMass and were recorded on a MAT 90 or MAT 95Q instrument. PLC is preparative layer chromatography on 20×20 cm glass plates, usually with 2 mm of Merck Silica gel 60 PF_{254}.

3.2. Materials

6,6,10,10-tetramethyl-4-thia-1,2-diazaspiro[4.5]dec-1-ene (**7C**).[2] The rate of the first-order N_2 extrusion was volumetrically measured and evaluated by $k_1t = \ln[V_\infty/(V_\infty - V_t)]$. Linear regression afforded 10^4k_1 [s^{-1}]: 1.48, 1.39 in DMSO at 95 °C; 2.53, 2.80 in mesitylene at 95 °C; 6.88, 7.92 in xylene at 100 °C. 4,4,8,8-Tetramethyl-1-thiaspiro[5.2]octane (**8C**);[2] 2,3-bis(trifluoromethyl)fumaronitrile (**11**);[12,36] dimethyl 2,3-dicyanofumarate (*E*)-**26**;[37] dimethyl 2,3-dicyanomaleate (*Z*)-**26**.[38]

3.3. Reactions of thiocarbonyl ylide 1C with bis(trifluoromethyl)fumaronitrile (11)

3.3.1. 1,1,5,5-Tetramethyl-9,10-bis(trifluoromethyl)-7-thia-12-azaspiro[5.6]dodeca-10,11-diene-9-carbonitrile (9C). Dihydrothiadiazole **7C** (1.91 g, 9.0 mmol) and **11** (2.14 g, 10.0 mmol) in benzene (25 mL) were refluxed for 15 h (incomplete N_2 elimination; see Section 3.3.4). After evaporation of the red solution, the pale-yellow ketene imine **9C** crystallized from pentane in 2 fractions (1.85 g, 52%), mp 93–94 °C. IR (KBr): ν 712 s cm^{-1}, 727m, 901m, 917m; 1080, 1126, 1159, 1191, 1208, 1254, 1268, 1288 (all vs, C–F); 1397m, 1476m; 2010+2030vs (C=C=N), 2245vw (C=N). ^{1}H NMR (80 MHz): δ 1.10, 1.25 (2s, 2Me), 1.33 (s, 2Me), 1.41–1.84 (m, 3CH_2), 3.14, 3.40 (AB,

J=15.4 Hz, 8-H_2). ^{13}C NMR (20.15 Hz): δ 18.3 (t, C-3), 24.6, 26.0, 29.5, 29.6 (4q, 4Me), 36.9, 38.3, 38.4 (3t, C-2, C-4, C-8), 41.9, 45.2 (2s, C-1, C-5), 43.7 (q, ^2J(C,F)=31.3 Hz, C-9), 60.6 (q, broadened, ^2J(C,F)=42.7 Hz, C-10), 95.2 (q, ^5J(C,F)=1.8 Hz, C-6), 112.9 (s, CN), 122.5 (q, ^1J(C,F)=269.8 Hz, CF_3), 122.8 (q, ^1J(C,F)=285.3 Hz, CF_3), 182.6 (q, ^3J(C,F)=4.3 Hz, C-11). ^{19}F NMR (376 MHz, 25 °C): −55.94 (q, ^5J(F,F)=5.8 Hz, 10-CF_3), −73.38 (br, 9-CF_3); (−30 °C): −55.74 (br, 10-CF_3), −73.16 (q, ^5J(F,F)=5.6 Hz, 9-CF_3); s.a. Figure 2. MS (MAT 90, CMass, 25 °C, calcd/found), *m/z* (%): 398.125/398.136 (5) [M^+, **16**, ^{13}C 0.92/0.90], 329.129/329.123 (17) [$C_{16}H_{20}F_3N_2S^+$, M^+-CF_3, **17**], 329.055/329.046 (22) [$C_{12}H_{11}F_6N_2S^+$, $M^+-C_5H_9$], 275.008/275.011 (7) [$C_8H_5F_6N_2S^+$, $M^+-C_9H_{15}$], 247.052/247.047 (15) [$C_{10}H_{10}F_3N_2S^+$, $M^+-CF_3-C_6H_{10}$], 170.113/170.110 (31) [$C_{10}H_{18}S^+$, **6C**$^+$, ^{13}C 3.4/3.9], 169.105/169.104 (21) [$C_{10}H_{17}S^+$], 137.133/137.132 (100) [$C_{10}H_{17}^+$, possibly **18**], 123.117/123.116 (28) [$C_9H_{15}^+$, probably trimethylcyclohexenyl$^+$], 114.050/114.046 (13) [$C_6H_{10}S^+$], 113.042/113.041 (30) [$C_6H_9S^+$], 100.035/100.033 (11) [$C_5H_8S^+$], 99.027/99.026 (16) [$C_5H_7S^+$], 95.086/95.085 (28) [$C_7H_{11}^+$], 88.035/88.032 (11) [$C_4H_8S^+$], 85.011/85.010 (12) [$C_4H_5S^+$], 81.070/81.075 (27) [$C_6H_9^+$], 79.055/79.053 (10) [$C_6H_7^+$], 69.070/69.069 (52) [$C_5H_9^+$], 68.995/68.994 (19) [CF_3^+], 67.055/67.054 (18) [$C_5H_7^+$], 57.070/57.069 (12) [$C_4H_9^+$], 55.055/55.054 (39) [$C_4H_7^+$], 53.039/53.038 (14) [$C_4H_5^+$], 41.039/41.041 (61) [$C_3H_5^+$]. Anal. Calcd for $C_{17}H_{20}F_6N_2S$ (398.41): C, 51.25; H, 5.06; N, 7.03. Found: C, 51.30; H, 5.17; N, 7.09.

3.3.2. Variable temperature NMR of 9C. *(a) ^{19}F NMR (376 MHz, [D$_8$]toluene).* After the spectrum was taken at 90 °C (Fig. 2, see above), a new recording at 30 °C indicated no irreversible changes. The standard signal (Cl_3CF) remained sharp over the whole temperature range. The half-width of the 9-CF_3 signal increases from 21 Hz at 0 °C to 55 Hz at 25 °C and decreases to 20 Hz at 90 °C; the half-width is ill-defined for structured quadruplets. The small unidentified peaks at −70 °C (Fig. 2), δ −55.26 on the low-frequency side of q (−54.67) and δ −72.69 which accompanies the q at δ −72.69 are not ^{13}C-satellites. The latter were recognized and showed ^1J(C,F)=271 Hz, high-field shifted by 54 Hz (isotope effect). Figure 2 reveals a greater height of the sharp q (δ −72.69) at 90 °C than at lower temperatures. At −70 °C quadruplets, both signals lose fine structure at −90 °C. Besides the increasing viscosity of the solvent toluene at low temp., beginning hindrance of CF_3 rotations may be responsible, as recently studied for an adamantyl-spiro-thiolane.[14]

(b) ^{1}H NMR (400 MHz, [D$_8$]toluene). The 8-H_2 appears at −90 °C as AM spectrum at δ 1.98 and 2.45 with ^2J=15.6 Hz and at 20 °C as AB at δ 2.70 and 2.75; the $\Delta\delta$ diminishes with increasing temperature: 12 Hz at 50 °C, ~2 Hz at 60 °C, and an A_2 spectrum with δ 2.92 at 90 °C. The half-width of the signals were not measured.

3.3.3. X-ray diffraction analysis of 9C. The monocyclic crystal (0.17×0.33×0.53 mm^3) of space group $P2_1/c$ No. 14 was sealed in a glass capillary and mounted on the goniometer head of CAD4 diffractometer operating with Mo K_α radiation (λ=0.71069 Å) and graphite monochromator. Unit cell dimensions: a=1187.9(3) Å, b=1059.3(2) Å, c=1472.1(5) Å, β=100.89(2)°, V=1.8191 nm^3, Z=4, D_{calc}=1.455 g/cm^3, $F(000)$=824, T=294(1) K, μ=2.39 cm^{-1}. The unit cell dimensions resulted from a least-square fit of the setting angles of 25 centered reflections; ω–2θ scan, width 1.00° +0.35 tan θ, maximum measuring time 120 s, 2θ range 4–46° for all $\pm h/\pm k/+l$ reflections; 2638 reflections collected, 2521 unique, and 2074 with $I>2\sigma(I)$. The structure was solved by the SHELXTL program package,[39] non-hydrogen atoms refined anisotropically, hydrogen atoms fixed isotropically with U_i=1.2×U_{eq} of the adjacent carbon atom, full matrix refinement; final R_1=0.0365 and R_w=0.0315. The final difference map was featureless with 239 refined variables; ZORTEP plot.[40] The deposition No. CCDC-160826 contains supplementary data, which can be obtained from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 IEZ, UK (fax: +44 (1233) 336-003; e-mail: deposit@ccdc.cam.ac.uk

3.3.4. Kinetics of formation and conversion of ketene imine 9C. (a) The solution of **7C** (298 µmol), **11** (325 µmol), and DICHLO (190 µmol) as weight standard in C_6D_6 (0.6 mL) in a closed NMR tube was immersed in a 80 °C bath. Periodically, within 242 h, ^{19}F NMR spectra were recorded, and the concentrations of **9C**, **13** and **11** were determined by machine integrals. The comparison with the integral of the standard compensates field inconstancies over the reaction time. The (*E*),(*Z*) isomerization of **11** was catalyzed by the dihydrothiadiazole **7C**; (*E*)-**11**/(*Z*)-**11** amounted to 94:6 after 3.3 h, and the 90:10 equilibrium was established after 14.5 h. This catalysis has been studied with dihydrothiadiazole **7A**, and (*E*)-**11**/(*Z*)-**11**=93:7 was reported for C_6D_6 at 40 °C.[12] The concentration of **9C** passed a shallow maximum of 73% after ~16 h. The formation of 1,2-bis(trifluoromethyl)cyclopropane-1,2-dicarbonitrile (**13**, *trans*/*cis*=95: 5)[14] displayed an induction period: % *trans*-**13**+ *cis*-**13** (after h at 80 °C)=2 (3.25), 4 (7), 11 (14.5), 13 (18.5), 18 (26.5), 43 (70), 57 (114), 73 (177). The increase of the product concentrations, (**9C**)+(**13**), corresponds to the decrease of (**7C**), invisible in ^{19}F NMR spectrum, and follows the first-order law. Linear regression of the time function of ln (**7C**)$_o$/[(**7C**)$_o$−(**9C**+**13**)$_t$] furnished $k_1=3.8\times10^{-5}$ [s^{-1}] (five values up to 82% reaction and 14.5 h, r=0.998). After 50 h, new ^{19}F NMR signals suggested secondary reactions, and after 242 h, the sum (**9C**+**13**) amounted only to 67% of (**7C**)$_o$. Thus, the given rate constant is only an approximative value.

(b) Pure ketene imine **9C** (240 µmol) and DICHLO in C_6D_6 (0.6 mL) in a sealed NMR tube were heated to 80 °C and ^{19}F NMR-analyzed as above. A first-order reaction described the decrease of (**9C**) up to 91% after 137 h with $k_2=5.0\times10^{-6}$ [s^{-1}] (six points, r=0.999). The cyclopropanes, *trans*-**13** and *cis*-**13**, were the only visible products for 30 h at 80 °C. On longer heating, small signals showed up; after 294 h, **9C** had disappeared, but (**13**)$_\infty$ reached only 182 µmol, that is, 76% of (**7C**)$_o$. Whether or not thiolane **12C** is one of the minor side-products, is not clear.

(c) Ketene imine **9C** stores astonishingly well. A specimen which was kept in a stoppered glass for more than 10 years,

contained, according to the IR spectrum, mainly **9C** and lactams **15** (hydration product of **9C**).

3.3.5. 11-Methoxy-1,1,5,5-tetramethyl-9,10-bis(trifluoromethyl)-7-thia-12-azaspiro[5.6]dodec-11-ene-9-carbonitrile (14). Ketene imine **9C** (1.0 mmol) was dissolved in $CHCl_3$ (5 mL) and MeOH (0.1 mL). After one hour at rt, the solvent was removed and ^{1}H NMR analysis indicated 67% of **14**. The colorless lactim ether (46%) crystallized from MeOH. Mp 106–108 °C. IR (KBr): ν 983m cm^{-1}; 1167s, 1207s, 1249s, 1279s (C–F), 1690s (C=N). ^{1}H NMR (80 MHz): δ 1.04, 1.10, 1.21, 1.30 (4s, 4Me), 1.0 – 2.1 (m, 3CH_2), 3.22, 3.55 (AB, ^2J=15.4 Hz, 8-H_2), 3.83 (s, OMe), 5.24 (q, ^3J(F,H)=8.2 Hz, 10-H). ^{13}C NMR (20.2 MHz): δ 18.9(t, C-3), 24.7, 26.0, 29.6, 29.8 (4q, 4Me), 37.0 (tq, ^3J(C,F)=2.4 Hz, C-8), 37.2, 37.9 (2t, C-2, C-4), 43.1, 46.6 (2s, C-1, C-5), 45.4 (q, ^2J(C,F)=31.7 Hz, C-9), 48.5 (dq, ^2J(C,F)=30.5 Hz, C-10), 54.3 (s, OMe), 81.9 (s, C-6), 113.7 (q, ^3J(C,F)=2.0 Hz, CN), 122.7 (q, ^1J(C,F)=285.6 Hz, CF_3), 123.2 (q, ^1J(C,F)=280.8 Hz, CF_3), 148.2 (s, C-11). ^{19}F NMR (376 MHz): δ −61.9 (dq, ^3J(F,H)∼8 Hz, ^5J(F,F)=9.1 Hz, 10-CF_3), −69.0 (q, ^5J(F,F)=9.2 Hz, 9-CF_3). MS (MAT 90, CMass), *m/z* (%): 430.151/430.151 (10) [M^+], 415.127/415.124 (8) [M^+−Me], 372.176/372.176 (32) [$C_{17}H_{24}F_6NO^+$], M^+−S−CN, ^{13}C 6.1/7.0], 348.073/348.071 (10) [$C_{12}H_{14}F_6N_2OS^+$, M^+−C_6H_{10}], 346.057/346.058 (10) [348−2H], 305.018/305.018 (12) [$C_9H_7F_6N_2OS^+$, M^+−C_9H_{17}], 278.007/278.008 (100) [$C_8H_6F_6NOS^+$, M^+−HCN−C_9H_{17}, ^{13}C 8.9/9.0], 152.144/152.143 (31) [$C_{10}H_{18}N^+$], 141 (23), 137.133/137.134 (15) [$C_{10}H_{17}^+$, **18**], 136.037/136.039 (18) [$C_5H_5NF_3^+$], 107 (23), 105 (10), 95.086/95.086 (9) [$C_7H_{11}^+$], 89.039/89.042 (26) [$C_4H_9S^+$], 79.053/79.053 (9) [$C_6H_7^+$], 77.039/77.040 (45) [$C_6H_5^+$], 69.070/69.070 (37) [$C_5H_9^+$], 68.995/68.995 (5) [CF_3^+], 68.050/68.057 (11) [$C_4H_6N^+$], 55.055/55.054 (37) [$C_4H_7^+$]. Anal. Calcd for $C_{18}H_{24}F_6N_2OS$ (430.45): C, 50.22; H, 5.62; N, 6.51. Found: C, 50.29; H, 5.59; N, 6.58.

3.3.6. 1,1,5,5-Tetramethyl-11-oxo-9,10-bis(trifluoromethyl)-7-thia-12-azaspiro[5.6] dodecane-9-carbonitrile (15). Ketene imine **9C** (1.0 mmol) was reacted with H_2O (0.25 mL) in THF (20 mL) 1 h at rt and gave **15** (48%) from MeOH. Mp 192–193 °C (green, gas evol.). IR (KBr): ν 1126 s cm^{-1}, 1169s, 1213s, 1268s (C–F), 1636vs (C=O), 3260m br (N–H). ^{1}H NMR (80 MHz): δ 1.11, 1.35 (2s, 2Me), 1.25 (s, 2Me), 1.3–1.8 (br s, 3CH_2), 3.27, 3.66 (AB, ^2J=16.5 Hz, right branch broadened, 8-H_2), 5.20 (q, ^3J(C,F)=6.8 Hz, 10-H), 6.70 (s, br, NH). ^{13}C NMR (100.6 MHz, DEPT): δ 17.9 (C-3), 24.8, 26.6, 28.4, 30.1 (slightly broadened, 4Me), 36.35, 36.83 (C-2, C-4), 36.45 (^3J(C,F)=1.9 Hz, C-8), 43.8, 44.8 (C-1, C-5), 44.6 (^2J(C,F)=29.4 Hz, C-9), 49.4 (^2J(C,F)=29.4 Hz, C-10), 77.2 (C-6), 112.7 (^3J(C,F)=1.9 Hz, CN), 122.51 (^1J(C,F)=286.1 Hz, CF_3), 122.76 (^1J(C,F)=280.6 Hz, CF_3), 163.8 (C=O). ^{19}F NMR (376 MHz): δ −61.9 (dq, 6 lines visible, ^5J(F,F)=9.2 Hz, ^3J(H,F)≈9 Hz, 10-CF_3), −69.0 (q, ^5J(F,F)=9.2 Hz, 9-CF_3). MS (MAT 95Q, CMass), *m/z* (%): 416.135/416.134 (0.8) [M^+], 358.160/358.161 (6) [$C_{16}H_{22}F_6NO^+$, M^+−S−CN; ^{13}C 2.8/2.4], 334.057/334.058 (29) [$C_{11}H_{12}F_6N_2OS^+$, M^+−C_6H_{10}; $^{13}C_2$+^{34}S 4.3/4.4], 247.031/247.033 (13) [$C_7H_5F_6N_2O^+$, M^+−**6C**+H], 224 (12), 211.028/211.029 (6) [$C_7H_8F_3NOS^+$], 152.144/152.144 (35) [$C_{10}H_{18}N^+$], 137.133/137.133 (100) [$C_{10}H_{17}^+$, **18**], 136.125/136.124 (8) [$C_{10}H_{16}^+$], 121.101/121.101 (12) [$C_9H_{13}^+$], 96.081/96.083 (12) [$C_6H_{10}N^+$], 95.086/95.085 (14) [$C_7H_{11}^+$; methylcyclohexenyl$^+$ or dimethylcyclopentyl$^+$], 82.078/82.076 (42) [$C_6H_{10}^+$], 71.073/71.074 (34) [$C_4H_9N^+$], 69.070/69.070 (47) [$C_5H_9^+$, dimethylallyl$^+$], 69.058/69.057 (33) [$C_4H_7N^+$], 68.995/68.995 (8) [CF_3^+], 55.055/55.055 (22) [$C_4H_7^+$, methallyl$^+$]. Anal. Calcd for $C_{17}H_{22}F_6N_2OS$ (416.43): C, 49.03; H, 5.33; N, 6.73. Found: C, 49.24; H, 5.30; N, 6.50.

3.4. Reactions of thiocarbonyl ylide 1C with ethenetetracarbonitrile (TCNE)

3.4.1. 6,6,10,10-Tetramethyl-1-thiaspiro[4,5]decane-3,3,4,4-tetracarbonitrile (3C). Dihydrothiadiazole **7C** (425 mg, 2.00 mmol) and TCNE (282 mg, 2.20 mmol) in C_6H_6 (10 mL) were refluxed for 20 h. After removal of the solvent, the ^{1}H NMR analysis in $CDCl_3$ with trichloroethene indicated quantitative formation of **3C**. From MeOH, **3C** (330 mg, 54%) was isolated as yellow plates, mp 181 °C (dec.). IR (KBr): ν 980m cm^{-1}, 1398m, 1404m, 1433m, 1465m, 2250vw (C≡N). ^{1}H NMR (80 MHz): δ 1.60 (s, 4Me), 1.28 – 1.75 (m, 6 ring-H), 3.58 (s, 2-H_2). ^{13}C NMR (20.2 MHz): δ 17.5 (t, C-8), 25.9, 32.3 (2s, 2×2 Me), 41.3 (t, C-2), 42.1 (t, C-7+C-9), 42.6 (s, C-6+C-10), 51.6, 55.0 (2s, C-3, C-4), 84.2 (s, C-5), 111.1, 112.7 (2s, 2×2 CN). MS (80 °C), *m/z* (%): 297 (3) [M^+−Me], 285 (3) [M^+−HCN], 259 (8) [M^+−HCN−CN; $^{13}C_2$+^{34}S 0.44/0.49], 234 (8) [$C_{13}H_{18}N_2S^+$, M^+−H_2C=C(CN)$_2$; ^{13}C 1.1/1.1; $^{13}C_2$+^{34}S 0.42/0.48], 228 (32) [$C_{11}H_8N_4S^+$, M^+−C_6H_{12}; HR 228.0469/228.0474], 219 (20) [$C_{12}H_{15}N_2S^+$, 234−Me; ^{13}C 2.6/2.3], 201 (28) [$C_{10}H_7N_3S^+$, 228−HCN; HR 201.036/201.019], 187 (31) [$C_{12}H_{15}N_2^+$, possibly dicyanomethylene-trimethylcyclohexyl$^+$; ^{13}C 4.1/4.3], 174 (11), 152 (13), 150 (33), 149 (13), 147 (16), 146 (13), 145 (15), 134 (33) [$C_{10}H_{14}^+$; ^{13}C 3.5/3.8; HR 134.109/134.096], 133 (78) [$C_{10}H_{13}^+$], 119 (17), 106 (18), 91 (11) [tropylium$^+$], 83 (57) [$C_6H_{11}^+$, trimethylallyl$^+$], 78 (54) [$C_4H_2N_2^+$, methylenemalononitrile$^+$; HR 78.022/78.023], 77 (35) [$C_6H_5^+$], 70 (100) [$C_5H_{10}^+$, ^{13}C 5.6/5.9], 69 (65) [dimethylallyl$^+$], 55 (77) [methylallyl$^+$]. Anal. Calcd for $C_{17}H_{20}N_4S$ (312.43): C, 65.35; H, 6.45; N, 17.93. Found: C, 64.94; H, 6.60; N, 17.84.

3.4.2. Interception of ketene imine 4C. In a cursory experiment, **7C** (198 μmol) and TCNE (258 μmol) in C_6H_6 (5 mL)+MeOH (100 μL, 2.5 mmol) were heated to 80 °C for 20 h. After evaporation of the solvent, the ^{1}H NMR signals ($CDCl_3$) of MeO (s, δ 3.83) and 8-H_2 (δ 3.32, 3.56, AB, ^2J=16.2 Hz) are indicative of the lactim methyl ether **5C**. Quantitative analysis with *sym*-$C_2H_2Cl_4$ pointed to 68% of **5C** and 13% of thiolane **3C**. During 20 h at 80 °C, part of the TCNE probably reacted with the MeOH, before **1C** was completely set free.

3.5. Reactions of 1C with dimethyl 2,3-dicyanofumarate ((*E*)-26) and dimethyl 2,3-dicyanomaleate ((*Z*)-26)

3.5.1. Isolation of spirothiolanes. Dihydrothiadiazole **7C** (1.06 g, 5.0 mmol) and (*Z*)-**26** (1.07 g, 5.5 mmol) in abs. octane (10 mL) were reacted in the 130 °C bath for 10 min. PLC (Et_2O/pentane 30:70, 2×) furnished *trans*-**28C**

(475 mg, 25%) as first fraction and *cis*-**28C** (340 mg, 18%) as second fraction.

3.5.2. Dimethyl *trans*-3,4-dicyano-6,6,10,10-tetramethyl-1-thiaspiro[4.5]decane-3,4-dicarboxylate (*trans*-28C). Recrystallised from MeOH, mp 141–143 °C (dec.). IR (KBr): ν 918m cm^{-1}; 1244s+1254s br (C–O), 1754vs (C=O), 2235, 2250vw (C≡N). ^{1}H NMR (80 MHz): δ 1.15, 1.59, 1.68, 1.76 (4s, 4Me), 1.3–1.5 (nonresolv. m, 3CH_2), 3.41, 3.60 (AB, ^2J=12.6 Hz, 2-H_2), 3.89, 3.95 (2s, 2MeO). ^{13}C NMR (20.2 MHz): δ 17.9 (t, C-8), 24.5, 25.5, 32.7, 33.0 (4q, 4Me), 39.0 (t, C-2), 41.3, 44.6 (2s, C-6, C-10), 43.9, 44.7 (2t, C-7, C-9), 54.5, 54.9 (2q, 2MeO), 63.9, 64.7 (2s, C-3, C-4), 83.5 (s, C-5), 116.7, 119.0 (2s, 2CN), 164.2, 164.5 (2s, 2C=O). MS (60 °C), *m/z* (%): 378 (3) [M^+], 364 (3) [M^+-CH_2; ^{13}C 0.7/0.9], 319 (58) [M^+-CO_2Me; ^{13}C 11.0/11.2; $^{13}C_2+^{34}S$ 3.6/3.1], 294 (28 [$C_{13}H_{14}N_2O_4S^+$, $M^+-C_6H_{12}$; $^{13}C_2+^{34}S$ 1.52/1.53; HR 294.067/294.074), 292 (30) [$C_{16}H_{22}NO_2S^+$, 319−HCN; HR 292.137/292.131], 267 (52) [$C_{14}H_{21}NO_2S^+$, M^+-H_2C=C(CN)−CO_2Me], ^{13}C 8.1/8.5; HR 267.129/267.124], 252 (14) [267−Me; ^{13}C 2.0/2.2], 237 (13), 235 (17) [267−S, $C_{14}H_{21}NO_2^+$], 211 (11), 191 (16), 185 (11), 177 (38), 176 (78) [$C_9H_8N_2S^+$, possibly dicyano-isopropyl-thiophene$^+$], 170 (54) [$C_{10}H_{18}S^+$, **6C**$^+$], 155 (10), 148 (33), 137 (37) [$C_{10}H_{17}^+$, **18**; ^{13}C 4.1/4.6], 127 (17), 125 (11), 121 (17) [$C_9H_{13}^+$], 114 (11), 101 (30), 95 (20) [$C_7H_{11}^+$], 93 (12), 88 (19), 83 (24) [$C_6H_{11}^+$], 82 (31) [$C_6H_{10}^+$], 81 (25), 69 (100) [$C_5H_9^+$, dimethylallyl$^+$], 67 (24), 59 (38) [MeO−C≡O$^+$], 55 (29) [methylallyl$^+$]. Anal. Calcd for $C_{19}H_{26}N_2O_4S$ (378.48): C, 60.29; H, 6.92; N, 7.40; S, 8.47. Found: C, 60.07; H, 6.87; N, 7.34; S, 8.47.

3.5.3. Dimethyl *cis*-3,4-dicyano-6,6,10,10-tetramethyl-1-thiaspiro[4.5]decane-3,4-dicarboxylate (*cis*-28C). Mp 101–103 °C (MeOH). IR (KBr): ν 1030w cm^{-1}, 1235+1245vs, br (C–O), 1437m; 1745vs, sh 1760 (C=O), 2250vw (C≡N). ^{1}H NMR (80 MHz): δ 1.21, 1.26, 1.70, 1.81 (4s, 4Me), 1.4–2.0 (m, 7-H_2, 8-H_2, 9-H_2), 3.44, 3.83 (AB, ^2J=12.8 Hz, 2-H_2), 3.83, 3.85 (2s, 2MeO). ^{13}C NMR (20.2 MHz): δ 17.9 (t, C-8), 24.6, 26.0, 31.0, 34.3 (4q, 4Me), 39.9 (t, C-2), 41.8, 44.1 (2s, C-6, C-10), 42.6, 45.4 (2t, C-7, C-9), 54.31, 54.43 (2q, 2MeO), 63.0, 66.6 (2s, C-3, C-4), 87.1 (s, C-5), 117.1, 118.0 (2s, 2CN), 164.6, 167.6 (2s, 2C=O). Anal. Calcd for $C_{19}H_{26}N_2O_4S$ (378.48): C, 60.29; H, 6.92; N, 7.40; S, 8.47. Found: C, 60.08; H, 6.90; N, 7.57; S, 8.62.

3.5.4. ^{1}H NMR product analysis of the reaction at 80 °C. (a) Dihydrothiadiazole **7C** (22.0 mg, 104 μmol) and (*E*)-**26** (22.0 mg, 113 μmol) in 7.6 mM H_2SO_4 in $CDCl_3$ (1.0 mL),[9] sealed in a NMR tube, were reacted at 80 °C for 17.5 h. After cooling of the pink solution with liquid N_2, the tube was opened, and 100 μL of a standard solution of dibenzyl in $CDCl_3$ was added. The ^{1}H NMR analysis (270 MHz) showed that still 17 μmol (16%) of **7C** (δ 0.53) remained unconsumed; product yields refer to consumed **7C**. The excess of dipolarophile (δ 4.04 for (*E*)-**26** and 3.98 for (*Z*)-**26**, OMe) turned out to be equilibrated: (*E*)-**26**/(*Z*)-**26**= 87:13. Thiolanes *trans*-**28C** (δ 3.60, 3.90, 3.96) and *cis*-**28C** (δ 3.85, 3.87, MeO) were present in yields of 26 and 15%, respectively. Furthermore, 27% of dimethyl *trans*-1,2-dicyanocyclopropane-1,2-dicarboxylate (*trans*-**29**, δ 2.60, 3.98) and 20% of the isomer *cis*-**29** (δ 2.34, 2.60, 3.88) were analyzed; both *trans*-**29** and *cis*-**29** were characterized previously.[41] Finally, ~10% of the lactam **30** (δ 3.82, 3.91) resulted from reaction with a trace of humidity.

(b) An analogous experiment with **7C** (102 μmol) and (*Z*)-**26** (114 μmol) showed likewise 17 μmol of unconsumed **7C** and afforded *trans*-**28C** (24%), *cis*-**28C** (14%), *trans*-**29** (26%), *cis*-**29** (21%), and **30** (~9%).

(c) Preceding studies dealt with the catalysis of equilibration, (*E*)-**26**⇌(*Z*)-**26** by dihydrothiadiazoles **7**.[8,9] The activity of **7C** could not be suppressed by a trace of acid, for example, (*Z*)-**26** in 7.6 mM H_2SO_4 in $CDCl_3$ at rt after 12 h showed 12% isomerization to (*E*)-**26**.

3.5.5. Thermolysis of *trans*-28C and *cis*-28C at 100 °C. The reactions were carried out in $CDCl_3$ in sealed NMR tubes and revealed after 3 h at 100 °C a complete fragmentation into 2,2,6,6-tetramethylcyclohexanethione (**6C**) and *trans*-**29**/*cis*-**29**=1:1 (^{1}H NMR analysis).

3.5.6. Interception of ketene imine 31. (a) Dihydrothiadiazole **7C** (3.3 mmol) and (*E*)-**26** (3.0 mmol) in dioxane +1 vol% H_2O (6 mL) were heated to 80 °C for 20 h. Treatment of the yellow residue (after evaporation) with Et_2O afforded lactam **30** (39%) in two diastereoisomers, one of which was obtained pure by fractional crystallization from Et_2O.

(b) In a separate experiment, **7C** was reacted with 1.1 equiv of (*E*)-**26** in THF+1 vol% H_2O 5 h at 100 °C. After evaporation and dissolving in $CDCl_3$, the diastereoisomer ratio of **30** (66:34) was determined by the ^{1}H NMR integrals of 10-H at δ 5.11 and 5.38, and comparison with Cl_2C=CHCl as weight standard showed 55% yield.

(c) Compound **7C** (0.69 mmol) was reacted with (*Z*)-**26** (1.1 mmol) in C_6H_6+2 vol% MeOH (5 mL) at 80 °C for 20 h. In the NMR analysis ($CDCl_3$), 2s at δ 5.14 and 5.39 (70:30) were assigned to the 10-H of diastereoisomeric lactim methyl ethers **32** (not isolated). The missing of the signals of *trans*- and *cis*-**28** suggested a complete trapping of **31** by MeOH.

3.5.7. Dimethyl 9-cyano-1,1,5,5-tetramethyl-11-oxo-7-thia-12-azaspiro[5.6]dodecane-9,10-dicarboxylate (30). Mp 148–149 °C. IR (KBr): ν 1182 cm^{-1}, 1214m, 1251m, 1290m, 1327m, 1388s (C–O), 1436m, 1659vs (C=O, amide I), 1752vs (C=O, ester), 2247vw (C≡N), 3260m (N–H, also in nujol). ^{1}H NMR (80 MHz): δ 1.10, 1.24, 1.28, 1.33 (4s, 4Me), 1.40–1.57 (m, 2-H_2, 3-H_2, 4-H_2), 3.31, 3.43 (AB, ^2J=15.2 Hz, 8-H_2), 3.78, 3.85 (2s, 2MeO), 5.11 (s, 10-H), 5.96 (s br, NH). MS (205 °C), *m/z* (%): 396 (10) [M^+], 365 (10) [M^+−OMe, ^{13}C 1.9/1.8], 338 (100) [$C_{18}H_{28}NO_5^+$, M^+-S-CN, S-free], 314 (45) [$C_{13}H_{18}N_2O_5S^+$, $M^+-C_6H_{10}$, ^{13}C 6.6/6.8, $^{13}C_2+^{34}S$ 2.5/2.7], 253 (11), 244 (20), 220 (10), 212 (53), 202 (17), 198 (33) [$C_8H_5NO_5^+$, ^{13}C 2.9/3.2], 185 (14), 184 (13) [perhaps **1C**$^+$], 170 (35) [$C_{10}H_{18}S^+$, **6C**$^+$], 154 (13), 153 (13), 152 (19), 138 (22), 137 (59) [$C_{10}H_{17}^+$], 117 (11), 71 (22), 69 (20). Anal. Calcd for $C_{19}H_{28}N_2O_5S$ (396.50): C, 57.55; H, 7.12; N, 7.07; S, 8.09. Found: C, 57.33; H, 7.29; N, 7.09; S, 8.09.

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