with 11 more being apparent above 120 ppm. Thus, there are four carbon atoms which are accidentally equivalent with other carbon atom(s). Gradual addition of the lanthanide chelate, $Pr(FOD)_3$, led to the eventual appearance of 29 of the 30 possible signals. The five methoxy carbons in reserpine (I) were located at 131.8, 136.4, 136.9, and 140.9 (2) ppm by chemical shift, intensity, and SFOR considerations. The signals at 131.8, 136.4, and 140.9 ppm were of greater intensity than most other peaks in the ^{13}C nmr spectrum of I, indicating possible degeneracy. Addition of the shift reagent produced two resonances from the 131.8- and 140.9-ppm signals, the 136.4-ppm absorption still remaining singular and unreduced in intensity. One of the peaks at 131.8 ppm was assigned to a nonmethoxyl carbon (C-3). The high-intensity signal at 136.4 ppm was assigned to the two isochronous C-30 methoxy carbon atoms. Because of its dramatic sensitivity to shift-reagent concentration, the other component of the 131.8-ppm resonance is assigned to the methoxy carbon, C-31. Of all the carbon atoms of I, C-29 displays the greatest sensitivity to lanthanide chelate concentration (Table III) and is followed in this respect by C-31, C-28, and C-30, in that order. The results suggest that the shift reagent complexes with reserpine preferentially, although probably by no means exclusively, at the oxygen which is connected to C-29. Because C-23 and C-24 are closer to the complexation site than C-32, we expect them to have an appreciably greater sensitivity to shift-reagent concentration than C-32 and therefore attribute two of the three components of the 140.9-ppm signal to C-23 and C-24. C-32 is then assigned to the signal at 136.9 ppm which shows, as expected, a diminished sensitivity to shift reagent concentration.

Further application of the above procedures to alkaloids I–VI has led to the other assignments given in Table I, which will not be discussed in detail. It seems clear that PFT ^{13}C nmr will play an increasingly important role in the structural analysis of natural products.

Experimental Section

The ^{13}C spectra were obtained using a "Brukarian" pulsed FT spectrometer which was the previously described[6,16] Varian digital frequency sweep instrument operating at 15.09 MHz, but modified by substitution of a Bruker pulse amplifier, probe, receiver, and internal deuterium lock. The pulses were derived from a Varian pulse box, and the free-induction decay was accumulated and transformed with a 16K Varian 620i computer.[17]

All of the alkaloids, except corynanthine (III), were dissolved in chloroform-*d* to yield 0.5–2.0 *M* solutions. Corynanthine was dissolved in chloroform-*d* containing a small amount of ethanol to enhance solubility. The spectra were referenced to external carbon disulfide by the relationship $\delta_C^{CS_2} = \delta_C^{CDCl_3} + 115.4$ ppm.

Registry No.—I, 50-55-5; II, 131-01-1; III, 483-10-3; IV, 146-48-5; V, 483-04-5; VI, 482-96-2; VII, 942-01-8.

Acknowledgment.—We thank Dr. M. W. Klohs of Riker Laboratories, Inc., for supplying us with samples of many of the Rauwolfia alkaloids used in this research.

(16) F. J. Weigert and J. D. Roberts, *J. Amer. Chem. Soc.*, **89**, 2967 (1967).

(17) We are much indebted to Dr. Bruce Hawkins for his help in the development of this spectrometer system.

Stable Carbocations. CXLIX.[1] Fourier Transform Carbon-13 Nuclear Magnetic Resonance Spectroscopic Study of Protonated Mono- and Dicarboxylic Acid Esters in FSO_3H–SbF_5 Solution

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The ^{13}C nmr chemical shifts for a series of protonated aliphatic carboxylic acid esters were determined in FSO_3H–SbF_5 solution together with those of their parent esters. Protonation of esters results in deshielding of the carbonyl carbon resonance of the order of 17–21 ppm, of the carbons α to the alkyl oxygen, 12–23 ppm, and those α to the carbonyl group, 0–3 ppm. At the same time generally a slight shielding of most other carbon resonances is observed. The results have been correlated with other substituent effects and with ^{13}C resonances in corresponding hydrocarbons. The pmr and cmr spectra of several protonated diesters in FSO_3H–SbF_5 at $-60°$ have also been studied. The results indicate that dicarboxylic acid esters, including those of oxalic acid, are diprotonated under these conditions.

Several recent instrumental developments in both slow passage and pulsed nuclear magnetic resonance spectrometers[3,4] have allowed for the routine determination of ^{13}C chemical shifts at ^{13}C natural abundance.[5]

The ^{13}C spectra of several carboxylic acids and their tetramethylammonium salts have been recorded in aqueous solution by Hagan and Roberts.[6] Using the INDOR technique[7] in our previous work, we obtained the ^{13}C spectra of protonated formic, acetic, propionic, and benzoic acids in FSO_3H–SbF_5 solution.[8] Carboxylic acid esters and their protonated derivatives have been examined by ^{13}C nmr spectroscopy to a much lesser extent. The carbonyl carbon shifts for a series of carboxylic acid esters have been reported[9] as well as

(1) Part CXLVIII: G. A. Olah and G. Liang, *J. Amer. Chem. Soc.*, **95**, 3792 (1973).

(2) Postdoctoral Research Fellow, 1971–1973.

(3) F. J. Weigert and J. D. Roberts, *J. Amer. Chem. Soc.*, **89**, 2967 (1967).

(4) T. C. Farrar and E. D. Becker, "Pulse and Fourier Transform NMR," Academic Press, New York, N. Y., 1971, pp 34–45.

(5) For example, see (a) J. B. Grutzner, M. Jautelat, J. B. Dence, R. A. Smith, and J. D. Roberts, *J. Amer. Chem. Soc.*, **92**, 7107 (1970); (b) A. J. Jones, D. M. Grant, M. W. Winkley, and R. K. Robins, *ibid.*, **92**, 4079 (1970); (c) J. D. Roberts, F. J. Weigert, J. I. Kroschwitz, and H. J. Reich, *ibid.*, **92**, 1338 (1970); (d) F. J. Weigert and J. D. Roberts, *ibid.*, **92**, 1347 (1970).

(6) R. Hagen and J. D. Roberts, *ibid.*, **91**, 4504 (1969).

(7) E. B. Baker, *J. Chem. Phys.*, **37**, 911 (1962).

(8) G. A. Olah and A. M. White, *J. Amer. Chem. Soc.*, **89**, 7072 (1967).

(9) J. B. Stothers and P. C. Lauterbur, *Can. J. Chem.*, **42**, 1563 (1964).

TABLE I

^{13}C CHEMICAL SHIFTS[a] OF ALIPHATIC ESTERS

No.	Registry no.	Ester	Carbonyl	R—C=O				—O—R		
				C_α	C_β	C_γ	C_δ	C_α	C_β	C_γ
1	107-31-3	Methyl formate	32.0					143.1		
2	79-20-9	Methyl acetate	23.1	173.3						
			23.0[b]	173.2[c]				142.2		
			21.0[c]					141.4[c]		
3	554-12-1	Methyl propionate	19.6	165.5	183.8			141.8		
4	623-42-7	Methyl butyrate	20.6	157.2	173.9	179.0		141.3		
5	624-24-8	Methyl valerate	19.4	157.9	164.3	168.9	177.7	141.2		
			17.5[c]	158.0[c]	164.4[c]	169.0[c]	177.6[c]	139.9[c]		
6	109-94-4	Ethyl formate	33.5					134.8	180.3	
			33.0[b]							
7	141-78-6	Ethyl acetate	23.8	172.7				133.1	178.8	
			22.9[b]	172.1				131.6[c]	178.6[c]	
			21.0							
8	105-37-3	Ethyl propionate	20.4	165.4	183.8			133.1	178.6	
			17.6[c]	165.3[c]	183.6[c]			131.7[c]	178.6[c]	
9	105-54-4	Ethyl butyrate	21.2	156.6	173.9	179.0		133.1	178.3	
10	625-55-8	Isopropyl formate	33.2					125.6	171.4	
11	108-21-4	Isopropyl acetate	23.5	173.3				125.2	171.2	
12	105-46-4	*sec*-Butyl acetate	24.2	173.3				121.2	163.6 (CH_2)	183.0
									171.9 (CH_3)	
13	540-88-5	*tert*-Butyl acetate	24.2	170.5				113.4	164.4	
14	598-98-1	Methyl pivalate	16.2	154.2	165.6			141.7		
15	547-63-7	Methyl isobutyrate	19.3	161.8	176.6			143.0		
16	97-62-1	Ethyl isobutyrate	18.5	158.5	173.7			133.0	178.3	
			15.1[c]	158.6[c]	173.8			131.7[c]	178.6[c]	
17	95-92-1	Diethyl oxalate	36.1					130.7	179.6	
18	105-52-3	Diethyl malonate	27.1	151.3				131.8	178.7	
19	123-25-1	Diethyl succinate	21.7	163.6				132.5	178.5	
20	818-38-2	Diethyl glutarate	21.2	159.5	172.2			132.8	178.5	
21	6279-86-3	Tricarboethoxymethane	31.5	135.7				132.6	180.8	
22	39000-70-9	Tetracarboethoxymethane	33.0	121.3				131.8	180.8	

[a] In parts per million (ppm) relative to $^{13}CS_2$. [b] Reference 9. [c] 20% (v/v) in SO_2 at −60°.

the methyl carbon shifts in a number of methyl esters.[10] In our previous studies,[11,12] we reported the ^{13}C nmr spectrum of a single ester, *i.e.*, methyl acetate. We felt it, therefore, of interest to extend these data by undertaking a systematic cmr study of protonated and parent esters, using the Fourier transform cmr method.

Results and Discussion

Protonated Monocarboxylic Acid Esters.—To extend our knowledge of the structure of protonated carbonyl compounds we undertook the cmr study of a series of protonated esters in the superacid system FSO_3H–SbF_5, and for comparison, their parent compounds. The chemical shift data obtained using pulsed nmr with Fourier transformation techniques[4,13] are summarized in Tables I and II.

The assignment of resonances was made by the now familiar procedures of Grant and coworkers.[14,15] These include use of the observation that a polar group exerts a large inductive effect on the shift of a directly attached carbon, and, if elements of symmetry are present in a molecule, it is possible to assign signals on the basis of relative intensities. Also, for closely grouped methylene resonances, minimal substituent effects can be assumed with respect to the corresponding hydrocarbons. Assignment of some signals was made by comparison of the carbon shifts for a particular ester with those of the homolog containing one less carbon atom. For example, the two methyl carbon resonances of ethyl acetate can be distinguished by comparing its spectrum with that of ethyl formate. To be assured of the correct assignment in a number of cases it was necessary to conduct "off-resonance" decoupling experiments.

The ^{13}C chemical shifts shown in Table I are given with reference to carbon disulfide, but were in fact experimentally measured from external methyl iodide. Details of the method by which chemical shifts were determined, as well as a description of the nmr instrumentation, are provided in the Experimental Section. Consistent with the usual conventions, positive values in Tables I and II represent chemical shifts shielded from carbon disulfide, whereas negative values are more deshielded in regard to the reference. ^{13}C nmr spectra of the parent esters were recorded neat at 30–35°, and in several cases at −60° in SO_2 solution. Only the carbonyl carbon shifts and the carbons α to the alkyl oxygen were found to differ by more than ±0.3 ppm in the two media. Solvent effects on carbonyl ^{13}C shifts in aprotic solvents have been interpreted in terms of carbonyl π-bond polarity as influenced by polar and van der Waals interactions with the solvent.[16] Our present experimental results may indicate slight solvent–solute interactions between the ester carbonyl groups

(10) W. McFarlane, *J. Chem. Soc. B*, 28 (1969).
(11) G. A. Olah, D. H. O'Brien, and A. M. White, *J. Amer. Chem. Soc.*, **89**, 5694 (1967).
(12) G. A. Olah and A. M. White, *ibid.*, **91**, 5801 (1969).
(13) R. R. Ernst and W. A. Anderson, *Rev. Sci. Instrum.*, **37**, 93 (1966).
(14) D. M. Grant and E. G. Paul, *J. Amer. Chem. Soc.*, **86**, 2984 (1964).
(15) D. K. Dalling and D. M. Grant, *ibid.*, **89**, 6612 (1967).
(16) G. E. Maciel and J. J. Natterstad, *J. Chem. Phys.*, **42**, 2752 (1965).

TABLE II

^{13}C CHEMICAL SHIFTS[a] OF PROTONATED ALIPHATIC ESTERS

No.	Registry no.	Compound	Carbonyl	R—C=O				—O—R		
				C_α	C_β	C_γ	C_δ	C_α	C_β	C_γ
1	39014-35-2	$H[C(OH)OCH_3]^+$	14.4					125.7		
2	39014-36-3	$CH_3[C(OH)OCH_3]^+$	1.8	171.6				126.5		
3	39014-37-4	$CH_3CH_2[C(OH)OCH_3]^+$	−0.7	164.0	185.5			129.4		
4	39014-38-5	$CH_3CH_2CH_2[C(OH)OCH_3]^+$	0.0	156.5	175.2	179.8		129.4		
5	39014-39-6	$CH_3CH_2CH_2CH_2[C(OH)OCH_3]^+$	−0.1	158.3	167.1	170.7	179.3	129.3		
6	39014-40-9	$H[C(OH)OCH_2CH_3]^+$	15.7					115.4	179.6	
7	39014-41-0	$CH_3[C(OH)OCH_2CH_3]^+$	2.7	171.3				116.8	179.5	
8	39014-42-1	$CH_3CH_2[C(OH)OCH_2CH_3]^+$	0.4	163.6	185.5			116.2	179.5	
9	39014-43-2	$CH_3CH_2CH_2[C(OH)OCH_2CH_3]^+$	1.3	156.5	175.3	179.8		116.5	180.0	
10	39532-21-3	$H[C(OH)OCH(CH_3)_2]^+$	16.6					102.2	172.2	
11	39014-44-3	$CH_3[C(OH)OCH(CH_3)_2]^+$	2.8	171.9				102.3	172.2	
12	39014-45-4	$CH_3[C(OH)OCH(CH_3)CH_2CH_3]^+$	3.5	172.0				99.6	164.5 (CH_2)	183.5
									174.4 (CH_3)	
14	39014-46-5	$(CH_3)_3C[C(OH)OCH_3]^+$	−4.7	151.5	167.2			128.7		
16	39014-47-6	$(CH_3)_2CH[C(OH)OCH_2CH_3]^+$	2.0	157.0	175.2			116.4	179.9	
17	39014-48-7	$[C(OH)OCH_2CH_3]_2^{2+}$	28.1					105.3	179.1	
18	39014-49-8	$CH_2[C(OH)OCH_2CH_3]_2^{2+}$	12.9	151.2				111.2	179.4	
19	39014-50-1	$(CH_2)_2[C(OH)OCH_2CH_3]_2^{2+}$	5.1	163.7				113.2	179.6	
20	39014-51-2	$(CH_2)_3[C(OH)OCH_2CH_3]_2^{2+}$	2.7	159.4	175.6			113.8	179.3	

[a] In parts per million (ppm) relative to $^{13}CS_2$.

and sulfur dioxide, but the effect is small and is not the major contribution to the large downfield shift that occurs for the carbonyl ^{13}C shift on oxygen protonation.

^{13}C chemical shifts of the protonated esters were measured at −60° in excess of FSO_3H–SbF_5 solution, using SO_2 as diluent.

In order to evaluate the effect of substituents on the chemical shift of a particular carbon atom in a molecule, it is customary to subtract the shift of the corresponding carbon of the unsubstituted parent hydrocarbon from the shift of the same carbon in the substituted hydrocarbon.[17,18] We have used this procedure to evaluate the substituent effects of the carboalkoxy and protonated carboalkoxy groups on both the alkoxy and acyl carbon shifts in the esters of Tables I and II. The validity of this approach in our present study, with the very large difference in environment in which the shifts of the unsubstituted and substituted hydrocarbons were measured is questionable. However, the results show that the substituent effects of the carboalkoxy and protonated carboalkoxy groups follow trends very much like those caused by the hydroxyl,[5a] keto,[5d] and carboxyl[6] groups in nonrigid systems and by a large number of substituents in the rigid norbornyl system.[5a] The α-substituent effect for the monoesters in Table III is always deshielding, being from 46.6 to 54.2 ppm for the RCOO– group and from 20.0 to 24.4 ppm for the –COOR group.

The α-substituent effect of a –COOR group on a particular carbon resonance is not this value if several –COOR groups are already attached to that carbon. Thus, inspection of the shift data in Tables I and III for ethyl acetate, ethyl malonate, tricarboethoxymethane, and tetracarboethoxymethane shows that the methane ^{13}C chemical shift is progressively deshielded 22.2, 21.4, 15.6, and 14.7 ppm by the successive replacement of the hydrogens with –COOR groups. Similar variations in the methane carbon shift, brought about by the successive replacement of hydrogens by substituent, have been extensively studied.[17,19,20] Nonlinearity in plots of chemical shift *vs.* degree of substitution, such as are observed for bromine and iodine, have been interpreted[17] in terms of an increasing neighbor anisotropy contributions to the carbon shift, as more substituents are added to the molecule. Recently, it has been claimed[20] that the failure to interpret these experimental plots in terms of simple additive relationships is a result of not allowing a diamagnetic correction.

The RCOO– group has almost the same α effect as the hydroxyl group in corresponding aliphatic alcohols (Table IV of ref 5a) with values for the alcohols consistently smaller by 2–3 ppm. This difference may be a result of the greater electronegativity[21] of the RCOO– functional group compared with the –OH group, a deshielding effect associated with the anisotropy of the carbonyl group, or a solvent effect. Similarly the ROOC– functional group has almost the same α effect as that of the HOOC– group (Table II of ref 6) with the latter causing the greater deshielding. The α substituent effect of the ROOC– group, however, is much smaller than that of the RCOO– group.

The increments caused by β carbons are also negative, and comparison of the results in Table III with those for the corresponding alcohols[5a] and carboxylic acids[6] show an effect of almost the same magnitude in both cases. The RCOO– functional group has a slightly

(17) H. Spiesecke and W. G. Schneider, *J. Chem. Phys.*, **35**, 722 (1961).
(18) E. G. Paul and D. M. Grant, *J. Amer. Chem. Soc.*, **86**, 2977 (1964).
(19) P. C. Lauterbur, *Ann. N. Y. Acad. Sci.*, **70**, 841 (1958).
(20) J. Mason, *J. Chem. Soc. A*, 1038 (1971).
(21) One definition of electronegativity is that provided by Dailey and Shoolery [*J. Amer. Chem. Soc.*, **77**, 3977 (1955)]

$$\text{electronegativity} = 0.684\delta_{\text{internal}} + 1.78$$

where δ_{internal} is the difference in chemical shift between the methyl and methylene protons of the appropriately substituted ethane derivative. Inspection of the pmr data[22] for ethyl acetate and ethanol show that δ_{internal} is slightly larger for the first compound. The RCOO– group is, therefore, more electronegative than the HO– group. The pmr data for ethyl acetate and methyl propionate show that δ_{internal} is larger for the first compound and thus the RCOO– group is also more electronegative than the –COOR group according to this definition. By a similar argument (see ref 11 for pmr data) the $RC(OH)^+O$– group is more electronegative than the $-C(OH)^+OR$ group.
(22) L. M. Jackman and S. Sternhell, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," 2nd ed, Pergamon Press, Oxford, 1969, p 164.

TABLE III

^{13}C CHEMICAL SHIFT[a] DIFFERENCE BETWEEN ESTERS AND THEIR CORRESPONDING UNSUBSTITUTED HYDROCARBONS[b]

		R—C=O				—O—R		
No.	Compound	C_α	C_β	C_γ	C_δ	C_α	C_β	C_γ
1	Methyl formate					−51.8		
2	Methyl acetate	−21.6				−52.7		
3	Methyl propionate	−21.4	−3.1			−53.1		
4	Methyl butyrate	−20.0	−2.8	1.8		−53.6		
5	Methyl valerate	−21.7	−3.5	1.1	−1.9	−53.7		
6	Ethyl formate					−52.1	−6.6	
7	Ethyl acetate	−22.2				−53.8	−8.1	
8	Ethyl propionate	−21.5	−3.1			−53.8	−8.3	
9	Ethyl butyrate	−20.6	−2.8	1.8		−53.8	−8.6	
10	Isopropyl formate					−51.1	−5.8	
11	Isopropyl acetate	−21.6				−51.5	−6.0	
12	*sec*-Butyl acetate	−21.6				−46.6	−4.2 (CH_2)	3.4
							−7.7 (CH_3)	
13	*tert*-Butyl acetate	−24.4				−54.2	−4.1	
17	Diethyl oxalate					−56.2	−7.3	
18	Diethyl malonate	−43.6						
		(−21.4)[c]				−55.1	−8.2	
19	Diethyl succinate[d]	−20.0				−54.4	−8.4	
20	Diethyl glutarate[e]	−19.5				−54.1	−8.4	
21	Tricarboethoxymethane	−59.2				−54.3	−6.1	
22	Tetracarboethoxymethane	−73.6				−55.1	−6.1	

[a] In parts per million (ppm). Negative sign indicates a deshielding. [b] The differences were calculated by subtracting the chemical shifts of an aliphatic ester from the shifts in the corresponding unsubstituted hydrocarbon.[18] [c] Shift increment calculated using ethyl acetate as model compound. [d] Shift increment calculated using ethyl propionate as model compound. [e] Shift increment calculated using ethyl butyrate as model compound.

TABLE IV

^{13}C CHEMICAL SHIFT[a] DIFFERENCES BETWEEN PROTONATED ESTERS AND THEIR CORRESPONDING UNSUBSTITUTED HYDROCARBONS[b]

	R—C=O$^+$—H				—O—R		
No.	C_α	C_β	C_γ	C_δ	C_α	C_β	C_γ
1					−69.2		
2	−23.3				−68.4		
3	−22.9	−1.1			−65.5		
4	−20.7	−1.5	2.6		−65.5		
5	−21.3	−0.7	2.9	−0.3	−65.6		
6					−71.5	−7.3	
7	−23.6				−70.1	−7.4	
8	−23.3	−1.4			−70.7	−7.4	
9	−20.7	−1.4	2.6		−70.4	−6.9	
10					−74.5	−5.0	
11	−23.0				−74.4	−5.0	
12	−22.9				−68.1	−3.3 (CH_2)	3.9
						−5.2 (CH_3)	
14	−16.1	−1.3			−66.2		
16	−19.7	−2.0			−70.5	−7.0	

[a] In parts per million (ppm). Negative sign indicates a deshielding. [b] The differences were calculated by subtracting the chemical shifts of an aliphatic ester from the shifts in the corresponding unsubstituted hydrocarbon.[18]

smaller effect than the hydroxyl group, but, as the factors which contribute to the β effect are less well understood than those which contribute to the α effect,[23,24] an explanation will not be attempted.

Table III shows a γ effect, for the RCOO– and –CO-OR groups, of the same magnitude and sign (positive) as that of the hydroxyl[5a] and carboxyl[6] groups. These same two groups have a negative δ effect,[5a,6] which is also the case for the sole δ effect recorded in Table III. As expected the magnitude of the substituent effect for both –COOR and RCOO– groups falls off rapidly with increasing chain length.

Inspection of Table IV shows that most of the above observations are also applicable to the protonated –COOR and RCOO– groups. The variations of the shielding of carbons α to most substituents are apparently dominated by the electronegativity of the substituent.[17,19,25,26] The protonated carboalkoxy group is substantially more electronegative than the carboalkoxy group,[21] and one would therefore expect a deshielding of the α carbons on protonation of a carboxylic acid ester. This is found to be the case for the carbon nuclei α to the carbonyl group, which are deshielded 0.1 to 2.7 ppm as well as those α to the alkyl oxygen (15.4 to 23.4 ppm). The greater electronegativity of the RC-(OH)$^+$O– group compared with the –C(OH)$^+$OR group

(23) B. V. Cheney and D. M. Grant, *J. Amer. Chem. Soc.*, **89**, 5319 (1967).
(24) D. M. Grant and B. V. Cheney, *ibid.*, **89**, 5315 (1967).
(25) J. W. Emsley, J. Feeney, and L. H. Sutcliffe, "High Resolution NMR Spectroscopy," Pergamon Press, Oxford, 1965, pp 136–138, 992–999.
(26) W. M. Litchman and D. M. Grant, *J. Amer. Chem. Soc.*, **90**, 1400 (1968).

TABLE V

^{13}C CHEMICAL SHIFT[a] DIFFERENCES BETWEEN PROTONATED ESTERS AND THEIR PARENTS[b]

No.	Ester	R—C=O				—O—R				$\Delta\delta_{^{13}C=O} + \Delta\delta_{O-^{13}CH_2}$
		C_α	C_β	C_γ	C_δ	C_α	C_β	C_γ	Carbonyl	
1	Methyl formate					−17.4			−17.6	−35.0
2	Methyl acetate	−1.7				−15.7			−21.3	−37.0
3	Methyl propionate	−1.5	2.0			−12.4			−20.3	−32.7
4	Methyl butyrate	−0.7	1.2	0.8		−11.9			−20.6	−30.8
5	Methyl valerate	−0.4	2.8	1.8	1.6	−11.9			−19.5	−31.4
6	Ethyl formate					−19.4	−0.7		−17.8	−37.2
7	Ethyl acetate	−1.4				−16.3	0.7		−21.1	−37.4
8	Ethyl propionate	−1.8	1.7			−16.9	0.9		−20.0	−36.9
9	Ethyl butyrate	−0.1	1.4	0.8		−16.6	1.7		−19.9	−36.5
10	Isopropyl formate					−23.4	0.8		−16.6	−40.0
11	Isopropyl acetate	−1.4				−22.9	1.0		−20.7	−43.6
12	*sec*-Butyl acetate	−1.3				−21.5	0.9 (CH_2) 2.5 (CH_3)	0.5	−20.7	−42.2
14	Methyl pivalate	−2.7	1.6			−13.0			−20.9	−33.9
16	Ethyl isobutyrate	−1.5	1.5			−16.6	1.6		−20.5	−37.1
17	Diethyl oxalate					−25.4	0.5		−8.0	−33.4
18	Diethyl malonate	−0.1				−20.6	0.8		−14.2	−34.8
19	Diethyl succinate	+0.1				−19.3	1.1		−16.6	−35.9
20	Diethyl glutarate	−0.1	3.4			−19.0	0.8		−18.5	−37.5

[a] In parts per million (ppm). Negative sign indicates a deshielding. [b] Differences calculated by subtracting the chemical shifts of the protonated esters from the corresponding shifts in the parent ester.

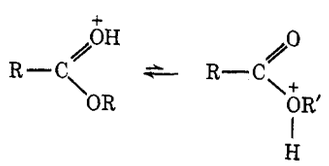
must be partly responsible for the greater deshielding of the latter α carbons. Inspection of Table V reveals that the greatest deshielding on ester protonation of carbons α to an alkyl oxygen occurs for isopropyl acetate, *sec*-butyl acetate, and isopropyl formate (22.9, 21.5, and 23.4 ppm, respectively). Furthermore, the deshielding of the α carbon, on protonation, increases in the series methyl, ethyl, and isopropyl acetate, as well as in the series methyl, ethyl, and isopropyl formate. This may reflect an increasing relative contribution of mesomer III in the protonated esters of secondary alcohols compared with those or primary alcohols.

The β, γ, and δ resonances become more shielded on protonation of esters (Table V). This may simply be a solvent effect. It is interesting to note that the shielding of the β-, γ-, and δ-carbon resonances changes in the opposite direction on carbonyl oxygen protonation to that of the proton resonances.[11] This is similar to the observations of Hagan and Roberts,[6] for carboxylic acids and their carboxylate anions, where ionization of the acids resulted in the expected shielding of the proton resonances, but deshielding of the carbon resonances.

Protonation of esters results in a deshielding of the carbonyl carbon resonances of 16.6 to 21.3 ppm (Table V). Deshielding of the carbonyl carbon resonances in esters has been observed by Maciel and Natterstad[16] for solvents capable of hydrogen bonding to the carbonyl oxygen. They gave several possible interpretations[16,27] of the observed deshieldings, principally in terms of changes in the carbonyl π-bond polarity.

The carbonyl chemical shift values in Table I are subject to a methyl substituent effect. Replacement of the carbonyl hydrogen in a formate ester by a methyl group results in the carbonyl carbon being deshielded approximately 9 ppm. Hence, the observed α-methyl substituent effect is of comparable magnitude to that in carbonyl compounds (5–8 ppm)[9] and carboxylic acids (11 ppm).[9] An α-methyl substituent effect (12–14 ppm) on the carbonyl carbon shift in protonated esters is also indicated by a comparison of the data for protonated formates and acetates (Table II). Similar comparisons (Table I) between acetates and propionates and between propionates and butyrates show a β-methyl substituent effect, that is deshielding (3.4 ± 0.1 ppm), and a γ-methyl substituent effect, that is shielding (0.8 ± 0.1 ppm). The corresponding substituent effects in protonated esters are of the same sign as for their parents and are 2.4 ± 0.1 ppm and 0.8 ± 0.1 ppm, respectively. Examination of the carbonyl chemical shifts in protonated and unprotonated methyl pivalate, methyl and ethyl isobutyrate show that the α and β effects are approximately additive. However, there is insufficient data in Tables I and II to summarize these observed α-, β-, and γ-methyl substituent effects by a relationship, similar to that used by Grant and Paul[14] for straight-chain and branched hydrocarbons.

None of the studied protonated esters, including the secondary alkyl esters which showed increased tendency of cleavage on standing even at low temperature, gives indication of ether oxygen protonation. As in acid-catalyzed ester hydrolysis the intermediacy of the ether oxygen protonated acylalkyloxonium ion is generally assumed, the latter could be formed in a minimal equilibrium from the carbonyl oxygen protonated form



Alternatively it is possible that in excess superacid as solvent system, carbonyl oxygen protonated esters can undergo a second protolytic attack on the ether oxygen unshared electron pairs leading to a highly destabilized

(27) G. E. Maciel, *J. Chem. Phys.*, **42**, 2746 (1965).

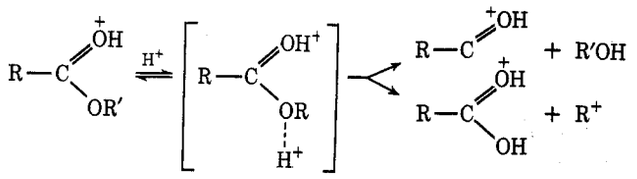
TABLE VI

PMR CHEMICAL SHIFTS[a] OF DIPROTONATED DICARBOXYLIC ACID ESTERS IN FSO_3H–SbF_5–SO_2 AT −60°

Ester	=O—H	R—C=O Cα	R—C=O Cβ	—O—R Cα	—O—R Cβ
Diethyl oxalate				1.98 (0.53)[b]	5.90 (1.55)
Diethyl malonate	14.6[c]	5.15 (1.65)		2.02 (0.63)	5.58 (1.25)
Diethyl succinate	13.26	3.94 (1.19)		2.02 (0.60)	5.51 (1.25)
Diethyl glutarate	12.55	3.54 (0.98)	2.73 (0.59)	2.02 (0.59)	5.47 (1.16)

[a] Parts per million (ppm) from capillary of TMS. [b] Chemical shift differences between protonated and unprotonated esters are in parentheses. [c] At −90°.

(through charge–charge repulsion) dispositive transition state, which leads to cleavage



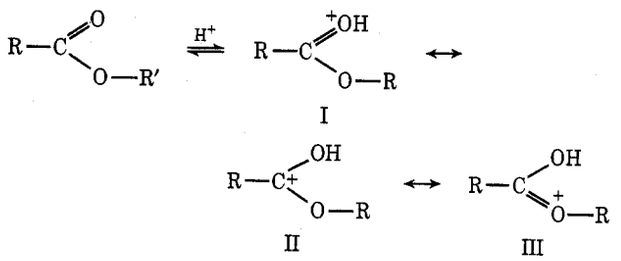
The possibility of diprotolytic cleavage is at the present time speculative as there has been no direct observation of any ether–oxygen protonated ester. Carbonyl oxygen protonated forms are highly stable and show little tendency to undergo intermolecular proton exchange. We are continuing our studies in the hope to clarify the possibility raised.

Diprotonated Dicarboxylic Acid Esters.—The protonation of dicarboxylic acids in superacid media has been studied by Olah and White.[28] It was shown by peak area integration of the pmr spectra of malonic, succinic, and glutaric acids in FSO_3H–SbF_5 that these acids existed as diprotonated species. It was not possible to decide, by the same method, if oxalic acid was also diprotonated, although the large deshielding of the oxygen protons (δ 15.70) suggested that this was the case.

We have studied by pmr and cmr spectroscopy the related problem of the extent of protonation of diesters in superacid systems at low temperatures. The diethyl esters of dicarboxylic acids gave well-resolved pmr spectra in FSO_3H–SbF_5 solution, diluted with SO_2. Chemical shift data are summarized in Table VI. Peak area integration of the spectra indicated that diethyl succinate and glutarate exist as diprotonated species at −60°. To observe the oxygen proton signals in protonated diethyl malonate it was necessary to record the spectrum at −90°, at which temperature the C–H protons were considerably broadened and a broad singlet was observed at δ 14.6. It was then possible by integration to show that this ester was diprotonated.

In principle, it should be possible using the same method to determine the extent of protonation in diethyl oxalate. This is not possible for oxalic acid because there are no other proton signals in the molecule, to compare with the oxygen proton signal. At −100°, the spectrum of diethyl oxalate in excess FSO_3H–SbF_5 indicated a very broad singlet at δ 11.6, implying that rapid proton exchange was still occurring between solvent and ester. Lowering the temperature did not slow the exchange rate sufficiently to observe a separate protonated ester signal. The changes in the methyl and methylene proton shifts, however, on protonation of diethyl oxalate are as large as those in the higher homologs, and, therefore, it seems that this ester, too, is diprotonated. For confirmation we have recorded the proton decoupled cmr spectrum of diethyl oxalate in FSO_3H–SbF_5 at −60°. The cmr spectra of protonated diethyl malonate, succinate, and glutarate, together with those of their parent compounds, have also been recorded; the results have been included in Tables I and II. The ^{13}C chemical shift data for the above esters, which are known to be diprotonated in FSO_3H–SbF_5, can be applied to the data for diethyl oxalate in order to determine its degree of protonation. Such a comparison of carbon shifts is more meaningful than for proton shifts, because of the lesser relative importance in the former case of field effects, and the greater sensitivity of the carbon shift to small structural changes within a molecule. The changes in the carbon shifts, on ester protonation, should be more a reflection of changes in the amount of charge located at a particular atom or on an adjacent oxygen or carbon atom than of solvent, field, or magnetic anisotropic effects.

It will be assumed in the following discussion that protonation of diesters in FSO_3H–SbF_5 occurs only on the acyl oxygen atom.[11] The equilibrium between an ester and its protonated form can be represented as

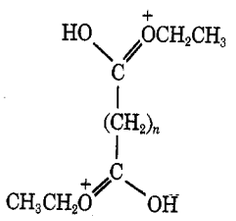


In excess HSO_3F–SbF_5, this equilibrium lies far to the right, and the carbonyl carbon and alkyl oxygen carbon resonances are deshielded 20 and 16 ppm, respectively, from their values in the unprotonated esters. In weaker acids, or where less than a molar amount of FSO_3H–SbF_5 is present, these chemical shifts should be the weighted average of the cationic species and the ester form, with which it is in rapid equilibrium. This was found to be the case for the methylene carbon resonance, the carbonyl carbon resonance, and the methylene and carbonyl oxygen proton resonances of ethyl formate in SO_2 at −60°, in the presence of less than molar amounts of FSO_3H–SbF_5. It should, therefore, be possible to use these chemical shifts to calculate the equilibrium position for a dicarboxylic acid ester in a superacid. For example, a mixture of equal numbers of monoprotonated diester and diprotonated diester species, in rapid equilibrium with each other, should have a carbonyl carbon resonance which is deshielded from the corresponding resonance in the unprotonated species by approximately three-quarters the amount observed in a protonated

(28) G. A. Olah and A. M. White, *J. Amer. Chem. Soc.*, **89**, 4752 (1967).

monoester. This assumes that the relative contribution of resonance forms I, II, and III is the same in a protonated diester as it is in a protonated monoester. If the ester groups are separated by a sufficient number of methylene carbons, this should be true; otherwise the relative contributions of I and III may increase, because of the larger charge separation in these forms. The relevant figures to be considered in a discussion of the data in Table V, is, therefore, the sum of the change, on protonation, of the carbonyl carbon resonance ($\Delta\delta_{^{13}C=O}$) and the methylene carbon resonance ($\Delta\delta_{O-^{13}CH_2}$). These values are shown in the last column of this table.

The value of $\Delta\delta_{^{13}C=O} + \Delta\delta_{O-^{13}CH_2}$ for diethyl oxalate is almost as large as it is for the other diesters and ethyl formate. Assuming that the changes in the carbon shifts in diethyl oxalate are predominantly a result of localized charge effects and not of field or solvent effects arising from the close proximity of the two charged ester groups, these results indicate that diethyl oxalate in FSO_3H–SbF_5, at $-65°$, exists primarily as the diprotonated species. The larger $\Delta\delta_{O-^{13}CH_2}$ for protonated diethyl oxalate, compared with the corresponding values in the other protonated diesters, suggests that resonance form IV (analog of III) may be a more important con-



IV

tributor for this ester ($n = 0$) than for the other diesters ($n = 1, 2, 3$). The slightly smaller value of $\Delta\delta_{^{13}C=O} + \Delta\delta_{O-^{13}CH_2}$ for protonated diethyl oxalate may indicate a larger amount of equilibrating monoprotonated ester than is the case from the other protonated diesters, or it may be a result of solvent and field effects.

Experimental Section

Materials.—All esters were either commercially available materials or were prepared by standard literature methods and purified by distillation.

Preparation of Protonated Esters.—A sample of a protonated ester was prepared by adding the ester (0.5 ml) to a stirred solution of 1:1 *M* FSO_3H–SbF_5 (1.5 ml) in an equal volume of SO_2 at $-76°$. Samples prepared in this manner gave spectra which showed no appreciable chemical shift differences with temperature or small concentration variations. The acid was always in excess as indicated by an acid peak at about δ 10.9 in the pmr spectrum. The cmr spectrum of a protonated ester was only recorded if its pmr spectrum was identical with the spectrum reported in the literature.[11] For esters previously not reported, the structure of the protonated form could be established from the pmr spectral data (chemical shifts, multiplicity patterns, and peak area integration). After obtaining the cmr spectrum of a protonated ester, the sample was again checked by pmr spectroscopy to determine if any decomposition had occurred. Only the esters of secondary alcohols showed any observable decomposition (10–20%), cleaving by an $A_{AL}1$ mechanism to give protonated acids and stable tertiary carbenium ions.[11] No attempt to record the cmr spectra of protonated tertiary alkyl esters, such as *tert*-butyl acetate, as it is known that esters of tertiary alcohols cleave so rapidly, even at $-80°$, that only the protonated acid and the tertiary carbenium ion can be observed.

Nmr Spectroscopy.—Pmr spectra were obtained on a Varian Associates Model A-56/60-A spectrometer equipped with a variable temperature probe.

Cmr spectra were obtained on a Varian Associates Model HA-100 spectrometer equipped with a FT-100 Fourier transform accessory (V-4357 pulsing and control unit), a broad-band proton decoupler (V-3512), and a variable temperature probe. A pulsed frequency of 25.14 MHz was derived from a gated power amplifier capable of putting out approximately 80 W into the transmitter coils. The pulse width used was 30 μsec, and the pulse interval, 2 sec. The available computer memory (4000 imput channels) and the need to provide multichannel excitation over the region of interest (sweep width 6500 Hz) limited the data acquisition time to 0.3 sec.

The free induction signal derived after each pulse is digitized and accumulated in a Varian 620/i computer (8K). Approximately 3000–4000 accumulations were made to obtain each spectrum. Field/frequency regulation was maintained by a homonuclear internal lock system. The lock used was the proton decoupled ^{13}C resonance of a 60% ^{13}C-labeled methyl iodide sample contained in a precision coaxially spaced capillary (o.d. *ca.* 0.2 and 0.4 mm) inserted in the sample nmr tube (5-mm o.d.).

Fourier transformation of the accumulated free-induction signal gave the frequency spectrum[13,29,30] from which was measured the chemical shift of each signal, relative to the reference methyl iodide signal. All the chemical shifts reported here have been corrected to a carbon disulfide reference by the relationship

$$\delta_{CS_2} = 212.2 - a\delta T - \delta_{CH_3I}$$

where δ_{CS_2} and δ_{CH_3I} are the chemical shifts in parts per million of a particular signal, from carbon disulfide and methyl iodide, respectively. The term $a\delta T$ allows for the observed temperature variation in the chemical shift of internal carbon disulfide with respect to that of external methyl iodide, and δT is the difference between the normal probe temperature (30–35°) and the temperature at which a spectrum is recorded. A plot of sample temperature *vs.* the ^{13}C chemical shift difference between external methyl iodide and carbon disulfide is linear with a slope of $a = 0.029 \pm 0.002$ ppm/°C. The slope was found to almost identical for several carbon disulfide–cosolvent systems; so the above expression is most likely valid for the superacid solvent systems employed in this study. The value 212.2, in the above expression, is the experimentally measured chemical shift difference between carbon disulfide and external methyl iodide, at normal probe temperature.

Acknowledgment.—Support of our work by the National Institutes of Health is gratefully acknowledged.

(29) R. Ernst, "Advances in Magnetic Resonance," Vol. 2, Academic Press, New York, N. Y., 1966, p 74 ff.

(30) A. Abragam, "Principles of Nuclear Magnetism," Oxford University Press, London, 1961, p 114.