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The first direct observation of an allylic [3,3] sigmatropic cyanate–isocyanate rearrangement†,‡

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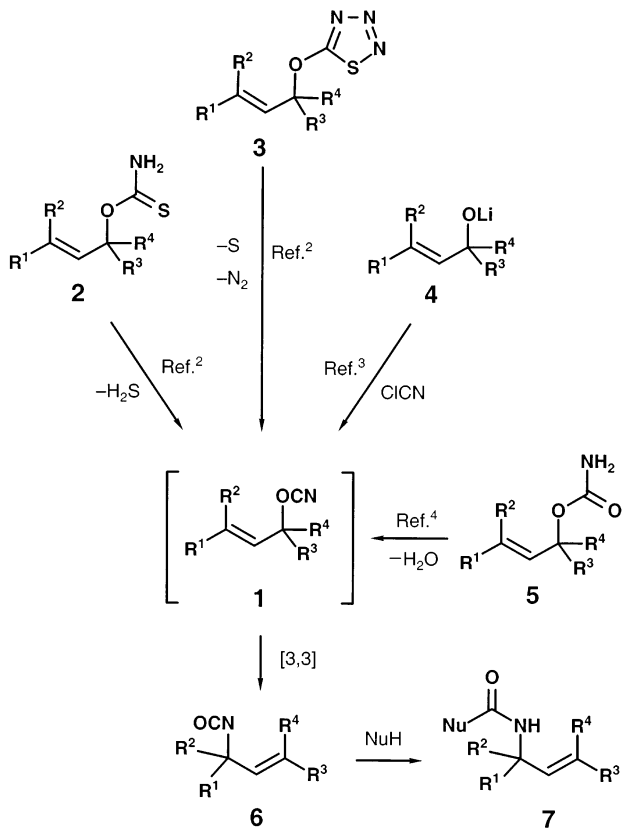
Abstract—Evidence is presented that the [3,3] sigmatropic rearrangement of simple allyl cyanates to give allyl isocyanates proceeds much more rapidly than the analogous reaction of propargyl cyanates. Nevertheless, a substituted allyl cyanate is isolated for the first time, and the activation parameters of its [3,3] sigmatropic isomerization are measured. © 2001 Elsevier Science Ltd. All rights reserved.

Allyl cyanates **1** are considered to be possible intermediates in several reactions leading to allyl isocyanates **6** via [3,3] sigmatropic isomerization (Scheme 1). However, direct proof of the presence of an allyl cyanate **1** is not yet available. Although the precursors **2**,[2] **3**,[2] **4**,[3] and **5**[4] led to moderate to excellent yields of the isocyanates **6** or their trapping products **7** (e.g. Nu = OR or NR_2), the postulated intermediates **1** could not be observed directly. The sequence **5**→**1**→**6**→**7** introduced by the group of Ichikawa[4a–g] involves the stereospecific transfer of chirality and proves to be a useful method to prepare optically active allyl amine derivatives **7** if starting materials **5** are derived from chiral allylic alcohols.

Recently, we succeeded in the first direct observation of a [3,3] sigmatropic cyanate→isocyanate rearrangement by NMR spectroscopic monitoring of the conversion **9**→**10**→**11** (Scheme 2).[5] The maximum proportion of the short-lived, quasi-stationary intermediate **10** in the reaction mixture was only 5%, however, in the presence of H_2S **10** could be effectively trapped to yield **12**. The transformation **8**→**9**→**10**→**11** is the first systematic route to prepare allenyl isocyanates.[6] In this paper, we present our attempts to observe and to isolate an allylic cyanate of type **1** for the first time and to investigate its [3,3] sigmatropic rearrangement to isocyanate **6**.

We treated the allylic alcohols **13** with sodium hydride followed by chlorothiatriazole[7] to produce the compounds **14**[8] in a convenient one-step procedure (Scheme 3).[9] In solution, **14** decomposed even at room tempera



Scheme 1. Reactions postulated to run via allyl cyanate **1**.

Keywords: dienes; cyanates; rearrangements; allenes; isocyanates.

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† See Ref. 1.

‡ This paper is dedicated to Professor Henri Patin.

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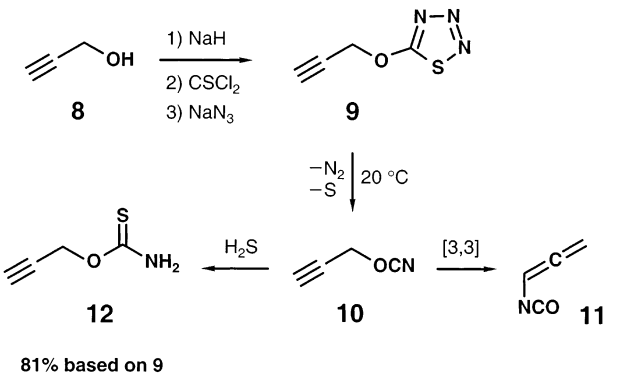
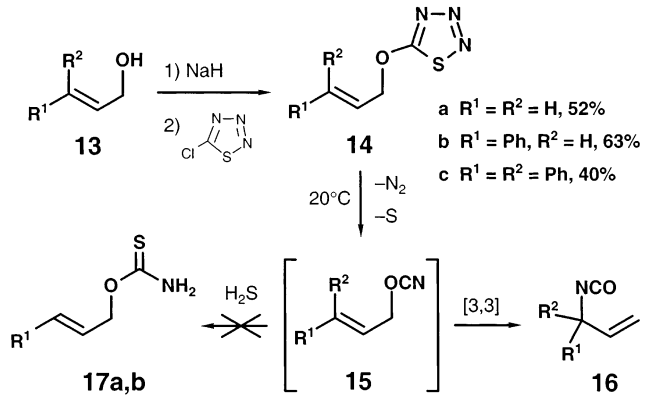


Scheme 2. Generation, trapping, and rearrangement of propargyl cyanate **10**.

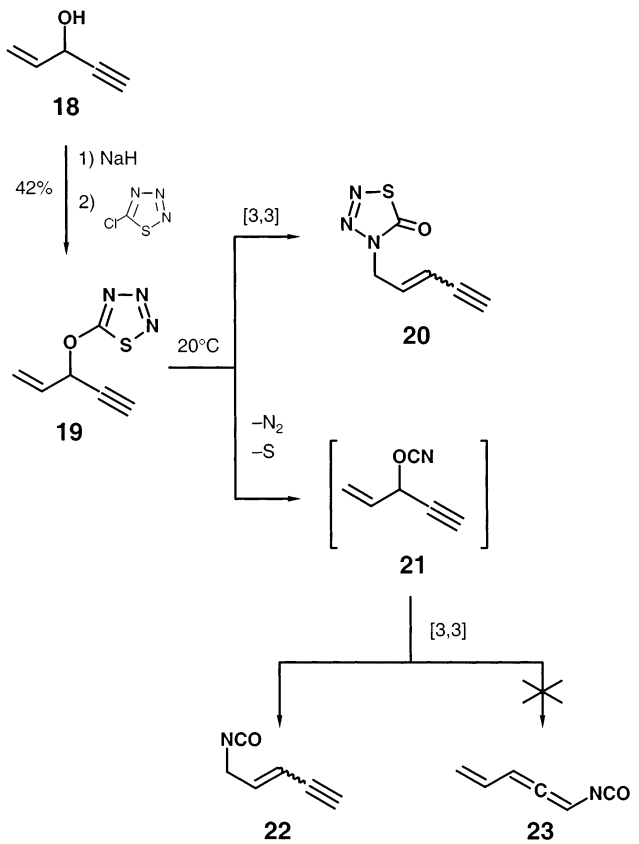


Scheme 3. Attempts to prove allyl cyanate **15**.

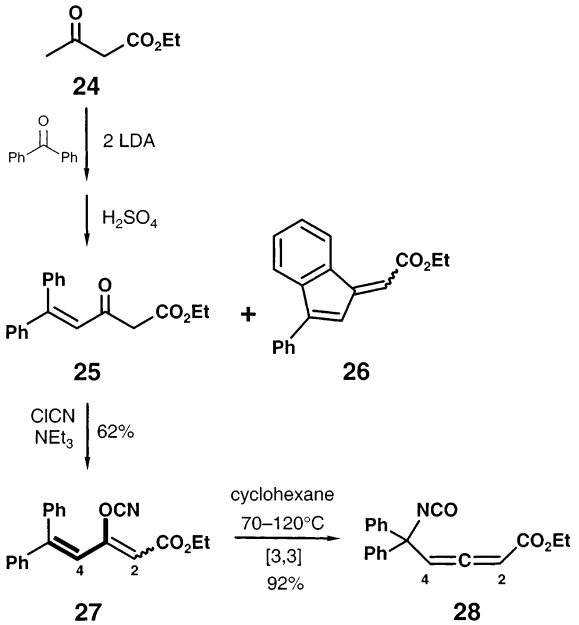
ture almost quantitatively to the rearranged isocyanates **16**. When the conversion **14**→**16** was followed by ^{1}H NMR spectroscopy, the intermediate **15** could not be detected. In the case of **14a** and **14b**, which were isolated as a very pure liquid and solid, respectively, the ^{1}H NMR signals of **15a**,**b** must be definitely smaller than those of the ^{13}C satellites of **14a**,**b**. Thus, the maximum proportion of the intermediates **15a**,**b** should be clearly less than 0.5%. The trapping experiment failed since decomposition of **14a**,**b** in the presence of H_2S produced **16a**,**b** instead of **17a**,**b**. All attempts to generate higher proportions of the intermediates **15a** or **15b** by photolysis[10] of **14a** or **14b** at low temperature were without success.

We interpret these results by the assumption that the allyl cyanates normally rearrange much more rapidly to isocyanates than do propargyl cyanates. To test this assumption, we transformed the alcohol **18** into thiatriazol **19** which should give rise to the cyanate **21** (Scheme 4). This short-lived intermediate could isomerize by allylic or propargylic migration of the cyanato group, however, only allyl isocyanate **22** (78%, $E/Z=$ 4.5:1) and the heterocyclic product **20** (22%, $E/Z=3$:2) were observed after decomposition of **19**. Thus, the rearrangement **21**→**23** is not able to compete with the very rapid allylic shift **21**→**22**. Because thiatriazolone **20** is stable at room temperature, it cannot be a precursor for **22**, as it was analogously discussed in the case of other 5-allyloxy-1,2,3,4-thiatriazoles.[2]

To synthesize an allyl cyanate with substituents, which retard the rapid [3,3] sigmatropic rearrangement, we prepared the known[11] ester **25** by treating the dicarbanion of ethyl acetoacetate with benzophenone, followed by dehydration of the resulting tertiary alcohol with concentrated sulfuric acid (Scheme 5). The yield of the first step (79%) was significantly increased by use of LDA (lithium diisopropylamide) in THF instead of KNH_2/NH_3,[11a] while the second step led to unknown **26**[12] (27% after separation by flash chromatography) in addition to **25** (55%). The reaction of **25** with ClCN/NEt_3 afforded the allyl cyanate **27**[13] ($E/Z\approx$1:10). The structure of the main isomer of **27**, which could be isolated as a stable crystalline compound, was proved by the spectroscopic data. This included ^{1}H NMR nuclear Overhauser enhancement (NOE) difference spectra which assigned the *Z* configuration. On heating in solution, both *E*-**27** and *Z*-**27** were irreversibly transformed into isocyanate **28**.[14] Obviously, the rate of this [3,3] sigmatropic rearrangement is strongly decreased by the fact that conjugation of the C=C bonds with the cyanato and the phenyl groups is present only in the case of **27**, whereas **28** possesses cumulated C=C bonds and isolated isocyanato and phenyl groups. When the conversion *Z*-**27**→**28** was followed by ^{1}H NMR spectroscopy in the range of 70–120°C, the activation parameters of this first-order reaction could be measured: $\log A=6.62\pm0.59$, $E_a=84.5\pm4.1$ kJ mol^{-1}, $\Delta H_{298}^{\neq}=81.0\pm4.1$ kJ mol^{-1}, $\Delta S_{298}^{\neq}=-126.5\pm11$ J mol^{-1} K^{-1}. The large negative activation entropy is characteristic of the cyclic transition state of the con-



Scheme 4. Generation and rearrangement of cyanate **21**.



Scheme 5. Synthesis and rearrangement of allyl cyanate **27**.

certed reaction **27**→**28**. If this transformation was carried out at 80°C in chloroform instead of cyclohexane, the rate was accelerated by a factor of 40.

At present, we are investigating whether the rearrangement **27**→**28** can be generalized as a synthetic method to produce functionalized allenes of type **28**.

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12. Compound **26**: Yellow crystals, mp 96.5–97.5°C. ^{1}H NMR ($CDCl_3$): δ 1.41 (t, $^3J=7$ Hz, 3H, Me), 4.33 (q, $^3J=7$ Hz, 2H, CH_2), 6.54 (s, 1H, CH-CO_2), 7.21–7.75 (m, 10H). ^{13}C NMR ($CDCl_3$): δ 14.36 (q, Me), 60.58 (t, CH_2), 113.59 (d), 120.54 (d), 120.99 (d), 123.67 (d), 126.40 (d), 127.53 (d), 128.60 (d), 128.88 (d), 129.48 (d), 134.60 (s), 137.75 (s), 142.00 (s), 151.19 (s), 151.28 (s), 166.31 (s, C=O). GC MS (70 eV) m/z (%): 276 (M^+, 99), 247 (29), 231 (57), 202 (100), 191 (33), 101 (34). Anal. calcd for $C_{19}H_{16}O_2$: C, 82.58; H, 5.84. Found: C, 82.13; H, 5.90.
13. Experimental procedure for **27**: Cyanogen chloride (210 μl, 249 mg, 4.05 mmol) was added dropwise to a solution of **25** (1.0 g, 3.4 mmol) in dry Et_2O (30 ml), which was stirred at −10°C. After dropwise addition of freshly distilled NEt_3 (0.35 g, 3.5 mmol), the reaction mixture was stirred for 3 h at 0°C. Then, the precipitate of ammonium salt was separated and repeatedly extracted with Et_2O. The combined ether solutions were concentrated in vacuo to give crude **27** with $E/Z \approx 1{:}10$. After separation by flash chromatography (SiO_2, Et_2O/hexane, 1:1), 0.67 g (62%) *Z*-**27** were isolated besides small amounts of *E*-**27**. Compound *Z*-**27**: Yellowish crystals, mp 66–67°C. IR (CCl_4): 2273 (OCN), 1729 (C=O) cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.25 (t, $^3J=7$ Hz, 3H, Me), 4.17 (q, $^3J=7$ Hz, 2H, CH_2), 5.35 (s, 1H, H-2), 6.46 (s, 1H, H-4), 7.22–7.45 (m, 10H, Ph). Saturating the proton H-2 led to 5% enhancement of the signal of H-4, which was measured with the help of NOE difference spectra. ^{13}C NMR ($CDCl_3$): δ 14.05 (q, $^1J=124$ Hz, Me), 60.98 (t, $^1J=148$ Hz, CH_2), 108.21 (s, OCN), 108.60 (d, $^1J=166$ Hz, C-2), 115.23 (d, $^1J=160$ Hz, C-4), 128.30 (d, Ph), 128.48 (d, Ph), 128.75 (d, Ph), 129.10 (d, *p*-Ph), 129.19 (d, Ph), 129.89 (d, *p*-Ph), 137.72 (*i*-Ph), 140.20 (*i*-Ph), 154.83 (s), 156.36 (s), 162.28 (s, C-1). Assignments were based on heteronuclear shift correlation. Anal. calcd for $C_{20}H_{17}NO_3$: C, 75.22; H, 5.37; N, 4.39. Found: C, 75.15; H, 5.46; N, 4.22.
14. Compound **28**: 92% isolated yield. Yellowish oil. IR (CCl_4): 2250 (NCO), 1970 (C=C=C), 1724 (CO_2Et) cm^{-1}. ^{1}H NMR ($CDCl_3$): δ 1.34 (t, $^3J=7.1$ Hz, 3H, Me), 4.25 (m, 2H, CH_2), 5.82 (d, $^4J=6$ Hz, 1H), 6.30 (d, $^4J=6$ Hz, 1H), 7.31–7.52 (m, 10H, Ph). ^{13}C NMR ($CDCl_3$): δ 14.23 (q, Me), 61.17 (t, CH_2), 68.23 (s, C-5), 93.37 (d), 104.27 (d), 125.50 (s, NCO), 126.46 (d, Ph), 126.66 (d, Ph), 127.98 (d, *p*-Ph), 128.04 (d, *p*-Ph), 128.30 (d, Ph), 128.37 (d, Ph), 142.59 (s, *i*-Ph), 143.20 (s, *i*-Ph), 164.51 (s, C-1), 210.31 (s, C-3).