Kinetics and Mechanism of a Double Thiocyanate–Isothiocyanate Isomerization: A Round Robin Rearrangement

David W. Emerson,* Richard L. Titus, Spencer M. Steinberg, and Marlon D. Jones

Department of Chemistry, The University of Nevada, Las Vegas, Box 454003, Las Vegas, Nevada 89154-4003

Received April 22, 1994

Some allylic thiocyanates, e.g., CH_2=$CHCH_2SC$≡N (**1**) readily rearrange to the corresponding allylic isothiocyanates, CH_2=$CHCH_2N$=C=S.[1-7] Allylic migration has been observed in the rearrangement of crotyl thiocyanate to α-methylallyl isothiocyanate.[3] These reactions are concerted[4,5] and are now categorized as [3,3] sigmatropic rearrangements.[7] Some allylic thiocyanates do not rearrange easily or by this pathway, however.[8-10] Cinnamyl thiocyanate (**2**) rearranges with difficulty[8] to cinnamyl isothiocyanate (**3**) but α-phenylallyl isothiocyanate (**4**) rearranges to cinnamyl thiocyanate (**2**).[9] Isothiocyanates are normally thermodynamically favored over the corresponding thiocyanates, but steric, electronic, and solvent factors may intervene. For example, the gain in stabilization by conjugation of the C=C double bond with the aromatic ring and the decreased steric hindrance of **2** compared to **4** is evidently more than enough to counteract the negative enthalpy change normally entailed in isomerization of a thiocyanate to an isothiocyanate.[9] In substituted allylic thiocyanates, increasing alkyl substitution at the point of attachment of the thiocyanato or isothiocyanato group normally results in an increase in the fraction of thiocyanate present at equilibrium, particularly in polar solvents.[5]

Results and Discussion

We are exploring what might be termed "round robin rearrangements". We choose as an example, the rearrangement[11] of thiocyanic acid, 2-methylene-1,3-propanediyl ester (**5**), which can be envisioned as proceeding via two successive [3,3] sigmatropic rearrangements first to thiocyanic acid, 2-(isothiocyanatomethyl)-1-propen-3-yl ester (**6**), thence to isothiocyanic acid, 2-methylene-1,3-propanediyl ester (**7**). As this happens, each of the methylene groups becomes vinylic at some stage in the course of the reaction and each has been bonded to either the sulfur or the nitrogen of the SCN moiety (reaction 1).

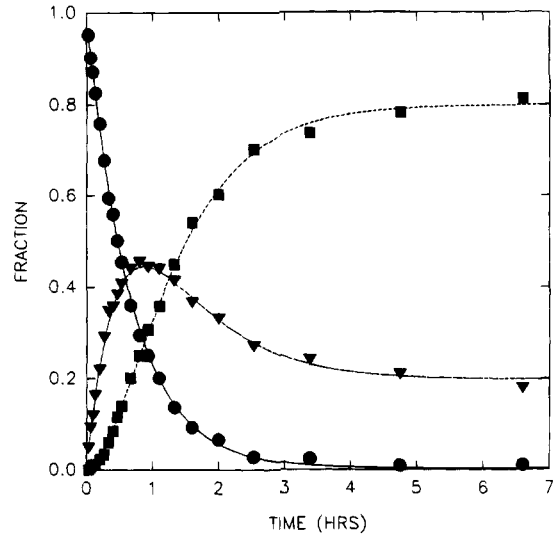
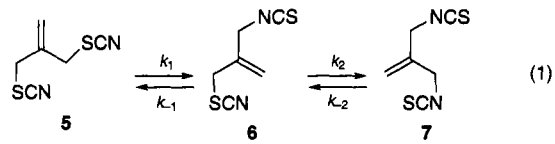


Figure 1. Isomerization of **5** in DMSO-d_6 at 90 °C: ●, **5**; ▽, **6**; ■, **7**.



(1)

The bis(thiocyanate) **5** rearranged smoothly at 95 °C in 80 min to **7**. When the isomerization was carried out in DMSO-d_6 or tetrachloroethene (TCE) at constant temperature and monitored by ^{1}H NMR, the buildup and decline in concentration of the intermediate half-isomerized thiocyanate **6** could clearly be observed (Figures 1 2), thus confirming that the reaction may be formulated as shown in eq 1.

The chemical shifts of the sp^3 methylene protons in **5**, **6**, and **7** allow the use of the integrals of the proton signals to follow the reaction quantitatively. First-order rate constants for the disappearance of **5** and **6** were determined in DMSO-d_6 and in TCE. From these rate constants, the enthalpies and entropies of activation, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$, were determined (Table 1). The reactions proceed at very nearly the same rates in the two solvents but substantial differences in the enthalpy of activation were observed, lower in DMSO than in TCE. Striking differences in the entropy of activation based on k_1 were observed: −19.2 eu in DMSO-d_6, −5 eu in TCE. Similar differences were seen for entropies based on k_2 in the two solvents. This suggests highly ordered solvation of a polarized, cyclic activated complex when the reaction is conducted in DMSO.

Experimental Section

Melting point temperatures are uncorrected. 3-Chloro-2-(chloromethyl)-1-propene (**8**) was obtained from the Aldrich Chemical Co. and used without further purification. DMSO-d_6, 99.8% D, was obtained from the Wilmad Glass Company and was dispensed from a freshly opened bottle. Tetrachloroethene (Baker, A.R.) was passed through a column of alumina prior to use. A stock solution of **5** was prepared from 0.0390 g of **5** and 5.00 mL (5.87 g) of DMSO-d_6 and kept in a refrigerator. It was thawed just prior to being transferred to NMR tubes. The thiocyanate **5** was not appreciably soluble in TCE at room temperature but was soluble at reaction temperatures. Transfer pipets, NMR tubes, and the glass storage container were flame dried prior to use.

(1) Gerlich, G. *Liebigs Ann. Chem.* **1875**, *178*, 80.
(2) Billeter, O. *Ber. Dtsch. Chem. Ges.* **1875**, *8*, 462.
(3) Mumm, O.; Richter, H. *Ber. Dtsch. Chem. Ges.* **1940**, *73*, 843.
(4) Smith, P. A. S.; Emerson, D. W. *J. Am. Chem. Soc.* **1960**, *82*, 3076.
(5) Ilicito, A.; Fava, A.; Mazzucato, V. *Tetrahedron Lett.* **1960**, No. 11, 27.
(6) Emerson, D. W.; Booth, J. K. *J. Org. Chem.* **1965**, *30*, 2480.
(7) Huber, S.; Stamouli, P.; Jenny, T.; Neier, R. *Helv. Chim. Acta* **1986**, *69*, 1898.
(8) Bergmann, E. *J. Chem. Soc.* **1935**, 1361.
(9) Ilicito, A.; Gaggia, G. *Gazz. Chim. Ital.* **1960**, *90*, 262.
(10) (a) von Braun, J.; Lemke, G. *Ber. Dtsch. Chem. Ges.* **1922**, *55B*, 3536. (b) Kataev, E. G.; Obukhova, M. F. *Uchenye Zapiski Kazan. Gosudarst. Univ. im. V. I. Ul'yanova-Lenina, Khim.* **1953**, *113*(8), 125; *Chem. Abstr.* **1958**, *52*, 3691.
(11) Mühlstädt, M.; Winkler, G.; Könnecke, A.; Schulze, K. *Z. Chem.* **1978**, *18*(3), 89–90.

0022-3263/94/1959-5109$04.50/0

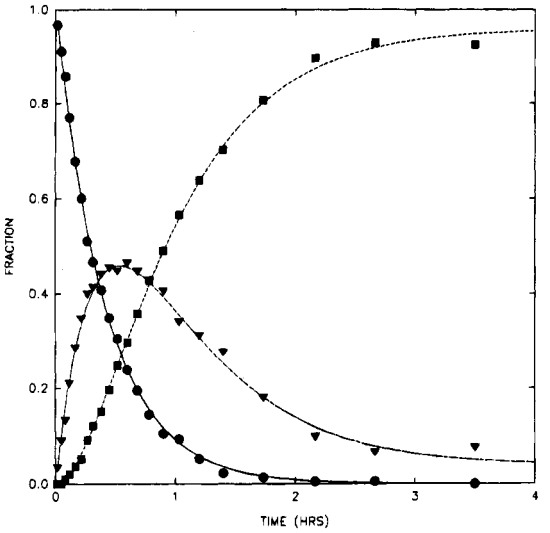


Figure 2. Isomerization of **5** in TCE at 90 °C: ●, **5**; ▽, **6**; ■, **7**.

The FTIR spectrometer had a resolution of 4 cm^{-1}. Proton FTNMR spectra were obtained at 300 MHz using DMSO-d_6 as an internal reference; TMS was used as the reference in TCE runs. ^{13}C FTNMR spectra were obtained at 75 MHz.

Two methods were employed for performing the kinetics experiments, both of which relied on ^1H NMR measurements of the relative concentrations of $-CH_2S-C\equiv N$ protons in the starting material **5** and the intermediate **6** and the $-CH_2N=C=S$ protons in the final product, **7**. **Method A.** The NMR tube was placed in the preheated sample probe and the spectrum was scanned periodically. **Method B.** A controlled temperature water bath was employed for heating the sample. The sealed NMR tube was removed from the bath at timed intervals and quickly chilled, and the NMR spectrum was obtained. After the measurement, the tube was reintroduced to the bath and timing was resumed. Rate constants and activation parameters were computed by standard methods.[12]

Preparation of Thiocyanic Acid, 2-Methylene-1,3-propanediyl Ester (5). A solution of 3.88 g, (40 mmol) of KSCN in 20 mL of DMSO and 2.50 g (20 mmol) of 3-chloro-2-(chloromethyl)-1-propene (**8**) was allowed to stand at room temperature for 24 h. Treatment with 50 mL of ice cold water afforded 2.06 g, 60.6%, of crude product. Pure product was obtained by recrystallization from 7:3 v/v hexane/2-propanol, mp 64–65 °C; lit.[13] mp 65–66 °C: ^1H NMR (TCE) δ 3.71 (s, 4 H), 5.46 (s, 2 H); (DMSO-d_6) δ 3.88 (s, 4 H), 5.44 (s, 2 H); ^{13}C NMR (DMSO-d_6) δ 137.50, 121.90, 112.69, 36.46; FTIR (KBr) 2159, 1419, 1292, 924, 713 cm^{-1}.

Thiocyanic Acid, 2-(Isothiocyanatomethyl)-1-propen-3-yl Ester (6). The compound was not isolated in pure form but its NMR spectrum was clearly observable in isomerizing mixtures: ^1H NMR (TCE) δ 3.60 (s, 2 H), 4.26 (s, 2 H), 5.37 (s, 1 H), 5.42 (s, 1 H); (DMSO-d_6) δ 3.85 (s, 2 H), 4.45 (m, 2 H), 5.40 (m, 2 H).

Table 1. Results from Kinetics Runs

Solvent: DMSO-d_6				
rate constant[a] 10^5k, s^{-1}	temperature, °C			
	90.0 ± 0.1[b]	80.1 ± 0.3[b]	70.0 ± 0.1[b]	65.0 ± 0.1[c]
k_1	41.4	16.3	7.28	4.44
k_{-1}	0.52	0.47	0.077	0.060
k_2	29.7	11.0	5.08	3.39
k_{-2}	7.36	2.41	1.17	0.975
CD(5)[d]	0.9993	0.9956	0.9995	0.9998
CD(6)[d]	0.9949	0.9775	0.9991	0.9956
CD(7)[d]	0.9990	0.9990	0.9999	0.9986

	activation parameters		
	$\Delta H^\ddagger$, kcal/mol	$\Delta S^\ddagger$, cal/(K*mol)	$\Delta G^\ddagger$, kcal/mol
basis			
k_1	20.1 ± 0.6	−19.2 ± 1.8	26
k_2	19.6 ± 1.2	−21.4 ± 3.4	25

Solvent: TCE			
rate constant[a] 10^5k, s^{-1}	temperature, °C		
	90.0 ± 0.1[b]	80.0 ± 0.1[b]	70.0 ± 0.1[b]
k_1	66.4	19.0	7.75
k_{-1}			0.015
k_2	41.5	12.4	4.86
k_{-2}	1.68	0.276	0.22
CD(5)[d]	0.9987	0.9936	0.9996
CD(6)[d]	0.9914	0.9811	0.9929
CD(7)[d]	0.9993	0.9979	0.9986

	activation parameters		
	$\Delta H^\ddagger$, kcal/mol	$\Delta S^\ddagger$, cal/(mol*K)	$\Delta G^\ddagger$, cal/mol
basis			
k_1	25.1 ± 3.0	−5 ± 9	24
k_2	25.1 ± 2.3	−5 ± 7	25

[a] First order. [b] Method A. [c] Method B. [d] Coefficient of determination, R^2, for compounds **5**, **6**, and **7**.

Preparation of Isothiocyanic Acid, 2-Methylene-1,3-propanediyl Ester (7).[11] A 0.10-g portion of **5** was placed in a clean test tube which was purged with nitrogen, stoppered, and placed in a heating block at 90 °C for 80 min: ^1H NMR (TCE) δ 4.15 (s, 4 H), 5.31 (s, 2 H); (DMSO-d_6) δ 4.40 (m, 4 H), 5.34 (m, 2 H); ^{13}C NMR (DMSO-d_6) δ 136.75, 118.30, 114.57, 46.78; FTIR (neat) 2096, 1432, 1328 cm^{-1}.

Supplementary Material Available: Description of rate constant determination and tables of raw kinetic data and kinetic plots (14 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(12) Laidler, K. J. *Chemical Kinetics*, 2nd ed.; McGraw-Hill: New York, 1965; Chapters 1–4.

(13) Kaiser, J.; Richter, R.; Sieler, J.; Schulze, K.; Mühlstädt, M. *Acta Crystallogr., Sect. B* **1977**, *B33*(3), 879–882.