(12) R. W. Taft, D. Gurka, L. Joris, P.v.R. Schleyer, and J. W. Rakshys, *Ibid.*, **91**, 4801 (1969).
(13) (a) W. M. Schubert and R. H. Quacchia, *J. Am. Chem. Soc.*, **84**, 3778 (1962); (b) A. J. Kresge, G. W. Barry, K. R. Charles, and Y. Chiang, *Ibid.*, **84**, 4343 (1962).
(14) Cf., for example, R. H. Boyd, R. W. Taft, A. P. Wolf, and D. R. Christman, *J. Am. Chem. Soc.*, **82**, 4729 (1960).
(15) Cf. F. Westheimer and M. S. Kharasch, *J. Am. Chem. Soc.*, **68**, 1871 (1946).
(16) K. Singer and P. A. Vamplew, *J. Chem. Soc.*, 3971 (1956).
(17) N. C. Deno, H. E. Berkheimer, W. L. Evans, and H. J. Peterson, *J. Am. Chem. Soc.*, **81**, 2344 (1959).

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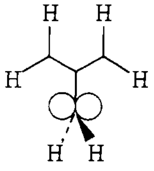
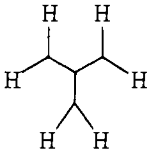
The Lowest Singlet State of Planar Trimethylenemethane

Sir:

Two calculations[1,2] have appeared that predict for singlet trimethylenemethane a large (>1 eV) barrier to the rotation of the nonconjugated methylene group from the orthogonal (**1**) to the planar (**2**) geometry. In contrast, in a recent theoretical study Yarkony and Schaefer[3] found a much smaller (2.8 kcal/mol) barrier to rotation in the lowest singlet, *provided* that the symmetry of the wave function for the planar geometry was allowed to relax from D_{3h} to C_{2v}. The latter result is in much better accord with the experimental observation that racemization competes with rearrangement in chiral methylenecyclopropanes.[4,5] This communication shows that the Yarkony-Schaefer result is, indeed, correct and can be readily understood on the basis of previously published work.[6]



1



2

In fully delocalized D_{3h} trimethylenemethane, it is impossible to find a combination of degenerate molecular orbitals that do not both have amplitude on at least one common atom. In the lowest singlet state, where the two electrons in these orbitals have opposite spin, the Pauli exclusion principle does not prohibit the simultaneous occupancy of an AO common to both MO's. Therefore, the wave function for this state contains ionic terms, corresponding to the simultaneous occupancy of the same AO by the two electrons in the degenerate MO's. These terms are of high energy, because of the large value for the one-center electron repulsion integral. If, however, one methylene group in the molecule is twisted, as in **1**, so that the wave function becomes that for an allyl radical plus an electron essentially localized in a p orbital, then the two nonbonding orbitals have no atoms in common, and the high energy ionic terms, present in the wave function for the fully delocalized singlet, are absent. The resulting decrease in the electron repulsion energy has been calculated to be greater than 2 eV.[6] Although this decrease in two-electron energy is achieved only at the expense of raising the one-electron energy from $2\sqrt{3}\beta$ to $2\sqrt{2}\beta$, the former effect is larger in magnitude than the latter, and it has been used[2,6] to explain the large barrier calculated[1,2] for conversion of orthogonal **1** to fully delocalized singlet trimethylenemethane.

It is crucial to note, however, that it is not the geometry (i.e., the spatial relationship between the orbitals) of **1** that lowers its energy relative to that of the fully delocalized planar singlet, but rather the fact that the nonbonding MO's of **1** have no atoms in common. *Provided* that the wave function in the planar geometry (**2**) is essentially the same as that in the orthogonal one (**1**), namely that of allyl plus an electron localized in a p orbital, the energy of **2** will be approximately the same as that of **1**. Since the wave function for allyl plus p has only C_{2v} symmetry, its utilization in **2** necessitates a reduction in the symmetry demanded of the wave function for **2** from the D_{3h} symmetry of fully delocalized trimethylenemethane. This explains the large drop in energy, calculated by Yarkony and Schaefer,[3] when the symmetry required of the singlet wave function for **2** is relaxed from D_{3h} to C_{2v}. Indeed, comparison of the MO's for singlet **2**, with D_{3h} and C_{2v} symmetry required of the total wave function, reveals the expected change from the MO's of fully delocalized trimethylenemethane to essentially those of allyl plus p.[7,8]

The failure of previous calculations[1,2] to predict correctly the energy required to convert **1** to **2** arises from their failure to arrive at the correct wave function for planar singlet trimethylenemethane. Calculations that employ the half-electron[1] or Nesbet[2] method for dealing with open-shell systems lead to the same set of MO's for singlet as for triplet states. However, in planar trimethylenemethane the proper MO's for the two states are quite different. The triplet does, indeed, utilize the familiar set of trimethylenemethane MO's that gives a fully delocalized D_{3h} wave function,[3] since the two electrons in the nonbonding MO's have the same spin and so are kept from simultaneously appearing in the same AO. Because no such exclusion prohibition exists for these two electrons in the singlet, the fully delocalized D_{3h} wave function contains high energy ionic terms, and the optimum MO's for the planar singlet are essentially those of allyl plus a p orbital.[9] Although the pitfalls in computing wave functions for open-shell atoms with SCF methods that lead to the same orbitals for triplets and singlets have been noted previously,[10] the case of the lowest singlet state of planar trimethylenemethane provides a striking example of the spurious results that can be obtained in calculating wave functions for open-shell molecules.

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References and Notes

(1) M. J. S. Dewar and J. W. Wasson, *J. Am. Chem. Soc.*, **93**, 3081 (1971).
(2) W. J. Hehre, L. Salem, and M. R. Willcott, *J. Am. Chem. Soc.*, **96**, 4328 (1974).
(3) D. R. Yarkony and H. F. Schaefer, *J. Am. Chem. Soc.*, **96**, 3754 (1974).
(4) E. F. Ullman, *J. Am. Chem. Soc.*, **82**, 505 (1960); J. J. Gajewski, *ibid.*, **93**, 4450 (1971); W. von E. Doering and L. Birladeanu, *Tetrahedron*, **29**, 449 (1973); W. von E. Doering, private communication.
(5) Triplet trimethylenemethane does not appear to be involved in the racemization. For instance, W. von E. Doering and S. Buchwalter (private communication) find that oxygen has no effect on the rate, distribution of products, or stereochemical characteristics of the rearrangement of optically active *trans*-2,3-dicyanomethylenecyclopropane.
(6) W. T. Borden and L. Salem, *J. Am. Chem. Soc.*, **95**, 932 (1973).
(7) I wish to thank Mr. Yarkony and Professor Schaefer for providing me with the MO's obtained from their calculation.[3]
(8) A wave function of C_{2v} symmetry will result in a distortion to an optimized geometry that also has C_{2v} symmetry. With a wave function that is essentially that of allyl plus p, the unique carbon–carbon bond will be longer than the other two. In contrast, the wave function for the other component ($^1A_1$ in C_{2v}) *of the* $^1E'$ *state* (D_{3h} symmetry)[3] can be shown to lead to an optimized geometry in which the unique bond will be shorter than the other two. These distortions may, of course, be viewed as a consequence of the theorem of H. A. Jahn and E. Teller, *Proc. Roy. Soc., London, Ser. A*, **161**, 220 (1937).
(9) Although the contribution of these ionic terms can also be reduced through the formalism of configuration interaction (CI), mixing of config-

urations that differ in just the assignment of electrons among the D_{3h} nonbonding orbitals[2] generates only the symmetry-correct D_{3h} wave functions for **2**.[3] Because these ionic terms are absent from the allyl plus p wave function, CI is less important in improving it.

(10) C. C. J. Roothaan and P. S. Bagus, *Methods Comput. Phys.*, **2**, 47 (1963).

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Conformational Studies of Pantetheine and the Pantetheine Moiety of Coenzyme A

Sir:

In recognition of the essential roles of coenzyme A in intermediary metabolism and numerous other biosynthetic pathways, considerable effort has been expended to establish the specificities of enzymes for various portions of the molecular unit.[1] Partially because no crystalline derivative of CoA has been investigated by diffraction techniques, there has been little speculation and no published work relating the conformation of CoA or its analogs to binding and specificity in enzyme systems requiring it as a cofactor. We now report our initial results in the area of conformational analysis, which help to define aspects of the preferred conformation of coenzyme A in aqueous solution based upon coupling constants derived from NMR spectra of CoA (Figure 1) and pantetheine (Figure 2).

Vicinal coupling in isolated, rapidly rotating ethylene units such as those of the β-alanine and cysteamine portions of coenzyme A is characterized by two coupling constants (J and J') commonly defined[2] by

$$J = n_t J_g + \tfrac{1}{2} n_g (J_t + J_g)$$

$$J' = n_t J_t + n_g J_g$$

where n_t and n_g are the mole fractions of the classical staggered rotamers in which the coupled vicinal atoms are trans and gauche, respectively, and where J_g and J_t are characteristic vicinal coupling constants associated with dihedral angles near 60 and 180°. Rotamer populations of isolated ethylene groups for which deceptively simple triplet AA′XX′ patterns are often observed may be obtained by applying the condition $n_t + n_g = 1$ to the previous equations to provide

$$n_t = 2[(J + J') - \tfrac{1}{2}(J_t + 3J_g)]/(J_t - J_g)$$

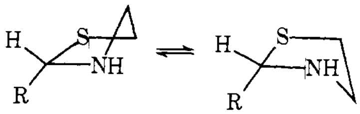
Thus the mole fraction of the trans rotamers of the cysteamine and β-alanine moieties may be obtained from the average coupling constants, $(J + J')/2$, measured for the triplet patterns of CoA and its derivatives at 220 MHz (Table I) provided the two additional coupling constants, J_g and J_t, are available for each moiety.

Table I. Coupling Constants and Mole Fraction of Trans Rotamer in the Cysteamine and β-Alanyl Moieties of CoA and Pantetheine

Compound	Temp, °C	Solvent	β-Alanyl (Hz) J_{av}	n_t	Cysteamine (Hz) J_{av}	n_t
Pantetheine	18	D_2O	6.40	0.34	6.50	0.42
	62	D_2O	6.50	0.42	6.55	0.46
	18	DMSO-d_6	6.9	0.74	*a*	
Coenzyme A	18	D_2O	6.13	0.19	6.72	0.60
	63	D_2O	6.68	0.58	6.62	0.55
	18	DMSO-d_6	6.9	0.74	*a*	

[a] Interference by DMSO resonance.

For the cysteamine moiety the value of J_g = 4.71 Hz was obtained from the spectrum of 1,3-thiazolidine[3] in which by analogy to the 1,3-oxathiolanes[4] only two equally populated pseudo-rotamers Ia and IIa with staggered ethylene units



Ia, R = H
Ib, R = *t*-Bu

IIa

are expected to be populated. The value for J_t = 9.77 Hz was taken from the largest coupling constant of the ABCD spectrum of 2-*tert*-butyl-1,3-thiazolidine for which only a single pseudorotamer Ib is expected to be significantly populated.

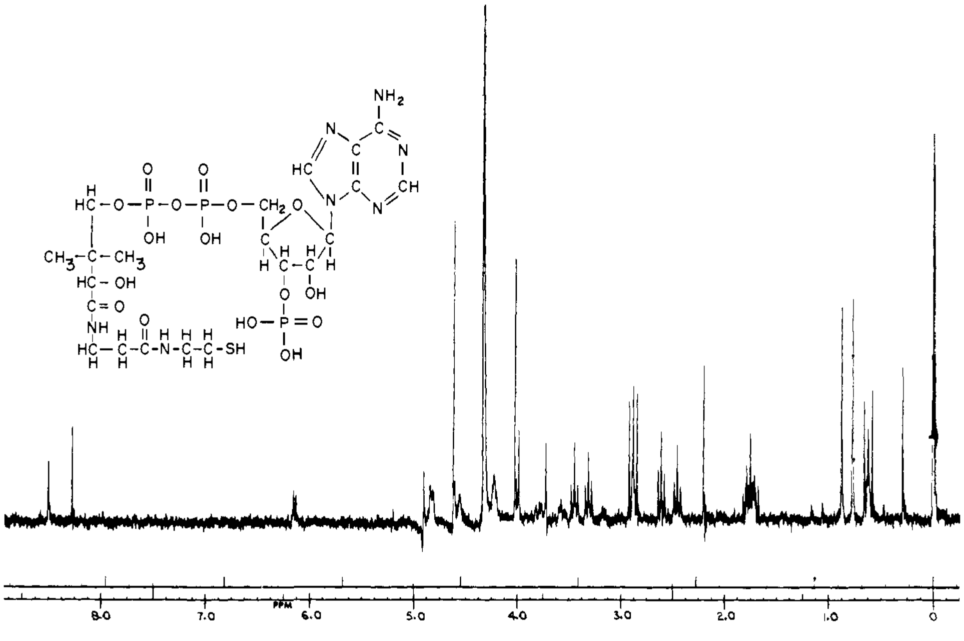


Figure 1. The 220-MHz NMR spectrum of coenzyme A obtained in D_2O at 63°. Methylene resonances of the cysteamine portion of the molecule give rise to deformed triplet resonances at 2.58 (CH_2S) and 3.29 ppm downfield from internal DSS. Deformed triplets occur at 2.43 (CH_2CO) and 3.43 ppm for the β-alanine moiety. The average coupling constants were measured on expanded spectra.