

as 1.82 eV ( $r = 0.937$ ). Therefore, silicon ( $\beta' = 0.54$  eV) is only one-third as effective as carbon and oxygen in  $\sigma$ - $\pi$  or  $n$ - $\pi$  conjugation where these atoms are involved to form a double bond to carbon. However, the silicon-silicon bond with a considerably lower ionization potential can interact with benzene or naphthalene  $\pi$  orbitals rather effectively. Large shifts of the second ionization energy of  $\beta$ -naphthylpentamethyldisilane (0.27 eV), which has been excluded from the arguments above,<sup>24</sup> can be understood only by the perturbation theory in the degenerated system of  $\sigma$ - $\pi$  conjugation model. Inductive effect models ( $\Delta E = c_1^2 \Delta\alpha$ ) only predict that the shift should be smaller than that of the first ionization energy of  $\alpha$ -pentamethyldisilanylnaphthalene. However, from the perturbation treatment by using the first term with  $\beta' = 0.54$  eV, the shift of the second ionization energy of  $\beta$ -naphthylpentamethyldisilane is calculated to be 0.32 eV, very close to the experimental value.

In above discussion, the role of Si 3d orbital is neglected for simplicity, although a number of problems in organometalloid chemistry are interpreted by the idea of (p-d) $\pi$  bonding. Probably such a (p-d) $\pi$  bonding may become more important for interactions with antibonding  $\pi$  orbitals.<sup>12</sup>

## Experimental Section

**Materials.**  $\alpha$ - and  $\beta$ -Pentamethyldisilanylnaphthalenes were prepared from the corresponding bromonaphthalene, magnesium, and chloropentamethyldisilane by *in situ* Grignard reaction in the mixed solvent consisting of benzene, ether, and THF (17:11:6). After work-up,  $\alpha$ - and  $\beta$ -pentamethyldisilanylnaphthalene were

obtained in 58 and 68% yields, respectively, and were purified by preparative glc:  $\alpha$ -C<sub>10</sub>H<sub>7</sub>SiMe<sub>2</sub>SiMe<sub>3</sub>,<sup>16</sup> nmr (CCl<sub>4</sub>,  $\delta$ ) 0.07 (s, 9 H), 0.51 (s, 6 H), 7.22–8.04 (m, 7 H); mass spectrum (70 eV)  $M^+$  ( $m/e$ , 258, 15.7%),  $M^+ - 15$  (5.4%),  $M^+ - 73$  (100%);  $\beta$ -C<sub>10</sub>H<sub>7</sub>SiMe<sub>2</sub>SiMe<sub>3</sub>, nmr (CCl<sub>4</sub>,  $\delta$ ) 0.08 (s, 9 H), 0.41 (s, 6 H), 7.36–7.93 (m, 7 H); mass spectrum (70 eV)  $M^+$  ( $m/e$  258, 15.1%),  $M^+ - 15$  (5.7%),  $M^+ - 73$  (100%).

$\alpha$ - and  $\beta$ -Trimethylsilylmethylnaphthalenes<sup>19c</sup> were prepared from the corresponding chloromethylnaphthalene, magnesium, and trimethylchlorosilane by *in situ* Grignard reaction in ether. After work-up  $\alpha$ - and  $\beta$ -trimethylsilylnaphthalene were obtained in 83 and 53% yields, respectively:  $\alpha$ -C<sub>10</sub>H<sub>7</sub>CH<sub>2</sub>Si(CH<sub>3</sub>)<sub>3</sub>, bp 110–112° (4 mm) [lit.<sup>19c</sup> bp 143° (11 mm)]; nmr (CCl<sub>4</sub>,  $\delta$  ppm) 0.10 (s, 9 H), 2.59 (s, 2 H), 7.2–8.0 (m, 7 H);  $\beta$ -C<sub>10</sub>H<sub>7</sub>CH<sub>2</sub>Si(CH<sub>3</sub>)<sub>3</sub>, mp 60–61° [lit.<sup>19c</sup> mp 61°]; nmr (CCl<sub>4</sub>,  $\delta$  ppm), 0.03 (s, 9 H), 2.25 (s, 2 H), 7.0–7.0 (m, 7 H).

$\alpha$ -Methylnaphthalene was prepared in the most pure state by hydrolysis of  $\alpha$ -naphthylmethylmagnesium chloride in ether in 62% yield, bp 74° (3 mm).  $\beta$ -Methylnaphthalene and naphthalene were used as supplied. Other materials appeared in this paper were reported elsewhere. All materials were purified before use by preparative glc, distillation, or recrystallization. Satisfactory elemental analyses of all new compounds were obtained by combustion analysis.

**Charge-Transfer Spectra.** The solutions of the TCNE complexes were prepared by mixing the components dissolved in methylene dichloride, which was purified according to the literature.<sup>25</sup> Their spectra were recorded at room temperature using a Hitachi EPS-3 recording spectrophotometer.

The spectra of trimethylsilylmethyl-, methyl-, and pentamethyldisilanylbenzene were separated to two bands, respectively, by using the method of Voigt.<sup>17</sup>

**Acknowledgment.** We thank Professor T. G. Traylor for helpful discussions during his stay in Tohoku University. Thanks are also due to Toshiba Silicone Co., Ltd. for gifts of chlorosilanes.

(25) M. Pestemer, *Angew. Chem.*, **63**, 121 (1951).

## Hindered Internal Rotation of the Methyl Group in $\alpha$ -Substituted Ethyl Radicals. Effect of Fluorine

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**Abstract:** Hindered internal rotation of a methyl group is examined in solution at various temperatures by the selective line broadening in the esr spectra of the ethyl radical with  $\alpha$ -fluoro,  $\alpha,\alpha$ -difluoro,  $\alpha,\alpha$ -dichloro, and  $\alpha,\alpha$ -di-*tert*-butyl substitution. Only the spectrum of CH<sub>3</sub>CF<sub>2</sub> shows selective alternation of line widths in the CH<sub>3</sub> quartets due to modulation of the hyperfine splitting of the three methyl protons resulting from hindered rotation about the C $\alpha$ -C $\beta$  bond. Line-shape analysis using the modified Bloch equation affords a barrier of 2.2 kcal mol<sup>-1</sup>, which is largely associated with the pyramidal configuration induced by two fluorines at the radical center. The latter is also responsible for the unusually small value of the proton hfs (13.99 G) of the  $\alpha$ -CH<sub>3</sub> group in this radical. The fitting of the experimental esr spectrum to a calculated one is based on a model involving exchange among three equivalent conformations and includes dipolar line broadening due to the  $\alpha$ -fluorine anisotropy. Inversion of the configuration at the radical site is too slow on the esr time scale to contribute to line broadening.

In contrast to the large number of barriers to hindered internal rotation examined for stable molecules,<sup>1</sup> there have been only a few studies of transient species such as charged species<sup>2</sup> and free radicals.<sup>3</sup> Further-

more, there is no experimental observation in solution of hindered rotation of the methyl group.<sup>3a</sup> The barrier

(1) (a) E. B. Wilson, Jr., *Advan. Chem. Phys.*, **2**, 367 (1959); (b) J. Dale, *Tetrahedron*, **22**, 3373 (1966); (c) G. J. Karabatsos and D. J. Fenoglio, *Top. Stereochem.*, **5**, 167 (1970).

(2) V. Buss, P. v. R. Schleyer, and L. C. Allen, *Top. Stereochem.*, **7**, 253 (1973).

(3) (a) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **39**, 2147

(1963); (b) R. W. Fessenden, *J. Chim. Phys. Physicochim. Biol.*, **61**, 1570 (1964); (c) J. K. Kochi and P. J. Krusic, *Chem. Soc., Spec. Publ.*, No. 24, 147 (1970); (d) P. J. Krusic and J. K. Kochi, *J. Amer. Chem. Soc.*, **93**, 846 (1971); (e) P. J. Krusic, P. Meakin, and J. P. Jesson, *J. Phys. Chem.*, **75**, 3438 (1971); (f) K. S. Chen, D. J. Edge, and J. K. Kochi, *J. Amer. Chem. Soc.*, **95**, 7036 (1973).

(3g) NOTE ADDED IN PROOF: We inadvertently missed an earlier reference to hindered rotation of a methylvinyl radical by Fessenden and Schuler.<sup>3a</sup>

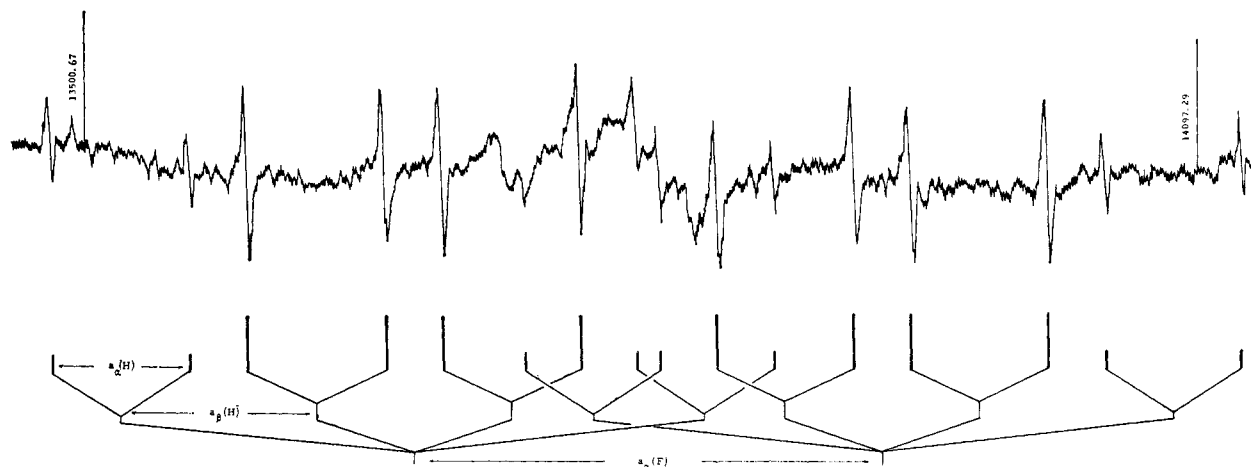


Figure 1. ESR spectrum of  $\alpha$ -fluoroethyl radical in cyclopropane solution at  $-106^\circ$ . The "stick" spectrum shows binomial intensity ratios. The proton nmr field markers are in kHz.

height for rotation in the  $\alpha$ -fluoroethyl cation has been recently calculated as 0.62 kcal/mol.<sup>4</sup> Among free radicals, the essentially free rotation in the ethyl<sup>3a-e</sup> and the  $\beta,\beta,\beta$ -trifluoroethyl radicals,<sup>5</sup> as well as the ethyl cation,<sup>6</sup> can be attributed to low barriers associated with the sixfold rotation symmetry along the  $C_\alpha$ - $C_\beta$  bond as a result of planarity at the trigonal  $\alpha$ -carbon center.

Indeed, a partial listing in Table I shows these species

Table I. Selected Barriers to Hindered Internal Rotation of a Methyl Group

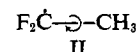
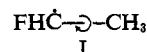
System		Rotational barrier, kcal mol <sup>-1</sup>	Method of det'n	Ref
CH <sub>3</sub> CH <sub>2</sub> ·	S	~0	Esr line shape	3a-e
CF <sub>3</sub> CH <sub>2</sub> ·	S	~0	Esr line shape	5
CH <sub>3</sub> CF <sub>2</sub> ·	S	2.2	Esr line shape	This work
CF <sub>3</sub> CF <sub>2</sub> ·	S	2.85	Esr line shape	9
CH <sub>3</sub> CH <sub>2</sub> <sup>+</sup>		~0	Theo. calcd	6
CH <sub>3</sub> CHF <sup>+</sup>		0.62	Theo. calcd	4
CH <sub>3</sub> NO <sub>2</sub>	G	0.006	Microwave spec.	a
CH <sub>3</sub> BF <sub>3</sub>	G	0.014	Microwave spec.	b
CH <sub>3</sub> CHO	G	1.16	Microwave spec.	c
CH <sub>3</sub> CH <sub>3</sub>	G	2.88	Thermodyn. data	d
CH <sub>3</sub> CH <sub>2</sub> F	G	3.30	Microwave spec.	e
CH <sub>3</sub> CHF <sub>2</sub>	G	3.18	Microwave spec.	e
CH <sub>3</sub> CF <sub>3</sub>	G	3.48	Microwave spec.	f

<sup>a</sup> E. Tannenbaum, R. J. Myers, and W. D. Gwinn, *J. Chem. Phys.*, **25**, 42 (1956). <sup>b</sup> R. E. Naylor, Jr., and E. B. Wilson, Jr., *ibid.*, **26**, 1057 (1957). <sup>c</sup> R. W. Kilb, C. C. Lin, and E. B. Wilson, Jr., *ibid.*, **26**, 1695 (1957). <sup>d</sup> K. S. Pitzer, *Discuss. Faraday Soc.*, No. 10, 66 (1951). <sup>e</sup> D. R. Herschbach, *J. Chem. Phys.*, **25**, 358 (1956). <sup>f</sup> H. T. Minden and B. P. Dailey, *Phys. Rev.*, **82**, 338 (1951). S = solution, G = gas phase.

(together with structurally similar analogs) to have significantly lower barriers to hindered internal rotation than related molecules with threefold barriers, such as ethane and fluorine-substituted ethanes. Since the rotation symmetry in alkyl radicals can be lowered by removing the planarity at the radical site, the question arises as to how much distortion is needed at  $C_\alpha$  in alkyl

radicals to raise the barrier for hindered rotation of a methyl group to an observable limit.

It is known that successive substitution of fluorine at  $C_\alpha$  in an alkyl radical results in an increasingly pyramidal configuration at the radical center.<sup>7</sup> In this study we examined the selective line broadening in the esr spectra of the simplest members in the series, *viz.*,  $\alpha$ -fluoroethyl radical I and  $\alpha,\alpha$ -difluoroethyl radical II.



The barrier height for the hindered internal rotation in II is obtained by line-shape analysis and the stable conformation deduced by INDO-MO calculations.

The effect on the barrier of fluorine substitution at the  $\beta$  carbon was also examined in a series of trifluoromethyl-substituted derivatives. These fluoroalkyl radi-



cals and the perfluoroalkyl analogs including  $\text{CF}_3\dot{\text{C}}\text{F}_2$ ,  $(\text{CF}_3)_2\dot{\text{C}}\text{F}$ , and  $(\text{CF}_3)_3\dot{\text{C}}$  reported previously by Lloyd and Rogers,<sup>8</sup> together with the line-shape analysis of  $\text{CF}_3\dot{\text{C}}\text{F}_2$  by Meakin and Krusic,<sup>9</sup> provide insight into the effect of fluorine on the barriers to hindered internal rotation.

Finally, the effect of  $\alpha$ -chlorine substitution was compared with that of fluorine in the chloro analogs.



## Results and Discussion

The esr spectrum of  $\text{CH}_3\dot{\text{C}}\text{HF}$  in Figure 1 shows no selective line broadening in the temperature range,  $-20$  to  $-140^\circ$ . On the other hand, the esr spectrum of the  $\alpha,\alpha$ -difluoro analog,  $\text{CH}_3\dot{\text{C}}\text{F}_2$ , shows the pronounced line-width behavior illustrated in Figure 2.

The esr parameters for these and related  $\alpha$ -methyl-substituted radicals are listed in Table II, together with their mode of generation and selective line-width behavior. Among these radicals, only the spectrum of II,  $\text{CH}_3\dot{\text{C}}\text{F}_2$ , shows a noticeable selective line-width effect. The outstanding feature of the spectra in

(4) D. T. Clark and D. M. J. Lilley, *Chem. Commun.*, 603 (1970).

(5) (a) A. J. Bowles, A. Hudson, and R. A. Jackson, *Chem. Phys. Lett.*, **5**, 552 (1970); (b) D. J. Edge and J. K. Kochi, *J. Amer. Chem. Soc.*, **94**, 6485 (1972).

(6) R. Sustmann, J. E. Williams, M. J. S. Dewar, L. C. Allen, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **91**, 5350 (1969).

(7) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **43**, 2704 (1965).

(8) R. V. Lloyd and M. T. Rogers, *J. Amer. Chem. Soc.*, **95**, 1512 (1973).

(9) P. Meakin and P. J. Krusic, *J. Amer. Chem. Soc.*, **95**, 8185 (1973).

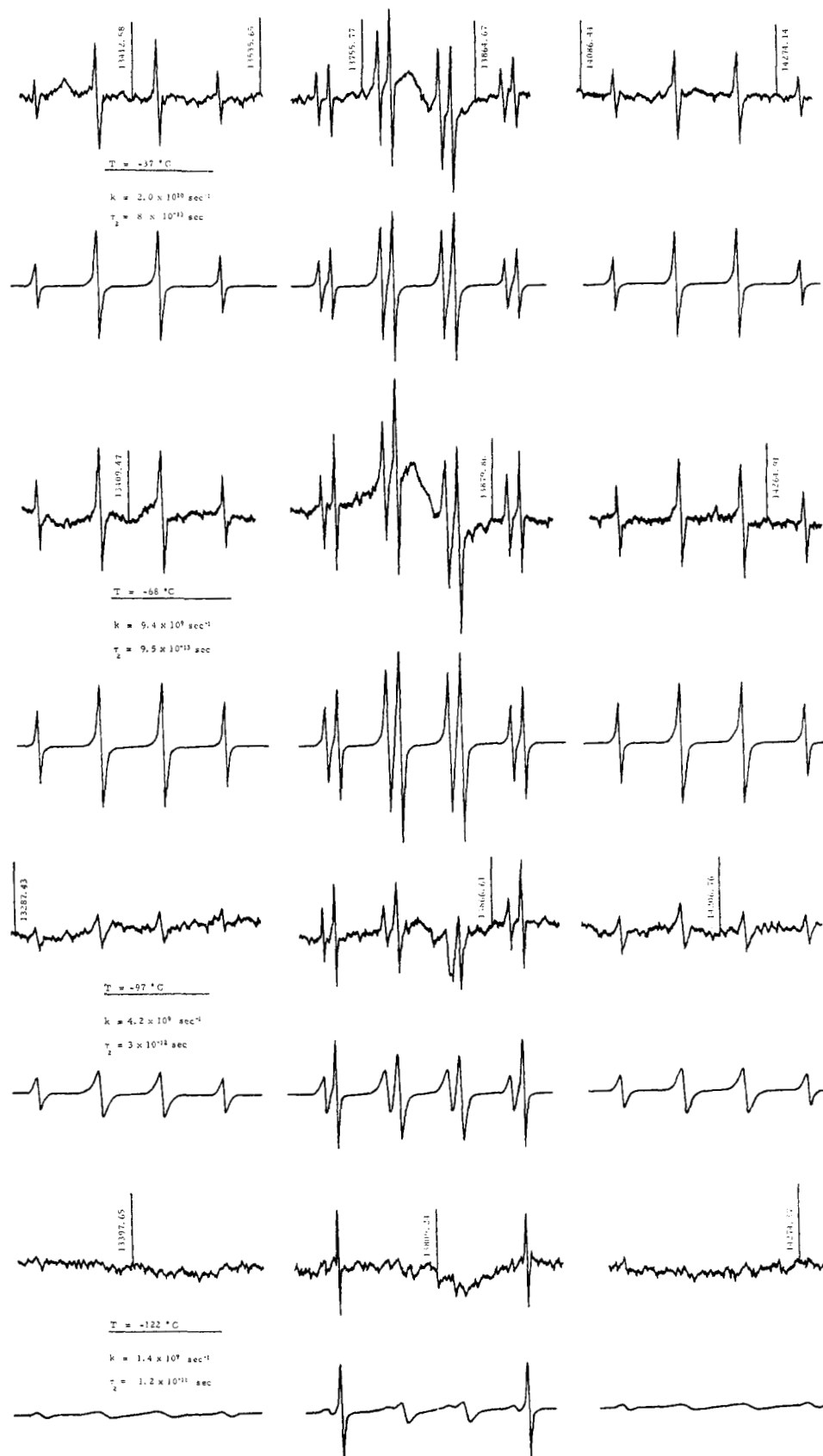


Figure 2. Experimental and calculated esr spectra of  $\alpha,\alpha$ -difluoroethyl radical (see text).

Figure 2 is the variations of line widths in the  $\text{CH}_3$  quartets due to the modulation of the hfs of the three methyl protons resulting from hindered internal rotation about the  $\text{C}_\alpha\text{--C}_\beta$  bond. [Further dipolar

broadening of the lines due to the modulations of the  $\alpha$ -fluorine anisotropic hyperfine tensor by rotational Brownian motion will be discussed later.]

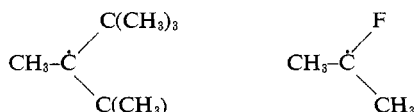
The unique magnitude of the hindered rotation in II

**Table II.** ESR Parameters of Fluoroalkyl Radicals Containing  $\alpha$ -CH<sub>3</sub> Groups in Solution

Radical	Temp, °C	Gen. <sup>a</sup>	$\langle g \rangle$	Hyperfine splitting, G			Line broad. <sup>b</sup>
				$a_{\text{CH}_3}$	$a_{\alpha\text{H}}$	$a_{\text{F}}$	
CH <sub>3</sub> CHF·	-106	P	2.00366	24.48	17.31	59.21	None <sup>c</sup>
CH <sub>3</sub> CF <sub>2</sub> ·	-78	H, S	2.00361	13.99		94.01	Severe <sup>d</sup>
(CH <sub>3</sub> ) <sub>2</sub> CF·	-48	H	2.00360	21.11		60.85	None <sup>c</sup>
CH <sub>3</sub> CH <sub>2</sub> ·	-113	P, S	2.00260	26.99	22.37		None <sup>c</sup>
(CH <sub>3</sub> ) <sub>2</sub> CH·	-113	S, P	2.00267	24.75	22.12		None <sup>c</sup>
(CH <sub>3</sub> ) <sub>3</sub> C·	-113	S, P	2.00270	22.93			None <sup>c</sup>
CH <sub>3</sub> C(Bu- <i>t</i> ) <sub>2</sub>	-89	S, P	2.00254	22.35 <sup>e</sup>			None <sup>c</sup>

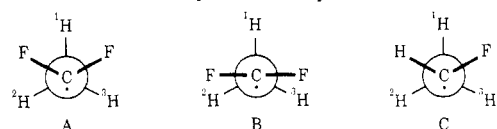
<sup>a</sup> Method of generation: P = *tert*-butyl perester, S = halogen abstraction by R<sub>3</sub>Si·, H = hydrogen abstraction by *t*-BuO· or CF<sub>3</sub>O· in cyclopropane or Freon-12 solutions (see Experimental Section). <sup>b</sup> Selective line broadening observed in temperature range, -20 to -140°. <sup>c</sup> None = not measurable. <sup>d</sup> See text. <sup>e</sup>  $a_{\gamma\text{H}} = 0.44$  G (18 H).

may be caused by: (i) the pyramidal configuration at C<sub>α</sub>, (ii) steric interactions between substituents on C<sub>α</sub> and C<sub>β</sub>, or (iii) hydrogen-fluorine interactions. The absence of any selective line broadening in the esr spectra of CF<sub>3</sub>CH<sub>2</sub>·, CH<sub>3</sub>CHF·, and CF<sub>3</sub>CHF· minimizes the importance of (iii). Furthermore, steric bulk is also not a deciding factor since the esr spectra of the highly encumbered  $\alpha,\alpha$ -di-*tert*-butyl ethyl radical, as well as  $\alpha$ -fluoroisopropyl and hexafluoroisopropyl radicals, show no significant alternating line-width effects.



We wish to show that the pyramidal geometry at C<sub>α</sub> is the most important factor in causing the hindrance to methyl rotation in II. The INDO-MO method<sup>10</sup> was used to determine the stable configuration at C<sub>α</sub> and the conformation of both CH<sub>3</sub>CHF and CH<sub>3</sub>CF<sub>2</sub> by optimizing the calculated proton and fluorine hfs to the experimental values. Interestingly, the geometry resulting from the optimization listed in Table III also

**Table III.** Conformational Dependence of ESR Parameters for  $\alpha$ -Fluoroalkyl Radicals by INDO-MO

Parameters <sup>a</sup> and Hfs			
	$\alpha,\alpha$ -Difluoroethyl radical A	$\alpha$ -Fluoroethyl radical B	$\alpha$ -Fluoroethyl radical C
$\angle \text{C}_\beta\text{C}_\alpha\text{F}(\text{H})$	115°	120°	119° (121°)
$\angle \text{FC}_\alpha\text{F}(\text{H})$	109°	120°	119°
$r(\text{C}_\alpha\text{-C}_\beta)$	1.51 Å	1.50 Å	1.52 Å
$a_{\beta\text{H}}$	(1) 37.21 (2) 2.92 (3) 2.92 $1/3 \sum a_i$ 14.35	49.90 13.51 13.51 25.64	52.28 11.10 13.64 25.67
$a_{\alpha\text{H}}$			-18.58
$a_{\text{F}}$	93.69	49.89	61.95
$a_{\alpha\text{C}}$	142.50	36.86	44.56
$a_{\beta\text{C}}$	0.89	-11.80	-11.22
Total energy (au)	-68.7374	-68.7258	-43.0303

<sup>a</sup>  $r(\text{C}_\alpha\text{-H}_\alpha) = 1.08$  Å,  $r(\text{C}_\alpha\text{-F}_\alpha) = 1.35$  Å,  $r(\text{C}_\beta\text{-H}_\beta) = 1.08$  Å, C<sub>β</sub> = tetrahedral; others listed below were optimized. Hfs in gauss.

(10) (a) J. A. Pople and D. L. Beveridge, "Approximate Molecular Orbital Theory," McGraw-Hill, New York, N. Y., 1970. (b) An INDO program obtained from QCPE, Indiana University, was converted for CDC 6600 operation.

corresponds to the minimized total energy.<sup>11</sup> Furthermore, the geometries of best fit at C<sub>α</sub> for I and II show the same trend in bending as a result of the introduction of successive  $\alpha$ -fluorine substituents as those obtained experimentally and theoretically for H<sub>2</sub>CF· and HCF<sub>2</sub>·, respectively.<sup>7,12,13</sup>

The extraordinarily small value of the proton hfs in CH<sub>3</sub>CF<sub>2</sub> ( $a_{\text{H}} = 13.99$  G) is striking for an  $\alpha$ -methyl group, in comparison with those of other alkyl radicals (23–26 G). Two factors may be considered for this unusual observation, *viz.*, (a) the bond polarization by an  $\alpha$ -fluorine substituent, and (b) the configuration of CH<sub>3</sub> relative to the half-empty orbital at C<sub>α</sub>. It is unlikely that bond polarization plays an important role since the INDO results in Table III indicate that the CH<sub>3</sub> hfs increases substantially from 14 to 25.6 G simply by constraining the radical site in CH<sub>3</sub>CF<sub>2</sub> to be planar. Furthermore, a single  $\alpha$ -fluorine is insufficient to cause the effects observed in II, since the esr spectrum of CH<sub>3</sub>CHF shows no selective line-width effect and the value of the CH<sub>3</sub> hfs (24.48 G) is similar to that in the ethyl radical (26.99 G). The excellent agreement between the experimental results and the INDO calculations suggests that the reduction in the value of the CH<sub>3</sub> hfs in CH<sub>3</sub>CF<sub>2</sub> is mainly due to the change in the configuration of the CH<sub>3</sub> group relative to the half-filled orbital at the pyramidal radical center. The change in the  $\alpha$ -proton hfs from -21.1 G in H<sub>2</sub>CF· to +22.2 G in HCF<sub>2</sub>· is another example of the effect of the configuration at the radical site on a proton hyperfine splitting.<sup>7,14</sup>

**Selective Line-Width Variations.** The stable conformations of CH<sub>3</sub>CHF and CH<sub>3</sub>CF<sub>2</sub>, thus, are the ones in which the  $\alpha$  fluorine and  $\beta$  hydrogens are staggered (see Table III).<sup>16</sup> Based on these stable conformations, three types of selective line-width variations are to be expected in the esr spectra.

I. Selective line broadening in the spectrum of II may be attributed to hindered internal rotation about the C<sub>α</sub>-C<sub>β</sub> bond which leads to exchange among the three equivalent conformations described in eq 1.

(11) Recent INDO calculations for CF<sub>3</sub>CH<sub>2</sub>· and CF<sub>3</sub>CHF· have provided good quantitative results for  $\alpha$ -H and  $\alpha$ -F hfs, but  $\beta$ -F hfs are poor [CF<sub>3</sub>CH<sub>2</sub>·,  $a_{\beta\text{F}} = 11.4$  (obsd), 67.9 G (calcd);<sup>8</sup> CF<sub>3</sub>CHF·,  $a_{\beta\text{F}} = 25.3$  (obsd), 93.2 G (calcd)].

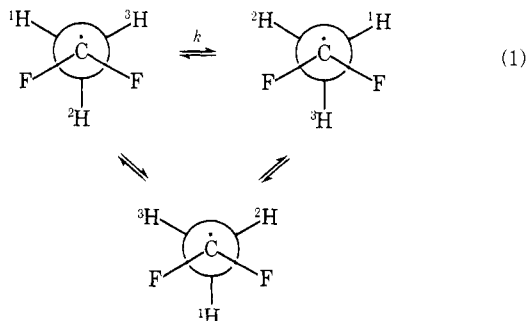
(12) K. Morokuma, L. Pederson, and M. Karplus, *J. Chem. Phys.*, **48**, 4801 (1968).

(13) D. L. Beveridge, P. A. Dobosh, and J. A. Pople, *J. Chem. Phys.*, **48**, 4802 (1968).

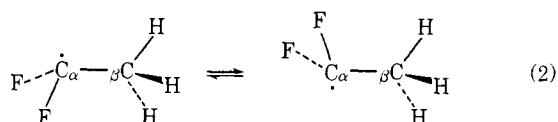
(14) Pauling<sup>15</sup> has employed a simple quantum-mechanical argument to show that electronegativity difference between bonded atoms is the major factor in determining the configuration of these radicals.

(15) L. Pauling, *J. Chem. Phys.*, **51**, 2767 (1969).

(16) On the other hand, acetaldehyde and  $\alpha$ -fluoroethyl cation preferentially exist in conformations in which the oxygen and fluorine are eclipsed by one of the methyl protons (see Table I).



II. Configurational inversion at the radical center as shown in eq 2 will lead to in-phase modulation of the  $\alpha$ -



fluorine hfs. However, it should not produce the severe broadening of the low field portion of the second-order splitting of the lines due to  $M_I^\alpha = 0$  as seen in Figure 2. Furthermore, the LCAO-MO-SCF calculations by Morokuma, Pederson, and Karplus<sup>12</sup> predict a barrier height of 27 kcal mol<sup>-1</sup> for the inversion of  $\dot{\text{C}}\text{F}_3$ . Although this value may be high, the correlation times for inversion at  $\text{C}_\alpha$  are too long to affect the esr line shapes.

III. Dipolar line broadening due to the modulation of the anisotropic  $\alpha$ -fluorine hyperfine tensors by rotational Brownian motion has been described for  $\text{C}_6\text{H}_5\dot{\text{C}}\text{F}_2$ ,  $\text{H}\dot{\text{C}}\text{F}_2$ ,  $\dot{\text{C}}\text{F}_3$ , and  $\text{CF}_3\dot{\text{C}}\text{F}_2$ .<sup>9,17</sup> The theory for describing this type of broadening is well understood.<sup>18-20</sup> For the present system, we have obtained

$$T_{2d}^{-1} = \frac{1}{60} (T:T) \{ [3K(K+1) + 5K_z^2] J_0 + [7K(K+1) - K_z^2] J_1 \} \quad (3)$$

$$J_0 = \tau_2$$

$$J_1 = \tau_2 / (1 + \omega_0^2 \tau_2^2)$$

where  $(T:T)$  is the inner product of the anisotropic tensor,  $K$  and  $K_z$  are the nuclear quantum numbers for defining the hyperfine components,<sup>21</sup>  $\omega_0$  is the resonance frequency of a given hyperfine component ( $K, K_z$ ), and  $\tau_2$  is the correlation time for the molecular motion. Although the anisotropic fluorine hyperfine tensor is not available for  $\text{CH}_3\dot{\text{C}}\text{F}_2$ , it is known for related radicals such as  $\dot{\text{C}}\text{F}_2\text{CO}_2^-$ ,  $\dot{\text{C}}\text{F}_2\text{CONH}_2$ , and  $\dot{\text{C}}\text{F}_3$ .<sup>22</sup> Consideration of the available data on  $\alpha$ -fluorine hyperfine tensors suggests that no serious errors are introduced by assuming axial symmetry, and we take the principal component of the tensor to be 125 G.

**Line-Shape Analysis for the ESR Spectrum of  $\text{CH}_3\dot{\text{C}}\text{F}_2$ .** Hindered internal rotation about the  $\text{C}_\alpha\text{-C}_\beta$  bond in  $\text{CH}_3\dot{\text{C}}\text{F}_2$  can be attributed to exchange among three

equivalent conformations described in eq 1. The esr line shapes for such an exchanging system represented schematically in eq 1 can be calculated from the imaginary part of the total magnetization,  $G$ , using the modified Bloch equation<sup>23</sup>



inary part of the total magnetization,  $G$ , using the modified Bloch equation<sup>23</sup>

$$G = \frac{-1}{3k} i\gamma H_1 M_0 \times \frac{k[(\alpha_1 + 3k)^{-1} + (\alpha_2 + 3k)^{-1} + (\alpha_3 + 3k)^{-1}]}{1 - k[(\alpha_1 + 3k)^{-1} + (\alpha_2 + 3k)^{-1} + (\alpha_3 + 3k)^{-1}]} \quad (4)$$

where  $\alpha_j = T_{2j}^{-1} + i(\omega - \omega_j)$ ,  $T_{2j}^{-1} = (\sqrt{3}/2)0.470\text{G}$ , and the notations have their usual significance.<sup>24</sup>

The simulated spectra shown in Figure 2 were calculated as a function of the rate constant  $k$  in eq 4, combining the contribution from the dipolar broadening due to  $\alpha$ -fluorine anisotropy in eq 3. The two sets of the proton hfs at the slow limit were obtained from the INDO calculations in Table III,<sup>25</sup> since we were experimentally unable to obtain them from the spectrum at the slow exchange limit.

The excellent fit of the line shapes between the experimental and calculated spectra at various temperatures in Figure 2 confirms our choice of the process described in eq 1 together with the dipolar broadening due to the  $\alpha$ -F anisotropy. It also excludes inversion at the radical site as an important contribution.<sup>26</sup> A value of  $2.2 \pm 0.5$  kcal/mol was obtained for the rotation barrier in  $\text{CH}_3\dot{\text{C}}\text{F}_2$  from an Arrhenius plot of the temperature dependence of  $k$  as shown in Figure 3. Interestingly, the correlation times  $\tau_2$  which fit the spectra best are typical of those found for small molecules in liquids from the measurement of nuclear relaxation times or the Fourier inversion of vibrational band contours.<sup>9,27</sup>

**Effect of Halogen on the Barriers to Hindered Internal Rotation.** The rather higher barrier in  $\text{CH}_3\dot{\text{C}}\text{F}_2$  is in contrast to essentially free rotation of the methyl groups in alkyl radicals such as ethyl, isopropyl, and *tert*-butyl radicals, which have sixfold barriers due to planarity at  $\text{C}_\alpha$ .<sup>3,28</sup> Therefore, the esr spectra of a series of trifluoromethyl-substituted radicals were also examined as a comparison to  $\text{CH}_3\dot{\text{C}}\text{HF}$  and  $\text{CH}_3\dot{\text{C}}\text{F}_2$ . The esr parameters are listed in Table IV, together with their mode of generation and the selective line-broadening behavior of the esr spectra at various temperatures. The perfluoroalkyl radicals,  $\text{CF}_3\dot{\text{C}}\text{F}_2$ ,  $\text{CF}_3\text{-CFCF}_3$ , and  $(\text{CF}_3)_3\dot{\text{C}}$ , previously reported<sup>8,9</sup> are also included in Table IV.

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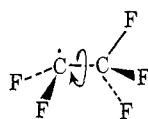
Table IV. ESR Parameters of Trifluoromethyl-Substituted Radicals in Solution

Radical	Temp, °C	Gen. <sup>a</sup>	$\langle g \rangle$	Hyperfine splitting, G			Line broad. <sup>b</sup>
				$a_{CF_3}$	$a_{\alpha H}$	$a_{\alpha X}$	
CF <sub>3</sub> CH <sub>2</sub> ·	-113	S	2.00234	29.61	23.77		None <sup>c</sup>
CF <sub>3</sub> ĊFH	-106	P	2.00363	25.25	21.47	66.18	None <sup>c</sup>
CF <sub>3</sub> ĊF <sub>2</sub>	-84	P <sup>d</sup>	2.00386	11.36		87.26	e, f
CF <sub>3</sub> CHCF <sub>3</sub>	-113	P	2.00221	22.64	24.61		None <sup>c</sup>
CF <sub>3</sub> ĊCF <sub>3</sub>	-60	I	2.0033	19.2		67.4	f
CF <sub>3</sub> C(CF <sub>3</sub> ) <sub>2</sub>	-60	I	2.0015	17.9			f

<sup>a</sup> Method of generation. P = photolysis of *tert*-butyl peresters, S = halogen abstraction by R<sub>3</sub>Si·, I = photolysis of R<sub>2</sub>I with peroxide.

<sup>b</sup> Selective line broadening observed between -20 to -140°. <sup>c</sup> None = not measurable. <sup>d</sup> Also studied by S in ref 9 and I in ref 8. <sup>e</sup> See ref 9. <sup>f</sup> Reference 8.

Among this series of radicals only the spectrum of CF<sub>3</sub>ĊF<sub>2</sub> shows a pronounced selective line broadening. An elegant esr line-shape analysis by Meakin and Krusic<sup>9</sup> using the Redfield relaxation matrix theory gave an activation energy of 2.85 kcal mol<sup>-1</sup> for hindered internal rotation about the C<sub>α</sub>-C<sub>β</sub> bond in this radical. The similarity between the C<sub>α</sub>-C<sub>β</sub> rotation



barriers in CH<sub>3</sub>ĊF<sub>2</sub> and CF<sub>3</sub>ĊF<sub>2</sub> is striking, and points to the pyramidal configuration at C<sub>α</sub> as the single common factor. Furthermore, comparisons in Table IV indicate that β,β,β-trifluoro substitution by itself contributes minimally to the barrier to hindered internal rotation in these radicals. Similar conclusions can be drawn for barriers to hindered rotations in fluorine-substituted ethanes listed in Table I, and the fluorine effects have been discussed qualitatively by Dale.<sup>1b</sup>

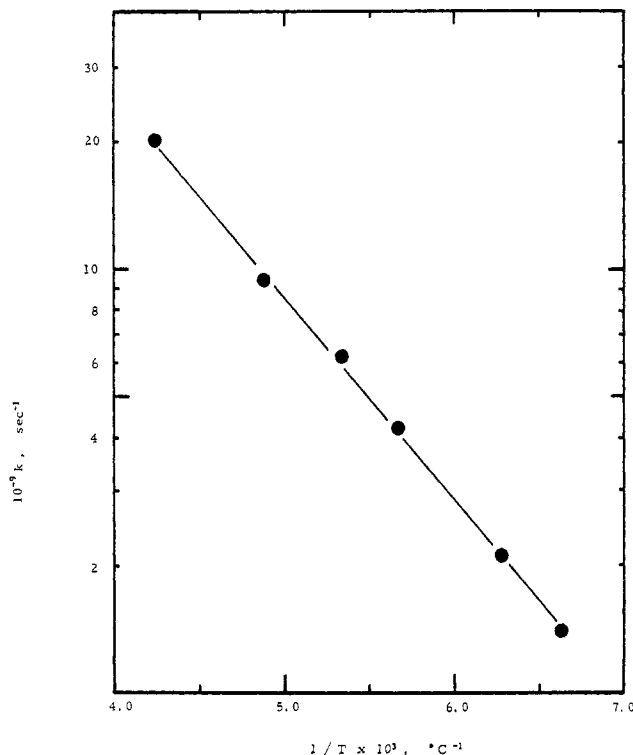
The esr spectra of the α,α-dichloro-substituted analogs CH<sub>3</sub>ĊCl<sub>2</sub> and CF<sub>3</sub>ĊCl<sub>2</sub> were also examined, and the esr parameters are presented in Table V in comparison to the fluorine and alkyl analogs.

Table V. ESR Parameters for α-Chloroalkyl Radicals in Solution. Comparison with Fluorine and Alkyl Analogs

Radical	Temp, °C	$\langle g \rangle$	Hyperfine splittings, G		Line broad.
			$a_{CX_3}$	$a_{\alpha}$	
CH <sub>3</sub> ĊCl <sub>2</sub> <sup>a</sup>	-108	2.00727	19.70	4.34 <sup>d</sup> 3.61 <sup>e</sup>	None
CH <sub>3</sub> ĊF <sub>2</sub>	-78	2.00361	13.99	94.01	Severe <sup>b</sup>
CH <sub>3</sub> ĊH <sub>2</sub>	-113	2.00260	26.99	22.37	None
CF <sub>3</sub> ĊCl <sub>2</sub> <sup>a</sup>	-81	2.00797	18.56	4.14 <sup>d</sup> 3.45 <sup>e</sup>	None
CF <sub>3</sub> ĊF <sub>2</sub>	-84	2.00386	11.36	87.26	Severe <sup>c</sup>
CF <sub>3</sub> ĊH <sub>2</sub>	-113	2.00234	29.61	23.77	None

<sup>a</sup> Generated from the corresponding α,α,α-trichloroethane and R<sub>3</sub>Si· in Freon 12. <sup>b</sup> See text. <sup>c</sup> See ref 9. <sup>d</sup> <sup>35</sup>Cl. <sup>e</sup> <sup>37</sup>Cl.

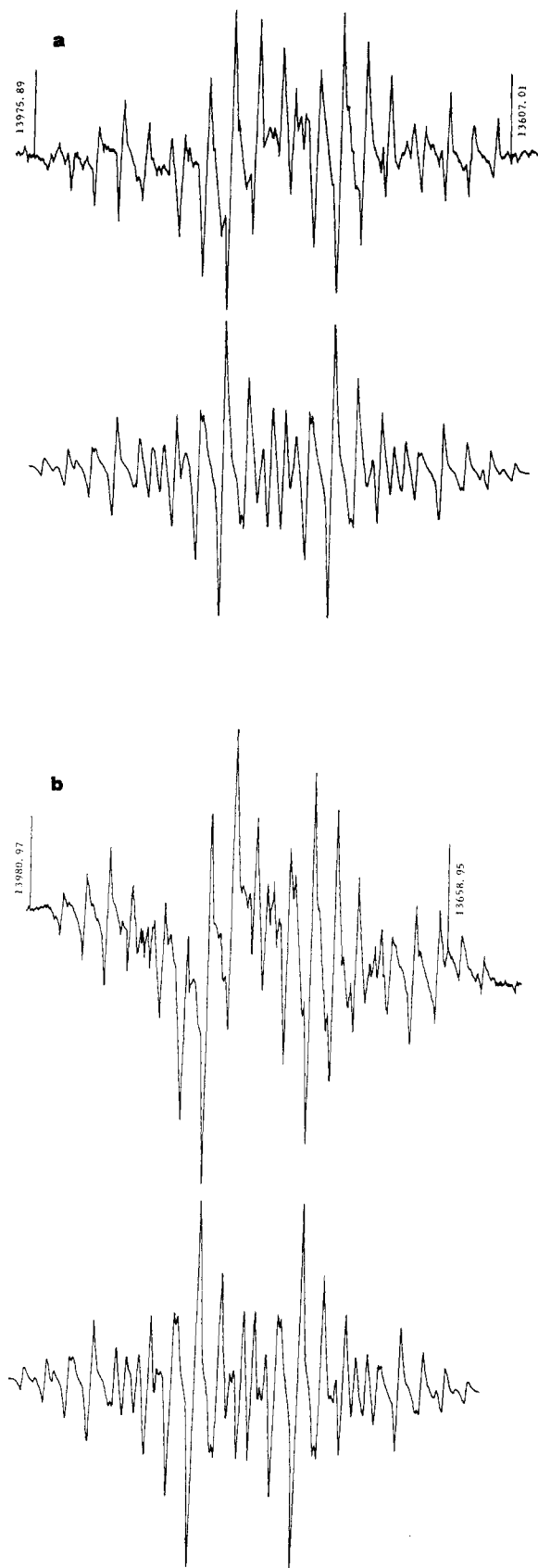
Chlorine substitution at the radical site does not affect the line broadening behavior in the same way fluorine does. The esr spectra of CH<sub>3</sub>ĊCl<sub>2</sub> and CF<sub>3</sub>ĊCl<sub>2</sub> shown in Figure 4 coincide with the simulated spectra using theoretical line intensities with no selective broadening, even to temperatures as low as -140°. The difference in bond angles in ClĊCl<sub>2</sub> and FĊF<sub>2</sub> is about 6° using Pauling's electronegativity arguments.<sup>15</sup> If we assume that ∠FC<sub>α</sub>F in CH<sub>3</sub>ĊF<sub>2</sub> is 106°, the cor-

Figure 3. Temperature dependence of the rate constant *k* for exchange in the α,α-difluoroethyl radical in eq 1.

responding ∠ClC<sub>α</sub>Cl in CH<sub>3</sub>ĊCl<sub>2</sub> would be approximately 112° by simple interpolation, and perhaps even larger due to steric repulsions of chlorine atoms. The larger bond angles in α,α-dichloroalkyl radicals are in accord with the absence of selective line broadening in the spectra of CH<sub>3</sub>ĊCl<sub>2</sub> and CF<sub>3</sub>ĊCl<sub>2</sub>, and suggest that C<sub>α</sub> in these radicals are more nearly planar than their fluorine analogs.

## Conclusions

The uniquely high barrier to hindered internal rotation of the methyl group in CH<sub>3</sub>ĊF<sub>2</sub> is attributed to the pyramidal configuration at the radical site. As a result, the hyperfine splittings of the methyl protons in this radical are also unusually small. A single α fluorine has only a minor effect as does α substitution by two chlorine atoms. Trifluoromethyl substitution at the radical site as well as increased steric bulk by *tert*-butyl groups do not materially affect barriers to hindered rotation about the C<sub>α</sub>-C<sub>β</sub> bond. The barrier of 2.2 kcal mol<sup>-1</sup> for CH<sub>3</sub>ĊF<sub>2</sub> is, thus, indicative of a



**Figure 4.** Experimental and calculated esr spectra of (a)  $\text{CH}_3\dot{\text{C}}\text{Cl}_2$  at  $-81^\circ$  and (b)  $\text{CF}_3\dot{\text{C}}\text{Cl}_2$  at  $-108^\circ$  in cyclopropane solutions. Simulated spectra included hyperfine splittings by  $^{35}\text{Cl}$  and  $^{37}\text{Cl}$  in natural abundance.

threefold rotation symmetry as a result of a pyramidal configuration at the radical site.

## Experimental Section

**Materials.** Di-*tert*-butyl peroxide was obtained from Shell Chemical Co., washed with water, dried, passed through an alumina column, and redistilled at reduced pressure prior to use. Triethylsilane was obtained from Columbia Chemicals Co., refluxed over molecular sieve, and redistilled prior to use. Bistrifluoromethyl peroxide was obtained from PCR, Inc. Bromoethane, 2-bromopropane, 2-bromo-2-methylpropane and 1,1,1-trichloroethane (obtained from Matheson Coleman and Bell), 1,1,1-trifluoro-2-bromoethane (obtained from Pierce Chemical Co.), and 1,1,1-trichlorotrifluoroethane (obtained from PCR, Inc.) were all washed with water, dried, and redistilled prior to use. *tert*-Butyl peresters of propionic acid, isobutyric acid, and  $\alpha,\alpha$ -dimethylbutyric acid were prepared *via* the acid chlorides.<sup>29</sup> Di-*tert*-butylmethylcarbonyl chloride was kindly donated by Dr. V. J. Shiner, Jr. 1,1-Difluoroethane (Genetron 152A) and 1,1-difluoro-1-chloroethane (Genetron 142B) were obtained from Matheson. Perfluoropropionyl chloride was obtained from Pierce Chemical Co.

*tert*-Butyl hexafluoroisobutyryl perester was prepared *via* the acid chloride<sup>29</sup> [nmr  $\delta$  1.31 (s) and 4.03 (septet)]. *tert*-Butyl  $\beta,\beta$ -trifluoro- $\alpha$ -fluoropropionyl perester was prepared *via* the anhydride<sup>29</sup> [nmr  $\delta$  1.31 (s) and 5.17 (d  $\times$  q)]. *tert*-Butyl perfluoropropionyl perester was prepared *via* the acid chloride<sup>29</sup> [nmr  $\delta$  1.31 (s)].

***tert*-Butyl  $\alpha$ -Fluoropropionyl Perester.** Preparation of  $\alpha$ -Mesyloxyethyl Lactate [ $\text{CH}_3\text{CH}(\text{OSO}_2\text{CH}_3)\text{COOC}_2\text{H}_5$ ].  $\alpha$ -Mesyloxyethyl lactate was prepared by the method of Crossland and Servis,<sup>30</sup> yield 95% [nmr  $\delta$  1.32 (t), 1.58 (d), 3.07 (s), 4.25 (q), and 5.04 (q)].

**Preparation of Ethyl  $\alpha$ -Fluoropropionate [ $\text{CH}_3\text{CHF}\text{COOC}_2\text{H}_5$ ].**  $\alpha$ -Mesyloxyethyl lactate (20 g, 0.1 M) and 12 g (0.2 M) of anhydrous potassium fluoride in 65 ml of hexamethylphosphoric triamide were heated and stirred at  $100^\circ$  over a period of 24 hr. The reaction mixture was cooled, diluted with cold water, and extracted with anhydrous ether. The extracts were washed with water, dried over anhydrous magnesium sulfate, and distilled, bp  $51^\circ$  (93 mm), yield 50% [nmr  $\delta$  1.30 (t), 1.50 (d  $\times$  d), 4.20 (q), and 4.87 (d  $\times$  q)].

**Preparation of  $\alpha$ -Fluoropropionic Acid [ $\text{CH}_3\text{CHF}\text{COOH}$ ].** Ethyl  $\alpha$ -fluoropropionate (15 g, 0.125 M) and 100 ml of 10% potassium hydroxide aqueous solution were stirred at room temperature over a period of 3 hr. The reaction mixture was extracted with ether, dried, and distilled, bp  $84\text{--}85^\circ$  (54 mm), yield 70% [nmr  $\delta$  1.62 (d  $\times$  d) and 5.06 (d  $\times$  q)].

***tert*-Butyl  $\alpha$ -fluoropropionic perester** was prepared *via* the acid chloride:<sup>29</sup> nmr  $\delta$  1.31 (s), 1.63 (d  $\times$  d), and 5.14 (d  $\times$  q).

**2-Fluoropropane** was prepared by the method of Edgell and Parts<sup>31</sup> *via* the mesylate: nmr  $\delta$  1.32 (d  $\times$  d) and 4.86 (d  $\times$  septet).

**Esr Measurements.** The modified Varian X-band spectrometer, microwave frequency measurements, light source, and sample tube are as described previously.<sup>3d,6b</sup>

To minimize the error in the  $g$  value determinations, all measurements were made on spectra recorded on the same day for increasing magnetic field. Perylene cation radical  $g = 2.00258$ <sup>32</sup> was used as standard in the configuration employed. The accuracy of the measurements is estimated as  $\pm 0.00003$ . Hyperfine splittings were corrected for second-order shifts and confirmed by computer simulation.

For photolytic reduction of alkyl halides,<sup>33</sup> equal volumes of di-*tert*-butyl peroxide and triethylsilane were diluted with sufficient cyclopropane (and ethane) to give a final ratio of approximately 1:1:1:4 (v/v).

For the photolysis of acyl peresters,<sup>34</sup> a small amount of the peroxide (ca. 100 mg) was dissolved in a relatively large volume (15:1) of cyclopropane or cyclopropane-ethane mixtures.

For the photolytic abstraction of hydrogen atom from the fluoro-hydrocarbons,<sup>35</sup> a solution with a half a volume of di-*tert*-butyl peroxide or bistrifluoromethyl peroxide was diluted with cyclo-

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propane or Freon-12 ( $\text{CF}_2\text{Cl}_2$ ) to give a final ratio of approximately 1:0.5:4. For the generation of 1,1-difluoroethyl radical from 1,1-difluoroethane, bistrifluoromethyl peroxide was used, since di-*tert*-butyl peroxide under the same conditions did not afford sufficiently high concentrations of radicals for esr measurements. For the generation of 2-fluoropropyl radical from the photolytic abstraction of hydrogen from 2-fluoropropane, spectra of radicals

with good signal to noise ratios could only be observed at temperatures higher than  $-80^\circ$ .

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## Study of the Conformation in the Excited State of Two Tryptophanyl Diketopiperazines<sup>1</sup>

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*Contribution from the Centre de Biophysique Moléculaire, Orleans Cedex, France. Received September 18, 1973*

**Abstract:** In this work, we studied two aromatic diketopiperazines in solution, by the method of "time resolved spectroscopy." It can be shown that, in DMSO, the folded form of both *cyclo*(glycyl-tryptophyl) and *cyclo*(alanyl-tryptophyl) is much less stable in the excited state than in the ground state. We are able to determine the rate parameters and the equilibrium constant characteristic of these excited-state interactions. The height of the potential barrier which restrains the exchange between the two conformers is about 6 kcal/mol. In addition to this, it is shown that the folded form of *cyclo*(glycyl-tryptophyl) is much more stable in aqueous solution than in DMSO. The nature of the forces responsible for this behavior is discussed.

The diketopiperazines are single rigid molecules, with restricted rotational freedom, which offer a model system for the study of the structure of natural peptides and proteins.

It has been shown by nmr<sup>2</sup> spectroscopy<sup>3,4</sup> that the preferential conformation in solution of the diketopiperazines containing an aromatic side chain (tyrosyl, phenylalanyl, tryptophanyl residues) is a folded one, in which the aromatic side chain faces the diketopiperazine ring. The two open forms, in which the aromatic side chain lies away from the dipeptide ring, are unfavored at room temperature. Studies in water, DMSO, and TFA suggest that this behavior is not dependent on the nature of the solvent. However, data are lacking for tryptophanyl cyclopeptide in water.

The existence of an optical activity in the lowest energy absorption band also supports this interaction between the aromatic chromophore and the dipeptide ring.<sup>5a</sup> These authors have found that the ellipticity is the same for the peptide *cyclo*(Gly-Trp), in water and DMSO.

The fluorescence of aromatic diketopiperazines is strongly quenched in water; in contrast, the quantum yields of the cyclodipeptides in DMSO and dioxane are very similar to the quantum yields of AcTrpNH<sub>2</sub> and AcTyrNH<sub>2</sub>.<sup>5b</sup> These findings suggest that the interac-

tions of the diketopiperazine rings are very different when the chromophore is in its ground state and when it is in its excited state. The quenching of fluorescence of phenylalanyl, tyrosyl, and tryptophyl residues by the peptide bond has been studied many times.<sup>6</sup> It is generally attributed to the interaction between the carbonyl and the aromatic ring. It may be interpreted in terms of intramolecular charge transfer from the excited aromatic ring to the carbonyl.<sup>7,8</sup>

In the present work, we study the peptides *cyclo*(Gly-Trp) and *cyclo*(Ala-Trp) in solution, using an aspect of the method of time resolved spectroscopy.<sup>9-11</sup> The fluorescence decay is studied as a function of the emission wavelength; the method allows one to detect the existence of various fluorescent species and to analyze the kinetics of interaction of excited molecules.

### Experimental Section

**Materials.** Acetyltryptophanamide was brought from Sigma Chemical Co. The diketopiperazines were synthesized by a method described elsewhere<sup>3</sup> and were analytically and chromatographically pure. Skatole<sup>12</sup> was sublimated. DMSO was purchased from Merck; it was kept on molecular sieves and used in a dehydrated atmosphere.

Absorption spectra were measured in a Cary Model 14 spectrophotometer. Emission spectra were measured in a quartz cell (1 × 1 cm) with a Jobin Yvon spectrofluorimeter, modified in our

(1) Paper written with the technical assistance of J. C. Auchet.

(2) Abbreviations used are: AcTrpNH<sub>2</sub>, acetyltryptophanamide; AcTyrNH<sub>2</sub>, acetyltyrosinamide; *cyclo*(Gly-Trp), cyclic diketopiperazine of glycine and tryptophan; *cyclo*(Ala-Trp), cyclic diketopiperazine of alanine and tryptophan; DMSO, dimethyl sulfoxide; TFA, trifluoroacetic acid; nmr, nuclear magnetic resonance; CD, circular dichroism.

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