Stereochemistry and Mechanism of π-Assisted Solvolysis of *endo*-Bicyclo[3.3.1]non-6-ene-3-methyl Tosylate

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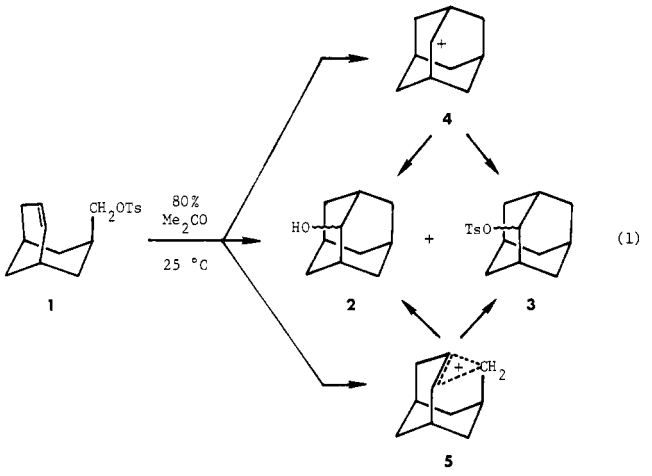
Abstract: The stereochemistry of the title reaction in several solvents has been established by ^2H NMR configurational analysis of the 2-adamantyl-*4,4-d*$_2$ products obtained from the α,α-dideuterated reactant **6**. Solvent nucleophilic attack occurs predominantly on the side of the 2-adamantyl position away from the initial reaction site, the stereoselectivity increasing with increasing solvent nucleophilicity. Tosylate ion return in each case studied exhibits mainly though less selectively the same stereochemistry, i.e., is predominantly a non-least-motion process. Solvolysis in 80% aqueous ethanol in the presence of 0.06 M NaN_3 produces only 1% of 2-adamantyl azide. The results constitute strong evidence for reaction through bridged carbonium ions and demonstrate that the structures of the carbocations in the initial ion pairs along the direct route and the π route to 2-adamantyl solvolysis products are markedly differentiated by the location of the counterion.

Raber, Kane, and Schleyer in 1970 reported the double-bond assisted solvolysis of *endo*-bicyclo[3.3.1]non-6-ene-3-methyl tosylate (**1**).[1] Hydrolysis of **1** in 80% aqueous acetone at 25.0 °C was found to proceed 2×10^4 times faster than that of its saturated analogue and to produce only 2-adamantanol (**2**) along with a small quantity of unreactive 2-adamantyl tosylate (**3**) from ion-pair return, eq 1. The reaction exemplifies the π route to 2-substituted



(1)

and 2,4-disubstituted adamantanes discovered by Udding, Wynberg, and Strating[2] and since exploited by a number of workers.[1b,c,3]

Consideration of the detailed mechanism of the solvolysis of **1** involves two limiting possibilities for intermediate carbocation structure.[2] Reaction could be initiated on one hand by π-assisted ionization of the primary reactant directly to the 2-adamantyl cation (**4**). Substantial driving force is apparent in this pathway through a conversion of a π to a σ bond, possibly with net relief of strain associated with the reactant double bond. Alternatively, ionization could produce a strongly bridged cation, **5**, with stable three-center, two-electron bonding, as postulated for numerous other cases of π-assisted solvolysis.[4] A complication relatively likely in this event might be hydride shift converting **5** to degenerate isomer **5′**, eq 2. An additional contribution could be

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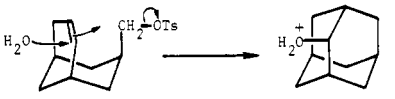
made by nucleophilically induced π-assisted ionization whereby the conjugate acid of the product would be formed from the substrate in a single step,[5] eq 3.



(3)

A stereochemical distinction among the possible mechanisms appeared promising for this system. Reaction via the C_{2v} carbenium ion **4** per se would lead to nucleophilic attack equally at both faces of the cationic carbon. Product formation from bridged ion **5**, on the other hand, would be expected to occur with nucleophilic attachment wholly on the side opposite the ring closure. The latter results would also attend the concerted process of eq 3. This paper reports determination of the stereochemistry and related evidence on the solvolysis of **1** which provide substantial mechanistic clarification.

Results

The stereochemistry was established by 15.4-MHz ^2H NMR configurational analysis of the 2-adamantanols-*4,4-d*$_2$, **7** (R = H) and **8** (R = H), obtained as the immediate or derived products

(1) (a) Raber, D. J.; Kane, G. J.; Schleyer, P. v. R. *Tetrahedron Lett.* **1970**, 4117. See also: (b) Numan, H.; Wynberg, H. *J. Org. Chem.* **1978**, *43*, 2232. (c) Wnuk, T.; Tonnis, J. A.; Dolan, M. J.; Padegimas, S. J.; Kovacic, P. *Ibid.* **1975**, *40*, 444. (d) Compare: Woodward, R. B.; Gosteli, J.; Ernest, I.; Friary, R. J.; Nestler, G.; Raman, H.; Sitrin, R.; Suter, C.; Whitesell, J. K. *J. Am. Chem. Soc.* **1973**, *95*, 6853. Ernest, I. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 207.

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(5) For previous consideration of such a possibility, see: Cope, A. C.; Peterson, P. E. *J. Am. Chem. Soc.* **1959**, *81*, 1643.

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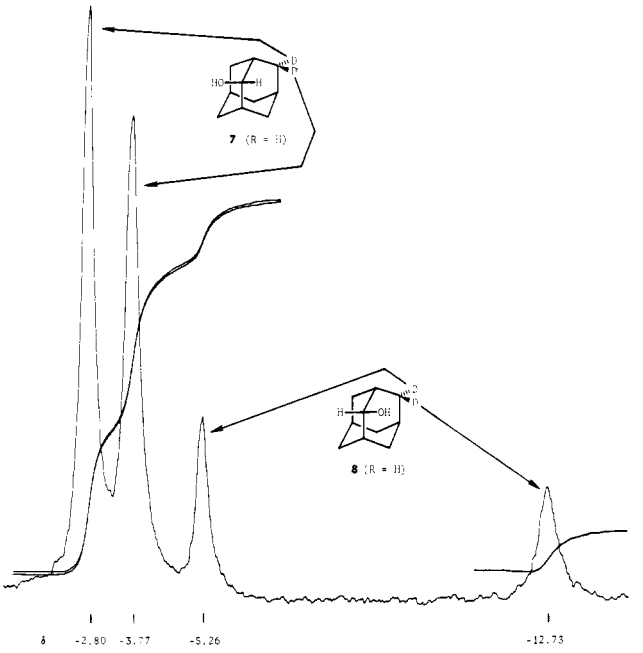
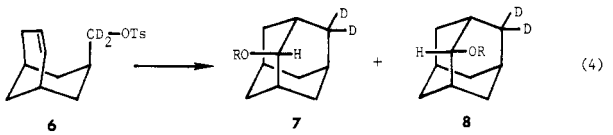


Figure 1. Pr(fod)$_3$-dispersed, proton-decoupled 15.4-MHz ^{2}H NMR spectrum of the 2-adamantanols-*4,4-d*$_2$ derived from the corresponding tosylates formed in acetolysis of *endo*-bicyclo[3.3.1]non-6-ene-3-(methyl-d_2) tosylate (**6**).

of reaction of α,α-dideuterated substrate **6**[1b] in several solvents, eq 4. Identification of the epimeric alcohols followed straightforwardly from the separate ^{2}H chemical shifts previously ascertained for the four diastereomeric 2-adamantanols-*4-d* in the presence of shift reagent Pr(fod)$_3$.[6] A typical spectrum is shown in Figure 1. The earlier line assignments are reconfirmed by the matched intensities of the signals for **7** (R = H) and for **8** (R = H).



6 **7** **8**

The alcohol precursor[1b] to tosylate **6** was obtained by $LiAlD_4$ reduction of the corresponding carboxylic acid, prepared by the abnormal Schmidt reaction of adamantanone developed by Sasaki[7] and McKervey[3b] and co-workers.[8] Solvolysis of **6** proceeded cleanly at room temperature in buffered 80% aqueous acetone, acetic acid, methanol, and 2,2,2-trifluoroethanol. The analogous smooth rearrangement of **6** in chloroform[1a] was also investigated. Products **7** and **8** both from solvent incorporation and where feasible from tosylate isomerization were degraded to the alcohols as necessary by reactions preserving the configurations. The acetate esters were cleaved by methanolic KOH, methyl ethers by $(CH_3)_3SiI$,[9] and trifluoroethyl ethers[10] and tosylates[11] by sodium α-(dimethylamino)naphthalenide. A control reaction was run to prove sulfonyl–oxygen fission in the tosylate degradation. The fraction of isomerized tosylate in each product mixture was determined following workup by integration of the tolyl methyl ^{1}H NMR signal against a suitable second absorption. The products throughout were found to be free from possible 4-protoadamantyl and other byproducts within ^{1}H NMR spectroscopy detectability limits. Carbonium ion isomerization of type **5** → **5′** was also excluded in each case by the absence of a distinctively shifted ^{2}H >CD–OH signal, corresponding to that exhibited by 2-adamantanol-*2-d*.

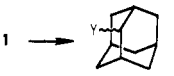
The product distributions are recorded in Table I.

The product composition for reaction of **1** in 80% aqueous ethanol containing 0.06 M NaN_3 was determined in order to probe the possibility of ionization of **1** induced by solvent nucleophilic attack, eq 3. Schleyer and co-workers have found the fraction of azide product formed under these conditions to be a sensitive measure of the susceptibility of a secondary alkyl substrate to react with nucleophilic solvent assistance.[12] The results are given in Table II.

Table I. Solvolysis Products from *endo*-Bicyclo[3.3.1]non-6-ene-3-(methyl-d_2) Tosylate (**6**) at 20 °C, eq 4

solvent	R	% (7 + 8)	config anal % 7	% 8
MeOH	Me	93	98	2
	Ts	7		
80% aq Me_2CO	H	93	98	2
	Ts	7		
HOAc	Ac	88	96	4
	Ts	12	78	22
CF_3CH_2OH	CF_3CH_2	71	86	14
	Ts	29	71	29
$CHCl_3$	Ts	100	54	46

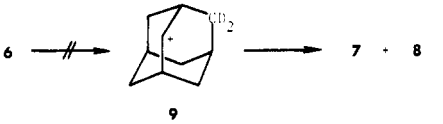
Table II. Products of Solvolysis of 0.01 M *endo*-Bicyclo[3.3.1]non-6-ene-3-methyl Tosylate (**1**) in 80% EtOH Containing 0.06 M NaN_3 at 20 °C



Y	%
HO	65
EtO	17
N_3	1
TsO	17

Discussion

Solvent-Capture Products. The moderate to strong preference for formation of stereoisomers **7** over **8** in the solvolysis products from labeled tosylate **6** allows us first to rule out the corresponding 2-adamantyl cation **9** (and **4** in eq 1) as a major intermediate.



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Free carbenium ion **9**, as noted, would give rise to solvent-derived products **7** and **8** in equal amount. If, more realistically, the tosylate gegenion is envisioned in a solvent-separated ion-pairing relationship on the CD_2 side of **9**, then predominant formation of products **8** is predicted. Such ion pairs are the evident major intermediates in solvolyses of labeled 2-adamantyl tosylates, where retention of configuration has been found to prevail.[6c,13] The preferred retention in direct 2-adamantyl solvolysis can be un-

(6) (a) Nordlander, J. E.; Haky, J. E. *J. Org. Chem.* **1980**, *45*, 4780. See also: (b) Nordlander, J. E.; Haky, J. E.; Landino, J. P. *J. Am. Chem. Soc.* **1980**, *102*, 7487. (c) Nordlander, J. E.; Haky, J. E. *Ibid.* **1981**, *103*, 1518.

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(12) (a) Raber, D. J.; Harris, J. M.; Hall, R. E.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 4821. (b) Raber, D. J.; Harris, J. M.; Schleyer, P. v. R. *Ibid.* **1971**, *93*, 4829. See also: (c) Kovačević, D.; Majerski, Z.; Borčić, S.; Sunko, D. E. *Tetrahedron* **1972**, *28*, 2469.

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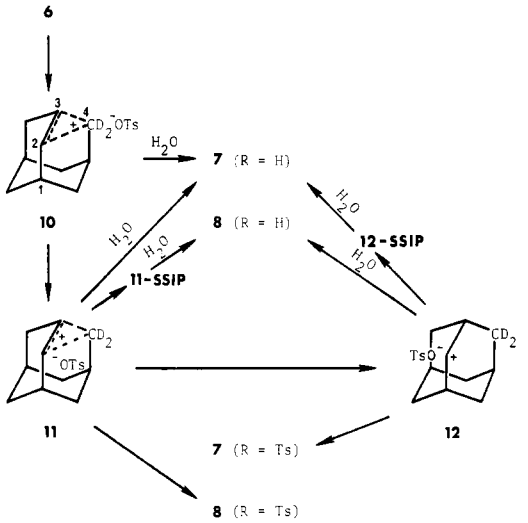
Scheme I[a]



[a] **11-SSIP** and **12-SSIP** are the solvent-separated ion pairs corresponding to intimate ion pairs **11** and **12**.

derstood as the combined consequence of steric hindrance and perhaps weak bridging at the backside[14] and hyperpolarization of a solvent molecule within the ion-pair field at the frontside.[12a,13,15]

Any significant contribution by the concerted mechanism of eq 3 is also disproved by the results of the solvolysis employing azide ion. Reaction of **1** in 80% EtOH containing 0.06 M NaN_3 at room temperature yields only ~1% of 2-adamantyl azide. 2-Propyl tosylate (50 °C) and 1-phenyl-2-propyl tosylate (75 °C) in this medium, by comparison, produce 65% and 67–71% of the corresponding azide products.[12] The formation of 2-adamantyl azide from **1** is not appreciably greater than the 0.7% produced in the same medium (75 °C) from 2-adamantyl tosylate, a normative reactant for ionization without nucleophilic solvent assistance.[12a,16]

The stereochemistry of the products of solvent incorporation from **6** is explained by the mechanism of Scheme I, showing water as a representative nucleophile. π-Assisted ionization generates initially a strongly, while unsymmetrically, bridged carbonium ion within an intimate ion pair, **10**. In comparatively nucleophilic media a substantial fraction of the product is reasonably attributed to solvent attack at the backside of C-2 in **10** (positions numbered as in the product), yielding **7** (R = H) in the example shown. We ascribe the strongly bridged character evidenced for the cation in **10** to polarization of the anchimerically participating electrons by the proximate tosylate counterion. Thus, charge separation is minimized in this structure relative to an alternative 2-adamantyl cation, **9**, in contact with tosylate ion at the CD_2 ionization site.

Concurrent isomerization of **10** to tight ion pair **11** by tosylate ion migration from C-4 to C-2 should be stabilizing by virtue of electron redistribution in the carbonium ion permitting a greater fraction of the positive charge to be borne by a secondary rather than a primary carbon. The cation in **11** is nevertheless formulated as still significantly bridged at the frontside in view of the preference for formation of return products **7** (R = Ts) over **8** (R = Ts), as discussed in the following section. Ion pair **11** is seen as a second precursor to **7** (R = H) by efficient backside solvent attack as well as a precursor to **8** (R = H) by dissociation to the corresponding solvent-separated ion pair, **11-SSIP**, and frontside attack by an included water molecule (and likewise in other solvents).

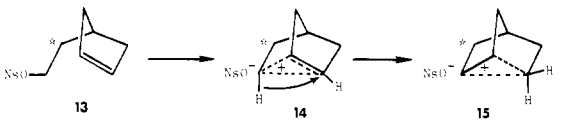
Ion-pair epimerization **11** → **12** is shown to make an important contribution by the stereochemistry of tosylate return, discussed below. Tight ion pair **12** is presumably closely similar to the first intermediate produced in direct solvolysis (at higher temperature) of 2-adamantyl tosylate.[13,16] Accordingly **12** is postulated to give rise to **8** (R = H), for the most part prior to dissociation, together with **7** (R = H) by way of the corresponding solvent-separated ion pair, **12-SSIP**.

Tosylate Isomerization Products. Return of tosylate ion to produce unreactive 2-adamantyl tosylate competes significantly with the formation of solvent-derived products from substrate **6** or **1** in all media studied. The proportion of rearranged tosylate, Tables I and II, appears to increase with increasing ionizing power and decreasing nucleophilicity of the solvent, as would be anticipated.

The very minor generation of azide product in the solvolysis of **1** with added 0.06 M NaN_3, Table II, establishes that the isomerization of **1** to **3** and **6** to **7** (R = Ts) + **8** (R = Ts) occurs essentially entirely within ion pairs. Nucleophilic attack by free dissociated tosylate ions would have to be even less effective than that measured for the more nucleophilic[12] and more concentrated azide ions. The substantial return fractions observed make it likely, moreover, that the intermediates along this route are all contact ion pairs.

The stereochemical data in Table I (from spectra exemplified by Figure 1) for isomerization of tosylate **6** reveal, remarkably, that ion-pair return in the three diverse solvents studied is mainly a non-least-motion process. The direct 1,5 migration of tosylate ion from **6** affords **8** (R = Ts) via **10** and **11**. The epimeric **7** (R = Ts), however, is formed in larger amount in each case. This selectivity indicates that the bridging characteristic of tight ion pair **10** is significantly preserved in the isomeric **11**, rendering the distal face of C-2 more electrophilic than the proximal face. Thus tosylate return follows predominantly the circuitous pathway from **11** to **7** (R = Ts) through **12**.

Related Systems. Effects related to those inferred here have been observed in other π-route solvolyses. Lee and co-workers found the production of *exo*-2-norbornyl esters in the acetolysis (60 °C) and formolysis (60 °C) of 2-(Δ^3-cyclopentenyl)ethyl-2-^{14}C 4-nitrobenzenesulfonate[17,18] (**13**, * = ^{14}C) to be attended by



substantially larger fractions of 6,2-type hydride shift than in the corresponding reactions (45 and 25 °C, respectively) of *exo*-2-norbornyl-*2-t* brosylate.[18,19] Hydride shift would stabilize particularly the initial ion pair in the π-assisted reactions by converting the carbonium ion position next to the anion from a primary to a secondary center, **14** → **15**, thereby diminishing charge separation. The polarization of the positive charge toward the counterion in **15** also provides a basis for explanation of the greater fraction of ^{14}C label found at C-3 than at C-7 in the *exo*-2-norbornyl acetate from **13**.[17a,b] Collins has pointed out that this disparity is inconsistent with product formation solely from a C_{2v} bridged carbonium ion, and he also proposed counterion control, possibly of an equilibrium between open ions.[18] The nonoccurrence of analogous hydride shift in tight ion pair **10** (Scheme I and eq

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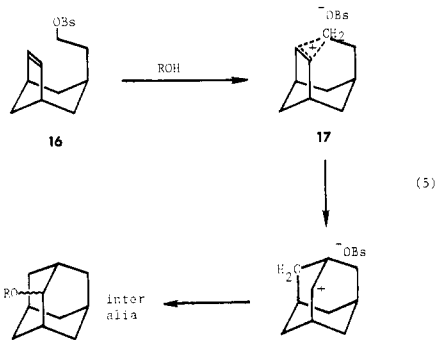
(17) (a) Lee, C. C.; Hahn, B.-S. *J. Am. Chem. Soc.* **1969**, *91*, 6420. (b) Lee, C. C.; Lam, L. K. M. *Ibid.* **1966**, *88*, 2834. (c) See also: Humski, K.; Borčič, S.; Sunko, D. E. *Croat. Chem. Acta* **1965**, *37*, 3.

(18) See also: Collins, C. J.; Lietzke, M. H. *J. Am. Chem. Soc.* **1967**, *89*, 6565. Collins, C. J. *Chem. Soc. Rev.* **1975**, *4*, 251.

(19) (a) Lee, C. C.; Lam, L. K. M. *J. Am. Chem. Soc.* **1966**, *88*, 2831. (b) Lee, C. C.; Lam, L. K. M. *Ibid.* **1966**, *88*, 5355. (c) See also: Roberts, J. D.; Lee, C. C.; Saunders, W. H., Jr. *Ibid.* **1954**, *76*, 4501. Roberts, J. D.; Lee, C. C. *Ibid.* **1951**, *73*, 5009.

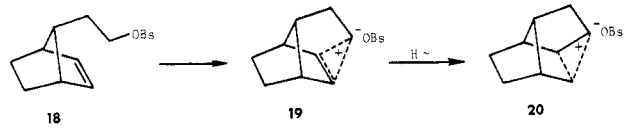
2) in the present system points to a longer bridging bond (C-2–C-4) and correspondingly higher activation energy than in the norbornyl case. The firm demonstration here that **10** is nevertheless strongly bridged adds to the extensive evidence for exceptional bridging in the 2-norbornyl cation.[20]

Predominant hydride shift takes place in π-assisted solvolysis of bicyclooctenylethyl brosylate **16**, shown by Spurlock and Clark[21,22] to give 2-adamantyl derivatives as the principal cyclized products over a range of solvents, eq 5. This facile rearrangement



again implicates a bridged ion, **17**, in the light of our results with **6**. An ad hoc driving force here is attainment of the stable adamantyl ring skeleton. Weak bridging may also be present in the 2-adamantyl cation formed from **17** in view of the immediate location of the counterion opposite the bridgehead.

Bly, Bly, and co-workers[4i,j] in a detailed analysis of the complex course of π-assisted solvolysis of β-(*syn*-7-norbornenyl)ethyl brosylate (**18**) in several media have also reached conclusions based on counterion influence. Displacement in this system occurs entirely subsequent to hydride shift in either the first formed ion pair, most reasonably **19**, or else a degenerate second- or later-



generation cation reached by Wagner–Meerwein rearrangement. The preference observed for hydride shift, **19** → **20**, prior to Wagner–Meerwein automerization was attributed to the distinctive associated decrease in ion-pair charge separation.

The anchimeric acceleration factor $k_{unsat}/k_{sat} = 2 \times 10^4$ for the solvolysis of **1** in 80% acetone (25 °C)[1] compares with values of 95 (60 °C) for **13**,[23] 18 (100 °C) for **16**,[21,22] and 1.4×10^5 (25 °C) for **18**,[24] all in HOAc. These data reflect the comparative tightness of incipient bonding in the ionization transition states. Unlike the others, the π assistance in **1**, as noted, is constrained to be unsymmetrical.

A further plain example of counterion control in a π-route displacement is the major formation of *exo*-5-norbornenyl isothiocyanate over 3-nortricyclyl isothiocyanate on ionization of *exo*-5-norbornenyl thiocyanate under kinetic control, contrary to the result from 3-nortricyclyl thiocyanate.[25,26]

The deduction of delocalized structures for reactive intermediates **10** and **11** (and **5**) here on stereochemical grounds is in accord with the conclusions of studies of several analogous stable ions by NMR spectroscopy.[14,27]

Experimental Section

Melting points in capillary tubes were obtained with a Thomas-Hoover apparatus and are uncorrected.

^{1}H NMR spectra were recorded at 60 MHz on a Varian A-60A or EM-360A spectrometer, using $CDCl_3$ as solvent and Me_4Si as internal standard. ^{2}H NMR spectra were recorded at 15.4 MHz on a Varian XL-100-15 Fourier transform spectrometer with modulation proton decoupling, using α,α,α-trifluorotoluene for external lock. The solvent used was $CHCl_3$ containing 0.5% $CDCl_3$ as internal standard.

***endo*-Bicyclo[3.3.1]non-6-ene-3-methyl Tosylate (1) and *endo*-Bicyclo[3.3.1]non-6-ene-3-(methyl-d_2) Tosylate (6).** Following the directions of Numan and Wynberg,[1b] we prepared the alcohols precursory to **1** and **6** by $LiAlH_4$ and $LiAlD_4$ reduction, respectively, of the corresponding (racemic) carboxylic acid, obtained by the reaction of adamantanone with hydrazoic acid followed by treatment with base.[3a] The tosylates were prepared in 92–95% yields by the method of Numan and Wynberg[1b] modified by the inclusion of 0.1 equiv of 4-pyrrolidinopyridine[28] and by hydrolysis of the unreacted excess tosyl chloride with a slight molar excess of water prior to neutralization of the pyridines with a large volume of cold aqueous HCl. The products were recrystallized from pentane between room temperature and −70 °C: both mp's 53.0–54.0 °C (lit.[1a] mp 52.2–53.8 °C); ^{1}H NMR of **1** δ 1.1–2.4 (m, 11 H, alicyclic), 2.43 (s, 3 H, CH_3), 3.8–4.2 (m, 2 H, CH_2O), 5.2–5.9 (m, 2 H, CH=CH), 7.54 (d of d, 4 H, aromatic).

Methanolysis of 6. Tosylate **6** (500 mg, 1.62 mmol) was dissolved in 32.4 mL of methanol (Fisher, certified) containing 207 μL (191 mg, 1.78 mmol) of 2,6-lutidine and allowed to react at room temperature for 15 h. The colorless solution was poured into 250 mL of cold water and extracted with four 25-mL portions of ether. The combined ether solution was washed successively with cold 5% hydrochloric acid, water, 5% aqueous $NaHCO_3$, and water and was dried over anhydrous $MgSO_4$. Gentle rotary evaporation of the solvent afforded a colorless oil. The composition of the crude product was analyzed by ^{1}H NMR, the fraction of 2-adamantyl tosylate being determined by integration of the tolyl CH_3 peak at δ 2.43[29] against the ether CH_3 signal at δ 3.30.

For conversion of the labeled ethers to the corresponding alcohols, the crude product was dissolved in MeCN and treated with 2 equiv of Me_3SiI generated in situ from Me_3SiCl and NaI by the method of Olah et al.[9c] The resultant 2-adamantanol was purified by careful vacuum sublimation followed by recrystallization from hexane. The sublimation residue was found by ^{1}H NMR spectroscopy to retain the isomerized tosylate. Both the recrystallized alcohol and the concentrated mother liquors were found to be free from possible byproducts *exo*- and *endo*-4-protoadamantanol by ^{1}H NMR transparency at δ 4.38 and 4.05, respectively.[30] The 2-adamantanol **7** (R = H) + **8** (R = H) was subjected to ^{2}H NMR configurational analysis as described below.

Hydrolysis of 6 in 80% Acetone. Tosylate **6** (500 mg, 1.62 mmol) was solvolyzed in 32.4 mL of 80% aqueous acetone containing 207 μL (191 mg, 1.78 mmol) of 2,6-lutidine at room temperature for 9 h. The colorless crude product was isolated by the same procedure employed for the methanolysis. Quantitative ^{1}H NMR comparison of the >CHO signal for the 2-adamantanol at δ 3.88[30] and the methyl signal for the 2-adamantyl tosylate at δ 2.43[29] established the relative yields. Possible products *exo*- and *endo*-4-protoadamantanol were again shown to be absent by the ^{1}H NMR criterion described under methanolysis. The 2-adamantanol was purified in the same manner as the alcohol derived from the methanolysis and was configurationally analyzed by ^{2}H NMR spectroscopy as described below.

Acetolysis of 6. Tosylate **6** (1.0 g, 3.2 mmol) was solvolyzed in 64.8 mL of acetic acid containing 295 mg (3.6 mmol) of NaOAc and 1% (wt) of acetic anhydride at room temperature for 11 h. The solution was

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poured into 400 mL of cold water and extracted with three 50-mL portions of ether. The combined ether extract was washed with aqueous $NaHCO_3$ followed by water and then dried over anhydrous $MgSO_4$. Rotary evaporation left a pale yellow oil. The integrated intensities of the >CHO signal of the 2-adamantyl acetate at δ 4.85[30] and the CH_3 signal of the 2-adamantyl tosylate at δ 2.43[29] in the ^1H NMR spectrum of the crude product were used to determine the relative yields of the solvent-derived and return components. Possible *exo*-4-protoadamantyl acetate was seen to be absent by the lack of absorption at δ 5.08.[30] The acetate and tosylate were separated by chromatography on silica gel (30 × 2.5 cm column) using 10% EtOAc in hexane as elutant. The isolated tosylate (131 mg, 0.43 mmol) was cleaved to the alcohol by treatment with 4 equiv of sodium α-(dimethylamino)naphthalenide in dry 1,2-dimethoxyethane by the method of Bank and Platz.[11] The acetate (600 mg, 3.1 mmol) was saponified with 5% methanolic KOH at room temperature for 16 h. The resultant 2-adamantanols-*4,4-d*$_2$ were purified by vacuum sublimation and recrystallization from hexane and subjected to ^2H NMR analysis as described below.

Trifluoroethanolysis of 6. 2,2,2-Trifluoroethanol (Fisher, certified) was dried over freshly dehydrated (120 °C) 4-Å molecular seives and distilled under N_2. The solvolysis of tosylate **6** in this solvent buffered with 2,6-lutidine and the associated workup were carried out in the same manner as described for the methanolysis. The overlapping ^1H NMR signals for the OCH_2CF_3 protons at δ 3.80 (q, J = 8.4 Hz)[31] and the >CHO protons at δ 3.54 (s) of the 2-adamantyl trifluoroethyl ether product were integrated against the CH_3 peak of the 2-adamantyl tosylate at δ 2.43[29] to establish their relative yields. The ether and tosylate were separated by chromatography on a silica gel column (25 × 2.5 cm) using 5% EtOAc in hexane as the elutant. The isolated ether (291 mg, 1.2 mmol) and tosylate (139 mg, 0.45 mmol) were treated separately with 4 equiv of sodium α-(dimethylamino)naphthalenide[10,11] to cleave them to the corresponding 2-adamantanols, which were purified as described under methanolysis and subjected to ^2H NMR configurational analysis as detailed below. Possible products *exo*- and *endo*-4-protoadamantanol were again shown to be absent by the ^1H NMR criterion described under methanolysis.

Isomerization of 6 in Chloroform. Tosylate **6** (500 mg, 1.62 mmol) was dissolved in 32.4 mL of $CHCl_3$ and allowed to stand at room temperature for 5 days. The solvent was removed by rotary evaporation. The resultant white solid was indicated by ^1H NMR spectroscopy to consist entirely of 2-adamantyl tosylate. The product (480 mg) was cleaved to the corresponding 2-adamantanols-*4,4-d*$_2$ by treatment with 4 equiv of sodium α-(dimethylamino)naphthalenide[11] and subsequent purification as described above.

Configurational Analysis of the Product 2-Adamantanols-*4,4-d*$_2$. The labeled 2-adamantanols **7** (R = H) + **8** (R = H) were analyzed by ^2H NMR spectroscopy under the sample conditions optimized previously for the stereoisomeric 2-adamantanols-*4-d*:[6] 15 mg of alcohol and 70 mg of $Pr(fod)_3$ (Norell, Inc., stored under vacuum (30 mmHg) at 40 °C and used with minimal exposure to air) dissolved in 400 μL of $CHCl_3$ containing 0.5% of $CDCl_3$ as internal chemical shift reference. The four ^2H signals for the present epimeric dideuterated alcohols had the same general appearance as the peaks observed earlier for the four diastereomeric monodeuterated alcohols.[6] The induced shifts reported here, however, are substantially greater than those measured in the previous work under nominally the same conditions, evidently the result of drier shift reagent in the present study.[32] Thus **7** (R = H) absorbed at δ −2.8 ± 0.1 and −3.7 ± 0.1, and **8** (R = H) at δ −5.2 ± 0.2 and −12.6 ± 0.2. The chemical shifts measured in ppm relative to internal $CDCl_3$ were converted to δ values (relative to $(CD_3)_4Si$) by subtraction from 7.27.[6,33] The signals were digitally integrated with the integration subroutine in the Varian SSFT Fourier transform spectrometer control program.

None of the spectra exhibited detectable absorption near δ −19.87, the line position observed for 2-adamantanol-*2-d* (prepared from 2-adamantanone and $LiAlD_4$[6b]) in the presence of $Pr(fod)_3$ as specified. This finding excludes as much as 1% of 1,3-type deuteride shift in the solvolysis of **6**, whereby 2-adamantanol-*2,4-d*$_2$ would have been produced.

Synthesis and Cleavage of 7 (R = Ts). A control experiment was run to secure the stereochemistry of the 2-adamantyl tosylate cleavages. The mixed alcohol product (218 mg, 1.42 mmol) acquired from the acetates produced in the acetolysis of **6** was converted to the corresponding tosylates, thus 96% **7** (R = Ts) + 4% **8** (R = Ts), by the procedure used for the synthesis of **1** and **6**. This tosylate mixture (217 mg, 0.704 mmol) was cleaved by reaction with sodium α-(dimethylamino)naphthalenide as earlier employed,[11] and the resultant 2-adamantanol (76 mg, 0.49 mmol, 70%) was subjected to ^2H NMR configurational analysis under the standard conditions described above. The alcohol composition was found to be 96% **7** (R = H) + 4% **8** (R = H), establishing the expected total retention of configuration in the tosylate degradation.

80% Aqueous Ethanolysis of 1 with Added NaN_3. Tosylate **1** (500 mg, 1.63 mmol) was dissolved in a solution of 637 mg (9.80 mmol) of NaN_3 in 163 mL of 80% (v/v) aqueous ethanol and allowed to react for 5 h. After workup in the same manner as that following methanolysis, omitting the acidic and basic washes, the pale yellow solid crude product was analyzed by ^1H NMR spectroscopy. The methyl signal of the 2-adamantyl tosylate (**3**) at δ 2.43[29] and the overlapping >CHO– and $-CH_2O-$ signals of the 2-adamantyl ethyl ether at δ 3.29–3.71 were integrated against the essentially isochronous >CHO– and $>CHN_3$ peaks of the 2-adamantyl alcohol (**2**) and azide at δ 3.88 to determine the yields of the tosylate and ether relative to the combined alcohol and azide. A sample of 2-adamantyl azide was independently acquired by synthesis from 2-bromoadamantane as reported by Schleyer and co-workers.[12] Gas chromatographic analysis using a 3 × 4 mm (i.d.) column of 25% SE-30 on 60–80 mesh Chromosorb W, DMCS, at 150 °C afforded well-resolved peaks for the 2-adamantyl ethyl ether, azide, and alcohol with retention times in the ratio 2:5.2:9, respectively. The signals were identified by coinjection with authentic samples. The 2-adamantyl tosylate was found to be retained with no complicating decomposition. The relative yields of alcohol and azide from the peak areas (uncorrected for relative thermal conductivities in view of the meager yield of the azide) were 81:1, respectively.

Note Added in Proof. A recent additional example of non-least-motion counterion return in solvolysis has been reported by Gassman and coworkers.[34]

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Registry No. 1, 30860-11-8; **6**, 84063-98-9; **7** (R = H), 84063-99-0; **8** (R = H), 83213-55-2; NaN_3, 26628-22-8.

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