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The Stevens Rearrangement of Sulfur Ylide Generated by Electrochemical Reduction of Sulfonium Salt

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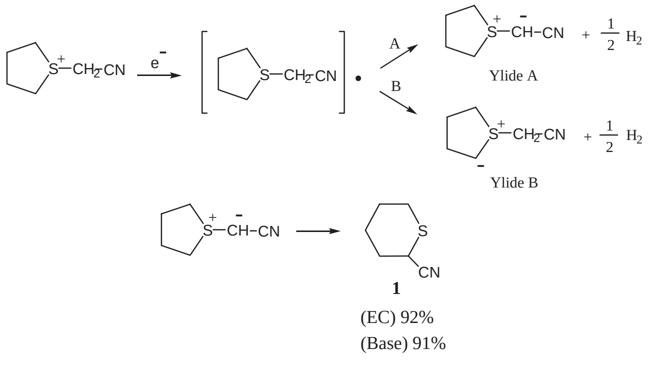
The cathodic reduction or a base treatment of a 1-cyanomethyltetrahydrothiophenonium salt gave the stabilized ylides which were conformed by the reaction with benzaldehyde. In the absence of benzaldehyde, the ring expanded product was obtained through the [1,2] Stevens rearrangement in good yield by both methods. The reaction mechanism was investigated by using B3LYP density functional calculations.

Rearrangements in various ylides have attracted much attention from synthetic and mechanistic view point because of the formation of new carbon–carbon bonds in a variety of fashions under mild conditions and the ability to prepare stereospecific compounds.[1,2] We have recently reported the Sommelet–Hauser rearrangement of sulfur-ylide (abbreviated as S-Y hereafter) generated by an electrochemical reduction of an allyl or benzyltetrahydrothiophenonium salt.[3] In this paper, we have investigated the rearrangement of stabilized S-Y which has no allylic or benzylic substituents on the sulfur atom of the ylides, and found the [1,2] Stevens rearrangement could proceed through radicalish mechanism by electrochemical reduction and the base method of 1-cyanomethyltetrahydrothiophenonium bromide.

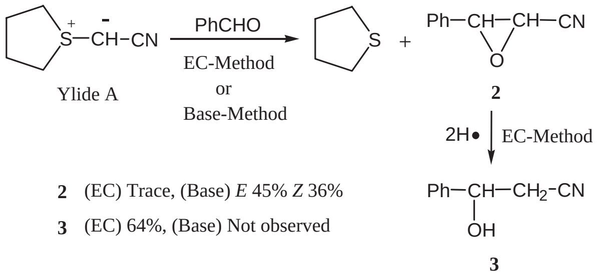
The electrochemical reduction might proceed through two paths to generate S-Ys as described in Scheme 1. The two routes were designated as A and B route based on the positional difference of hydrogen abstraction. Electrochemical generation of S-Y in the absence of benzaldehyde obviously proceeded as one-electron reduction, since sulfonium salt disappeared almost completely when 1 F/mol of electric current had been passed. This mechanism can be supported by the fact that the hydrogen gas evolved at the cathode during the reaction. The reaction product was separated and proved to be 2-cyanotetrahydrothiopyran (**1**) by the analytical data.[4]

In the presence of benzaldehyde, the electrochemical reduction of the sulfonium salts by passing 1 F/mol gave 3-hydroxy-3-phenylpropiononitrile (**3**)[5] in 64% yield as a result of hydrogen addition to epoxide generated by the Corey–Chaykovsky reaction as shown in Scheme 2. The H radical might be generated not only from the sulfonium salts but also the other activated minor products at the cathode; therefore, 30% sulfonium salts were remained even after passing 1 F/mol under the presence of benzaldehyde. To enhance the yield of the alcohol, we attempted to apply the electric current of more than 1 F/mol, however, the yield could not be improved because of the decomposition of the generated alcohol.



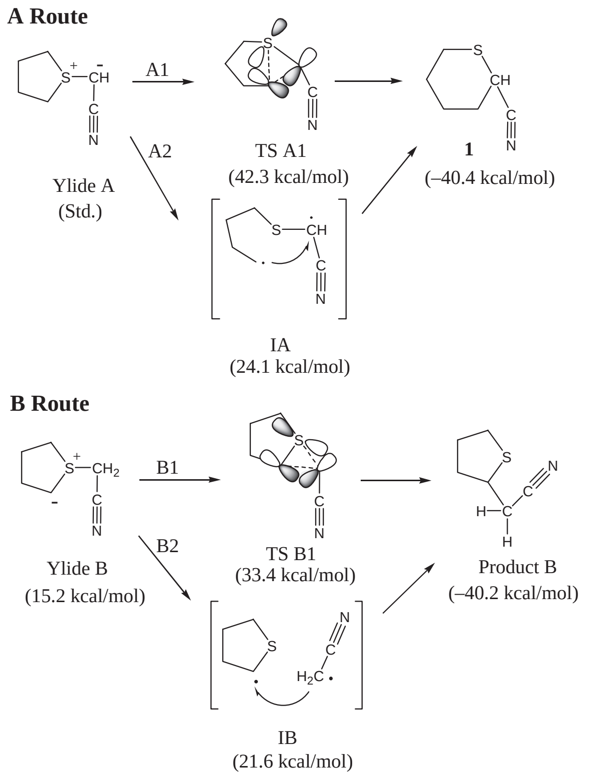
Scheme 1.

The generation of S-Y by a base such as sodium amide has been confirmed by reaction with benzaldehyde. The epoxides **2** was obtained from the A route as a mixture of (*E*)-and (*Z*)-isomers[6] and no hydrogen addition occurred. In our previous report, we referred to the tendency of stereoselectivity for the Corey–Chaykovsky reaction of benzyl and allyl S-Ys.[3] The same explanation given for allyl S-Y can be applied here to explain the stereoselectivity of the epoxide.



Scheme 2.

As reported in the previous papers,[3] the rearrangement of the S-Y can be considered to proceed via the two routes through stable Ylide A and unstable Ylide B. The possible pathways for the [1,2] Stevens rearrangement of the S-Y are also considered to proceed through sigmatropic routes A1, B1 or through the radical routes A2, B2 as shown in Scheme 3. The six-membered product **1** was found to be the [1,2] Stevens rearrangement product formed through a stable Ylide A by the both electrochemical and base methods. This rearrangement could be a radical process shown as A2 in the Scheme 3, because the sigmatropic route A1 will give transition state of 3 orbitals and 4 electrons which is forbidden by the conservation of orbital symmetry. However, we have reported the theoretical calculations about the mechanism of the [1,2] Stevens rearrangement of P-Y and As-Y and found that the sigmatropic route might be more preferable than the radical route with the migrating groups[7] such as hydrogen, vinyl, and silyl groups. In case of S-Y reported here, the sigmatropic route might be more unfavorable, because the migration group is methylene group which does not have an adequate orbitals such as a 2p atomic orbital or a d-orbital to stabilize the three-centered TS.[7]



Scheme 3.

With regard to the energetics of the ylides and the transition states in the [1,2] Stevens rearrangement, we have investigated the energy differences of Ylide B and each TSs (A1, IA, B1, and IB) relative to Ylide A using B3LYP density functional calculations[8] and the results are shown in parentheses in Scheme 3. These results lead us to the conclusion that the energy difference between Ylides A and B is large (15.2 kcal/mol) compared to those of allyl (10.2 kcal/mol) and benzyl (8.1 kcal/mol) ylides, therefore, the equilibrium between Ylides A and B is shifted largely to Ylide A. This is the reason why the product **1** was obtained selectivity and the product B from the B route was not observed. The energy difference between the radical intermediate IA and the sigmatropic TSA1 is very large (18.2 kcal/mol), therefore, the Stevens rearrangement of this S-Y goes through the radical mechanism.

In conclusion, the six-membered product was obtained through the radicalish [1,2] Stevens rearrangement via stable Ylide A from 1-cyanomethyltetrahydrothiophenonium salt by both electrochemical and base methods and detailed mechanism of this rearrangement was elucidated theoretically. This facile ring expansion might be exploited to get the heterocyclic compounds with various ring sizes.

References and Notes

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4 A typical procedure for isolation of product **1** by the EC-method is as follows: 1-Cyanomethyltetrahydrothiophenonium bromide (2.08 g, 0.01 mol) was dissolved in acetonitrile (0.05 dL) at the cathodic side of the cell. In an anodic side, 0.01 dL of acetonitrile containing 0.01 mol of tetraethylammonium perchlorate was used as electrolyte. As the electrodes, two platinum plates ($2 \times 1\,\mathrm{cm}^2$) were equipped in the cell. The cathodic reduction was carried out under condition of −2.5 V vs SCE. at 22 °C under nitrogen. After 1 F/mol electricity based on the sulfonium salt was passed, the reaction mixture was dissolved in diethyl ether and extracted with the same amount of water to remove inorganic salts and the organic solution was dried over anhydrous Na_2SO_4. The crude mixture was purified by column chromatography on silica-gel adsorbent using $CHCl_3$ as an eluent to give 1.17 g (92%) of 1-cyanotetrahydrothiopyran. (**1**): Yellow liquid; bp 208–210 °C; IR (KBr Coat) 2935 (m), 2854 (m), 2233 (m), 1440 (m), 1257 (m), 966 (w) cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.70–1.74 (3H, m), 1.92–1.94 (2H, m), 2.07–2.11 (1H, m), 2.56–2.59 (1H, m), 2.91–2.97 (1H, m), 3.63 (1H, t, $J = 3.9$ Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.8, 25.8, 26.6, 27.6, 29.6, 118.7; MS m/z 127 [M^+] (100), 112 (31), 100 (20), 93 (19), 85 (38), 80 (63), 66 (78), 55 (79). Anal. Calcd for C_6H_9NS: C, 56.65; H, 7.13; N, 11.01%. Found: C, 56.31; H, 7.32; N, 10.59%.

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8 Method of Calculations; The structure of all the reactions, products, and TSs were optimized using Gaussian03 program package at B3LYP density functional level together with the 6-31+G(d) basis set. In addition, relative energies were also computed at the same level. Zero point energy corrections were also computed and used to obtain the energetics of the reaction. The radical dissociation products were optimized by the unrestricted B3LYP method. Vibrational analysis was carried out at the B3LYP level to characterize all the stationary points as minima or saddle points. When the B3LYP (RB3LYP) wave functions for the TSs were unstable, we carried out the geometry determination of the TS structure by using the theory of UB3LYP density function.

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