Cross Cage Interactions in Substituted Bicyclo[1.1.1]pent-1-yl Radicals. Dissociation to [1.1.1]Propellane

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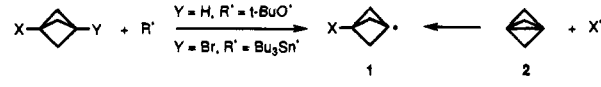
Abstract: A series of 3-substituted bicyclo[1.1.1]pent-1-yl radicals, including the 3-fluoro derivative, was generated by bromine atom abstraction from 1-bromo-3-substituted-bicyclo[1.1.1]pentanes and examined by EPR spectroscopy. The exceptionally large hyperfine splittings obtained from magnetic nuclei of the 3-substituents indicated that cross cage electronic interactions were substantial in these species. Bromine atom abstraction by triethylsilyl radicals from 1-bromo-3-fluorobicyclo[1.1.1]pentane was found to take place more rapidly than bromine abstraction from the unsubstituted parent, i. e., the fluorine substituent mediated a significant polar effect. Evidence was found of a novel disproportionation process in which the γ-fluorine atom was transferred from the 3-fluoro radical to a triethylsilyl or to a second bicyclo[1.1.1]pent-1-yl radical; an analogous chlorine atom transfer process was found for the 3-chloro radical. *Ab initio* MO calculations (6-31G* basis with electron correlation up to MP4) on the 3-fluoro- and 3-methyl-substituted radicals indicated that loss of the substituent to give [1.1.1]propellane would be comparatively easy for both species.

The bicyclo[1.1.1]pentane skeleton is of exceptional interest because of the short 1,3-distance between its bridgeheads. Experiment[1] and *ab initio* calculations[2] indicate that this distance is only ca. 1.85 Å and hence large cross cage interactions are anticipated, i.e., a substituent at C^3 is expected to have a very powerful influence on the detailed structure and reactivity at C^1. Cross cage interactions should be manifested particularly readily in 3-substituted bicyclo[1.1.1]pent-1-yl radicals (**1**) which are amenable to study by EPR spectroscopy and for which reaction modes can be established by well-understood homolytic methods. Prior to this work, only the parent radical **1** (X = H), which demonstrated an exceptionally large electron-nuclear hyperfine splitting (hfs) of 69.6 G from the bridgehead hydrogen,[3] and two staffanyl radicals[4] had been characterized by EPR spectroscopy. However, radicals of type **1** are easily made by hydrogen or halogen abstraction from bridgehead-substituted bicyclo[1.1.1]pentanes or by addition of radicals to [1.1.1]propellane (**2**). Several research groups have examined the latter technique and shown that 3-substituted bicyclopent-1-yl radicals function effectively as propagating intermediates in many chain sequences and add rapidly to electron deficient alkenes and carbonyl compounds.[5−7]



Several theoretical assessments of the parent radical have appeared.[2,8,9] Although the cage possesses ca. 68 kcal mol^{-1} of strain energy,[10] the activation energy for ring scission was calculated to be very high. This agrees with experimental evidence[11] of the reluctance of **1** to undergo β-scission to methylenecyclobutyl derivatives. A particularly significant theoretical result, obtained by Feller and Davidson,[9] implied that comparatively little expenditure of energy was entailed in the loss of the bridgehead hydrogen of **1** (X = H) to give [1.1.1]-propellane. The hydrogen atom has no significant stabilization energy, and hence, the implication is that a 3-substituted bicyclo-[1.1.1]pent-1-yl radical might convert quite readily to **2** by loss of a radical with a greater stabilization energy. Experimental evidence on this point is rather meager. When X in **1** is carbon-centered, the resulting bicyclo radicals are stable in solution at moderate temperatures, with the probable exception of the benzyl and allyl species which could not be made by addition of benzyl or allyl halides to **2**.[6,12] The 3-iodobicyclo[1.1.1]-pent-1-yl radical was found to readily lose an iodine atom.[6] Loss of a bromine atom from **1** (X = Br) has also been noted,[13] and addition of thiyl radicals to **2** was reported to be reversible.[14] Iodine atom and thiyl radical additions to alkenes are also reversible, while carbon-centered radical addition is not, so

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(1) (a) Almenningen, A.; Andersen, B.; Nyhus, B. A. *Acta Chem. Scand.* **1971**, *25*, 1217−1223. (b) Chiang, J. F.; Bauer, S. H. *J. Am. Chem. Soc.* **1970**, *92*, 1614−1617. (c) Cox, C. W.; Harmony, M. D. *J. Mol. Spectrosc.* **1970**, *36*, 34.
(2) Wiberg, K. B.; Hadad, C. M.; Sieber, S.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1992**, *114*, 5820−5828.
(3) Maillard, B.; Walton, J. C. *J. Chem. Soc., Chem. Commun.* **1983**, 900−901.
(4) McKinley, A. J.; Ibrahim, P. N.; Balaji, V.; Michl, J. *J. Am. Chem. Soc.* **1992**, *114*, 10631−10637.
(5) Wiberg, K. B.; Waddell, S. T. *J. Am. Chem. Soc.* **1990**, *112*, 2194−2216.
(6) Kaszynski, P.; McMurdie, N. D.; Michl, J. *J. Org. Chem.* **1991**, *56*, 307−316.
(7) Kaszynski, P.; Friedli, A. C.; Michl, J. *J. Am. Chem. Soc.* **1992**, *114*, 601−620.
(8) Bews, J. R.; Glidewell, C.; Walton, J. C. *J. Chem. Soc., Perkin Trans. 2* **1982**, 1447−1453.
(9) Feller, D.; Davidson, E. R. *J. Am. Chem. Soc.* **1987**, *109*, 4133−4139.
(10) Wiberg, K. B. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 312−322.
(11) Wiberg, K. B.; Connor, D. S. *J. Am. Chem. Soc.* **1966**, *88*, 4437−4441. Wiberg, K. B.; Williams, V. Z., Jr. *J. Org. Chem.* **1970**, *35*, 369−373.
(12) Kaszynski, P.; Michl, J. *J. Am. Chem. Soc.* **1988**, *110*, 5225−5226.
(13) Della, E. W.; Taylor, D. K. *J. Org. Chem.* **1994**, *59*, 2986−2996.
(14) McGarry, P. F.; Johnston, L. J.; Scaiano, J. C. *J. Am. Chem. Soc.* **1989**, *111*, 3750−3751.

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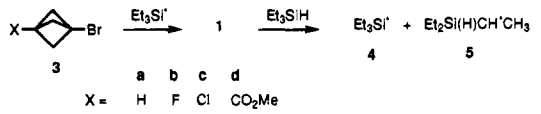
broadly speaking the γ-fragmentations of **1** resemble β-fragmentations of 2-substituted alkyl radicals.

The research reported in this paper was undertaken to examine the influence of 3-substituents on the structure and reactivity of **1**. In spite of their high strain energies and high reactivities, a short series of such radicals was successfully observed by EPR spectroscopy at low temperatures. This spectroscopic technique revealed unprecedentedly large hyperfine interactions from the magnetic nuclei of the 3-substituents. Bromine atom abstraction from 3-fluorobicyclo[1.1.1]pentyl bromide was found to be subject to a dramatic kinetic polar effect originating from the γ-fluorine atom. Fluorine atom abstractions are extremely rare in homolytic processes, but evidence was found for a novel type of disproportionation reaction in which a fluorine atom was transferred from a 3-fluorobicyclo[1.1.1]pent-1-yl radical to another radical. The feasibility of fluorine atom, and methyl group, loss from radicals of type **1** was also investigated by *ab initio* MO theory which indicted that γ-scission (i.e., loss of X) to give **2** would be comparatively easy.

Results and Discussion

Bromine Atom Abstraction from Substituted Bicyclo[1.1.1]pentanes. EPR Spectra of Bicyclo[1.1.1]pent-1-yl Radicals. The 3-substituted bicyclo[1.1.1]pent-1-yl bromides (**3**) chosen as radical precursors were synthesized by literature methods, except for the 3-fluoro compound (see Experimental Section). Radicals **1b–d** were generated from these bromides in cyclopropane solution at low temperatures by bromine atom abstraction with photochemically generated triethylsilyl radicals and observed by EPR spectroscopy. Similar methodology was



recently employed to generate the parent radical (**1a**).[3,4] The spectra degraded rather rapidly, except for that of **1d**, and in each case a second spectrum due to the silylethyl radical **5**, with EPR parameters the same as those given in the literature,[15,16] was observed. This species is formed, along with triethylsilyl radicals, only when highly reactive σ-radicals like **1** abstract hydrogen from triethylsilane. The proportion of this silylethyl radical could be reduced to spectroscopically acceptable levels by working with lower than normal amounts of triethylsilane. For the generation of the 3-fluoro radical **1b**, a 2:1 mixture of **3b** and **3a** was used. In addition to **5**, the EPR spectrum at 155 K showed a weak and extremely wide doublet [a(F) = 167 G]. The components of this doublet were not resolvable so that the coupling from the six bridge hydrogen atoms of **1b** was less than the peak-to-peak line width (ΔH_{pp} = 1 G). Surprisingly, none of the unsubstituted radical **1a** was observed. This suggested that triethylsilyl radicals abstracted bromine atoms from the 3-fluoro bromide *in preference* to the unsubstituted bromide, i.e., that the 3-fluorine atom exerted a favorable substituent effect. The spectrum obtained on bromine abstraction from **1c** (Figure 1) showed two sets of four lines with corresponding components having an intensity ratio of ca. 3 as expected from the natural abundances of ^{35}Cl and ^{37}Cl ($I = {}^3/_2$ for both isotopes).

The measured ^{35}Cl and ^{37}Cl hfs of **1c** are probably the largest known for carbon-centered radicals, being greater than the α-Cl hfs and β-Cl hfs of chloroalkyl radicals.[17] The ratio of the hfs of the two isotopes (1.21) was equal to the ratio of their magnetic moments (1.201) to within the experimental error. The decrease in the apparent intensities of the individual component lines toward higher field (Figure 1) was reproducible. Similar intensity variation within chlorine multiplets has been observed before and attributed to the modulation by Brownian diffusion of the anisotropic g and hyperfine tensors.[18] Hyperfine interaction from the six bridge hydrogen atoms could not be resolved, as was found for **1b**. The spectrum of **1d** consisted of a single narrowly spaced septet which was more intense and longer lasting than the spectra of **1b,c** (spectra for **1b** and **1d** are available as supplementary material). The EPR parameters for the series of radicals are collected in Table 1. The exceptionally large magnitudes of the hyperfine couplings from the radical center to the substituents at C^3 confirm the basic fact of strong cross cage electronic interactions. It is interesting to compare the hfs of the cross cage bridgehead atoms of **1** with analogous bridgehead hydrogens in bicyclo[2.2.2]oct-1-yl radicals **6** and cubyl radicals **7**. In these latter two radicals the cross cage

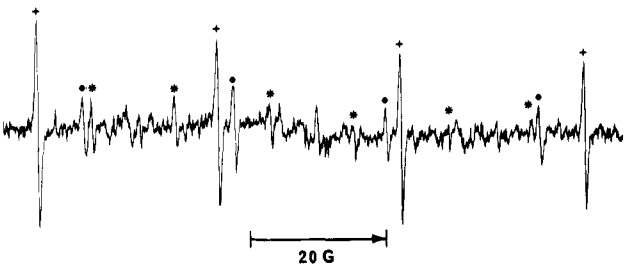


Figure 1. 9.0-GHz EPR spectrum obtained on photolysis of 1-bromo-3-chlorobicyclo[1.1.1]pentane (**3c**), triethylsilane, and di-*tert*-butyl peroxide in cyclopropane at 155 K. The four lines of the ^{35}Cl containing radical **1c** are indicated with + and the four lines of the ^{37}Cl-containing analog are indicated with ●. Some of the main resonance lines of $Et_2Si(H)CH^{\bullet}CH_3$ are distinguished by a *.

Table 1. EPR Parameters of Bicyclo[1.1.1]pent-1-yl Radicals (**1**) at 155 K in Cyclopropane[a]

radical	R	a(6H)	a(X)	$a(^{13}C^1)$
1a[b]	H	1.2	69.6(H)	223[c]
1b	F	≤0.5	167(F)	
1c	^{35}Cl	≤0.2	26.2(^{35}Cl)	
1c	^{37}Cl	≤0.2	21.7(^{37}Cl)	
1d	CH_3O_2C	1.12	≤0.07(CH_3)	

[a] Hfs in gauss, all g-factors 2.003 ± 0.001. [b] Data from ref 3. [c] Data from ref 38.

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bridgehead C–H bonds are in similar orientations with respect to the radical SOMO, i.e., at 180° to the σ-orbital containing the unpaired electron and exactly in line, but at greater distances of ca. 2.44 and 2.67 Å, respectively.[19] The experimental EPR hfs of H^4 in **6** and **7** are 2.7[20] and 6.3 G,[16] respectively. Thus, the hfs are not linearly related to the distance separating the radical center from the hydrogen nucleus. This is not surprising and is in accord with expectations that through bond as well as through space interactions will play important roles in such cage

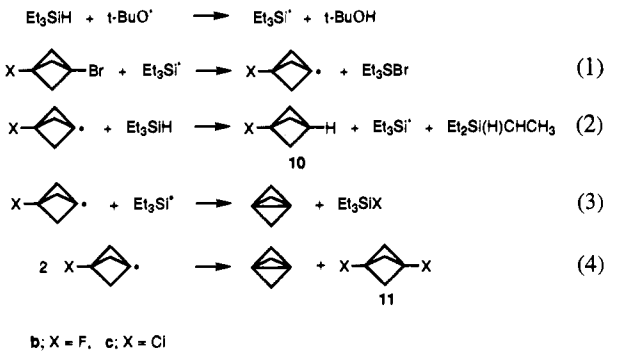
(15) Bowles, A. J.; Hudson, A.; Jackson, R. A. *J. Chem. Soc. B* **1971**, 1947–1949.
(16) Della, E. W.; Head, N. J.; Mallon, P.; Walton, J. C. *J. Am. Chem. Soc.* **1992**, *114*, 10730–10738.
(17) Kochi, J. K. *Adv. Free Radical Chem.* **1975**, *5*, 189–317.
(18) Hudson, A. *Chem. Phys. Lett.* **1969**, *4*, 295–296.
(19) These distances were computed by the AM1-UHF method for **6** and **7**.
(20) Krusic, P. J.; Rettig, T. A.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1972**, *94*, 995–997.

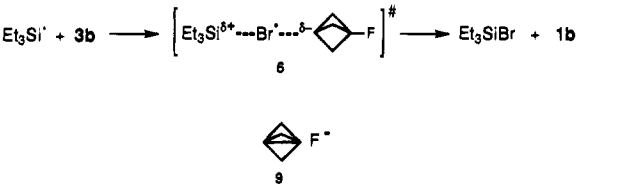
molecules.[21] Through bond transmission of spin density is at a maximum when every bond separating the nucleus from the unpaired electron is *trans* with respect to flanking bonds.[22] This structural situation is present in **1** but not in **6** or **7**, and therefore, the huge magnitudes of the hfs from substituents at C^3 in **1** result from mutual reinforcement of the short through space distance and the *all trans* through bond orbital overlap. A detailed theoretical analysis of spin density propagation in **1a** and staffanyl radicals has been published.[4] The $a(H^3)$ hfs in **1a** is 11.0 times $a(H^4)$ in **7** whereas the analogous ratios for a(F) and $a(^{35}Cl)$ are 5.7 and 6.1; these differences are a good indication that the strength of the cross cage interaction is substantially modified by the nature of the substituent. A further indication of this comes from the magnitude of the hfs of the six bridge hydrogens in **1** which was strongly reduced by electron-withdrawing substituents (Table 1). For all four radicals the magnitude of the hfs from these six bridge atoms was very small for β-hydrogens. This is not at all surprising because the $C-H_\beta$ bonds are orthogonal to the SOMO. The analogous NMR coupling constants between bridgehead hydrogen and bridge methylenes are also unresolvably small in the corresponding monosubstituted bicyclo[1.1.1]pentanes.[23]

The EPR signals from **1b** were only detectable up to ca. 160 K, but the spectrum from **1c** was observed up to 200 K and that from **1d** up to 240 K. On shuttering the light beam the spectra of all the bicyclo[1.1.1]pent-1-yl radicals decayed instantly, within the spectrometer response time. Thus, as expected, all the radicals were transient. No spectroscopic evidence of any rearranged species was obtained at higher temperatures. It is probable, therefore, that radicals **1** take part exclusively in intermolecular processes in the temperature range covered. The spectra from **1b,c** were too weak and short-lived for accurate intensity measurements, but for **1d** the dependence of the radical concentration on incident light intensity was determined by measuring the change in signal height on attenuating the light beam with calibrated gauzes. This gave a value of 0.62 ± 0.17 for the exponent of the light intensity, which is not greater than the theoretical value for bimolecular termination (0.5) by more than the experimental error, i.e., the main termination(s) of **1d** occurred by radical−radical reactions, but a minor amount of decay by process(es) first-order in radical concentration could not be ruled out.

The photochemical reaction of each bridgehead bromide (**3**) with triethylsilane was examined in solution at 200 K, and products were characterized by NMR and mass spectral analysis. For the 2.4:1 mixture of **3b** and **3a** the products were 1-fluorobicyclo[1.1.1]pentane, fluorotriethylsilane, 2-bromo-2-methylpropane, and hexaethyldisiloxane. The product chromatogram was quite "clean" and all peaks were identified, apart from a minor compound C_5H_7Br, which was probably 3-bromo-(methylene)cyclobutane (see Experimental Section) and some minor, long retention time siloxanes. Thus, neither [1.1.1]-propellane nor bicyclo[1.1.1]pentane was present nor were any dimers of **3b** or cross combination products. Propellane **2** readily polymerizes and is volatile and therefore might easily have eluded detection. Bicyclo[1.1.1]pentane is volatile, but had significant quantities been formed, it should have been detected.[24] The proportion of unreacted **3b** in the product mixture was lower than that in the starting mixture, i.e., final ratio of **3b** to **3a** was 1.2:1 and this, together with the absence of bicyclo[1.1.1]pentane, indicated that the triethylsilyl radicals *selectively* abstracted bromine from the fluorobromide **3b**; this agrees with the absence of the EPR spectrum of **1a** (see above). Thus, our experiments clearly show that the fluoro-radical is formed much more easily than the parent radical. We attribute this to a dramatic kinetic polar effect. There is much evidence of extensive charge transfer in the transition state (TS) for halogen abstraction by the triethylsilyl radical.[25] In the case of radical **1b** such a polar TS, i.e. **8**, would be markedly stabilized by an electrostatic field effect *and* by through space electron delocalization (homohyperconjugation, see canonical structure **9**). The really unprecedented aspect of the reaction was the discovery of fluorotriethylsilane, with possible traces of 1,3-difluorobicyclo[1.1.1]pentane (**11b**). Entirely analogous products, i.e., chlorotriethylsilane and 1,3-dichlorobicyclo[1.1.1]-pentane (**11c**), were identified in the reaction of the chlorobromide **3c**. The main process is the expected chain reduction of the halobromides **3b,c** to the corresponding monohalides **10b,c** (reactions 1 and 2 of Scheme 1). Abstraction of a fluorine atom from the parent bromide **3b** by triethylsilyl radicals is most unlikely on thermodynamic grounds, and such a reaction has no precedent. We attribute, therefore, the formation of the halotriethylsilanes to an unusual termination step in which the triethylsilyl radical abstracts a fluorine (or chlorine) atom from **1b** (or **c**) (reaction 3).[26] Fluorine atom abstractions are rare, but in this case the fluorine atom transfer will be favored because of the propensity of radical **1b** (and **1c**) to convert to [1.1.1]-propellane (see *ab initio* calculations below). Similarly, disproportionation of two halobicyclo[1.1.1]pent-1-yl radicals will give **2** together with the 1,3-dihalides **11b,c** (reaction 4). The absence of radical dimers and cross-coupled products suggests that steps 3 and 4 are the main chain terminations under the present experimental conditions. Alternative routes to fluorotriethylsilane such as the production of HF and its subsequent reaction with triethylsilane (reactions 5 and 6) are implausible; evidence for HF formation, such as etching of the quartz tubes,

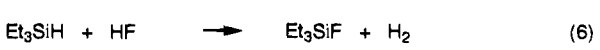
Scheme 1





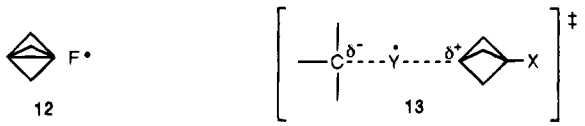
(21) Paddon-Row, M. N. *Acc. Chem. Res.* **1982**, *15*, 245−251.
(22) Ingold, K. U.; Nonhebel, D. C.; Walton, J. C. *J. Phys. Chem.* **1986**, *90*, 2859−2869, and references cited therein.
(23) Della, E. W.; Cotsaris, E.; Hine, P. T. *J. Am. Chem. Soc.* **1981**, *103*, 4131−4135. See also Experimental Section.
(24) It is no more volatile than 1-fluorobicyclo[1.1.1]pentane and less so than cyclopropane, and both these molecules were readily detected.
(25) Chatgilialoglu, C.; Scaiano, J. C.; Ingold, K. U. *J. Org. Chem.* **1987**, *52*, 938−940.
(26) (a) An attempt to synthesize 1-fluorobicyclo[1.1.1]pentane by treatment of 1-bromo-3-fluorobicyclo[1.1.1]pentane (**3b**) with tri-*n*-butyltin hydride in cyclohexane containing AIBN led to only a trace of the desired compound. The major product was propellane apparently formed as a result of fluorine atom abstraction from the initially formed radical, **1b**.[26b] (b) Adcock, W.; Krstic, A. R. Unpublished work.

was completely absent. The mechanism outlined in Scheme 1



requires the formation of *tert*-butyl alcohol and bromotriethylsilane, whereas 2-bromo-2-methylpropane and hexaethyldisiloxane were detected. It is probable, however, that the former are the initial products which convert to 2-bromo-2-methylpropane and triethylsilanol after admission of air and $CDCl_3$ during analysis. The silanol readily transforms to hexaethyldisiloxane in the presence of peroxides.[27] The formation of 2-bromo-2-methylpropane and hexaethyldisiloxane in reductions of organobromides with triethylsilane has been observed previously.[28] The bromo−ester reaction products were largely as expected (see Experimental Section).

Finally, it should be noted that the generation of a mixture of the radicals (**1a** and **1b**, 29:71, respectively) by use of Barton's methodology in halothane ($CF_3CHClBr$) was unexceptional and led to the desired mixture of the bromides (**3a** and **3b**, 29:71, respectively) in good yield with the formation of only a trace of pyridyl sulfide byproducts. In stark contrast, a similar radical chain halodecarboxylation of an identical mixture of Barton thioesters in fluorotrichloromethane, performed in connection with another study,[29] revealed a dramatic 3-fluorine atom substituent effect. Thus, whereas the parent radical **1a** gave 1-chlorobicyclo[1.1.1]pentane in good yield (>80%, as expected[30]) with 1-(2-pyridylthio)bicyclo[1.1.1]-pentane as a minor component, the fluoro radical **1b** gave 3-(2-pyridylthio)bicyclo[1.1.1]pent-1-yl fluoride as a major product (ca. 90%) and 1-chloro-3-fluorobicyclo[1.1.1]pentane in low yield (ca. 10%). Interestingly, a similar pattern of bromine and chlorine atom abstraction vs pyridyl sulfide formation (via unimolecular decarboxylative rearrangement of the precursor Barton thioester)[31] as observed for **1b** has recently been reported for a 6-tricyclodecadienonyl radical.[32] However, whereas the presence of *tert*-butyl hypochlorite significantly increased the yield of the chloro compound in the latter case, the efficiency of chlorine atom abstraction for **1b** was not similarly improved. The behavior of the 6-tricyclodecadienonyl radical was explained by invoking pronounced resonance stabilization as being responsible for ineffective chlorine atom abstraction from CCl_4, but that this was overcome by a weaker bond (Cl_3C-Br).[32] An analogous explanation for the difference in behavior of **1a** and **1b** is very unlikely because the fluoro radical **1b** will not have sufficient resonance stabilization. This is confirmed by a recent electrochemical study[33] which indicated that through space bonding stabilization (depicted by canonical structure **12**) is relatively small in **1b**. Consequently, we believe the difference between **1a** and **1b**, with respect to chlorine atom abstraction vs pyridyl sulfide formation, is probably a manifestation of a kinetic polar effect.[34] It can be envisaged that the transition state for halogen atom abstraction is polarized in the direction to place a partial positive charge on the bridgehead carbon atom of the bicyclopentyl radical (**13**). Thus, a large rate retardation



due to an unfavorable electrostatic field and homohyperconjugative influence (relative to X = H) is induced by 3-fluoro substitution. This tips the balance against chlorine atom abstraction which becomes uncompetitive relative to pyridyl sulfide formation. However, for bromine atom abstraction the bond strength factor is overwhelmingly dominant and camouflages the kinetic polar effect from being similarly exposed. In conclusion, we wish to emphasize that the observed effects of 3-fluoro substitution in the bicyclo[1.1.1]pent-1-yl radical strongly suggest that an understanding of the chemical behavior of this species necessitates consideration of polar factors. Moreover, because of the ability of **1** to support either negative or positive charge at the bridgehead as a consequence of its electronegativity and cross cage interaction (homohyperconjugation), respectively, the direction of charge transfer in a particular transition state will depend on the nature of the radical reaction in question.

Ab Initio Calculations on Bicyclo[1.1.1]pent-1-yl Radicals and Related Species. The unsubstituted radical **1a** was previously studied by the semiempirical MINDO/3 method[8] and by several groups using *ab initio* methods.[2,4,9] With a 6-31G* basis set at the MP2 level, and geometries frozen at the optimal bicyclo[1.1.1]pentane SCF geometry, Feller and Davidson found that removal of the first bridgehead hydrogen from bicyclo-[1.1.1]pentane costs 106 kcal mol^{-1} but, most interestingly, that loss of the second hydrogen to give [1.1.1]propellane costs only 47 kcal mol^{-1}. Wiberg et al.[2] took calculations for **1a** to the MP4 level and found 104 kcal mol^{-1} for removal of the first hydrogen with 1.797 Å as the 1−3 nonbonded, cross cage, distance. We carried out a number of *ab initio* molecular orbital calculations on 3-substituted bicyclo[1.1.1]pent-1-yl radicals, and related molecules, using the GAUSSIAN 92 series of programs.[35] Equilibrium geometries were optimized, within any imposed symmetry constraints, at the Hartree−Fock level using the 6-31G* basis set; the spin-restricted (RHF) and spin-unrestricted (UHF) methods were used for closed shell molecules and open shell radicals, respectively. Electron correlation was included using Møller−Plesset perturbation theory taken to fourth order (MP4); geometries were optimized at the MP2 level, and electronic energies at the MP3 and MP4 levels were obtained with geometrical parameters frozen at the MP2 values. Normal harmonic vibrational frequencies and zero-point vibrational energies (ZPVEs) were evaluated at the HF level. Total energies (E_0) at 0 K were obtained using eq 7 in which the ZPVE is scaled by a factor of 0.9 to allow for the overestimation of vibrational frequencies at this level of theory.[36]

$$E_0 = E(\text{MP4/6-31G*//MP2}) + 0.9\text{ZPVE(HF/6-31G*)} \quad (7)$$

Calculated energies are given in Table 2, and the equilibrium

(27) Armitage, D. A. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., eds.; Pergamon: Oxford, 1982; Vol. 2, pp 132 and 155.

(28) Walton, J. C. Unpublished. See also Harris, J. M.; MacInnes, I.; Walton, J. C.; Maillard, B. *J. Organomet. Chem.* **1991**, *403*, C25−C28.

(29) Adcock, W.; Krstic, A. R. *Tetrahedron Lett.* **1992**, *33*, 7397−7398.

(30) Della, E. W.; Taylor, D. K. *Aust. J. Chem.* **1991**, *44*, 881.

(31) Barton, D. H. R.; Zard, S. Z. *Pure Appl. Chem.* **1986**, *58*, 675.

(32) Zhu, J.; Klunder, A. J. H.; Zwanenburg, B. *Tetrahedron Lett.* **1993**, *34*, 3335−3338.

(33) Adcock, W.; Clark, C. I.; Houman, A.; Krstic, A. R.; Pinson, J.; Savéant, J.-M.; Taylor, D. K.; Taylor, J. F. *J. Am. Chem. Soc.* **1994**, *116*, 4653−4659.

(34) Roberts, B. P.; Steel, A. J. *Tetrahedron Lett.* **1993**, *34*, 5167−5170, and references cited therein.

(35) Frisch, M. J.; Trucks, G. W.; Head-Gordon, M.; Gill, P. M. W.; Wong, M. W.; Foresman, J. B.; Johnson, B. G.; Schlegel, H. B.; Robb, M. A.; Replogle, E. S.; Gomperts, R.; Andres, J. L.; Raghavachari, K.; Binkley, J. S.; Gonzalez, C.; Martin, R. L.; Fox, D. J.; Defrees, D. J.; Baker, J.; Stewart, J. J. P.; Pople, J. A. *Gaussian 92*; Gaussian Inc.: Pittsburgh PA, 1992.

(36) Hehre, W. J.; Radom, L.; Schleyer, P. v. R.; Pople, J. A. *Ab Initio Molecular Orbital Theory*; Wiley: New York, 1986.

Table 2. GAUSSIAN 92 Energies Calculated in Conjunction with the 6-31G* Basis Set

molecule[a]	imposed symmetry	U(R)HF	MP2	MP3[b]	MP4[b]	ZPVE,[c] kcal mol^{-1}	E_0,[d] hartree
bicyclo[1.1.1]pentane	C_{3v}	−193.905681	−194.557591	−194.593356	−194.627670	79.2	−194.514081
1-methylbicyclo[1.1.1]pentane	C_{3v}	−232.946643	−233.732362	−232.776316	−233.817696	97.7	−233.677605
1-fluorobicyclo[1.1.1]pentane	C_{3v}	−292.765480	−293.585476	−293.615393	−293.658863	74.1	−293.552534
[1.1.1]propellane	C_{3v}	−192.691066	−193.350283	−193.370394	−193.410992	63.1	−193.320445
bicyclo[1.1.1]pent-1-yl	C_{3v}	−193.264893	−193.894170	−193.928942	−193.962928	70.6	−193.860894
3-methylbicyclo[1.1.1]pent-1-yl	C_{3v}	−232.304884	−233.067740	−233.110605	−233.151778	89.3	−233.023708
3-fluorobicyclo[1.1.1]pent-1-yl	C_{3v}	−292.117949	−292.914454	−292.943728	−292.986774	65.7	−292.892520
methyl	D_{3h}	−39.561984	−39.670739	−39.685844	−39.690571	19.4	−39.662696
F atom		−99.367040	−99.488228	−99.496116	−99.499075		−99.499075

[a] Energies of open shell species after spin annihilation, $E(H^{\bullet}) = -0.498233$ hartree. [b] Computed with fixed MP2 geometries. [c] Zero-point vibrational energy computed at the U(R)HF/6-31G* level. [d] E(MP4) + 0.9ZPVE.

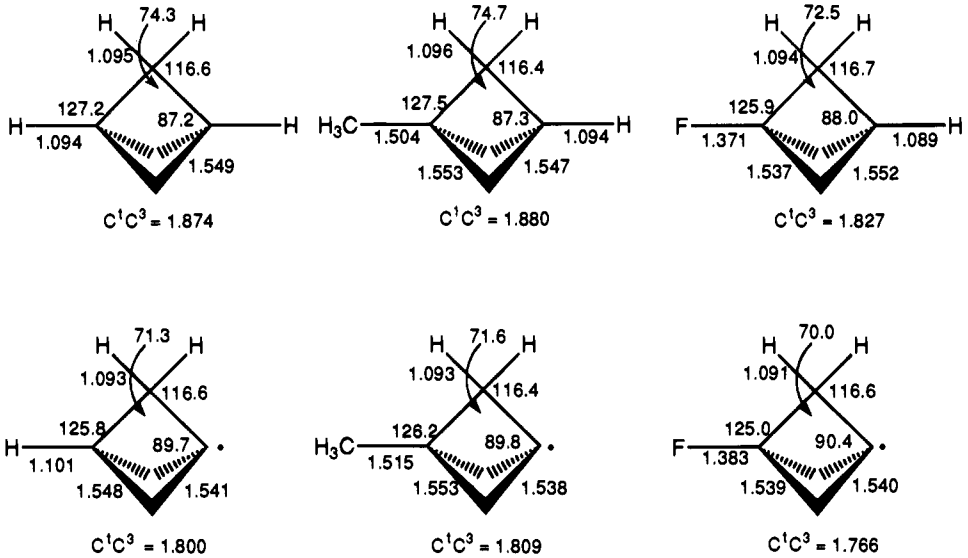


Figure 2. *Ab initio* calculated structures of bicyclo[1.1.1]pentanes and bicyclo[1.1.1]pent-1-yl radicals. Structures were obtained with a 6-31G* basis set and optimized with electron correlation at the MP2 level. Bond angles are in degrees and distances in Å.

geometries are shown in Figure 2. The computed energies (MP4 level) of bicyclo[1.1.1]pentane, the bicyclo[1.1.1]pent-1-yl radical, and [1.1.1]propellane were essentially the same as those obtained by Wiberg *et al.*[2]

Our computed structure of bicyclo[1.1.1]pentane was also the same as that of Wiberg *et al.* and in good agreement with the most recent experimental electron diffraction study.[1a] Introduction of a bridgehead methyl substituent caused only small changes in the structural parameters, including a slight lengthening of the bridgehead to bridgehead distance [C^1 to C^3]. However, introduction of the bridgehead fluorine atom caused the C−C bonds to shrink by ca. 0.02 Å and the C^1 to C^3 distance by ca. 0.05 Å. This is in good accord with previous computations of Wiberg with a 3-21G basis set on 1,3-difluoro- and 1,3-dichlorobicyclopentane which indicated a decrease in the C^1 to C^3 distance of 0.07 to 0.08 Å in both cases.[37] Several common features were observed on removal of the first bridgehead hydrogens to form the neutral radicals. The C^1−C^2 bond lengths significantly shortened in all three cases, as did the cross cage distances. This was accompanied in each case by significant lengthening of the bond from the bridgehead to the substituent (C^3−X). The $C^3C^2C^{1\bullet}$ angles all closed up and the $C^2C^{1\bullet}C^4$ angles all opened up relative to their values in the parent molecules; i.e., there was a small trend toward flattening at the radical centers. Thus, in forming bridgehead radicals, the cage structures moved toward that of [1.1.1]-propellane, which would be formed on loss of the second bridgehead substituent. The configuration at each radical center remained strongly pyramidal, each having a calculated CC•C angle close to 90°. For the parent radical **1a** this angle was estimated experimentally from the ^{13}C EPR hyperfine tensor.[38] The experimental value of 110.3° was based on the assumption of "complete orbital following". Comparison with the calculated value, which was over 20° smaller, gave a strong indication that the bonding orbitals do not follow the direct lines between the carbon nuclei in these highly strained radicals; i.e., the bonds are strongly bent.

Quantitative calculations of bond dissociation energies (BDEs) are known to be difficult to achieve and require large basis sets and a high level of correction for electron correlation. However, with the MP4/6-31G* and similar basis sets, good agreement with experiment can be achieved provided zero-point vibrational energy changes are taken into account.[2,39,40] Calculated ΔE_0 values, where the ZPVE changes have been estimated according to eq 7, are given in Table 3. The ΔE_0 values refer to isolated molecules and are not corrected to 300 K but should be close to experimental BDEs and will be referred to as calculated BDEs. For the dissociation of the bicyclo[1.1.1]pentanes giving radicals **1**, inclusion of electron correlation increased the calculated BDEs by ca. 15 kcal mol^{-1}. Introduction of a 3-methyl substituent had little effect on the calculated ΔE_0, but this increased by ca. 4 kcal mol^{-1} for a 3-fluoro substituent.

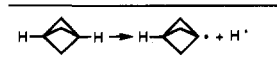
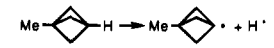
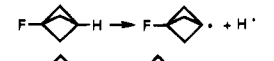
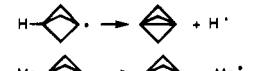
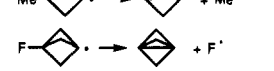
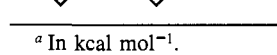
(37) Wiberg, K. B. *Tetrahedron Lett.* **1985**, *26*, 599−602.

(38) Rhodes, C. J.; Walton, J. C.; Della, E. W. *J. Chem. Soc., Perkin Trans.* 2 **1993**, 2125−2128.

(39) Kirwan, J. N.; Roberts, B. P. *J. Chem. Soc., Perkin Trans. 2* **1989**, 539−550.

(40) Curtis, L. A.; Pople, J. A. *J. Chem. Phys.* **1988**, *88*, 7405−7409. Curtis, L. A.; Pople, J. A. *J. Chem. Phys.* **1989**, *91*, 2420−2423.

Table 3. Gaussian 92 Computed Total Energy Changes[a] with a 6-31G* Basis Set

dissociation	ΔE_0 U(R)HF	ΔE_0 (MP2)	ΔE_0 (MP3)	ΔE_0 (MP4)
	81.7	95.9	96.6	96.8
	82.5	96.9	97.5	97.7
	86.1	100.8	101.3	101.5
	40.7	21.9	31.1	27.0
	26.5	23.2	28.1	25.5
	35.2	45.3	46.1	45.8

[a] In kcal mol^{-1}.

The calculated values were somewhat less than the measured BDE of cyclopropane (106 kcal mol^{-1}).[41] The only experimental datum for the bicyclo[1.1.1]pentane series is the observation that the main radical observed by EPR spectroscopy on hydrogen abstraction by *tert*-butoxyl radicals from a dilute solution (ca. 2%) of bicyclo[1.1.1]pentane in cyclopropane was cyclopropyl.[3] The fact that radical **1a** was observable when the precursor was present as the minor component implies that the BDE for bicyclo[1.1.1]pentane is less than that of cyclopropane, in qualitative agreement with the calculation. The cause of this may again be a polar effect which operates in the transition state for formation of **1a**. The bridgehead carbon atoms of bicyclo[1.1.1]pentane may be able to accommodate positive charge more readily than the carbon atoms of cyclopropane. Recent computations indicated that the bridgehead carbon atoms of cubane are particularly well able to accommodate positive charge.[42]

The calculated energies for dissociation of radicals **1** into [1.1.1]propellane are remarkably low (Table 3) as previously found by Feller and Davidson[9] for dissociation of **1a**. The dissociation to give a fluorine atom requires somewhat more energy than that to give a hydrogen atom or methyl radical but, at ca. 46 kcal mol^{-1}, is still so low as to suggest that abstraction of fluorine (and chlorine) in processes such as reactions 3 and 4 should be easy. Furthermore, the low BDE to give **2** and a methyl radical allows us to predict that 3-substituted bicyclo[1.1.1]pent-1-yl radicals would dissociate even at comparatively low temperatures to give a stabilized radical such as benzyl or allyl, which is in accord with qualitative experimental observations, *vide supra*.

The isotropic hyperfine splitting to a nucleus N is directly proportional to the Fermi contact integral ϱ(N) (eq 8):

$$a_N = (8\pi/3)g_e g_N \beta_e \beta_N \varrho(N) \qquad (8)$$

The proportionality constants are 1594.9, 1501.2, and 401.2 for ^{1}H, ^{19}F, and ^{13}C, respectively, and hence, hfs can be theoretically estimated by computation of the Fermi integrals. Computations of ϱ(N) by *ab initio* methods are questionable because of the difficulty in predicting electron density *at the nucleus* using Gaussian basis functions. However, useful computed spin densities for solvated electrons[43] and radicals derived from amine–boranes[39] have been reported. Very good correspondence between *ab initio* Fermi integrals and experimental hfs was found for various phosphoranyl radicals.[44] The Fermi integrals for ^{1}H, ^{19}F, and ^{13}C nuclei in radicals **1a,b** and some other radicals of this study are given in Table 4. The *ab initio* data were obtained after spin annihilation ($\langle S^2\rangle = 0.7500$ in each case) at the MP2 and MP4 levels. Comparison with experiment indicates that the agreement for ^{19}F and ^{13}C data is qualitative at best but that rather better predictions are obtained for hydrogen hfs. Linear regression analysis of the MP2 data (Table 4) together with the phosphoranyl radical data of Cramer[44] gave $a(H)/G = 1670\varrho(N) + 7.5$ with a correlation coefficient of $r^2 = 0.997$.

Table 4. Comparison of *ab Initio* Fermi Contact Integrals[a] and Computed hfs with Experimental EPR hfs

radical	nucleus	ϱ_N MP2	hfs MP2	ϱ_N MP4	hfs MP4	hfs exptl/G
H$^\bullet$	H	0.298	475	0.298	475	507
$CH_3^\bullet$	H	−0.0303	−48.3	−0.0303	−48.3	−23.0
$CH_3^\bullet$	^{13}C	0.199	79.7	0.199	79.7	38.3
1a	H^3	0.0404	64.4	0.0377	60.1	69.6
1a	^{13}C^1	0.264	106	0.341	137	223
1a	H^2	−0.00082	−1.3	−0.00095	−1.5	(±)1.2
1b	F	0.0830	125	0.0817	123	167
1b	^{13}C^1	0.345	138	0.421	169	
1b	H^2	−0.00021	−0.3	0.00031	0.5	<0.5

[a] After spin anihillation $\langle S^2\rangle = 0.7500$ for each radical.

The gradient is within 5% of the product of fundamental constants given above, but the intercept differs significantly from zero. Possibly this is an indication that spin density reaches the hydrogen nucleus by mechanisms other than Fermi contact. Obviously, however, computational errors with the nonideal Gaussian basis set cannot be ruled out. It is worth noting that the calculated hfs for the bridge hydrogens of **1b** are a factor of 3 smaller than the analogous hfs of **1a**. This is in good agreement with the experimental finding that this splitting for **1b** was too small to resolve (Table 1) and confirms our identifications of the spectra of **1b,c**.

Conclusions

Substituents at C^3 in bicyclo[1.1.1]pentanes are only a short distance in space from C^1 and can exert a profound influence by a combination of through space and through bond mechanisms. EPR spectra showed that an unprecedentedly large amount of spin density from an unpaired electron produced at C^1 reaches substituents at C^3. Competitive experiments of several types with 1-bromo-3-fluorobicyclo[1.1.1]pentane showed that the fluorine substituent exerted a powerful activating kinetic polar effect on bromine atom abstraction. It is probable that analogous polar effects will operate in homolytic reactions of 3-substituted bicyclo[1.1.1]pent-1-yl radicals. *Ab initio* MO theory predicted that 3-methyl- and 3-fluoro-substituted bicyclo[1.1.1]pent-1-yl radicals would undergo γ-scission to [1.1.1]propellane with loss of the substituent comparatively easily. Experimental evidence was forthcoming for the easy loss of the 3-fluorine atom in a novel disproportionation process.

Experimental Section

Routine ^{1}H NMR spectra (200 MHz) were obtained on Varian Gemini 200 and Hitachi RS-1200 spectrometers. ^{13}C and some ^{1}H NMR (300 MHz) data were collected on Bruker AM300 and Varian Gemini-300 instruments. NMR measurements were made in $CDCl_3$ solution unless otherwise stated, and chemical shifts relative to TMS are reported in ppm (δ). Mass spectra and high resolution mass spectra (HRMS) were recorded on a Kratos M25RF spectrometer. GC–MS

(41) Baghal-Vayjooee, M. H.; Benson, S. W. *J. Am. Chem. Soc.* **1979**, *101*, 2838–2840. DePuy, C. H.; Gronert, S.; Barlow, S. E.; Bierbaum, V. M.; Damrauer, R. *J. Am. Chem. Soc.* **1989**, *111*, 1968–1973.

(42) Hrovat, D. A.; Borden, W. T. *J. Am. Chem. Soc.* **1994**, *116*, 6459–6460.

(43) Clark, T.; Illing, G. *J. Am. Chem. Soc.* **1987**, *109*, 1013–1020.

(44) Cramer, C. J. *J. Am. Chem. Soc.* **1991**, *113*, 2439–2447. Waal, B. F. M. de; Aagaard, O. M.; Janssen, R. A. J. *J. Am. Chem. Soc.* **1991**, *113*, 9471–9479.

analyses were run on a Finnigan Incos 50 quadrupole mass spectrometer coupled to a Hewlett Packard HP5890 gas chromatograph.

Synthesis of Compounds. Literature procedures were followed in the preparation of 1-bromo-3-chlorobicyclo[1.1.1]pentane (**3c**),[13] methyl 3-bromobicyclo[1.1.1]pentane-1-carboxylate (**3d**),[13] and 3-bromobicyclo-[1.1.1]pentane-1-carboxylic acid.[13] The synthesis of 1-bromo-3-fluorobicyclo[1.1.1]pentane led to a mixture of the desired compound together with 1-bromobicyclo[1.1.1]pentane[45] as a minor component (see below).

Mixture of 1-Bromo-3-fluorobicyclo[1.1.1]pentane and 1-Bromobicyclo[1.1.1]pentane (3b, 3a). Thionyl chloride (4.2 mL, 1 equiv) was added rapidly at room temperature to a well-stirred solution of 3-bromobicyclo[1.1.1]pentane-1-carboxylic acid[13] (11.0 g, 57.6 mmol) in anhydrous dichloromethane (50 mL) under nitrogen. The mixture was warmed to 50 °C and stirred overnight before being back-flushed thoroughly with dry nitrogen to remove the solvent and residual thionyl chloride. The crude acid chloride obtained upon cooling was used in the next step without further purification. ^{1}H NMR ($CDCl_3$) δ 2.61 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 35.56 (C1), 59.65 (C2), 46.86 (C3), 167.9 (CO). By use of a modified version of a known procedure for converting an acyl chloride group to the oxazoline moiety,[46] the acid chloride (57.6 mmol) in dichloromethane (50 mL) was added dropwise (Braun perfusor) to a well-stirred solution of 2-amino-2-methylpropan-1-ol (30.8 g, 346 mmol) in anhydrous dichloromethane (70 mL) under nitrogen at 0 °C. After the mixture was stirred overnight at room temperature, sufficient dichloromethane was added to dissolve all precipitated material, and then excess 2-amino-2-methylpropan-1-ol was removed by successively washing with water (3 × 50 mL), 5% aqueous hydrochloric acid containing 2% sodium chloride (50 mL), and finally with water (100 mL) before drying over $MgSO_4$. Removal of the solvent in vacuum afforded a solid which after recrystallization (2 × 1) from dichloromethane afforded 3-bromo-*N*-(2,2-dimethyl-3-hydroxypropyl)bicyclo[1.1.1]pentane-1-carboxamide (13.13 g, 87%) as white platelets: mp 168−169 °C; ^{1}H NMR ($CDCl_3$) δ 3.57 (s, 2H), 2.45 (s, 6H), 1.29 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 35.83 (C1), 58.74 (C2), 41.68 (C3), 167.6 (CO), 56.31 (CNH), 24.55 (CH_3), 70.12 (CH_2O); EIMS *m/z* (relative(rel) intensity) 232 (M^+ − 31, 33), 230 (M^+ − 31, 33), 175 (17), 150 (24), 110 (33), 93 (37), 65 (100), 58 (56).

A dry rotary evaporation flask (1000 mL) fitted with a reflux condenser, suba seal, and large-bore vent needle was charged with the aforementioned hydroxyamide (8 g, 30.53 mmol), anhydrous dichloromethane (50 mL), and dry benzene (19 mL). The well-stirred two-phase mixture under nitrogen was heated by means of an oil bath to 50 °C. Thionyl chloride (7.76 mL, 3.5 equiv) was injected rapidly[46] causing almost instantaneous evolution of sulfur dioxide and hydrogen chloride. After 5 min the oil bath was turned off, but left in place, and the resultant orange-tinted homogeneous solution stirred for a further 2 h under nitrogen. The oil bath was replaced by a liquid nitrogen bath, the suba seal removed, and the mixture stirred with cooling until it appeared as a viscous oil. Diethyl ether (AR grade, 300 mL) and an aqueous solution of 10 M sodium hydroxide (56 mL) were added with stirring in alternating portions causing the reaction mixture to assume an opaque appearance. The cold bath was removed and after addition of water (80 mL), followed by stirring for a further 5 min, the solution became clear and diphasic with the aqueous layer having a pH ≈ 12−14. The contents of the flask were then poured into a separatory funnel, the aqueous phase removed, and the residual organic layer washed with water (4 × 50 mL). The solvents were then removed in vacuo at room temperature. Commercial pentane fraction (500 mL) was added to the remaining benzene solution. The mixture was dried over anhydrous potassium carbonate and filtered, and the solvents were evaporated under reduced pressure. Sublimation (2 × 1; 60 °C/0.05 mm) of the crude product afforded 1-bromo-3-(4,4-dimethyl-2-oxazolinyl)bicyclo[1.1.1]pentane as a white solid (6.33 g, 85%): mp 96−98 °C; ^{1}H NMR ($CDCl_3$) δ 3.91 (s, 2H), 2.49 (s, 6H), 1.26 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 36.24 (C1), 59.19 (C2), 36.05 (C3), 160.3 (CO), 67.34 (C=N), 28.20 (CCH_3), 79.19 (CH_2O); EIMS *m/z* (rel intensity) 246 ([M + 1]$^+$, 12), 244 ([M + 1]$^+$, 12), 230 ([M − 15]$^+$, 6), 228 ([M − 15]$^+$, 6), 164 (100), 148 (22), 134 (33), 110 (50), 92 (37), 73 (22), 65 (56), 55 (46).

A flame-dried, three-necked, round-bottomed flask (500 mL) fitted with a thermometer (−120 °C) and suba seal was charged with 1-bromo-3-(4,4-dimethyl-2-oxazolinyl)bicyclo[1.1.1]pentane (10 g, 40.98 mmol) and anhydrous diethyl ether (300 mL) and then cooled with stirring to −75 °C under nitrogen in a liquid nitrogen/ethanol bath. A pentane solution of 1.7 M *tert*-butyllithium (53 mL, 2.2 equiv) was slowly added by use of a Braun perfusor (150 mL per h) so that the temperature of the reaction mixture was maintained at −70 ± 2 °C. After addition was complete the reaction mixture was allowed to warm to −65 °C and then swirled by hand briefly to ensure homogeneity. The reaction mixture was cooled again to −70 °C before a solution of *N*-fluoro-3,3-dimethyl-2,3-dihydro-1,2-benzothiazol 1,1-dioxide (11.51 g, 1.3 equiv; freshly sublimed, see below) in anhydrous tetrahydrofuran (45 mL) was added by perfusor at a rate of 150 mL per h with stirring under nitrogen. The opaque canary yellow solution was maintained at −55 °C with stirring before being allowed to warm to room temperature. A GC analysis of the crude unquenched reaction mixture consistently gave a product distribution ratio favoring the desired fluoro-substitution product (ca. 71%) over the reduction product, 1-(4,4-dimethyl-2-oxazolinyl)bicyclo[1.1.1]pentane (ca. 29%).[47] The crude reaction mixture was quenched with methanol (3 mL) and, after stirring for 5 min, was allowed to stand for ca. 30 min to enable a small amount of an orange-tinted mucilaginous layer of byproducts to settle out. The ether layer was decanted and the residual gum extracted with commercial pentane fraction. The decanted ether and pentane extracts were combined and dried over magnesium sulfate, and the solvents were evaporated *in vacuo*. Kugelrohr distillation (80 °C/0.05 mm) of the residue gave a mixture of the oxazolines as a white solid (5.88 g; ca. 81% based upon the oxazoline moiety). GC and ^{1}H NMR analyses confirmed the composition of the product mixture (71% fluoro-substitution vs 29% reduction) 3-(4,4-dimethyl-2-oxazolinyl)bicyclo-[1.1.1]pent-1-yl fluoride: ^{1}H NMR ($CDCl_3$) δ 3.85 (s, 2H), 2.26 (d, $^3J_{FH}$ = 2.46 Hz; 6H), 1.18 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 74.32, d, $^1J_{FC}$ = 326.7 Hz (C1), 55.02, d, $^2J_{FC}$ = 22.0 Hz (C2), 24.04, d, $^3J_{FC}$ = 50.70 Hz (C3), 160.9, d, $^4J_{FC}$ = 34.10 Hz (CO), 67.14 (C=N), 27.83 (CH_3), 78.91 (CH_2O); ^{19}F NMR ($CDCl_3$, relative to $FCCl_3$) δ −148.58; HRMS(EI) calcd (found) for $C_{10}H_{14}ONF$, 183.1059 (183.1046). 1-(4,4-Dimethyl-2-oxazolinyl)bicyclo[1.1.1]pentane: ^{1}H NMR ($CDCl_3$) δ 3.81 (s, 2H), 2.36 (s, 1H), 2.01 (s, 6H), 1.18 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 38.75 (C1), 51.24 (C2), 28.07 (C3), 162.3 (C4), 67.08 (C5), 27.90 (C6), 78.56 (C7); HRMS(EI) calcd (found) for $C_{10}H_{15}ON$, 165.1154 (165.1192).

By use of the procedure of Meyers et al.,[46,48] the mixture of oxazolines (8.00 g, ca. 45 mmol) was treated with 4.5 M hydrochloric acid (888 mL), and the resulting solution was stirred at room temperature for 15 h. The reaction mixture was then saturated with sodium chloride and extracted thoroughly with dichloromethane (6 × 350 mL). After the combined extracts were dried ($MgSO_4$), the solvent was removed in vacuo at room temperature to afford the crude product which, after sublimation (80 °C/0.01 mm), gave a mixture of the acids as a white solid (5.61 g, 44.9 mmol) almost quantitatively. Attempts to separate the mixture by differential sublimation and fractional recrystallization from pentane were unsuccessful. 3-Fluorobicyclo[1.1.1]pentane-1-carboxylic acid: ^{1}H NMR ($CDCl_3$) δ 10.88 (bs, 1H), 2.39 (d, 6H, $^3J_{FH}$ = 2.46 Hz); ^{13}C NMR ($CDCl_3$) δ 28.08, $^3J_{CF}$ = 47.80 Hz (C1), 55.54, $^2J_{CF}$ = 22.10 Hz (C2), 74.67, $^1J_{CF}$ = 329.0 Hz (C3), 175.2, $^4J_{CF}$ = 36.70 Hz (C4); ^{19}F NMR ($CDCl_3$, relative to $FCCl_3$) δ −150.31; EIMS *m/z* (rel intensity) 111 (M^+ − 19, 10), 85 (71), 82 (48), 68 (58), 59 (67), 57 (32), 43 (100). Bicyclo[1.1.1]-pentane-1-carboxylic acid: ^{1}H NMR ($CDCl_3$) δ 9.56 (bs, 1H), 2.43 (s, 1H), 2.10 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 42.42 (C1), 51.54 (C2), 27.86 (C3), 175.8 (C4); EIMS *m/z* (rel intensity) 112 (M^+, 2), 111 (20), 97

(45) Della, E. W.; Taylor, D. K. *Aust. J. Chem.* **1990**, *43*, 945.

(46) Meyers, A. I.; Pansegrau, P. D.; Ricker, W. F. *J. Am. Chem. Soc.* **1988**, *110*, 7178−7184.

(47) (a) The reaction of an organolithium compound with the *N*-fluorosultam is believed to proceed via two different competing pathways (nucleophilic attack on fluorine via an S_N2 mechanism vs electron transfer). The latter pathway leads to the formation of a free radical which readily abstracts hydrogen from the ethereal solvent system to form the reduction product.[47b,c] (b) Differding, E.; Wherli, M. *Tetrahedron Lett.* **1991**, *32*, 3819−3822. (c) Differding, E.; Bersier, P. M. *Tetrahedron* **1992**, *48*, 1595−1604.

(48) Meyers, A. I.; Gabel, R.; Mihelich, E. D. *J. Org. Chem.* **1978**, *43*, 1372−1379.

(19), 69 (30), 67 (100), 66 (80), 41 (86). An authentic sample of this known parent acid[11] which was available in connection with other studies[33,49] gave identical NMR and MS spectral parameters.

By use of the procedure of Barton et al.,[31,50] molten dicyclohexylcarbodiimide (1.16 g, 5.61 mmol, 1.0 equiv) was added in one shot with stirring to a mixture (700 mg, ca. 5.61 mmol) of 3-fluorobicyclo[1.1.1]pentane-1-carboxylic acid (71%) and bicyclo[1.1.1]pentane-1-carboxylic acid (29%) as well as 1-hydroxypyridine-2(1*H*)-thione (750 mg, 1.05 equiv) in dichloromethane (15 mL) contained in a foil-covered round-bottom flask maintained at 0 °C. After stirring for 2.25 h at 0 °C, the reaction mixture was filtered and the solvent removed in vacuo in the dark to afford the thioester mixture almost quantitatively. If kept in the dark and stored under anhydrous conditions at −4 °C, these esters remained intact for several months. The thioester mixture was then dissolved in halothane ($CF_3CHBrCl$, 40 mL), and the solution was irradiated (300-W lamps) under nitrogen at reflux temperature for 40 min. The solution was then washed successively with concentrated hydrochloric acid (3 × 10 mL), saturated aqueous sodium bicarbonate (2 × 10 mL), and water (15 mL). After drying ($MgSO_4$), the halothane was removed by careful distillation at 760 Torr using a short column packed with glass helices. Kugelrohr distillation (80 °C/0.01 mm) gave a mixture of 1-bromo-3-fluoro-bicyclo[1.1.1]pentane (**3b**, 71%) and 1-bromobicyclo[1.1.1]pentane (**3a**, 29%) as a colorless volatile oil (400 mg) contaminated with a trace of halothane. No attempt was made to separate the mixture. 1-Bromo-3-fluorobicyclo[1.1.1]pentane (**3b**): ^{1}H NMR ($CDCl_3$) δ 2.46 (d, 6H, $^3J_{FH}$ = 2.16 Hz); ^{13}C NMR ($CDCl_3$) δ 75.72, $^1J_{CF}$ = 332.9 Hz (C1), 60.31, $^2J_{CF}$ = 19.50 Hz (C2), 27.74, $^3J_{CF}$ = 72.10 Hz (C3); ^{19}F NMR ($CDCl_3$, relative to $FCCl_3$) δ −158.77; EIMS, *m/z* (rel intensity) 165, 163 (M^+, 3) 107, 105 (11), 85 (84), 65 (86), 59 (82), 57 (25), 39 (100). 1-Bromobicyclo[1.1.1]pentane (**3a**):[45] ^{1}H NMR ($CDCl_3$) δ 3.10 (s, 1H), 2.24 (s, 6H); ^{13}C NMR ($CDCl_3$) δ 37.53 (C1), 58.19 (C2), 28.60 (C3); EIMS *m/z* (rel intensity) 148, 146 (M^+, 10), 67 (100), 65 (22), 41 (43), 40 (32), 39 (58).

***N*-Fluoro-3,3-dimethyl-2,3-dihydro-1,2-benzothiazol 1,1-Dioxide (*N*-Fluorosultam).** This compound was prepared by modification of a known procedure.[51] A conical flask (1000 mL), modified to function as a simple fluorination reaction vessel,[49] was charged with anhydrous powdered sodium fluoride (60 g; oven dried at 200 °C for 24 h), anhydrous chloroform (600 mL), 3,3-dimethyl-2,3-dihydro-1,2-benzothiazol 1,1-dioxide[51] (20 g, 101 mmol), and the resulting mixture was allowed to stir at room temperature under nitrogen until the latter compound had completely dissolved. The reaction vessel was then immersed in a cryo-cooled thermostatically controlled (−40 °C) ethanol bath. A mixture of 10% (v/v) fluorine in helium (spectral purity) was then administered (slightly more than 1 equiv) by means of a fritted glass tube to the vigorously stirred reaction mixture at a flow rate of 210 mL/min for 135 min, while rigorously maintaining the external bath temperature (−35 to −40 °C). The cold bath was then removed and the reaction mixture purged of fluorine gas by bubbling nitrogen through at a flow rate of 525 mL/min for 45 min. The sodium fluoride−hydrogen fluoride complex was removed from the reaction mixture by frit filtration and rinsed copiously with chloroform. The combined chloroform solution was then evaporated to dryness in vacuo and the residue sublimed (55 °C/0.01 mm) to afford the *N*-fluorosultam as a white solid almost quantitatively (21.50 g; lit.[51] 49%): mp 111−112 °C (lit.[51] mp 114−116 °C); ^{1}H NMR ($CDCl_3$) δ 7.93−7.34 (m, 4H), 1.78 (d, $^4J_{FH}$ = 3.54 Hz, 6H); ^{13}C NMR ($CDCl_3$) δ 144.2 (C1), 135.1 (C2), 131.4 (C3), 129.8 (C4), 123.9 (C5), 123.0 (C6), 69.80, $^2J_{CF}$ = 11.60 Hz (C7), 26.24, $^3J_{CF}$ = 9.15 Hz (C8); ^{19}F NMR ($CDCl_3$, relative to $FCCl_3$) δ −47.26 (lit.[51,52] + 9.80 ppm).

It should be noted that when an excess of fluorine was used in the above synthesis, a low melting, volatile white byproduct was obtained. ^{1}H NMR ($CDCl_3$) δ 8.47−8.23 (m, H), 7.90−7.50 (m, 3H), 1.97 (m, 6H). These spectral details suggest the compound is 2-(1-methyl-1-(difluoroamino)ethyl)benzenesulfonyl fluoride.[47c]

EPR spectra were recorded with a Bruker ER 200D spectrometer operating at 9.3 GHz with 100 kHz modulation. Solution phase samples were prepared in Spectrosil tubes, degassed, and photolyzed in the microwave cavity by light from a 500-W superpressure Hg lamp. The incident light intensity was varied by placing calibrated gauzes in the photolyzis beam. The amplitude of a single resonance line from the 3-carbomethoxybicyclo[1.1.1]pent-1-yl radical was rapidly recorded as a function of incident light intensity. The normal slow reduction in signal amplitude with time of photolysis was compensated for by averaging sets of experiments carried out with increasing and decreasing light intensity. Only the spectra of 3-carbomethoxybicyclo[1.1.1]pen-1-yl were sufficiently strong and long lasting for successful application of this procedure. Radical *g*-factors were measured relative to the known values for the cyclopropyl and $Et_2Si(H)CH^{\bullet}CH_3$ radicals.

Photochemical Reaction of 1-Bromo-3-fluorobicyclo[1.1.1]pentane (3b) with Triethylsilane. A mixture containing 1-bromo-3-fluorobicyclo[1.1.1]pentane and 1-bromobicyclo[1.1.1]pentane (40 μL mole ratio 2.4:1) and ca. 5% 1-bromo-1-chloro-2,2,2-trifluoroethane was combined with triethylsilane (20 μL) and di-*tert*-butyl peroxide (30 μL) and passed through a short plug of neutral alumina into a quartz tube (diameter 4 mm). Cyclopropane (ca. 500 μL) was distilled in and the solution was degassed by a series of freeze−pump−thaw cycles before flame sealing. The mixture was photolyzed with unfiltered light from a 500-W superpressure mercury arc for 90 min at 200 K. The reaction was monitored by EPR spectroscopy at 155 K during the first 10 min, which showed the 3-fluoro radical but none of the unsubstituted radical derived from the minor amount of unsubstituted bromide. The tube was cooled, opened, and suspended in a Dewar just above liquid nitrogen so that the cyclopropane slowly evaporated over ca. 3 h. $CDCl_3$ (1 mL) containing TMS and CCl_3F was added and the product mixture was examined by NMR spectroscopy and GC−MS. The spectra showed all the solvents and reference standards together with unreacted 1-bromo-3-fluorobicyclo[1.1.1]pentane and 1-bromobicyclo[1.1.1]-pentane in a mole ratio (estimated from the ^{1}H NMR spectrum) of 1.2:1; i.e., *selective* consumption of the fluoro-derivative was indicated. The products, listed in order of GC elution, were as follows. 1-Fluorobicyclo[1.1.1]pentane: ^{19}F NMR δ_F −133.4 (d sep, J = 70.2, 3.0 Hz), ^{1}H NMR δ_H 2.04(d, 6H, J = 3.0 Hz), 2.42 (d, 1H, J = 70 Hz) lit.;[23,49] EIMS *m/z* (rel intensity) 86 (M^+, 6), 85 (59), 71 (16), 66 (18), 65 (28), 60 (25), 59 (100), 57 (19), 53 (24), 41 (43), 40 (41), 39 (79). 2-Bromo-2-methylpropane: ^{1}H NMR and MS essentially identical to the literature. Fluorotriethylsilane: ^{19}F NMR δ_F −176.4 (sep, J = 6.1 Hz) lit.,[53] EIMS *m/z* (rel intensity) 134 (M^+, 8), 105 (74), 77 (100), 49 (24), 47 (30), 43 (30), 41 (12); the ^{1}H and ^{13}C NMR spectra were very weak and/or overlapped by signals from ethyl groups of triethylsilane and other products. A minor unidentified component with a MS similar to that of 1-bromobicyclo[1.1.1]pentane, possibly 3-bromomethylenecyclobutane. Hexaethyldisiloxane, with ^{1}H, ^{13}C NMR and MS spectra in accord with the literature. The GC−MS showed no other products, apart from some minor, long retention time Si-containing compounds. The ^{19}F NMR spectrum showed an additional, very weak signal at −217 ppm which we attribute to 1,3-difluorobicyclo[1.1.1]-pentane. This compound was not observed on the GC−MS but could have been obscured by the large solvent and reactant peaks.

Photochemical Reaction of 1-Bromo-3-chlorobicyclo[1.1.1]pentane (3c) with Triethylsilane. The reaction was carried out as described above for the 3-fluoro compound. The chromatogram showed all the solvents and reactants including 1-bromo-3-chlorobicyclo[1.1.1]pentane. The products, listed in order of GC elution, were as follows. 2-Bromo-2-methylpropane: ^{1}H NMR essentially identical to the literature (this compound was not observed on the GC−MS because it was obscured by the large $CDCl_3$ peak). 1-Chlorobicyclo[1.1.1]pentane: ^{1}H NMR δ_H 2.79 (s, 1H), 2.18 (s, 6H), ^{13}C NMR δ_C 49.58 (CCl), 56.81 (CH_2), 24.69 (CH); EIMS *m/z* (rel intensity) 103 (M^+, 1), 67 (100), 66 (31), 65 (53), 53 (10), 41 (70), 40 (29), 39 (82), 27 (27). A minor unidentified component with a MS similar to that of 1-chlorobicyclo-[1.1.1]pentane, possibly 3-chloro(methylene)cyclobutane. A minor peak with *m/z* (rel intensity) 103, 101 ($M - Cl^+$, 9, 27), 75 (8), 65 (100), 61 (17), 49 (11), 40 (15), 39 (51), 38 (17) which we identify as

(49) Krstic, A. R., Ph. D. Dissertation, The Flinders University of South Australia, 1994.

(50) (a) Barton, D. H. R.; Ozbalic, N.; Vacher, B. *Tetrahedron* **1988**, *44*, 7385−7392. (b) Barton, D. H. R.; Crich, D.; Motherwell, W. B. *Tetrahedron* **1985**, *41*, 3901−3924.

(51) Differding, E.; Lang, R. W. *Helv. Chim. Acta* **1989**, *72*, 1248−1252.

(52) Error acknowledged by Dr R. W. Lang (private communication).

(53) Emsley, J. W.; Phillips, L. In *Progress in NMR Spectroscopy*; Emsley, J. W., Feeney, J., Sutcliffe, L. H., eds.; Pergamon: Oxford, 1971; Vol. 7, pp 1−520.

1,3-dichlorobicyclo[1.1.1]pentane. 1-Bromobicyclo[1.1.1]pentane: *m/z* (%) 148 (M^+, 4), 146 (M^+, 5), 67 (100), 65 (18), 41 (38), 40 (33), 39 (51), 27(16). Chlorotriethylsilane: *m/z* (%) 150 (M^+, 7), 123 (40), 121 (94), 95 (30), 93 (100), 92 (16), 65 (44), 63 (28), 28 (17); the ^1H and ^{13}C NMR spectra were very weak and/or overlapped by signals from ethyl groups of triethylsilane and other products. Hexaethyldisiloxane, with ^1H, ^{13}C NMR and MS spectra in accord with the literature was again a major side product of the reaction. Longer t_R (retention time) components included a series of minor siloxanes, but no dimers or cross-coupled products were observed.

Photochemical Reaction of Methyl 3-Bromobicyclo[1.1.1]pentane-1-carboxylate (3d) with Triethylsilane. The reaction was carried out as described above for the 3-fluoro compound. The spectra showed all the solvents and the reference standard together with the reduction product methyl bicyclo[1.1.1]pentane-1-carboxylate: ^1H NMR δ_H 3.67 (s, 3H), 2.43 (s, 1H), 2.11 (s, 6H); ^{13}C NMR δ_C 42.40 (C1), 51.59 (C2), 27.65 (C3), 51.28 (CH_3), 169.90 (CO); EIMS (rel intensity) 125 ($M^+ - 1$, 2), 111 (9), 95 (13), 83 (13), 67 (100), 66 (49), 65 (42), 41 (83), 39 (70). The NMR spectral properties of this ester were identical to those of an authentic sample.[49] The conversion was high in this case, and the only other products which could be identified with certainty were 2-bromo-2-methylpropane and hexaethyldisiloxane. A minor unidentified bicyclo[1.1.1]pentyl derivative, possibly the dimer, was also detected.

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Supplementary Material Available: Display of the EPR spectra of bicyclo[1.1.1]pent-1-yl radicals **1b** and **1d** and a plot of *ab initio* calculated Fermi integrals [ϱ(N)] vs experimental *a*(H) values for the radicals of Table 4 (4 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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