Stereoselective Synthesis of α-Amino and α-Thio β-Lactones by Conjugate Addition of Amine and Thiol Nucleophiles to α-Methylene β-Lactones and Their Decarboxylation to Allylamines and Sulfides

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The stereoselective, conjugate addition of secondary, cyclic amines (pyrrolidine and piperidine) and mercaptans (thiophenol, isopropyl, and benzyl thiols and β-mercaptoethanol) to α-methylene β-lactones **1** and **2** was investigated. The corresponding α-(aminomethyl) and α-(thiomethyl) β-lactones **3–5** and **6–10** were obtained in excellent yields through protonation of the intermediary enolates. In methanol the *trans* isomers were the major products, while considerable amounts of the *cis* isomers were formed in THF and acetone. The decarboxylation of these α-aminomethyl and α-thiomethyl β-lactones as neat samples at 180 °C produced in excellent yields the corresponding allyl amines and sulfides **11–13** and **14–18** with retention of the initial β-lactone geometry. This unprecedented sequence of Michael-type addition followed by decarboxylation, in which the α-methylene β-lactones serve as allene equivalents, provides a useful alternative to the Wittig olefination for the preparation of allylic amines and sulfides.

Introduction

The highly functional α-methylene β-lactones constitute potentially valuable building blocks in organic synthesis, which have become readily accessible through a variety of methods.[1] They constitute convenient allene equivalents,[2,3] as was demonstrated in the stereoselective cycloaddition of α-methylene β-lactones to dienes and their stereoselective decarboxylation to the corresponding olefins with retention of the initial geometry.[4] Recently they have been employed for the topological resolution through Diels–Alder cycloaddition and retrocleavage at moderate temperatures.[5]

Since the conjugate addition of amines[6] and thiols[7] to α,β-unsaturated carbonyl compounds occurs under mild conditions, we expected that such nucleophiles would also undergo preferential Michael-type addition with α-methylene β-lactones to give the corresponding α-(aminomethyl) and α-(thiomethyl) β-lactones. Should this conjugate addition take place stereoselectively, decarboxylation of these adducts would provide a novel and convenient synthesis of geometrically defined allylamines and sulfides. These structural units are contained in natural products,[8] but the usual synthetic methods[9] for their preparation lead to *Z*/*E* mixtures, which are cumbersome to separate. Herein we demonstrate that the sequence of conjugate addition to α-methylene β-lactones followed by decarboxylation of the resulting adducts constitutes a useful, stereoselective preparation of allylamines and sulfides (Scheme 1).

Results and Discussion

The conjugate addition of secondary amines to the α-methylene β-lactones **1** and **2** (Scheme 1) gave the α-(aminomethyl) β-lactones **3–5** in good yields (Table 1). The well-established vicinal coupling constants (J_{cis} ca. 6.5 Hz and J_{trans} ca. 4.5 Hz)[10] for α,β-disubstituted β-lactones were used to assign the *cis* and *trans* diastereomers. The *cis*/*trans* ratios of the β-lactones **3–5** were determined by ^{1}H NMR analysis.

The stereoselective protonation of enolates has been shown to be influenced by the proton source and solvent.[11] Therefore, it was not surprising that the present diastereomeric ratios of the β-lactone products also depended on the nature of the solvent. While in THF the *cis* diastereoisomers were obtained as major products (Table 1, entries 1, 3, 5, and 6), high *trans* diastereoselectivity (up to 93%) was observed in methanol (Table 1, entries

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Scheme 1

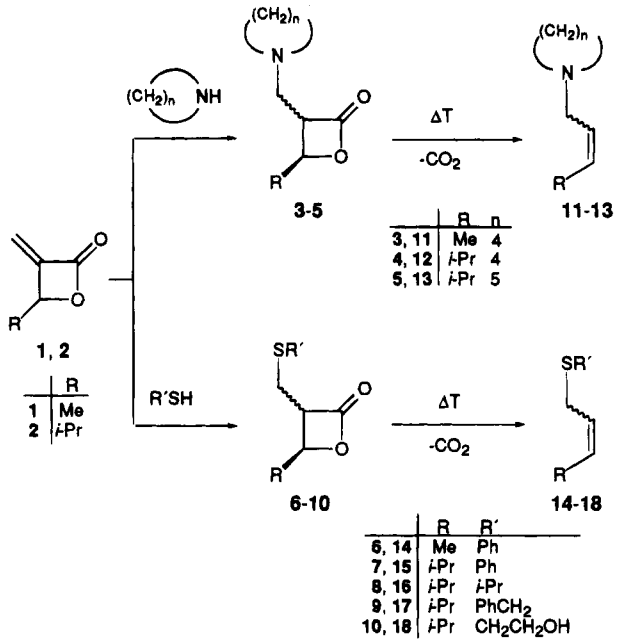

Table 1. Conjugate Nucleophilic Addition of Secondary Amines to α-Methylene β-Lactones 1 and 2[a]

entry	nucleophile	product[a]	solvent	temp (°C)	time[b] (h)	yield[c] (%)	*cis*:*trans*[d]
1	pyrrolidine	**3**	THF	68	0.5	64	66:34
2	pyrrolidine	**3**	MeOH	20	0.25	92	28:72
3	pyrrolidine	**4**	THF	68	0.5	76	73:27
4	pyrrolidine	**4**	MeOH	20	0.25	91	10:90
5	pyrrolidine	**4**	THF-d_8	20	28	*e*	71:29
6	piperidine	**5**	THF	68	3	69	77:23
7	piperidine	**5**	MeOH	20	0.25	84	7:93

[a] For structure code see Scheme 1; entries 1–2 are for β-lactone **1** and the others for **2**. [b] For 100% conversion. [c] Yield of isolated material after distillation. [d] Determined by ^{1}H NMR analysis on the isolated material, mass balance >95%, normalized to 100%, error ca. 5% of stated values. [e] Run on NMR scale.

2, 4, and 7). The same *cis*/*trans* ratio (Table 1, entries 3 and 5) in THF at 68 *versus* 20 °C shows that a temperature effect was not responsible for the *cis* stereoselectivity in this solvent.

The conjugate addition of thiols to the α-methylene β-lactones **1** and **2** afforded the α-(thiomethyl) β-lactones **6**–**10** (Scheme 1) in high yields (Table 2).

However, in contrast to the secondary amines, catalytic amounts (0.1 equiv) of triethylamine were necessary to promote the reaction. The relative rates of the base-catalyzed thiol addition with β-lactone **2** followed the order PhSH > $PhCH_2SH$ > iPrSH in acetone. This reactivity trend reflects the acidity of the thiols, as given by their pK_a values.[12] When sodium thiophenolate,

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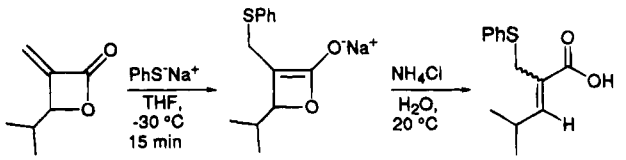
Table 2. Base-Catalyzed Conjugate Nucleophilic Addition of Mercaptans to α-Methylene β-Lactones 1 and 2[a]

entry	nucleophile[b]	product[a]	solvent	time[c] (h)	yield[d] (%)	*cis*:*trans*[e]
1	PhSH	**6**	MeOH	1	72	26:74
2	PhSH	**7**	MeOH	1	97	16:84
3	PhSH	**7**	*i*-PrOH	1	86	53:47
4	PhSH	**7**	MeCOMe	1	94	45:55
5	PhSH	**7**	CCl_4	1	94	45:55
6	PhSH	**7**	THF-d_8[b]	2	*f*	47:53
7	*i*-PrSH	**8**	MeOH	1	62	<5:95
8	*i*-PrSH	**8**	MeCOMe	96	91	44:56
9	$PhCH_2SH$	**9**	MeOH	1	81	11:89
10	$PhCH_2SH$	**9**	MeCOMe	15	99	43:57
11	$HOCH_2CH_2SH$	**10**	MeOH	1	82	10:90
12	$HOCH_2CH_2SH$	**10**	MeCOMe	2	99	26:74

[a] For structure code see Scheme 1; entry 1 is for β-lactone **1** and the others for **2**. [b] Triethylamine (0.1 equiv) was used as base catalyst, except entry 6 (0.1 equiv of NaH), all at 20 °C. [c] For 100% conversion. [d] Yield of isolated material after silica gel chromatography. [e] Determined by ^{1}H NMR analysis on the isolated material, mass balance >95%, normalized to 100%, error ca. 5% of stated values. [f] Run on NMR scale, but no ring opening to **20** was detected.

Scheme 2

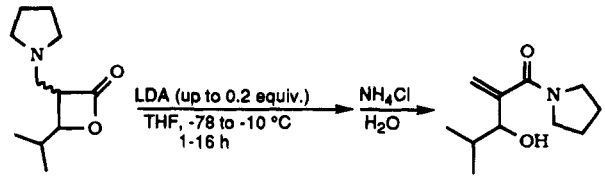


generated with NaH in THF, was used, the β-lactone **2** was consumed very quickly (ca. 15 min) to give a low yield (ca. 8%) of adduct **7** (*cis*/*trans* ratio ca. 5:95) and mainly (ca. 27%) the acrylic acid **20** (Scheme 2); the rest was undefined material. Thus, the use of PhSH and catalytic amounts of Et_3N is clearly advantageous over PhS^-Na^+, since in the former no acrylic acid was formed and the yields of the β-lactone products **6**–**10** were high (Table 2).

Analogous to the amine addition (Table 1), the *cis*/*trans* ratio depended on the nature of the solvent. Thus, for thiophenol and β-lactone **2**, in THF (Table 2, entry 6), carbon tetrachloride (Table 2, entry 5), or acetone (Table 2, entry 4), essentially no stereoselectivity (*cis*/*trans* ca. 45:55) was observed. In methanol (Table 2, entry 2), the *trans* isomer was obtained in high diastereoselectivity (*cis*/*trans* 16:84). However, in the protic isopropyl alcohol (Table 2, entry 3) this *trans* preference was lost (*cis*/*trans* 53:47). That the acetone *versus* methanol solvent effect on the diastereoselectivity is general is displayed in Table 2 for the thiols iPrSH (entries 7 and 8) and $PhCH_2SH$ (entries 9 and 10); i.e., essentially no stereoselectivity in acetone and a high *trans* preference in methanol was observed. Yet, for β-mercaptoethanol as nucleophile (entries 11 and 12), even in acetone the *trans* diastereomer was favored (*cis*/*trans* ca. 26:74). Presumably, this protic nucleophile serves as its own proton source.

For mechanistic understanding it was important to elucidate the reasons for the observed *cis*/*trans* diastereoselectivity (Tables 1 and 2). ^{1}H NMR analysis at different reaction times for both the amine and the thiol addition revealed that no change in the *cis*/*trans* ratios was observed even at low conversion. Thus, under the employed reaction conditions no *cis*/*trans* equilibration

Scheme 3



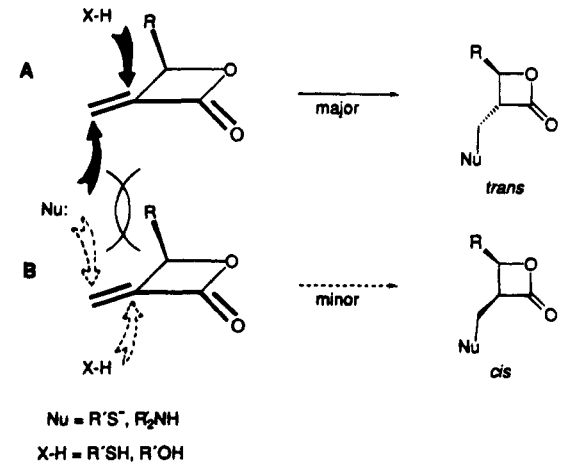
occurred. Deliberate attempts to equilibrate β-lactones **4** or **7** with Et_3N (as solvent) or DABCO (0.2 and 0.5 equiv) in THF or benzene at 60–90 °C failed, which indicates that these bases are not strong enough to deprotonate the β-lactones. Complete deprotonation of the lactone *cis,trans*-**4** (65:35 mixture) was accomplished by treatment with LDA (1 equiv) in THF at −78 °C and workup with aqueous NH_4Cl gave *cis,trans*-**4** (3:97 mixture). Similarly, pure *cis*-**7** was isomerized under these conditions to pure *trans*-**7** in 52% yield; the rest was undefined material. As expected, the *trans* isomer is the thermodynamically favored product.[13] The use of catalytic amounts of LDA without a proton source resulted in partial (ca. 5%) *cis* to *trans* isomerization. Unfortunately, appreciable amounts (ca. 10%) of the pyrrolidine (retro Michael-type reaction) and carbonyl attack of the latter on the resulting α-methylene β-lactone **2** to afford the corresponding acrylamide **21** (Scheme 3) constituted a serious side reaction.

The observed *cis*/*trans* ratios (Table 1 and 2) are far from the thermodynamically favored *trans* isomer in THF, MeCOMe, and CCl_4, but in MeOH predominantly the *trans* isomer was formed. Nevertheless, appreciable amounts (except entry 7, Table 2) of the sterically unfavorable *cis* isomer were produced. If in methanol the enolate **19**, shown for PhS^- as nucleophile (Scheme 2), were to intervene, the resulting enol would unquestionably tautomerize essentially exclusively to the thermodynamically preferred *trans* isomer. Since in the PhS^-Na^+ addition without a proton source the enolate **19** rearranged to the acrylic acid **20** (Scheme 2), but no traces of the latter were observed under the reaction conditions of Tables 1 and 2, the enolate ion appears to be protonated faster than its electrocyclic ring-opening to the acrylate ion[14] (Scheme 2). We propose, therefore, that in MeOH nucleophilic addition and protonation could take place concurrently in an antiperiplanar geometry (Scheme 4).

It is expected that the R group in the α-methylene β-lactones **1** and **2** sterically obstructs the approach of the nucleophile; thus, attack should be preferred opposite to the R group. Indeed, in agreement with the steric demand for lactone **2** (R = *i*-Pr), the *trans* isomer is more prominent than for **1** (R = Me), as shown in Table 2 (entries 1 and 2). Furthermore, the steric size plays also its role in the protonation by the alcohol since in *i*-PrOH significantly more *cis* isomer is produced than in MeOH under otherwise identical conditions (Table 2, entries 2 and 3). Apparently the *i*-Pr group in β-lactone **2** encumbers the antiperiplanar entry of the sterically more demanding *i*-PrOH than MeOH.

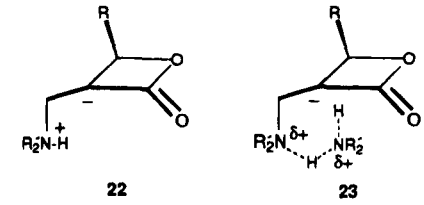
In the aprotic solvents, be it THF, acetone, or CCl_4, proportionally more *cis* isomer is formed; in fact, for the

Scheme 4



thiol addition the *cis* and *trans* isomers are formed in about equal amounts (Table 2), while for the amines the *cis* product dominates (Table 1). In the case of the thiols, the diastereoselectivity does not change by the use of catalytic amounts of NaH as base (Table 2, entry 6) instead of triethylamine (Table 2, entry 5). This suggests that the likely proton donor in both cases is the RSH itself, i.e., RSH serves as nucleophile and as proton source. Thus, the lack of diastereoselectivity (d.r. ca. 50:50) for the RSH case in aprotic solvents implies that both antiperiplanar approaches A and B (Scheme 4) are equally probable.

Still more unusual is the diastereoselectivity of the amine addition in THF, for which the *cis* adduct clearly dominates, in the case of β-lactone **2** (R = *i*-Pr) slightly more so than for **1** (R = Me), cf. Table 1 (entries 1 and 3). The proton donor is not immediately apparent, but potential candidates are the zwitterions **22** and **23**. The



former is initially formed by nucleophilic attack of the amine on the β-lactone and the latter subsequently by association of a second amine molecule through hydrogen bonding, preferably opposite to the β-lactone R group for steric reasons. Proton transfer prior to the electrocyclic ring-opening, necessarily from the same side as that of the amine attack, would afford the *cis* isomer. In MeOH, an effective proton donor, this mechanism appears to be of little importance since the *trans* product is preferentially formed (Table 1) by antiperiplanar protonation (Scheme 4).

Since β-lactones undergo facile stereoselective decarboxylation at moderate temperatures (below 200 °C),[10,15] they have been extensively employed in the synthesis of a variety of substituted and functionalized alkenes.[16]

Indeed, as shown in Scheme 1, the decarboxylation of the β-lactones **3**–**10** (as neat samples) proceeded smoothly at 180 °C to form the corresponding allyl amines **11**–**13** and sulfides **14**–**18** in good yields (Table 3). These olefins were purified by vacuum distillation (0.1 Torr) or silica gel chromatography.

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(14) Mulzer, J.; Kerkmann, T. *J. Am. Chem. Soc.* **1980**, *102*, 3620–3622.

Table 3. Decarboxylation[a] of β-Lactones 3–10 to the Allylamines 11–13 and Sulfides 14–18

entry	β-lactone[b] (*cis*:*trans*)	olefin[b]	yield[c] (%)	*Z*:*E*[d]
1	**3** (57:43)	**11**	51	56:44
2	**4** (10:90)	**12**	60	10:90
3	**5** (66:34)	**13**	73	64:36
4	**6** (24:74)	**14**	84	28:72
5	**7** (38:62)	**15**	86	25:75
6	**8** (0:100)	**16**	74	0:100
7	**8** (96:4)	**16**	70	84:16
8	**9** (0:100)	**17**	89	0:100
9	**10** (34:66)	**18**	89	25:75

[a] Decarboxylation was run at 180 °C on the molten β-lactone. [b] For structure code see Scheme 1. [c] Yield of isolated material after silica gel chromatography except for entries 1–3 (allylamines), which were distilled. [d] Determined by ^{1}H NMR analysis on the isolated material, normalized to 100%, error ca. 5% of stated values.

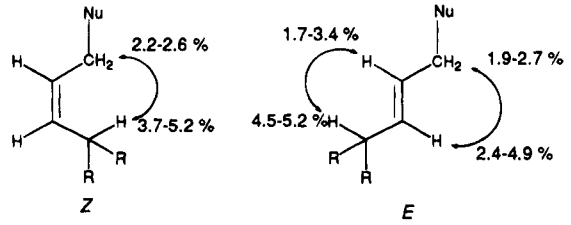


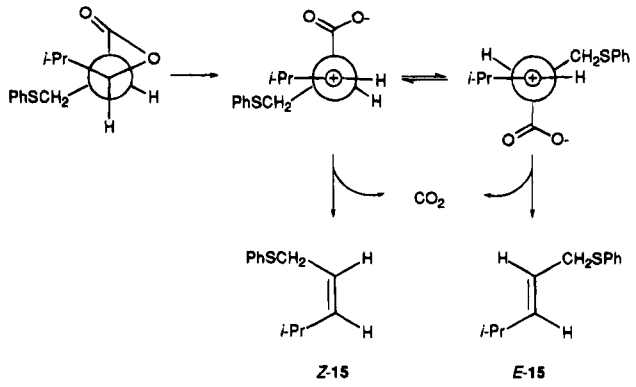
Figure 1. NOE effects *Z* and *E* isomers for the Allylamines **11–13** and sulfides **14–18**.

The configurations of the olefins were established with the help of NOE studies by irradiation of the allylic and olefinic protons (Figure 1). The *Z*:*E* diastereomeric ratios were determined by ^{1}H NMR analysis.

In accordance with previous work,[17] the majority of the decarboxylations proceeded with complete retention of the configuration, in that the *cis*/*trans* ratios of the initial β-lactones were conserved within the experimental error in the *Z*/*E* ratios of the final olefin (Scheme 1, Table 3). Thus, as expected, the *cis* β-lactone afforded stereoselectively *Z* olefin and correspondingly the *trans* β-lactone the *E* olefin.

Exceptions are the β-lactones **7**, **8**, and **10** (Table 3, entries 5, 7, and 9), for which some loss of the stereoselectivity was observed in the case of the *cis* isomers. This is particulary evident for β-lactone **8**, for which the pure *trans* isomer gave exclusively *E* olefin (Table 3, entry 6), while the enriched *cis* isomer afforded proportionally less *Z* olefin (Table 3, entry 7). A control experiment confirmed that no isomerization of the olefins nor the β-lactones took place under the decarboxylation

Scheme 5



conditions. Thus, isomerization appears to occur at the stage of the zwitterions[18] (Scheme 5).

The Newman projections make it evident that severe steric interactions between the large substituents in the *cis* isomer promote rotation around the original β-lactone C–C bond prior to decarboxylation and hence loss of stereoselectivity. In addition, neighboring group participation by the sulfide functionality may operate.

In summary, the present two-step sequence (Scheme 1), which starts from the α-methylene β-lactones **1** and **2**, constitutes an unprecedented, stereoselective synthesis of allylamines **11–13** and sulfides **14–18** through nucleophilic conjugate addition of secondary amines and thiols and subsequent decarboxylation of the resulting β-lactones **3–10**. In methanol, the diastereoselectivity in the nucleophilic conjugate addition can be quite high (*cis*/*trans* ratios up to 10:90). Since the disubstituted β-lactones **3–10** can be subsequently isomerized by lithium diisopropylamide (LDA) essentially completely to the thermodynamically preferred *trans* isomer, the *trans* diastereoselectivity can be dictated. As expected, the decarboxylation occurs with retention of configuration with some loss of diastereoselectivity for the sterically encumbered *cis* β-lactones. This methodology constitutes a useful alternative to the conventional Wittig olefination.[19]

Experimental Section

General. The IR spectra were recorded on a Perkin-Elmer 1420 instrument. ^{1}H and ^{13}C NMR spectra were run on a Bruker AC 200 (200 MHz) and 250 (250 MHz) spectrometer. Carbon multiplicities were established by DEPT and MULT experiments. Chemical shifts refer to $CDCl_3$. Mass spectra were obtained on a Varian 8200 Finnigan MAT. Elemental analyses were performed in the Analytical Division of the Institute of Inorganic Chemistry (University of Würzburg). For column chromatography, Merck silica gel (230–400 mesh) was employed. Commercial grade reagents were used without further purification except as indicated below. Pyrrolidine and piperidine were distilled from CaH_2 and acetone and CCl_4 from P_2O_5. Petroleum ether was distilled from P_2O_5, and only the fraction with bp 30–50 °C was used for column chromatography.

General Procedure for the Nucleophilic Conjugate Addition of Secondary Amines to α-Methylene β-Lac-

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tones 1 and 2. A. In Tetrahydrofuran (THF). A solution of the particular α-methylene β-lactone[20] (ca. 2.30 mmol) and the corresponding amine (ca. 2.53 mmol) in 5 mL of THF was warmed at reflux for 0.5–3 h. The reaction mixture was allowed to cool to room temperature (ca. 20 °C) and the solvent evaporated (ca. 20 °C/20 Torr). The residue was purified by Kugelrohr distillation to yield the amine adducts **3–5** in 64–76% yield (Table 1). Attempted separation of the isomers by silica gel chromatography led to decomposition of the β-lactone. The yields, physical constants, elemental analyses, and spectral data for the individual cases are described below.

B. In Methanol. The same amounts of the reactants (see procedure A) in 5 mL of CH_3OH were stirred at room temperature for 15 min, and the workup followed that of procedure A. The results are given in Table 1.

***cis*- and *trans*-4-Methyl-3-[(1-pyrrolidinyl)methyl]-1-oxetan-2-one (3).** According to general procedure A, from 219 mg (2.23 mmol) of 4-methyl-3-methyleneoxetan-2-one **(1)** and 173 mg (2.85 mmol) of pyrrolidine, 250 mg (64%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**3** was obtained as a colorless oil (40 °C/0.1 Torr). The *cis*/*trans* ratio was 66:34, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.73 (quint)] and *trans*-H [δ = 4.50 (dq)] directly on the crude product mixture: IR (CCl_4) 2940, 2900, 2780, 1810, 1370, 1340, 1270, 1190, 1110, 1015 cm^{-1}. Anal. Calcd for $C_9H_{15}NO_2$: C, 63.87; H, 8.93; N 8.27. Found: C, 63.54; H 9.13; N 8.29. *cis*-**3**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.45 (d, *J* = 6.4 Hz, 3H), 1.65–1.80 (m, 4H), 2.35–2.60 (m, 4H), 2.65 (dd, *J* = 6.0 and 12.9 Hz, 1H), 2.95 (dd, *J* = 8.7 and 12.9 Hz, 1H), 3.80 (dt, *J* = 6.2 and 8.7 Hz, 1H), 4.73 (quint, *J* = 6.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 15.8 (q), 23.5 (t), 49.5 (t), 52.6 (d), 54.2 (t), 71.9 (d), 170.7 (s). *trans*-**3**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.52 (d, *J* = 6.1 Hz, 3H), 1.65–1.80 (m, 4H), 2.35–2.60 (m, 4H), 2.83 (d, *J* = 4.8 Hz, 1H), 2.87 (d, *J* = 1.8 Hz, 1H), 3.33 (ddd, *J* = 4.0, 5.6 and 8.6 Hz, 1H), 4.50 (dq, *J* = 4.0 and 6.1 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 20.1 (q), 23.5 (t), 53.3 (t), 54.4 (t), 57.8 (d), 74.4 (d), 170.1 (s).

***cis*- and *trans*-4-(1-Methylethyl)-3-[(1-pyrrolidinyl)-methyl]-1-oxetan-2-one (4).** According to general procedure A, by starting from 300 mg (2.38 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one **(2)** and 203 mg (2.85 mmol) of pyrrolidine, 355 mg (76%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**4** was obtained as a colorless oil (90 °C/0.1 Torr). The *cis*/*trans* ratio was 73:27, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.18 (dd)] and *trans*-H [δ = 4.11 (dd)] directly on the crude product mixture: IR (CCl_4) 2980, 2890, 2810, 1840, 1475, 1400, 1360, 1280, 1125, 900 cm^{-1}. Anal. Calcd for $C_{11}H_{19}NO_2$: C, 66.97; H, 9.70; N, 7.10. Found: C, 66.58; H, 9.30; N, 7.49. *cis*-**4**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.02 (d, *J* = 6.6 Hz, 3H), 1.07 (d, *J* = 6.5 Hz, 3H), 1.65–1.81 (m, 4H), 1.99 (dsept, *J* = 6.5 and 10.2 Hz, 1H), 2.40–2.65 (m, 4H), 2.69 (dd, *J* = 6.3 and 12.9 Hz, 1H), 3.08 (dd, *J* = 7.6 and 12.9 Hz, 1H), 3.85 (dt, *J* = 6.3 and 7.6 Hz, 1H), 4.18 (dd, *J* = 6.2 and 10.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.9 (q),18.9 (q), 23.6 (t), 28.7 (d), 52.1 (d), 54.2 (t), 54.6 (t), 80.5 (d), 171.1 (s). *trans*-**4**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.98 (d, *J* = 6.8 Hz, 3H), 1.04 (d, *J* = 6.6 Hz, 3H), 1.65–1.81 (m, 4H), 1.99 (dsept, *J* = 6.5 and 7.7 Hz, 1H), 2.40–2.65 (m, 4H), 2.81 (dd, *J* = 6.2 and 12.8 Hz, 1H), 2.92 (dd, *J* = 7.4 and 12.8 Hz, 1H), 3.41 (ddd, *J* = 4.0, 6.2 and 7.5 Hz, 1H), 4.11 (dd, *J* = 4.0 and 7.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.0 (q), 17.7 (q), 23.6 (t), 32.0 (d), 49.9 (t), 53.6 (t), 54.2 (d), 81.7 (d), 170.8 (s).

***cis*- and *trans*-4-(1-Methylethyl)-3-[(1-piperidinyl)-methyl]-1-oxetan-2-one (5).** According to general procedure A, from 300 mg (2.38 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one **(2)** and 243 mg (2.85 mmol) of piperidine, 345 mg (69%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**5** was obtained as a colorless oil (110 °C/0.1 Torr). The *cis*/*trans* ratio was 77:23, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.17 (dd)] and *trans*-H [δ = 4.03 (dd)] directly on the crude product mixture: IR (CCl_4) 2980, 2960, 2870, 2820, 1840, 1475, 1450, 1280, 1125, 870 cm^{-1}. Anal. Calcd for $C_{12}H_{21}NO_2$: C, 68.21; H, 10.02; N 6.63. Found: C, 68.57; H, 10.47; N 6.87. *cis*-**5**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.01 (d, *J* = 6.5 Hz, 3H), 1.05 (d, *J* = 6.4 Hz, 3H), 1.30–1.62 (m, 6H), 1.97 (dsept, *J* = 6.6 and 10.0 Hz, 1H), 2.20–2.58 (m, 4H), 2.58 (dd, *J* = 5.8 and 13.4 Hz, 1H), 2.82 (dd, *J* = 7.5 and 13.4 Hz, 1H), 3.86 (dt, *J* = 6.0 and 7.5 Hz, 1H), 4.17 (dd, *J* = 6.3 and 10.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz δ 18.0 (q), 18.7 (q), 24.0 (t), 25.8 (t), 28.6 (d), 50.8 (d), 52.9 (t), 54.5 (t), 80.5 (d), 171.4 (s). *trans*-**5**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.97 (d, *J* = 6.8 Hz, 3H), 1.04 (d, *J* = 6.6 Hz, 3H), 1.30–1.62 (m, 6H), 1.97 (dsept, *J* = 6.5 and 7.9 Hz, 1H), 2.20–2.58 (m, 4H), 2.69 (d, *J* = 6.6 Hz, 1H), 2.70 (d, *J* = 7.4 Hz, 1H), 3.42 (ddd, *J* = 4.0, 6.7 and 7.3 Hz, 1H), 4.03 (dd, *J* = 4.0 and 7.9 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.0 (q), 17.8 (q), 23.4 (t), 25.8 (t), 32.1 (d), 50.8 (d), 54.8 (t), 56.6 (t), 82.1 (d), 170.9 (s).

General Procedure for the Nucleophilic Conjugate Addition of Thiols to α-Methylene β-Lactones 1 and 2. C. In Aprotic Solvents. A solution of the particular α-methylene β-lactone[20] (1.02–1.59 mmol) and the corresponding thiol (1.02 to 1.74 mmol) in 5 mL of CCl_4 or acetone was added 20.0 mg (0.190 mmol) of triethylamine. The reaction mixture was stirred for 1–96 h at room temperature (ca. 20 °C). The solvent was evaporated (ca. 20 °C/20 Torr), and the residue was purified by column chromatography on silica gel to yield the thiol adducts **6–10** in 91–99% (Table 2). The yields, elemental analyses, and spectral data for the individual cases are described below.

D. In Methanol. The same amounts of the reactants (see procedure C) in 5 mL of CH_3OH were stirred at room temperature (ca. 20 °C) for 1 h, and the workup followed that of procedure C. The results are given in Table 2.

***cis*- and *trans*-4-Methyl-3-[(phenylthio)methyl]-1-oxetan-2-one (6).** According to general procedure C, from 100 mg (1.02 mmol) of 4-methyl-3-methyleneoxetan-2-one **(1)** and 112 mg (1.02 mmol) thiophenol, 152 mg (72%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**6** was obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as a pale yellow oil. The *cis*/*trans* ratio was 26:74, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.92 (quint)] and *trans*-H [δ = 4.63 (dq)] directly on the crude product mixture: IR (CCl_4) 3050, 2960, 2900, 1805, 1570, 1465, 1420, 1265, 1110, 1015 cm^{-1}. Anal. Calcd for $C_{11}H_{12}SO_2$: C, 63.43; H, 5.76. Found: C, 63.67; H, 5.81. *cis*-**6**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.68 (d, *J* = 6.4 Hz, 3H), 3.20–3.37 (m, 1H), 3.43–3.60 (m, 1H), 3.96 (ddd, *J* = 5.1, 6.3 and 11.4 Hz, 1H), 4.92 (quint, *J* = 6.4 Hz, 1H), 7.35–7.58 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 15.4 (q), 28.0 (t), 51.7 (d), 71.8 (d), 127.4 (d), 129.2 (d), 130.8 (d), 133.7 (s), 169.3 (s). *trans*-**6**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.62 (d, *J* = 6.1 Hz, 3H), 3.20–3.37 (m, 1H), 3.43–3.6 (m, 2H), 4.63 (dq, *J* = 3.6 and 6.1 Hz, 1H), 7.35–7.58 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ = 20.1 (q), 31.9 (t), 56.8 (d), 74.8 (d), 127.4 (d), 129.2 (d), 130.8 (d), 133.6 (s), 169.1 (s).

***cis*- and *trans*-4-(1-Methylethyl)-3-[(phenylthio)methyl]-1-oxetan-2-one[2] (7).** According to general procedure C, from 200 mg (1.59 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one **(2)** and 192 mg (1.74 mmol) of thiophenol, 350 mg (99%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**7** was obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as a pale yellow oil. The *cis*/*trans* ratio was 45:55, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.14 (dd)] and *trans*-H [δ = 4.03 (dd)] directly on the crude product mixture. The spectral data were in agreement with the reported data.[2]

***cis*- and *trans*-4-(1-Methylethyl)-3-[[(1-methylethyl)-thio]methyl]-1-oxetan-2-one (8).** According to general procedure C, from 200 mg (1.59 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one **(2)** and 181 mg (2.38 mmol) of 1-methylethylmercaptan, 126 mg of *cis*-**8** and 161 mg of *trans*-**8** (total 91%) were obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as pale yellow oils. The *cis*/*trans* ratio was 44:56, as determined by NMR analysis of the

(20) The α-methylene β-lactones were prepared according to the procedures described in the literature; see refs 1 and 5.

characteristic β-lactone protons *cis*-H [δ = 4.19 (dd)] and *trans*-H [δ = 4.08 (dd)] directly on the crude product mixture. *cis*-**8**: IR (CCl_4) 2940, 2900, 1810, 1450, 1380, 1360, 1260, 1110, 990, 880 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 1.02 (d, J = 6.6 Hz, 3H), 1.08 (d, J = 6.5 Hz, 3H), 1.28 (d, J = 6.7 Hz, 3H), 1.29 (d, J = 6.7, 3H), 2.06 (dsept, J = 6.6 and 10.2 Hz, 1H), 2.86 (dd, J = 8.2 and 13.5 Hz, 1H) , 2.96 (dd, J = 6.5 and 13.5 Hz, 1H), 3.01 (sept, J = 6.7 Hz, 1H), 3.85 (dt, J = 6.4 and 8.2 Hz, 1H), 4.19 (dd, J = 6.2 and 10.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 18.3 (q), 18.9 (q), 23.1 (q), 23.2 (q), 24.3 (t), 28.7 (d), 36.1 (d), 53.1 (d), 80.6 (d), 170.3 (s). Anal. Calcd for $C_{10}H_{18}SO_2$: C, 59.37; H, 8.96. Found: C, 59.48; H, 8.96. *trans*-**8**: IR (CCl_4) 2940, 2900, 1810, 1450, 1250, 1230, 1110, 880, 850 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 1.00 (d, J = 6.8 Hz, 3H), 1.06 (d, J = 6.6 Hz, 3H), 1.27 (d, J = 6.7 Hz, 3H), 1.28 (d, J = 6.7, 3H), 1.95 (dsept, J = 6.7 and 8.0 Hz, 1H), 2.83 (dd, J = 9.5 and 13.3 Hz, 1H), 2.96 (sept, J = 6.8 Hz, 1H), 2.98 (dd, J = 5.2 and 13.2 Hz, 1H), 3.43 (ddd, J = 4.2, 5.0 and 9.4 Hz, 1H), 4.08 (dd, J = 4.0 and 8.1 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.1 (q), 17.9 (q), 23.2 (2xq), 27.9 (t), 32.1 (d), 35.7 (d), 53.9 (d), 82.6 (d), 169.8 (s). Anal. Calcd for $C_{10}H_{18}SO_2$: C, 59.37; H, 8.96. Found: C, 59.56; H 9.18.

***cis*- and *trans*-4-(1-Methylethyl)-3-[(benzylthio)methyl]-1-oxetan-2-one (9).** According to the general procedure C, from 200 mg (1.59 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one (**2**) and 217 mg (1.74 mmol) of benzylmercaptan, 168 mg of *cis*-**9** and 224 mg of *trans*-**9** (total 99%) were obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as pale yellow oils. The *cis*/*trans* ratio was 43:57, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.12 (dd)] and *trans*-H [δ = 3.98 (dd)] directly on the crude product mixture. *cis*-**9**: IR (CCl_4) 3040, 3000, 2940, 2900, 2820, 1810, 1520, 1260, 1110, 695 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.89 (d, J = 6.6 Hz, 3H), 1.01 (d, J = 6.5 Hz, 3H), 1.91 (dsept, J = 6.5 and 10.2 Hz, 1H), 2.69 (dd, J = 7.7 and 13.8 Hz, 1H) , 2.81 (dd, J = 7.1 and 13.8 Hz, 1H), 3.77 (dt, J = 6.3 and 7.4 Hz, 1H), 3.82 (d, J = 1.2 Hz, 2H), 4.12 (dd, J = 6.2 and 10.2 Hz, 1H), 7.15–7.40 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 18.1 (q), 18.8 (q), 24.6 (t), 28.5 (d), 36.8 (t), 52.5 (d), 80.3 (d), 127.2 (d), 128.6 (d), 128.9 (d), 137.3 (s), 170.1 (s). Anal. Calcd for $C_{14}H_{18}SO_2$: C, 67.10; H, 7.24. Found: C, 67.48; H, 7.58. *trans*-**9**: IR (CCl_4) 3060, 3040, 3000, 2940, 2900, 1810, 1530, 1240, 1105 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.96 (d, J = 6.8 Hz, 3H), 1.02 (d, J = 6.6 Hz, 3H), 1.91 (dsept, J = 6.8 and 7.8 Hz, 1H), 2.73 (dd, J = 8.9 and 13.6 Hz, 1H), 2.83 (dd, J = 5.4 and 13.6 Hz, 1H), 3.34 (ddd, J = 3.9, 5.2 and 9.1 Hz, 1H), 3.77 (s, 2H), 3.98 (dd, J = 4.0 and 8.0 Hz, 1H), 7.15–7.40 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.1 (q), 17.8 (q), 28.5 (t), 32.0 (d), 36.8 (t), 53.6 (d), 82.3 (d), 127.4 (d), 128.7 (d), 128.9 (d), 137.4 (s), 169.7 (s). Anal. Calcd for $C_{14}H_{18}SO_2$: C, 67.10; H, 7.24. Found: C, 67.37; H 7.53.

***cis*- and *trans*-4-(1-Methylethyl)-3-[[(2-hydroxyethyl)thio]methyl]-1-oxetan-2-one (10).** According to general procedure C, from 200 mg (1.59 mmol) of 4-(1-methylethyl)-3-methyleneoxetan-2-one (**2**) and 136 mg (1.74 mmol) of 2-mercaptoethanol, 320 mg (99%) of a mixture (not separable by TLC on silica gel in various solvents) of *cis*- and *trans*-**10** was obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (3:1)] as a pale yellow oil. The *cis*/*trans* ratio was 25:75, as determined by NMR analysis of the characteristic β-lactone protons *cis*-H [δ = 4.12 (dd)] and *trans*-H [δ = 4.02 (dd)] directly on the crude product mixture: IR (CCl_4) 3500, 2940, 2900, 1810, 1450, 1380, 1110, 1050, 880 cm^{-1}. Anal. Calcd for $C_9H_{16}SO_3$: C, 52.91; H, 7.89. Found: C, 53.18; H, 7.89. *cis*-**10**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.92 (d, J = 6.6 Hz, 3H), 1.01 (d, J = 6.4 Hz, 3H), 1.98 (dsept, J = 6.6 and 10.7 Hz, 1H), 2.18 (br s, exchangeable with D_2O, 1H), 2.70–3.00 (m, 4H), 3.71 (t, J = 5.8 Hz, 2H), 3.85 (dt, J = 6.3 and 7.4 Hz, 1H), 4.12 (dd, J = 6.3 and 10.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 18.1 (q), 18.9 (q), 25.7 (t), 28.7 (d), 36.1 (t), 53.0 (d), 60.8 (t), 80.4 (d), 170.4 (s). *trans*-**10**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.93 (d, J = 6.8 Hz, 3H), 0.99 (d, J = 6.6 Hz, 3H), 1.91 (dsept, J = 6.8 and 8.1 Hz, 1H), 2.18 (br s, exchangeable with D_2O, 1H), 2.70–3.00 (m, 4H), 3.43 (ddd, J = 4.0, 5.4 and 8.4 Hz, 1H), 3.71 (t, J = 5.8 Hz, 2H), 4.02 (dd, J = 4.0 and 8.1 Hz, 1H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 17.0 (q), 17.8 (q), 29.2 (t), 32.1 (d), 35.7 (t), 54.0 (d), 60.8 (t), 82.2 (d), 169.7 (s).

General Procedure E for the Decarboxylation of the β-Lactones 3–10 to the Allylamines 11–13 and Sulfides 14–18. The particular β-lactone (0.25–0.75 mmol) was placed into a round-bottomed flask, provided with a condenser and a bubble counter. The flask was heated in an oil bath at 170 °C at atmospheric pressure until cessation of carbon dioxide evolution. The allylamines **11–13** were purified by distillation at reduced pressure, since attempted separation of the isomers by silica gel chromatography led to decomposition of the allylamines and the sulfides **14–18** by column chromatography (silica gel). Yields are given in Table 3, and the physical constants, elemental analyses and the spectral data are described below for the individual cases.

(*Z*)- and (*E*)-1-(1-Pyrrolidinyl)-2-butene[21] (11). According to general procedure E, from 171 mg (1.01 mmol) of *cis,trans*-**3** (d.r. 57:43), 64.0 mg (51%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**11** was obtained as a colorless liquid (20 °C/0.1 Torr). The *Z*/*E* ratio was 56:44, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.22 (d)] and (*E*)-1-H [δ = 3.11 (d)] directly on the crude product mixture. The spectral data were in agreement with the reported data.[21]

(*Z*)- and (*E*)-4-Methyl-1-(1-pyrrolidinyl)-2-pentene (12). According to general procedure E, from 145 mg (0.730 mmol) of *cis,trans*-**4** (d.r. 10:90), 56.0 mg (56%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**12** was obtained as a colorless liquid (60 °C/0.1 Torr). The *Z*/*E* ratio was 10:90, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.18 (d)] and (*E*)-1-H [δ = 3.08 (d)] directly on the crude product mixture: IR (CCl_4) 3070, 2940, 2850, 1675, 1630, 1455, 1250, 1035, 945, 905, 860 cm^{-1}. Anal. Calcd for $C_{10}H_{19}N$: C, 78.36; H, 12.49; N, 9.13. Found: C, 78.16; H, 12.65; N 9.04. *Z*-**12**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.98 (d, J = 6.6 Hz, 6H), 1.72–1.90 (m, 4H), 2.47–2.60 (m, 4H), 2.67 (dsept, J = 6.6 and 8.8 Hz, 1H), 3.18 (d, J = 6.5 Hz, 2H), 5.30–5.70 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 23.0 (q,), 23.4 (t), 26.7 (d), 52.5 (t), 53.9 (t), 124.3 (d), 139.5 (d). *E* -**12**: ^1H NMR ($CDCl_3$, 250 MHz) δ 1.01 (d, J = 6.8 Hz, 6H), 1.72–1.90 (m, 4H), 2.30 (oct, J = 6.6 Hz, 1H), 2.47–2.60 (m, 4H), 3.08 (d, J = 5.5 Hz, 2H), 5.30–5.70 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.3 (q), 23.4 (t), 30.8 (d), 53.7 (t), 58.2 (t), 124.1 (d), 140.6 (d).

(*Z*)- and (*E*)-4-Methyl-1-(1-piperidinyl)-2-pentene (13). According to general procedure E, from 104 mg (0.490 mmol) of *cis,trans*-**5** (d.r. 66:34), 40.0 mg (49%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**13** was obtained as a colorless liquid (60 °C/0.1 Torr). The *Z*/*E* ratio was 64:36, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 2.98 (d)] and (*E*)-1-H [δ = 2.88 (d)] directly on the crude product mixture: IR (CCl_4) 3070, 2920, 2840, 1665, 1455, 1290, 1100, 985, 965, 860 cm^{-1}; MS (EI) *m*/*z* (relative intensity) = 167 (M^+, 14), 84 (100); HRMS (EI) calcd for $C_{11}H_{21}N$ 167.16739, found 167.16684. (*Z*)-**13**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.93 (d, J = 6.6 Hz, 6H),1.35–1.52 (m, 2H), 1.52–1.67 (m, 4H), 2.29 (oct, J = 6.8 Hz, 1H), 2.29–2.50 (m, 4H), 2.98 (d, J = 6.4 Hz, 2H), 5.25–5.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.9 (q), 24.3 (t), 25.9 (t), 26.2 (d), 54.5 (t), 55.9 (t), 123.8 (d), 141.3 (d). (*E*)-**13**: ^1H NMR ($CDCl_3$, 250 MHz) δ 098 (d, J = 6.8 Hz, 6H), 1.35–1.52 (m, 2H), 1.52–1.67 (m, 4H), 2.29–2.50 (m, 4H), 2.61 (dsept, J = 1.7 and 6.7 Hz, 1H), 2.88 (d, J = 5.8 Hz, 2H), 5.25–5.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.4 (q), 24.4 (t), 25.9(t), 30.8 (d), 54.3 (t), 61.7 (t), 123.5 (d), 140.2 (d).

(*Z*)- and (*E*)-1-(Phenylthio)-2-butene[9j] (14). According to general procedure E, from 97.0 mg (0.470 mmol) of *cis,trans*-**6** (d.r. 26:74), 64.0 mg (84%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**14** was obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (95:5)] as a pale yellow oil. The *Z*/*E* ratio was 28:72, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.75 (d)] and (*E*)-

(21) Castro, B.; Selve, C. *Bull. Soc. Chim. Fr.* **1971**, 4368–4373.

1-H [δ = 3.68 (d)] directly on the crude product mixture. The spectral data were in agreement with the reported data.[9j]

(*Z*)- and (*E*)-4-Methyl-1-(phenylthio)-2-pentene (15). According to the general procedure E, from 100 mg (0.420 mmol) of *cis,trans*-**7** (d.r. 38:62), 70.0 mg (86%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**15** was obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as a colorless oil. The *Z*/*E* ratio was 25:75, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.50 (d)] and (*E*)-1-H [δ = 3.40 (d)] directly on the crude product mixture: IR (CCl_4) 3050, 3000, 2940, 2900, 1570, 1470, 1085, 1020, 960, 690 cm^{-1}. Anal. Calcd for $C_{12}H_{16}S$: C, 74.97; H, 8.38. Found: C, 74.76; H, 8.16. (*Z*)-**15**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.80 (d, J = 6.6Hz, 6H), 2.48 (dsept, J = 6.6 and 8.8 Hz, 1H), 3.50 (d, J = 6.6 Hz, 2H), 5.20–5.45 (m, 2H), 7.05–7.45 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.9 (q), 26.6 (d), 30.8 (t), 121.9 (d), 126.1 (d), 127.1 (d), 130.1 (d), 136.1 (s), 141.0 (d). (*E*)-**15**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.85 (d, J = 6.8 Hz, 6H), 2.48 (oct, J = 6.6 Hz, 1H), 3.40 (d, J = 5.2 Hz, 2H), 5.20–5.45 (m, 2H), 7.05–7.45 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.2 (q), 29.7 (d), 36.7 (t), 127.5 (d), 128.6 (d), 129.0 (d), 130.2 (d), 137.0 (s), 141.5 (d).

(*Z*)- and (*E*)-4-Methyl-1-[(1-methylethyl)thio]-2-pentene (16). According to general procedure E, from 65.0 mg (0.320 mmol) of *cis,trans*-**8** (d.r. 96:4), 30.0 mg of (*Z*)-**16** and 5.0 mg of (*E*)-**16** (total 70%) were obtained after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (95:5)] as colorless liquids. The *Z*/*E* ratio was 84:16, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.19 (d)] and (*E*)-1-H [δ = 3.12 (d)] directly on the crude product mixture. (*Z*)-**16**: IR (CCl_4) 3020, 3000, 2940, 2900, 2840, 1450, 1370, 1350, 900, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.96 (d, J = 6.6 Hz, 6H), 1.27 (d, J = 6.7 Hz, 6H), 2.62 (dsept, J = 6.5 and 8.7 Hz, 1H), 2.90 (sept, J = 6.7 Hz, 1H), 3.19 (d, J = 6.4 Hz, 2H), 5.20–5.37 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 23.2 (q), 23.3 (q), 26.5 (d) 27.5 (t), 34.2 (d), 123.4 (d), 139.7 (d). Anal. Calcd for $C_{19}H_{18}S$: C, 68.28; H, 11.46. Found: C, 67.92; H, 11.44. (*E*)-**16**: IR (CCl_4) 3020, 3000, 2940, 2900, 1640, 1450, 1350, 1230, 960, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.97 (d, J = 6.7 Hz, 6H), 1.23 (d, J = 6.7 Hz, 6H), 2.27 (oct, J = 6.7 Hz, 1H), 2.85 (sept, J = 6.7 Hz, 1H), 3.12 (d, J = 5.3 Hz, 2H), 5.25–5.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.4 (q), 23.1 (q), 30.8 (d) 32.9 (t), 33.5 (d), 123.2 (d), 140.2 (d). Anal. Calcd for $C_{19}H_{18}S$: C, 68.28; H, 11.46. Found: C, 68.10; H 11.80.

(*E*)-4-Methyl-1-(benzylthio)-2-pentene (17). According to general procedure E, from 100 mg (0.400 mmol) of *trans*-**9**, there was obtained 72.0 mg of (*E*)-**17** (86%) after column chromatography [silica gel; petroleum ether/CH_2Cl_2 (1:1)] as a colorless oil: IR (CCl_4) 3040, 3000, 2930, 2900, 1585, 1480, 1450, 1210, 960, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.93 (d, J = 6.7 Hz, 6H), 2.25 (oct, J = 6.7 Hz, 1H), 2.93 (d, J = 6.5 Hz, 2H), 3.57 (s, 2H), 5.20–5.50 (m, 2H), 7.10–7.30 (m, 5H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.5 (q), 30.9 (d), 33.3 (t), 34.7 (t), 122.6 (d), 126.8 (d), 128.4 (d), 128.9 (d), 138.5 (s), 141.3 (d). Anal. Calcd for $C_{13}H_{18}S$: C, 75.66; H, 8.79. Found: C, 75.42; H, 8.96.

(*Z*)- and (*E*)-4-Methyl-1-[(hydroxyethyl)thio]-2-pentene (18). According to general procedure E, from 100 mg (0.490 mmol) of *cis,trans*-**10** (d.r. 34:66), 70.0 mg (89%) of a mixture (not separable by TLC on silica gel in various solvents) of (*Z*)- and (*E*)-**18** was obtained after column chromatography (silica gel; CH_2Cl_2) as a colorless oil. The *Z*/*E* ratio was 25:75, as determined by NMR analysis of the characteristic allylic protons (*Z*)-1-H [δ = 3.12 (d)] and (*E*)-1-H [δ = 3.02 (d)] directly on the crude product mixture: IR (CCl_4) 3620, 3520, 3015, 2945, 2915, 1645, 1455, 1375, 1055, 965, 890 cm^{-1}. Anal. Calcd for $C_8H_{16}SO$: C, 59.95; H, 10.06. Found: C, 59.95; H, 10.33. (*Z*)-**18**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.90 (d, J = 6.7 Hz, 6H), 2.07 (br s, exchangeable with D_2O, 1H), 2.51 (dsept, J = 6.6 and 8.9 Hz, 1H), 2.63 (t, J = 6.7 Hz, 2H), 3.12 (d, J = 6.7 Hz, 2H), 3.65 (t, J = 5.3 Hz, 2H), 5.16–5.31 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 23.1 (q), 26.5 (d), 28.0 (t), 29.6 (t), 53.4 (t), 122.6 (d), 140.7 (d). (*E*)-**18**: ^1H NMR ($CDCl_3$, 250 MHz) δ 0.93 (d, J = 6.8 Hz, 6H), 2.07 (br s, exchangeable with D_2O, 1H), 2.24 (oct, J = 6.7 Hz, 1H), 2.61 (t, J = 6.0 Hz, 2H), 3.02 (d, J = 6.9 Hz, 2H), 3.63 (t, J = 5.9 Hz, 2H), 5.31–5.50 (m, 2H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 22.4 (q), 30.8 (d), 33.7 (t), 33.6 (t), 60.1 (t), 122.6 (d), 141.3 (d).

Formation of (*E*)-4-Methyl-2-[(phenylthio)methyl]-2-pentenoic Acid (20) in the Sodium Thiophenolate Addition to 4-(1-Methylethyl)-3-methyleneoxetan-2-one (2). A 50-mL, three-necked, round-bottomed flask, equipped with two rubber septa and an argon inlet adapter, was charged with 9.5 mg (0.390 mmol) of NaH in 5 mL of THF. The reaction mixture was cooled by means of an ice bath, and 43.7 mg (0.390 mmol) of thiophenol in 1 mL of THF was added dropwise with a syringe over 2 min. After ca. 10 min, the ice bath was replaced with a dry ice–acetone bath (−30 °C), and 50.0 mg (0.390 mmol) of **2** in 1 mL of THF was added dropwise by means of a cannula over 5 min. The resulting solution was stirred at −30 °C for 15 min, allowed to warm to room temperature (ca. 20 °C), and after 15 min treated with 10 mL of saturated NH_4Cl solution. The resulting mixture was extracted with diethyl ether (2 × 20 mL), and the combined organic phases were dried over $MgSO_4$ and concentrated. Purification of the residue by column chromatography [silica gel; CH_2Cl_2/ethyl acetate (1:1)] provided 35.0 mg of **7** and 24.0 mg of pentenoic acid **20** (total 35%) as pale yellow oils. The major product was the *E* isomer, and only traces (<5%) of the *Z* isomer were detected. (*E*)-**20**: IR (CCl_4) 3500–2400, 3040, 2930, 1660, 1620, 1430, 1245, 860, 690 cm^{-1}; ^1H NMR ($CDCl_3$, 250 MHz) δ 0.82 (d, J = 6.3 Hz, 6H), 2.40 (dsept, J = 6.5 and 10.5 Hz, 1H), 3.74 (s, 2H), 6.70 (d, J = 10.5 Hz, 1H), 7.10–7.50 (m, 6H); ^{13}C NMR ($CDCl_3$, 63 MHz) δ 19.9 (q), 26.5 (d), 27.7 (t), 123.2 (s), 125.1 (d), 126.9 (d), 129.9 (d), 133.7 (s), 152.5 (d), 170.0 (s). Anal. Calcd for $C_{13}H_{16}SO_2$: C, 66.07; H, 6.82. Found: C, 66.14; H, 6.91.

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