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β-THIOXO ESTERS—II[a]

EVIDENCE FOR ESTER GROUP ROTAMERISM AND PERTUBATION OF THE INTRAMOLECULAR HYDROGEN-BONDING IN ENETHIOLIZED 2-THIOXO CYCLOALKANECARBOXYLIC ESTERS

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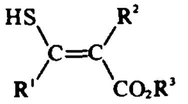
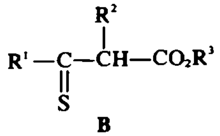
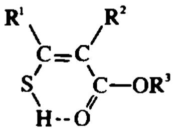
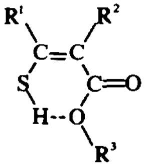
Abstract—Ethyl 2-thioxo cycloalkanecarboxylates of ring sizes 5–9 exist in CCl_4 solution in the tautomeric *cis*-enethiol form, whereas the 10–12 membered ring compounds exist as an equilibrium mixture of several tautomeric forms. On the basis of NMR and IR spectral data it is concluded that the *cis*-enethiols exist as equilibrium mixtures of two rapidly interconverting rotameric forms, one involving intramolecular H-bonding, the other having the ester group rotated through 180° so that the ester carbonyl group is unable to form an intramolecular H-bond, although still conjugated with the enethiolic double bond. The relative equilibrium concentrations at ~35° of the two rotameric *cis*-enethiol forms have been determined for all investigated compounds.

Previous NMR and IR spectroscopic studies on open-chain α-unsubstituted β-thioxo esters have shown[1,2] that such compounds exist predominantly in the tautomeric *cis*-enethiol form (C), energetically favoured with respect to the corresponding *trans*-enethiol form (A) by its ability to form a stabilising, intramolecular hydrogen-bond. In contrast, the structure of β-thioxo esters bearing an α-subsubstituent depends on the steric nature of the α-substituent.[1] Thus, a bulky group gives rise to predominance of the thione form (**B**). In the general case, however, this tautomer is of neglibible importance, and instead the *trans*-enethiol form (A) appears in appreciable amounts, the equilibrium percentages being almost comparable with those of the *cis*-enethiol form. Apparently, the steric crowding brought about by the groups R^1, R^2, and OR^3 in C counterbalances the energy gain obtained by the formation of the intramolecular hydrogen-bonding. A comparison of carbonyl band intensities in the vibrational spectra of the α-substituted compounds with NMR chemical shifts and lownrange coupling constants of the mercapto-protons of the *cis*-enethiol forms led to the conclusion that the *cis*-enethiol tautomer of α-substituted β-thioxo esters is not correctly described by the classic C-structure, but rather as an equilibrium mixture of the rotamers C and C*.[1] Evidently, conversion between C and C* is too fast to allow NMR spectroscopic distinction between the rotamers, thus giving rise to a weighted average signal shift for the *cis*-enethiolic proton. On the other hand, the conversion is still slow enough to allow for IR spectroscopic distinction, i.e. the ester carbonyl stretching vibration band of the C-rotamer is observed in the region 1675–1690 cm^{-1} (the region for a chelating, conjugated ester carbonyl group[1,2]), whereas the corresponding band of the C*-rotamer appears at a frequency 20–35 cm^{-1} higher, in the region characteristic for stretching vibrations of common conjugated ester carbonyl groups. It should be noted that C–C* rotamerism is absent or at least unimportant in the case of the α-unsubstituted esters ($R^2 = H$), in which no steric crowding exist, as the intensities of the relevant ester carbonyl stretching vibration bands agree perfectly with the percentages of the A and C isomers as calculated from NMR integrals.[1,3]


A


$$R^1-\underset{\underset{S}{\|}}{C}-\overset{\overset{R^2}{|}}{C}H-CO_2R^3$$
B


C


C*

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[a] Part I, see Ref 1.

Similarly, correspondance has been found[3] between the NMR calculated percentages of the **A** and **C** isomers of α-thioacyl lactones[4] (in which a rotameric effect is out of the question), and the intensities of the relevant carbonyl as well as the C=C double bond stretching vibration bands.

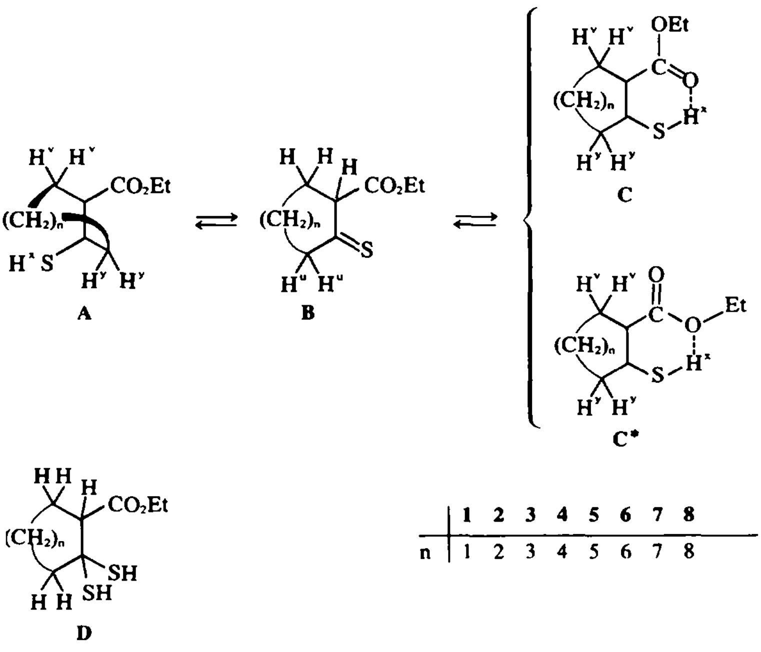
The purpose of the present work was to study the C–C* rotameric effect with special reference to a more quantitative description of the phenomenon. Regarded as a special class of β-thioxo esters, 2-thioxo cycloalkanecarboxylic esters were chosen as convenient model substances, because, leaving out of account the higher membered rings, these compounds cannot exist in the *trans*-enethiol form (**A**). Consequently, the existence of the C*-rotamer of such a compound is easily verified by the appearance of an IR ester carbonyl stretching vibration band that is unambigously assignable to a non-chelating, conjugated ester carbonyl function; the intensity of this band is related solely to the equilibrium concentration of the C*-rotamer. Similarly, the intensity of a carbonyl band, assignable to the chelating, conjugated ester carbonyl function, will reflect solely the equilibrium concentration of the C-rotamer.

RESULTS AND DISCUSSION

Preparation and tautomerism of 2-thioxo cycloalkanecarboxylic esters. The title compound **1–8** were easily synthesized by treatment of their oxygen analogs with H_2S in strongly acidic ethanolic solution, with the exception of **1**, which was generated in acidic MeCN. The general acid-catalysed reaction of β-keto esters with H_2S is now rather well-investigated,[1,5] and experience has shown that this reaction under certain conditions may lead to formation of a gem-dithiol together with, or instead of, the thione, especially when open-chain α-substituted β-keto esters are involved.[1] Ethyl 2-oxo cyclopentanecarboxylate showed no tendency at all to form a gem-dithiol, but ethyl 2-oxo cyclohexanecarboxylate reacted with H_2S in acidic MeCN to yield a mixture of **2** (~40%) and **2D** (~60%). In ethanolic solution, but otherwise under almost identical reaction conditions, the latter β-keto ester gave only **2** upon the H_2S treatment (compare Ref 1). Therefore ethanol was preferred as reaction medium for the syntheses of **3–8**. These compounds were obtained in high yields with the exception of **6–8**, the yields of which were reduced due partly to the somewhat more complicated reaction procedures involving preparative layer chromatography.

Freshly distilled, the compounds **1–8** appear as red liquids with varying intensities of the red colour, depending on the concentration of thione tautomer present. On standing in sealed flasks or ampoules, compounds **1**, **2**, and **4** turn colourless, whereas the intensities of the colours of compounds **5–8** remain practically unchanged, and **3** gradually assumes a pale red colour.

The compounds **1** and **2** have been described earlier in the literature[2,6,7] and were recently characterized as *cis*-enethiols.[2] The ^1H NMR spectra of **1–5** (data given in Table 2) are closely related in the sense that they show the existence of



	1	2	3	4	5	6	7	8
n	1	2	3	4	5	6	7	8

SCHEME 1

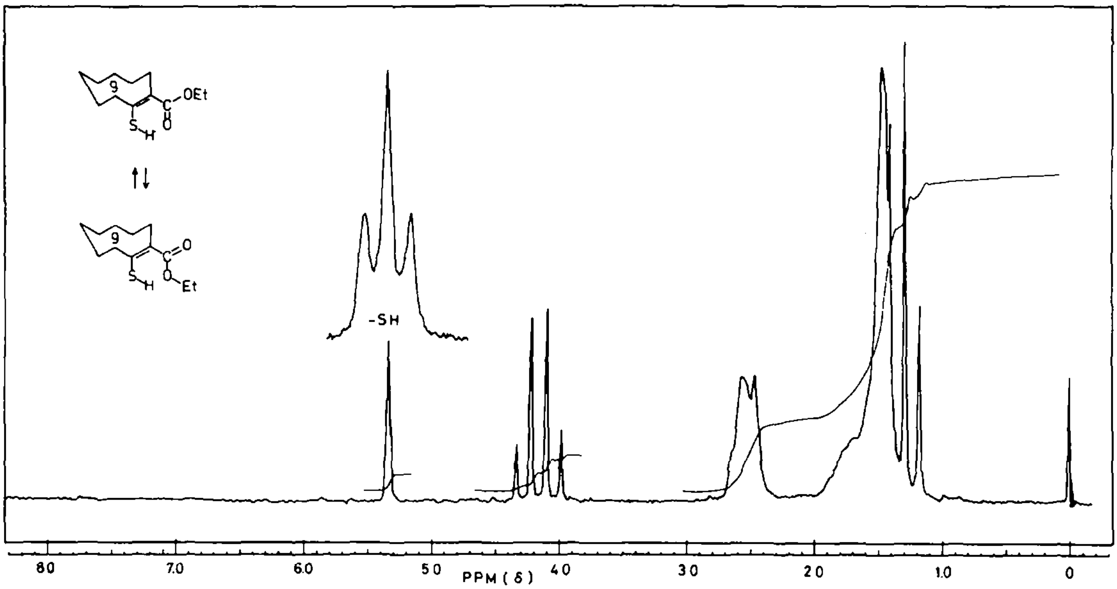


Fig 1. NMR spectrum of ethyl 2-thioxo cyclononanecarboxylate **5** demonstrating the existence of solely the *cis*-enethiol tautomer (solvent: CCl_4).

only the *cis*-enethiol tautomer, the other possible tautomers being non-existent or present in concentrations too small for detection by NMR. This is exemplified by the NMR spectrum of **5** shown in Fig 1. With respect to the medium-sized rings **6–8**, the NMR spectra (data given in Table 2) in all cases show the co-existence of several tautomeric forms. The *cis*-enethiol form is still predominating in **6** (Fig 2), but in the cases of **7** and **8**, the thione form **B** appears as the most abundant tautomer, as illustrated by the NMR spectrum of **7** (Fig 3). (See footnote on next page).

Naturally, the *trans*-enethiol form **A** is not physically feasible for the small-ring compounds **1–3**, but also with respect to the compounds **4** and **5**, this tautomer appears not to be detectable under

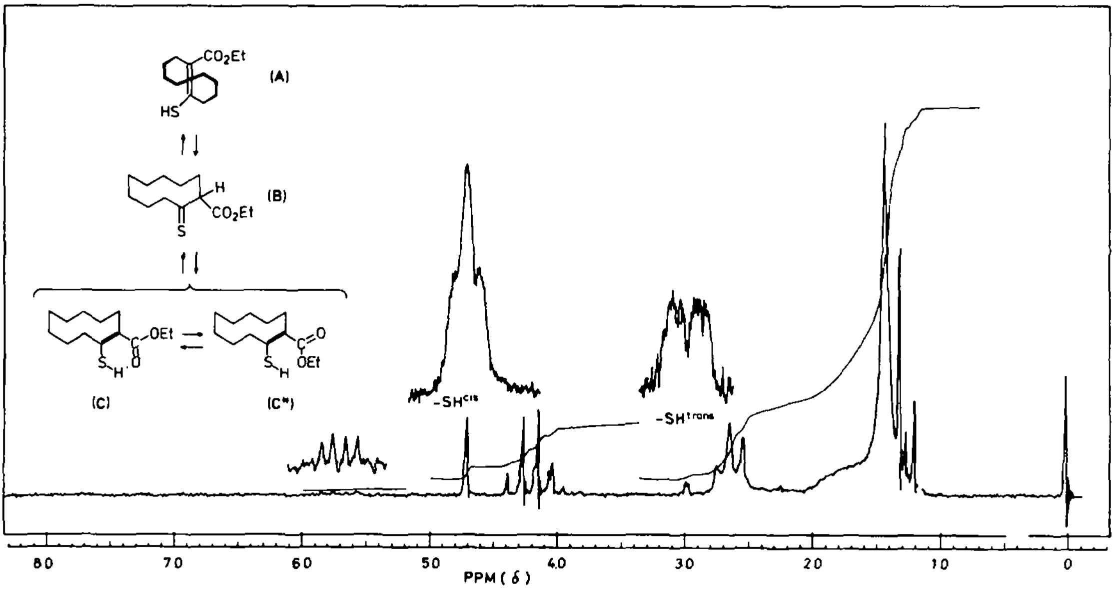


Fig 2. NMR spectrum of ethyl 2-thioxo cyclodecanecarboxylate **6** demonstrating the co-existence of several tautomeric forms (solvent: CCl_4).

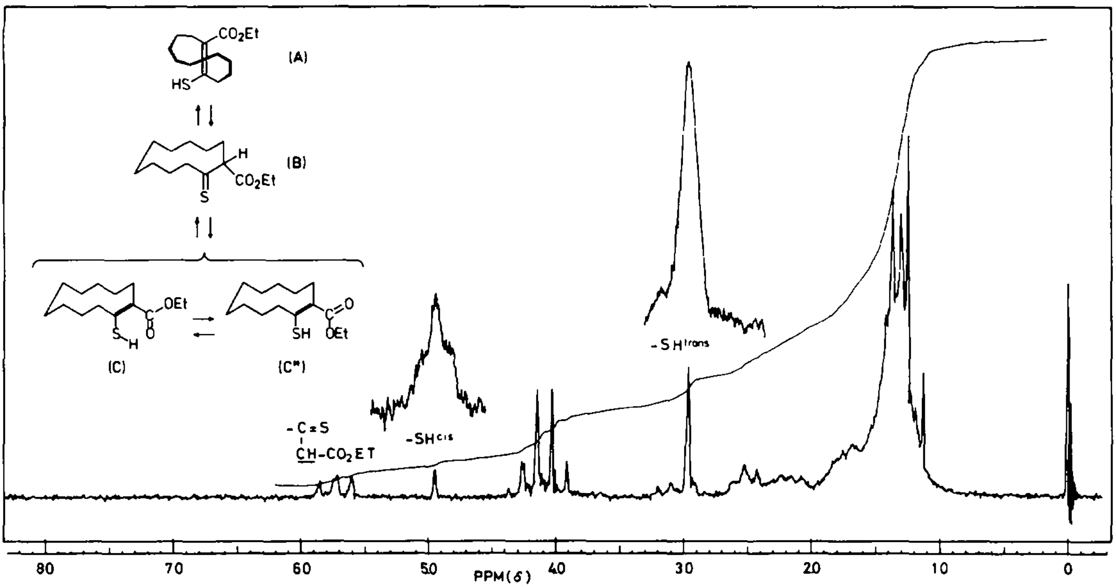


Fig 3. NMR spectrum of ethyl 2-thioxo cycloundecanecarboxylate 7 demonstrating the co-existence of several tautomeric forms (solvent: CCl_4).

equilibrium conditions. In the cases of **6–8**, however, the *trans*-enethiol form is unambigously discernible, and its equilibrium concentration is found to increase with increasing ring size. The equilibrium percentages of the tautomers as calculated from NMR integrals are for all investigated compounds given in Table 1.

NMR and IR spectra. The NMR data are listed in Table 2. Regarding those of the thione forms, the unusual low-field displacement of the methine proton (H^W) signals, which in accordance with expectations exhibit X-part structure of an ABX-system, is particularly noteworthy.‡ The mercapto-proton signal of the *trans*-enethiol forms is in the relevant cases found near $\alpha = 3$ ppm, a value that is slightly higher, but otherwise in good accordance with those found for the same protons in the related open-chain compounds.[1]

Table 1. Percentages of tautomers in equilibrium in CCl_4 solution at 35 ± 3°C, as measured from NMR integrals

	A	B	C–C*
1	—	—	100%
2	—	—[a]	100%
3	—	—[a]	100%
4	—	—	100%
5	—	—[a]	100%
6	19%	8%	73%
7	20%	57%	23%
8	29%	38%	33%

[a] Traces are detectable in the IR spectrum.

Concerning the NMR data of the *cis*-enethiol forms, the unmistakable variation in the chemical shift of the mercapto-proton ($4{\cdot}79\ \text{ppm} \leqq \delta_{SH} \leqq 6{\cdot}87\ \text{ppm}$) is of particular interest. The same shift variation was also observed for the *cis*-enethiolic protons of the open-chain α-substituted esters, and the phenomenon was a strongly contributive motive for advancing the theory concerning the occurrence of C–C* rotamerism in these compounds.[1] It is further important to notice that also the size of the coupling constant $^4J_{XY}$ displays a clear variation (see Fig 4 and Table 2), harmonizing with the variation in chemical shift mentioned above. Thus, besides effecting a weighted average chemical shift of the *cis*-enethiolic proton, the presence of the C*-rotamer (with its probably more freely rotating

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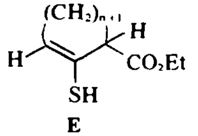
‡The assignment of this signal to the thione tautomer is tentative. According to a recent suggestion by Dr. D. Paquer (University of Caen, France), it is possible that this signal reflects the presence of another enethiol form **E** rather than the thione form **B**. A preponderant equilibrium concentration of **E** in **7** and **8** would not be inconsistent with the appearance of the intense bands at $\sim 1735\ cm^{-1}$ in the IR spectra of these compounds, as the ester carbonyl group in **E** is also non-conjugated. The mercapto–proton signal of **E** may be undistinguishable from that of the *trans*-enethiol form **A**. Hence the equilibrium percentages for the compounds **6**, **7** and **8** in Table 1 should be accepted with reservation. The ambiguity of the assignment is a subject of going investigations. I thank Dr. Paquer for his valuable suggestion.



E

Table 2. ^{1}H NMR chemical shifts (δ-values, ppm) and coupling constants (Hz) of tautomeric ethyl 2-thioxo cycloalkanecarboxylates[a]

	A	B		C–C*		A and C–C*	δ of other
	δ_{SH}[b]	δ_HW	δ_HU	δ_{SH}[b]	$^4J_{XY}$	δ_HY,δ_HV	ring-protons
1	—	—	—	6·20 s	—	2·62 t[c]	1·87 p[c]
2	—	—	—	5·23 s	—	2·1–2·6 br. m	1·5–1·9 m[d]
3	—	—	—	6·87 t	1·3	2·35–2·75 br. m	1·1–2·0 br. m[e]
4	—	—	—	6·05 t	1·25	2·35–2·70 br. m	1·1–1·9 br. m[e]
5	—	—	—	5·50 t	1·10	2·3–2·7 br. m	1·1–2·0 br. m[e]
6	2·96 d[f]	5·69 q[g]	—	4·79 t	0·6	2·64 t[c]	1·2–2·0 br. m[e]
7	2·97 s[h]	5·73 q[g]	2·9–3·3 br. m	5·05 t	0·65	2·54 t[c]	1·1–2·0 br. m[e]
8	3·02 s[h]	5·78 q[g]	2·9–3·4 br. m	5·27 t	0·75	2·3–2·7 br. m	1·1–2·0 br. m[e]

The following abbreviations are used: s (singlet), d (doublet), t (triplet), q (quartet), p (quintet), m (multiplet), and br. (broad). For further explanation of used symbols, see Scheme 1. The solvent is CCl_4.

[a] The trivial NMR data of the ester group protons are omitted. Ester group signals are coalescing for A- and B-forms (δ_{CH_2} = 4·09–4·10 ppm, δ_{CH_3} = 1·24–1·26 ppm). Ester group protons of the C-form are relatively more deshielded (δ_{CH_2} = 4·15–4·20 ppm, δ = 1·27–1·30 ppm). [b] In normally concentrated solutions, δ_{SH} is sensitive to small changes in concentration. The tabulated values are obtained by extrapolation to zero concentration.[1,2] [c] Unsymmetrical signal with a further, badly resolved fine-structure. [d] Apparently a narrow quintet signal. [e] Unsymmetrical. [f] Doublet signal with further non-resolved fine-structure. [g] X-part of ABX system. The line separations are 5·5 Hz and 11·5 Hz (**6B**), 6·8 Hz and 8·3 Hz (**7B**), and 5·5 Hz and 9·0 Hz (**8B**). [h] Relatively broad singlet, $w_{1/2}$ = 0·9 Hz (**7A**), and 1·0 Hz (**8A**).

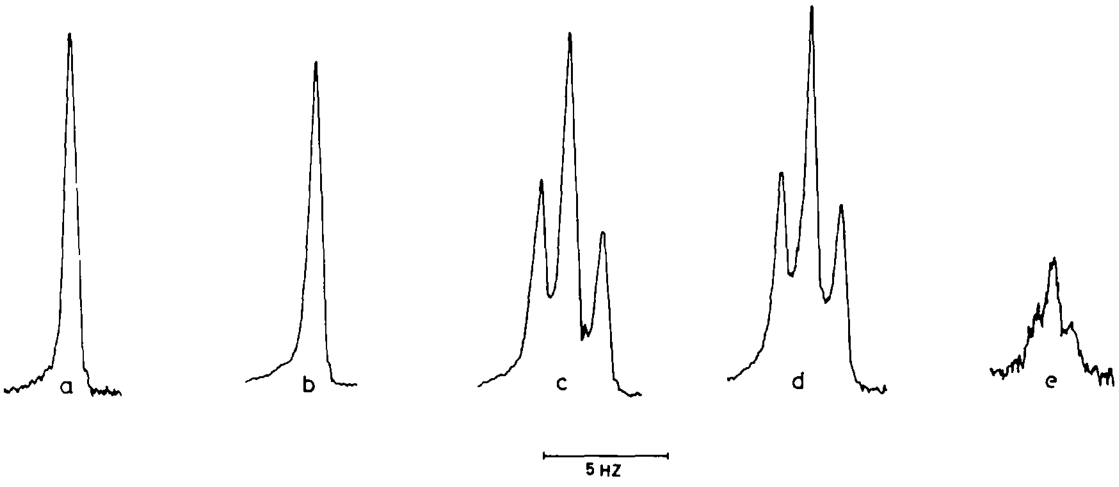


Fig 4. Mercapto-proton signals of *cis*-enethiol tautomers, taken from the NMR spectra of **1** (a), **2** (b), **3** (c), **4** (d), and **8** (e).

mercapto-group) also brings about the expected[1] reduction in the effective coupling between the mercapto-proton and the γ-protons (H^{γ}) according to the weighted average principle.

According to their NMR spectra the compounds **1–5** exist exclusively as *cis*-enethiols in CCl_4 solution. Nevertheless, the IR spectra of the same compounds in all cases show two strong carbonyl adsorption bands, one in the region of conjugated ester carbonyl stretching vibrations, the other in the region of chelating, conjugated ester carbonyl stretchings[1] (see Fig 5 and Table 3). The IR spectra were measured on 1–20% CCl_4 solutions of the compounds, i.e. under conditions identical with those under which the NMR spectra were measured (see Experimental section). Consequently, the appearance of the two C=O stretching bands cannot be the result of a tautomeric displacement, but must be due to some property connected solely with the *cis*-enethiol molecule, most probably the C–C* rotameric effect. In accordance with the increased thione percentages found in **6–8**, the IR spectra of these compounds are more or less dominated by the ester carbonyl band at 1732–1736 cm^{-1}, and the carbonyl bands originating from the other tautomers are of considerably weaker intensity, and, in the cases of **7** and **8**, present as shoulders only (Fig 5).

Intramolecularly H-bonded *cis*-enethiols that are represented solely or practically solely by the C-structure (*cis*-enethiol forms of α-unsubstituted β-thioxo esters[1] and α-thioacyl lactones[4]) display in their IR spectra the S—H stretching vibration band in the region 2420–2460 cm^{-1}, i.e. at a frequency more than 100 cm^{-1} below that region within which non-associated mercapto-groups[8] display their stretching adsorption bands (2550–2600 cm^{-1}). The IR spectra of the compounds **1–6** show bands of varying broadness and intensity in the region 2460–2500 cm^{-1} (Fig 5, Table 3). Apparently, the intramolecular H-bonding is somewhat weaker in the C-form of the open-chain esters and lactones mentioned above.† In addition to the

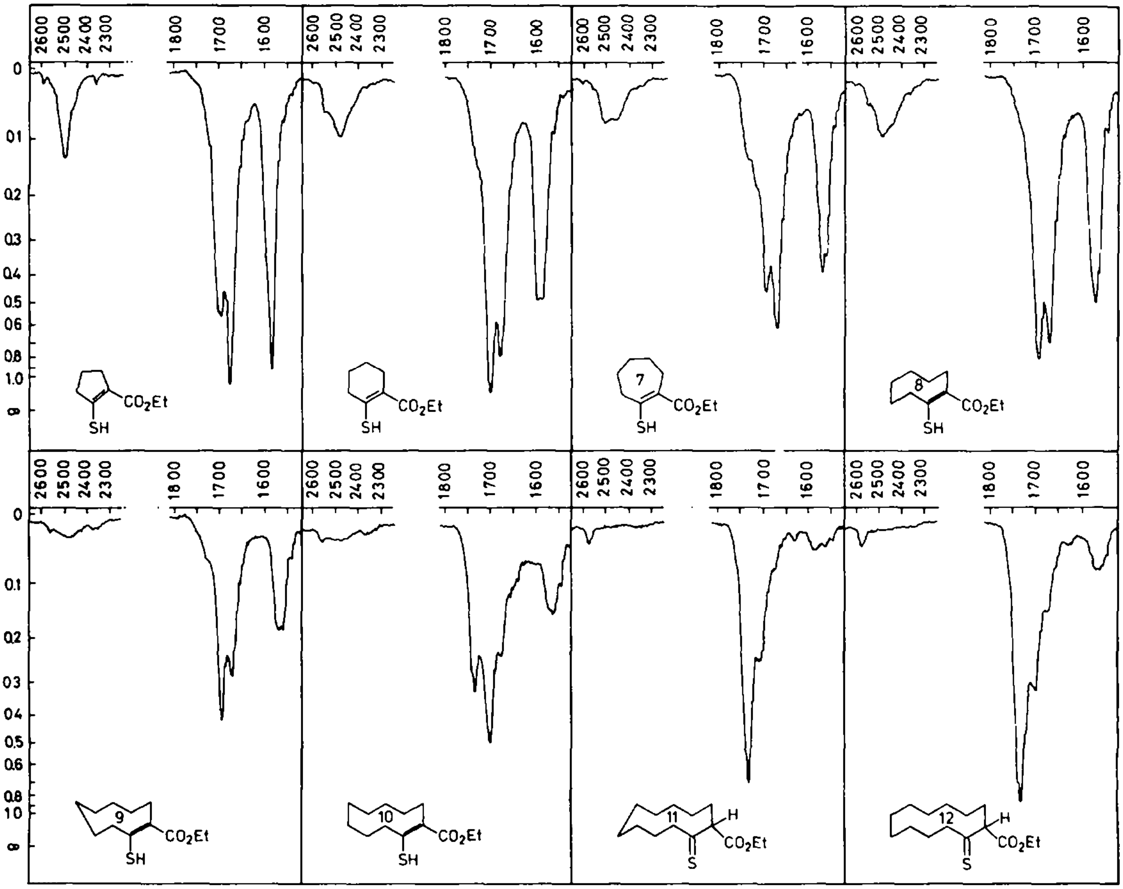


Fig 5. Regions of S—H stretching vibration bands and C=O stretching vibration bands, extracted from the IR spectra of compounds 1–8.

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†In the H-bonding system X—H . . . . . Y, the displacement against lower frequencies of the donor X—H stretching vibration band is generally accepted to reflect the strength of the H-bonding.[9]

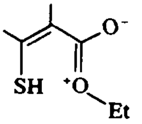
Table 3. IR absorption bands of tautomeric ethyl 2-thioxo cycloalkanecarboxylates

	ν[S–H][b]	ν[S–H][c]	ν[C=O][d]	ν[C=O][e]	ν[C=O][f]	ν[C=C][g]	ν[C=C][h]	ν[C=C][i]
1	2590 vw	2495 m	—	1698 s [0·543]	1675 s [1·03]	—	1585 s [0·88]	—
2	2550 sh, w	2485 m, br.	—	1701 s [1·22]	1679 s [0·77]	—	1595 1586 s[j] [0·46]	—
3	~2560 sh, vw	2460 m, br.[k]	1734 sh, vw	1694 s [0·464]	1671 s [0·623]	—	1570 s [0·386]	1562 sh[l]
4	2550 sh, w	2485 m, br.	—	1695 s [0·758]	1671 s [0·667]	—	1569 s [0·458]	1562 sh[l]
5	2550 sh, vw	2470 w, br.	1735 sh, vw	1697 s [0·560]	1674 s [0·379]	—	1572 s [0·234]	1562 sh[l]
6	2560 w	~2500 w, br.	1733 s [0·328]	1699 s [0·500]	1674 sh	—	1570 sh[l]	1562 m
7	2575 w	—	1732 s [0·82]	1706 sh, w	1674 sh, vw	1629 vw	~1580 w	1560 sh,vw
8	2575 w	—	1736 s [0·89]	1705 sh, m	~1680 sh, w	1632 vw	~1570 w, br.	

Frequencies are in cm^{-1}. Relative intensities are given in brackets[a] and otherwise indicated as follows: s (strong), m (medium), w (weak), vw (very weak), br. (broad), and sh (shoulder). The solvent is CCl_4.

[a] These intensities were measured on an expanded frequency scale. [b] Non-chelated mercapto-groups. [c] Chelated mercapto-groups (C-rotamer). [d] Non-chelating, non-conjugated ester carbonyl stretching (thione form). [e] Non-chelating, conjugated ester carbonyl stretchings (*trans*-enethiol form (A), or C*-rotamer of the *cis*-enethiol form). [f] Chelating, conjugated ester carbonyl stretching (*cis*-enethiol form, C-rotamer). [g] Tentatively ascribed to the *trans*-enethiol tautomer (A). [h] Tentatively ascribed to the C-rotamer of the *cis*-enethiol form. [i] Tentatively ascribed to the C*-rotamer of the *cis*-enethiol form. [j] The two bands are of equal intensity. [k] Asymmetric band with an extra maximum at ~2505 cm^{-1}. [l] This band has a slightly lower intensity than the neighbouring C=C band.

low-frequency S—H band mentioned above, the IR spectra of **1–8** in all cases display a narrow band of weak intensity in the region 2550–2575 cm^{-1}. In all probability, this band reflects the presence of a non-chelated mercapto-group (although the possibility cannot be completely excluded that it is an overtone or a combination band). Its occurrence is so far in accordance with expectations with respect to the compounds **6–8**, because, according to the NMR spectra, measurable concentrations of the *trans*-enethiol form (A) do exist in the tautomeric equilibrium mixture of these compounds. However, in the cases of **1–5**, in which the *trans*-enethiol form is definitely absent, it seems both attractive and reasonable to assign this band to the S—H stretching of the mercapto-group of the C*-rotamer. If this assignment is correct, then it must be concluded that the H-bonding in the C*-rotamer of the *cis*-enethiol form (as shown in Scheme 1) is extremely weak or non-existent. Evidently, the oxygen atom in the ethoxy-group has relatively little significance as a H-bonding acceptor. This is understandable, if the likely contribution of the resonance structure **9** to the description of the whole molecule is recognized.



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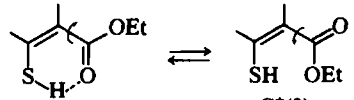
Quantitative description of the C–C* *rotameric effect.* The above discussion clearly indicates the existence of a fast conversion process between the rotameric *cis*-enethiol forms C and C*. In the following a quantitative description of this phenomenon will be attempted. Regarded as weighted average chemical shifts, the observed



C(1) C*(2)

chemical shifts of the *cis*-enethiolic protons are related to the "true" chemical shifts δ_1 (chemical shift of the mercapto-proton in C) and δ_2 (chemical shift of the mercapto-proton in C*) by the equation[10]

$$\delta_{obs} = x_1\delta_1 + x_2\delta_2 \qquad \text{(a)}$$

in which x_1 and x_2 denote the mole fractions of C and C* rotamers, respectively. Introducing $x_2 = 1 - x_1$, eq. (a) may be written

$$\delta_{obs} = x_1(\delta_1 - \delta_2) + \delta_2 \qquad \text{(b)}$$

Of the two IR carbonyl stretching vibration bands originating solely from the *cis*-enethiol tautomer, the low-frequency band is assigned to the chelating, conjugated ester carbonyl group of the C-rotamer, and the high-frequency band similarly to the non-chelating, conjugated ester carbonyl group of the C*-rotamer. It is now presumed that corresponding absorption bands within the series of the closely related cyclic compounds has approximately the same molar extinction. The same presumption may not hold with respect to carbonyl bands originating from different rotamers, because the H-bonding in the C-rotamer very probably will influence the band intensity of the chelating ester carbonyl group. Lambert-Beer's law[11] states that $A = k \cdot l \cdot c$, where A is the measured absorbance, c is the molar concentration of the specimen giving rise to the absorption, l is the path length, and k is the molar extinction coefficient. This law generally applies to IR spectra. If molar concentrations are replaced by mole fractions, then the ratio between the carbonyl band absorbances of the C-rotamer (A_1) and the C*-rotamer (A_2) for a given compound is

$$\frac{A_1}{A_2} = \frac{k_1}{k_2} \cdot \frac{x_1}{x_2}$$

Substituting $x_2 = 1 - x_1$, and solving for x_1, we obtain

$$x_1 = \frac{1}{1 + \dfrac{k_1}{k_2}\dfrac{A_2}{A_1}} \qquad \text{(c)}$$

Combination of eqs. (b) and (c) yields

$$\frac{A_1}{A_2} = \frac{k_1}{k_2}\frac{(\delta_{obs} - \delta_2)}{(\delta_1 - \delta_{obs})} \qquad \text{(d)}$$

Eq. (d) expresses the relation between the observed chemical shift of the *cis*-enethiolic proton and the calculated ratio between the measurable absorbances of the carbonyl bands of the two rotamers. Mathematically, (d) describes A_1/A_2 as a hyperbolic function of δ_{obs}, characterized by the assymptotes $A_1/A_2 = -k_1/k_2$ and $\delta_{obs} = \delta_1$, and with $\delta_{obs} = \delta_2$ marking the intersection between the hyperbola and the δ_{obs}-axis (however, only the region between δ_1 and δ_2 has physical relevance). If the idea concerning the occurrence of the rotameric effect is correct, then the curve obtained by plotting experimentally measured δ_{obs}-values against calculated absorbance ratios, A_1/A_2, must satisfy eq. (d). According to this criterion, the parameters δ_1, δ_2, and k_1/k_2 were computed from sets of observables $[\delta_{obs}, A_1/A_2]$ of the compounds **1–5**. Omitting the set of observables of **1**, the values $\delta_1 = 8{\cdot}63$ ppm, $\delta_2 = -8{\cdot}90$ ppm, and $k_1/k_2 = 0{\cdot}15$ were obtained, and neglecting observables of both **1** and **2**, the values $\delta_1 = 9{\cdot}47$ ppm, $\delta_2 = 0{\cdot}91$ ppm, and $k_1/k_2 = 0{\cdot}59$ were obtained. Fig 6 shows the correlation between the experimentally determined points and the hyperbolic curves determined by the computed parameters. With respect to the compounds **2–5** the criterion stated above is fulfilled, and conclusive evidence for the existence of the rotameric effect is thus obtained. On the other hand, the values found for δ_1 and δ_2 have only little physical relevance. The lower limit for δ_2 ought to be represented by the chemical shift of the freely rotating mercapto-group in α,β-unsaturated β-mercapto-carbonyl compounds, which, however, display the mercapto-proton signal within the range 2·7–3·2 ppm.[1,4] The highest δ-value ever reported for a C-form mercapto-proton, 8·44 ppm, is found for *cis*-2-[α-mercapto-furfurylidene]-γ-butrolactone, **10C**, in which the occurrence of C–C* rotamerism is out of the question.[4] It should, however, be noticed that

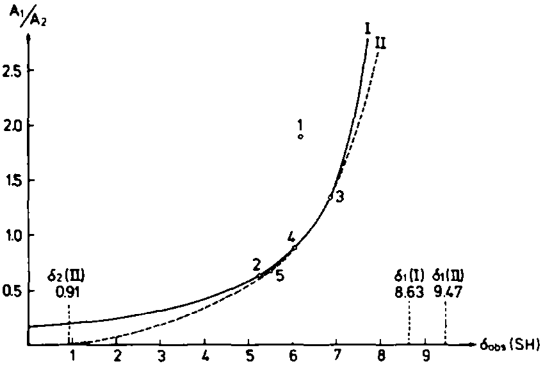
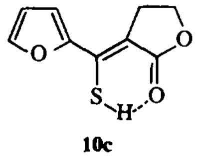


Fig 6. Correlation of experimentally determined points (numbers refer to compounds) with hyperbolas characterized by the computationally derived parameters $\delta_1 = 8{\cdot}63$ ppm, $\delta_2 = -8{\cdot}90$ ppm, $k_1/k_2 = 0{\cdot}15$ (I), and $\delta_1 = 9{\cdot}47$ ppm, $\delta_2 = 0{\cdot}91$ ppm, $k_1/k_2 = 0{\cdot}59$ (II).



10c

eq. (d) has been derived under the presumptions that (i) the screening of the mercapto-proton effected by the intramolecular surroundings is the same for all cyclic enethiols under investigation, (ii) the δ_1-value is the same for all these compounds, i.e. the respective H-bondings are all of equal strength, and (iii) the acidities of the enethiols, and hence the tendencies of the mercapto-protons to undergo intermolecular exchange, are the same for all compounds in question. Concerning the second presumption, the differences in the S—H stretching vibration frequencies of the intramolecularly H-bonded mercapto-groups (Table 3) do indeed reflect small differences in H-bonding strength. With respect to the third point, it is believed that the divergence of **1** according to the system is due mainly to the enhanced acidity of **1** relative to the other cyclic enethiols.[12] This is in good agreement with the results found for the corresponding oxygen compounds.[13,14]

On the other hand, it is possible to compensate for the first-mentioned presumption. The compounds under consideration differ in the number of ring methylene groups. If the screening effect of every ring methylene group on the mercapto-proton is approximately the same, and this effect is additive for each extra methylene group, then δ_{obs} in eq. (d) may be replaced by $\delta_{obs}^{corr} = \delta_{obs} - n \cdot \epsilon$, where ϵ is the screening contribution from a single methylene group, and n is the number of ring methylene groups greater then 6 (i.e. **2** serves as reference compound). Eq. (d) may thus be rewritten:

$$\frac{A_1}{A_2} = \frac{k_1}{k_2} \cdot \frac{\delta_{obs} - n \cdot \epsilon - \delta_2}{\delta_1 - \delta_{obs} + n \cdot \epsilon} \qquad (e)$$

Using data for **2–5** only, the calculations based on eq. (e) gave the parameters $\delta_1 = 9{\cdot}80$ ppm, $\delta_2 = 0{\cdot}98$ ppm, $k_1/k_2 = 0{\cdot}69$, and $\epsilon = 0{\cdot}06$ ppm. These values appear to be more reliable, although those of δ_1 and δ_2 still diverge about 2 ppm from the expected values. Fig 7 shows the correlation between A_1/A_2 and $\delta_{obs}^{corr} = \delta_{obs} - n \cdot \epsilon$, compared with the hyperbola determined by the last-named values for the parameters δ_1, δ_2, and k_1/k_2.

Accepting $k_1/k_2 = 0{\cdot}69$ as a reliable value for the ratio between the molar extinction coefficients corresponding to the carbonyl adsorption bands of the C- and the C*-rotamers, respectively, the equilibrium mole fractions of the C-rotamers of **1–5** (at the working temperature of the apparatus, i.e. ~35°C) may be calculated from eq. (c) (Table 4).

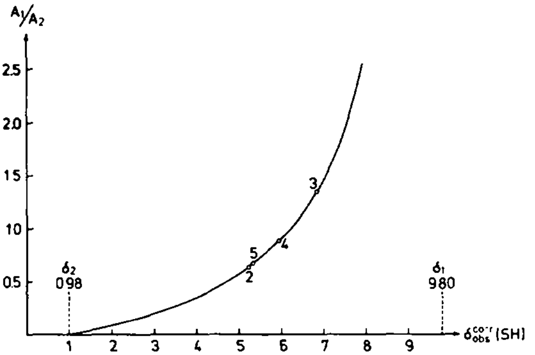


Fig 7. Correlation between A_1/A_2 and $\delta_{obs}^{corr} = \delta_{obs} - n \cdot \epsilon$, thrown in relief to the hyperbola determined by the parameters $\delta_1 = 9{\cdot}80$ ppm, $\delta_2 = 0{\cdot}98$ ppm, and $k_1/k_2 = 0{\cdot}69$, computationally derived according to eq. (e).

Using the reference values $\delta_1 = 9{\cdot}80$ ppm and $\delta_2 = 0{\cdot}98$ ppm, x_1-values of **6–8** may be calculated from eq. (b), replacing δ_{obs} by $\delta_{obs}^{corr} = \delta_{obs} - n \cdot \epsilon$ (Table 4).

Finally, it should be pointed out that the scope with respect to the applicability of eq. (d) in principle includes any two-component equilibrium system for which the interconversion process takes place sufficiently rapidly to give rise to weighted average NMR chemical shifts, but also slowly enough to allow for IR or UV spectroscopic distinction between the two components.

Table 4. Calculated mole fractions of C-rotamers (x_1) at ~35°C[a]

Compound	x_1	formula used
1[b]	0·73	(c)
2	0·48	(c)
3	0·66	(c)
4	0·56	(c)
5	0·50	(c)
6[c]	0·41	(b)
7[c]	0·43	(b)
8[c]	0·45	(b)

[a] The calculations are based on parameters derived according to eq. (e). [b] The discrepant behaviour of the five-membered ring compound is probably reflected in its mercapto-proton chemical shift rather than the absorbance ratio, thus allowing for a tentative estimation of x_1 with reference to A_1/A_2. [c] Due to the considerable equilibrium concentrations of the *trans*-enethiol tautomer, evaluation of x_1 on the basis of the carbonyl band absorbance ratio is not possible. Instead, x_1 is calculated from eq. (b), substituting δ_{obs}^{corr} for δ_{obs}.

EXPERIMENTAL

^1H NMR spectra were recorded as 15–20% CCl_4 solns on both a Jeol C-60 HL spectrometer, and a Varian A-60 spectrometer. TMS was used as internal reference standard. The chemical shifts are expressed in δ-values (ppm) downfield from TMS, and are correct within ±0·02 ppm.† The coupling constants, measured on the 50 Hz scale, are expressed numerically in Hz with an accuracy within ±0·1 Hz.

Equilibrium concentrations of tautomers were determined on solns kept in closed tubes at room temp for at least a week before determination. All usable signals were integrated 6–10 times. The equilibrium percentages of the tautomers in compounds **6–8** are accurate within ±4%.

IR spectra were recorded as 1–20% solns in CCl_4 on a Perkin–Elmer 457 grating spectrophotometer. Absorbances were measured on expanded scales (cm^{-1}).‡

The synthesized compounds **1–8** are, in the following, named in accordance with their predominating tautomeric form. B.ps are uncorrected. Yields refer to the isolated, pure products.

Ethyl 2 - mercapto - 1 - cyclopentenecarboxylate (**1**). 15·6 g (0·1 moles) of ethyl 2-oxo cyclopentanecarboxylate were dissolved in 200 ml MeCN. After cooling to −50°, a brisk stream of H_2S gas was passed through the soln for 1 h. Then dry HCl gas was passed through the soln similarly for 1½ h, whilst the temp of the soln was allowed to raise to −10°. Keeping the temp at about −10°, a moderate stream of H_2S gas was finally passed through the reaction soln for 2 h. The reaction mixture was poured into a mixture of 500 ml of ice-water and 250 ml of light petroleum under stirring. The layers were separated, the organic layer was washed with water until neutral, and then dried ($CaSO_4$). The solvent was removed, and the remaining oil distilled to give 13·6 g (80%) of pure **1** as a light red liquid, b.p.$_{11}$: 113°, n_D^{25}: 1·5241 (lit b.p.$_5$: 104–105°,[7] b.p.$_{5\cdot5}$: 110°,[6] b.p.$_{11}$: 110·5–112°,[2] n_D^{20}: 1·5243[7]).

Ethyl 2 - mercapto - 1 - cyclohexenecarboxylate (**2**). A soln of 28·3 g (0·17 moles) of ethyl 2-oxo cyclohexanecarboxylate in 250 ml of 99% EtOH was treated as above with H_2S for 2 h at −50°, with dry HCl gas for 2 h (temp raised to −20°), and finally again with H_2S gas for 2 h at −30° to −20°. Otherwise the same working-up procedure as described above for **1** was followed. Yield: 21·7 g (69%). Pale red liquid, b.p.$_{11}$: 134–135°, n_D^{25}: 1·5320 (lit b.p.$_6$: 112°,[6] b.p.$_{10\cdot5}$: 132–133°[2]).

In another experiment, 17·0 g (0·1 moles) of 2-ethoxycarbonyl-cyclohexanone were dissolved in 200 ml of MeCN and treated with H_2S and HCl exactly as described for **1**. Also following the same working-up procedure, 8·9 g of a red oil was obtained, b.p.$_{0\cdot15}$: 76–82°. The NMR analysis showed that the oil was a mixture of ~40% of **2** and ~60% of ethyl 2,2-dimercapto-1-cyclohexanecarboxylate (**2D**), the latter being easily identified by the characteristic signals at δ = 2·67 ppm (1H, m, methine proton), δ = 2·88 ppm (1H, s, non-chelated mercapto-proton), and δ = 3·26 ppm (1H, narrow m, chelated mercapto-proton). Attempts to isolate **2D** by distillation were unsuccessful, apparently because of partial decomposition of **2D** into **2** and H_2S.[1]

Ethyl 2 - mercapto - 1 - cycloheptenecarboxylate (**3**). A soln of 18·4 g (0·1 moles) of ethyl 2-oxo cycloheptanecarboxylate[15] in 250 ml of 99% EtOH was treated with H_2S and HCl as described for the preparation of **2**. Before working-up, the reaction mixture was allowed to stand (without gas-supply) overnight, whilst the temp raised to −10°. Otherwise the usual working-up procedure was followed, yielding 15·1 g (76%) of pure **3** as a light red oil, b.p.$_{0\cdot13}$: 70°, n_D^{25}: 1·5274. (Found: C, 60·03; H, 8·08; S, 15·74. $C_{10}H_{16}O_2S$ requires: C, 59·98; H, 8·05; S, 15·98%).

Ethyl 2 - mercapto - 1 - cycloötenecarboxylate (**4**). A soln of 19·8 g (0·1 moles) of ethyl 2-oxo cycloöctanecarboxylate[15] in 250 ml of 99% EtOH was treated with H_2S and HCl as described for the preparation of **2**. In addition, however, H_2S gas was passed slowly through the reaction soln for further 24 h, while the temp was kept within 0° to 10°. Otherwise the usual working-up procedure was followed, yielding 18·0 g (84%) of pure **4** as a pale red oil, b.p.$_{0\cdot07}$: 72°, n_D^{25}: 1·5315. (Found: C, 61·80; H, 8·52; S, 14·74. $C_{11}H_{18}O_2S$ requires: C, 61·66; H, 8·47; S, 14·94%).

Ethyl 2 - mercapto - 1 - cyclononenecarboxylate (**5**). A soln of 9·6 g (45 mmoles) of ethyl 2-oxo cyclononanecarboxylate[15] in 125 ml of 99% EtOH was treated with H_2S and HCl as described for the preparation of **2**, except that the second H_2S gas supply was prolonged to 4 h. Following the usual work-up procedure, 8·3 g (81%) of pure **5** was isolated as red oil, b.p.$_{0\cdot09}$: 99–101°, n_D^{25}: 1·5329. (Found: C, 62·90; H, 8·88; S, 13·83. $C_{12}H_{20}O_2S$ requires: C, 63·13; H, 8·83; S, 14·02%).

Ethyl 2 - mercapto - 1 - cyclodecenecarboxylate (**6**). A soln of 11·3 g (50 moles) of ethyl 2-oxo cyclodecanecarboxylate[15] in 125 ml of 99% EtOH was cooled to −50°. A stream of H_2S gas was passed through the soln for 1 h, then dry HCl gas was supplied similarly for 1 h (temp raised to −40°), and finally a moderate stream of H_2S gas was further supplied during 27 h, whilst the temp was raised continously to 0°. The reaction soln was poured into a mixture of 300 ml of ice-water and 200 ml of light petroleum under stirringing. The layers were separated, the organic layer was washed with water until neutral, and dried ($CaSO_4$). The solvent was removed, and the remaining reddish oil distilled. The fraction with b.p.$_{0\cdot3}$: 110–115° (9·6 g) was collected, and subjected to PLC purification on 6 25 × 45 cm glass sheets with a 3 mm coating of Kieselgel $PF_{254-366}$ (Merck). Elution was performed twice with a mixture of ether and light petroleum (1:19). The material absorbed within the $R_f{}'$-region 0·54–0·66 was isolated and distilled to give 5·6 g (46%) of pure **6** as a red oil, b.p.$_{0\cdot06}$: 100–102°, n_D^{25}: 1·5258. (Found: C, 65·15; H, 9·32; S, 12·74. $C_{13}H_{22}O_2S$ requires: C, 64·44; H, 9·15; S, 13·20%).

Ethyl 2-thioxo cycloundecanecarboxylate (**7**). 12·0 g (50 mmoles) of ethyl 2-oxo cycloundecanecarboxylate[15] was treated with H_2S and HCl under the same conditions as described above for the preparation of **6**. The crude product was distilled, and the fraction with b.p.$_{0\cdot15}$: 118–120° (8·6 g) was purified by PLC as described for **6**,

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†Mercapto-proton chemical shifts may vary with the concentration of the solution due to intermolecular solute interactions,[1,2] but the statement is fulfilled with respect to the shift values obtained by extrapolation to infinite dilution (in practice, ~2% solns).

‡A variation in solute concentration within the range 20% to 1% had no influence on the relative intensities of absorption bands in the regions of S—H and C=O stretching vibrations, neither gave the dilution rise to disappearance of any band. This seems to indicate that intermolecular H-bondings involving mercapto- and carbonyl groups are weak, and unimportant even in the rather concentrated 20% solns.

except that elution was performed three times. The material absorbed in the R_f''-region 0·61–0·80 was collected and distilled to give 7·2 g (56%) of pure **7** as a red oil, b.p.$_{0.05}$: 105°, n_D^{25}: 1·5173. (Found: C, 65·70; H, 9·55; S, 12·55. $C_{14}H_{24}O_2S$ requires: C, 65·59; H, 9·44; S, 12·48%).

Ethyl 2-thioxo cyclododecanecarboxylate (**8**). A soln of 12·7 g (50 mmoles) of ethyl 2-oxo cyclododecanecarboxylate[15] in 200 ml of 99% EtOH was cooled to −50°. H_2S gas was passed through the soln for 1 h, followed by dry HCl gas for 2 h (temp raised to −20°). The subsequent working-up was performed exactly as described above for **7**. Thus the material adsorbed in the R_f''-region 0·59–0·75 (3 elutions) was collected and yielded upon distillation 2·9 g (21%) of pure **8** as a thick, red oil, b.p.$_{0.2}$: 142–145°. (Found: C, 67·07; H, 9·81; S, 11·40. $C_{15}H_{26}O_2S$ requires: C, 66·63; H, 9·69; S, 11·83%).

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