New Methods for the Synthesis of Triflones

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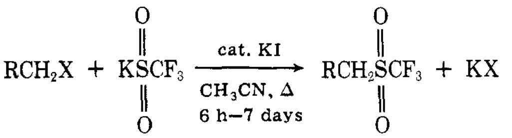
The preparation of triflones from electrophilic triflating agents has been examined. Primary and secondary triflones are available by reaction of alkyllithium or copper organometallics with the less active electrophile, phenyltriflimide, but methyl, aryl, and vinyl triflones could not be prepared in this way. Arenes of medium reactivity can be converted to aryl triflones by Friedel–Crafts triflation with triflic anhydride and aluminum chloride.

The trifyl group ($CF_3SO_2^-$) is an extremely versatile activating functionality for organic synthesis.[1,2] Triflones (CSO_2CF_3) are particularly useful intermediates in this respect because of the ease with which they undergo C–C bond-forming (construction) reactions.[3,4] With the completion of the construction step(s) the trifyl group can be removed or converted to a wide variety of other functionalities.[3–5]

Previously, various triflones had been synthesized by nucleophilic substitution of primary halides by KSO_2CF_3 (eq 1),[3]



$$RCH_2X + KSO_2CF_3 \xrightarrow[CH_3CN,\ \Delta,\ 6\ h\text{–}7\ days]{cat.\ KI} RCH_2SO_2CF_3 + KX \quad (1)$$

or by thermal rearrangement of triflinate esters (Scheme I).[4] These methods were generally limited to primary alcohols and halides. Furthermore, the trifyl reagents used in these reactions required separate preparation, often several steps, from simpler available trifyl sources. Other older methods (e.g., the preparation and oxidation of trifluoromethyl sulfides) were even less convenient.[6]

We therefore sought simpler, more general routes to triflones in order to increase their synthetic utility. The convenient trifyl sources are electrophiles [e.g., $(CF_3SO_2)_2O$,[7] CF_3SO_2Cl,[8] and $PhN(SO_2CF_3)_2$[9]]; hence, the reactions of these compounds with various readily available organometallic nucleophiles were investigated. Previously, only two reactions of this kind had been reported; both employed CF_3SO_2F.[10,11]

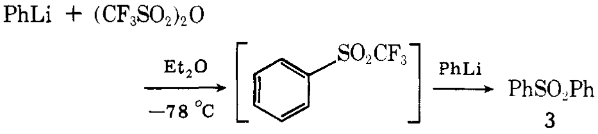
The reaction of $(CF_3SO_2)_2O$ with organolithium reagents was investigated first. Excess *n*-BuLi and *sec*-BuLi reacted rapidly with $(CF_3SO_2)_2O$ in Et_2O at −78 °C to give *n*-$BuSO_2CF_3$ (1) in 56% yield and *sec*-$BuSO_2CF_3$ (2) in 43% yield, respectively, along with some ditriflated products (eq 2 and 3). The problem of ditriflation is inherent to all organometallic routes to triflones because any monotriflone with α protons is more acidic than the organometallic reagent (eq 4).[10] Unreacted organometallic reagent will therefore act as a base, removing a proton to give an α-trifyl anion which can in turn react with $(CF_3SO_2)_2O$ to give the ditriflated product. This necessitates the use of 2 equiv of the organometallic reagent.

$$CH_3CH_2CH_2CH_2Li + (CF_3SO_2)_2O \xrightarrow[-78\ ^\circ C]{Et_2O} \underset{1\ (56\%)}{CH_3CH_2CH_2CH_2SO_2CF_3} + CH_3CH_2CH_2CH(SO_2CF_3)_2 \quad (2)$$

$$CH_3CH_2CH(Li)CH_3 + (CF_3SO_2)_2O \xrightarrow[-78\ ^\circ C]{Et_2O} \underset{2\ (43\%)}{CH_3CH_2CH(SO_2CF_3)CH_3} + CH_3CH_2C(SO_2CF_3)_2CH_3 \quad (3)$$

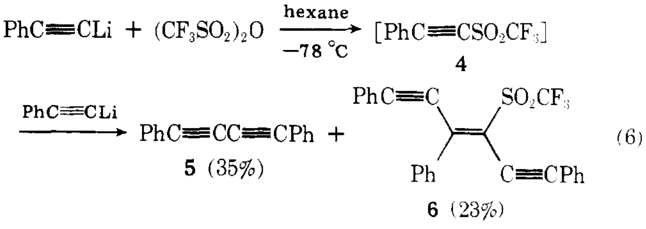
$$RCH_2M \xrightarrow{(CF_3SO_2)_2O} RCH_2SO_2CF_3 \xrightarrow{RCH_2M} R\bar{C}HSO_2CF_3 \xrightarrow{(CF_3SO_2)_2O} RCH(SO_2CF_3)_2 \quad (4)$$

When *t*-BuLi was allowed to react with $(CF_3SO_2)_2O$, no triflone was isolated although $(CF_3SO_2)_2O$ was consumed.[12] Similarly, no triflones were produced when PhLi was used as the organometallic reagent. The main product, isolated in low yield, was diphenyl sulfone (3) (eq 5). Unexpectedly, when



CH_3Li, $CH_2{=}CHLi$, or Ph_3CLi was used, little or *no* reaction occurred at −78 °C or at −20 °C; the $(CF_3SO_2)_2O$ and organometallic reagent were found unchanged.

When $PhC{\equiv}CLi$ reacted with $(CF_3SO_2)_2O$, a complex mixture of products (containing triflone) was isolated (eq 6).

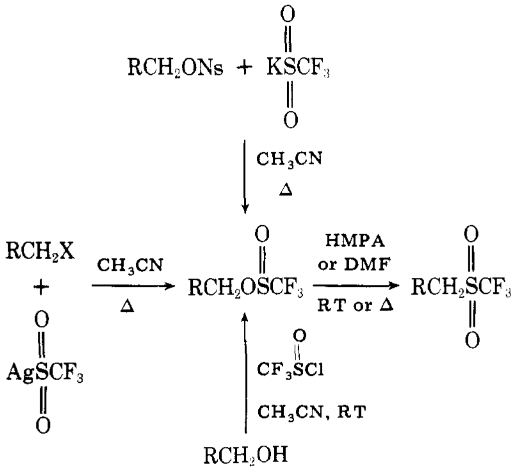


6 (23%)

Two products were characterized: 1,4-diphenylbutadiyne (5) (35%) and a golden crystalline compound that was shown to be the acetylenic Michael diadduct (6) (23%). The presumed intermediate, $PhC{\equiv}CSO_2CF_3$ (4), has since been made by the same method as above except that the crude reaction mixture was flash distilled at low pressure. The product, a clear yellow oil, was very reactive and decomposed above −40 °C.[13]

Seeking both to minimize ditriflation and to find conditions for triflation in the unsuccessful cases, we turned to variants

Scheme I



on both the nucleophile and electrophile. First we examined the reaction of several organocuprates with $(CF_3SO_2)_2O$. Although these reagents are more nucleophilic than the corresponding organolithium compounds in some types of reactions, only $(n\text{-}Bu)_2CuLi$ gave a reaction (34% yield of $n\text{-}BuSO_2CF_3$). Interestingly, no ditriflated product was observed in this reaction.

The other variant to be explored was the trifyl electrophile. Previously, $PhN(SO_2CF_3)_2$ had been successfully used as a mild triflating agent for the preparation of both triflamides and triflates.[9] This reagent has several advantages: it is a stable, crystalline compound which is easily prepared. The by-product of the reaction, $PhNHSO_2CF_3$, is an acidic ($pK_a = 4.45$)[14] material easily removed by alkaline extraction. Furthermore, unlike $(CF_3SO_2)_2O$, both $PhN(SO_2CF_3)_2$ and $PhNHSO_2CF_3$ can be observed on TLC plates so that their reactions can be easily monitored.

When excess *n*-BuLi, *sec*-BuLi, and EtLi were allowed to react with $PhN(SO_2CF_3)_2$ in Et_2O at −78 °C, $n\text{-}BuSO_2CF_3$ (74%), $sec\text{-}BuSO_2CF_3$ (67%), and $EtSO_2CF_3$ (89%) were obtained, respectively (eq 7). A 92% yield of $n\text{-}BuSO_2CF_3$ was obtained when $(n\text{-}Bu)_2CuLi$ was used as the organometallic reagent. The reaction of PhC≡CLi with $PhN(SO_2CF_3)_2$ gave the same result as with $(CF_3SO_2)_2O$.

$$RLi + PhN(SO_2CF_3)_2 \xrightarrow[\text{2. } H_2O\text{, workup}]{\text{1. } Et_2O\text{, } -78\ ^\circ C} RSO_2CF_3 + PhNHSO_2CF_3 \quad (7)$$

$$R = n\text{-Bu } (74\%),\ sec\text{-Bu } (67\%),\ \text{Et } (89\%)$$

As with $(CF_3SO_2)_2O$, however, reactions of $PhN(SO_2CF_3)_2$ with the other organolithium reagents were unsuccessful. It was found that CH_3Li, *t*-BuLi, C_5H_5Li, furanyllithium, and thienyllithium all reacted to some extent as evidenced by the presence of $PhNHSO_2CF_3$ in the crude reaction product [$PhN(SO_2CF_3)_2$ is stable to the workup conditions], but no triflones could be isolated. Reactions of several other less reactive organometallic reagents [EtMgI, *i*-PrMgI (and Cu-catalyzed cases), PhC≡CCu, and $PhC{\equiv}CSi(CH_3)_3$] with either $(CF_3SO_2)_2O$ or $PhN(SO_2CF_3)_2$ were equally unsuccessful. Reactions of the remaining trifyl sources (e.g., CF_3SO_2Cl, CF_3SO_2Im,[15] and $PhOSO_2CF_3$[15]) with either *n*-BuLi or $(n\text{-}Bu)_2CuLi$ were also examined but only $(n\text{-}Bu)_2CuLi$ and $PhOSO_2CF_3$ gave any triflone product (a 34% yield of $n\text{-}BuSO_2CF_3$).

It appears from the above results that primary and some secondary saturated triflones can be synthesized from organometallic reagents and either $(CF_3SO_2)_2O$ or $PhN(SO_2CF_3)_2$, the latter apparently preferred.

Attention was then directed toward the aryl triflones. Previously, these compounds were available only from the oxidation of aryl trifluoromethyl sulfides.[6,16] As yet, Friedel–Crafts acylation of aromatic substrates with trifyl sources had not been investigated, although such reactions with sulfonic anhydrides, sulfonyl halides, and $(CF_3CO)_2O$ were known.[17] Accordingly, the reactions of $(CF_3SO_2)_2O$ and CF_3SO_2Cl with various aromatic substrates were investigated (eq 8).

$$ArH + CF_3SO_2Z \xrightarrow{MX_n} ArSO_2CF_3 + HZ{\cdot}MX_n \quad (8)$$

The first reactions were done with $AlCl_3$, $(CF_3SO_2)_2O$, and various liquid aromatic substrates as the solvent. Excess $AlCl_3$ was suspended in the substrates and cooled, and $(CF_3SO_2)_2O$ (neat or in a solution with the substrate) was then added. The reaction mixture was warmed to room temperature or higher and stirred overnight, and the product was isolated. The results of these experiments are shown in Table I.

The attachment of the trifyl moiety with its large electron-withdrawing power leads to strong deactivation of the aromatic ring toward electrophilic substitution;[18,19] hence, as expected, no ditriflated products were detected. When CF_3SO_2Cl was used as the acylating agent, no triflones were produced in any cases. Attention was then directed to other representative aromatic substrates; 1,4-dibromobenzene, naphthalene, piphenyl, and ferrocene. When dissolved in CH_2Cl_2 and added to a mixture of $AlCl_3$ and $(CF_3SO_2)_2O$, each compound except 1,4-dibromobenzene gave a deeply colored solution. None of these materials reacted with $(CF_3SO_2)_2O$ alone and starting material was regenerated upon hydrolysis with H_2O. Reactions with numerous other Friedel–Crafts catalysts all failed.

In the light of these results it may be surmised that $(CF_3SO_2)_2O/AlCl_3$ is a relatively weak acylating complex. The aromatic substrates can be arranged in order of their reactivity to electrophiles as follows:[20] ferrocene > anisol > naphthalene > biphenyl > *p*-xylene > toluene > benzene > chlorobenzene > 1,4-dibromobenzene > nitrobenzene. Those below chlorobenzene in the reactivity order are too unreactive to be acylated by the weak complex (at room temperature), while the four most reactive at the top of the order appear to form stable π complexes with $AlCl_3$ which do not then dissociate sufficiently to allow triflation to occur. Thus our results indicate that only a narrow range of mildly activated aromatic substrates can be used for Friedel–Crafts triflation.

Experimental Section

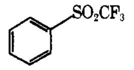
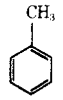
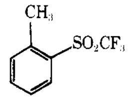
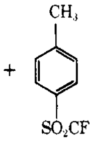
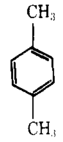
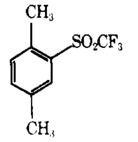
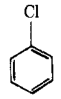
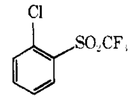
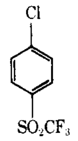
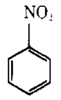
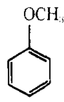
IR spectra were recorded on either a Perkin-Elmer Infracord (Model 137) or Perkin-Elmer (Model 567) spectrophotometer as liquid films or CH_2Cl_2 solutions. NMR spectra were taken on a Varian A-60-A or Perkin-Elmer R-32 spectrometer as $CDCl_3$ solutions using Me_4Si as an internal reference. The high-resolution mass spectrum was taken on a CEC 110B (DuPont Instruments Inc.) double-focusing high-resolution mass spectrometer using photographic plates at the NIH Mass Spectra Facility at Massachusetts Institute of Technology under NIH Division of Research Resoruces Grant RR00317, K. Bieman, principal investigator. All compounds had spectral and physical properties identical with those of known compounds. Melting points were determined on a Fisher-Johns melting point apparatus and are uncorrected.

Materials. All trifyl sources were prepared by literature methods (see text). Et_2O was distilled from Na/benzophenone ketyl. Hexane, benzene, toluene, and xylene were distilled from Na dispersion. $AlCl_3$ was sublimed prior to use. All other materials were of reagent quality and were used without further purification. All reactions were done under a dry nitrogen atmosphere.

Preparation of Triflones from $PhN(SO_2CF_3)_2$ and RLi Reagents. General Procedures. $n\text{-}BuSO_2CF_3$ (1) from $PhN(SO_2CF_3)_2$ and *n*-BuLi. $PhN(SO_2CF_3)_2$ (3.57 g, 10 mmol) was dissolved in dry Et_2O (50 mL) and cooled to −78 °C. To this was added dropwise *n*-BuLi (10 mL, 25 mmol) over 15 min. The reaction was stirred at −78 °C for 3 h and allowed to warm to room temperature and stirred for 1 h. The reaction was quenched with cold H_2O (50 mL) and diluted with an additional 100 mL of Et_2O. The organic layer was washed with 10% NaOH (2 × 20 mL), neutralized with 5% HCl solution, washed with saturated NaCl (3 × 50 mL), dried ($MgSO_4$), and concentrated on a stream bath. Kugelrohr distillation (185 °C) gave 1.41 g (74%) of pure product (lit.[3] liquid): IR (film) 3020 (s), 2960 (s), 1475 (m), 1450 (s), 1365 (s), 1200 (s), 1120 (s), 940 (m), 885 (m) cm^{-1}; NMR ($CDCl_3$) δ 3.23 (t, 2 H, J = 7 Hz), 2.20–0.75 (m, 7 H).

$n\text{-}BuSO_2CF_3$ (1) from $PhN(SO_2CF_3)_2$ and $(n\text{-}Bu)_2CuLi$. Cuprous iodide (purified by the procedure of Kauffman[21]) (1.90 g, 10 mmol) was suspended in dry Et_2O (100 mL) and cooled to −50 °C. *n*-BuLi (9.0 mL, 21.6 mmol) was added dropwise over 10 min. The Et_2O suspension was warmed to −30 °C until all of the cuprous iodide had dissolved. The resulting homogeneous black solution was then cooled to −78 °C. To this was added a solution of $PhN(SO_2CF_3)_2$ (1.79 g, 5 mmol) in Et_2O (50 mL) over 15 min. The mixture was stirred for 3 h at −78 °C, warmed to RT, stirred for 1 h and poured into saturated NH_4Cl (100 mL). The crude reaction mixture was extracted with Et_2O (3 × 100 mL). The organic layer was then washed with 10% NaOH (3 × 50 mL), H_2O (3 × 50 mL), and saturated NaCl (2 × 50 mL), dried ($MgSO_4$), and concentrated on a steam bath. Kugelrohr distillation

Table I. Synthesis of Aryl Triflones

Substrate	Registry no.	Reaction time (temp)	Registry no.	Product(s) and yield(s)[a]	Registry no.
	71-43-2	Overnight (RT)[e]	426-58-4	 7 (61%)	
	108-88-3	Overnight (RT)	63641-17-8	 8 +  9 (69%, 1:2 ratio)	383-10-8
	106-42-3	Overnight (RT)	63641-18-9	 10 (73%)	
	108-90-7	72 h (RT)	382-70-7	 11 +  12 (~10%, 1:1.5 ratio)	383-11-9
	98-95-3	Overnight (RT)		b,c	
	100-66-3	72 h (reflux)		b,d	

[a] Isolated yield. [b] No trifyl-containing material isolated. [c] Immediate decomposition of substrate occurred. [d] Complex formation occurred immediately but no reaction. [e] RT = room temperature.

(185 °C) gave 0.87 g (92%) of pure product. IR and NMR spectra were the same as above.

Reaction of $\mathrm{PhC{\equiv}CLi}$ with $(\mathrm{CF_3SO_2})_2\mathrm{O}$. Phenylacetylene (1.02 g, 10 mmol) was dissolved in dry hexane (40 mL) and cooled to −78 °C. To the flask was added over 10 min *t*-BuLi (11.0 mL, 10.6 mmol). The mixture was allowed to warm to RT and stirred for 1 h ($\mathrm{PhC{\equiv}CLi}$ precipitated from the reaction mixture upon addition of the *t*-BuLi). The heterogeneous mixture was then cooled to −78 °C. To the flask was added a solution of $(\mathrm{CF_3SO_2})_2\mathrm{O}$ (2.82 g, 10 mmol) in hexane (10 mL). The reaction mixture was allowed to warm to −40 °C and stirred for an additional 1 h. The reaction mixture was quenched at −40 °C by the addition of cold 10% HCl (20 mL) and extracted with $\mathrm{Et_2O}$ (2 × 100 mL). The $\mathrm{Et_2O}$ layer was washed with $\mathrm{H_2O}$ (2 × 100 mL) and saturated NaCl (2 × 100 mL), dried ($\mathrm{MgSO_4}$), and concentrated to give 1.23 g of crude yellow oil which contained several components by TLC. The crude product was then chromatographed on neutral $\mathrm{Al_2O_3}$ (50 g). Two main components were identified. The first of these, eluted with $\mathrm{CCl_4}$ and recrystallized from hexane, was 1,4-dephenylbutadiyne (5): mp 88 °C (lit.[22] 88 °C); yield 0.37 g (35% based on $\mathrm{PhC{\equiv}CH}$); IR ($\mathrm{CH_2Cl_2}$) 3100 (m), 2980 (m), 1590 (m), 1450 (s), 1430 (m), 1130 (w), 1040 (m) cm^{-1}; NMR ($\mathrm{CDCl_3}$) δ 7.65–6.15 (m). The second component, eluted with $\mathrm{CCl_4/CHCl_3}$, was the golden-yellow acetylenic Michael adduct 6: mp 113–115 °C; yield 0.342 g (23% based on $\mathrm{PhC{\equiv}CH}$); IR ($\mathrm{CH_2Cl_2}$) 3120 (m), 2230 (s), 1500 (m), 1365 (s), 1200 (s), 1120 (s) cm^{-1}; NMR ($\mathrm{CDCl_3}$) as 8.25–7.30 (m); MS *m/e*calculated for $\mathrm{C_{25}H_{15}F_3O_2S}$, 436.0745; found, 436.0713.

Synthesis of $\mathrm{PhSO_2CF_3}$ (7) from $\mathrm{AlCl_3}$, PhH, and $(\mathrm{CF_3SO_2})_2\mathrm{O}$. General Procedure. Dry PhH (20 mL) and anhydrous $\mathrm{AlCl_3}$ (1.47 g, 11 mmol) were cooled in an ice bath. To this was added $(\mathrm{CF_3SO_2})_2\mathrm{O}$ (2.82 g, 10 mmol) in dry PhH (10 mL) over 15 min. The reaction mixture was allowed to warm to room temperature and stirred overnight. It was then poured into $\mathrm{H_2O}$ (100 mL) and afterwards extracted with $\mathrm{Et_2O}$ (2 × 100 mL). The $\mathrm{Et_2O}$ layer was washed with $\mathrm{H_2O}$ (2 × 100 mL) and saturated NaCl (2 × 100 mL) and dried ($\mathrm{MgSO_4}$). The $\mathrm{Et_2O}$ and excess PhH were removed on a steam bath to give 1.38 g (65%) of crude product. Distillation (110 °C, 30 mm) gave 1.29 g (61%) of pure product (lit.[23] 205 °C): IR (film) 1595 (m), 1355 (s), 1270 (s), 1150 (s), 1075 (s), 775 (m), 755 (m), 720 (s), 685 (m) cm^{-1}; NMR ($\mathrm{CDCl_3}$) δ 8.35–7.55 (m).

Registry No.—1, 52208-94-3; 5, 886-66-8; 6, 63641-19-0; $(\mathrm{CF_3SO_2})_2\mathrm{O}$, 358-23-6; $\mathrm{PhN(SO_2CF_3)_2}$, 37595-74-7; phenylacetylene, 536-74-3.

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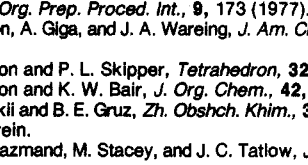
(12) $(\mathrm{CF_3SO_2})_2\mathrm{O}$ reacts only slowly with cold $\mathrm{H_2O}$; so after quenching and drying the crude reaction mixture, an aliquot was added to an $\mathrm{Et_2O}$ solution of Mischler's ketone. This material reacts with $(\mathrm{CF_3SO_2})_2\mathrm{O}$ to give a complex (probably **13**) which has an intense blue color, thus providing a simpler test of reaction in this series.



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Carbon-13 Chemical Shifts in Bicyclo[3.3.0]octanes

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From a detailed analysis of the carbon-13 spectral data of 52 bicyclo[3.3.0]octanes a set of substituent effects was derived from the monosubstituted compounds. Using the shift change values (ΔS) from this basis set, it is possible to accurately predict chemical shifts for polyfunctionalized bicyclo[3.3.0]octanes. These predictions, used in conjunction with statistical tools ($|\bar{E}|$ and R values), permit regio- and stereochemical analysis of new bicyclo[3.3.0] derivatives.

As part of our general program directed at the total synthesis of natural products from bicyclo[3.3.0]octanes,[1] we had occasion to examine the ^{13}C spectra for a number of these compounds. Although the same substituent effects derived from other rigid systems[2] qualitatively applied here, it soon became apparent that we needed to develop an independent set of substituent effects if reliable structural and stereochemical assignments were to be deduced from ^{13}C spectral data. We thus undertook the accumulation and detailed analysis of the spectra of 52 mono- and polyfunctionalized bicyclo[3.3.0]octanes, and wish to report here our results, which should be of considerable utility to others working with this class of compounds.

Assignments

The influences of a variety of substituents on the chemical shifts of each carbon in the [3.3.0] framework were ascertained from analysis of the spectra of the monofunctionalized compounds listed in Table I. Besides the chemical shift assignments, we have provided the shift changes (ΔS) for each carbon vis-á-vis its counterpart in the unsubstituted hydrocarbon **1**. The assignments were based on established α, β, and γ effects,[2] and, where necessary, on stepped off-resonance decoupling (SORD) experiments, used to distinguish between methylene and methyne carbons. In ambiguous cases (usually involving differences of <2 ppm), assignments were made so as to maximize consistency within the entire collection of spectral data. We feel that this approach is justified because of the high self-consistency that is thus obtained (vide infra).

Discussion

The compounds listed in Table I, comprising the *basis set*, were used to analyze the di- and polyfunctionalized structures shown in Table II. For every Table II compound for which the necessary basis compounds were available, *predicted* chemical shifts of each nonheteroatom-substituted sp^3 carbon were calculated assuming strict additivity of ΔS values. For example, the predicted shift of 31.0 ppm (observed, 31.2) for carbon 6 in alcohol **20** was obtained by adding the requisite ΔS values from *endo-cis*-bicyclo[3.3.0]octan-2-ol (**2**, −4.9) and *cis*-bicyclo[3.3.0]oct-2-ene (**4**, +1.7) to 34.2 ppm (the chemical shift of C-2 in the parent hydrocarbon **1**). For each compound thus examined, we have calculated the average of the absolute values of the errors ($|\bar{E}|$) and the correlation factor R;[3] this information is compiled in Table III. For over 175 separate shift predictions, the observed errors ranged from −2.5 to +2.5 (except as noted below), and the average absolute error was 0.7 ppm (SD = 0.6).

It is instructive to consider two cases where the predictions were not as accurate. For bis-*endo*-diol **16**, $|\bar{E}|$ was 2.7 (R = 0.244). This relatively large $|\bar{E}|$ is doubtless due to intramolecular hydrogen bonding (evident in the IR spectrum), which would be expected to distort the conformation of the molecule. This contention is supported by the low $|\bar{E}|$ values for bis-*exo*-diol **22** and for bis-*endo*-diacetate **24** of 0.23 and 0.17 ppm, respectively. The second case for which poor predictions were calculated is enone **32**, showing large errors for carbons 4 and 6. Here, the electronic influence of the carbonyl is transmitted through the π system, causing an observed shift of the γ carbons that is downfield from that predicted. These two cases demonstrate that, in applying the prediction method, one cannot ignore unusual internal interactions.

Conclusions

The ^{13}C NMR data presented herein provide a simple, accurate basis for the determination of regio- and stereochemical features of bicyclo[3.3.0]octanes. Given the ^{13}C spectrum of an unknown compound, one may quickly test logical structural possibilities by comparing predicted chemical shifts with observed ones. Typically, correct structures give $|\bar{E}|$ values within the standard deviation of $|\bar{E}|$ for the whole system, and incorrect structures usually give an $|\bar{E}|$ larger than the largest $|\bar{E}|$ ever observed for any single compound of known structure. This system is especially useful when the number of possible structures is low, as when only one stereochemical assignment is uncertain. In those cases, the problem is often solved by inspection. For example, an *exo*-methyl group at C-2 consistently absorbs at ca. δ 19, compared with an *endo*-methyl at ca. δ 15.

Such qualitative assessments can be placed on a quantitative, statistical footing through the use of the agreement factor R. Values of R (in Table III) were calculated using all sp^3, nonheteroatom-bearing carbons, according to the equation[4]

$$R = \left[\frac{\Sigma(|\delta_{330} - \delta_{obsd}| - |\delta_{330} - \delta_{calcd}|)^2}{\Sigma|\delta_{330} - \delta_{obsd}|^2}\right]^{1/2} \qquad (1)$$

where δ_{calcd} is the calculated chemical shift of a carbon in the structure under consideration, δ_{obsd} is the shift for that carbon in the ^{13}C spectrum, and δ_{330} is the shift of that carbon in