Pergamon

Tetrahedron 58 (2002) 507–519

TETRAHEDRON

Cycloadditions of two thiocarbonyl ylides with α,β-unsaturated esters and nitriles: steric course and mechanism☆

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Dedicated to Professor Jürgen Sauer on the occasion of his 70th birthday

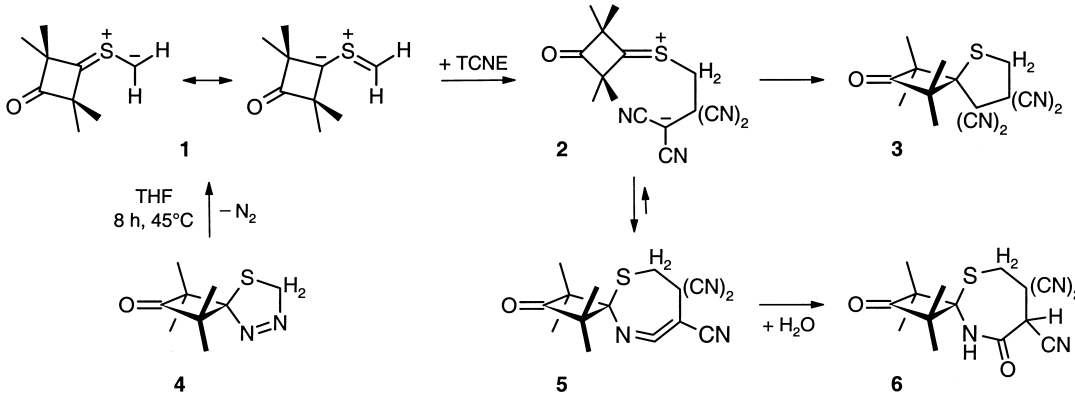
Received 24 September 2001; accepted 5 November 2001

Abstract—In the probably concerted cycloadditions of the sterically hindered thiocarbonyl ylide **1** with fumaronitrile, maleonitrile, and dimethyl fumarate, the dipolarophile configuration is retained whereas retention/inversion 99:1 for dimethyl maleate (51 times less reactive than fumarate) signals a small involvement of a two-step pathway. The latter becomes dominant when two acceptor groups stabilize the anionic terminus of a zwitterionic intermediate. Nonstereospecific cycloadditions of **1** with dimethyl 2,3-dicyanofumarate (**16**, retention/inversion 60:40) and dimethyl 2,3-dicyanomaleate (**17**, 76:24) were observed. Special conditions were required to avoid a preceding *cis*, *trans* isomerization, **16**⇄**17**, catalyzed by thiadiazoline **4**, the precursor of **1**. In the case of the related thiocarbonyl ylide **37**, this catalysis could not be suppressed and the same ratio of adducts (55:45) was obtained with **16** and **17**.

1. Introduction

Concerted formation of two new σ-bonds vs. two-step reaction via an intermediate is a fundamental question of cycloaddition chemistry. Experiment and theory support the conclusion that the majority of Diels–Alder reactions (DAR)[2] and 1,3-dipolar cycloadditions[3a] use the concerted pathway. Since the advantage of the concert in terms of activation energy is limited, much effort was spent in the last decades on borderline crossings, i.e. on the promotion of the two-step process by suitable choice of reactants. The model systems can be targeted on the formation of diradical or zwitterionic intermediates. The experimental approach is based on the interception of intermediates, violation of stereoretention for *cis*-, *trans*-isomeric substrates, and on kinetic phenomena.

In the framework of Sustmann's reactivity model,[4] we



Scheme 1.

☆ See Ref. 1.

Keywords: 1,3-dipolar cycloadditions; thiocarbonyl ylides; stereospecificity; zwitterionic intermediates.

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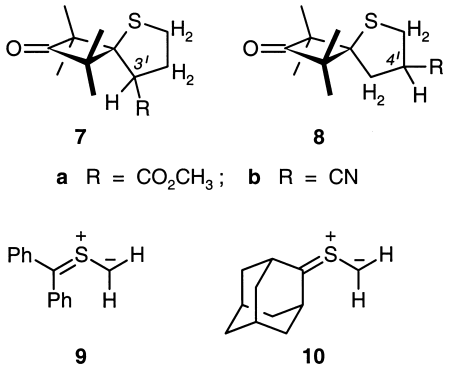
0040–4020/02/$ - see front matter
PII: S0040-4020(01)01147-4



Scheme 2.

studied reactions of nucleophilic 1,3-dipoles (high π-HOMO energies) with electron-deficient dipolarophiles (low π-LU energies) in the hope of stabilizing a zwitterionic intermediate. Thiocarbonyl ylides[5] are closely related to the allyl anion, and tetra-acceptor-substituted ethylenes were chosen as dipolarophiles. It turned out that a further condition has to be fulfilled to divert the cycloaddition from the orthodox concerted pathway: massive steric hindrance at one terminus of the 1,3-dipole.[6]

The easily available and storable 1,3,4-thiadiazoline **4** is the precursor of thiocarbonyl ylide **1**. A preceding paper dealt with the capturing of the 7-membered cyclic ketene imine **5** in the reaction of **1** with tetracyanoethylene (TCNE); **5** was in situ converted by water to the lactam **6** (Scheme 1) and by methanol to the corresponding methyl imidate.[7,8] The zwitterionic intermediate **2** enters into the reversible formation of **5** and the irreversible closure of the thiolane ring. Products **6** and **3** were obtained in 65:35 ratio.

Here we report on the steric course of the 1,3-cycloadditions of thiocarbonyl ylides **1** and **37** with electrophilic *cis*-, *trans*-isomeric dipolarophiles. The results of two preliminary communications[9,10] are supplemented with new experimental material.

2. Reactions of 2,2,4,4-tetramethyl-3-thioxocyclobutanone *S*-methylide (1) with mono- and di-acceptor-substituted ethylenes

When the not isolable **1** was set free from its precursor **4** in an excess of methyl acrylate or acrylonitrile as solvent, the regioisomeric cycloadducts **7** and **8** were formed (Scheme 2).[11] The ratios, **7a/8a**=65:35 and **7b/8b**=80:20, reflect the nucleophilicities at both termini of **1**. In accordance with a concerted addition, no polymerization of the vinyl monomers was observed.[11] The cycloadditions of thiocarbonyl ylides **9** and **10** with methyl acrylate and acrylonitrile furnished exclusively the 3′-substituted thiolanes, corresponding to **7**.[12,13] Thus, the higher steric demands of **1** enforced some formation of **8**.

In the reaction of **1** with methyl methacrylate as solvent, the cycloadduct (3′/4′-substitution now 20:80) was accompanied by 2.6% of polymer.[11] Thanks to the amplification effect associated with polymerization, very small quantities of intermediates in cycloadditions can be elegantly detected by this trapping technique.[14]

When **4** was reacted with dimethyl fumarate (1.1 equiv.) in abs. THF at 40°C (N_2 elimination with $t_{1/2}$=86 min) for 8 h, the ^{1}H NMR analysis with weight standard indicated 95% of the *trans*-cycloadduct **11** (Scheme 3). The signals of *cis*-adduct **12** were missing in the ^{1}H NMR spectrum (500 MHz), although comparison with the ^{13}C-satellites of **11** would allow to detect as little as 0.03% of **12**. Thus, the retention of *trans* structure amounts to >99.97%.

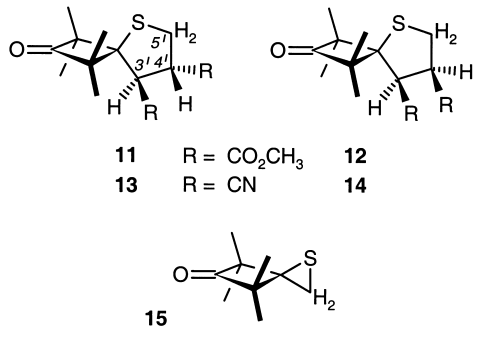
cis-Disubstituted ethylenes are weaker dipolarophiles than the *trans* compounds.[3b] In the product obtained with 1.1 equiv. of dimethyl maleate, 27% of thiirane **15**, formed by the electrocyclic ring closure of **1**,[15] signaled the incompleteness of the interception with the dipolarophile. The cycloadduct consisted of **12** (70%) and **11** (<1%).

The commercial sample of the liquid dimethyl maleate contained 0.34±0.03% of dimethyl fumarate. By cycloaddition with 0.12 equiv. of diphenyldiazomethane (k_{trans}/k_{cis}=36)[16] and subsequent distillation, the fumarate content is expected to be reduced to 0.004%. When this purified maleate sample (neat, 3.4 equiv.) was reacted with **4**, the ^{1}H NMR analysis (500 MHz, ^{13}C-satellite technique) revealed *cis*/*trans*=**12**/**11**=98.9:1.1. The minor violation of the dipolarophile retention suggests some involvement of a pathway via an intermediate which is capable of rotation.

The cycloaddition of **1** to a mixture of dimethyl fumarate and dimethyl maleate provided the competition constant, κ=51, i.e. **1** reacts 51 times faster with fumarate than with maleate. Recently we reported κ=65 for the same *trans*/*cis* pair vs. **9** and discussed the mechanistic significance of such relative reactivities.[12] Competition experiments of fumaronitrile and maleonitrile for **1** furnished κ=2.6. The different order of magnitude suggests the importance of steric hindrance for the diester pair.

Both fumaronitrile and maleonitrile are crystalline and easy to purify. The fumaronitrile adduct **13** was obtained in 93% yield without **14** becoming visible.

The recrystallized sample of maleonitrile contained 0.058±0.006% of fumaronitrile. The preparative reaction with **4** (benzene, 40°C) furnished 88% of the *cis*-adduct **14** and 11% of thiirane **15**. In the subsequent test on



Scheme 3.

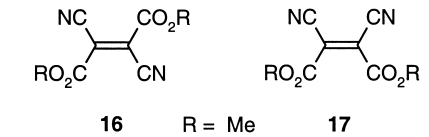
stereospecificity, **4** was reacted with 2 equiv. of maleonitrile (neat), and the ^{1}H NMR analysis as above afforded **13** and **14** in a ratio of 0.13:99.87. The fumaronitrile content (0.058%) of the dipolarophile entered the competition with κ=2.6 and was responsible for 0.080% of **13** (based on **4**). Thus, the retention in the cycloaddition with dimethyl maleate amounts to 99.95%, and the residual 0.05% is insufficient evidence for a second pathway.

The spectra of **11**–**14** are consistent with the structures. The cyclobutanone carbonyl gives rise to IR bands at 1775–1791 cm^{-1} and δ (^{13}C) 216–219. The ^{1}H signals of the four ring protons of **11** and **13** are resolved at 400 MHz, and the assignments rest on a synopsis of the parameters for a multitude of thiolanes. Four different ^{1}H and ^{13}C signals of C–*Me* are the consequence of chirality. In the mass spectra, the elimination of dimethylketene accounts for the base peaks. Both fragments can appear as radical cations, as 93% of *m/z* 70 ($C_4H_6O^+$) for **13** and 81% for **14** testify. Further losses of CO_2Me, HCO_2Me and HCN, respectively, are noticeable and possibly lead to thiophene radical cations. No reversion of the original cycloaddition was observed.

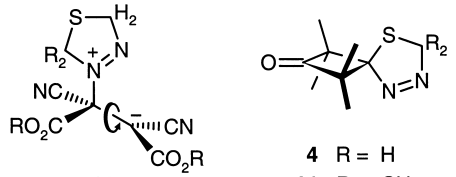
3. Reactions of 1 with 2,3-dicyanofumaric esters and 2,3-dicyanomaleic esters

When the dipolarophile bears two electron-attracting substituents at the same C-atom, the stability of the zwitterionic intermediate takes a quantum jump. Such intermediates were intercepted in the reactions of **1** with TCNE[8] and arylidenemalononitriles.[11] The cycloadditions of **1** with dimethyl 2,3-dicyanofumarate (**16**) and dimethyl 2,3-dicyanomaleate (**17**) are nonstereospecific. However, to quantify the inversion *during* the cycloaddition, it has to be checked whether *cis*, *trans* isomerization occurs *before* or *after* the cycloaddition step.

The tetra-acceptor-substituted ethylenes **16** and **17** are fairly thermostable, but sensitive to base: suspended KF in $CDCl_3$

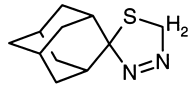


16 R = Me **17**
18 R = iPr **19**



20

4 R = H
21 R = CH_3



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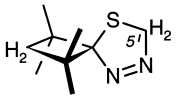


23

Scheme 4.

Table 1. Isomerization of **17** (0.11 M) to **16** (equilibrium **17/16**=12:88) and of **19** to **18** in $CDCl_3$ at room temperature; catalysis by thiadiazolines (0.10 M) and its inhibition with acid (7.6 mM H_2SO_4 in $CDCl_3$ as solvent)

Thiadiazoline	**17/16**			**19/18**		
Time (min)	0	60	250	0	70	270
4	98:2	91:9	81:19	96:4	96:4	96:4
4+H_2SO_4	98:2	98:2	98:2	96:4	96:4	96:4
21	98:2	89:11	63:37			
21+H_2SO_4	98:2	98:2	98:2			
22	98:2	84:16	54:46	96:4	95:5	93:7
22+H_2SO_4	98:2	92:8	77:23	96:4	95:5	92:8
23+H_2SO_4	98:2	39:61	[a]	96:4	75:25	61:39

[a] **16** crystallizes.

catalyzed the slow equilibration, and **16/17**=88:12 was attained in 3 d from both sides.[12] We were alarmed by some *cis*, *trans* isomerization, **16**⇄**17**, which occurred before the cycloaddition with **1**. It turned out that the precursor of **1**, the spirothiadiazoline **4**, catalyzed the isomerization of the dipolarophile at room temperature, i.e. conditions where the formation of the thiocarbonyl ylide, **4**→**1**+N_2, was still slow. The conversion **17**→**16** in 0.1 M **4** in $CDCl_3$ reached 9% in 60 min and 19% in 250 min (Table 1) while no isomerization was noticed without **4**.

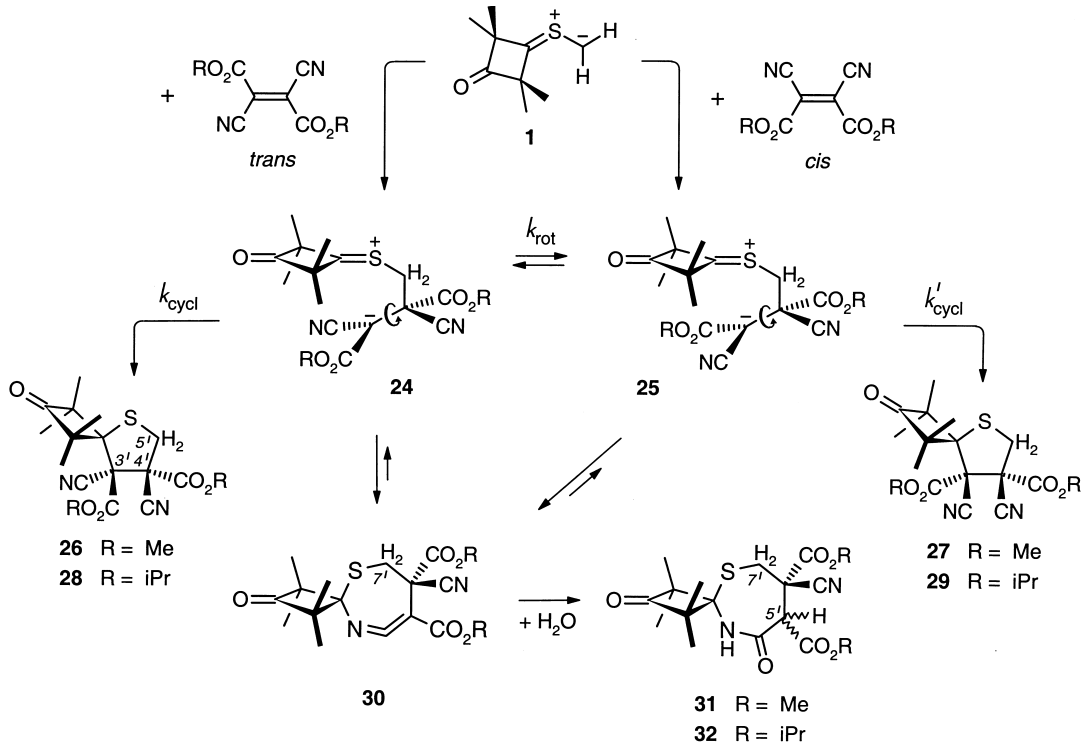
The catalytic activity of several thiadiazolines increased in the sequence **4**<**21**<**22**<**23** (Scheme 4) and showed no correlation with the rate of N_2 elimination. The thioether function of the cycloadducts exerted no catalysis. The reversible formation of a type **20** complex appears to be responsible for the isomerization **16**⇄**17**. Experiments with 2,3-bis(trifluoromethyl)maleonitrile, i.e. another tetra-acceptor-substituted ethylene, established the catalytic activity of 1-pyrazolines and other cyclic azo compounds.[17]

We observed that strong acid inhibited or even prevented the thiadiazoline catalysis, and found that 0.0076 M sulfuric acid in $CDCl_3$ was optimal. In this medium 0.11 M *cis*-diester **17** was not isomerized in the presence of 0.10 M thiadiazoline **4** or **21** (Table 1); thus, 7 mol% of H_2SO_4 preserved the stereostability of **17**. Less complete was the protection in the case of thiadiazoline **22** and it failed for **23** which differs from **4** by the absence of the carbonyl group.

The diisopropyl esters **18** and **19** were found to be resistant to the catalysis by thiadiazoline **4** (Table 1) whereas **22** and **23** still initiated some *cis*, *trans* isomerization, **18**⇄**19**. The pair **18/19** was included in our study of the steric course of cycloaddition.

A higher reaction temperature (80°C) helped in curbing the detrimental catalysis of *cis*, *trans* isomerization. The thiadiazoline **4** enters into competing pathways: bimolecular catalysis of the process **16**⇄**17** and unimolecular extrusion of N_2. The rate constant of the latter is expected to rise faster with increasing temperature.

The reactions of **4** with **16** and **17** produced mixtures of *trans*- and *cis*-thiolanes, **26** and **27**, which were difficult to separate, but modest amounts were obtained pure (Scheme 5). The δ_H of the diastereotopic 5′-H_2 offered an empirical



Scheme 5.

criterion of *trans*, *cis* assigment: 3.56 and 3.64 (J= 11.4 Hz) for **26** (*trans*), and 3.43 and 3.87 (J=12.1 Hz) for **27** (*cis*). The AB spectrum (small $\Delta\delta$) was observed for all *trans*-adducts of **16** and **17** and the AX type for all *cis*-adducts obtained with the thiocarbonyl ylides which were formed from thiadiazolines **4**, **21**–**23** and several more. For one of those *cis*, *trans* pairs X-ray analyses proved the structures.[18] Obviously, the thiolane conformations of *trans*- and *cis*-adducts are only little influenced by the substituents in 2′-position. The diisopropyl esters **28** and **29** follow the same rule: $\Delta\delta$=0.06 for the *trans* and 0.47 ppm for the *cis*-structure.

The stereochemical tests were run in 7.6 mM H_2SO_4 in $CDCl_3$ and ^1H NMR analyzed without workup in the presence of a weight standard (Table 2). In the experiments at 80°C (10 min), the excess of **16** and **17** was not isomerized, and the product ratios were virtually identical for dimethyl esters and diisopropyl esters:

	trans/*cis*-Adduct
Dimethyl ester **16** (*trans*)	**26**/**27**=60:40
Dimethyl ester **17** (*cis*)	**26**/**27**=24:76
Diisopropyl ester **18** (*trans*)	**28**/**29**=61:39
Diisopropyl ester **19** (*cis*)	**28**/**29**=25:75

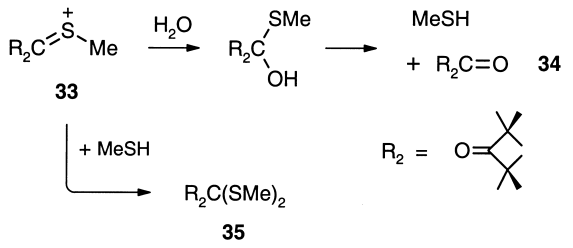
The preponderance of retention over inversion shows that rotational equilibrium of the assumed zwitterionic intermediates **24** and **25** was not reached. As a consequence of **24**⇄**25**, the ratio k_{cycl}/k_{rot} is smaller than the ratio of retention/inversion. The inversion was higher in the experiments with the *trans*-dipolarophiles **16** and **18** than in those with the *cis*-compounds **17** and **19**. There could, but must not be, a connection of the kinetic preference with the higher thermodynamic stability (see later) of the *cis*-cycloadducts. The lack of *cis*, *trans* isomerization in the unconsumed dipolarophile indicates that the zwitterions **24** and **25** do not dissociate back to the reactants (Scheme 5).

The *cis*, *trans* ratios of Table 2 are results of kinetic control. The cycloadducts **26**–**29** were stable under the reaction conditions. No stereoisomerization of *trans*-adduct **26** was noticed in benzonitrile at 139°C (7 h).

The last column of Table 2 refers to a competition experiment of **16** and **17** for thiocarbonyl ylide **1**. The evaluation took care of the isomerization rates, which were observed in separate experiments. It is no surprise that $\kappa=k_{16}/k_{17}$=4.7 is smaller than for the pair dimethyl fumarate and maleate, κ=51. Competition constants of 5.6 and 65 were found for the reactions of thiobenzo-

Table 2. Reactions of thiocarbonyl ylide **1** with dimethyl 2,3-dicyanofumarate (**16**) and dimethyl 2,3-dicyanomaleate (**17**) in 7.6 mM H_2SO_4 in $CDCl_3$ (1 mL); ^1H NMR analysis of steric course

Experiment	1	2	3	4	5
4 (μmol)	20.3	23.3	20.9	100.1	57.5
16 (*trans*) (μmol)	26.3	34.7			29.0
17 (*cis*) (μmol)			32.7	118.9	76.1
Temperature (°C)	40	80	40	80	80
Reaction time	10 h	10 min	10 h	10 min	10 min
26 (*trans*) (%)	45	31	16	21	26
27 (*cis*) (%)	22	21	47	66	33
Ratio **26**/**27**	68:32	60:40	25:75	24:76	44:46
Dione **34** (%)	9	19	23	4	25
S,*S*-Acetal **35** (%)		11	1	4	6
All products (%)	76	82	87	95	90



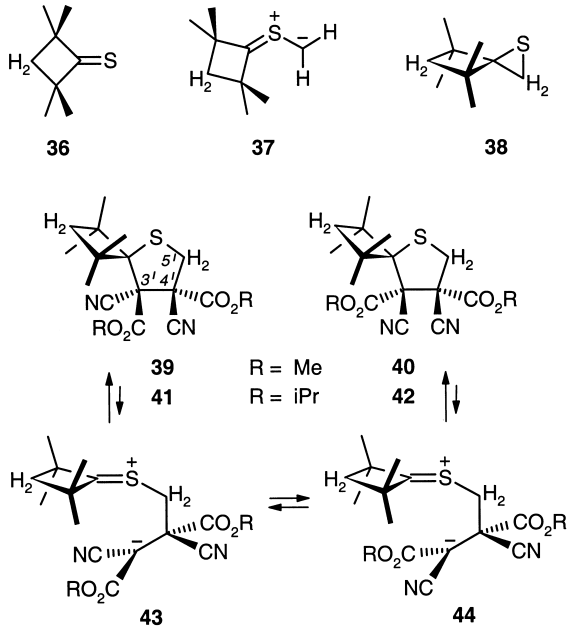
Scheme 6.

phenone *S*-methylide (**9**) with the same two pairs of dipolarophiles.[12]

The yields of cycloadducts **26**–**29** were lower (52–87%, Table 2) for the experiments run in the presence of H_2SO_4 than for those in THF without acid (up to 94%). Dione **34** and dimethyl dithioacetal **35** were found as side-products, and Scheme 6 shows a conceivable pathway of their formation via the protonated species **33**.

When **4** was reacted with **16** or **18** in THF containing 2 vol% of water, the spirolactams **31** and **32** emerged with yields of 25 and 30%, respectively, alongside the thiolanes. The lactams appeared in the ^{1}H NMR spectra as 2:1 mixtures of diastereoisomers A and B which probably differ in the configuration at C-5′. Form A isomerized to B on the silica gel layer. The lactams show the amide I frequency, e.g. at 1685 cm^{-1} for **31**, well separated from the ester carbonyl at 1753 and the cyclobutanone absorption at 1787 cm^{-1}; NH signals are visible in IR and ^{1}H NMR spectra. Four different ^{13}C-signals for C–*Me* demonstrate chirality.

In the trapping of an intermediate by water, the reaction of **1** with **16** corresponds to that observed with TCNE, in which lactam **6** was formed (Scheme 1).[8] Thus, the rotameric zwitterions **24** and **25** reversibly cyclize to the ketene imine **30** and close irreversibly the thiolane ring to give



Scheme 7.

26–**29** (Scheme 5). The previous discussion[8] needs no repetition. Ketene imine **30** might occur in diastereoisomers since the allenic bond system is equivalent to one stereocenter. In noteworthy contrast to the tricyano-substituted ketene imine **5**, the ester-bearing **30** was not intercepted by methanol.

3.1. Cycloadditions of 2,2,4,4-tetramethylcyclobutanethione *S*-methylide (37)

Thiocarbonyl ylide **37** differs from **1** by the absence of the keto group, and its cycloadditions to **16**–**19** showed deviations in several respects. Thiadiazoline **23**, the precursor of **37**, was the most active catalyst in the *cis*, *trans* isomerization, **16**⇄**17** (Table 1). A small concentration of strong acid did not prohibit the catalysis by **23**. The *cis*-form **17** in $CDCl_3$ (7.6 mM in H_2SO_4) reached **16/17**=61:39 in the presence of 0.10 M **23** in 1 h. The diisopropyl esters **18/19** were somewhat more resistant.

Thiadiazoline **23** was prepared from thione **36** and diazomethane. The first-order rate constant of N_2 elimination was smaller by 30% than that of **4** (xylene, 40°C, $t_{1/2}$=1.6 h). The electrocyclization of **37** gave rise to thiirane **38** (81%).

The reaction of **23** with dimethyl 2,3-dicyanofumarate (**16**, 1.2 equiv.) in CH_2Cl_2 (40°C, 15 h) furnished the thiolanes **39** and **40** in 87% yield (Scheme 7). The structural assignment confirmed the empirical rule, based on $\Delta\delta(5'\text{-}H_2)$ and described above: AB for **39** (*trans*, δ 3.51 and 3.59) and AX for **40** (*cis*, δ 3.39 and 3.85). Similar parameters were observed for the pair of diisopropyl esters, **41** and **42**. The 3-H_2 are likewise diastereotopic, and the AB-spectra of **39** and **40** are resolved in the 400 MHz spectra, e.g. δ 1.60, 1.65 for **39**.

The ^{1}H NMR analytical tests on the steric course were carried out at 80°C without acid. Virtually identical cycloadduct ratios, **39/40**=55:45, were observed for the reactions of **23** with **16** and **17**. In the second experiment the 20% excess of **17** was largely isomerized to **16** after the reaction.

Thiocarbonyl ylide **1** reacts 4.7 times faster with **16** (*trans*) than with **17** (*cis*). Since a similar rate ratio k_{16}/k_{17} appears probable in the reactions with **37**, at least some rotation must take place on the level of the zwitterions **43** and **44**. Otherwise the nearly 1:1 ratio of *trans*- and *cis*-adduct, **39** and **40**, would not be understood. However, the competing equilibration **16**⇄**17** which is catalyzed by the precursor **23** does not allow to quantify the nonstereospecificity of the cycloaddition itself. Nevertheless, full equilibration of the zwitterions **43** and **44** is supposed.

When the pure cycloadducts **39** and **40** were heated in separate experiments in benzonitrile at 139°C, an equilibrium of **39/40**=31:69 was established from both sides. The absence of side-reactions allowed the kinetic measurement of the reversible first-order reactions. The equilibrium is attained with a half-life ($\ln 2/(k_{39}+k_{40})$) of 12.8 h (benzonitrile, 139°C). There is no doubt that the above tests on the steric course of cycloaddition ($CDCl_3$, 80°C, 5 min) reflect kinetic control.

The zwitterions **43** and **44** are the logical intermediates in the adduct isomerization. In contrast, adduct **26** which contains the 1-oxo group did not isomerize in benzonitrile at 139°C. It is tempting to ascribe the difference in thermostability to the lower energy level of the thiocarbonylium zwitterions **43/44**, compared with that of **24/25**. The intracyclic field effect of the keto group destabilizes **24/25**. The cycloadduct of thiobenzophenone *S*-methylide (**9**) to **16** equilibrates even in acetonitrile at 80°C to *trans*/*cis*=30:70.[12] The ring-opening profits from the conjugation of the thiocarbonylium ion with two phenyl groups.

Diisopropyl 2,3-dicyanomaleate (**19**) is less prone to the thiadiazoline catalysis of *cis*-, *trans*-isomerization than dimethyl ester **17** (Table 1). In the reactions of **23** with **18** and **19** ($CDCl_3$, 80°C), *trans*/*cis* ratios of **41/42**=63:37 and 49:51, respectively, were observed, i.e. a slight preference for retention.

In the mass spectra of **39**–**42**, the molecular peaks are very small. A large peak is $[M-C_4H_8]^+$; the isobutene elimination is analogous to that of dimethylketene in the MS of **26**–**29**. The smaller fragments are identical in both series, and their molecular formulae show that alkoxycarbonyl functions break off easier than cyano groups. Most of the radical cations fit molecular formulae of thiophene derivatives.

4. Discussion and conclusions

"*The pure and simple truth is rarely pure and never simple*".—Oscar Wilde

Full configurational retention of dipolarophile and 1,3-dipole is mandatory for concerted cycloadditions. Retention could also be the outcome when the intermediate of a two-step pathway undergoes cyclization much faster than rotation ($k_{cycl}>k_{rot}$). For distinguishing the two cases, it is helpful to determine the analytical limit of the missing isomer in *artificial* mixtures of *cis*- and *trans*-adducts. It has been shown, e.g. that diazomethane addition to methyl angelate proceeds with >99.997% retention (GC analysis),[19] and >99.992% resulted for the 1,3-addition of *N*-benzylidene-3-pyrazolidone to (*E*)-β-nitrostyrene (HPLC).[20] A stereospecificity of >99.89% was elegantly concluded from an equilibration study of 3,4-dihydroisoquinoline *N*-oxide and (*E*)-β-nitrostyrene with their cycloadduct.[21]

A free energy consideration teaches that the pertinent rotational barriers of hypothetical zwitterionic intermediates for the three examples mentioned should exceed $\Delta G^{\neq}$ of its cyclization by >6.2, >5.6, and >4.2 kcal mol^{-1}, respectively. Rotations about C(sp^3)–C(sp^2) bonds have notoriously low barriers. The high barriers inferred discredit the assumption of an intermediate and offer a criterion for concertedness.[3c]

The retention of >99.97% in the cycloaddition of **1** with dimethyl fumarate, described above, would correspond to $\Delta G^{\neq}_{rot}-\Delta G^{\neq}_{cycl}>5.0$ kcal mol^{-1} for a hypothetical (but rejected) intermediate. In the addition of **1** with dimethyl maleate which is 51 times less reactive than the *trans*-isomer vs. **1**, the retention is not complete, and 1.1% of *trans*-adduct **11** implies a low-grade involvement of a two-step mechanism. Fumaronitrile is superior to maleonitrile only by a factor of 2.6 in the addition of **1**. Retention was observed for the reaction of **1** with maleonitrile.

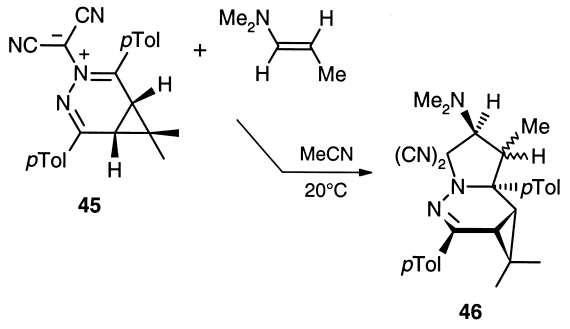
In the cycloadditions of **1** with dimethyl (and diisopropyl) 2,3-dicyanofumarate and 2,3-dicyanomaleate (**16**–**19**), the borderline from the concerted to the two-step pathway is crossed. Two acceptor substituents stabilize the anionic terminus of the intermediate to such an extent that the concerted mechanism does not even appear to be partially involved. Retention still preponderates over inversion (Table 2), i.e. cyclization and rotation of the zwitterionic intermediates are in keen competition.

Successful validation of a two-step mechanism requires evidence that the loss of stereochemical integrity occurs *during* the cycloaddition and not *before* or *afterwards*. In this respect, the reactions of thiocarbonyl ylides **1** and **37** with **16**–**19** offer textbook examples and warnings. The thiadiazoline precursors **4** and **23** catalyze the *cis*, *trans* isomerization of the dipolarophile, and that more effectively for the dimethyl esters **16** and **17** than for the diisopropyl esters **18** and **19**. Only the catalysis by **4**, and not that by **23**, was counteracted with some mol% of strong acid. As a consequence, the ratio of retention/inversion was determinable for the cycloadditions of **1**, whereas in the case of **37** the configurational losses *before* and *during* the cycloadditions could not be separated.

Kinetic control was confirmed for the reactions of both **1** and **37** with **16**–**19**. An interesting difference emerged: the cycloadducts of **1** are stable in benzonitrile at 139°C, while those of **37** slowly equilibrated. These conditions are more drastic than those of the cycloaddition experiments.

The zwitterions **24** and **25** do not only close the five-membered ring of **26**–**29**. A reversible closure of the seven-membered ring was revealed by the partial interception of ketene imine **30** by water, giving rise to lactams **31** and **32**. The desirable evidence that the trapping of the intermediate does not influence the formation rate of the latter was not procurable here, however. The liberation of the thiocarbonyl ylide from its precursor is always rate-determining.

The steric course of a 1,3-dipolar cycloaddition has rarely been used as evidence for a two-step pathway. The group of



Scheme 8.

Sauer recently presented kind of pendant to the system described here, namely the nonstereospecific cycloaddition of an electron-deficient 1,3-dipole to an electron-rich dipolarophile.[22] The *N*-dicyano-azomethine ylide **45** (and a second related model) reacted with (*E*)-1-dimethylamino-1-propene to afford *trans*- and *cis*-adduct **46** in 48:52 ratio (Scheme 8). Both adduct structures were elucidated by X-ray, and kinetic studies with substituent variation were in accordance with LU(1,3-dipole)–HO(dipolarophile) control.[23]

The borderline region between concerted and two-step DAR has been the topic of extensive exploration.[2] The occurrence of open-chain 1,3-dienes in *s-cis* and *s-trans* conformations confers new complexity. Only the *s-cis* form is amenable to the concerted DAR whereas both *s-cis* and *s-trans* conformations can undergo two-step reactions with dienophiles which afford (4+2) or (2+2) cycloadducts, respectively. Bartlett's classic studies on concerted and biradical pathways in cycloadditions of dienes with fluorinated and chlorinated ethylenes may be recalled.[24] Among recent examples, the studies of the Sustmann group are quoted. (*E*)-1-Dimethylamino-1,3-butadiene reacted with fumaronitrile and maleonitrile with retention, whereas **16** and **17** furnished the same *trans*-adduct; a preceding isomerization, **17**⇄**16**, restricted conclusions.[25] The DAR of 1,4-bis(dimethylamino)-1,3-butadiene with **16** and **17** at −50°C is accompanied by an electron-transfer mechanism.[26]

Nonstereospecificity was observed for (2+2) cycloadditions via tetramethylene zwitterions: the reactions of *cis*/*trans* isomeric enol ethers and thioenol ethers with TCNE[27] or 2,2-bis(trifluoromethyl)ethylene-1,1-dicarbonitrile.[28] Further criteria, such as structure-rate relationship, the dependence of rate on solvent polarity, reversibility of the first step, and a wealth of interception reactions were in accordance with zwitterionic intermediates.[28] Rotation about the acceptor bond was demonstrated by the (2+2) cycloadditions of *trans*- and *cis*-1,2-bis(trifluoromethyl)ethylene-1,2-dicarbonitrile with methyl vinyl ether.[29]

5. Experimental

5.1. General

IR: Perkin–Elmer 125 or Beckmann FT model IFS 45. NMR: Bruker WP80CW (80 MHz) for ^{1}H and WP80DS (20 MHz) for ^{13}C (multiplicities by comparison of ^{1}H-decoupled with off-resonance spectra), Varian XR 400S for ^{1}H (400 MHz) and ^{13}C (100 MHz). Solvent: acid-free $CDCl_3$, if not otherwise stated. The precision of the ^{1}H NMR analysis with weight standard and machine integration depends on the signals and amounts in the average to ±4% (relative). The result was improved by using several signals and repeated integrations (4–6 times). MS (EI, 70 eV): AET 902 or Finnigan MAT 90; intensities of isotope peaks are given in the form, e.g. ^{13}C calcd (%)/found (%). PLC: Preparative thick-layer chromography on 2 mm of silica gel 60 PF (Merck).

5.1.1. Dimethyl 2,2,4,4-tetramethyl-1-oxospiro[cyclobutane-3,2′-thiolane]-3′,4′-*trans*-dicarboxylate (11). (a) Reaction of **1** with 1.1 equiv. of dimethyl fumarate (DF). Thiadiazoline **4** (396 mg, 2.00 mmol),[11,30] was dissolved in the stirred suspension of DF (317 mg, 2.20 mmol) in abs. THF (5 mL) and heated to 40°C for 8 h. After removal of the solvent at the rotary evaporator and dissolving the residue in $CDCl_3$, the weight standard (*sym*-tetrachloroethane, δ 5.92) was added. Comparison of the ^{1}H NMR integral at δ 3.93 (3′-H) with that of the standard indicated 95% of **11**. Purification by PLC (acetone/petroleum ether 2:8) gave a colorless oil (378 mg, 60%) that crystallized on cooling. Fine needles were obtained from pentane, mp 58–60°C. IR (KBr): ν 1171 cm^{-1}s, 1200s, 1216s (C–O), 1331m, 1366m, 1388m, 1437m; 1748vs. (C=O, ester), 1775s (C=O, ketone). ^{1}H NMR (400 MHz): δ 1.25 (s, Me), 1.31 (s, 2Me), 1.38 (s, Me), 3.08, 3.12 (ddd, AB of ABMX, $J_{5'A,5'B}$=11.6 Hz, $J_{4',5'A}$=6.7 Hz, $J_{4',5'B}$=8.0 Hz, 5′-H_A, 5′-H_B; the 5′-H_B part is long range-split by 0.5 Hz), 3.45 (ddd, M part of ABMX, 4′-H), 3.93 (d, X part, $J_{3',4'}$= 3.5 Hz, 3′-H), 3.75, 3.77 (2s, 2MeO). ^{13}C NMR (20.2 MHz): δ 20.8, 22.7 (2q, 2Me), 23.0 (q, 2Me), 32.9 (t, C-5′), 52.2, 52.5 (2d, C-3′, C-4′), 53.1, 53.3 (2q, 2MeO), 62.3, 66.3, 68.6 (3s, C-2, C-3, C-4), 172.1, 173.2 (2s, C=O, ester), 219.6 (s, C=O, ketone). MS (40°C); *m*/*z* (%): 314 (0.3, M^+), 283 (4, $[M-MeO]^+$), 255 (2, $[M-CO_2Me]^+$), 244 (100, $[M-C_4H_6O]^+$; ^{13}C calcd 12/found 13; $^{13}C_2+^{34}S$ 5.1/5.8), 212 (37, $[244-MeOH]^+$), 184 (35, $[244-HCO_2Me]^+$, ^{13}C 10.0/10.7), 143 (5), 125 (34, $[184-CO_2Me]^+$), 91 (4), 85 (6), 70 (15, $C_4H_6O^+$), 59 (8, $MeOC{\equiv}O^+$). Anal. calcd for $C_{15}H_{22}O_5S$ (314.39): C 57.30, H 7.05, S 10.20; found: C 57.44, H 7.07, S 10.22.

(b) Stereospecificity test. DF (1.01 g, 7.0 mmol) was dissolved in dimethyl succinate (6 mL) by stirring at 41°C for 1 h. After further stirring with **4** (407 mg, 2.05 mmol) at 41°C for 8 h, solvent and excess of DF were removed by bulb to bulb distillation at 0.2 Torr. ^{1}H NMR analyses of the residue in C_6D_6 with *sym*-$C_2H_2Cl_4$ showed a nearly quantitative yield of **11**. In the 500 MHz spectrum in C_6D_6, the 2s at δ 1.228 and 1.278 (2Me) of **11** show low-frequency ^{13}C satellites (0.555%) at 1.096 and 1.149 ppm, corresponding to $^1J_{CH}$=133 and 129 Hz. It was concluded from their integrals that the presence of 0.03% of **12** should give rise to a discrete peak at 0.985 ppm (s, Me). Since no signal was visible in that region, the concentration of **12** must be <0.03%.

5.1.2. Dimethyl 2,2,4,4-tetramethyl-1-oxospiro[cyclobutane-3,2′-thiolane]-3′,4′-*cis*-dicarboxylate (12). (a) Reaction of **1** with 1.1 equiv. of dimethyl maleate (DM). The experiment in THF at 40°C was run as described above for the isolation of **11**. The ^{1}H NMR analysis of the crude product with standard indicated 70% of **12** (δ 2.81–3.37, 4′-H+5′-H_2) and 27% of spirothiirane **15** (δ 2.57, 3′-H_2); closer inspection of the adduct fraction revealed a content of <1% of **11**. Thiolane **12** was obtained after PLC as a colorless oil (329 mg, 52%) which crystallized after 2 weeks at 5°C, mp 54–56°C (methanol). IR (KBr): ν 1177 cm^{-1}s, 1202s, 1242s (C–O); 1743s (C=O, ester), 1780s (C=O, ketone). ^{1}H NMR (80 MHz): δ 1.21, 1.30, 1.36, 1.39 (4s, 4Me), 2.82–3.37 (m, 4′-H+5′-H_2), 3.67, 3.69 (2s, 2MeO), 3.69 (d, J=10.6 Hz, 3′-H); (500 MHz, C_6D_6): 0.987, 1.19, 1.25, 1.30 (4s, 4Me), 2.63 (m, 5′-H_2), 3.27, 3.34 (2s, 2MeO), 3.44 (t, 4′-H), 3.64 (d, 3′-H). ^{13}C NMR (20.2 Hz): δ 20.7,

22.6, 23.0, 23.6 (4 q, 4Me), 30.3 (t, C-5′), 50.8, 53.1 (2d, C-3′, C-4′), 51.9, 52.2 (2q, 2MeO), 61.8, 65.8, 67.6 (3s, C-2, C-3, C-4), 170.3, 170.5 (2s, 2C═O, ester), 219.4 (s, C═O, ketone). MS (30°C); *m/z* (%): 314 (5, M^+), fragments similar to MS of **11**. Anal. calcd for $C_{15}H_{22}O_5S$ (314.39): C 57.30, H 7.05, S 10.20; found: C 57.09, H 7.11, S 10.21.

(b) Purification of dimethyl maleate (DM). The ^{1}H NMR spectrum (80 MHz) of a commercial quality (neat liquid) shows at δ 6.76 the s (vinyl-H) of DF; with 1,3,5-tribromobenzene as weight standard (δ 7.69), a content of 0.34± 0.03% of DF was analyzed. 25.0 g (173 mmol) of this sample was stirred in an ice-bath and treated with 4.00 g of diphenyldiazomethane (20.6 mmol) in two portions, until the deep-red color disappeared. Distillation at 86°C/15 Torr gave DM with an estimated DF content of <0.01% (NMR test as above). The concentration of DF should be reduced from 0.34 to 0.0041% (i.e. below the analyt. limit of the 80 MHz spectrum) on the basis of Eq. (1); diphenyldiazomethane reacts at 40°C with DF 36 times faster than with DM.[16]

(c) Stereospecificity test. The purified DM (840 mg, 5.83 mmol) and freshly recrystallized **4** (334 mg, 1.68 mmol) were heated to 41°C without solvent for 8 h. After removal of the excess DM at 40°C/10^{-3} Torr and PLC (hexane/acetone 7:3; no separation of **11** and **12**), the ^{1}H NMR spectrum (500 MHz, C_6D_6) at high attenuation showed the s of 2C–Me of **11** at δ 1.382 and 1.408. Comparison of the integrals (gravimetry of cut-outs) with those of two high-frequency ^{13}C-satellites at 1.374 and 1.430 ppm, each 0.555% of the C–Me singlets of **12** at δ 1.247 and 1.303 led to 1.28 and 1.09% of **11** in two recordings with different spinning frequencies. Furthermore, comparison of the area at δ 1.408 (**11**) with those of the 32-fold diminished integrals of **12** at 1.186, 1.247, and 1.303 ppm (3Me) provided 1.05% of **11** in the isomer mixture. A middle value of 1.14% of **11** appeared reasonable. Calculated with κ=51 (see below), the DF content (2.37 μmol) in the purified DM should generate 0.014% of **11**, a negligible amount.

(d) Competition constant of DF and DM for thiocarbonyl ylide **1**. DM (10.00 mmol) and DF (0.506 mmol) were stirred at 41°C, until DF was dissolved. After addition of thiadiazoline **4** (0.409 mmol) and 7 h at 41°C (without solvent), 8.8 mL of N_2 (94%) was eliminated. The excess of DM and DF was removed at 40°C (bath)/10^{-3} Torr by Kugelrohr distillation. The ^{1}H NMR analysis (80 MHz, C_6D_6) with *sym*-$C_2H_2Cl_4$ yielded 0.265 mmol of **11** (d at 3.91, 3′-H) and 0.141 mmol of **12** (d at 3.64, 3′-H), together 99%. The 1.14% portion of **11** in the product from DM (see above) requires correction to 0.262 mmol of **11** and 0.143 mmol of **12** to reflect the relative dipolarophilic activities (κ=51) which were evaluated by Eq. (1)[31] with $(A)_o=(DF)_0$, $(B)_0=(DM)_0$, etc.

$$\kappa = \frac{k_A}{k_B} = \frac{\log(A)_0 - \log(A)_e}{\log(B)_0 - \log(B)_e} = \frac{\log(A)_0 - \log[(A)_0 - (A\text{–Adduct})_e]}{\log(B)_0 - \log[(B)_0 - (B\text{–Adduct})_e]} \quad (1)$$

(e) Stability test. Thiadiazoline **4** (0.71 mmol) was decomposed in the solution of **12** (0.57 mmol) in abs. THF (1 mL) at 41°C for 8 h. After PLC (hexane/acetone 7:3), no **11** was found in the ^{1}H NMR spectrum (500 MHz).

5.1.3. 2,2,4,4-Tetramethyl-1-oxospiro[cyclobutane-3,2′-thiolane]-3,4-*trans*-dicarbonitrile (13). Fumaronitrile (FN, 2.20 mmol) was reacted with **4** (2.00 mmol) in THF (4 mL) at 41°C for 8 h, and ^{1}H NMR analysis of the crude product with standard indicated 93% of **13**. Evaporation of solvent and excess dipolarophile, refluxing of the residue in ethanol (3 mL), and storing for 1 day at +5°C afforded **13** (341 mg, 69%) as colorless crystals, mp 112–113°C. IR (KBr): ν 971 cm^{-1}m, 1017m, 1245m, 1368m, 1386m, 1459s, 1468s; 1791vs (C═O), 2247m (C≡N). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.31, 1.45, 1.58, 1.68 (4s, 4Me), 3.18 (dd, $J_{5'A,5'B}$=12.0 Hz, $J_{5'A,4'}$=4.0 Hz, 5′-H_A), 3.57 (dd, $J_{5'A,5'B}$=12.0 Hz, $J_{4',5'B}$=8.6 Hz, 5′-H_B), 3.82 (ddd, 4′-H), 3.93 (d, $J_{3',4'}$=2.0 Hz, 3′-H); (500 MHz, C_6D_6): δ 1.13, 1.14, 1.29, 1.32 (4s, 4Me, signals used for stereospecificity test). ^{13}C NMR (100 MHz, DEPT): δ 21.0, 22.7, 22.88, 22.90 (4Me), 33.8 (C-5′), 36.9 (C-4′), 42.3 (C-3′), 62.5, 66.2, 68.8 (C-2, C-3, C-4), 117.7, 118.3 (2CN), 216 (C═O). MS (60°C); *m/z* (%): 248 (1, M^+), 221 (0.3 $[M-HCN]^+$), 178 (100, $[M-C_4H_6O]^+$), 163 (7, $[178-Me]^+$), 151 (18, $[178-HCN]^+$), 136 (5), 125 (4), 85 (5), 70 (93, $C_4H_6O^+$). Anal. calcd for $C_{13}H_{16}N_2OS$ (248.34): C 62.87, H 6.49, N 11.28, S 12.91; found: C 63.03, H 6.60, N 11.44, S 12.93.

5.1.4. 2,2,4,4-Tetramethyl-1-oxospiro[cyclobutane-3,2′-thiolane]-3,4-*cis*-dicarbonitrile (14). (a) Purification of maleonitrile (MN). A sample of MN which was prepared from maleamide by treatment with $POCl_3$,[32] contained 20% fumaronitrile (FN), as shown by the ^{1}H NMR spectrum in MeOD. Three recrystallizations from ethanol furnished MN as colorless rods, mp 32–32.5°C (31–32°C).[32] According to the ^{1}H NMR analysis (500 MHz, MeOD), the FN content was reduced to 0.058%. The magnetic nonequivalence of the 2 olefinic H[33] generates a ^{13}C-satellite spectrum of AA′X type with $^1J_{CH}$=185 Hz and $^3J_{CH}$=11.4 Hz. The integrals of the high-frequency ^{13}C-satellites at δ 6.742 and 6.765 of MN were compared with that of the FN singlet at δ 6.705; the sum of the two satellites corresponds to 0.555% of the vinyl-H signal of MN.

(b) Cycloaddition with 1.1 equiv. of MN. The reaction with **4** (2.00 mmol) was carried out as usual, and ^{1}H NMR-analysis showed 92% of **14**. Trituration of the residue with pentane gave colorless crystals (382 mg, 77%), mp 140–142°C (methanol). IR (KBr): ν 1031 cm^{-1}m, 1447m, 1465m; 1786s (C═O), 2248m (C≡N). ^{1}H NMR (80 MHz): δ 1.27 (s, 2Me), 1.32, 1.59 (2s, 2Me), 2.85–3.40 (m, ABC, 4′-H+5′-H_2), 3.88 (d, $J_{3',4'}$=4.5 Hz, 3′-H); (500 MHz, C_6D_6, used for stereospecificity test): 0.54, 0.86, 1.08, 1.25 (4s, 4Me), 1.94 (ddd, 5′-H_A), 2.21 (dd, 5′-H_B), 2.76 (t, 4′-H), 2.91 (d, 3′-H). MS (70°C); *m/z*: 248 (9, M^+), 233 (0.3, $[M-Me]^+$), 205 (1), 178 (100, $[M-C_4H_6O]^+$), 163 (7, $[178-Me]^+$), 151 (21, $[178-HCN]^+$), 125 (5), 70 (81, $C_4H_6O^+$). Anal. calcd for $C_{13}H_{16}N_2OS$ (248.34): C 62.87, H 6.49, N 11.28, S 12.91; found: C 63.14, H 6.65, N 11.10, S 13.05.

(c) Reaction with 2 equiv. of MN in NMR tube. **4**

(0.22 mmol) and MN (0.44 mmol) in C_6D_6 (0.5 mL) were reacted at 40°C for 16 h. With *sym*-$C_2H_2Cl_4$ as standard, 88% of **14** (δ 1.25, Me) and 11% of thiirane **15** (δ 0.76 for 2Me) were analyzed.

(d) Stereospecificity test. **4** (1.14 mmol) and MN (2.20 mmol) in C_6D_6 (1 mL) were reacted 8 h at 40°C. After removal of the solvent and Kugelrohr distillation of excess MN, the colorless crystalline residue was ^{1}H NMR-analyzed (500 MHz) with 50 mg/mL of C_6D_6. The integrals of the ^{13}C-satellites of **14** at δ 0.954 and 1.377 were compared with those of two s at 1.134 and 1.144 ppm (2Me) of **13** and gave a ratio of **13/14**=0.13:99.87. The reliability was checked with the 500 MHz spectrum of an artificial mixture of **14**+0.80% of **13** (result 0.77%). The FN content (0.058%, see above) of the MN sample competes with MN for 1,3-dipole **1** (κ=2.6) and allows to expect 0.080% of **13** besides **14**. Thus, only 0.05% of **13** are unaccounted.

(e) Competition constant of FN and MN for thiocarbonyl ylide **1**. FN (2.12 mmol) and MN (3.39 mmol) were competing for **1** which was generated from **4** (0.804 mmol) in C_6D_6 (1.5 mL) at 40°C. The ^{1}H NMR analysis (80 MHz) indicated 0.395 mmol of **13** and 0.244 mmol of **14**, together 80%. The FN content (0.058%) in MN has to be taken in account for the evaluation of κ=2.74 with Eq. (1). A second experiment with FN (3.08 mmol), MN (5.16 mmol), and **4** (0.278 mmol) provided (κ)=2.52; middle value 2.6.

5.1.5. *cis,trans*-Isomerization of 2,3-dicyanofumaric esters and 2,3-dicyanomaleic esters. (a) Stability in solution. Dimethyl dicyanomaleate[12] (**17**, 0.10 mmol) in 1 mL of solvent was stored at 20°C for 18 h in the dark under N_2 in the NMR-tube and ^{1}H NMR-analyzed by the s of MeO which appears for **16** at δ 4.03 and for **17** at 3.94 ($CDCl_3$). The small δ difference requires recording with 5 Hz/cm and calibration with artificial mixtures. In $CDCl_3$, octane, and C_6D_6 the original content of ~2% of **16** was not increased, whereas it reached 70% in CD_3CN. In a second series, the solutions of **17** were heated at 80°C in closed NMR-tubes for 30 min: **17/16**=90:10 in $CDCl_3$ (equilibr. 12:88),[12] 91:8 in C_6D_6 and in octane, 22:78 in CD_3CN (probably close to equilibrium). The solubility of **16** is lower than that of **17** in all tested solvents, e.g. in $CDCl_3$ 8.50 mg/mL and in MeCN 38.2 mg/mL at 20°C. It is not clear whether the isomerization in CD_3CN is a function of solvent polarity or a consequence of impurities. We observed that small amounts of strong acids in CD_3CN conc. H_2SO_4 was superior to CF_3CO_2H—stabilized **17**. No isomerization of **17** (0.10 mmol) was noticed in 16 mM H_2SO_4 in CD_3CN (1 mL) after 18 h at rt and 2 h of refluxing.

(b) 1,3,4-Thiadiazolines as isomerization catalysts. The *cis*-dicarboxylic esters **17** and **19** as the minor component in the equilibria with **16** and **18** were chosen to compare the catalytic activity of several thiadiazolines and their inhibition by acid. In volumetric flasks (1 mL), **17** (0.11 mmol, contains 2% of **16** as above) and **19** (0.11 mmol, 5% content of **18**, see later) were treated with freshly recrystallized thiadiazolines (0.10 mmol each) in $CDCl_3$ and stored at rt in the dark. The Me groups of *i*PrO appear as doublets; the left branch (δ 1.39 for **19**, 1.44 for **18**) was suitable for ^{1}H NMR analysis (80 MHz). Time-dependent ratios of **17/16** and **19/18** are listed in Table 1. The catalytic activity of the thiadiazolines increases in the sequence given in Table 1. The efficiency of **4** was similar in octane, C_6D_6, and $CDCl_3$, but as a consequence of the low solubility of **16** the octane solution became turbid after several minutes, and **16** began to crystallize from the C_6D_6 solution after 3 h.

(c) Inhibition of thiadiazoline catalysis by strong acid. Conc. H_2SO_4 (0.5 mL) was vigorously shaken with 20 ml of $CDCl_3$ and stored for 20 h. The clear $CDCl_3$ phase was carefully decanted from the yellow drops of H_2SO_4 into a Schlenk flask, kept under argon for another 10 h, and then decanted into a second Schlenk flask for storing. Titration (1.0 mL+2 mL of H_2O) with 0.01N NaOH indicated 7.6 mM H_2SO_4 in $CDCl_3$. When C_6D_6 was subjected to the same treatment, 2.0 mM H_2SO_4 in C_6D_6 was obtained. Methanesulfonic acid and trifluoromethane-sulfonic acid likewise inhibited the thiadiazoline catalysis.

The experiments with **4** described above were repeated in 7.6 mM H_2SO_4 in $CDCl_3$ as medium (Table 1). The isomerization catalysis by **4** and the tetrasubstituted thiadiazoline **21** was prevented by 7.6 mol% of H_2SO_4. The protection was incomplete in the case of **22**, and much less so for **23**.

(d) Diisopropyl 2,3-dicyanomaleate (**19**) by photoisomerization of **18**. The photoreaction **16**→**17** was carried out by Gotoh et al.[34] in the presence of 1 equiv. of benzene-1,4-dicarbonitrile. We found that direct irradiation with a high-pressure mercury arc was effective and saved the trouble of removing the sensitizer.[12] Similarly, the irradiation of **18** (7.50 g) in CH_2Cl_2 (300 mL) for 18 h gave **19/18**=75:25, and fractional crystallization from hexane furnished 1.60 of **19** (4–5% content of **18**). A NMR-pure sample showed mp 51–52°C. The mixed fractions were used for the next photoexperiment. IR (KBr): ν 1073 cm^{-1} m, 1101s, 1198s, 1282vs 1299vs (C–O), 1739s (C=O), 2235vw (C≡N). ^{1}H NMR ($CDCl_3$): δ 1.37 (d, J=6.0 Hz, 4Me), 5.17 (sept, J=6.0 Hz, 2CH); (C_6D_6): 0.90 (d, J=6.1 Hz, 4Me), 4.72 (sept, 2CH). ^{13}C NMR (20.2 MHz): δ 21.3 (q, 4Me), 73.7 (d, 2CH), 111.4 (s, 2CN), 125.7 (s, C=C), 157.0 (s, 2C=O). Anal. calcd for $C_{12}H_{14}N_2O_4$ (250.25): C 57.59, H 5.64, N 11.20; found: C 57.49, H 5.69, N 11.24.

5.1.6. Dimethyl 3′,4′-dicyano-2,2,4,4-tetramethyl-1-oxo-spiro[cyclobutane-3,2′-thiolane]-3′,4′-*trans*-dicarboxylate (26) and *cis*-isomer 27. (a) Reaction with **16** without acid and isolation of **26** and **27**. The suspension of **16** (427 mg, 2.20 mmol) in abs. THF (6 mL) was stirred in a 40°C-bath for 30 min, **4** (396 mg, 2.00 mmol) was added, and **16** dissolved during 8 h of stirring at 40°C. The solvent was evaporated, and volatile side-products (e.g. **15**) were removed at 40°C/10^{-3} Torr. The ^{1}H NMR analysis with *sym*-$C_2H_2Cl_4$ was based on the C–*Me* singlets and showed **26/27**=52:48 and 94% yield. PLC did not separate the isomers. A top fraction of pure **26** (17%), mp 151–153°C, came from hot ethanol. Fractional crystallization from methanol and, finally, from ether at −78°C gave pure *cis*-adduct **27** (5%), mp 132–133°C. A cycloaddition experiment carried out in acetonitrile afforded **26/27**=48:62 and offered a richer source for the isolation of **27**.

(b) Data of **26** (*trans*). IR (KBr): ν 1247 cm^{-1} s, 1258s (C–O), 1749s (C=O, ester), 1794s (C=O, ketone), 2250vw (C≡N). ^1H NMR (400 MHz): δ 1.43, 1.47, 1.56, 1.85 (4s, 4Me), 3.56, 3.64 (AB, J=11.4 Hz, 5′-H_2), 3.95, 3.97 (2q, 2MeO). ^{13}C NMR (20.2 MHz): δ 23.3 (q, 2Me), 24.1, 24.5 (2q, 2Me), 36.3 (t, C-5′), 54.7, 55.0 (2s, 2MeO), 60.6, 62.6 (2s, C-3′, C-4′), 67.7, 68.9, 70.2 (3s, C-2, C-3, C-4), 114.5, 116.0 (2s, 2CN), 163.7, 163.8 (2s, C=O, ester), 217.3 (s, C=O, ketone). Anal. calcd for $C_{17}H_{20}N_2O_5S$ (364.41): C 56.03, H 5.53, N 7.69, S 8.80; found: C 55.79, H 5.68, N 7.96, S 8.82.

(c) Data of **27** (*cis*). IR (KBr): ν 1258 cm^{-1}s, br (C–O), 1745, 1753s (C=O, ester), 1790s (C=O, ketone), 2245vw (C≡N). ^1H NMR (400 MHz): δ 1.15, 1.64, 1.83, 2.03 (4s, 4Me), 3.43, 3.87 (AX, J=12.1 Hz, 5′-H_2), 3.91, 3.95 (2s, 2MeO). ^{13}C NMR (100 MHz, DEPT): δ 22.2 (Me), 23.0 (2Me), 23.8 (Me), 35.4 (C-5′), 54.8, 55.1 (2MeO), 58.3, 60.9 (C-4′, C-3′), 64.6, 70.4, 71.1 (C-2, C-3, C-4), 114.9, 116.5 (2CN), 163.3, 164.0 (2C=O, ester), 216.2 (C=O, ketone). MS (60°C, high resolution data of many peaks with CMASS on MAT 95Q provided molecular formulae; R≤500); m/z (%): 364 (0.09, M^+), 333 (1.1, $[M-MeO]^+$), 305 (1.7, $[M-CO_2Me]^+$), 294 (100, $[M-C_4H_8O]^+$, $C_{13}H_{14}N_2O_4S^+$; ^{13}C 14.5/15.0, $^{13}C_2+^{34}S$ 5.4/5.9), 262 (2, $[294-MeO]^+$), 249 (4, $[294-CO_2H]^+$, $C_{12}H_{13}N_2O_2S^+$), 235 (4, $[294-CO_2Me]^+$, $C_{11}H_{11}N_2O_2S^+$], 209 (6, $[235-CN]^+$), 194 (7, $C_9H_8NO_2S^+$), 193 (10), 192 (7, $C_{10}H_{12}N_2S^+$), 191 (49, $[235-CO_2]^+$, $C_{10}H_{11}N_2S^+$), 183 (22, $C_8H_9NO_2S^+$), 177 (19, $C_9H_7NOS^+$), 176 (10, $C_{10}H_8OS^+$), 161 (6, $C_8H_5N_2S^+$), 150 (18, $C_8H_8NS^+$), 149 (6, $C_8H_7NS^+$), 125 (8, $C_6H_5OS^+$), 70 (19, $C_4H_6O^+$), 59 (12, $MeOC{\equiv}O^+$), 41 (9, $Allyl^+$). Anal. calcd for $C_{17}H_{20}N_2O_5S$ (364.41): C 56.03, H 5.53, N 7.69; found: C 55.74, H 5.29, N 7.55.

(d) Thermal stability of cycloadducts. Sample of pure **26** and **27** were refluxed in toluene for 2 h, and the ^1H NMR analysis did not reveal any change. In another test, pure *trans*-adduct **26** (90 mg) and octamethylcyclotetrasiloxane (9 mg, weight standard) in freshly distilled benzonitrile (0.4 mL) were heated in a sealed NMR-tube under argon at 139°C for 7 h; the ^1H NMR spectrum indicated beginning decomposition, but the CMe signals did not reveal **27**.

(e) ^1H NMR analysis of steric course. The following signals of the 360 MHz spectrum were suitable for machine integration: **16**, s δ 4.03 (MeO); **17**, s 3.94 (MeO, joint integration with one MeO of **26**); **26** (*trans*), 3s at 1.47, 1.56, 1.85 (3Me), AB of 5′-H_2 at 3.56, 3.64; **27** (*cis*), 4s (4Me), d at 3.43 (5′-H_A); dione **34**, s 1.32 (4Me); dithioacetal **35**, s 2.05 (2SMe); thiirane **15**, s 2.57 (3′-H_2). Weight standards: 2,6-dimethylnaphthalene, s 2.47 (2Me), *as*-$C_2H_2Cl_4$, s 4.28 (2H).

Experiment 4 of Table 2 serves as example. Freshly recryst. **4** (19.8 mg, 100 μmol) and pure **17** (23.1 mg, 119 μmol) in 7.6 mM H_2SO_4 in $CDCl_3$ (1 mL) were heated in a closed NMR tube under argon for 10 min at 80°C. After releasing the N_2 pressure at −78°C, 2,6-dimethylnaphthalene (2.67 mg, 17.1 μmol) was added, and the 360 MHz spectrum recorded. Despite sectionwise expansion and amplification, integrations in such a multi-component spectrum are problematic and high precision is not expected. The excess of **17** is (qualitatively) observed, but no **16** is visible. For *trans*-thiolane **26**, the Me signals indicated 23.9 μmol and that of 5′-H_2 18.4 μmol.

The corresponding data for *cis*-adduct **27** were 69.8 and 62.0 μmol, bringing the yield of cycloadducts to about 87% with **26/27**=24:76. Furthermore, 3.7 μmol of **34** and 4.5 μmol of **35** were analyzed. Thus, 95% of the initial thiadiazoline **4** were accounted for. Prior to the evaluation, an artificial mixture of **16**, **17**, and the four products in the same solvent was analyzed with fair results; **16** (85%) showed the largest deviation. In run 3 of Table 2 (**17**, 40°C), some **16** was observed in the unconsumed dipolarophile.

(f) Competition of **16** and **17** for thiocarbonyl ylide **1**. Experiment no. 5 of Table 2 followed the above procedure. The amounts of unconsumed **16** and **17** were corrected for signal overlap, and application of Eq. (1) furnished (an unreliable) κ=4.4. More trustworthy is the determination from the yields of **26** and **27** (in μmol):

$$\kappa = \frac{\log(\mathbf{16})_0 - \log[(\mathbf{16})_0 - x]}{\log(\mathbf{17})_0 - \log[(\mathbf{17})_0 - y]} = 4.7$$

where x and y are functions of the ratios of **26/27** observed in separate experiments with **16** and **17** (No. 2 and 4, Table 2):

$$0.60x + 0.24y = (26)_e = 15.3; \qquad x = 18.9$$

$$0.40x + 0.76y = (27)_e = 19.2; \qquad y = 15.3$$

5.1.7. Dimethyl 6′-cyano-2′,3′,4′,5′,6′,7′-hexahydro-2,2,4,4-tetramethyl-1,4′-dioxospiro[cyclobutane-3,2′-(1,3)-thiazepine]-5′,6′-dicarboxylate (31). (a) Interception of ketene imine **30** with water. Thiadiazoline **4** (2.00 mmol) and **16** (2.20 mmol) in THF (5 mL, contained 2 vol% of H_2O) were reacted at 50°C (bath) for 5 h. After the usual workup, the ^1H NMR analysis with trichloroethylene as standard indicated the thiolanes **26** (δ 1.85, Me) and **27** (2.03, Me) in 71% yield with **26/27**=52:48 as well as the lactams **31A** (4.32, 5′-H) and **31B** (4.42, 5′-H) in 25% yield with **31A/31B**~2:1. PLC (CH_2Cl_2/acetone 95:5) furnished **26**+**27** (485 mg, 67%), as the first zone, followed by **31B** (130 mg, 17%) which crystallized from methanol at 4°C, mp 190.5–191°C. The conversion **31A→31B** took place on the silica gel layer. IR (KBr): ν 1034 cm^{-1}m; 1214+1238+1261s, br. (C–O), 1685s (C=O, amide-I), 1753s (C=O, ester), 1787s (C=O, ketone), 2255vw (C≡N), 3240sh, br. (N–H). ^1H NMR: δ 1.33, 1.41 (2s, 2Me), 1.48 (s, 2Me), 3.43 (s, 7′-H_2), 3.78, 3.88 (2s, 2MeO), 4.34 (s, 5′-H), 6.85 (s, br., NH). ^{13}C NMR (100 MHz, DEPT): δ 19.7, 21.8, 22.6, 23.4 (4Me), 37.2 (C-7′), 45.5 (C-6′), 52.6 (C-5′), 53.3, 54.7 (2MeO), 66.6, 69.0, 69.8 (C-2, C-3, C-4), 161.7, 166.1, 167.7 (3 C=O, ester, amide), 216.6 (C=O, ketone). MS (145°C); m/z (%): 382 (0.04, M^+), 367 (0.85, $[M-Me]^+$), 322 (100, $[M-HCO_2Me]^+$), 312 (21, $[M-C_4H_6O]^+$, ^{13}C 3.0/3.3, $^{13}C_2+^{34}S$ 1.1/1.3), 263 (5), 222 (20), 219 (18), 217 (21), 204 (14), 203 (14), 189 (16), 183 (18), 178 (15), 125 (7), 70 (11, $C_4H_6O^+$), 69 (17, $C_4H_5O^+$), 59 (13,

CO_2Me^+). Anal. calcd for $C_{17}H_{22}N_2O_6S$ (382.43): C 53.39, H 5.80, N 7.33; found: C 53.72, H 5.74, N 7.09.

(b) No interception with methanol. After the reaction of **4** with **16** in $CDCl_3$, containing 2 vol% of methanol (10 min, 80°C), the ^1H NMR spectrum showed **26/27**=60:40, but no imidate signals. Even in methanol as solvent (3 h, 65°C) only the thiolanes were formed.

5.1.8. Diisopropyl 3′,4′-dicyano-2,2,4,4-tetramethyl-1-oxospiro[cyclobutane-3,2′-thiolane]-3′,4′-*trans*-dicarboxylate (28) and *cis*-isomer 29. (a) Isolation of cycloadducts **28** and **29**. Diisopropyl 2,3-dicyanofumarate (**18**, 450 mg, 1.80 mmol) in octane (5 mL) was vigorously stirred in a 120°C bath. The solution of **4** (396 mg, 2.00 mmol) in octane (5 mL) was dropwise added in 20 min. After removal of the solvent in vacuo, the residue was taken up in hot 2-propanol and afforded a first-fraction (90 mg, 12%) of **28** as colorless prisms, mp 129–130°C (diisopropyl ether). The isomer separation of further fractions by PLC failed. An analogous experiment was carried out with **19** and furnished **29** (210 mg, 28%) as the first crystal fraction, mp 125–126°C, from 2-propanol.

(b) Data of **28** (*trans*). IR (KBr): ν 1099 cm^{-1}s, 1253+1269s (C–O), 1745sh, 1750s (C=O, ester), 1784s (C=O, ketone), 2260vw (C≡N). ^1H NMR (400 MHz): 1.35, 1.38, 1.39, 1.43 (4 d, J=6.4 Hz, 2 pairs of diastereotopic Me, 2*i*Pr), 1.43, 1.52, 1.57, 1.88 (4s, 4Me), 3.53, 3.59 (AB, J=11.2 Hz, 5′-H_2), 5.17, 5.20 (2sept, J=6.4 Hz, 2CH of 2*i*Pr). ^{13}C NMR (20.2 MHz): δ 21.0, 21.1, 21.2, 21.5 (4q, 4Me of 2*i*Pr), 23.4, 23.5, 24.2, 24.6 (4q, 4Me at C-2, C-4), 36.1 (t, C-5′), 60.9, 62.9 (2s, C-2, C-4), 67.5, 68.9, 70.3 (3s, C-3, C-3′, C-4′), 73.4, 74.1 (2d, 2CH of 2*i*Pr), 114.7, 116.4 (2s, 2CN), 162.7 (s, 2C=O, ester), 217.7 (s, C=O, ketone). Anal. calcd for $C_{21}H_{28}N_2O_5S$ (420.52): C 59.98, H 6.71, N 6.66, S 7.63; found: C 60.08, H 6.68, N 6.54, S 7.65.

(c) Data of **29** (*cis*). IR (KBr): δ 1099 cm^{-1}s, 1254s, 1266s (C–O), 1742s, 1757s (C=O, ester), 1788s (C=O, ketone), 2240vw (C≡N. ^1H NMR (360 MHz): δ 1.15, 1.64, 1.88, 2.03 (4s, 4Me), 1.38 (d, J=6.0 Hz, 2CH*Me*$_2$), 3.38, 3.85 (AX, J_{gem}=11.9 Hz, 5′-H_2), 5.08, 5.12 (2sept, J=6.0 Hz, C*H*Me$_2$). ^{13}C NMR (20.2 MHz): δ 21.3 (br., q, 2CH*Me*$_2$), 22.2, 22.8, 23.0, 23.9 (4 q, 4Me), 35.2 (t, C-5′), 58.1, 61.3, 64.3, 70.7, 71.4 (5s, C-2, C-3, C-4, C-3′, C-4′), 73.5, 74.3 (2d, 2O*C*HMe$_2$), 115.2, 117.1 (2s, 2CN), 162.4, 162.9 (2s, 2C=O, ester), 216.2 (C=O, ketone). MS (60°C); *m/z* (%): 420 (0.06, M^+), 361 (2.4, $[M-iPrO]^+$, ^{13}C 0.47/0.44), 350 (47, $[M-C_4H_6O]^+$, ^{13}C 10.9/11.3, $^{13}C_2+^{34}S$ 3.5/4.0), 319 (13), 264 (7, $[350-CO_2C_3H_6]^+$, $C_{13}H_{16}N_2O_2S^+$), 237 (19, $[264-HCN]^+$, ^{13}C 2.5/2.8), 222 (100, $[264-C_3H_6]^+$, $C_{10}H_{10}N_2O_2S^+$, ^{13}C 11.1/12.5, $^{13}C_2+^{34}S$ 5.0/5.5), 195 (93, $[237-C_3H_6]^+$, $C_9H_9NO_2S^+$), 179 (22, $[237-OC_3H_6]^+$), 177 (41, $[264-CO_2iPr]^+$, $C_9H_9N_2S^+$), 150 (16, $[177-HCN]^+$), 125 (8), 70 (26, $C_4H_6O^+$), 59 (4, $C_3H_7O^+$), 43 (71, iPr^+). Anal. calcd for $C_{21}H_{28}N_2O_5S$ (420.52): C 59.98, H 6.71, N 6.66, S 7.63; found: C 60.03, H 6.88, N 6.55, S 7.68.

(d) Steric course of addition of **1** with **18** and **19**. **4** (5.01 mg, 25.3 μmol) and **18** (8.45 mg, 33.8 μmol), dissolved in 7.6 mM H_2SO_4 in $CDCl_3$ (1 mL), was heated in a closed NMR tube at 80°C (bath) for 10 min. After cooling and adding *sym*-$C_2H_2Cl_2$ as standard, the 360 MHz ^1H NMR spectrum showed the undisturbed 5′-H_2 signals of **28** (AB) and **29** (AX). The ratio **28/29** was 61:39 and the yield 56%. The analogous reaction of **4** with **19** (1.4 equiv.) afforded **28/29**=25:75 and 49% yield. The side-products were not investigated. In both reactions, an isomerization of the excess **18** or **19**, respectively, was not noticed.

5.1.9. Diisopropyl 6′-cyano-2′,3′,4′,5′,6′,7′-hexahydro-2,2,4,4-tetramethyl-1,4′-dioxospiro[cyclobutane-3,2′-(1,3)-thiazepine]-5′,6′-dicarboxylate (32). Reaction with **18** in THF +2 vol% of H_2O as described for **31**. The ^1H NMR spectrum (C_6D_6, trichloroethylene as standard) showed thiolanes **28** and **29** (about 45%), thiirane **15** (s, 2.60, 4%), as well as lactams **32A** (s 4.37, 5′-H, 20%), and **32B** (s 4.55, 5′-H, 10%). PLC (CH_2Cl_2 and a second run in CH_2Cl_2/acetone 95:5) was accompanied by isomerization of **32A→32B**; the oil crystallized from pentane, mp 147–148°C. IR (KBr): ν 1032 cm^{-1} m; 1104s, 1209s, 1233m, 1259m, 1286m (C–O); 1377s, 1390s; 1682vs. (amide I), 1745vs (C=O, ester), 1788s (C=O, ketone), 2250vw (C≡N), 3100w, 3280m, br. (N–H). ^1H NMR (80 MHz): δ 1.00–1.60 (m, 8Me), 3.39 (s, 7′-H_2), 4.24 (s, 5′-H), 5.07, 5.08 (2sept, J=6.1 Hz, 2O*C*H*Me*$_2$), 7.44 (s, br., NH), (C_6D_6): δ 0.62–1.55 (m, 8Me), 3.28, 3.47 (AB, J=15.0 Hz, 7′-H_2), 4.52 (s, 5′-H), 4.89 (sept, J=6.1 Hz, 2O*C*H*Me*$_2$), 7.93 (s, NH). Anal. calcd for $C_{21}H_{30}N_2O_6S$ (438.53): C 57.51, H 6.90, N 6.39, S 7.31; found: C 57.87, H 7.28, N 6.25, S 7.29.

5.1.10. 1,5′-Dihydro-2,2,4,4-tetramethylspiro[cyclobutane-1,2′-(1,3,4)-thiadiazole] (23). (a) 2,2,4,4-Tetramethylcyclobutanethione (**36**). The methylation of cyclobutanone by the procedure with MeI and KOH in DMSO[35] furnished 2,2,4,4-tetramethylcyclobutanone in 49% yield, bp 128–130°C (128°C).[36] For the conversion to thione **36**, the ketone (5.00 g) in abs. MeOH (40 mL) and trimethyl orthoformate (7.2 mL) was treated with HCl and H_2S at 0°C for 12 h. The usual workup afforded **36** (5.04 g, 89%) as an orange oil. ^1H NMR: δ 1.26 (s, 4Me), 2.24 (s, 3-H_2).

(b) Preparation of thiadiazoline **23**. The reaction of **36** with diazomethane in diethyl ether proceeded as described for **4**.[11,30] Twice recrystallized from pentane at −78°C, **23** (57%) was obtained colorless, mp 9–10°C. ^1H NMR: δ 1.03, 1.23 (2s, 4Me), 1.94, 2.37 (AB, J=11.6 Hz, 3-H_2), 5.58 (s, 5′-H_2). Anal. calcd for $C_9H_{16}N_2S$ (184.30): C 58.65, H 8.75, N 15.20, S 17.40; found: C 59.11, H 8.97, N 15.81, S 17.40.

(c) Kinetics of N_2 extrusion. The nitrometric technique followed the earlier description.[37] Triple measurements in each solvent provided values for 10^4k_1 (s^{-1}) at 40±0.2°C: 1.19 (xylene), 1.14 (THF), 0.71 (acetonitrile).

(d) 2,2,4,4-Tetramethylspiro[cyclobutane-1,2′-thiirane] (**38**). The above thermolysis solutions afforded the oily **38** (81%), bp 90–110°C (bath)/12 Torr. ^1H NMR (80 MHz): δ 1.00, 1.17 (2s, 4Me), 1.87, 1.95 (AB, J=8.5 Hz, 3-H_2), 2.48 (s, 3′-H_2). ^{13}C NMR (20.2 MHz): δ 27.41, 30.2 (2q, 4Me),

27.53 (t, C-3′), 36.3 (s, C-2, C-4), 47.6 (t, C-3), 66.1 (s, C-1). MS (20°C); *m/z* (%): 156 (34%, M^+), 141 (20, $[M-Me]^+$), 109 (15, $[141-S]^+$), 100 (100, $[M-C_4H_8]^+$), 85 (95, $[100-Me]^+$), 67 (32, $C_5H_7^+$), 55 (19, $C_4H_7^+$). Anal. calcd for $C_9H_{16}S$ (156.28): C 69.16, H 10.32, S 20.52; found: C 69.42, H 10.32, S 20.52.

5.1.11. Dimethyl 3′,4′-dicyano-2,2,4,4-tetramethylspiro-[cyclobutane-1,2′-thiolane]-3′,4′-*trans*-dicarboxylate (39) and *cis*-isomer 40. (a) Cycloaddition of **37** with **16**. Thiadiazoline **23** (750 mg, 4.07 mmol) and **16** (871 mg, 4.49 mmol) in CH_2Cl_2 (20 mL) were refluxed for 15 h. After evaporation of the solvent, the residue was triturated with $CDCl_3$, and the excess of **16** was filtered. The ^1H NMR analysis with *sym*-$C_2H_2Cl_4$ indicated **39** (2s at 1.36, 1.40, 2Me, 1.64 mmol, 40%) and **40** (2s at 1.01, 1.96, 2Me, 1.93 mmol, 47%), i.e. in the ratio 46:54. Adduct **40** (378 mg, 27%) crystallized from methanol at room temp., followed on cooling to 0°C by **39** (200 mg, 14%, colorless needles). Further fractions consisted of mixtures which were partially separated manually. Solubilities in methanol at 20°C: 20.1 mg of **39** per mL, 15.7 mg of **40** per mL.

(b) Variation of solvent. Analogous experiments were carried out in acetonitrile at 40°C (**39/40**=27:43, 88% yield) and in toluene at 40°C (**39/40**=63:37, 90%). A cycloaddition of **23** with **16** (1.4 equiv.) in $CDCl_3$ (0.5 mL) was carried out in the closed NMR tube (10 min, 80°C-bath) and gave **39/40**=56:44.

(c) Reaction of **37** with **17**. The experiment in the NMR tube, carried out at 80°C with **23** (0.10 mmol) and **17** (0.12 mmol) in $CDCl_3$ (0.5 mL), provided **39/40**=55:45. The excess of **17** was largely isomerized to **16**. According to Table 1, **23** was the most active catalyst in the equilibration **16**⇄**17**, and the catalysis was hardly suppressed in 7.6 mM H_2SO_4 in $CDCl_3$.

(d) Data of **39** (*trans*). Mp 122–123°C. IR (KBr): ν 1179 cm^{-1}m, 1248s, 1263s (C–O), 1746s (C=O), 2249vw (C≡N). ^1H NMR (400 MHz): δ 1.36, 1.40, 1.48, 1.72 (4s, 4Me), 1.60, 1.65 (AB, J=11.6 Hz, 3-H_2), 3.51, 3.59 (AB, J=11.5 Hz, 5′-H_2), 3.91, 3.94 (2s, 2MeO). ^{13}C NMR (20.2 MHz): δ 27.6, 27.9, 30.7, 31.0 (4 q, 4Me), 36.2 (t, C-5′), 42.6, 46.4 (2s, C-2, C-4), 49.5 (t, C-3), 54.2, 54.8 (2q, 2MeO), 60.2, 63.1, 74.6 (3s, C-4′, C-3′, C-1), 114.8, 116.5 (2s, 2CN), 164.0, 164.3 (2s, 2C=O). MS (70°C, for assignments below *m/z* 294, see MS of **27**); *m/z* (%): 351 (0.04, M^++1), 350 (0.05, M^+), 319 (2.6, $[M-MeO]^+$), 294 (100, $[M-C_4H_8]^+$), 249 (3), 235 (4), 208 (4), 194 (5), 192 (7), 191 (46), 183 (32), 177 (15), 176 (9), 150 (17), 125 (8), 109 (5), 59 (15), 55 (4, $C_4H_7^+$), 41 (9, $Allyl^+$). Anal. calcd for $C_{17}H_{22}N_2O_4S$ (350.43): C 58.26, H 6.32, N 8.00, S 9.15; found: C 58.35, H 6.24, N 7.89, S 9.17.

(e) Data of **40** (*cis*). Mp 141°C. IR (KBr): ν 1251 cm^{-1}+1260s, br. (C–O), 1429s; 1742s, 1753s (C=O), 2246vw (C≡N). ^1H NMR (400 MHz): δ 1.01, 1.55, 1.78, 1.96 (4s, 4Me), 1.71, 1.77 (AB, J=11.1 Hz, 3-H_2), 3.39, 3.85 (AX, J=12.2 Hz, 5′-H_2), 3.86, 3.90 (2s, 2MeO). ^{13}C NMR (20.2 MHz): δ 26.7, 27.7, 29.1, 29.4 (4 q, 4Me), 35.1 (t, C-5′), 40.6, 47.3 (2s, C-2, C-4), 48.1 (t, C-3), 54.3, 54.7 (2q, 2MeO), 57.0, 61.2, 75.1 (3s, C-4′, C-3′, C-1), 115.5, 117.0 (2s, 2CN), 164.1, 164.7 (2s, 2C=O). Anal. calcd for $C_{17}H_{22}N_2O_4S$ (350.43): C 58.26, H 6.32, N 8.00, S 9.15; found: C 58.56, H 6.29, N 7.80, S 9.16.

(f) Equilibration kinetics of cycloadducts **39** and **40**. **39** (0.312 mmol) and octamethylcyclotetrasiloxane (OMCTS, 0.0151 mmol) in benzonitrile (0.4 mL) were sealed in an NMR tube under argon and heated to 139°C. Based on OMTCS, the integrals of s δ 1.20 (Me of **39**) and s 0.83 (Me of **40**) were used for the analysis. After 74.3 h, the equilibrium **39/40**=31:69 was reached from both sides within the analyt. limits; no loss by decomposition was noticeable. Evaluation of 15 integrals each for **39** and **40** was based on the integrated rate Eq. (2) for reversible first-order reactions and gave $10^5\times(k_{39}+k_{40})=1.51\pm0.03\ s^{-1}$ (benzonitrile, 139°C). Partitioning afforded $k_{39}=1.06\times10^{-5}\ s^{-1}$ and $k_{40}=0.45\times10^{-5}\ s^{-1}$

$$(k_{39}+k_{40})t=\log[(c_0-c_e)/(c_t-c_e)] \quad (2)$$

The concentrations, i.e. the integrals, fit well the conversion curves which were calculated with above parameters.

5.1.12. Diisopropyl 3′,4′-dicyano-2,2,4,4-tetramethylspiro[cyclobutane-1,2′-thiolane]-3′,4′-*trans*-dicarboxylate (41) and *cis*-isomer (42). (a) Reaction of **37** with **18**. The solution of **23** (4.14 mmol) in octane (5 mL) was dropped into the stirred suspension of **18** (4.14 mmol) in octane (10 mL) at 80°C in 15 min. After further 15 min at 80°C, the filtered solution was evaporated in vacuo. A partial separation of the thiolane mixture was achieved by repeated PLC (pentane/ether 9:1, 4 times). Bulb-to-bulb distillation of the top fraction (240 mg) at 200°C/10^{-2} Torr gave pure **42** as a viscous oil which crystallized after several months at −24°C, mp 38–41°. The third PLC fraction (280 mg) was enriched in **41** which crystallized from diisopropyl ether, mp 100–101°C.

(b) Data of **41** (*trans*). IR (KBr): ν 1100 cm^{-1}s, 1257s, br. (C–O), 1745s (C=O), 2245vw (C≡N). ^1H NMR (400 MHz): δ 1.32, 1.35, 1.39, 1.41 (4 d, J=6.4 Hz, 4Me of 2*i*Pr), 1.35, 1.46, 1.50, 1.74 (4s, 4Me), 1.59, 1.64 (AB, J=11.6 Hz, 3-H_2), 3.49, 3.55 (AB, J=11.4 Hz, 5′-H_2), 5.13, 5.18 (2sept, J=6.4 Hz, 2CH of 2*i*Pr). ^{13}C NMR (20.2 MHz): δ 21.0, 21.2 (2×), 21.5, 27.9, 28.1, 30.8, 31.1 (8 q, 8Me), 36.1 (t, C-5′), 42.4, 46.6 (2s, C-2, C-4), 49.5 (t, C-3), 60,5, 63.5 (2s, C-4′, C-3′), 73.0, 73.2 (2d, 2*C*HMe$_2$), 74.8 (s, C-1), 115.0, 116.9 (2s, 2CN), 163.1, 163.3 (2s, 2C=O). MS (70°); *m/z* (%): 407 (0.05, M^++1), 391 (0.01, $[M-Me]^+$), 350 (43, $[M-C_4H_8]^+$, ^{13}C 8.1/8.4, $^{13}C_2+^{34}S$ 2.6/2.8), 347 (5, $[M-i\text{PrO}]^+$, $C_{18}H_{23}N_2O_3S^+$, ^{13}C 1.1/1.1, $^{13}C_2+^{34}S$ 0.33/0.35), 305 (3, $[347-C_3H_6]^+$, ^{13}C 0.5/0.6), 264 (6, $[350-CO_2-C_3H_6]^+$, $C_{13}H_{16}N_2O_2S^+$, ^{13}C 0.9/1.0; this peak as the following ones occur also in the MS of **29**), 237 (33, $C_{12}H_{15}NO_2S^+$, ^{13}C 4.5/4.6), 222 (88, $[264-C_3H_6]^+$, $C_{10}H_{10}N_2O_2S^+$, ^{13}C 9.7/10.4, $^{13}C_2+^{34}S$ 4.4/4.6), 195 (100, $[237-C_3H_6]^+$, $C_9H_9NO_2S^+$, fits isopropyl cyanothiophene-carboxylate$^+$, ^{13}C 10.0/10.8, $^{13}C_2+^{34}S$ 4.4/4.6), 194 (6), 178 (17), 177 (44, $[264-CO_2i\text{Pr}]^+$, $C_9H_7NOS^+$), 176 (17), 161 (12, $C_8H_5N_2S^+$), 150 (20, $C_8H_8NS^+$), 149 (7), 109 (9, $C_5H_3NS^+$, fits cyanothiophene$^+$), 80 (8), 43 (55, $C_3H_7^+$), 41 (22). Anal. calcd for $C_{21}H_{30}N_2O_4S$ (406.53): C 62.04, H 7.44, N 6.89, S 7.89; found: C 62.02, H 7.25, N 6.87, S 7.91.

(c) Data of **42** (*cis*). IR (film): ν 1102 cm^{-1}s, 1249vs, br. (C–O), 1377m, 1390m; 1752vs (C═O), 2245vw (C≡N). ^{1}H NMR (400 MHz): δ 1.04, 1.55, 1.83, 1.96 (4s, 4Me), 1.33, 2×1.364, 1.375 (4 d, J=6.3 Hz, 4Me of 2*i*Pr), 1.70, 1.76 (AB, J=11.1 Hz, 3-H_2), 3.35, 3.83 (AX, J=12.2 Hz, 5′-H_2), 5.08, 5.11 (2sept, 2CH of 2*i*Pr). ^{13}C NMR (20.2 MHz): 21.14, 21.23, 21.29, 21.38, 26.6, 27.7, 29.0, 29.6 (8 q, 8Me), 34.8 (t, C-5′), 40.5, 47.4 (2s, C-2, C-4), 48.2 (t, C-3), 56.9, 61.7 (2s, C-4′, C-3′), 73.0, 73.6 (2d, 2*C*HMe$_2$), 115.9, 117.6 (2s, 2CN), 163.2, 163.8 (2s, 2C═O); C-1 covered by $CDCl_3$ signal. Anal. calcd for $C_{21}H_{30}N_2O_4S$ (406.53): C 62.04, H 7.44, N 6.89, S 7.89; found: C 62.13, H 7.34, N 6.95, S 7.88.

(d) NMR tests on steric course. Thiadiazoline **23** (0.269 mmol) and **18** (0.350 mmol) in $CDCl_3$ (0.75 mL) were reacted in the closed NMR tube at 80°C for 5 min. After cooling, *sym*-$C_2H_2Cl_4$ (0.203 mmol) was added, and the ^{1}H NMR analysis (AB spectra of 5′-H_2) showed **41/42**=63:37 and a yield of 89%. An analogous experiment with **19** provided **41/42**=49:51, also with 89% yield.

Acknowledgements

We express sincere thanks to the Fonds der Chemischen Industrie, Frankfurt, for the support of our work. G. M. is grateful to the Alexander von Humboldt Foundation for a stipend. Furthermore, we thank Helmut Huber for excellent NMR spectra, Reinhard Seidl and Dr Werner Spahl for the MS, and Helmut Schulz and Magdalena Schwarz for the elemental analyses.

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