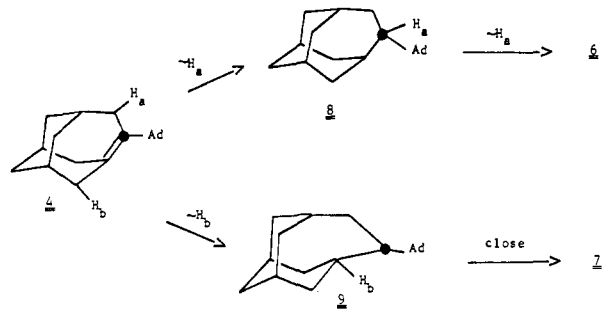
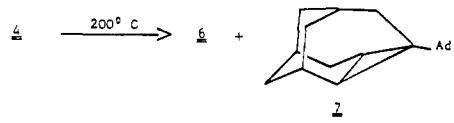
Scheme I



been ineffective in our hands. Although the purity of **4** suffices for NMR and chemical observations, it complicates the determination of the C=C double-bond stretching frequency. A number of weak bands appear in the infrared between 1600 and 1550 cm^{-1}, and there is a weak band in the Raman[10] spectrum at 1577 cm^{-1}. Any assignment must remain tentative for the moment.

Compound **4** is extraordinarily stable thermally. Heating in benzene-d_6 or toluene-d_8 results in no change over 24 h at 185 °C! Only at 200 °C does reaction begin. Two isomeric products are found (80–90% conversion) in approximately equal amounts, **6** and a compound assigned the structure of the cyclopropane **7**.



On the surface, **6** is the result of a 1,3-hydrogen shift. It takes but a cursory examination of the alignment of the orbitals involved to convince one that a direct 1,3-shift is unlikely on steric grounds.[11] Yet isomerization in deuteriotoluene proceeds at qualitatively the same rate as in deuteriobenzene, and both reactions yield undeuterated **6** and **7**. The reaction does not go by hydrogen abstraction from solvent followed by hydrogen loss or by any other intermolecular route. Alternate routes to **6** and **7** involve 1,2-hydrogen shifts from the two possible allylic positions in **4** (H_a and H_b). Migration of H_a gives **6**, as closure of **8** would yield a badly strained cyclopropane (see Scheme I). Migration of H_b gives **9**, which has no easy further 1,2-shift available but is presented with a relatively simple closure to **7**, in a formal reverse of the usual cyclopropane-to-propene thermal rearrangement. This mechanism predicts that the ^{13}C label must appear in the quaternary cyclopropyl carbon of **7**, and an off-resonance ^{13}C NMR experiment confirms this expectation. Cyclopropane **7** is the same compound as is formed by low-temperature photolysis of **5**.[12] Although the initial 1,2-shifts from **4** to **8** and **9** are symmetry forbidden,[13] the reaction is known to be intramolecular, and the economy of a process leading to both **6** and **7** is attractive.[14] Reverse processes, in which cyclopropanes are converted to propenes in closely related systems, have ample precedent.[15]

Thus the replacement of the vinyl hydrogen in **1** by adamantyl confers exceptional kinetic stability on **4** and effectively stifles dimerization. It does not reduce the strain inherent in such *trans*-cycloheptene bridgehead olefin systems, and the thermodynamic instability of **4** opens the way for otherwise unfavorable reactions.[16] The potential of 1-adamantyl or similar groups to stabilize other, inherently even more reactive bridgehead olefin systems is obvious.

Registry No. 4, 82665-12-1; **5**, 54821-20-4; **6**, 82665-13-2; **7**, 82665-14-3.

(10) We thank Professor T. G. Spiro and G. Woolery for this measurement.

(11) Although the direct 1,3-shift is also symmetry forbidden, the application of the Woodward–Hoffmann rules to reactions in which poor orbital connectivity is obligatory is not obvious.

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(14) Another explanation for **6** involves delivery of hydrogen by the adamantyl group to the 3-position of **4**, followed by rotation and abstraction of H_a. Coleman, B., Shell Research, Amsterdam, private suggestion. This mechanism, though attractive, fails to account for the presence of **7**.

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(16) Two groups[17,18] have provided theoretical results that bear on this point. Compound **4** is calculated (MM2) to have 9.2 kcal/mol *greater* olefin strain[2] than **1a**.[17] The effect of the adamantyl group is to produce a greater dihedral angle (42.3° vs. 26.0°; CFF)[18] between the orbitals making up the "double" bond and thus to decrease the thermodynamic stability. These calculations make the kinetic stability conferred by the adamantyl group even more remarkable.[2]

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(18) Ermer, O., Bochum, private communication.

Carbon-14 and Deuterium Isotope Effects in the Borderline Solvolysis of Isopropyl β-Naphthalenesulfonate

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In spite of the increasing use of carbon isotope effects in the study of organic reaction mechanisms in recent years,[1] there is a considerable shortage of basic knowledge and experimental data. The carbon isotope effect at the reaction center of aliphatic nucleophilic substitution is believed to be large in S_N2 and small in S_N1. However, the experimental data are mostly limited to primary substrates for the former and a tertiary one for the latter;[1,2] no systematic study with a simple secondary substrate has been reported.[3] In addition, secondary carbon isotope effects are assumed without sufficient investigation to be very small.[4-6] We herein report carbon-14 and deuterium isotope effects at the α and β positions of isopropyl β-naphthalenesulfonate (**1**) in the solvolysis in ethanol–2,2,2-trifluoroethanol (EtOH–TFE). In this solvent system the mechanism of the solvolysis of simple secondary substrate is considered to vary from S_N2-like to S_N1-like.[7,8] Thus, this is the first systematic study of the kinetic isotope effects of all the atoms constructing the isopropyl moiety in a single substrate solvolyzing within a broad spectrum of the borderline mechanism.

Solvolysis of **1** in EtOH, 20% EtOH–80% TFE (20E–80T, v/v), and TFE at 65 °C was followed spectrophotometrically. Carbon-14 kinetic isotope effects were determined according to the procedures described before.[9] Results are summarized in Table I.[10]

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Table I. Rate Constants and Kinetic Isotope Effects in the Solvolysis of Isopropyl β-Naphthalenesulfonate[a]

	EtOH	20E-80T[b]	TFE
$10^5(^Hk)$, s^{-1}	7.05 ± 0.08	6.34 ± 0.03	6.08 ± 0.07
$^Hk/^Dk$ at α[c]	1.07 ± 0.01	1.11 ± 0.01	1.15 ± 0.01
$^Hk/^Dk$ at β (D_6)[c]	1.22 ± 0.01	1.49 ± 0.01	1.77 ± 0.03
$^{12}k/^{14}k$ at α[d]	1.095 ± 0.004	1.089 ± 0.003	1.055 ± 0.002
$^{12}k/^{14}k$ at β[d]	1.009 ± 0.002	1.015 ± 0.002	1.019 ± 0.001

[a] 0.036 M in substance at 65 °C with added 1.1 equiv of 2,6-lutidine. [b] 20% EtOH-80% TFE (v/v). [c] Average of two runs. [d] For errors of $^{12}k/^{14}k$ see ref 9.

EtOH-TFE is a nearly isodielectric solvent system, in which nucleophilicity and electrophilicity change distinctly in opposite directions.[7,8,11] Almost identical rate constants observed in the three solvents indicate that these two factors are energetically counterbalanced with each other.

Results of deuterium isotope effects support the expected variation of the mechanisms. α-Deuterium effects in EtOH ($^Hk/^Dk$ = 1.07) and TFE (1.15) at 65 °C are almost the same as those reported for the solvolysis of the brosylate in 90% EtOH (1.083) and 97% TFE (1.16) at 25 °C, respectively,[12,13] when the difference in temperature is taken into consideration. These values reflect the steric congestion of the transition states: tight nucleophilic attachment of a solvent and a leaving group in EtOH and loose attachment in TFE. β-Deuterium effects indicate a strong hyperconjugative electron demand in TFE and a much reduced demand in EtOH. The observed difference between these two extremes is much larger than that between the values reported for 97% TFE (1.46 per D_6) and 90% EtOH (1.28 per D_6).[12]

The primary ^{14}C effect for the α carbon varied considerably with the solvent used. The effect in EtOH is large and close to the largest value ($^{12}k/^{14}k$ = 1.105) reported for the nucleophilic substitution of a secondary substrate,[14] while the effect is much smaller in TFE. Thus, it is confirmed experimentally with the simplest member of secondary alkyl derivatives that the carbon isotope effect at the reaction center is sensitive to the mechanism of the solvolysis and is large in S_N2 and small in S_N1.

It is surprising that significant isotope effects, $^{12}k/^{14}k$ = 1.01-1.02, were observed for carbon-14 at the β carbon, adjacent to the reaction center. These are the first reported examples of secondary carbon-14 isotope effects of significant magnitude in solvolysis without neighboring group participation.[9,15] A larger effect in TFE and a smaller one in EtOH indicate that the effects originate from the C_β-H bond weakening incident to hyperconjugation. It is noteworthy that these values are much larger than the secondary carbon-13 equilibrium isotope effect observed in 1,2-dimethylcyclopentyl caton, where one methyl group was labeled with carbon-13.[6]

In 20E-80T, all the effects other than that of α carbon-14 are just the averages of the corresponding values for EtOH and TFE. The characteristics of the transition state, e.g., steric congestion and hyperconjugative electron demand, should be in the middle between the two extremes. The different behavior of the α-carbon-14 effect reflects the fact that the symmetry of the transition state is the chief determining factor of the effect.[16] In this mixed solvent, the transition state seems fairly symmetrical, though it is looser than that in EtOH.

The present investigation verifies that α- and even β- carbon-14 kinetic isotope effects are sensitive to mechanistic changes in the borderline solvolysis. Model calculations of kinetic isotope effects using the observed data for all the carbons and deuteriums will enable us to describe the variable transition-state structures of the solvolysis of simple secondary substrates,[9,17] which is still a subject of much debate in recent years.[18] A study along this line is now in progress.

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Registry No. Isopropyl β-naphthalenesulfonate, 67199-42-2; carbon-14, 14762-75-5; deuterium, 7782-39-0.

(10) The product analysis by ^1H NMR showed that no olefin was produced in TFE (in the absence of 2,6-lutidine) or in EtOH-d_6. Although the addition of 2,6-lutidine into TFE resulted in the formation of 6% propene, almost no change was observed in the deuterium isotope effects: $^Hk/^Dk$ = 1.16 ± 0.01 for α-D and $^Hk/^Dk$ = 1.82 ± 0.02 for β-D_6 in the absence of 2,6-lutidine. Thus, the occurrence of the elimination does not affect the following discussion. In 20E-80T, 56% 2,2,2-trifluoroethyl ether and 36% ethyl ether were obtained (by ^{13}C NMR) along with 8% propene (by ^1H NMR).

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Identification of Degradation Products of d(C-G) by a 1,10-Phenanthroline-Copper Ion Complex

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The 1,10-phenanthroline-cuprous complex $(OP)_2Cu^+$ has been reported to cleave double-stranded DNA in an oxygen-dependent reaction.[1-4] It is assumed that hydrogen peroxide is formed as an essential reactant[3,4] and that hydroxyl radical is the reactive species in DNA degradation.[3] It is also known that an antitumor drug, bleomycin, cleaves DNA in the presence of Fe^{2+} and oxygen by a similar mechanism involving hydroxyl radicals.[5] Recently some DNA degradation products by the drug have been identified.[6] However, in the case of phenanthroline, the mode of action on DNA is not well understood.[7] Investigation of the DNA cleavage products will provide information for a general understanding of DNA cleavage reactions catalyzed by free radicals as observed for many antitumor drugs such as neocarzinostatin,[8] daunomycin,[9] and mitomycin[10] and in radiolysis.[11] In this communication, we report identification of degradation products (**1**, **2**, cytosine, guanine, and deoxyguanosine 5'-phosphate) from a self-complementary dinucleoside monophosphate, d(C-G),[12] by phenan-

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