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Approaches to Destabilized 7-Norbornyl Cations*

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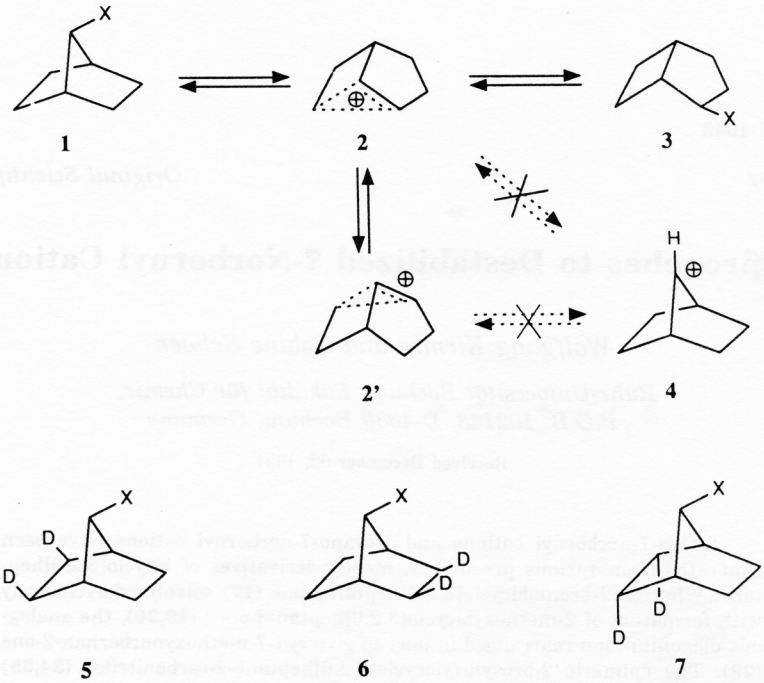
2-Oxo-7-norbornyl cations and 1-cyano-7-norbornyl cations have been generated from various precursors, mostly derivatives of bicyclo[3.2.0]heptane. Whereas 2-bromobicyclo[3.2.0]heptan-3-one (**17**) solvolyzed exclusively with formation of 2-methoxybicyclo[3.2.0]heptan-3-ones (**19,20**), the analogous diazonium ion rearranged in part to give *syn*-7-methoxynorbornan-2-one (**29**). The epimeric 2-brosyloxybicyclo[3.2.0]heptane-2-carbonitriles (**34,35**) solvolyzed with predominant migration of C-7, yielding 1-cyano-7-norbornyl derivatives without significant *anti*→*syn* leakage. Similarly, the decomposition of 5-cyanobicyclo[3.2.0]heptane-2-diazonium ions (**47**) led to 7-hydroxynorbornane-1-carbonitrile (**38**) in a stereospecific manner. Slightly lower stereoselectivity (*ca.* 90%) was observed in solvolyses of labeled 1-cyano-7-norbornyl triflate (**39**). While the stereochemical data conform with those of the parent system, the lack of bridge flipping (**40**⇄**42**) points to graded destabilization of bridged and open ions.

INTRODUCTION

In 1958 Winstein *et al.*[1] observed that acetolysis of either 7-norbornyl brosylate (**1**-OBs) or *exo*-2-bicyclo[3.2.0]heptyl brosylate (**3**-OBs) led to similar product distributions (**1**-OAc:**3**-OAc = 95:5). The bridged ion **2** was proposed as a common intermediate. Subsequent studies focused on 7-norbornyl substrates. The solvolytic rates of **1**-OTs conform to the Foote-Schleyer correlation and exclude significant k_s contributions.[2] The products from the deuterated precursors **5** (X = OTs, OBs, and OTf) were predominantly the *anti* isomers **5**-OR, but *ca.* 10% of the *syn* isomers **6**-OR was also present.[3-5] Sunko *et al.*[5] measured the γ-isotope effects in **5**-OTf (1.024) and **7**-OTf (1.011). These data indicate little, if any, anchimeric assistance in the ionization of **1**. Neither bridged nor open ions can account for the entirety of the stereochemical results.

* Dedicated to Professor Dionis E. Sunko on the occasion of his seventieth birthday



The ionization of **3** proceeds more readily and cleanly. The *anti*→*syn* leakage associated with the solvolyses of 7-norbornyl sulfonates[3-5] is not observed with 2-bicyclo-[3.2.0]heptyl precursors.[6] Partial equilibration, **2**⇌**2'**, occurs without exchange of C-3,4 with C-6,7 and is referred to as »same-side bridge flipping«.[7,8] 7-Norbornyl cations of C_{2v} symmetry (**4**) do not intervene in the reactions of **3**. Introduction of a methyl group either at C-2 or C-5 removes the degeneracy of **2,2'** and generates two bridged ions of different energy which interconvert competitively with solvent capture.[6]

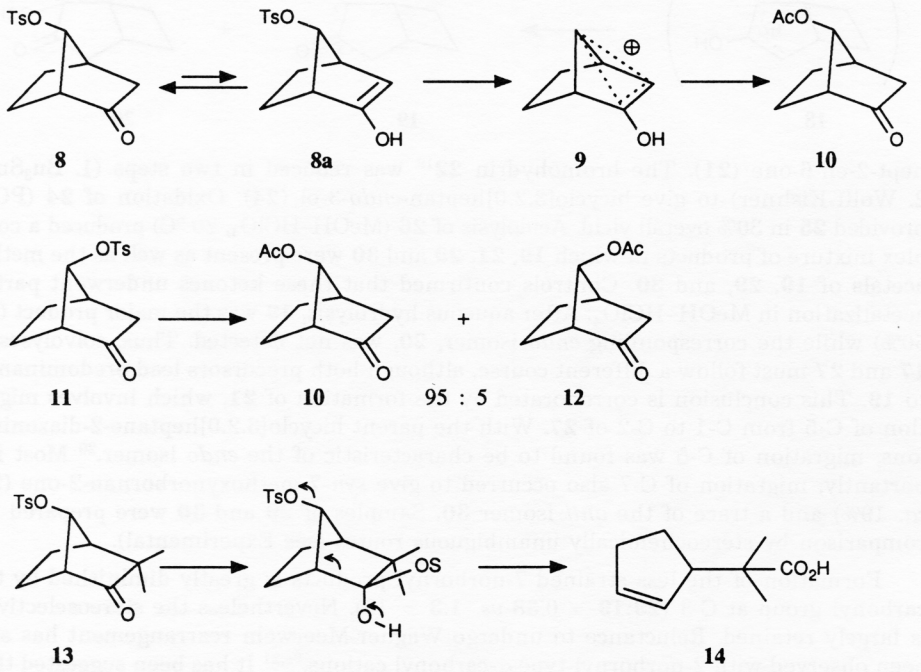
Over the past decade, there has been intense interest in the chemistry of carbocations that have formally electron-withdrawing groups attached to the cationic center.[9] The effect of electron-withdrawing groups on bridged carbocations was also explored. Fluoro,[10] trifluoromethyl,[10] and cyano[11] substituents at C-6 of the 2-norbornyl cation were found to decrease the rate of Wagner-Meerwein rearrangement (relative to solvent capture and 2,3-hydride shift). The stereoselectivity of the parent 2-bicyclo[2.1.1]-hexyl cation[12] was completely lost on introduction of cyano groups at C-1 or C-2.[13] We have now applied similar probes to the 7-norbornyl cation. In this paper, we report on our approaches to 2-oxo- and 1-cyano-7-norbornyl cations.

RESULTS AND DISCUSSION

2-Oxo-7-norbornyl Cations

Attempts at generating the 2-oxo-7-norbornyl cation are not without precedent. Gassman *et al.*[14] studied the acetolysis of *anti*- and *syn*-7-tosyloxynorbornan-2-one (**8,11**). The *anti*-tosylate **8** reacted at a rate of 2.10^7 relative to 7-norbornyl tosylate

to give exclusively the *anti*-acetate **10**. These observations are consistent with formation of the enol **8a** followed by solvolysis of **8a** with participation of the enol double bond as in **9**. A study of the non-enolizable 3,3-dimethyl derivative **13** was frustrated by fragmentation to give the carboxylic acid **14**.[15] Acetolysis of the *syn*-tosylate afforded the acetates **10** and **12** in the ratio of 95:5. In addition to slowing the overall rate of the reaction, the carbonyl group of **11** causes a dramatic increase in the S_N2 character of the substitution process. It appears that the 2-oxo-7-norbornyl cation is bypassed in the solvolysis of both **8** and **11**. These findings prompted us to approach the 2-oxo-7-norbornyl cation from bicyclo[3.2.0]heptyl precursors.



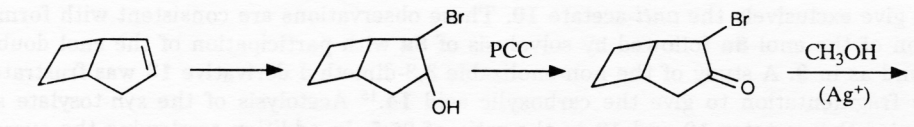
8 **8a** **9** **10**

11 **10** **12**

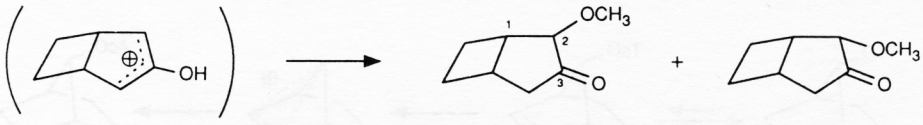
13 **14**

Since monobromination of bicyclo[3.2.0]heptan-3-one (**25**) was not practical, we obtained *exo*-2-bromobicyclo[3.2.0]heptan-3-one (**17**) by oxidation of the bromohydrin **16**[16] derived from bicyclo[3.2.0]hept-2-ene (**15**). Solvolysis of **17** in methanol (100 °C, 4h) afforded *exo*- and *endo*-2-methoxybicyclo[3.2.0]heptan-3-one (**19,20**) in a 1:1 ratio. With »catalysis« by silver perchlorate, the **19**:**20** ratio was 79:21. The isomeric ethers are readily distinguished by the vicinal coupling of 1–H and 2–H ($J<1$ Hz for **19**, $J=8.0$ Hz for **20**). The absence of rearranged products and the formation of *exo* and *endo* isomers suggest the intervention of the hydroxyallyl cation **18** in the methanolysis of **17**. Ample evidence for analogous intermediates in solvolyses of 2-mesyloxycyclohexanones has been adduced.[17]

We argued that the failure of **17** to give 2-oxo-norbornyl cations might be remedied by better leaving groups, such as diazonium ions. The α-diazo ketone **26** was prepared from bicyclo[3.2.0]heptan-3-one (**25**) according to the directions of Wiberg.[18] However, we developed a more convenient route to **25**, starting from bicyclo[3.2.0]-



15 16 17



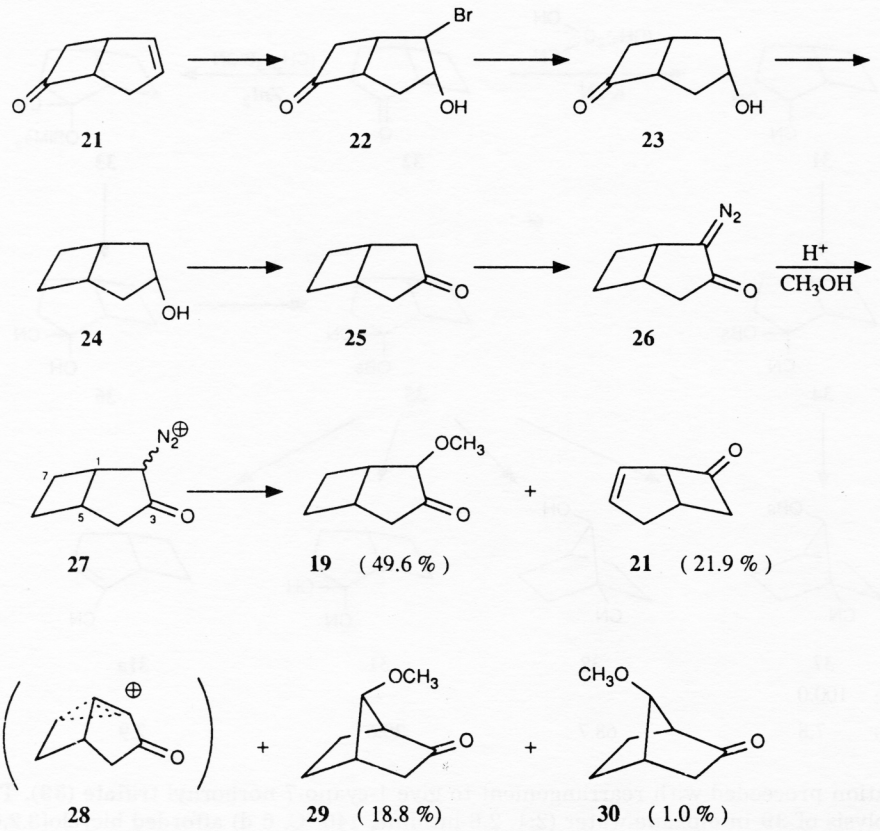
18 19 20

hept-2-en-6-one (**21**). The bromohydrin **22**[19] was reduced in two steps (1. Bu_3SnH, 2. Wolff-Kishner) to give bicyclo[3.2.0]heptan-*endo*-3-ol (**24**). Oxidation of **24** (PCC) provided **25** in 30% overall yield. Acidolysis of **26** (MeOH–$HClO_4$, 20 °C) produced a complex mixture of products in which **19**, **21**, **29** and **30** were present as well as the methyl acetals of **19**, **29**, and **30**. Controls confirmed that these ketones underwent partial acetalization in MeOH–$HClO_4$. After aqueous hydrolysis, **19** was the major product (*ca.* 50%) while the corresponding *endo* isomer, **20**, was not detected. Thus, solvolyses of **17** and **27** must follow a different course, although both precursors lead predominantly to **19**. This conclusion is corroborated by the formation of **21**, which involves migration of C-5 from C-1 to C-2 of **27**. With the parent bicyclo[3.2.0]heptane-2-diazonium ions, migration of C-5 was found to be characteristic of the *endo* isomer.[20] Most importantly, migration of C-7 also occurred to give *syn*-7-methoxynorbornan-2-one (**29**, *ca.* 19%) and a trace of the *anti* isomer **30**. Samples of **29** and **30** were prepared for comparison by stereochemically unambiguous routes (see Experimental).

Formation of the less strained 7-norbornyl products is greatly diminished by the carbonyl group at C-3 (**29**:**19** = 0.38 *vs.* **1**:**3** = 19). Nevertheless the stereoselectivity is largely retained. Reluctance to undergo Wagner-Meerwein rearrangement has also been observed with 2-norbornyl-type α-carbonyl cations.[9e,21] It has been suggested that the adverse inductive effect of C=O is more than offset by π donation. The latest calculation (MP2/6-31G**) indicates that $^+CH_2CHO$ is stabilized relative to $^+CH_3$.[22] Similar considerations may apply to the distribution of charge in the hypothetical bridged ion **28**.

1-Cyano-7-norbornyl Cations

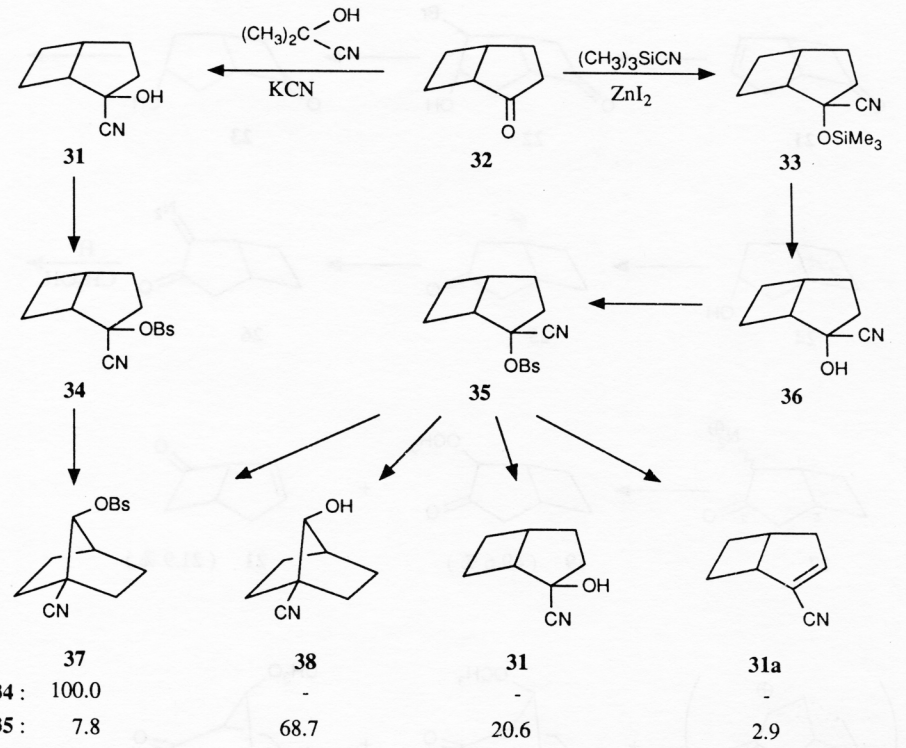
Treatment of bicyclo[3.2.0]heptan-2-one (**32**) with acetone cyanohydrin and potassium cyanide (equilibrating conditions)[23] afforded predominantly *exo*-2-hydroxybicyclo[3.2.0]heptane-*endo*-2-carbonitrile (**31**). Lewis acid-catalyzed reaction of **32** with trimethylsilyl cyanide (kinetic control),[24] followed by hydrolysis of the silyl ether **33**, gave mainly *endo*-2-hydroxybicyclo[3.2.0]heptane-*exo*-2-carbonitrile (**36**). The epimeric cyanohydrins were purified by HPLC to > 99% and converted into the analogous brosylates, **34** and **35**. The solvolysis of **34** in dioxane-water (2:1; 100 °C, 2 h) proceeded with rearrangement and internal return to give exclusively 1-cyano-7-norbornyl brosy-



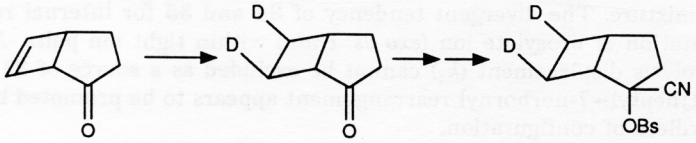
late (**37**). The brosylate **37** proved to be inert even under forcing conditions (130 °C, 7 d). The epimeric brosylate **35** was also less reactive than **34** but solvolyzed within 4 d at 100 °C to give cyanohydrin **31** and 1-cyano-7-norbornanol (**38**) as major products. Return of the brosylate ion, with formation of **37**, accounted for a minor fraction (*ca.* 8%) of the mixture. The divergent tendency of **34** and **35** for internal return is due to the orientation of brosylate ion (*exo vs. endo*) within tight ion pairs. Although inverting solvolysis displacement (k_s) cannot be excluded as a source of **31**, cationic 2-bicyclo[3.2.1]heptyl→7-norbornyl rearrangement appears to be promoted by the cyano group, regardless of configuration.

The stereochemistry of the rearrangement was explored with the aid of the deuterated precursor, *exo*-[6,7-^{2}H]-**35**. The addition of deuterium to bicyclo[3.2.0]hept-6-en-2-one[25] proceeded with excellent *exo* selectivity but was associated with a small amount of H-D-exchange α to the carbonyl group (C-3). Following the procedures described above, the deuterated brosylate *exo*-[6,7-^{2}H]-**35** was prepared and solvolyzed. ^{2}H NMR analysis of the 7-norbornyl products, **37** and **38**, indicated ≤2% of *anti*→*syn* leakage. We conclude that the cyano group does not affect the stereochemistry of the 2-bicyclo[3.2.0]-heptyl→7-norbornyl rearrangement.

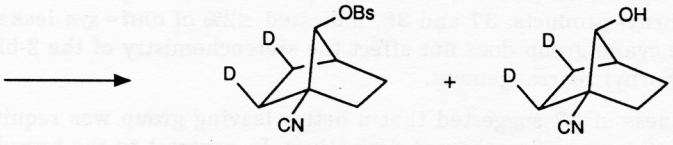
The inertness of **37** suggested that a better leaving group was required to study the solvolysis of 1-cyano-7-norbornyl derivatives. In contrast to the brosylation of **31**,



triflation proceeded with rearrangement to give 1-cyano-7-norbornyl triflate (**39**). The solvolysis of **39** in dioxane-water (2:1, 2,6-lutidine, 140 °C, 6 d) afforded bicyclo[3.2.0]-hept-3-ene-1-carbonitrile (**41**) and 7-hydroxynorbornane-1-carbonitrile (**38**) as major products, together with small amounts of **31** and several unidentified, minor components. In the absence of buffer, **41** was hydrolyzed to the analogous amide. The product dis-



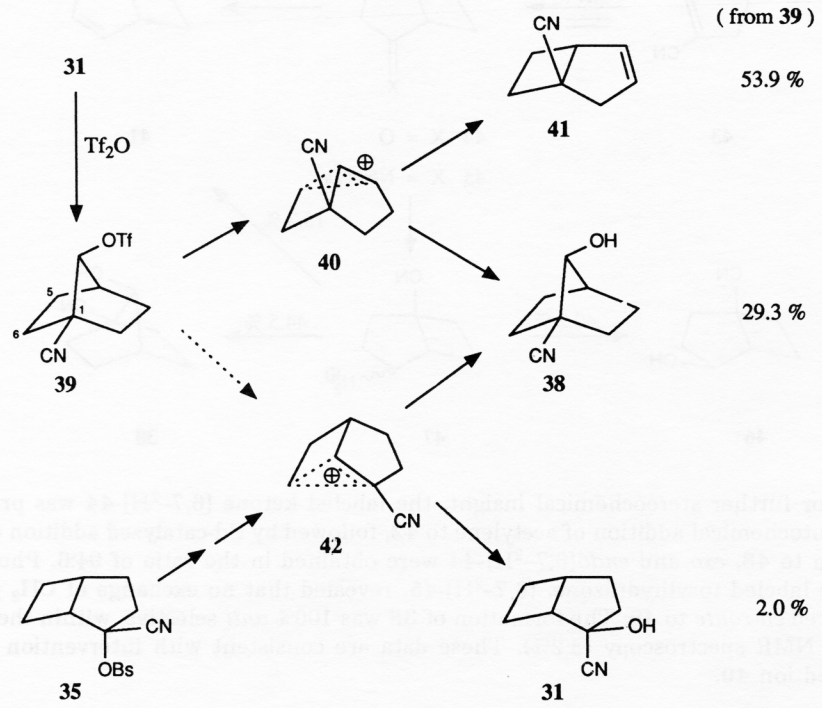
[6,7-^{2}H]-**32** [6,7-^{2}H]-**35**

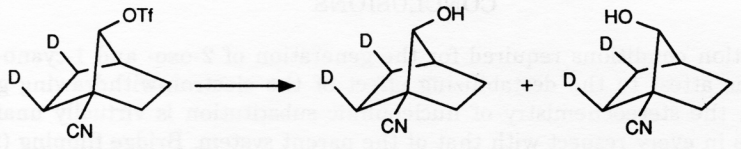


[5,5-^{2}H]-**37** [5,5-^{2}H]-**38**

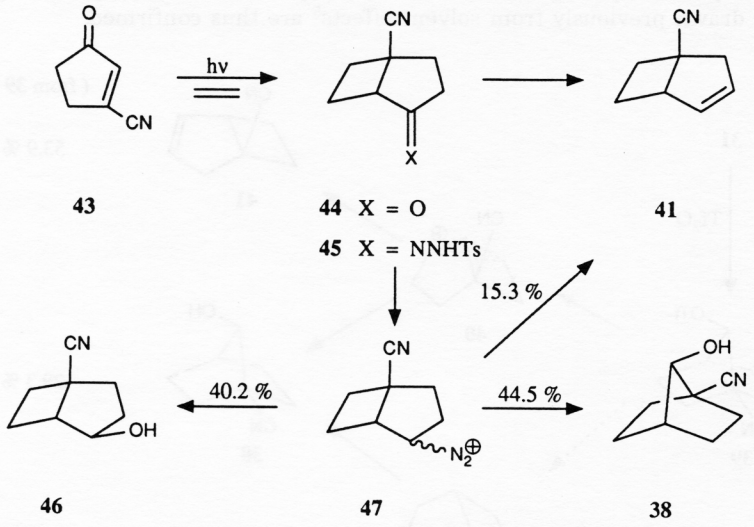
tribution indicates that **39** ionizes with predominant participation of C-5 (rather than C-6). In terms of bridged intermediates, **40** is preferred to **42**. The desire to separate the positive charge from the cyano group compensates for the enhanced strain of **41** relative to **38**. Remarkably, **41** was not observed in solvolyses of **35** (see above). Bridge-flipping (**42**→**40**), although exothermic, does not occur – in obvious contrast to the degenerate rearrangement (**2**⇌**2'**) of the parent ion.

The solvolysis of the labeled triflate, [5,6-^{2}H]-**39**, was found to proceed with predominant retention of configuration, although *anti*→*syn* leakage was slightly enhanced over that observed with [6,7-^{2}H]-**35**. The stereochemical results closely parallel those obtained with labeled 7-norbornyl triflate (**3**-OTf)[5] and support the bridged ion formulation (**40**,**42**) of the intermediates. Since **39** ionizes much less readily than **3**-OTf, inverting nucleophilic displacement (k_s) is not a likely source of *anti*→*syn* leakage. The conclusions drawn previously from solvent effects[5] are thus confirmed.





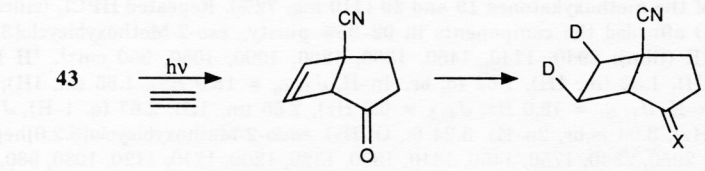
In the course of an unequivocal synthesis of **41**, ethene was added photochemically to 3-oxocyclopentene-1-carbonitrile (**42**)[26] with formation of 4-oxobicyclo[3.2.0]heptane-1-carbonitrile (**44**). The tosylhydrazone **45**, derived from **44**, provided **41** on pyrolysis of its sodium salt. The photolysis of **45** in 0.2 M NaOH was also investigated, in order to approach the cation **40** by way of the diazonium ion(s) **47**. The products **38** (44.5%), **41** (15.3%), and **46** (40.2%) were obtained while the *endo* isomer of **46** was not detected. The formation of bicyclo[3.2.0]heptyl derivatives now proceeds with predominant substitution, rather than elimination, and **38** is more abundant than it was in the solvolysis of **39**. These differences may be attributed to the divergent reaction conditions (room temperature *vs.* 140 °C). A significant feature is the absence of **31** in the product mixture, excluding the interconversion of **40** with **42**.

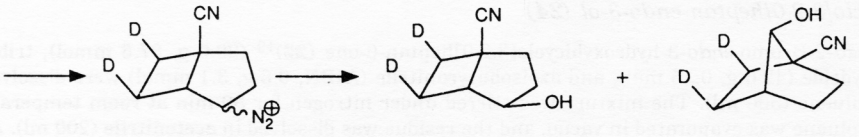


For further stereochemical insight, the labeled ketone [6,7–^{2}H]-**44** was prepared by photochemical addition of acetylene to **42**, followed by Pd-catalyzed addition of deuterium to **48**, *exo* and *endo*[6,7–^{2}H]-**44** were obtained in the ratio of 94:6. Photolysis of the labeled tosylhydrazone, [6,7–^{2}H]-**45**, revealed that no exchange of CH_2 groups occurred *en route* to **46**. The formation of **38** was 100% *anti* selective, within the limits of ^{2}H NMR spectroscopy (±2%). These data are consistent with intervention of the bridged ion **40**.

CONCLUSIONS

The reaction conditions required for the generation of 2-oxo- and 1-cyano-7-norbornyl cations attest to the destabilizing effect of the electron-withdrawing groups. Nevertheless, the stereochemistry of nucleophilic substitution is virtually unaffected and conforms in every respect with that of the parent system. Bridge flipping (**2**⇌**2'**), however, is eliminated by the presence of a cyano group (**40**≠ **42**). This observation implies that the transition state of bridge flipping, closely resembling the 7-norbornyl





cation (C_s) is destabilized more strongly by CN than either of the bridged structures (C_1). Contrasting results were obtained with 2-bicyclo[2.1.1]hexyl and 1-cyano-2-bicyclo[2.1.1]hexyl cations,[12] pointing to the crucial influence of the carbon skeleton. More work is required before general conclusions can be drawn as to the relative destabilization of bridged and open carbocations.

EXPERIMENTAL

Melting points were determined on a Kofler hot-stage apparatus and are uncorrected. ^{1}H NMR spectra were obtained at 80 (Bruker WP 80) and 400 MHz (Bruker AM-400). ^{2}H (61.42 MHz) and ^{13}C (100.61 MHz) NMR spectra were recorded on the Bruker AM-400 spectrometer. Chemical shifts in $CDCl_3$ are reported in δ relative to tetramethylsilane as an internal standard, unless otherwise indicated. Gas chromatography (GC) was performed by the use of a Siemens Sichromat equipped with glass capillary columns. Varian Aerograph 920 instruments equipped with packed glass columns. were used for preparative gas chromatography (PGC). High-pressure liquid chromatography (HPLC) was carried out with LDC (Milton Roy) chromatographs and refractometric detection.

exo-2-*Bromobicyclo[3.2.0]heptan-3-one (**17**)*

To a solution of *exo*-2-bromobicyclo[3.2.0]heptan-*endo*-3-ol (**16**)[16] (100 mg, 0.52 mmol) in dry methylene chloride (20 ml) was added at 0 °C with stirring pyridinium chlorochromate (PCC)[27] (170 mg, 0.79 mmol). After being stirred for 4 h at 0 °C, the mixture was diluted with ether (100 ml) and filtered. The filtrate was concentrated in vacuo, and the residue was purified by HPLC (silica gel, pentane-ether 2:1) to give 88 mg (89%) of **17** as a yellow oil. IR (C_6D_6): 2950, 2860, 1730, 1400, 1350, 1260, 1220, 1000, 780, 680, 650 cm^{-1}. ^{1}H NMR: δ 1.55 (ddt, 6n–H, $J_{6x,6n}$ = 12.5 Hz, $J_{6n,7n}$ = 8.5 Hz, $J_{6n,7x}$ = 2.5 Hz), 1.58 (dq. 7n–H, $J_{7x,7n}$ = 13.5 Hz, $J_{1,7n} \cong J_{6x,7n}$ = 8.5 Hz), 2.18 (d, 4n–H, J_{4x4n} = 17.0 Hz), 2.25 (dtdd, 7x–H, J_{7x7n} = 13.5 Hz, $J_{1,7x} \cong J_{6x7x}$ = 8.5 Hz, $J_{5,7x}$ = 3.5 Hz, $J_{6n,7x}$ = 2.5 Hz), 2.41 (dq, br. 6x–H, $J_{6x,6n}$ = 12.5 Hz, $J_{5,6x} \cong J_{6x,\,7x} \cong J_{6x,7n}$ = 8.5 Hz) 3.07 (m, 5–H), 3.09 (dd, 4x–H, J_{4x4n} = 17.0 Hz, J_{4x5} = 10.0 Hz, 3.19 (q, 1–H, $J_{1,5} \cong J_{1,7x} \cong J_{1,7n}$ = 8.5 Hz), 3.93 (s, br, 2n–H). Assignments were confirmed by H/H-COSY.

A solution of **17** (206 mg, 1.1 mmol) in methanol (4 ml) was heated for 4 h at 100 °C (sealed tube). After concentration in vacuo (20 °C), the residue was neutralized with aqueous sodium carbonate and extracted with ether. The extracts were dried (Na_2SO4) and concentrated to give

a mixture (1:1,GC) of the methoxyketones **19** and **20** (110 mg, 72%). Repeated HPCL (silica gel, pentane-ether = 2.1) afforded the components in 92–95% purity,. *exo*-2-Methoxybicyclo[3.2.0]-heptan-3-one (**19**): IR (film): 2940, 1740, 1450, 1380, 1260, 1090, 1050, 950 cm^{-1}. ^1H NMR (C_6D_6): δ 1.18 (m, 1H), 1.32 (m, 1H), 1.82 (d, br, 4n–H, $J_{4x,4n}$ = 18.0 Hz), 1.85 (m, 1H), 1.95 (m, 1H), 2.45 (dd, 4x–H, $J_{4x,4n}$ = 18.0 Hz, $J_{4x,5}$ = 9.5 Hz), 2.55 (m, 1H), 2.67 (q, 1–H), $J_{1,5} \cong J_{1,7x} \cong J_{1,7n}$ = 8.0 Hz), 3.04 (s,br, 2n–H), 3.24 (s, OCH_3). *endo*-2-Methoxybicyclo[3.2.0]heptan-3-one (**20**): IR (film): 2950, 2840, 1750, 1450, 1410, 1350, 1320, 1260, 1210, 1120, 1080, 980, 950, 920m 820 cm^{-1}. ^1H NMR (C_6D_6): δ 1.23 (m, 1H), 1.75 (m, 1H), 1.79 (dd, 4n–H, $J_{4x,4n}$ = 18.0 Hz, $J_{4n,5}$ = 1.5 Hz), 1.92–2.05 (m, 2H), 2.14 (ddd, 4x–H, $J_{4x,4n}$ = 18.0 Hz, $J_{4x,5}$ = 8.0 Hz, $J_{2x,4x}$ = 2.5 Hz), 2.28 (m, 1H), 2.69 (quin, 1–H, $J_{1,2x} \cong J_{1,5} \cong J_{1,7x} \cong J_{1,7n}$ = 8.0 Hz), 3.27 (s, OCH_3), 3.43 (dd, 2x–H, $J_{1,2x}$ = 8.0 Hz, $J_{2x,4x}$ = 2.5 Hz).

Bicyclo[3.2.0]heptan-endo-3-ol (24)

exo-2-Bromo-*endo*-3-hydroxybicyclo[3.2.0]heptan-6-one (**22**)[19] (20.0 g, 97.5 mmol), tributyltin hydride (42.6 g, 0.15 mol), and azoisobutyronitrile (AIBN, 0.5 g, 3.1 mmol) were dissolved in dry toluene (500 ml). The mixture was stirred under nitrogen for 30 min at room temperature. The toluene was evaporated in vacuo, and the residue was dissolved in acetonitrile (200 ml). After repeated extraction with hexane (5 × 100 ml), the acetonitrile solution was concentrated in vacuo. Short-path distillation of the residue afforded 9.2 g (75%) of crude *endo*-3-hydroxybicyclo[3.2.0]heptan-6-one (**23**); ^1H NMR (C_6D_6): δ 1.08–2.32 (m, 7H), 2.85 (m, 1–H), 3.10 (m, 5–H), 4.10 (t, 3x–H, $J_{2x,3x} \cong J_{3x,4x}$ = 4.0 Hz).

The hydroxyketone **23** (9.0 g, 71 mmol), 100% hydrazine hydrate (10.3 g, 0.11 mol), potassium hydroxide (34 g, 0.54 mol), and diethylene glycol (100 ml) were heated at reflux (140 °C) for 2 h. After cooling to room temperature, the mixture was continuously extracted with ether for 24 h. The extracts were washed with water, dried (Na_2SO_4), and concentrated. The residue was purified by sublimation in vacuo to give 4.95 g (63%) of **24**, m.p. 41 °C, which contained 5% of the *exo* isomer (GC). IR (CCl_4): 3360, 2970, 2880, 1450, 1350, 1325, 1270, 1230, 1185, 1155 1070, 1025, 1000, 970, 940, 780 cm^{-1}. ^1H NMR (C_6D_6): δ 1.09 (s, OH), 1.58–1.70 (m, 4H), 1.93–2.24 (m, 4H), 2.48–2.80 (m, 2H), 4.18 (quin, 3x–H, J = 4Hz).

Anal. Calc. for $C_7H_{12}O$ (M.w. = 112.17): C 74.95, H 10.78; found: C 74.79, H 10.75.

2-Diazobicyclo[3.2.0]heptan-3-one (26)

The alcohol **24** (4.0 g, 35.7 mmol) was oxidized with PCC (11.5 g, 53 mmol) in methylene chloride (100 ml) for 12 h at room temperature. Conventional workup (see **17**) afforded 2.95 g (75%) of **25**[18] which was converted into **26** as reported.[1]

To a solution of **26** (380 mg, 2.8 mmol) in methanol (10 ml) was added dropwise a solution of 70% perchloric acid (0.5 ml) in methanol (5 ml) until the evolution of nitrogen had ceased. The mixture was neutralized with potassium carbonate and partitioned between water and ether. The organic phase was dried (Na_2SO_4) and concentrated. Analysis by GC (24 m Marlophen, 100 °C) detected bicyclo[3.2.0]hept-3-en-6-one (**21**) (21.4%), 2,2,*syn*-7-trimethoxybicyclo[2.2.1]heptane (2.1%), 2,2,*anti*-7-trimethoxybicyclo[2.2.1]heptane (0.6%), *exo*-2,3,3-tri-methoxybicyclo[3.2.0]-heptane (50.5%), *anti*-7-methoxybicyclo[2.2.1]heptan-2-one (**30**) (0.5%), *syn*-7-methoxybicyclo-[2.2.1]heptan-2-one (**29**) (16.5%), and three unidentified compounds (2.3,3.8, and 2.3%). *exo*-2.3.3-Trimethoxybicyclo[3.2.0]heptane was isolated in 87% purity by HPLC (silica gel, pentane-ether = 7:3); ^1H NMR (C_6D_6): δ 1.73 (m, 1H), 1.93 (d,br, 4n–H, $J_{4x,4n}$ = 14.0 Hz), 1.98–2.13 (m, 4H), 2.63–2.78 (m, 2H), 3.10 (s, OCH_3), 3.16 (s, OCH_3) 3.27 (s, OCH_3), 3.38 (s, 2n–H). The remaining products were assigned by comparison with authentic samples (see below).

The product distribution was simplified when the reaction mixture was stirred for 1 h with 2 N hydrochloric acid (2.5 ml) prior to neutralization: **21** (21.9%), **19** (49.6%), **29** (18.8%), **30** (1.0%), and two unidentified compounds (3.5 and 5.2%). A sample of **21** was obtained by irradiation of bicyclo[2.2.1]hept-5-en-2-one.[28] Methanolysis of *anti*-7-chlorobicyclo[2.2.1]heptan-2-one afforded **30**;[29] ^1H NMR (C_6D_6): δ 1.15–1.55 (m, 2H), 1.82–2.25 (m, 4H), 2.42 (m, 1H), 2.56 (m, 1H), 3.37 (s, OCH_3), 3.57 (m, 1H); ^{13}C NMR (C_6D_6): δ 22.85 (C-5), 26.27 (C-6), 39.71 (C-4), 46.11

(C-1), 54.49 (C-3), 56.96 (OCH_3), 86.67 (C-7), 213.3 (C-2). For the preparation of **29**, *syn*-7-methoxybicyclo[2.2.1]heptan-*exo*-2-ol[30] was oxidized according to a published procedure[31] ($Py–SO_3$, Et_3N, DMSO). ^1H NMR (C_6D_6): δ 1.3–1.7 (m, 2H), 1.7–2.16 (m, 3H), 2.17–2.44 (m, 2H), 2.60 (m, 1H), 3.38 (s, OCH_3), 3.80 (m, 1H); ^{13}C NMR: δ 22.36 (C-5), 26.52 (C-6), 39.02 (C-4), 41.46 (C-3), 53.89 (C-1), 58.01 (OCH_3), 89.17 (C-7), 215.21 (C-2).

Anal. Calc. for $C_8H_{12}O_2$ (M.w. = 140.22): C 68.54, H 8.63; found: C 68.43, H 8.60.

The ketones **19**, **29**, and **30** were converted into dimethyl acetals by treatment with methyl orthoformate/methanol/HCl. The crude acetals were not purified but served to identify the additional products obtained by methanolysis of **26** (prior to hydrolysis). Partial acetalization of **29** and **30**, and virtually complete acetalization of **19** was also achieved by methanol/perchloric acid (the conditions used for methanolysis of **26**).

exo-2-*Brosyloxybicyclo[3.2.0]heptane-endo-2-carbonitrile (34)*

Bicyclo[3.2.0]heptan-2-one (**32**)[32] (2.0 g, 18 mmol), 2-hydroxy-2-methylpropionitrile (acetone cyanohydrin, 50 ml), and potassium cyanide (0.5 g) were stirred at room temperature for 24 h. Vacuum (12 Torr) was occasionally applied to remove acetone. Ether (100 ml) was added to the dark reaction mixture. The resulting solution was washed with water (3 × 10 ml), dried ($MgSO_4$), and concentrated. LC (silica gel, pentane-ether = 7:3) provided crude **31** which was separated from its epimer (5–6%) by HPLC (silica gel, pentane-ether = 8.2). *exo*-2-hydroxybicyclo[3.2.0]-heptane-*endo*-2-carbonitrile (**31**): IR (film): 3420, 2960, 2930, 2220, 1440, 1380, 1310, 1280, 1250, 1230, 1210, 1180, 1140, 1100, 1060, 1030, 1000, 965, 930, 710 cm^{-1}; ^1H NMR: δ 1.52 (m, 1H), 1.60 (dd, 4n–H, $J_{4x,4n}$ = 14.0 Hz, $J_{3n,4n}$ = 7.0 Hz), 1.72 (m, 1H), 1.97 (tt, 4x–H, $J_{3n,4x} \cong J_{4x,4n}$ = 14.0 Hz, $J_{3x,4x} \cong {}_{4x,5}$ = 7.0 Hz), 2.18–2.20 (m, 2H), 2.23 (dd, 3x–H, $J_{3x,3n}$ = 14.40 Hz, $J_{3x,4x}$ = 7.0 Hz), 2.43 (td, 3n–H, $J_{3x,3n} \cong J_{3n,4x}$ = 14.0 Hz, J_{3n4n} = 7.0 Hz), 2.80 (m, 1–H), 2.92 (m, 5–H), 2.97 (s, OH).

To a solution of **31** (200 mg, 1.46 mmol) in dry pyridine (4 ml) was added at 0 °C 4-bromobenzenesulfonyl chloride (410 mg, 1.60 mmol). The mixture was stirred at room temperature for 4 days. It was then poured into ice-water, stirred for 1 h, and extracted with ether. The extracts were dried ($MgSO_4$) and concentrated in vacuo. HPLC (silica gel, pentane-ether = 7:3) of the residue afforded 260 mg (50%) of **34**; m.p. 91 °C; IR (KBr): 3090, 2980, 2950, 2240, 1680, 1570, 1470, 1460, 1450, 1390, 1370, 1310, 1300, 1280, 1260, 1190, 1170, 1150, 1090, 1070, 1010, 980, 965, 930, 890, 830, 760, 700, 690, 645 cm^{-1}; ^1H NMR: δ 1.56 (m, 1H), 1.70 (dd, 4n–H, J = 14 and 7 Hz), 1.76 (m, 1H), 2.07 (tt, 4x–H, J = 14 and 7 Hz), 2.25–2.36 (m, 2H), 2.58 (td, 3n–H, J = 14 Hz), 2.80 (dd, 3x–H, J = 14 and 7 Hz), 2.95 (m, 5–H), 3.25 (m, 1–H), 7.69 and 7.82 (4H, AA'BB').

Anal. Calc. for $C_{14}H_{14}BrNO_3S$ (M.w. = 356.24): C 47.20, H 3.96, N 3.93; found: 47.24, H. 4.00, N 3.84.

A solution of **34** (80 mg, 0.22 mmol) in dioxane-water (2:1, 3 ml) was heated at 100 °C for 2 h. The mixture was partitioned between ether and aqueous potassium carbonate. The organic phase was dried ($MgSO_4$) and concentrated in vacuo. No volatile products were detected by GC. HPLC (silica gel, pentane-ether = 1:1) gave 56 mg (70%) of 7-brosyloxybicyclo[2.2.1]-heptane-1-carbonitrile (**37**); m.p. 157 °C; IR (KBr): 3080, 2960, 2230, 1640, 1570, 1470, 1460, 1380, 1350, 1330, 1310, 1300, 1280, 1260, 1190, 1180, 1100, 1070, 1020, 1000, 970, 950, 930, 880, 860, 820, 800, 760 cm^{-1}; ^1H NMR: δ 1.40 (m, 1H), 1.48 (ddd, 3n-H, $J_{3x,3n}$ = 12.0 Hz, $H_{2n,3n}$ = 8.5 Hz, $J_{2x,3n}$ = 4.0 Hz), 1.67–1.78 (m, 2H), 1.79 (ddd, 2n-H, $J_{2x,2n}$ 12.5 Hz, $J_{2n,3n}$ = 8.5. Hz, $J_{2n,3x}$ = 4.0 Hz, 1.94 (tt, 6x-H, $J_{5x,6x} \cong J_{6x,6n}$ = 12. Hz, $J_{2x,6x} \cong J_{5n,6x}$ = 3.5 Hz), 2.04 (m, 1H), 2.19 (tt, 2x-H, $J_{2x,2n} \cong J_{2x,3x}$ = 12.5 Hz, $J_{2x,3n} \cong J_{2x,6x}$ = 4.0 Hz), 2.46 (m, 1H), 4.59 (s, 7-H), 7.72 and 7. 83 (4H, AA'BB').

endo-2-*Brosyloxybicyclo[3.2.0]heptane*-exo-2-*carbonitrile (35)*

To a solution of **32** (1.0 g, 9.1 mmol) and zinc iodide (18 mg) in dry methylene chloride (20 ml) was added dropwise trimethylsilyl cyanide (1.08 g, 10.9 mmol). The mixture was heated at reflux for 8 h. It was then washed with aqueous sodium thiosulfate, dried ($MgSO_4$) and concentrated. GC indicated 89% of the silyl ether **33** and 11% of unreacted **32**. HPLC (silica gel,

pentane-ether = 7:3) afforded 1.02 g (54%) of **33**, ^{1} NMR: δ 0.15 (s, $SiMe_3$), 1.25–1.72 (m, 2H), 1.75–2.10 (m, 3H), 2.12–2.45 (m, 3H), 2.60–3.16 (m, 2H). The silyl ether **33** (1.0 g, 4.8 mmol) and 2 N hydrochloric acid (28 ml) were heated at 50 °C for 1 h. After cooling to room temperature, the mixture was extracted with ether (3 x 50 ml). The combined extracts were washed with water, dried ($MgSO_4$), and concentrated by distillation (Vigreux column) to give 620 mg (95%) of *endo*-2-hydroxybicyclo[3.2.0]heptane-*exo*-2-carbonitrile (**36**); IR (film): 3400, 2950, 2860, 2240, 1450, 1380, 1320, 1280, 1250, 1230, 1210, 1190, 1075, 990, 970, 910 cm^{-1}; ^{1}H NMR: δ 1.53 (m, 1H), 1.63 (dd, 4n-H, $J_{4x,4n}$ = 14.0 Hz, $J_{3n,4n}$ = 6.5 Hz), 1.95-2.02 (m, 2H), 1.98 (tt, 4x-H, $J_{3n,4x} \cong J_{4x,4n}$ = 14.0 Hz, $J_{3x,4x} \cong J_{4x,5}$ = 6.5 Hz), 2.23–2.78 (m, 2H), 2.86 (m, 5-H), 3.05 (q, 1-H. $J_{1,5} \cong J_{1,7x} \cong J_{1.7n}$ = 7.5 Hz), 3.86 (s, br, OH).

The procedure described for **34** was followed in the preparation of the brosylate **35**; yield 52%; IR (CCl_4): 3080, 2950, 2860, 1570, 1470, 1380, 1190, 1170, 1130, 1090, 1070, 1010, 990, 970, 950, 930, 860, 780, 660 cm^{-1}; ^{1}H NMR: δ 1.57 (m, 1H), 1.73 (dd, 4n-H, J = 14 and 7 Hz), 2.01 (m, 1H), 2.03 (tt, 4x-H, J = 14 and 7 Hz), 2.12 (m, 1H), 2.35 (m, 1H), 2.59 (dd, 3x-H, J = 14 and 7 Hz), 2.65 (td, 3n-H, J = 14 and 7 Hz), 2.90 (m, 5-H), 3.15 (m, 1-H), 7.72 and 7.85 (4H, AA'BB').

Anal. Calc. for $C_{14}H_{14}BrNO_3S$ (M.w. = 356.24): C 47.20, H 3.96, N 3.92; found: C 47.13, H 4.00, N 3.86.

A solution of **35** (300 mg, 0.82 mmol) in dioxane-water (2:1, 12 ml) was heated at 100 °C for 4 days. Workup, as described for the solvolysis of **34**, followed by HPLC (Polygosil-NO_2, pentane-ether = 1:1) afforded **37** (7.8%), **31a** (2.9%), **31** (20.6%), and **38** (68.7%). The spectra of **37** and **31** were in agreement with those reported above (for **38**, see below). 7-Hydroxybicyclo[2.2.1]-heptane-1-carbonitrile (**38**): IR (CCl_4): 3600, 3450, 2950, 2920, 2860, 2220, 1540, 1450, 1380, 1350, 1260, 1215, 1150, 1110, 1070, 1000, 980, 750 cm^{-1}; ^{1}H NMR (C_6D_6): δ 0.58 (m, 1H), 0.80 (ddd, 3n-H, $J_{3x,3n}$ = 12.0 Hz, $J_{2n,3n}$ = 9.0 Hz, $J_{2x,3n}$ = 4.0 Hz), 1.00 (m, 1H), 1.09 (m, 1H). 1.20 (ddd, 2n-H, $J_{2x,2n}$ = 12.0 Hz, $J_{2n,3n}$ = 9.0 Hz, $J_{2n,3x}$ = 4.0 Hz), 1.42 (m, 1H), 1.55 (t, 4-H, $J_{3x,4} \cong J_{4,5x}$ = 4.0 Hz), 1.82 (tt, and s, br, 3x-H and OH, $J_{2x,3x} \cong J_{3x,3n}$ = 12.0 Hz, $H_{2n,3x} \cong J_{3x,4}$ = 4.0 Hz), 2.08 (tt, 2x-H, $J_{2x,2n} \cong J_{2x,3x}$ = 12.0 Hz, $J_{2x,3n} \cong J_{2x,3x}$ = 4.0 Hz), 3.52 (s, 7-H).

Anal. Calc. for $C_8H_{11}NO$ (M.w. = 137.18): C 70.04, H 8.08, N 10.21; found: C 70.00, H 8.11, N 10.18.

Starting from [6,7-^{2}H]-**32**[33], the preparation of the brosylate was repeated to obtain [6,7-^{2}H]-**35**, ^{2}H NMR: 2.05 (6x-D, 46.7%), 2.35 (7x-D, 43.5%), 2.62 (3x-D and 3n-D, 9.8%). Solvolysis of the labeled brosylate, as described for **35**, afforded deuterated **37**, ^{2}H NMR: 1.73 (5x-D and 2n-D, 49.2%), 1.92 (6x-D, 44.0%), 2.17 (2x-D, 6.8%), and deuterated **38**, ^{2}H NMR (C_6D_6): 0.98 (5x-D, 43.1%), 1.18 (2n-D, 6.3%), 1.39 (6x-D, 45.1%), 2.05 (2x-D, 5.5%). Significantly, no signal (< 1%) of 3x-D, expected at 1.82 ppm, was observed.

*Bicyclo[3.2.0]hept-2-ene-2-carbonitrile (**31a**)*

To a solution of **33** (300 mg, 1.43 mmol) in pyridine (3 ml) was added dropwise with cooling (0 °C) phosphoryl chloride (0.4 ml, 4.3 mmol). The mixture was heated at reflux for 70 h. Progress of the reaction was monitored by GC. Hydrochloric acid (1 N, 100 ml) was then added with cooling, and the mixture was extractewd with ether. The extracts were washed with water, dried ($MgSO_4$), and concentrated by distillation (Vigreux column). The volatile product **31a** was isolated by PGC (1.6 m DC 200, 100 °C), in 79% yield (135 mg). IR (film): 2970, 2930, 2850, 2830, 2220, 1720, 1605, 1430, 1375, 1320, 1280, 1260, 1240, 1220, 1160, 1140, 1120, 1070, 1040, 970, 940, 930, 880, 820, 795, 750, 700, 670 cm^{-1}. ^{1}H NMR: δ 1.78 (m, 1H), 1.93 (dt, 7n-H, $J_{7x,7n}$ = 12.0 Hz, $J_{6n,7n}$ = 8.0 Hz, $J_{1,7n} \cong J_{6x,7n}$ = 2.5 Hz), 2.23 (m, 1H), 2.33 (dt, 4n-H, $J_{4x,4n}$ = 19.0 Hz, $J_{3,4n} \cong J_{4n,5}$ = 3.0 Hz), 2.38 (m, 1H), 2.69 (ddt, 4x-H, $J_{4x,4n}$ = 19.0 Hz, $J_{4x,5}$ = 8.0 Ht, $J_{1,4x} \cong J_{3,4x}$ = 2.0 Hz), 3.05 (quin, 5-H, $J_{1,5} \cong J_{4x,5} \cong J_{5,6x} \cong J_{5,6n}$ = 8.0 Hz), 3.42 (m, 1-H), 6.67 (m, 3-H). The assignments were confirmed by H/H-COSY. ^{13}C NMR: δ 26.33 (C-6), 28.02 (C-7), 36.02 (C-5), 41.44 (C-4), 47.82 (C-1) 116.68 (C-2), 119.63 (CN), 148.52 (C-3).

Anal. Calc. for C_8H_9N (M.w. = 119.17): C 80.63, H 7.61, N 11.75; found: C 80.59, H 7.56, N 11.75.

7-(Trifluoromethanesulfonyloxy)bicyclo[2.2.1]heptane-1-carbonitrile (39)

To a solution of **31** (1.0 g, 7.3 mmol) in dry pyridine (1.2 ml) and dry methylene chloride (20 ml) was added dropwise at 0 °C trifluoromethanesulfonic anhydride (1.76 ml, 10.8 mmol). The mixture was stirred at 0 °C for 2 h and was then kept at –20 °C for 16 h. The mixture was poured into ice-water (50 ml) and extracted with ether (3 x 50 ml). The combined extracts were washed with 2 N hydrochloric acid and with water, dried ($MgSO_4$), and concentrated in vacuo. HPLC (silica gel, pentane-ether = 7:3) of the residue afforded **39** in 98% purity (GC). IR ($CDCl_3$): 3240, 3080, 2960, 2890, 2860, 2280, 1620, 1450, 1420, 1330, 1250, 1210, 1150, 1030,1010, 980, 810, 700, 615 cm^{-1}; ^1H NMR: δ 1.48 (m, 1H), 1.61 (ddd, 3n-H, $J_{3x,3n}$ = 12.5 Hz, $J_{2n,3n}$ = 8.5 Hz, $J_{2x,3n}$ = 4.5 Hz), 1.79–1.90 (m, 2H), 1.91 (ddd, 2n-H, $J_{2x,2n}$ = 12.5 Hz, $J_{2n,3n}$ = 8.5 Hz, $J_{2n,3x}$ = 4.5 Hz), 2.09 (tt, 3x-H, $J_{2x,3x} \cong J_{3x,3n}$ = 12.5 Hz, $J_{2n,3x} \cong J_{3x,4}$ = 4.5 Hz), 2.10 (m, 1H), 2.36 (tt, 2x-H, $J_{2x,2n} \cong J_{2x,3x}$ = 12.5 Hz, $J_{2x,3n} \cong J_{2x,6x}$ = 4.5 Hz), 2.55 (m 4-H), 5.02 (s, 7-H); ^{13}C NMR: δ 24.56 (C-5), 29.36 (C-6), 30.49 (C-3), 31.73 (C-2), 40.07 (C-4), 40.62 (C-1), 92.42 (C-7), 118.42 (CF_3, $J_{C\text{-}F}$ = 329 Hz), 118.74 (CN).

A solution of **39** (50 mg. 0.02 mmol) and 2,6-lutidine (44 mg, 0.4 mmol) in dioxane-water (2:1, 3 ml) was heated in a sealed ampule at 140 °C for 6 days. After cooling to room temperature, the mixture was saturated with solid potassium carbonate. The organic phase was separated and analyzed by GC (38 m OV 17, 140 °C): **41** (53.9%) (for a synthesis of **41**, see below), **38** 29.3%), and **31** 2.0%). Two unidentified compounds (5.4 and 9.5%) were more volatile than **41**, but none of these was **31a**.

When the solvolysis of **39** (1.0 g, 3.7 mmol) was performed in the absence of 2,6-lutidine, only a trace of **41** was observed. The major product (65%) of this run, bicyclo[3.2.0]hept-3-ene-1-carboxamide, was isolated by HPLC (silica gel, pentane-ether = 1:1); IR ($CDCl_3$): 3690, 3520, 3160, 2930, 2860, 1690, 1650, 1610, 1560, 1470, 1380, 1350, 1320, 1290, 1260, 1200, 900 cm^{-1}; ^1H NMR: δ 1.73 (ddt, 6n-H, $J_{6x,6n}$ = 11.0 Hz, $J_{6n,7n}$ = 8.0 Hz, $J_{6n,7x}$ = 3.5 Hz), 1.99 (dt, 7n-H, $J_{7x,7n}$ = 12.0 Hz, $J_{6n,7n} \cong J_{6x,7n}$ = 8.0 Hz), 2.43 (dd, 2n-H, $J_{2x,2n}$ = 16.5 Hz, $J_{2n,3}$ = 3.0 Hz), 2.48 (dt, 6x-H, $J_{6x,6n}$ = 11.0 Hz, $J_{5,6x} \cong J_{6x,7x}$ = 8.0 Hz), 2.62 (ddd, 7x-H, $J_{7x,7n}$ = 12.0 Hz, $J_{6x,7x}$ = 8.0 Hz, $J_{6n,7x}$ = 3.5 Hz), 2.98 (d, 2x-H, $J_{2x,2n}$ = 16.5 Hz), 3.49 (m, 5-H), 5.76 (m, 3-H and 4-H); ^{13}C NMR: δ 25.73 (C-6), 29.65 (C-7). 43.56 (C-2). 50.64 (C-1), 50.70 (C-5), 129.73 (C-3), 132.87 (C-4), 182.89 C=0). The assignments were confirmed by H/H and C/H-COSY.

Starting from [6,7-^{2}H]-**32**, the preparation of the triflate was repeated to obtain [6,7-^{2}H]-**39**, ^2H NMR: 1.80 (5x-D, 45.2%), 2.04 (6x-D and 2n-D, 51.8%). 2.34 (2x-D, 3.0%), Solvolysis of the deuterated triflate in the presence of 2,6-lutidine, as described above, followed by HPLC (silica gel, pentane-ether = 1:1), afforded deuterated **38**, ^2H NMR: 1.00 (5x-D, 42.5%), 1.22 (2n-D, 3.0%), 1.43 (6x-D, 44.1%), 1.83 (3x-D, 4.9%), 2.07 (2x-D, 5.6%). A well-defined signal of 3x-D distinguishes the present sample from that obtained in the solvolysis of [6,7-^{2}H]-**35** (see above).

4-Tosylhydrazonobicyclo[3.2.0]heptane-1-carbonitrile (45)

A solution of 3-oxocyclopent-1-ene-1-carbonitrile (**43**)[26] (4.0 g, 37 mmol) in dry methylene chloride (250 ml) was saturated with ethylene and irradiated (medium pressure mercury arc, quartz vessel, 0 °C) while ethylene was continuously passed through the solution. The reaction was monitored by GC and carried to 90% conversion. Distillation of the solvent (Vigreux column) was followed by LC (silica gel, pentane-ether = 1:1) of the residue to give 4.33 g (86%) of 4-oxobicyclo[3.2.0]heptane-1-carbonitrile (**44**); IR (film). 2950, 2870, 2215, 1730, 1450, 1410, 1370, 1320, 1280, 1270, 1240, 1170, 1100, 1050, 1010, 950, 880, 790, 760 cm^{-1}; ^1H NMR: δ 1.95 (dddd, 6n-H, J = 10.5, 9.5, 6.0, and 4.5 Hz), 2.25–2.37 (m, 2H), 2.39 (ddd, 2x-H, $J_{2x,2n}$ = 13.0 Hz, $J_{2x,3x}$ = 10. 0 Hz, $J_{2x,3n}$ = 9.5 Hz), 2.55 (ddd, 3n-H, $J_{3x,3n}$ = 18.5 Hz, $J_{2x,3n}$ = 9.5 Hz, $J_{2n,3n}$ = 4.5 Hz), 2.68 (m, 1H), 2.73 (m, 1H and ddd, 3x-H, $J_{3x,3n}$ = 18.5 Hz, $J_{2x,3x}$ = 10.0 Hz, $J_{2n,3x}$ = 9.5 Hz), 3.10 (d,br, 5-H, $J_{5,6x}$ = 10.5 Hz); ^{13}C NMR: δ 20.59 (C-6), 29.70 (C-7), 31.59 (C-2), 34.93 (C-1), 36.61 (C-3), 48.84 (C-5), 122.60 (CN), 215.57 (C-4). Assignments were confirmed by H/H and C/H-COSY.

Anal. Calc. for C_8H_9O (M.w. = 135.17): C 71.09, H 6.71, N 10.36; found: C 71.01, H 6.66, N 10.26.

Tosylhydrazine (3.3 g, 18 mmol) was dissolved in hot methanol (10 ml). The ketone **44** (2.0 g, 15 mmol) and a saturated solution of hydrogen chloride in methanol (3 drops) were added. The mixture was stirred at room temperature for 16 h while **45** precipitated. Recrystallization of the solid from ethanol gave 1.56 g (35%) of **45**; m.p. 161 °C; IR (KBr): 3200, 2950, 2215, 1650, 1600, 1490, 1450, 1415, 1340, 1310, 1240, 1170, 1090, 1030, 920, 810, 790, 740, 710, 670 cm^{-1}; ^1H NMR: δ 1.85–1.95 (m, 1H), 1.98–2.97 (m, 8H), 2.44 (s, CH_3), 3.50 (m, 1H), 7.32 and 7.83 (4H. AA'BB').

Anal. Calc. for $C_{15}H_{17}N_3O_2S$ (M.w. = 303.38): C 59.39, H 5.65, N 13.85; found: C 59.29, H 5.75, N 13.79.

A solution of **45** (550 mg, 1.8 mmol) in aqueous sodium hydroxide (0.2 N, 100 ml) was irradiated for 4 h (medium, pressure mercury arc, pyrex vessel, 20 °C). The photolysate was saturated with sodium chloride and extracted with ether. The extracts were dried ($MgSO_4$), concentrated by distillation (Vigreux column), and analyzed by GC: **41** (15.3%), **38** (44.5%), and **46** (40.2%) (average of three runs). Two minor components (<5%) were not reproducible. The alcohols **38** and **46** were separated by HPLC (silica gel, pentane-ether = 8:2). Their spectra were in agreement with those of authentic **38** (see above) and **46** (see below).

Bicyclo[3.2.0]hept-3-ene-1-carbonitrile (41)

To a solution of **45** (1.0 g, 3.3 mmol) in dry tetrahydrofuran (15 ml) was added sodium hydride (80 mg, 3.3 mmol). The mixture was stirred at 0 °C for 30 min. Pentane (75 ml) was then added, and stirring was continued for 2 h with exclusion of light and moisture. The sodium salt of **45** (1.02 g, 95%) was filtered with suction, washed with pentane, and dried in vacuo (10^{-2} Torr). According to a standard procedure,[34] the sodium salt of **45** was pyrolyzed at 320 °C and $5 \cdot 10^{-3}$ Torr. Volatile materials were collected in a trap cooled with liquid nitrogen. The major product **41** (73–80%) was purified by repeated HPLC (silica gel, pentane-ether = 7:3). IR ($CDCl_3$): 3160, 3000, 2950, 2860, 2230, 1610, 1440, 1340, 1315, 1260, 1240, 1200, 1170, 1090, 1080, 1020, 970, 900, 800 cm^{-1}; ^1H NMR: δ 1.75 (m, 1H), 2.15 (m 1H), 2.48–2.58 (m, 2H), 2.60 (dd, 2n-H, $J_{2x,2n}$ = 17 Hz, $J_{2n,3}$ = 2 Hz), 2.85 (dq, 2x-H, $J_{2x,2n}$ =/9 = 17 Hz, $J_{2x,3} \cong J_{2x,4} \cong J_{2x,5}$ = 2 Hz), 3.60 (m, 1H), 5.72 (dq, 3-H, $J_{3,4}$ = 6 Hz, $J_{2x,3} \cong J_{2n,3} \cong J_{3,5}$ = 2 Hz), 5.77 (dq, 4-H, J = 6 and 2 Hz); ^{13}C NMR: δ 25.66 (C-6), 31.23 (C-7) 35.70 (C-1), 44.97 (C-2), 51.76 (C-5), 124.41 (CN), 128.84 (C-3), 132.64 (C-4). Assignments were confirmed by H/H and C/H-COSY.

Anal. Calc. for C_8H_9N (M.w. = 119.17): C 80.63, H 7.61, N 11.75; found: C 80.54, H 7.54, N 11.73.

4-Hydroxybicyclo[3.2.0]heptane-1-carbonitrile (46)

To a solution of **44** (500 mg, 3.7 mmol) in ethanol (125 ml) was added sodium borohydride (63 mg, 1.9 mmol). The mixture was stirred at room temperature for 3 h, concentrated by distillation, diluted with water, and extracted with ether. The extracts were dried ($MgSO_4$) and concentrated by distillation. Two isomers (95:5) were detected by GC. The major product (410 mg, 81%) was isolated by HPLC (silica gel, pentane-ether = 8:2) and assigned as *endo*-4-hydroxybicyclo[3.2.0]heptane-1-carbonitrile; IR (film): 3410, 2960, 2870, 2230, 1450, 1410, 1390, 1325, 1310, 1290, 1260, 1200, 1180, 1150, 1075, 1030, 910, 800 cm^{-1}; ^1H NMR: δ 1.64 (s, br, 1H). 1.89-2.17 (m, 7H), 2.65 (m, 1H), 3.12 (m, 1H), 4.36 (dt, 4x-H, $J_{4x,5}$ = 9.5 Hz, $J_{3x,4x} \cong J_{3n,4x}$ = 6.7 Hz).

A solution of the *endo*-alcohol (200 mg, 1.5 mmol) aluminium isopropoxide (670 mg, 3.2 mmol). and acetone (0.5 ml) in toluene (15 ml) was heated at reflux. After 7 days the reaction did not proceed further (GC). Residual *endo* alcohol (49%), alkene **41** (6%), ketone **44** (11%), and two unidentified compounds (7%) were present in addition to the desired *exo* alcohol (27%). HPLC (Polygosil-CN, pentane-ether = 1:1) provided 12 mg (6%) of *exo*-4-hydroxybicyclo[3.2.0]-heptane-1-carbonitrile (**46**); IR ($CDCl_3$); 3690, 3610, 3160, 2980, 2950, 2900, 2865, 2250, 1640, 1600, 1560, 1470, 1380, 1170, 1120, 1095, 1050, 990, 895 cm^{-1}; ^1H NMR: δ 1.43 (dddd, 6n-H, $J_{6x,6n}$ = 13 Hz, $J_{5,6n}$ = 10.5 Hz, $J_{6n,7n}$ = 7 Hzm $J_{6n,7x}$ = 6 Hz), 1.88 (dd, 7n-H, $J_{7x,7n}$ = 13 Hz, $J_{6n,7n}$ = 7 Hz), 1.93 (dd, 2n-H, $J_{2x,2n}$ = 13 Hz, $J_{2n,3x}$ = 7 Hz), 2.01 (ddm, 3n-H, $J_{3x,3n}$ = 13 Hz, $J_{2x,3n}$ = 7 Hz), 2.15 (tdd, 3x-H, $J_{2x,3x} \cong J_{3x,3n}$ = 13 Hz, $J_{2n,3x}$ = 7 Hz, $J_{3x,4n}$ = 3.5 Hz), 2.26 (m,

6x-H), 2.33 (td, 2x-H, $J_{2x,2n} \cong J_{2x,3x}$ = 13 Hz, $J_{2x,3n}$ = 7 Hz), 2.58 (ddd, 7x-H, $J_{7x,7n}$ = 13 Hz, $J_{7x,6x}$ = 11.5 Hz, $J_{7x,6n}$ = 6 Hz), 3.03 (dd, 5-H, $J_{5,6n}$ = 10.5 Hz, $J_{5,6x}$ = 5.5 Hz), 4.12 (d, 4n-H, $J_{3n,4n}$ = 3.5 Hz).

*[6,7-^{2}H]-4-Tosylhydrazonobicyclo[3.2.0]heptane-1-carbonitrile (**45**)*

A solution of **43** (1.3 g, 12.1 mmol) in dry methylene chloride (150 ml) was irradiated (medium pressure mercury arc, quartz vessel, 0 °C) while acetylene was continuously passed through the solution. Due to excessive formation of polymers, the reaction was terminated at *ca.* 75% conversion. Distillation of the solvent (Vigreux column) was followed by flash chromatography (silica gel) and HPLC (Polygosil-CN, pentane-ether = 65:35) to give 440 mg (27%) of 4-oxobicyclo[3.2.0]hept-6-ene-1-carbonitrile (**48**); IR (film): 3060, 2970, 2940, 2870, 2215, 1730, 1450, 1410, 1320, 1280, 1260, 1230, 1170, 1140, 980, 960, 830, 750 cm^{-1}; ^{1}H NMR: δ 2.25 (ddd, 2x-H, $J_{2x,2n}$ = 14 Hz, $J_{2x,3x}$ = 11.5 Hz, $J_{2x,3n}$ = 9 Hz), 2.37 (ddd, 2n-H, $J_{2x,2n}$ = 14 Hz, $J_{2n,3x}$ = 9 Hz, J_{2n3n} = 1.5 Hz), 2.40 (ddd, 3n-H, $J_{3x,3n}$ = 18 Hz, $J_{2x,3n}$ = 9 Hz, $J_{2n,3n}$ = 1.5 Hz), 2.93 (dddd, 3x-H, $J_{3x,3n}$ = 18 Hz, $J_{2x,3x}$ = 11.5 Hz, $J_{2n,3x}$ = 9 Hz, $J_{3x,5}$ = 1.5 Hz), 3.55 (m, 5-H), 6.32 (dd, 6-H, $J_{6,7}$ = 2.7 Hz, $J_{5,6}$ = 1 Hz), 6.36 (d, 7-H, $J_{6,7}$ = 2.7 Hz).

Anal. Calc. for C_8H_7N (M.w. = 133.15): C 72.17, H 5.30, N 10.52; found: C 72.06, H 5.32, N 10.57.

To a solution of **48** (600 mg, 4.5 mmol) in ether (25 ml) was added 10% Pd-C catalyst (50 mg). The mixture was shaken with deuterium gas for 3 h (normal pressure, room temperature). After filtration, the solution was concentrated by distillation (Vigreux column) to give 590 mg (95%) of [6,7-^{2}H]-**44**, ^{2}H NMR: 1.95 (6n-D, 2.7%), 2.30 (7n-D, 2.8%), 2.62 (6x-D, 47.2%), 2.73 (7x-D, 47.3%).

The labeled ketone was converted into the tosylhydrazone [6,7-^{2}H]-**45** (360 mg, 45%), as described above for **44**. The photolysis of the labeled tosylhydrazone (260 mg, 0.85 mmol) in 0.2 N NaOH (100 ml) and separation of the products followed the directions given for **45**. ^{2}H NMR of deuterated **38**: 0.60 (5n-D, 1.2%), 1.03 (5x-D and 6n-D, 50.5%), 1.44 (6x-D, 48.3%). ^{2}H NMR of deuterated **46**: 1.40 (6n-D, 1.8%), 1.90 (7n-D, 2.1%), 2.25 (6x-D, 50.0%), 2.57 (7x-D, 46.1%). No relocation of deuterium to C-2,3 was detected in either of these compounds.

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SAŽETAK

Destabilizirani 7-norbornil-kationi

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Istražene su mogućnosti generiranja 2-oksi-7-norbornil- i 1-cijano-7-norbornil-kationa iz raznovrsnih perkursora, a poglavito derivata biciklo[3.2.0]heptana. Potanko se rapravlja o generiranju tih kationa iz odgovarajućih diazonijevih iona kao i o mogućnosti priprave 1-cijano-7-norbornil-kationa u solvolitskim uvjetima. Ukratko se razmatra utjecaj oksi- i cijano-skupine na stabilnost kationa.