The organic layer was separated and the aqueous phase was extracted with methylene chloride. The combined organic phases were dried (Na_2SO_4) and concentrated under reduced pressure at room temperature. The viscous residue was recrystallized twice from pentane to yield 0.402 g (6.7%) of a colorless solid: mp 74–75°; nmr (CCl_4) δ 4.36 (dd, 1, J = 5, 7 Hz, $-CHOSO_2$), 3.22 (s, 2, $-CH_2SO_2-$), 0.97 (s, 2 CH_3), 0.89 (s, CH_3).

Anal. Calcd for $C_{11}H_{18}O_3S$: C, 57.37; H, 7.88; S, 13.60. Found: C, 57.37; H, 7.91; S, 13.72.

Thermal Rearrangement of 4-Methyl-10-isobornyl Sultone (18).—4-Methyl-10-isobornyl sultone (280 mg) was placed in a sublimer and maintained between 75 and 85° for 3 hr. Sublimation gave 202 mg of a solid [75° (0.1 mm)]. Analysis by nmr showed a 1:3 mixture of **18** and a rearranged sultone, respectively. In addition to the starting material the nmr showed two doublets centered at δ 3.41 (J = 14 Hz) and 2.83 (J = 14 Hz) and three singlet methyls at 1.44, 1.32, and 1.15, which suggested structure **29**.[4]

Reduction of Sultone Mixture 18 and 29.—A procedure similar to the reduction of **8** was used. Thus, 200 mg of the sultone mixture was first treated with 1.1 g (29 mmol) of lithium aluminum hydride in ether and then with 2.4 g (10 mmol) of hexaaquonickel(II) chloride and 1.23 g (33 mmol) of sodium borohydride in absolute ethanol. Analysis by vpc showed a 1:3 mixture. The spectroscopic properties (ir and mass spectrum) of the major component, collected by preparative vpc, were identical with those of **22**. The minor component was likewise isolated by preparative vpc, and its ir and mass spectrum data were identical with those of **25**.

3,4-Dimethylcumene (35) from 4-Methyl-10-isobornyl Sultone (18).—Sultone **18**, 0.25 g, was heated to 100° for 2 hr. The resulting brown solution was found to be an aromatic hydrocarbon: ir 882, 818, 718 cm^{-1} (1,2,4-trisubstituted aromatic); nmr (CCl_4) δ 6.90 (s, 3, aryl protons), 2.78 (m, 1, ArCH), 2.20 (s, 6, 2 CH_3) and 1.21 (d, 6, J = 7 Hz, $-CH(C_3)H_2$); mass spectrum (70 eV) m/e (rel intensity) 149 (3), 148 (25), 134 (13), 133 (100), 117 (12), 105 (13), 91 (14), 77 (8), 51 (6), 41 (11), 39 (12), and 29 (12). The ir and nmr spectra were in complete agreement with those of 2,3-dimethylcumene. A vpc collected sample showed the same spectral properties.[5]

Registry No.—**1**, 13131-57-2; **8**, 41366-78-3; **14**, 41429-86-1; **18**, 41366-79-4; **21**, 1195-79-5; **22**, 28462-85-3; **23**, 13567-57-2; **24**, 10470-41-4; **25**, 41366-83-0; **26**, 13144-43-9; **28**, 2371-42-8; **29**, 41366-86-3; **35**, 4132-77-8; methyl iodide, 74-88-4; camphor, 76-22-2.

Sultone Rearrangements. II. Deuterated Analogs of 10-Isobornyl Sultone. Evidence for Exo-3,2-Methyl Shifts and Discrete 2-Norbornyl Cations

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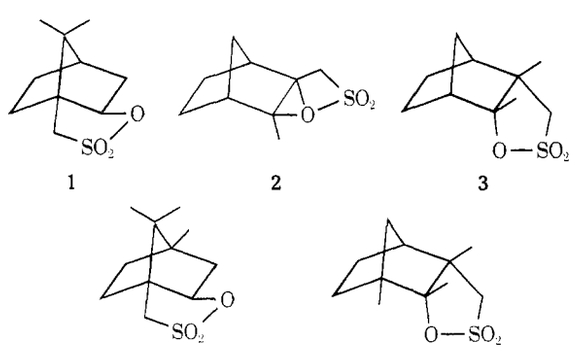
Received May 4, 1973

The *3,3-d_2* and *9-d_1* analogs of 10-isobornyl sultone (**1**) were synthesized. There is no scrambling of the deuterium label during the syntheses, even though a 2-norbornyl cation is a likely intermediate in one of the steps. The deuterated 10-isobornyl sultones were thermally converted to deuterated *exo*-camphene sultones (**2**) in hopes of clarifying the nature of the 3,2-methyl shifts which occur during the rearrangement reactions. The label at C-9 is scrambled during the thermal reactions such that a distinction between exo- *vs.* endo-3,2-methyl shifts cannot be made. However, analysis of the deuterium atom position in the product of the thermal rearrangement of 1-*3,3-d_2* shows that an exo-3,2-methyl shift prevails over endo shift in the formation of *exo*-camphene sultone. Studies using optically active reagents showed that the two methods of synthesizing 10-isobornyl sultone were highly stereospecific, meaning that the probable 2-norbornyl cation intermediate does undergo racemizing 6,2-hydride shifts. However, racemization does occur during the thermal rearrangement of **1** to **2**.

In the previous paper we described the thermal rearrangement of 10-isobornyl sultone (**1**) to *exo*- and *endo*-camphene sultones (**2** and **3**).[1] Rearrangement of a methyl analog, sultone **4**, gave only an endo sultone **5** and 3,4-dimethylisopropylbenzene and no exo sultone



1 **2** **3**

4 **5**

comparable to **2**. The formation of the endo sultones **3** and **5** most likely occurs *via* a exo-3,2-methyl shift. The exact manner by which the exo sultone **2** is formed is still in doubt. It was anticipated that its formation may be a result of a relatively rare rearrangement, namely an endo-3,2-methyl shift.[2] Previous results[1] suggested, but did not prove, that the endo sultone **3** may be the precursor of **2** and, consequently, endo-3,2-methyl shifts do not have to be involved.

Since introduction of a methyl group changed the course of the reaction, we decided to keep the structural variations to a minimum by employing deuterium labeling. In order to get deuterium into the structure we had to develop a new way of synthesizing 10-isobornyl sultone. The previous methods[3] usually employed camphene as the starting material and the task of synthesizing specifically labeled camphene derivatives appeared to be both expensive and involved. A synthesis of 10-isobornyl sultone from camphene is shown in eq 1.

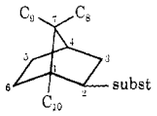
A major problem in specifically deuterating these systems is the ease with which these compounds undergo rapid rearrangements, *i.e.*, Wagner–Meerwein and 6,2- and 3,2-hydride shifts.[4] For example, a rapid

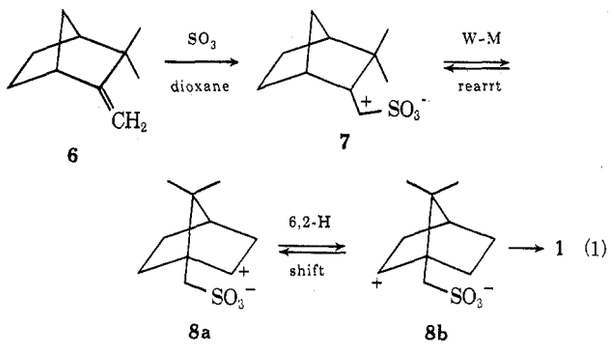
(1) D. R. Dimmel and W. Y. Fu, *J. Org. Chem.*, **38**, 3778 (1973).

(2) See footnote 3 of ref 1.

(3) J. Wolinsky, D. R. Dimmel, and T. W. Gibson, *J. Org. Chem.*, **32**, 2087 (1967).

(4) The number system for bicyclo[2.2.1]heptanes is as follows:



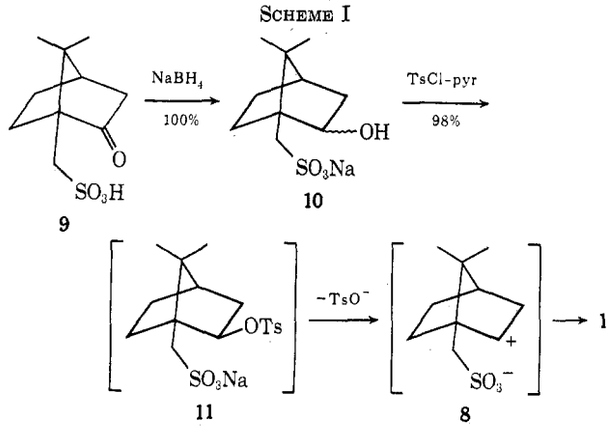


6,2-hydride shift, like **8a** ⇌ **8b**, would render any labeling of the methyl groups useless.[5] We felt we could live with 6,2-hydride shifts if the labels were in the 3 position. This paper describes our syntheses of 3,3-dideuterio- and 9-deuterio-10-isobornyl sultone and their rearrangements to deuterated *exo*-camphene sultone.

Results and Discussion

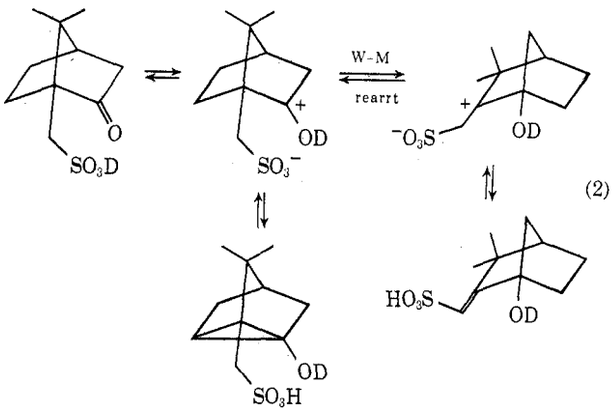
3,3-Dideuterio-10-isobornyl Sultone.—A modification of an earlier method[3] of synthesizing 10-isobornyl sultone from readily available 10-camphorsulfonic acid was developed; this is shown in Scheme I. The reduction of 10-camphorsulfonic acid with sodium borohydride went smoothly, and the product **10** was separated from the inorganic salts by Soxhlet extraction with absolute alcohol. The reaction of **10** with *p*-toluenesulfonyl chloride in pyridine was also quite clean, giving uncontaminated 10-isobornyl sultone in good yield.

SCHEME I



By heating **9** with D_2O twice, 3,3-dideuterio-10-camphorsulfonic acid was obtained; the internal acidity of **9** appears to be sufficient to catalyze the exchange. If homoenolization and/or Wagner–Meerwein rearrangements were occurring, the deuterium label could conceivably become incorporated into the C-6 and C-10 carbons (eq 2). The nmr spectrum, however, gave no indication of deuteriums other than at the C-3 position.

The deuterated 10-camphorsulfonic acid was dissolved in D_2O and added to D_2O–sodium borohydride. These conditions were employed in order to lessen the chance of exchange of the existing label. It was feared



that plain water or alcohol solvent would exchange the C-3 deuterium prior to reaction with the sodium borohydride. The disadvantage of using D_2O as the solvent is the possibility that the following exchange could occur:[6] $NaBH_4 + D_2O \rightleftharpoons NaBH_3D + HOD$. This could lead to some deuterium at the C-2 position (by reduction of the carbonyl). Another problem that could arise is at the completion of the borohydride reduction; the basic solution could possibly promote deuterium exchange of the $-CH_2SO_3Na$ group.[7] Analysis of the nmr spectrum of deuterated **10** for the amount and position of the deuterium was complicated by the fact that **10** is a mixture of exo and endo isomers. Its limited volatility precluded using mass spectroscopy for obtaining the deuterium atom content. Consequently, the material was taken right into the next step, cyclization with tosyl chloride and pyridine to 10-isobornyl sultone.

The most apparent thing about the nmr spectrum of the deuterated 10-isobornyl sultone is the singlet at δ 4.28 which is assigned to the HCO proton. In nondeuterated **1** this proton appears as a doublet of doublets due to unequal coupling to the C-3 hydrogens. The peak is, however, slightly broader than the other singlets in the spectrum. This could be a result of some long-range proton–proton coupling, vicinal deuterium coupling, or an indication that the C-3 position is not fully deuterated.[8]

A comparison of the integrated areas of the peaks in the nmr spectrum of the deuterated 10-isobornyl sultone with the nondeuterated sultone indicated that the deuterium was confined to the 3, 4, 5, and 6 positions. The peaks related to the two methyl groups, the $-CH_2SO_2-$ hydrogens, and the HCO hydrogen, integrated for the same values in both spectra, namely, 3.0, 3.0, 1.81, and 0.82, respectively. The multiplet in the δ 1.2–2.5 region integrated for 6.9 protons in the nondeuterated sultone and 5.0 in the deuterated sultone. The mass spectrum of deuterated **1** was similar to the other sultones that we have encountered in that it dis-

(5) 3,2-Hydride shifts are known to occur much more slowly than 6,2-hydride shifts: M. Saunders, P. v. R. Schleyer, and G. A. Olah, *J. Amer. Chem. Soc.*, **86**, 5680 (1964).

(6) Sodium borohydride apparently does not exchange with D_2O under conditions where impurities are carefully excluded; however, micromolar amounts of heavy metals greatly catalyze the exchange. Several workers have observed exchange under "normal" conditions. See R. E. Davis, J. A. Bloomer, D. R. Cosper, and A. Saba, *Inorg. Chem.*, **3**, 460 (1964).

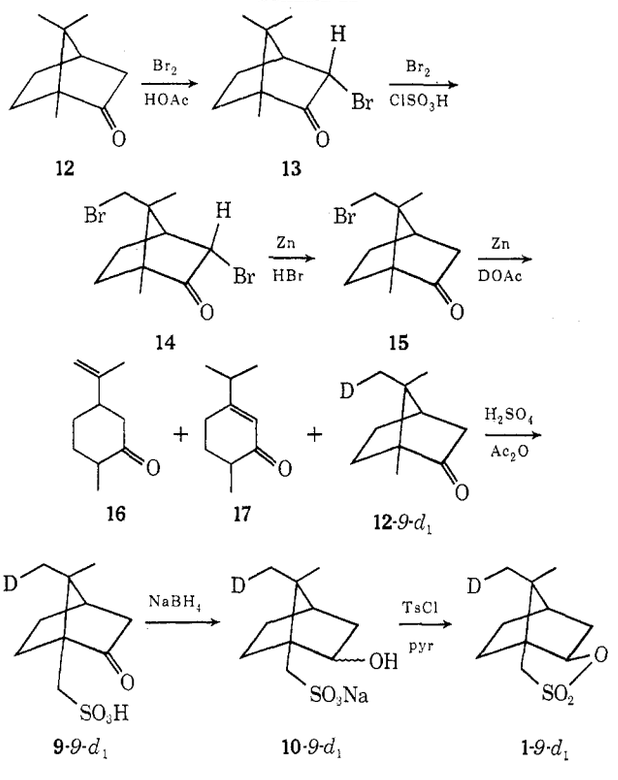
(7) The protons of sodium methanesulfonate undergo exchange with D_2O in the presence of OD^- at 100–160°: J. Hochberg and K. Bonhoefer, *Z. Phys. Chem., Abt. A*, **184**, 419 (1939).

(8) The coupling constant between cis-2,3-endo hydrogens is about 8.5 Hz and between 2-endo,3-exo hydrogens is about 2.5 Hz [A. F. Thomas, R. A. Schneider, and J. Meinwald, *J. Amer. Chem. Soc.*, **89**, 68 (1967)]. One could have possibly 20–30% hydrogen in place of the exo-3 deuterium and not affect the shape of the HCO signal much.

played only a very, very weak molecular ion.[9] A possible useful fragment was the weak peak at m/e 152, which probably corresponds to the loss of SO_2 from 10-isobornyl sultone.[10] This peak shifts significantly to m/e 154 in the deuterated sultone. Because of the weakness of the peaks, it is difficult to completely assess the exact deuterium content; however, there appear to be small amounts (*ca.* 15%) of d_1 and d_3 present in the deuterated sultone. The spectral analysis, however, strongly indicated that the deuterated 10-isobornyl sultone was largely *3,3-d*$_2$.

9-Deuterio-10-isobornyl Sultone.—The success in preparing **1**-*3,3-d*$_2$ without scrambling of the label led us to attempt to synthesize **1**-*9-d*$_1$. Camphor-*9-d*$_1$ was prepared from *d*-camphor[11] by the following sequence of reactions: (1) bromination of C-3 in acetic acid;[12] (2) bromination of C-9 in chlorosulfonic acid;[13] (3) debromination of C-3 by zinc–hydrogen bromide;[13] and (4) debromination of C-9 by zinc–acetic acid-d_1[14] (Scheme II). The desired product **12**-*9-d*$_1$ was contaminated with *ca.* 35% of fragmentation products **16** and **17**. These latter impurities were selectively removed by means of bromination and distillation. The mass spectrum of purified camphor-*9-d*$_1$, mp 179°, showed 19% d_0, 71% d_1, and 10% d_2. The nmr spectrum displayed methyl signals at δ 0.83 (s, C-8), 0.85 (s, C-10), and 0.95 (m, C-9);[15] the multiplet of the latter signal arises because of H/D geminal coupling. Also, since the 0.95 signal integrated for roughly two thirds of the other methyl signals, it is clear that only the C-9 methyl was deuterated.

SCHEME II



Treatment of camphor-*9-d*$_1$ with sulfuric acid in acetic anhydride[16] afforded 10-camphorsulfonic-*9-d*$_1$ acid (**9**-*9-d*$_1$). Reduction of **9**-*9-d*$_1$ with sodium borohydride and subsequent cyclization with *p*-tolylsulfonyl chloride in pyridine gave the desired 10-isobornyl-*9-d*$_1$ sultone (**1**-*9-d*$_1$). The sultone was contaminated with a small amount (*ca.* 5%) of ethyl tosylate (EtOTs), which probably arose from tosyl chloride reacting with a trace amount of ethanol left over from the previous step.[17] The nmr spectrum of **1**-*9-d*$_1$ was identical with the undeuterated sultone **1**, except that the upfield methyl signal at δ 0.95 was broadened due to H/D coupling and integrated for only around two protons relative to the other signals.

Optical Studies.—The fact that the preparations of 9-deuterio- and 3,3-dideuterio-10-isobornyl sultones showed no scrambling of the deuterium label must mean that the deuterated analog of ion **8** closes to the sultone prior to 6,2-hydride shifts. It seems quite likely that ion **8** is an intermediate in the cyclization step, **10** → **1**; regardless of the geometry[18] of the epimeric tosylates **11**, displacement of –OTs by the poor nucleophile RSO_3^- is geometrically prohibited in this system. Although molecular models suggest that both exo and endo closures of **8** are feasible, only an exo sultone **1** is formed. In order to verify these results and determine the actual degree of stereospecificity in the cyclization step, the optical integrity of these reactions was studied. This was accomplished by directly comparing a derivative common to both starting material and product. The reactions are outlined in Scheme III[19] and definitely show that no racemization occurred in the tosylate cyclization since **19** had the same rotation whether derived from **18** or **20**.

A few years ago we observed that sulfonation of camphene, which was partially optically active gave, what appeared to be optically inactive 10-isobornyl sultone (**1**) (eq 1).[3] Since 10-isobornyl sultone (**1**) prepared from 10-camphorsulfonic acid (96% optically pure) had such a small observed rotation, *ca.* 0.05°,[20] it is not surprising that **1** prepared from partially active

(9) At inlet temperatures of *ca.* 100°, **1** rearranges to the other sultones, but one is not certain what the exact composition is and, consequently, the interpretation of the spectrum would be on shaky grounds. A unique spectrum of **1** can be obtained at 100°, but its fragmentation patterns are complicated.

(10) The loss of SO_2 seems to be a reasonable postulate for the m/e 152 peak (weak) but, unfortunately, high resolution spectra were not available to collaborate this. Unsaturated sultones are known to thermally lose SO_2 to give furans: A. Mustafa, in "Organic Sulfur Compounds," Vol. I. N. Kharasch, Ed., Pergamon Press, New York, N. Y., 1961, p 186.

(11) *d*-Camphor was chosen over *dl*-camphor since the 3-bromo derivative (**9**) of *d*-camphor could be obtained crystalline in high yield while the 3-bromo derivative of *dl*-camphor is difficult to crystallize. Problems in purifying racemic **9** have been reported by A. W. Ingersoll and S. H. Babcock, *J. Amer. Chem. Soc.*, **55**, 341 (1933), and references cited therein.

(12) W. L. Meyer, A. P. Lobo, and R. N. McCarty, *J. Org. Chem.*, **32**, 1754 (1967).

(13) E. J. Corey, S. W. Chow, and R. A. Scherrer, *J. Amer. Chem. Soc.*, **79**, 5773 (1957).

(14) K. M. Baker and B. R. Davis, *Tetrahedron*, **24**, 1655 (1968).

(15) The assignment of the methyl signals is based on a shift reagent study of camphor: C. C. Hinckley, *J. Org. Chem.*, **35**, 2834 (1970).

(16) P. D. Bartlett and L. H. Knox, *Org. Syn.*, **45**, 12 (1965).

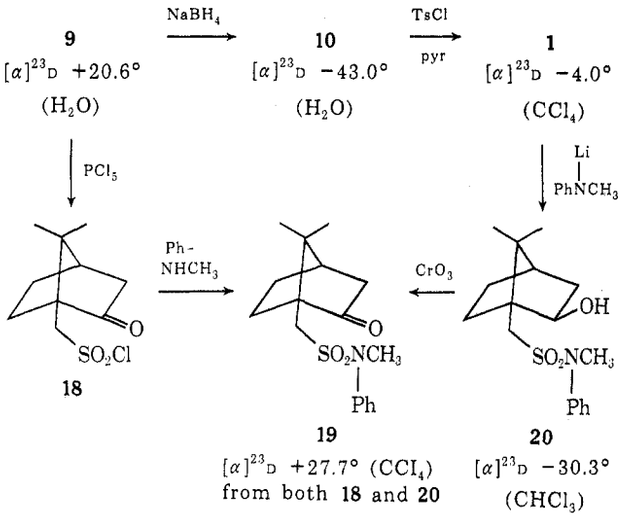
(17) The ethyl tosylate impurity was difficult to separate because its functionality is very similar to that of the sultone. The sultone is quite labile toward various types of chromatography and recrystallization was only partially successful.

(18) A comparison of the nmr spectra of **6** derived from sodium borohydride and sodium/ethanol reduction of **5** showed a 9:1 mixture of isomers in the case of $NaBH_4$ and a 3:2 mixture with Na/EtOH. This similarity to the reductions of camphor suggests that the exo-2-hydroxy sulfonate is the major isomer.

(19) The experimental details for the optically inactive series of some of these reactions are reported in ref 3.

(20) A solution of 0.1541 g of 10-isobornyl sultone in 25 ml of CCl_4 when placed in a 2-dm cell gave an average rotation of −0.05°, but the deviation ranged from 0.00 to −0.10°.

SCHEME III

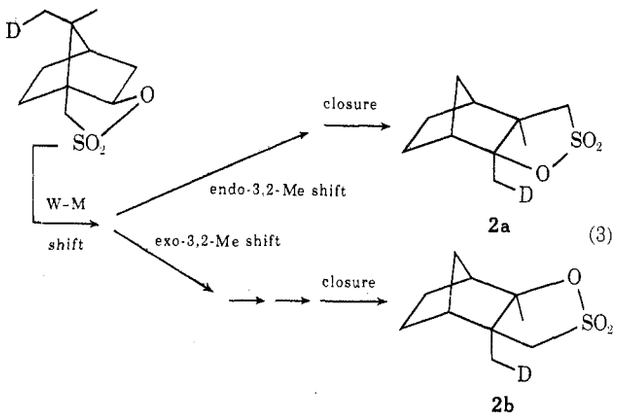


camphene would appear optically inactive. In order to determine the extent of racemization occurring in the sulfonation reaction, camphene, $[\alpha]^{23}D$ +39.8 ± 0.2° (ether) (38.4 ± 0.2% optically pure),[21] was treated with sulfur trioxide–dioxane complex[19] to afford 10-isobornyl sultone, which in turn was allowed to react with *N*-lithio-*N*-methylaniline to give **20**, $[\alpha]^{23}D$ −11.5 ± 0.5° ($CHCl_3$). Since 96% optically pure **20** has a rotation of $[\alpha]^{23}D$ −30.3 ± 0.7°, the optical purity of **20** obtained from the sulfonation reaction was 36.5 ± 2.4%. Consequently, the sulfonation reaction appears to be at least 95% stereospecific, implying that racemizing 6,2-hydride shifts do not occur to any great extent prior to ion **8** cyclization to sultone **1**.

Wagner–Meerwein rearrangement with the absence of 6,2-hydride shifts has been observed by Winstein and coworkers using poor ionizing solvents.[22] The sulfonations of camphene in tetrachloroethylene–dioxane solvent, as reported here, also appear to be an example of a Wagner–Meerwein rearrangement occurring with the exclusion of 6,2-hydride shifts.

Thermal Rearrangements.—The simplest way to establish which methyl migrates during the rearrangement of **1** to **2** is to label one of the methyl groups and see which one ends up on the C-2 carbon. According to a mechanism involving an endo-3,2-methyl shift, the C-9 methyl of **1** becomes the C-2 methyl of **2**. With an exo-3,2-methyl shift prevailing, the C-9 methyl of **1** would become the C-3 methyl of **2**. Equation 3 indicates the anticipated results.

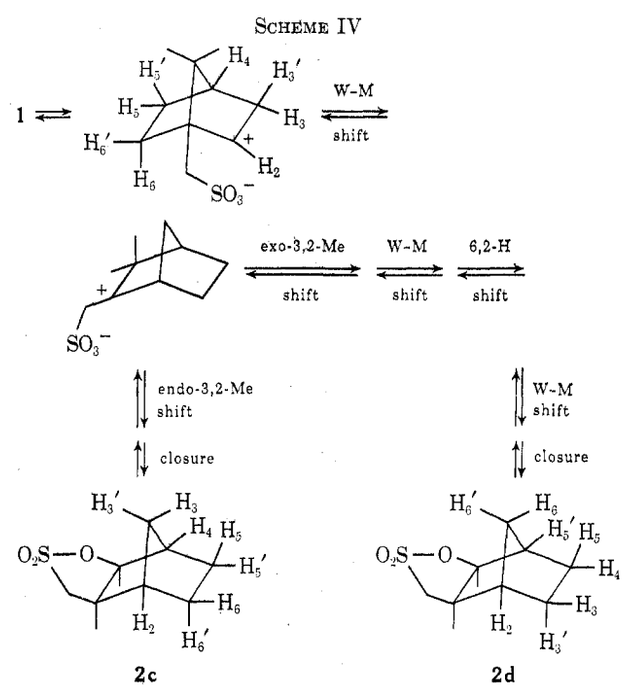
The neat thermal rearrangement of **1**-*9*-d_1 at 140° for 20 min afforded, after sublimation, *exo*-camphene-d_1 sultone (2-d_1). The nmr spectrum of 2-d_1 was complicated by the fact that there were minor amounts of **3** and EtOTs present; however, even with these substances present, it was clear from the spectrum that the deuterated *exo*-camphene sultone was a 50:50 mixture of **2a** and **2b** (see Experimental Section). Thus, the thermal rearrangement of **2** either involves a nonselective migration of methyl groups, which seems quite unlikely, or rapid 6,2-hydride shifts occur which



render the two methyl groups identical. Indeed, the latter possibility appears quite real since the thermal rearrangement of nearly optically pure **1**, $[\alpha]^{23}D$ −4.0°, gave optically inactive **2**, presumably *via* racemizing 6,2-hydride shifts. A derivative of **2**, the hydroxy sulfone **20**, was also optically inactive. Although the rotations of optically pure **2** and **20** were not known, it seems highly unlikely that both compounds would have no rotations at the sodium D line.

Although the rearrangement of **1**-*9*-d_1 did not answer the question as to which methyl migrates, the 3,3-dideuterio derivative could provide the answer. Scheme IV[23] indicates where the hydrogens of **1** would

SCHEME IV



end up in the product, *exo*-camphene sultone, considering the two mechanisms. Assuming ion **8** undergoes rapid 6,2-hydride shifts, the label at C-3 would get spread to the C-5 hydrogens and could, in the case of the exo-methyl shift mechanism, work its way into the C-1 position of the product. Consequently, an observation of about 50% deuterium at C-1 of **2** would establish an exo-methyl shift mechanism, while no

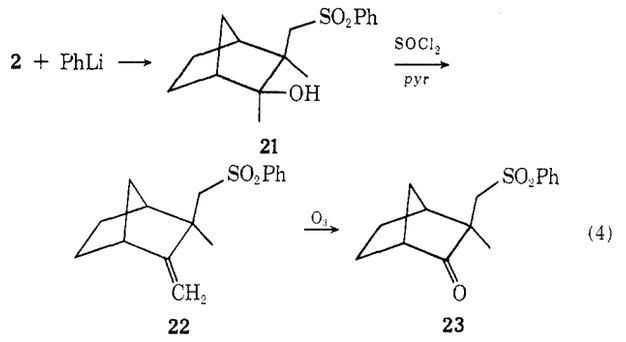
(21) The absolute rotation for *d*-camphene is $[\alpha]^{17}D$ +103.5° in ether: "The Merck Index," 8th ed, P. G. Stecher, Ed., Merck & Co., Rahway, N. J., 1968, p 198.

(22) A. Colter, E. C. Friedrich, N. J. Holness, and S. Winstein, *J. Amer. Chem. Soc.*, **87**, 378 (1965).

(23) Exact details of the various steps in the rearrangement can be found in ref 1.

deuterium at C-1 of **2** would favor the endo-methyl shift mechanism.

It would seem to be a simple task to pick up the extent of label at the C-1 position of **2** by employing the reactions outlined in eq 4. The nmr spectrum of



(4)

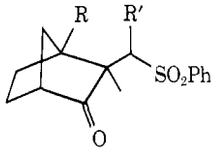
nondeuterated keto sulfone **23** displayed signals at δ 3.33 and 2.50, which were assigned to the syn-7 and C-1 protons, respectively. The assignment of these protons to the two signals was based on a comparison of the nmr spectra of **23–28** (Table I). The keto sulfone

TABLE I
NMR CHEMICAL SHIFTS (δ UNITS) OF SOME SELECTED NORBORNYL DERIVATIVES

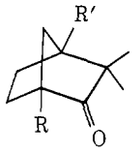
Compd	C-1 H	C-4 H	Syn-7 H
23	2.50	<2.0	3.30
24	2.44		3.05
25[a]	2.59	<2.5	3.54
26	2.45	2.20	<2.0
27	2.45		<2.2
28		2.12	<1.9

[a] The only spectrum taken[3] in $CDCl_3$; all others employed CCl_4 as the solvent.

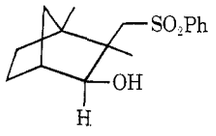
24 was prepared by oxidation of the known hydroxy sulfone **29**.[3] Compound **24**, like **25**, showed two single



24, R = CH_3; R′ = H
25, R = H; R′ = Et



26, R = R′ = H
27, R = H; R′ = CH_3
28, R = CH_3; R′ = H

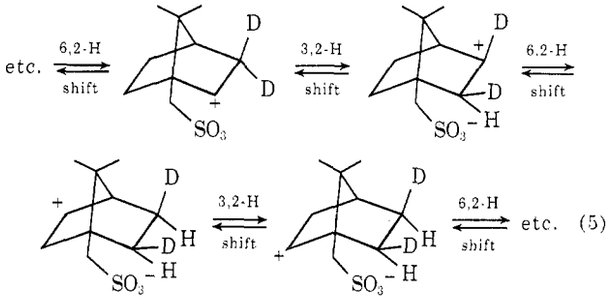


29

proton downfield multiplets; since there is a methyl at C-4 and the signal at δ 2.43 corresponds very closely to the 2.45 signal of **26** and **27**, the only logical candidate for the 3.05 signal is the syn-7 hydrogen. By analogy, the peaks were then assigned to **23**. It is quite possible that the C-4 hydrogen of **23** is shifted upfield just as the C-4 methyl of **24** appears to be. Molecular models prove very beneficial in understanding the large downfield shift of syn-7 hydrogens of **23** and **24**. Based on the premise that there will be strong repulsive forces between the oxygens of the carbonyl and SO_2 group, conformations naturally arise which place the syn-7 hydrogen very close to one of the sulfonyl oxygens.

Heating 10-isobornyl-*3,3-d*$_2$ sultone for 3 hr in refluxing *n*-octane (bp 124°) gave *exo*-camphene-*d*$_2$ sultone. An nmr spectrum of the resulting deuterated sultone showed, relative to the $-CH_2SO_2-$ signal, an approximate decrease of 1.5 protons in the δ 1.2–1.7 region, which contains the methyl groups and the hydrogens attached to C-5, C-6, and anti-C-7, and a decrease of 0.5 proton in the δ 1.9–2.4 region, which probably corresponds to the two bridgehead hydrogens and syn-7 hydrogen. In order to more accurately locate the positions of the deuteriums, *exo*-camphene-*d*$_2$ sultone was converted to deuterated keto sulfone **23**. Relative to the integrated area of the $-CH_2SO_2-$ signal, the nmr spectrum of deuterated **23** was compared to undeuterated **23** to give δ 7.57 and 7.93 (area 5.00, phenyl protons), 3.33 (area 0.96, syn-7 proton), 3.00 (area 2.00, $-CH_2SO_2-$ protons), 2.50 (area 0.59, C-1 proton), 1.35–2.18 (area 4.43, anti-7, C-4, C-5, and C-6 protons), and 1.30 (area 3.00, methyl protons).

The distribution of the deuterium label in the keto sulfone is indicative of an exo-3,2-methyl shift mechanism. The small amount of deuterium at the syn-7 position and less than 50% deuterium at C-1 in **23**-*d*$_2$ may be due to experimental error, the occurrence of small amounts of endo-3,2-methyl shift, or scrambling of the label *via* 6,2- and 3,2-hydride shifts, as shown in eq 5.



(5)

Sultone **1**-*3,3-d*$_2$ was also rearranged to *exo*-camphene sultone (**2**-*d*$_2$) by heating the compound neat at 150° for 30 min. The resulting deuterated sultone was converted to the keto sulfone **23**-*d*$_2$, which had the following nmr spectrum: δ 3.33 (area 0.8) assigned to the syn-7 hydrogen, 3.00 (area 2.0) assigned to the $-CH_2SO_2-$ protons, and 2.50 (area 0.7) assigned to the C-1 bridgehead proton. The incorporation of deuterium at both the syn-7 and C-1 positions can be best explained by a scrambling procedure as outlined in eq 5.

Conclusions

The syntheses of the *3,3-d*$_2$ and *9-d*$_1$ analogs of 10-isobornyl sultone from the corresponding labeled 10-camphorsulfonic acids indicate that a 2-norbornyl cation, **8**, can exist momentarily without undergoing 6,2-hydride (racemization) shifts. The retention of optical activity in going from optically active 10-camphorsulfonic acid to 10-isobornyl sultone to the ketosulfonanilide **19** verifies that the cyclization of **10** to **1**, *via* cation **8**, is highly stereospecific. However, rapid 6,2-hydride shifts do occur in the thermal rearrangement

of **1** to **2**, as proven by the loss of optical activity which accompanies this rearrangement and the scrambling of the deuterium label in the rearrangement of both **1**-*9*-d_1 and **1**-*3,3*-d_2. Why should racemization reactions occur in the thermal rearrangement of **1** and not in the preparation of **1**? A possible answer is that in the preparation of sultone **1** cyclization of ion **8** is very rapid in comparison to 6,2-hydride shifts, while 6,2-hydride shifts are probably rapid[24] in comparison to the 3,2-methyl shift which is necessary for the conversion of **1** to **2**.

Extensive scrambling of the deuterium, presumably *via* a combination of 6,2- and 3,2-hydride shifts, occurs in the high-temperature neat thermal rearrangement of **1**-*3,3*-d_2. The milder rearrangement conditions of refluxing *n*-octane do not extensively scramble the label of **1**-*3,3*-d_2 such that the deuterium pattern in the product (and its derivatives) can be deciphered to show that an exo-3,2-methyl shift occurs in preference to an endo-3,2-methyl shift in the formation of sultone **2**. Although it is difficult to come up with an accurate number from the nmr spectrum of **2**3-d_2, the proportion of endo-3,2-methyl shift must be at best only a few per cent. Our results are in agreement with those of Vaughan and coworkers,[25] who, by means of carbon-13 nmr, showed that the proportion of endo-3,2-methyl shifts in competition with exo-3,2 shifts is only 0–5%.

Experimental Section[26]

Sodium *l*-10-(2-Hydroxy)bornanesulfonate (10).—An aqueous solution of 46 g (0.20 mol) of *d*-10-camphorsulfonic acid (**9**)[27] in 100 ml of water was slowly added to a large beaker containing an excess of sodium borohydride (14 g, 0.27 mol). After all the sulfonic acid was added, the aqueous solution was concentrated with a rota-evaporator and the residue thoroughly dried in a 110° oven. The powdered solid was placed in a Soxhlet and extracted with absolute alcohol, which removed the sulfonate salt from the inorganic salts. The ethanolic extract was evaporated to afford a quantitative yield of **10**: ir (KBr) 3500, 1150, 1050 cm^{-1}; $[\alpha]^{23}D$ −43.0° (*c* 10, H_2O).[3]

***l*-10-Isobornyl Sultone (1).**—To a rapidly stirred, cold solution of 35 g (0.132 mol) of dried sodium *l*-10-(2-hydroxy)bornanesulfonate (**10**) in 80 ml of anhydrous pyridine was added 45 g (0.236 mol) of recrystallized *p*-tolylsulfonyl chloride. The reaction flask was allowed to warm to room temperature and stirred for 5 hr. The mixture was then poured into 20 g of water–ice slurry, filtered to give 27.7 g (98%) of solid, and recrystallized from hexane to give **1**: mp 116–116.5° (lit.[3] mp 117–119°); $[\alpha]^{25}D$ −4.05° (*c* 10, CCl_4); ir (Nujol) 1340, 1175, 877, 812, and 725 cm^{-1}; nmr (CCl_4) δ 4.30 (d of d, 1, *J* = 4 and 7 Hz, HCO), 3.12 (s, 2, $-CH_2SO_2-$), 1.2–2.5 (m, 6, ring protons), 1.11 (s, 3, syn-CH_3), and 0.94 (s, 3, anti-CH_3).[3]

Preparation of 3,3-Dideuterio-10-isobornyl Sultone (1-*3,3*-d_2).—A solution of 25 g (0.108 mol) of 10-camphorsulfonic acid (**9**), recrystallized and dried, in 25 ml of 99.7% deuterium oxide was refluxed for 2 days. The solvent was distilled off and the residue dried in a 110° oven overnight. The residue was then combined with a fresh 25 ml of 99.7% D_2O and refluxed for another 2 days. An nmr at this point, in the solvent D_2O, showed δ 3.32 (d, 1, one of the $-CH_2SO_2-$ protons, *J* = 15 Hz), 2.83 (d, 1.1, one of the $-CH_2SO_2-$ protons, *J* = 15 Hz), 1.2–2.6 (m, 5, ring protons), 1.03 (s, 3, syn-7-CH_3), and 0.83 (s, 3, anti-7-CH_3).

The previous D_2O solution of **9**-*3,3*-d_2 was added gradually to 12 g (0.32 mol) of sodium borohydrde dissolved in a little D_2O and kept at ice-bath temperatures. After the addition was complete, the solvent was slowly distilled off. The green residue was dried in an oven to yield a purple solid. This dried material was placed in a Soxhlet extractor and extracted with absolute ethanol. Evaporation of the ethanol gave, after drying, 23 g (90%) of slighly pink solid (**10**-*3,3*-d_2): nmr (D_2O) δ 4.07 (s, 1, HCO), 3.34 (d, 1, one of the $-CH_2SO_2-$ protons, *J* = 14.5 Hz), 2.82 (d, 1, one of the $-CH_2SO_2-$ protons, *J* = 14.5 Hz), 1.1–1.9 (m, 5, ring protons), 1.02 (s, 3, syn-CH_3), 0.86 (s, 3, anti-CH_3), and singlets at 3.04 and 0.93 for the $-CH_2SO_2-$ and methyls of a minor alcohol (about 10%).

Using the same procedure as the nondeuterated compounds, 6.5 g of deuterated sodium 10-isobornylsulfonate (**10**-*3,3*-d_2) was cyclized to yield 4.2 g (76%) of deuterated 10-isobornyl sultone: mp 120–121°; nmr (CCl_4) δ 4.28 (s, 0.82, HCO), 3.12 (s, 1.81, $-CH_2SO_2-$), 1.2–2.1 (m, 5.00, ring protons), 1.11 (s, 3.06, syn-CH_3), and 0.95 (s, 3.00, anti-CH_3). The nmr spectrum of nondeuterated 10-isobornyl sultone was identical to the one just described except that the δ 1.2–2.1 region integrated for 6.9 protons and the signal at 4.28 was a doublet of doublets.

4-Methyl-9-(phenylsulfonyl)camphenilone (24).—An ethereal solution of 83 mg (0.3 mmol) of 4-methyl-9-(phenylsulfonyl)-camphenilol (**29**) was treated with 0.3 mmol of Jones reagent. After stirring for 1 hr, the ether was separated, washed with sodium bicarbonate solution and water, dried with sodium sulfate, and evaporated to yield an oily residue: nmr (CCl_4) δ 7.42–7.98 (m, 5, aryl H), 3.05 (m, 1), 2.44 (m, 1), 1.2–1.8 (m, 8, with a singlet methyl at 1.30), and 0.80 (s, 3, CH_3).

D-3-Bromocamphor (13).—This compound was prepared in 81% yield according to the procedure of Meyer, *et al.*[12] The bromo ketone **13** had mp 68–70°; ir 1770 cm^{-1}; nmr (CCl_4) δ 4.54 (d, *J* = 5 Hz), 1.09 (s, 3), 0.97 (s, 6) (lit.[12] mp 76°).

D-3,9-Dibromocamphor (14).—This compound was prepared in 86% yield according to the procedure of Corey, *et al.*[13] The dibromo ketone **14** had mp 147–152°; ir 1745 cm^{-1}; nmr (CCl_4) δ 4.54 (d, *J* = 5 Hz), 3.68 and 3.28 (neq,[29] *J* = 10 Hz), 1.14 (s, 6) (lit.[27] mp 152–153°).

D-9-Bromocamphor (15).—This compound was prepared in 45% yield according to the procedure of Corey, *et al.*[13] The bromo ketone **15** had mp 71–75°; ir 1750 cm^{-1}; nmr (CCl_4) δ 3.60 and 3.17 (neq, *J* = 10 Hz), 1.01 (s, 3), 0.92 (s, 3) (lit.[28] mp 93–94°).

Camphor-*9*-d_1 (12-*9*-d_1).[14]—To a mixture of 50 g (2.5 mol) of deuterium oxide and 253 g (2.48 mol) of freshly distilled acetic anhydride was added 25.5 g (0.11 mol) of 9-bromocamphor. The mixture was stirred and kept cold on an ice bath in an inert atmosphere (nitrogen and drying tube). Zinc powder (49 g) was added in small portions such that the exothermic reaction was kept under control. The mixture was stirred for 48 hr at 40° and filtered. The filtrate was neutralized with $NaHCO_3$ and extracted three times with ether; the combined ether extracts were washed with saturated $NaHCO_3$ and water. The ether solution was dried ($MgSO_4$) and concentrated to give 14 g (83%) of a yellow liquid. Vpc analysis showed 65% camphor, 29% dihydrocarvone (**16**), and 6% of an unidentified material assumed to be **17**.[14] A flask containing 5 g of the above mixture in ether was kept in the dark at 5°. Bromine was added dropwise to the mixture with stirring. The ether solution was washed with saturated $NaHSO_3$, dried ($MgSO_4$), concentrated, and dis-

(24) J. A. Berson, J. H. Hammons, A. W. McRowe, R. G. Bergman, A. Remanick, and D. Houston, *J. Amer. Chem. Soc.*, **89**, 2590 (1967). A careful examination of the solvolysis products of *d*-3-*exo*-methyl-2-norbornyl cation reveals that Wagner–Meerwein and 6,2-hydride shifts are more rapid than either 3,2-methyl or hydride shifts. The retention of optical purity of the product 2-*endo*-methyl-2-*exo*-norbornyl acetate suggests the preference for a circuitous route of Wagner–Meerwein, 6,2-hydride, Wagner–Meerwein and 3,2-hydride shifts; a 3,2-methyl shift, *i.e.*, racemization, is stringently avoided.

(25) C. W. David, B. W. Everling, R. T. Killian, J. B. Stothers, and W. R. Vaughan, *J. Amer. Chem. Soc.*, **95**, 1265 (1973).

(26) All boiling points and melting points are uncorrected. Infrared spectra were determined with a Perkin-Elmer Infracord spectrophotometer, Model 137B. Nmr spectra were obtained on a Varian A-60A spectrometer, using TMS or DSS as internal standards and D_2O or CCl_4 as solvents. Mass spectra were obtained using a CEC 21-103 mass spectrometer. Optical rotations at the sodium-D line were measured in water or CCl_4, using a Rudolph Model 70 polarimeter and a 1-dm polarimeter tube. Deuterium oxide, 99.7%, was supplied by Aldrich Chemical Co. Gas chromatographic analyses were performed on a 6 ft × 0.25 in. aluminum column packed with SE-30 on 60–80 mesh Chromosorb W or an 8 ft × 0.25 in. aluminum column packed with DEGS on 30–60 mesh Chromosorb W, using an F&M Model 700 gas chromatograph.

(27) The *d*-10-camphorsulfonic acid was purchased from Aldrich Chemical Co., Milwaukee, Wis., and recrystallized prior to use. The observed specific rotation was +20.6° as a concentrated solution in water. The reported rotation is $[\alpha]^{20}D$ + 21.5° (H_2O); "The Merck Index," ref 21, p 199.

(28) F. S. Kipping and W. J. Pope, *J. Chem. Soc.*, **67**, 371 (1895).

(29) Nonequivalent methylene protons.

tilled to yield 2.50 g of a crude yellow solid [95–100° (0.4 mm)], which was further purified by sublimation at atmospheric pressure to afford 1.70 g of product: mp 176–179°; nmr (CCl_4) indicated that the deuterium was located at the C-9 methyl;[15] a mass spectrum showed 11% d_0, 79% d_1, and 10% d_2.

9-Deuterio-10-isobornyl Sultone (1-9-d_1).—9-Deuterio-10-camphorsulfonic acid (9-9-d_1) was prepared in 51% yield according to the procedure of Bartlett and Knox.[16] The sulfonic acid 9-9-d_1 was reduced with sodium borohydride and cyclized with *p*-tolylsulfonyl chloride in pyridine according to our procedure reported earlier in this paper. The desired sultone 1-9-d_1 was contaminated with a small amount (*ca.* 5%) of ethyl tosylate (EtOTs). This mixture was repeatedly washed with hot hexane. The hexane solution was concentrated to afford 0.2 g of 1-9-d_1, still containing *ca.* 2% EtOTs. Its nmr spectrum (CCl_4) showed δ 4.30 (d of d, 1, J = 4 and 7 Hz, HCO), 3.12 (s, 2, $-CH_2SO_2-$), 1.2–2.5 (m, 6, ring protons), 1.11 (s, 3, syn-CH_3), and 0.95 (m, 2, anti-CH_2D).

***exo*-Camphene Sultones (2a and 2b).**—9-Deuterio-10-isobornyl sultone (1-9-d_1) (0.1 g), containing *ca.* 2% EtOTs, was warmed at 140° for 20 min and sublimed (0.4 mm) to afford *ca.* 50 mg of a mushy solid: ir (CCl_4) 1330, 1280, 868 cm^{-1}; nmr (CCl_4) δ 7.21–7.7 (m), 4.08 (q, J = 7 Hz), 3.36 and 2.80 (neq J = 14 Hz), 3.00 (s), 1.50 (s), 1.28 (m). The ratio of exo isomer to endo isomer and to EtOTs in this mixture was 47:35:18, as ascertained by integration of the $-CH_2SO_2-$ resonances of exo sultone (2-d_1) (δ 3.00), the endo sultone (3-d_1) (δ 3.36 and 2.80), and the $-CH_2O$ resonance of EtOTs (δ 4.08). The methyl signal of the sultone 2-d_1 at δ 1.28 was masked by the triplet methyl signal of EtOTs at δ 1.29. A mixture of sultones **2** and **3** and EtOTs in a ratio of 47:34:19 was prepared; the nmr (CCl_4) of this mixture was identical with the deuterated mixture. The integration ratio of the two methyl signal at δ 1.50 and 1.28 (39:27) was also identical with the methyl signal ratio of the deuterated mixture.

An nmr spectrum of a small amount of material which was not sublimed in the above procedure was identical with the nmr spectrum of nondeuterared *exo*-camphene sultone; the impurities of sultone **3** and ethyl tosylate were apparently sublimed out. The great similarity of what is supposed to be deuterated **2** with nondeuterated **2** adds additional support for the deuterium label being spread equally between the two methyl groups. (A content of 40% deuterium in one of three hydrogens of a methyl group may not significantly change the shape of the signal.)

Solution Rearrangement of 10-Isobornyl-3,3-d_2 Sultone.—A solution of 4.0 g of 10-isobornyl-3,3-d_2 sultone (1-3,3-d_2) in approximately 25 ml of *n*-octane was refluxed for 3 hr. The hot octane solution was decanted from the black residue and cooled to give 0.7 g of colorless crystals of *exo*-camphene sultone (2-d_2). A comparison of the integrated areas of **2** with 2-d_2 showed that the latter compound had the following nmr spectrum: δ (CCl_4) 3.00 (s, 2.0, $-CH_2SO_2-$), 1.9–2.4 (m, 2.5, probably C-1, C-4, and syn-C-7 protons), and 1.2–1.7 (m with 2 s at 1.28 and 1.50, 9.5, remaining ring hydrogens and 2 methyls); mass spectrum (70 eV) *m/e* (rel intensity) 39 (19), 41 (25), 42 (18), 43 (100), 44 (17), 67 (31), 68 (41), 69 (50), 84 (25), 85 (16), 111 (27), 148 (29), and 149 (19). The octane filtrate was added to the black residue and evaporated. The resulting residue was extracted several times with hot hexane and cooled to give an additional 1.5 g (55% overall isolated yield) of solid which had the same spectral characteristics as those described above.

Using previously described procedures,[3] the deuterated *exo*-camphene sultone was converted to the deuterated keto sulfone **23**-d_2. A comparison of the nmr spectrum of **23** and **23**-d_2 gave the following results for **23**-d_2: nmr (CCl_4) δ 7.93 (m, 2.00, *o*-H of Ph), 7.57 (m, 3.00, *m*- and *p*-H of Ph), 3.33 (m, 0.96, syn-7 proton), 3.00 (s, 2.00, $-CH_2SO_2-$), 2.50 (m, 0.59, C-1 proton), 1.35–2.18 (m, 4.43, anti-7, C-4, 5 and 6 protons), and 1.30 (s, 3.00, CH_3).

Neat Rearrangement of 10-Isobornyl-3,3-d_2 Sultone.—In a 50-ml round-bottom flask under a N_2 atmosphere 1 g of 10-isobornyl-3,3-d_2 sultone (1-3,3-d_2) was heated at 150° for 30 min. It took about 2 min for the solid to melt and another 2 min for it to turn brown. The dark-colored solid was recrystallized twice from hexane to give 0.44 g of colorless solid, mp 131–133°. The nmr and mass spectra were similar to the other sample of 2-d_2 prepared above. This sultone was converted to the keto sulfone **23**-d_2, which showed an nmr spectrum very similar to the other sample of **23**-d_2 prepared above except that the δ 3.33 and 2.50 multiplets integrated for 0.8 and 0.7 protons, respectively.

Registry No.—**1**, 41348-33-8; 1-9-d_1, 41348-34-9; 1-3,3-d_2, 41348-35-0; 2-d_2, 41348-30-5; **2a**, 41348-36-1; **2b**, 41348-37-2; 3-d_1, 41348-31-6; **9**, 3144-16-9; 9-9-d_1, 41348-39-4; 9-3,3-d_2, 41348-40-7; **10**, 41348-41-8; 10-3,3-d_2, 41348-42-9; 12-9-d_1, 41348-43-0; **13**, 41348-44-1; **14**, 10293-10-4; **15**, 10293-09-1; **23**-d_2, 41348-32-7; **24**, 41348-47-4; **29**, 41523-55-1.

Carbon-13 Nuclear Magnetic Resonance Spectra of Keto Steroids

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Received June 25, 1973

Fourier transform C-13 nuclear magnetic resonance spectra have been obtained and assigned for a complete series of keto steroids—the steroid skeletons being those of androstane and cholestane. The assignments were performed by comparing the spectra of these closely related compounds and correlating the shifts due to differences in structure, and by use of off-resonance decoupled spectra. Furthermore, the spectra of a series of specific deuterium-labeled analogs have been obtained for assignment purposes. The assignments show strong internal consistency. It is shown that previous assignments to C-12 and C-16 in these systems is erroneous. The effects of deuterium substitution in the steroid system are described, and the observed deuterium isotope shifts are presented.

While it is now possible to obtain high-resolution carbon-13 nuclear magnetic resonance (cmr) spectra of larger molecules such as steroids within a reasonably short time using pulsed Fourier transform technique, the task of assigning the spectra even of known steroids is still far from routine; day-to-day use of cmr with the purpose of structure elucidation in the steroid field is therefore not yet possible, even though it is quite apparent that cmr spectroscopy has great potential in this respect, as illustrated by the cmr spectra of some 30 steroids investigated by Roberts, *et al.*[2] A few other investigations have dealt with cmr of steroids,[3–6] but a considerable amount of well-documented (empirical) correlations of chemical shifts are needed before it is possible to predict the cmr spectrum of a given ste-

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