J. Org. Chem. 1988, *53*, 2497–2504

^{13}C–^{1}H Coupling Constants in Carbocations. 5.[1] Trishomocyclopropenium Cations Generated from Bicyclo[3.1.0]hex-3-yl, Tricyclo[3.2.1.0^{2,4}]oct-8-yl, and Pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-9-yl Precursors

David P. Kelly,* Joseph J. Giansiracusa, D. Ralph Leslie, Ian D. McKern, and
Georgia C. Sinclair

Department of Organic Chemistry, University of Melbourne, Parkville, Victoria 3052, Australia

Received January 11, 1988

One-bond ^{13}C–H coupling constants have been measured for the trishomocyclopropenium cations derived from bicyclo[3.1.0]hex-3-yl (**1**), tricyclo[3.2.1.0^{2,4}]oct-8-yl, (**12**, **14**) and pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-9-yl (**26**, **27**) precursors under stable ion conditions and compared with those of the corresponding model ketones. The ΔJ values thus obtained for the bridging carbons (21–32 Hz) and the adjacent methylene or methine carbons (18–27 Hz) are large and not consistent with static or equilibrating classical structures for these cations. The data provide additional confirmation of the $\pi\sigma$-bridged, nonclassical nature of these cations.

A systematic investigation of the factors influencing one-bond ^{13}C–^{1}H coupling constants ($^{1}J_{CH}$) in carbocations[2] resulted in the development of an empirical equation of the form

$$\Delta J = A - B \cos^2 \theta$$

where ΔJ is the difference between $^{1}J_{C\alpha H}$ for the group adjacent to the cationic center and that in a neutral model compound (ketone), θ is the dihedral angle between the vacant p orbital and the $C_{\alpha}H$ bond, A is the maximum inductive enhancement of $J_{C\alpha H}$ (22.5 Hz for trialkyl cations), and B is the maximum hyperconjugative diminution of $J_{C\alpha H}$ (33.1 Hz for trialkyl cations).[3] This equation has been applied successfully to give conformations of acyclic trialkyl,[2] dialkylaryl,[4] and bicyclic carbocations.[1]

The original motivation for this work was the idea that the formation of a nonclassical σ-bridged structure for the cyclopropylcarbinyl cation would result in a large value of $^{1}J_{CH}$ of the apical methine group due to the expected increase in s character of the C–H bond, which would result from the increasing internal bond angle strain generated on the formation of bicyclobutane structures.[2,5] As has been demonstrated, the ΔJ criterion failed to provide convincing evidence for nonclassical character in the cyclopropylcarbinyl cations, the enhancements of ca. 22 Hz being consistent with classical bisected geometries.[2,3] Since there is still uncertainty as to the precise structure of this cation,[6] we turned our attention to trishomocyclopropenium systems where there is general agreement, particularly in the case of "Coates cation" that the intermediates generated under both solvolytic[7–10] and superacidic[11–13] conditions are true nonclassical σ-bridged carbocations.[14]

We now report our investigation of ^{13}C–H coupling constants for these cations, generated from bicyclo[3.1.0]hex-3-yl, *endo*-tricyclo[3.2.1.0^{2,4}]oct-8-yl, and pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-9-yl alcohols, and for the appropriate model ketones.

Results and Discussion

Bicyclo[3.1.0]hex-3-yl Cations. A small rate enhancement over that for the trans isomer, retention of stereochemistry, and statistical distribution of a deuterium label lead Winstein and Sonnenberg to postulate the trishomocyclopropenium cation **1a** as the intermediate involved in the acetolysis of the tosylate of *cis*-bicyclo[3.1.0]hexan-3-ol (**2a**, X = OTs).[15,16] Direct NMR observation of this cation in superacid by Masamune and co-workers[17] and later by Olah and co-workers[18] confirmed the nonclassical structure, the bridging carbons being exceptionally shielded ($\delta(^{13}C)$ = 4.7 ppm) and exhibiting large one-bond coupling constants ($^{1}J_{CH}$ = 196 Hz) (Table I). Application of Saunder's deuterium isotopic perturbation technique[13] by Olah et al. provided additional confirmation.[19]

Application of the concept of the ΔJ equation, that is the comparison of the $^{1}J_{CH}$ values in the cation with those of an appropriate model neutral compound (ketone), necessitated measurement of the values for bicyclo[3.1.0]hexan-3-one (**3**) (Table II). Since C_2, C_4, and C_6 are averaged in **1a**, they must also be averaged in **3**, which leads to a value of 141 Hz and a ΔJ value of 27 Hz for the methylene groups and 24 Hz for the bridging methine groups at $C_{1,3,5}$ [$^{1}J_{CH}$(cation) − $^{1}J_{CH}$(ketone)]. The exceptionally large value for the methylene groups is in fact

---

[1] Part 4: Kelly, D. P.; Leslie, D. R.; Smith, B. D. *J. Am. Chem. Soc.* **1984**, *106*, 687–694.

[2] Kelly, D. P.; Brown, H. C. *J. Am. Chem. Soc.* **1975**, *97*, 3897–3900.

[3] Kelly, D. P.; Underwood, G. R.; Barron, P. F. *J. Am. Chem. Soc.* **1976**, *98*, 3106–3111.

[4] Kelly, D. P.; Farquharson, G. J.; Giansiracusa, J. J.; Jensen, W. A.; Hügel, H. M.; Porter, A. P.; Rainbow, I. J.; Timewell, P. H. *J. Am. Chem. Soc.* **1981**, *103*, 3539–3543.

[5] Olah, G. A.; Kelly, D. P.; Jeuell, C. L.; Porter, R. D. *J. Am. Chem. Soc.* **1970**, *92*, 2544–2546.

[6] (a) Brown, H. C. *The Non-classical Ion Problem*; Plenum: New York, 1977; Chapter 5. (b) Kirmse, W. In *Topics in Current Chemistry*; Dewar, M. J. S., et al., Eds.; Springer Verlag: New York, 1979. See also: Gassman, P. G.; Doherty, M. M. *J. Am. Chem. Soc.* **1982**, *104*, 3742–3744. Gassman, P. G.; Hall, J. B. *J. Am. Chem. Soc.* **1984**, *106*, 4267–4269.

[7] Coates, R. M.; Kirkpatrick, J. L. *J. Am. Chem. Soc.* **1970**, *92*, 4883–4892.

[8] Coates, R. M.; Fretz, E. R. *J. Am. Chem. Soc.* **1977**, *99*, 297–299.

[9] Brown, H. C.; Ravindranathan, M. *J. Am. Chem. Soc.* **1977**, *99*, 299–300.

[10] Jenner, G.; Srivastava, S.; Le Noble, W. J. *Tetrahedron Lett.* **1983**, *24*, 2429–2430.

[11] Coates, R. M.; Fretz, E. R. *J. Am. Chem. Soc.* **1975**, *97*, 2538–2540.

[12] Farnum, D. G.; Clausen, T. P. *Tetrahedron Lett.* **1981**, *22*, 549–552.

[13] Saunders, M.; Kates, M. R. *J. Am. Chem. Soc.* **1980**, *102*, 6867–6868.

[14] Theoretical calculations (MINDO/3) also support the nonclassical structure: Jorgensen, W. L. *Tetrahedron Lett.* **1976**, 3029–3033.

[15] Winstein, S.; Sonnenberg, J. *J. Am. Chem Soc.* **1961**, *83*, 3235–3244, 3244–3251.

[16] Winstein, S.; Friedrich, E. C.; Baker, R.; Lin, Y.-I. *Tetrahedron* **1966**, 621–645.

[17] Masamune, S.; Sakai, M.; Kemp-Jones, A. V.; Nakashima, T. *Can. J. Chem.* **1974**, *52*, 855–857.

[18] Olah, G. A.; Prakash, G. K. S.; Rawdah, T. N.; Whittaker, D.; Rees, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 3935–3939.

[19] Prakash, G. K. S.; Arvanaghi, M.; Olah, G. A. *J. Am. Chem. Soc.* **1985**, *107*, 6017–6019.

0022-3263/88/1953-2497$01.50/0

Table I. ^{13}C NMR Spectral Parameters for Trishomocyclopropenium Cations[a]

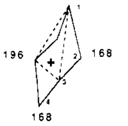
ion	C_1	$C_{2,4}$	C_3	C_5	$C_{6,7}$	C_8	C_9	R
1a[b]	4.7	17.3	4.7	4.7	17.3			
	(196)	(168)	(196)	(196)	(168)			
12[c]	29.8	19.7	5.9	29.8	25.6	0.0		
	(177)	(199)	(165)	(177)	(136)	(208)		
14	33.4	20.9	8.8	33.4	25.3	29.1		15.7
	(169)	(197)	(164)	(169)	(132)			(132)
26[d]	31.4	29.5	31.4	31.4	41.3	41.3	29.5	
	(179)	(204)	(179)	(179)	(185)	(185)	(204)	
27[e,f]	37.0	29.6	34.8	37.0	40.5	39.6	68.8	16.1
	(174)	(201)	(178)	(174)	(181)	(178)		(133)

[a] Chemical shifts ±0.1 ppm from external (capillary) Me_4Si; coupling constants ($^1J_{CH}$) ±1 Hz are in parentheses. [b] From ref 17. [c] Chemical shifts first reported by Masamune.[36] [d] Data from ref 11; the numbering system has been altered from the original to allow easy comparison with other cations. [e] Chemical shifts first reported in ref 11. [f] Numbering system as for **26**.

greater than that for α C–H bonds orthogonal to a full positive charge in a classical static cation (22 Hz).[3] Even if this were a classical system the dihedral angle would be less than 90° and thus give reduced ΔJ values.[3,20]

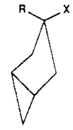
Comparison of $J_{C\alpha H}$ values in the 1-methylcyclohexyl cation[21] with those for cyclohexanone[22] gives $\Delta J = 3$ Hz using averaged values for equatorial and axial dihedral bond angles.[23] Although this is a conformationally mobile system, cations with more rigid chair conformations have bridgehead carbons at the α positions, for example, 2-methyl-2-adamantyl, and are less appropriate for comparison purposes.[24] Nevertheless, even in this system the ΔJ value is only 10 Hz.[25]

The ΔJ value of 24 Hz for the bridging positions is also greater than that observed for carbons two removed from the positive charge (β) in classical systems, for example, 2-methylbicyclo[2.2.1]hept-2-yl $\Delta J_{C4H} = 10$ Hz,[26] 2-methylbicyclo[2.1.1]hex-2-yl $\Delta J_{C4H} = 7$ Hz, $\Delta J_{C5H} = 11$ Hz (see below), 1-methylcyclopentyl $\Delta J_{C3H} = 6$ Hz,[3] 2-methyladamantan-2-yl $\Delta J_{C4H} = 8$ Hz, $\Delta J_{C6H} = 2$ Hz.[24,25]

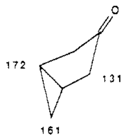


1a

1b



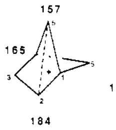
2



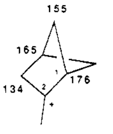
3

The question then arises as to whether such enhanced coupling constants might be consistent with equilibrating structures. It has been shown previously in classical equilibrating cations that groups adjacent to one of two carbons sharing the positive charge, for example, C_1–H in 2,3-dimethylbicyclo[2.2.1]heptyl, have ΔJ values approximately one-half of those in the corresponding static cation.[3] When the C–H bond is itself involved in the equilibration, that is, this proton is undergoing rapid 1,2-hydride shifts, as for example in bicyclo[3.3.0]oct-1-yl cation, the ΔJ value is large, but negative (−33 Hz), that is, the value of J_{CH} is *less* in the cation than in the ketone.[3] This is clearly not the case for **1a**.

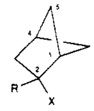
Bicyclo[2.1.1]hex-2-yl cations **4** and **5** generated in superacids from **6a,b** (X = Cl) have thermodynamic and spectroscopic properties intermediate between those of classical (cyclopentyl) and bicyclo[2.2.1]hept-2-yl (2-norbornyl) cations.[27] The highly symmetrical NMR spectrum of the secondary cation **4**[28,29] may be rationalized by a degenerate Wagner–Meerwein shift whereby the C_1–C_6 and C_2–C_6 bonds interchange, as well as a rapid C_2–$C_6 \rightarrow C_2$–C_5



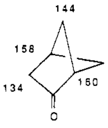
4



5



6 a, R = H
b, R = CH_3



7

---

(20) The conformation of **3** has been shown to be a flattened boat: Abraham, R. J.; Chadwick, D. J.; Sancassan, F. *Tetrahedron Lett.* **1979**, 265–268. See also ref 58.

(21) Kirchen, R. P.; Sorensen, T. S. *J. Am. Chem. Soc.* **1978**, *100*, 1487–1494.

(22) For cyclohexanone $^1J_{C_\alpha H} = 130$ Hz. The equatorial C_α–H bond nearly eclipses the C=O bond. Eliel, E. L. *Stereochemistry of Carbon Compounds*, McGraw-Hill: New York, 1962; p 240.

(23) For the 1-methylcyclohexyl cation the measured $^1J_{CH}$ values are $C_{2,6}$ 127 Hz, $C_{3,5}$ 133 Hz, C_4 127 Hz (Jensen W. A., Kelly, D. P., unpublished results). Kirchen and Sorensen have shown that this cation is conformationally mobile with an activation energy < 6 kcal/mol between the chair and the (more stable) twist-boat conformations.[21] They thus suggested using 2-methylbicyclo[2.2.2]oct-2-yl as a more appropriate model cation. This cation was thus generated from a mixture of epimeric methyl alcohols obtained from bicyclo[3.2.1]octan-2-one, since they had reported the rapid rearrangement of the cation generated from these alcohols to the 2-methylbicyclo[2.2.2]octyl system.[21] 2-Methylbicyclo[2.2.2]oct-2-yl cation: δ (^{13}C) (FSO_3H/SO_2ClF, 0.71 M, −65 °C) 67.2 (d, $J = 156$ Hz, C_1), 322.1 (s, C^+), 59.0 (t, $J = 128$ Hz, C_3), 36.4 (d, $J = 143$ Hz, C_4), 23.9 (t, $J = 134$ Hz, $C_{5,7}$), 30.9 (t, $J = 142$ Hz, $C_{6,8}$). Bicyclo[2.2.2]octan-2-one: δ(^{13}C) ($CDCl_3$) 44.2 (d, $J = 140$ Hz, C_1), 218.0 (s, C=O), 44.8 (t, $J = 129$ Hz, C_3), 27.9 (d, $J = 136$ Hz, C_4), 23.3 (t, $J = 132$ Hz, $C_{5,7}$), 24.7 (t, $J = 132$ Hz, $C_{6,8}$). Chemical shifts have been reported previously: Stephens, K. R.; Stothers, J. B.; Tan, C. T. In *Mass Spectrometry and NMR Spectroscopy in Pesticide Chemistry*; Hague, Rizwanul, Ed.; Plenum: New York, 1974. Berger, S. *J. Org. Chem.* **1978**, *43*, 209–212. ΔJ at C_3 is thus ~0 Hz for this cation. [**Note added in proof**: Sorensen has recently reinvestigated the 1-methylcyclohexyl cation and now reports that the two equilibrating species do not include a twist-boat conformer but different chain forms, one of which involves substantial C_α–H hyperconjugation and the other predominantly C_α–C_β hyperconjugation. This does not alter our interpretation that in cyclohexyl systems the ΔJ value will be relatively small. Kirchen, R. P.; Ranganayakulu, K.; Sorensen, T. S. *J. Am. Chem. Soc.* **1987**, *109*, 7811–7816.]

(24) Kelly, D. P.; Brown, H. C. *Aust. J. Chem.* **1976**, *29*, 957–965. Chemical shifts have been reported previously by Olah, G. A.; Liang, G.; Mateescu, G. *J. Org. Chem.* **1974**, *39*, 3750–3754.

(25) 2-Adamantanone: δ ^{13}C ($CDCl_3$) 46.7 (d, $J = 137$ Hz, $C_{1,3}$), 218.7 (s, C=O), 39.1 (t, $J = 129$ Hz, $C_{4,8,9,10}$), 27.4 (d, $J = 134$ Hz, $C_{5,7}$), 36.2 (t, $J = 129$ Hz, C_6). Chemical shifts have been reported previously: Hawkes, G. E.; Herwig, K.; Roberts, J. D. *J. Org. Chem.* **1974**, *39*, 1017–1028. [**Note added in proof**: In a recent study of adamantyl cations Sorensen has proposed that the skeleton may not be as rigid as previously believed and that the cationic center may be distorted from trigonal symmetry by as much as 20°. This is consistent with our finding that ΔJ_{C1H} is much less in the 2-adamantyl system (10 Hz) than that predicted for a dihedral angle of 90° (22 Hz). Finne, E. S.; Gunn, J. R.; Sorensen, T. S. *J. Am. Chem. Soc.* **1987**, *109*, 7816–7823.]

(26) Bicyclo[2.2.1]heptan-2-one: δ(^{13}C) ($CDCl_3$), 49.8 (d, $J = 148$ Hz, C_1), 215.3 (s, C_2), 45.2 (t, $J = 133$ Hz, C_3), 35.4 (d, $J = 144$ Hz, C_4), 27.3 (t, $J = 132$ Hz, C_5), 24.2 (t, $J = 134$ Hz, C_6), 36.7 (t, $J = 135$ Hz, C_7). $^1J_{CH}$ values were obtained by the selective excitation technique, e.g., J_{C4H}. See also ref 3.

(27) Schmitz, L. R.; Sorensen, T. S. *J. Am. Chem. Soc.* **1980**, *102*, 1645–1648.

(28) Olah, G. A.; Liang, G., Jindal, S. P. *J. Am. Chem. Soc.* **1976**, *98*, 2508–2511. 4: δ ^{13}C (−110 °C) 157.8 (d, 184.5 $C_{1,2}$), 49.1 (t, 156.9, $C_{3,5,6}$), 43.4 (d, 164.6, C_4).

(29) Saunders, M.; Kates, M. R.; Wiberg, K. B.; Pratt, W. *J. Am. Chem. Soc.* **1977**, *99*, 8072–8073. Seybold, G.; Vogel, P.; Saunders, M.; Wiberg, K. B. *J. Am. Chem. Soc.* **1973**, *95*, 2045–2046.

Table II. ^{13}C NMR Spectral Parameters for Neutral Compounds[a]

compd	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	CH_3
3[b]	12.1	40.9	218.3	40.9	12.1	13.2				
	d, 172	t, 131	s	t, 131	d, 172	t, 161				
7[c,d]	56.07	213.71	40.76	35.99	40.93					
	d, 160.5	s	t, 133.5	dm, 158.0, 12.6, 2.6	tm, 144, 7					
8b (X = OH)	43.5	18.3	13.6	18.3	43.5	25.4		94.2	20.1	
	d	d	t	d	d	t		t	q	
8b (X = OCH_3)	41.4	20.0	14.3	20.0	41.4	25.8		98.8	29.8	51.3
	d	d	d,d	d	d	t		s	q	q
9b (X = OH)	43.6	19.7	17.1	19.7	43.6	24.3		97.9	19.8	
	d, 140	d, 162	dd, 155, 164	d, 158	d, 140	t, 131		s	q, 125	
9b (X = OCH_3)	41.8	20.4	16.26	20.4	41.8	24.5		102.9	16.30	52.2
	d, 140	d, 169	dd, 154, 162	d, 169	d, 140	t, 133		s	q, 125	q, 140
11b (X = OCH_3)	49.1	86.6	28.2	32.1	25.3	24.8	24.5	22.3	19.0	56.7
	d	d	t	d	d	t	t	s	qd	qd
13	37.7	8.2	5.9	8.2	37.7		20.5	203.4		
	d, 151	d, 156	t, 161	d, 176	d, 151		t, 136	s		
17[e]	45.4	133.3		45.4	21.1		205.1			
	d, 153	d, 175		d, 153	dd, 137. 142		s			
18[c]		74.31	42.07	27.52		43.44	42.07	93.34		16.92
		d, 155	t, 131	t, 130		d, 137	t, 131	s (C_6a)		q, 125
19[c]	89.36	37.23	33.05	82.66	33.05	37.23	21.28	32.94		18.21
	s	t, 129	t, 133	s	t, 133	t, 129	q, 125	d, 126		q, 125
24b (X = OH)	51.3	36.9[f]		38.5[f]	35.4[f]	34.8[f]			103.6	20.7
	d, 144	d, 173		d, 169	d, 169	d, 173			s	q, 126
25	41.5	29.3		33.3		29.3		41.5	204.4	
	d, 152	d, 172		d, 177		d, 172		d, 152	s	

[a] Chemical shifts ±0.1 ppm from internal $(CH_3)_4Si$; coupling constants ±1 Hz. [b] Prepared according to Winstein and Sonnenberg.[15] Chemical shifts reported previously.[58,59] [c] Recorded at 100 MHz, ±0.05 ppm, J_{CH} ± 0.5 Hz. [d] Chemical shifts reported previously.[59] [e] Chemical shifts reported previously.[40] [f] Assignments may be interchanged.

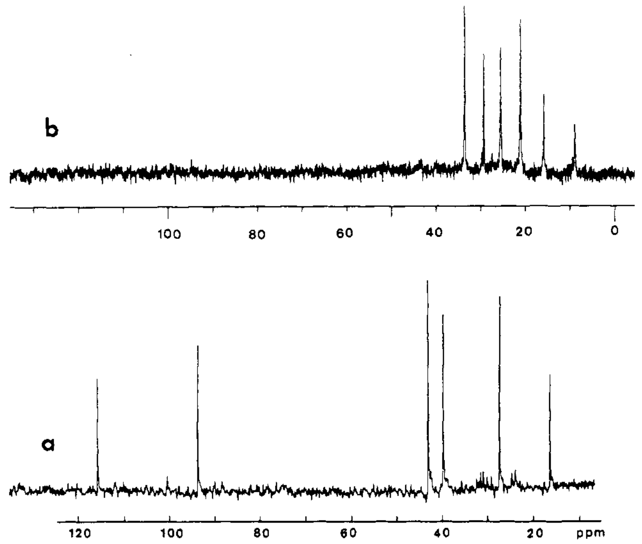


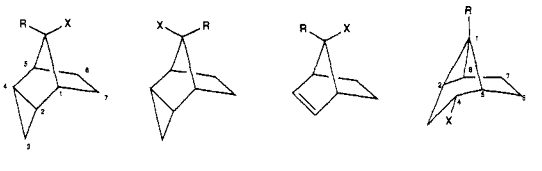
Figure 1. ^{13}C NMR spectra of oxonium cation **22** (a) and trishomocyclopropenium cation **14** (b).

bridging switch.[27] Since the ^{13}C–^{1}H coupling constants for bicyclo[2.1.1]hexan-2-one (**7**) were unavailable, they were determined by two-dimensional J spectroscopy.[30] Using an averaged value of 140 Hz for $J_{C\alpha H}$ of the methylene carbons (C_3, C_5, C_6) of **7**, ΔJ = 17 Hz, significantly less than for **1a**. However, at the bridging positions C_1 and C_2 of **4**, ΔJ = 24 Hz, similar to that for the bridging carbons of **1a**.

No such intermediate behavior is shown by **5**. A cationic carbon chemical shift of 322 ppm and no $^1J_{CH}$ values greater than 176 Hz (C_1) were consistent only with a static classical cation.[28] ΔJ values for the groups two bonds removed from the charge (β) are 7–11 Hz while $\Delta J_{C\alpha H}$ = 0 (C_3) and 16 Hz (C_1). The high ΔJ values observed for **1a** are thus consistent with the original contention for the formation of bridged structures.[2]

In an attempt to generate the methyl-substituted cation **1b**, the methyl alcohol **2b** derived from **3** was added to different mixtures of superacids (FSO_3H/SO_2ClF, SbF_5/SO_2ClF, $FSO_3H/SbF_5/SO_2ClF$) but in all cases the only identifiable species was the ring-opened 1-methylcyclohexenyl cation as also found by Olah and co-workers.[18]

Tricyclo[3.2.1.0^{2,4}]oct-8-yl Cations. Solvolyses of esters of *anti-endo*-tricyclo[3.2.1.0^{2,4}] octan-8-ol, e.g., **8a** (X = OPNB), proceed with exceptionally large rate enhancements (10^{11}) over those of syn-endo epimers **9a** and also significant enhancements (10^3) over those of *anti*-norbornen-7-ol (**10**) (K_{rel} = 1 for the *anti*-7-norbornanol derivative).[31,32] The solvolyses were accompanied by rearrangement to **11a** (X = OH) in neutral solution[31] and by both rearrangement and retention of configuration (**8a**, X = OH) in alkaline solution.[33] The superior participating ability of an anti-orientated cyclopropyl group over that of a double bond was also demonstrated by the nulling of



8 9 10 11

a, R = H
b, R = CH_3

---

(30) For examples, see: Chandrakumar, N.; Subramanian, S. *Modern Techniques in High-Resolution FT-NMR*; Springer-Verlag; New York, 1987. Bax, A. *Two-Dimensional Nuclear Magnetic Resonance in Liquids*; Reidel: Holland, 1982. Freeman, R.; Morris, G. A. *Bull. Magn. Reson.* **1979**, *1*, 5–26.

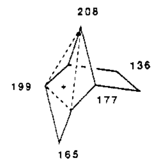
(31) Tanida, H.; Tsuji, T.; Irie, T. *J. Am. Chem. Soc.* **1967**, *89*, 1953–1954.

(32) Battiste, M. A.; Deyrup, C. L., Pincock, R. E.; Haywood-Farmer, J. *J. Am. Chem. Soc.* **1967**, *89*, 1954–1955; see also ref 6a.

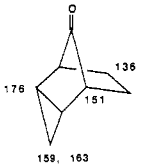
(33) Haywood-Farmer, J. S.; Pincock, R. E. *J. Am. Chem. Soc.* **1969**, *91*, 3020–3028.

this participation which occurs for the *p*-anisyl derivative of **10** (R = $C_6H_4OCH_3$, X = OPNB), whereas a large rate enhancement was still observed for the analogous derivative of **8** ($\simeq 10^3$).[34]

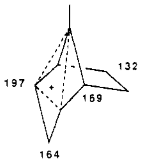
Intermediacy of symmetrical ethano-bridged trishomocyclopropenium cation **12** is supported both by the results of methyl substitution at the participating bond ($C_{2,4}$)[35] and by its direct ^{13}C NMR observation in superacid, the spectrum indicating highly shielded bridging carbons at 19.6 ($C_{2,4}$) and 0.0 ppm (C_8).[36] In order to obtain the coupling constants, **12** was prepared from a mixture of secondary chlorides **8a** and **11a** (X = Cl)[37] in SbF_5/SO_2ClF (Table I). Comparison with $^1J_{CH}$ values obtained for the ketone **13** again yields exceptionally high ΔJ values at both the bridging positions (23 Hz) and the bridgehead carbons (26 Hz), almost identical with those for **1**. Following a similar argument to that for the parent cation **1**, these values are inconsistent with any form of classical cation, static or equilibrating. The bridgehead C_1–H bond could make an angle of 90° with a vacant p orbital at C_8 of a static classical cation. This would lead to a maximum value of 22 Hz for ΔJ as observed for cyclopropylcarbinyl type systems,[3] although this value is reduced in other bridgehead cases such as 2-adamantyl as noted above. However, there is no other evidence to support such a structure, particularly the fact that the ΔJ value at $C_{2,4}$, formally two carbons removed (β) from the cationic center, is exceptionally large (23 Hz). Equilibration by a C_8–C_2 $\rightarrow$ C_8–C_4 bond migration should give rise to a *reduced* value of ΔJ at C_1 as noted above as well as an averaged chemical shift for C_2,C_4 much greater than the observed value of 19.7 ppm.



12

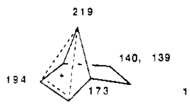


13

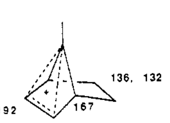


14

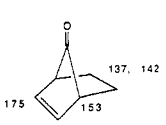
The 7-norbornenyl system provides an interesting comparison. Although there is still some debate as to the exact nature of the intermediate generated during the solvolyses of 7-*anti*-norbornenyl derivatives **10**,[6a] there is a large body of data[6b] that supports the symmetrically π-bridged nonclassical structures **15** and **16** particularly in superacids.[38]



15



16



17

Measurements of the coupling constants for the ketone **17**,[39,40] together with those for the cations recorded by Olah,[38] provided ΔJ values of 19 Hz (**15**) and 17 Hz (**16**) for the bridging carbons ($C_{2,3}$) and 20 Hz (**15**) and 14 Hz (**16**) for the bridgehead carbons ($C_{1,4}$).

For equilibrating classical structures formed by a C_7–C_1 $\rightarrow$ C_7–C_2 bond migration the ΔJ value at C_1 would be anticipated to be substantially reduced from that observed in static bicyclic systems, e.g., 2-methylbicyclo[2.2.1]hept-2-yl (22 Hz)[3] and 2-methyl bicyclo[2.2.2]oct-2-yl (16 Hz)[23] as is the case for the 2,3-dimethyl-substituted cation (10 Hz).[3] The ΔJ values for these norbornenyl cations thus support the π-bridged structures **15** and **16**. The higher values observed for **12** reflect the greater strain involved in the formation of the $\pi\sigma$-bridge of the trishomocyclopropenium cation than for the π-bridge in **15** and **16**.

Solvolysis of the tertiary tricyclooctyl anti ester **8b** (X = OPNB) proceeds with participation of the cyclopropyl bond as evidenced by an α-CH_3/H rate ratio of 31.[41] The products of the reaction were identified as **11b** (X = OPNB) (66%) resulting from internal return of the ion pair and **11b** (X = OH) (33%) resulting from solvent capture of the cationic intermediate, presumably **14**.

For observation of **14** directly, ionization in superacid was first attempted using the epimeric mixture of alcohols resulting from methyl lithium addition to **13**.[33,41,42] Treatment of the predominantly syn alcohol **9b** (X = OH) (95:5 syn:anti) with FSO_3H/SO_2ClF at −78 °C gave a clear orange solution, the ^{13}C NMR spectrum of which showed six resonances for nine carbons attached to 14 protons (Figure 1a). A singlet at δ 116, a doublet at 94.1 (J = 173 Hz), and the absence of any one-bond ^{13}C–^{1}H coupling constants larger than 173 Hz were inconsistent with a nonclassical cation. The absence of a deshielded singlet at approximately 300 ppm (e.g., **5**, $\delta(C^+)$ = 322 ppm) also precluded a classical static cation where the positive charge formally resides on a single carbon. Finally, a set of equilibrating classical cations is also ruled out since these cations should have only exhibited 13 protons attached to six carbon atoms. In addition, the chemical shifts and coupling constants were not consistent with those anticipated by the averaging of values for the equilibrating structures.

Quenching of the cationic solution in sodium methoxide/methanol afforded a 9:1 mixture of two compounds, neither of which showed a methoxy resonance in the ^{1}H NMR spectrum after separation by preparative GLC. The ^{13}C NMR spectrum of the major component showed only six resonances, two triplets at 27.5 ($^1J_{CH}$ = 130 Hz) and 42.1 ppm ($^1J_{CH}$ = 131 Hz), two doublets at 43.4 ($^1J_{CH}$ = 137 Hz) and 74.31 ppm ($^1J_{CH}$ = 155 Hz), a singlet at 93.3 ppm, and a quartet at 16.9 ppm (Table II). Together with the ^{1}H NMR spectral data and the mass spectrum, this compound was identified as the previously unreported tricyclic ether **18**, 6a-methylhexahydro-2,6-methano-2*H*-cyclopenta[*b*]furan.[43] NMR data for related cyclic ethers **19** and **20** support this structure. Thus the ^{13}C singlet at 93.3 ppm (C_{6a}) is similar to that observed for the quaternary (C_1) bridgehead carbon of 1,4-cineole (**19**) while that at 74.3 ppm (C_2) is consistent with the shielding anticipated (ca. 8 ppm) upon a replacement of CH_3 by H at C_4 of **19**.[44] The ^{1}H NMR spectrum of **18** showed a triplet at

---

[34] Gassman, P. G.; Fentiman, A. M. *J. Am. Chem. Soc.* **1970**, *92*, 2551–2552.

[35] Gassman, P. G.; Chasman, J. N.; Reus, W. F.; Battiste, M. A.; Haywood-Farmer, J. *J. Org. Chem.* **1979**, *44*, 2814–2816.

[36] Masamune, S.; Sakai, M.; Kemp-Jones, A. V. *Can. J. Chem.* **1974**, *52*, 858–860.

[37] The mixture was prepared by T. M. Ford by photochlorination of bicyclo[3.2.1.$0^{2,4}$]octane with *tert*-butyl hypochlorite: Freeman, P. K.; Ziebarth, T. D.; Raghavan, R. S. *J. Am. Chem. Soc.* **1975**, *97*, 1875–1881.

[38] Olah, G. A.; Liang, G. *J. Am. Chem. Soc.* **1975**, *97*, 6803–6806.

[39] Gassman, P.; Marshall, J. L. *Org. Synth.* **1968**, *48*, 25.

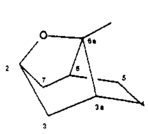
[40] Bicker, R.; Kessler, H.; Steigel, A.; Zimmermann, G. *Chem. Ber.* **1978**, *111*, 3215–3221.

[41] The α-CH_3/H rate ratio for 7-norbornanyl is 10^8 and for **10** (X = OPNB) is 10^3. Gassman, P. G.; Schaffhausen, J. G.; Raynolds, P. W. *J. Am. Chem. Soc.* **1982**, *104*, 6408–6411.

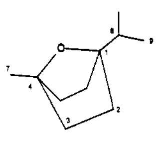
[42] Baird, M. S.; Reese, C. B. *J. Chem. Soc., Chem. Commun.* **1972**, 523–524.

[43] A preliminary communication has appeared: Kelly, D. P.; Giansiracusa, J. J.; Leslie, D. R.; McKern, I. D. *Tetrahedron Lett.* **1986**, *27*, 2311–2312.

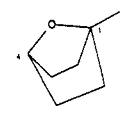
[44] 1-Isopropyl-4-methyl-7-oxabicyclo[2.2.1]heptane (1,4-cineole) (**19**): δ (^{1}H) ($CDCl_3$, 400 MHz), 2.08 (septet, J = 7 Hz, 1 H), 1.75–1.50 (m, 8 H), 1.45 (s, 3 H), 0.96 (d, J = 7 Hz, 6 H) ppm; δ(^{13}C) (100 MHz), see Table II.



18



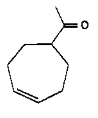
19



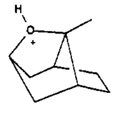
20

δ 4.33 and a singlet at δ 1.45 similar to those reported for the bridgehead methine ($\delta(H_4)$ 4.49) and methyl groups (δ 1.50) of **20**[45] and measured here for 1,4-cineole (**19**) (δ 1.45).[44]

Comparison of the literature data with the spectroscopic data for the minor component of the quenching reaction indicated that this compound was the cycloheptenyl ketone **21**.[46] This was confirmed by synthesis of an authentic sample.



21



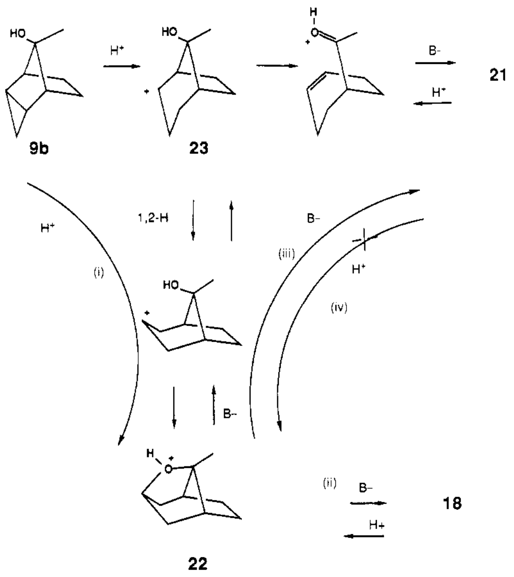
22

The ^{13}C NMR spectrum of **18** was remarkably similar to that of the FSO_3H solution. They both showed the same number of resonances in the same intensity and multiplicity pattern with only marginal differences in chemical shifts and CH coupling constants. In fact, the only two resonances for which the chemical shift differences were greater than 4 ppm were those of C_2 and C_{6a} in **18**, the two carbons bearing the ether linkage. Since such deshielding ($\Delta\delta$ 23.4 and 19.8 ppm, respectively) could be caused by protonation of **18** on oxygen, the species present in the ion solution was identified as the protonated ether **22**.[43] This was confirmed by addition of **18** to FSO_3H solution, whereupon **22** was regenerated.

This cation could be formed by preferential protonation of the cyclopropyl ring at $C_{2,4}$ followed by a 1,2-hydride shift to give the unobserved cation **23**. A chair–boat interconversion would then place the vacant orbital at C_3 adjacent to the syn hydroxyl lone pair of electrons. Internal nucleophilic capture would then give **22** (Scheme I, route i). In the presence of sodium methoxide during quenching, **22** simply deprotonates to give **18** (Scheme I, route ii). The absence of ^{13}C NMR signals attributable to the protonated form of **21** in the superacid solution indicated that it could be produced during quenching of the cationic solution. Thus ring opening at the C_2–O bond of **22** followed by a 1,2-hydride shift (to give **23**), ring cleavage at the methano bridge, and deprotonation would give **21** (Scheme I, route iii). This immediately suggested that **21** might serve as a precursor for the carboxonium ion **22** if protonation occurred preferentially on oxygen. Formation of the methano bridge by participation of the π electrons of the olefinic bond would then generate the same unstable secondary 8-hydroxy-8-methylbicyclo[3.2.1]oct-2-yl cation (**23**) as formed by protonation of **9b** (X = OH) (Scheme I, route iv).

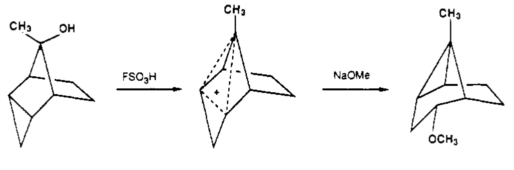
Addition of **21** to either FSO_3H/SO_2ClF or $FSO_3H/SbF_5/SO_2ClF$ at low temperature gave clear yellow solutions, the ^{13}C NMR spectra of which showed no sign of the protonated ether **22** at temperatures between −60 and −10 °C. The spectra were consistent however with the O-protonated ketone (δ(C) = O 248.0 ppm).[47] This suggested

Scheme I



that **21** is formed directly from **23** by deprotonation of the hydroxy group with synchronous ring opening.

It was thus obvious that generation of trishomocyclopropenium cation **14** might only be possible in superacid media if participation accompanied ionization.[18,48] Treatment of **13** with lithium dimethylcuprate afforded the anti alcohol **8b** (X = OH)[41] which was added carefully to FSO_3H/SO_2ClF at −78 °C, resulting in a clear orange-brown solution. The ^{13}C NMR spectrum of this solution was completely different from that obtained from the syn alcohol, the most deshielded carbon giving rise to a doublet at 33.4 ppm (Table I, Figure 1b). The fully coupled ^{13}C and DEPT spectra allowed assignments to be made in accordance with the structure of the nonclassical cation **14**. Thus the bridging carbons appear at δ 29.1 (C_8) and 20.9 ($C_{2,4}$) with the expected deshielding of C_8 (29 ppm) upon methyl substitution of the unsubstituted cation **12**.[49] Otherwise the spectra of **12** and **14** are very similar. The ΔJ values at the bridging $C_{2,4}$ (21 Hz) and the bridgehead $C_{1,5}$ carbons (18 Hz) are slightly reduced from those for **12**, as observed also for **4** and **5** above, but are nevertheless substantial and inconsistent with any structure other than **14**.



8b 14 11b

Quenching of the solution of **14** in excess sodium methoxide–methanol and subsequent workup yielded a colorless oil, the proton NMR spectrum of which indicated it to be essentially a single compound. Following purification (preparative GLC), this compound was identified from its mass and ^1H and ^{13}C NMR spectra as the rear-

---

(45) Takahashi, H.; Ito, M. *Chem. Lett.* **1979**, 373–374.

(46) Marschall, H.; Vogel, F.; Weyerstahl, P. *Liebigs Ann. Chem.* **1977**, 1557–1571.

(47) Forsyth, D. A.; Osterman; V. M.; De Member, J. R. *J. Am. Chem. Soc.* **1985**, *107*, 818–822.

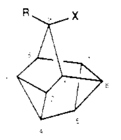
(48) Sorensen, T. S. *J. Chem. Soc., Chem. Commun.* **1976**, 45–47.

(49) There is a large body of data in the literature mainly due to Olah and co-workers which shows that the effect of replacement of H by CH_3 at a cationic center is +15 to 40 ppm (deshielding) depending on the substrate, e.g., alicyclic static cations, +15 ppm (Olah, G. A.; Donovan, D. J. *J. Am. Chem. Soc.* **1977**, *99*, 5026–5039), benzyclic, +20 ppm (Olah, G. A.; Prakash, G. K. S.; Liang, G. *J. Org. Chem.* **1977**, *42*, 2666–2671), nonclassical π-bridged, +38 ppm, see ref 38.

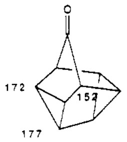
ranged methyl ether **11b** (X = OME). This product, briefly reported by Baird and Reese,[42] is characterized by a doublet of triplets in the proton spectrum at δ 3.53 with $^3J_{H_4H_5}$ = 6.5 Hz and $^3J_{H_4H_{3exo}} = {}^3J_{H_4H_{3endo}}$ = 8.8 Hz. This characteristic multiplet identifies the endo stereochemistry of the methyl ether.[50] Homodecoupling experiments at 400 MHz allowed most of the other assignments to be made (see Experimental Section). The structure was confirmed from the DEPT and SFOR ^{13}C spectra, in particular the doublet at δ 86.6 (C_4), the second-order distorted triplets (SFOR) due to two adjacent tightly coupled methylene groups ($C_{6,7}$),[51] and a doublet of doublets ($^1J_{CH_{3exo}} \neq {}^1J_{CH_{3endo}}$) due to an isolated methylene group (C_3). Although not observed under solvolytic conditions,[41] capture of the methyl-substituted cation **14** in FSO_3H by methoxide might have occurred at C_8 to give the *anti*-methyl ether **8b** (X = OMe). However, the spectra of the quenched secondary methyl ether were quite different from those of authentic samples of both the anti and syn tertiary methyl ethers **8b** and **9b** (X = OCH_3) prepared from the corresponding alcohols with sodium hydride and methyl iodide (Table II).

Capture of this trishomocyclopropenium cation thus occurs in both superacid and solvolytic media exclusively from the unprotected endo side at $C_{2,4}$. Similar capture of the 7-norbornenyl cation occurs under kinetic control with methoxide[52] or sodium borohydride[53] to give the analogous tricyclic ether.[6b]

Pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-9-yl Cations. As indicated previously, the behavior of derivatives of pentacyclo[4.3.0^{2,4}.0^{3,8}.0^{5,7}]nonan-9-ol (**24**) under both solvolytic and superacidic conditions is well-documented.[7-13] There is no dissent from the view that the intermediates generated from both secondary and tertiary derivatives are $\pi\sigma$-bridged, nonclassical, trishomocyclopropenyl cations, **26** and **27**, respectively. Solvolysis of the secondary ester **24a** (X = OPNB) proceeds with a large rate enhancement (10^{12}) over that of bicyclo[2.2.1]heptyl derivatives, statistical deuterium scrambling over $C_{2,3,9}$, and the formation of a single product (**24a**, X = OH).[7] Substitution by methyl at C_9 drops the rate of solvolysis of **24b** (X = OPNB) by a factor of 112, consistent with the reduced cyclopropyl participation in the formation of **27**[8] and comparable with the α-CH_3/H ratio observed for **8** (31)[35] and **10** (44).[54] Application of the "tool of increasing electron demand"[55] involving solvolysis of 9-aryl-9-*p*-nitrobenzoates **24c** (X = OPNB) provided an excellent linear Hammett plot and a value of the reaction constant $\rho^+ = -2.05$, consistent with substantial $\pi\sigma$-participation during solvolysis.[9]



24

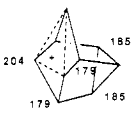


25

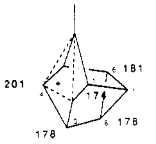
a, R = H

b, R = CH_3

c, R = Ar



26

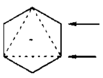


27

A plot of the ^{13}C substituent chemical shift $\Delta\delta(C^+)$ for **24c** [$\delta(C_9)$ (Ar = C_6H_5) − $\delta(C_9)$ (Ar = C_6H_4Y)] against a measure of electron demand, either σ^{C+} or δC^+ of 1-arylcyclopentyl[12,56] gives an excellent linear relationship with a *positive slope*, similar to but steeper than that for 7-aryl-7-norbornenyl cations,[57] indicative of the substantially greater stabilization of charge in these cations.

The $^1J_{CH}$ values have now been measured for the model ketone **25** and the tertiary cation **27**, which together with those for **26** measured previously[11] allow determination of the ΔJ values. At the bridging positions the values are 32 Hz and 29 Hz for **26** and **27**, respectively. These exceptionally high values, the largest so far measured, are inconsistent with static classical systems or equilibrating systems as previously discussed for **12** and **14**, leaving σ-bridging as the only satisfactory rationalization. Further proof is evidenced by the reduced but still high values of ΔJ for the $C_{1,5}$ bridgehead carbons, **26** ΔJ = 27, **27** ΔJ = 22 Hz.

Thus all of the C_{3v} symmetric trishomocyclopropenium cations are characterized by high values of ΔJ at both the bridging (21–32 Hz) and the intermediate methylene or bridgehead (18–27 Hz) carbons.



	1	**12**	**14**	**26**	**27**	
← ΔJ	27	26	18	27	22	Hz
← ΔJ	24	23	21	32	29	Hz

It is now possible to conclude that in both solvolytic and superacid solutions, the cations generated from *cis*-bicyclo[3.1.0]hex-3-yl, *endo-anti*-tricyclo[3.2.1.0^{2,4}]oct-8-yl, and 9-pentacyclo[4.3.0.0^{2,4}.0^{3,8}.0^{5,7}]non-9-yl derivatives are true $\pi\sigma$-bridged nonclassical cations, by all the criteria so far applied. They thus provide nonclassical standards by which other cations may be judged.

Experimental Section

NMR Spectra. The proton and carbon NMR spectra were recorded on a variety of instruments: VARIAN CFT-20, VARIAN FT-80A, NICOLET NT-360 (Purdue University), JEOL FX-100, and JEOL GX-400 (University of Melbourne). Proton (±0.1 ppm) chemical shifts were measured from internal Me_4Si at probe temperature for ($CDCl_3$) solutions of neutral compounds and from external Me_4Si for cationic solutions. For the latter, field stabilization was provided by a concentric capillary of acetone-d_6 containing Me_4Si or by an external ^7Li lock. Proton-coupled ^{13}C NMR spectra were obtained by the normal gated-decoupling technique with a minimum 50% duty cycle, using, for example, a 6000-Hz spectral width and either 16384 or 8192 data points at 25 MHz. Coupling constants (± 1 Hz) were measured by hand from expanded plots (e.g., 14.3 Hz cm^{-1}). In the cases where accurate coupling constants could not be obtained from the coupled spectrum due to overlapping signals, selective excitation of each individual ^{13}C–H multiplet was used to provide accurate J_{CH} values. This excitation was achieved by using a DANTE sequence of 50 pulses of 2-μs durations with a repetition period calculated for the first side-band frequency. The decoupler was gated off during acquisition only. Where only multiplicity was

---

(50) An axial substituent would give rise to dihedral angles for H_4H_{3exo} and H_4H_{3endo} corresponding to one large and one small value of $^3J_{HH}$. The characteristic multiplet has been reported for similar compounds: **11a** (X = OPNB), ref 32; **11a** (X = $OCOCH_3$), ref 33; **11a** (X = OH), ref 34; **11b** (X = OPNB), ref 41; **11b** (X = OCH_3), ref 42.

(51) Grutzner, J. B. *J. Chem. Soc., Chem. Commun.* **1974**, 64–65.

(52) Diaz, A.; Brookhart, M.; Winstein, S. *J. Am. Chem. Soc.* **1966**, *88*, 3133–3135.

(53) Brown, H. C.; Bell, H. M. *J. Am. Chem.* Soc. **1963**, *85*, 2324.

(54) Gassman, P. G.; Pascone, J. M. *J. Am. Chem. Soc.* **1973**, *95*, 7801–7813.

(55) Gassman, P. G.; Fentiman, A. F. *J. Am. Chem. Soc.* **1970**, *92*, 2549–2551.

(56) Brown, H. C.; Kelly, D. P.; Periasamy, M. *Proc. Natl. Acad. Sci. U.S.A.* **1980**, *77*, 6956–6960.

(57) Brown, H. C.; Periasamy, M.; Perumal, P. T.; Kelly, D. P. *J. Am. Chem. Soc.* **1984**, *106*, 2359–2363.

determined, it was achieved by single frequency off-resonance, by DEPT, or by gated spin–echo techniques. In some cases, two-dimensional methods were employed to determine J_{CH} values (hetero-2D-J), e.g., for **7**, or to determine carbon–proton correlations (CHCOR), e.g., for **6a** (X = OH), or proton coupling patterns (COSY 45), e.g., **8b** (X = OH), using the standard JEOL or NICOLET software. Assignments of proton spectra of some bicyclic compounds were assisted by homonuclear decoupling and NOE difference experiments.

Syntheses. Bicyclo[2.1.1]hexan-2-one (7). Ketone **7** was prepared according to literature procedures.[60] ^{13}C NMR data are reported in Table II. Chemical shifts have been reported previously.[59] ^{1}H NMR (400 MHz): δ 2.83 (m, 2 H, H_1, H_4), 2.22 (m, 2 H, H_5 anti), 2.14 (m, 2 H, H_5 syn), 1.62 (dd, J = 4.7, 2.2 Hz, H_3). These assignments were based on the expected coupling constants as determined by J. M. Shoolery for 5,5-dimethylbicyclo[2.1.1]hexan-2-one.

2-Methylbicyclo[2.1.1]hexan-2-ol (6b, X = OH). Ketone **7** was treated with methyllithium in diethyl ether for 3 h at 0 °C. Normal workup afforded **6b** as a low melting solid, mp 5–7 °C (lit.[28] mp 8–9 °C). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.41 (m, 1 H, H_4), 2.26 (d, t, $J_{1,4}$ = 7.1 Hz, $J_{1,5en,6en}$ = 2.6 Hz, H_1), 1.7 (m, 3H, H_{3a}, H_{5en}, H_{6en}), 1.63 (m, H_{3b}), 1.59 (dd, $J_{6ex,5ex}$ = 10.0 Hz, $J_{6ex,6en}$ = 6.8 Hz, H_6), 1.44 (s, CH_3), 1.17 (dd, $J_{5ex,6ex}$ = 10.0 Hz, $J_{5ex,5en}$ = 7.1 Hz, H_{5ex}). ^{13}C NMR (100 MHz): 77.50 (s, C_2) 51.70 (d, J = 152 Hz, C_1), 44.06 (t, J = 132 Hz, C_3), 40.34 (t, J = 137 Hz, C_5), 38.45 (dd, t, J = 151, 12, 3 Hz, C_4), 38.02 (t, J = 137 Hz, C_6), 26.31 (q, d, J = 125, 5 Hz, CH_3).

***endo*-Tricyclo[3.2.1.0^{2,4}]octan-8-one (13).** The ketone was prepared according to the literature procedure starting from hexachlorocyclopentadiene and cyclopropene.[33] ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.21 (m, $J_{1,6ex}$ = 2.3 Hz, $H_{1,5}$), 1.69 (m, $J_{6ex,6en}$ = 8.1, J = 2.3 Hz, H_{6ex}), 1.33 (m, $H_{2,4}$), 1.15 (d, J = 8.1 Hz, H_{6en}), 1.01 (d, t, $J_{3ex,3en}$ = $J_{3ex,2,4}$ = 7.1 Hz, H_{3ex}), 0.79 (d, t, $J_{3ex,3en}$ = 7.1 Hz, $J_{3en,2,4}$ = 3.4 Hz, H_{3en}). Assignments were based on ^{1}H NMR data previously reported at lower field strengths[33] for those reported for the exo ketone[61] and for deuteriated tricyclo[3.2.1.0^{2,4}]octane derivatives.[62] ^{13}C NMR, see Table II.

8-Methyl-*endo*-tricyclo[3.2.1.0^{2,4}]octan-*anti*-8-ol (8b, X = OH). This alcohol was prepared as described previously by treatment of **13** with lithium dimethylcuprate prepared from methyllithium and purified cuprous iodide, mp 111–113 °C (lit.[41] mp 114–115 °C). ^{1}H NMR (400 MHz): δ 1.78 (m, 2 H, H_{6ex}), 1.75 (m, 2 H, $H_{1,5}$), 1.58 (s, OH), 1.57 (s, 3 H, CH_3), 1.21 (m, 2 H, $H_{2,4}$), 1.4 (br d, J = 7.8 Hz, 2 H, H_{en}), 0.94 (d, t, J = 6.3, 3.1 Hz, 1 H, H_{3en}), 0.72 (dt, J = 6.3, 7.4, 1 H, H_{3ex}). ^{13}C NMR, see Table II.

***anti*-8-Methoxy-8-methyl-*endo*-tricyclo[3.2.1.0^{2,4}]octane (8b, X = OCH_3).** To the anti alcohol (**8b**, X = OH) (31.3 mg, 0.22 mmol) in tetrahydrofuran (4 ml) was added iodomethane (4.5 mL, 17.2 mmol) followed by sodium hydride (0.94 g, 39 mmol). The mixture was stirred at room temperature for 3 h, diluted with water, and extracted with ether. After washing with saturated sodium bicarbonate and brine, the solvent was dried ($MgSO_4$) and removed by a stream of nitrogen to give a yellow oil (21 mg, 61%), purified by preparative GLC.[63] ^{1}H NMR (400 MHz): δ 3.20 (s, OCH_3), 1.90 (m, 2 H, $H_{1,4}$), 1.69 (dm, J = 7.8 Hz, 2 H, $H_{6,7ex}$), 1.50 (s, 3 H, CH_3), 1.17 (m, 2 H, $H_{2,4}$), 0.99 (dt, J = 6.7, 3.2 Hz, 1 H, H_{3en}), 0.96 (d, J = 7.8 Hz, $H_{6,7en}$), 0.73 (dt, J = 6.2, 7.5 Hz, 1 H, H_{3ex}). ^{13}C NMR, see Table II.

8-Methyl-*endo*-tricyclo[3.2.1.0^{2,4}]octan-*syn*-8-ol (9b, X = OH). The ketone **13** was treated with excess methyllithium and worked up to yield a white solid as described previously.[42] Recrystallization afforded **9b** (X = OH) as white needles, mp 68–70 °C (lit.[42] mp 69–70 °C). ^{1}H NMR (400 MHz): δ 1.73 (p, 2 H, $H_{1,5}$), 1.54–1.59 (m, 4 H, $H_{2,4}$, $H_{6,7}$), 1.30 (s, CH_3), 1.25 (dt, J = 6.4, 3.1 Hz, 1 H, H_{3en}), 1.14 (m, 2 H, $H_{6,7en}$), 0.96 (dt, J = 6.4, 7.8 Hz, 1 H, H_{3ex}). ^{13}C NMR, see Table II.

***syn*-8-Methoxy-8-methyl-*endo*-tricyclo[3.2.1.0^{2,4}]octane (9b, X = OCH_3).** This compound was prepared from the syn alcohol (56.4 mg, 0.37 mmol) in an analogous manner to its epimer. This product was a yellow oil (33.9 mg, 54%, purified by preparative GLC.[63] ^{1}H NMR (400 MHz): δ 3.33 (s, OCH_3), 1.91 (p, J = 2.4 Hz, 2 H, $H_{1,5}$), 1.46–1.51 (m, 4 H, $H_{2,4}$, $H_{6,7ex}$), 1.25 (s, CH_3), 1.06–1.10 (m, 3 H, H_{3en}, $H_{6,7en}$), 0.85 (dt, J = 6.4, 7.4 Hz, 1 H, H_{3ex}). ^{13}C NMR, see Table II. MS (EI, 15 ev): m/z [relative to solvent, $CHCl_2^{+\bullet}$ 83 (100)], 152 ($M^{+\bullet}$, 0.8), 137 (3.2), 98 (28).

1-(4′-Cycloheptenyl)ethanone (21). Cyclopentanone and pyrrolidine (and a few crystals of *p*-toluenesulfonic acid) were heated under reflux in benzene to produce the enamine, bp 104–106 °C (18 mm) (lit.[64] bp 85–86 °C (10 mm)). ^{13}C NMR (25 MHz): δ 149.4 (C_1), 91.9 (d, C_2), 48.7 (t, C_α), 32.7 (t, C_5), 30.5 (t, C_3), 24.9 (t, C_β), 22.9 (t, C_4). The enamine was stirred at room temperature with acrolein for 67 h and the product distilled rapidly to give **2-(*N*-pyrrolidinyl)bicyclo[3.2.1]octan-8-one**,[46,65] bp 107–112 °C (0.1 mm) (lit.[65] bp 110–115 °C (0.5 mm)). IR (film) 2958 s, 2873 m, 2779 m, 1748 vs cm^{-1}. ^{13}C NMR (100 MHz): δ (two isomers, major isomer first) 220.03, 217.48 (s, C_8), 69.78, 71.82 (d, C_2), 51.63, 51.58 (t, C_α), 48.98, 47.36 (d, C_1), 43.84, 44.22 (d, C_5), 31.67, 31.55 (t), 24.11, 23.22 (t), 22.82, 22.34 (t, C_β), 21.87, 21.80, 20.94, 17.67 (all t, C_3,C_4,C_6,C_7, no firm assignments).

The bicyclic ketone was treated with methyl iodide in dioxane at 105 °C for 3.5 h followed by heating for 0.5 h with aqueous KOH. The solution was acidified and extracted ($CHCl_3$), and the organic layer was extracted with saturated $NaHCO_3$. The aqueous extract was acidified and extracted with $CHCl_3$ and the chloroform extract dried and evaporated to give a solid which was recrystallized (chloroform/diethyl ether) to give **4-cycloheptene-1-carboxylic acid**, mp 69.8–71.4 °C (lit.[46] mp 70 °C). IR (KBr) 3300–2500, 1713 vs, 1652 w, 1417, 1312, 1241, 1225, 931, 708 cm^{-1}. ^{1}H NMR (400 MHz): δ 5.78 (m, 2 H), 2.62 (m, 1 H), 2.31 (m, 2 H), 2.11 (m, 2 H), 2.01 (m, 2 H), 1.67 (m, 2 H). ^{13}C NMR (25 MHz): δ 182.6 (s), 131.6 (d), 47.0, 29.1, 26.6.

The carboxylic acid was treated with methyllithium and worked up as described previously except that quenching was achieved by addition of 1,2-dichloroethane to give **21**, bp 75 °C (13 mm) (lit.[46] bp 73 °C (13 mm)). IR (film) 3018, 2925, 2846, 1708 vs cm^{-1}. ^{1}H NMR (400 MHz): δ 5.77 (p, J = 2.2 Hz, 2 H, $C_{4'}$), 2.59 (tt, J = 10, 4 Hz, 1 H, H1′), 2.35–2.25 (m, 2 H), 2.15 (s, 3 H, CH_3), 2.15–2.05 (m, 2 H), 1.90 (m, 2 H), 1.53 (m, 2 H). ^{13}C NMR (100 MHz): δ 211.8 (s, C=O), 131.62 (d, J = 153 Hz, $C_{4'}$), 55.62 (d, J = 129 Hz, $C_{1'}$), 28.49 (t, J = 127 Hz, $C_{2'}$ or $C_{3'}$), 28.01 (q, J = 126 Hz, CH_3), 26.93 (t, J = 126 Hz, $C_{3'}$ or $C_{2'}$).

Generation and Quenching of Ions. The ions were prepared in known concentration from the appropriate precursors by slow addition to the precooled superacid solution (acetone/dry ice or ethanol/liquid N_2 slush) under a nitrogen atmosphere with vortex mixing.

2-Methylbicyclo[2.1.1]hexyl cation (5) was generated from the tertiary alcohol **6b** (X = OH) in FSO_3H/SO_2ClF. ^{13}C NMR (25 MHz, 0.7 M, −90 °C: 322.8 (s), 83.5 (d, J = 176 Hz, C_1), 57.8 (dd, J = 155 Hz, $C_{5,6}$), 57.3 (t, J = 134 Hz, C_3), 37.3 (d, J = 165 Hz, C_4), 38.5 ppm (q, J = 132 Hz, CH_3). Similar results have been reported by Olah.[28] J_{C_3H} and $J_{C_{5,6}H}$ were determined by selective excitation.

Tricyclo[3.2.1.0^{2,4}]oct-8-yl cation (12) was prepared by slow addition of a mixture of the secondary chlorides[37] **8a** and **11a**, (X = Cl) to SbF_5/SO_2ClF at −78 °C.

8-Methyl-*endo*-tricyclo[3.2.1.0^{2,4}]octyl Cation (14). Slow addition of the anti alcohol **8b** (X = OH) (98 mg, 0.71 mol) to FSO_3H/SO_2ClF (1:1, 2 mL) at −78 °C with rapid mixing gave an orange-brown solution (0.47 M). ^{13}C NMR, see Table I. Quenching of **14** was achieved by slow addition of the cold acid

---

(58) Rees, J. C.; Whittaker, D. *Org. Magn. Reson.* **1981**, *15*, 363–369.

(59) Grover, S. H.; Marr, D. H.; Stothers, J. B.; Tan, C. T. *Can. J. Chem.* **1975**, *53*, 1351–1361.

(60) Bond, F. T.; Jones, H. L.; Scerbo, L. In *Organic Photochemical Synthesis*; Srinivasan, R., Ed; Wiley-Interscience: New York, 1971; Vol. 1, p 33. Bond, F. T.; Jones, H. L.; Scerbo, L. *Tetrahedron Lett.* **1965**, 4685–4686. Butz, L. W.; Butz, E. J. W.; Gaddis, A. M. *J. Org. Chem.* **1940**, *5*, 171–183.

(61) Pincock, R. E.; Haywood-Farmer, J. S. *Tetrahedron Lett.* **1967**, 4759–4762.

(62) Johnson, B. L., private communication. Langley, J. W. Ph.D. Thesis, University of Western Australia, 1986.

(63) Preparative GLC was performed on a Hewlett Packard 5990A gas chromatograph fitted with a flame ionization detector and using a 12 ft × $^1/_4$ in glass column packed with 25% OV101 on Chromosorb W (60–80) programmed from 70 °C (2 min) to 170 °C (30 min) at 15 °C/min with gas (N_2) flow of 160 mL/min.

(64) Kuehne, M. E. *J. Am. Chem. Soc.* **1959**, *81*, 5400–5404.

(65) Stork, G.; Landesman, H. K. *J.* Am. *Chem. Soc.* **1956**, *78*, 5129–5130.

solution to an excess of precooled sodium methoxide in methanol. The colorless mixture was allowed to warm to room temperature, then diluted with water, and extracted with pentane. The organic extract was washed ($NaHCO_3$, NaCl), dried, and evaporated in a stream of nitrogen to give a colorless oil. ^1H NMR showed the product to be predominantly a single compound, **1-methyl-*endo*-4-methoxytricyclo[3.3.0.0^{2,8}]octane (11b, X = OCH_3).** ^1H NMR (400 MHz): δ 3.83 (dt, J = 8.8, 6.0 Hz, H_{4ex}), 3.21 (s, 3 H, OCH_3), 2.28 (m, 2 H), 1.98 (ddd, J = 3.0, 6.0, 13.2 Hz, H_5), 1.70 (m, 1 H), 1.45 (m, 1 H), 1.30 (s, 3 H, CH_3), 1.10–1.25 (m, 2 H), 0.80–0.95 (m, 2 H, $H_{2,8}$). ^{13}C NMR, see Table II. MS (E.I., 70 eV): m/z (relative intensity) 152 ($M^{+\bullet}$, 25), 120 (17), 105 (15), 94 (49), 91 (24), 81 (52), 79 (77), 77 (25), 71 (100); M^+ calcd 152.1201, obsd 152.1167.

6a-Methylhexahydro-2,6-methano-2*H*-cyclopenta[*b*]furanium (22). Addition of syn alcohol **9b** (X = OH) (100 mg, 0.72 mol) to FSO_3H/SO_2ClF at −78 °C gave a clear orange solution (0.36 M). ^{13}C NMR (25 MHz, −90 °C): 116.0 (s, C_{6a}), 94.1 (d, J = 173 Hz, C_2), 43.3 (d, J = 149 Hz, $C_{6,3a}$), 39.9 (t, J = 138 Hz, $C_{3,7}$), 27.4 (t, J = 134 Hz, $C_{4,5}$), 16.2 ppm (q, J = 133 Hz, CH_3). Addition of the ion solution to excess precooled sodium methoxide/methanol as above followed by similar workup yielded a pale yellow oil (90 mg). Preparative GLC yielded the two components identified as **21** (identical with authentic material) and **18** (1:9).

6a-Methylhexahydro-2,6-methano-2*H*-cyclopenta[*b*]furan (18). IR (film): 2942, 2868, 1380, 1131, 878 cm^{-1}. ^1H NMR (400 MHz): δ 4.33 (t, $J_{2,3ex}$ = 5 Hz, 1 H, H_2), 2.13 (m, $J_{3ex,3en}$ = 12 Hz, $J_{3ex,3a}$ = 10.5 Hz, $J_{3ex,2}$ = 5 Hz, 2 H, H_{3ex}), 1.87 (m, 4 H, H_{3a}, H_{4ex}), 1.65 (~d, J = 7.5 Hz, 2 H, H_{4en}), 1.43 (s, 3 H, CH_3), 1.22 (~d, J = 12 Hz, 2 H, H_{3en}). ^{13}C NMR, see Table II. MS (EI, 15 eV): m/z (relative intensity) 138 ($M^{+\bullet}$, 43), 95 (30), 94 (100), 88 (6), 86 (42), 84 (65), 80 (13), 71 (27), 68 (12), 43 (4); M^+ calcd 138.1044, obsd 138.1058. Anal. Calcd for $C_9H_{14}O$: C, 78.26; H, 10.14. Found: C, 78.60; H, 10.04.

Acknowledgment. We thank Professors R. M. Coates of the University of Illinois and P. G. Gassman of the University of Minnesota for samples of **25** and **13**, respectively, and for reading the manuscript, Dr. T. M. Ford for preparation of the tricyclooctyl chlorides **8** and **11**, Mr. S. K. Danek for one sample of the anti alcohol **8b**, Ms. V. Stokie for synthesis of **21**, Ms. W. A. Jensen for her contribution to the work on methylcyclohexyl cations, Dr. D. Brecknell of University of Queensland for a sample of 1,4-cineole, Ms. K. Karavokiros for preparation of 2-bicyclo[2.2.2]octanone, and Dr. J. M. Shooley of VARIAN for NMR data of 5,5-dimethylbicyclo[2.1.1]hexan-2-one. J.J.G. and D.R.L. acknowledge receipt of Commonwealth Postgraduate Awards. The hospitality of Professor H. C. Brown at Purdue University is gratefully acknowledged by D.P.K. The work was supported by the Australian Research Grants Committee.

Registry No. **3**, 1755-04-0; **5**, 59856-43-8; **6b** (X = OH), 87969-57-1; **7**, 5164-64-7; **8b** (X = OH), 83198-89-4; **8b** (X = OCH_3), 113894-45-4; **9b** (X = OH), 38310-50-8; **9b** (X = OCH_3), 113974-20-2; **11b** (X = OCH_3), 38310-54-2; **12**, 51900-16-4; **13**, 14224-86-3; **14**, 113892-33-4; **18**, 106200-60-6; **19**, 470-67-7; **20**, 70837-34-2; **21**, 65461-12-3; **22**, 113894-48-7; **24b** (X = OCH_3), 55794-07-5; **25**, 20682-66-0; cyclopentanone, 120-92-3; pyrrolidine, 123-75-1; 1-(1-cyclopenten-1-yl)pyrrolidine, 7148-07-4; *exo*-2-(*N*-pyrrolidinyl)bicyclo[3.2.1]octan-8-one, 113894-47-6; *endo*-2-(*N*-pyrrolidinyl)bicyclo[3.2.1]octan-8-one, 113894-46-5; 4-cycloheptene-1-carboxylic acid, 1614-73-9.

Computer-Assisted Mechanistic Evaluation of Organic Reactions. 15. Heterocycle Synthesis

Mark G. Bures and William L. Jorgensen*

Department of Chemistry, Purdue University, West Lafayette, Indiana 47907

Received November 11, 1987

CAMEO, an interactive computer program that predicts the products of organic reactions primarily through applying generalized rules governing reactivity, has been expanded to treat the major types of heterocycle-forming reactions, i.e., addition and substitution reactions under neutral and acidic conditions. Furthermore, syntheses involving base-catalyzed and pericyclic reactions, electrophilic aromatic substitution, and radical or carbenoid intermediates are handled via a mechanistic selection algorithm. This permits thorough coverage of the preparation of three- through eight-membered aromatic and nonaromatic heterocycles with one or more N, O, or S atom. Key considerations in the processing include determination of mechanistic type, classification of nucleophilic and electrophilic sites, and assessment of selectivity. A novel facet of the treatment is the construction of intermediates and products using a method that features "heterocyclic extended mechanistic steps". The study begins with a brief overview of the fundamental aspects of heterocycle-forming reactions. A discussion of the implementation of this module in CAMEO follows including sample reaction sequences predicted by the program.

I. Introduction

CAMEO is an interactive computer program that predicts the products of organic reactions given starting materials and reaction conditions. The program arrives at its predictions mainly through the use of mechanistic reasoning rather than through brute force recall of reaction precedents. Accordingly, development of CAMEO entails the formulation of general rules governing reactivity for different classes of organic reactions. Currently, the program can evaluate base-catalyzed and nucleophilic,[1] acid-catalyzed and electrophilic,[2] electrophilic aromatic substitution,[3] pericyclic,[4] oxidative,[5] and reductive[6] reactions. In addition, treatment of reactions involving radical, carbene, and nitrene intermediates is being implemented.

The program has also been expanded to include comprehensive coverage of reactions used in the synthesis of heterocyclic compounds as described here. This addition has much enhanced the program's capabilities for analyzing synthetic routes to biologically important molecules.

---

(1) Salatin, T. D.; Jorgensen, W. L. *J. Org. Chem.* **1980**, *45*, 2043. Salatin, T. D.; McLaughlin, D.; Jorgensen, W. L. *J. Org. Chem.* **1981**, *46*, 5284. Peishoff, C. E.; Jorgensen, W. L. *J. Org. Chem.* **1985**, *50*, 1056. Gushurst, A. J.; Jorgensen, W. L. *J. Org. Chem.* **1986**, *51*, 3513. Metivier, P.; Gushurst, A. J.; Jorgensen, W. L. *J. Org. Chem.* **1987**, *52*, 3724. Gushurst, A. J.; Jorgensen, W. L., in press.

(2) McLaughlin, D. R. Ph.D. Thesis, 1983, Purdue University.

(3) Bures, M. G.; Roos-Kozel, B. L.; Jorgensen, W. L. *J. Org. Chem.* **1985**, *50*, 4490.

(4) Burnier, J. S.; Jorgensen, W. L. *J. Org. Chem.* **1983**, *48*, 3923. Burnier, J. S.; Jorgensen, W. L. *J. Org. Chem.* **1984**, *49*, 3001.

(5) Paderes, G. Ph.D. Thesis, 1988, Purdue University.

(6) Metivier, P.; Jorgensen, W. L., manuscript under preparation.

0022-3263/88/1953-2504$01.50/0