90, 4462, 4464 (1968). The ethers of esters were prepared as in: C. Ainsworth, F. Chem, and Y.-N. Kuo, *J. Organomet. Chem.*, **46**, 59 (1972). The ketene bis(trimethylsilyl)acetal of stearic acid was prepared according to: C. Ainsworth and Y.-N. Kuo, *ibid.*, **46**, 73 (1972).

(6) Prepared according to ref 1a except that for good yields dimethyl(methylene)ammonium trifluoroacetate must be distilled before use in carbanion quenching experiments (bp 130–140 °C (0.05 mm)).

(7) Only recent reviews are listed: R. B. Hammill, C. A. Wilson, and T. A. Bryson, *Synth. Commun.*, **5**, 245 (1975); P. A. Grieco, *Synthesis*, 67 (1975).

(8) S. M. Kupchan, M. Eakin, and A. Thomas, *J. Med. Chem.*, **14**, 1147 (1971); S. M. Kupchan, *Trans. N.Y. Acad. Sci.*, **32**, 85 (1970); K. Lee, E. Haung, C. Piantadosi, J. Pagano, and T. Greissman, *Cancer Res.*, **31**, 1649 (1971); W. Herz, G. Hogenauer, and A. de Vivai, *J. Org. Chem.*, **29**, 1700 (1964); S. M. Kupchan, R. Hemingway, D. Werner, and A. Karim, *ibid.*, **34**, 3903, 3908, (1969).

(9) See ref 7 for discussion of activation.

(10) J. K. Rasmussen and A. Hassner, *J. Org. Chem.*, **39**, 2558 (1974). In our hands the yield was fairly modest (40%), and the products of C-silylation and Claisen condensation were observed. It appears that the O-ether can be prepared in good yield only on a small scale.

(11) The IR, ^{1}H NMR, refractive index, and boiling point were consistent with those reported by C. R. Hutchinson, *J. Org. Chem.*, **39**, 1854 (1974). The melting point of the methyl iodide derivative was 217–218 °C, or somewhat higher than the melting points between 200 and 207 °C reported in the Hutchinson paper.

Norman L. Holy,* Yu Fang Wang

Department of Chemistry, Western Kentucky University
Bowling Green, Kentucky 42101

Received August 24, 1976

An ab Initio Model for the Quenching of Ketone Phosphorescence by Amines

Sir:

The quenching of fluorescence and phosphorescence of ketones by electron donors such as amines has been attributed to a charge transfer interaction.[1] The sensitivity of this reaction to steric effects[2] implies that quenching requires close approach of the amine and ketone. Some have invoked transient, stable excited complexes (exciplexes) as obligate intermediates,[1,3] though formation of exciplexes in the *gas phase* quenching of ketone emission by amines has been questioned.[4] If one assumes that the exciplex can be approximated by the zero-order charge transfer state, one predicts a stable exciplex for triplet acetone and triethylamine, $\Delta G_{ex} \sim -16$ kcal/mol.[5] For triplet formaldehyde and ammonia, however, the exciplex energy is estimated to be 66 kcal/mol higher in energy than the isolated $CH_2=O^{*3}$.

One way of gaining insight into the quenching process is to use ab initio calculations to examine features of the hypersurface of two interacting molecules. Given a suitable model for the interacting species and a modest basis set, fairly large regions of the hypersurface can be searched and interesting geometries can be optimized. This approach is very useful to the organic photochemist who wishes broad insights into the general features of the interaction, but who does not have access to a vast computer budget.

We have investigated the interaction of ammonia and formaldehyde in the lowest singlet (ground) and triplet states using ab initio calculations at the STO-3G level without configuration interaction.[6] This system is the simplest model for the quenching of ketone phosphorescence by amines. We focussed on the "head-on" interaction in which ammonia approached the oxygen of formaldehyde. This seemed a reasonable place to begin our search of the hypersurface, since in this geometry NH_3 can donate electrons into the hole produced upon excitation of CH_2O to its $n\pi^*$ triplet state.[3] It quickly became evident that strong destabilization occurred in the ground state singlet at $r_{(NO)}$ distances more remote than in the corresponding triplet. This pointed to a readily accessible surface crossing[10] which could provide a quenching mechanism. This paper describes a region of the hyperspace where those surfaces cross.
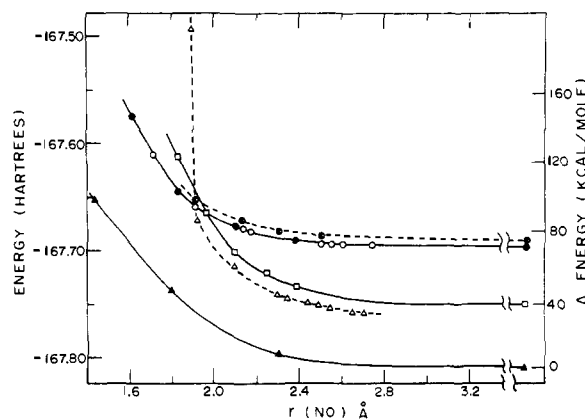

Figure 1. Plot of energy (in hartrees) vs. $r_{(NO)}$ for the approach of NH_3 to the oxygen of CH_2O in the ground state and lowest triplet state as determined by ab initio calculations (STO-3G). Several cross sections are shown. Solid symbols represent fully optimized geometries. The lowermost line represents the ground state in approach II. Other lines describe approach I. See text. The following symbols represent the lowest energy triplet state approach (-O-), its planar (C_S) distortion (- - -⊗- - -), the same geometries in the ground state (—□—), and its planar distortion (- - -△- - -), respectively.

We investigated two approaches of CH_2O and NH_3. The in-plane approach I becomes distorted from C_s symmetry as the two CH bonds are bent out of the plane originally defined by planar formaldehyde. The perpendicular approach II

I   II
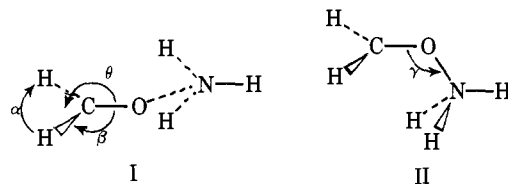
maintains C_s symmetry even when these CH bonds are bent. Geometries of NH_3 and ground state and triplet formaldehyde were fully optimized. In the supermolecules, those CH and NH bond lengths were fixed, as was the $O\hat{N}H$ pyramidal angle. For simplicity we assumed that the $H\hat{C}H$ angle (α) equalled the $H\hat{C}O$ angle (β). This allowed these angles and the pyramidal angle (θ) at carbon to be optimized via a single parameter. Other modes were fully optimized, often iteratively. The algorithm used was to optimize $r_{(CO)}$, the pyramidal angle θ, and then $C\hat{O}N$, for arbitrarily chosen $r_{(NO)}$ values. The closed symbols in Figure 1 represent geometries optimized in this manner. Calculations without configuration interaction give no indication of the correlation energy. Since they do give good relative energies, the triplet manifold was arbitrarily adjusted so that the isolated optimized formaldehyde triplet lay 72 kcal/mol[11] above the optimized ground state.

Figure 1 shows several cross-sections through the hyperspace resulting from the $CH_2O\cdots NH_3$ interaction. The lowermost line, for the perpendicular approach II, represents the lowest energy approach of NH_3 to the oxygen of ground state formaldehyde. It ultimately correlates with $(+)H_3N-O-CH_2(-)$, the proton tautomer of methoxyamine. The uppermost curve describes the best approach of NH_3 to the formaldehyde oxygen in the triplet state. Here the "in-plane" approach I is favored, with the two CH bonds bent out of the plane. The dashed line, somewhat higher in energy than the best approach in the triplet state, represents the corresponding cross-section of the hypersurface when the formaldehyde is kept planar.

At a surface crossing, the states share a common geometry. The energy of the lowest singlet state crosses that of the lowest triplet at $r_{(NO)} = 1.96$ Å when the singlet is constrained to the geometry of the best triplet approach. This crossing lies ap-

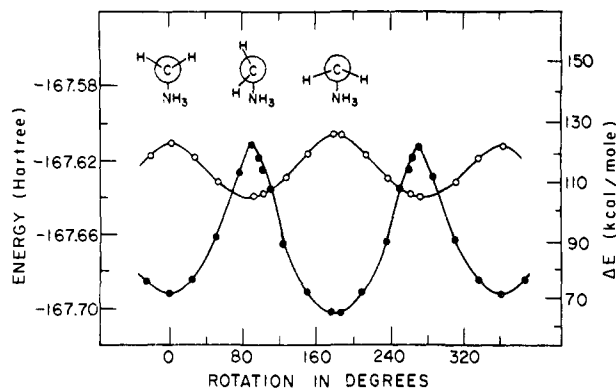Figure 2. A scan of the energy in hartrees for rotation about the C–O bond in the supermolecule H_2C–O–NH_3 for $r_{(NO)}$ chosen to be 1.90 Å. The points (O) refer to the otherwise optimized geometry of the lowest triplet state. The points (●) refer to the corresponding geometry of the lowest singlet "ground" state. The zero of energy on the right ordinate (kcal/mol) is that of (NH_3 + ground state CH_2O) at infinite distance; see Figure 1.

proximately 19 kcal/mol above the separated ammonia and triplet formaldehyde. While this geometry of interaction may not be readily accessible in gas phase collisions between NH_3 and CH_2O* [3] at ambient temperatures, it is worth noting that there is very little charge transfer at the crossing point (0.084 electrons).

The origin of the surface crossing becomes clear when one examines the corresponding potential for rotation about the C–O bond at $r_{(NO)}$ = 1.9 Å. This rotation, shown in Figure 2, connects approaches I and II. While the ground state potential appears "normal" in that the staggered Y and W conformations are more stable than the eclipsed forms, the rotamers represent maxima on the triplet surface. The rotational potential for the triplet is 90° out of phase. Rather surprisingly, the nearly eclipsed rotamer of the triplet is most stable.

When the formaldehyde is forced to be planar, a new surface crossing is found at $r_{(NO)}$ = 1.91 Å. The locus of the second crossing point depends upon the interplay of three factors: (i) a small destabilization energy associated with distorting triplet formaldehyde to be planar, (ii) a large stabilization due to allowing ground state formaldehyde to be planar, and (iii) a decrease in the polarizability of the nonbonding electron pair on O, giving rise to severe repulsive destabilization for $r_{(NO)}$ less than 1.92 Å. The amount of charge transferred from NH_3 to CH_2O at the planar surface crossing is 0.085 electrons. The stereochemistry of the supermolecule at the lower energy surface crossing is shown below.
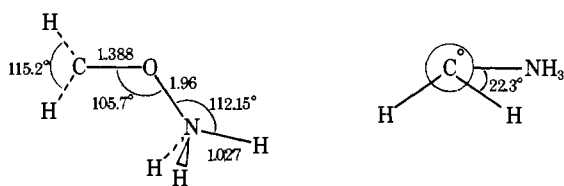
The source of the destabilization in the "in-plane" approach in the ground state is associated with trying to force four electrons (two in each nonbonding orbital on N and O) into the same space. In the perpendicular approach, the interaction is with the more polarizable π-bond. In the interaction with the $n\pi*$ triplet state, only three electrons are forced together in the "in-plane" approach. The repulsive destabilization occurs at much shorter $r_{(NO)}$ distances. When ammonia approaches triplet formaldehyde from the top or bottom, it senses the repulsion not only of the electrons in the π-bond but of the additional electron in $\pi*$.

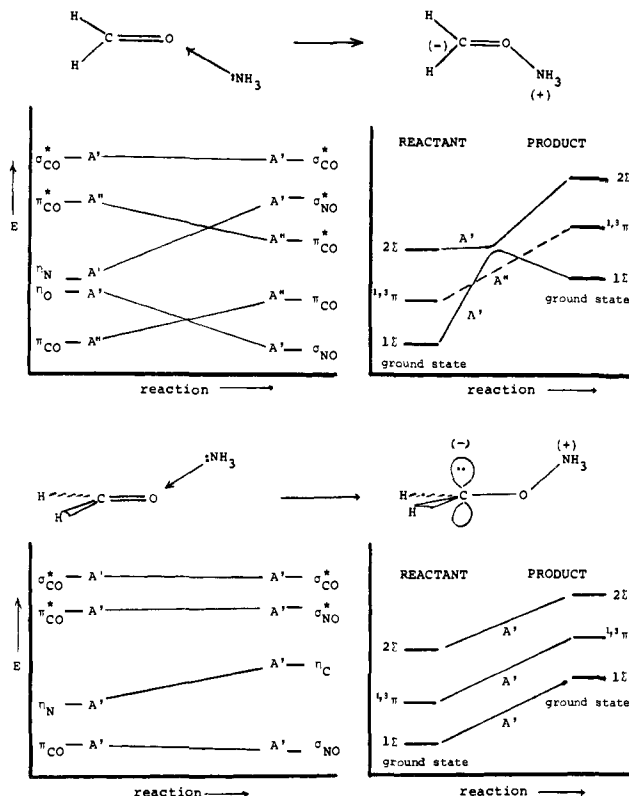The correlation diagrams for the reaction are shown in

Figure 3. Orbital (left) and state (right) correlation diagrams for the reaction of ammonia and formaldehyde to form the proton tautomer of methoxyamine, $(-)CH_2$–O–$NH_3(+)$. The upper diagram examines the reaction in the plane of the formaldehyde. The lower diagram examines the reaction in the plane perpendicular to the plane of the formaldehyde. A' and A" refer to the C_s symmetry group.

Figure 3. These differ for the two geometries of interaction. In the perpendicular approach (II), all the low-lying states are symmetric to the mirror plane. The ground states of H_2C=O and NH_3 correlate with the ground state of $(-)CH_2$–O–$NH_3(+)$. Approach of ammonia within the plane of formaldehyde (I) defines a different plane of symmetry. In this geometry, the ground states of CH_2=O and NH_3 correlate with an upper excited state of $(-)CH_2$–O–$NH_3(+)$. Both formation of the methoxyamine tautomer and its dissociation in the ground state require the reactants to surmount a severe barrier that has its origins in the avoided crossing between two states of A' symmetry. This barrier does not exist for the excited state reaction. Figures 1 and 2 indicate that the barrier in the ground state reaction is "remembered" in approach I, even when the formaldehyde is distorted from planarity.

The results presented above describe in a general way a mechanism whereby ammonia might quench the triplet state of formaldehyde. The importance of the results, however, is that these species serve as models for the interaction of all ketones with lowest $n\pi*$ triplet states with amines. Both the ab initio calculations and the correlation diagrams point to a quenching mechanism which depends in a general way on the symmetries of the interaction states, and only in detail on molecular structure. These latter features are also very important, but they go beyond the scope of the present investigation.

References and Notes

(1) R. O. Loutfy and R. O. Loutfy, Can. J. Chem., 50, 4052 (1972); R. W. Yip, R. O. Loutfy, Y. L. Chow, and L. K. Magdzinsky, ibid., 50, 3426 (1972).
(2) D. A. Hansen, and E. K. C. Lee, J. Chem. Phys., 62, 183 (1975); 63, 3272

(1975); G. L. Loper and E. K. C. Lee, *ibid.*, **63**, 264 (1975); J. Metcalf and E. K. C. Lee, *J. Am. Chem. Soc.*, **94**, 7 (1972); **95**, 1751 (1973).

(3) J. C. Dalton and J. J. Snyder, *J. Am. Chem. Soc.*, **97**, 5192 (1975); N. E. Schore and N. J. Turro, *ibid.*, **97**, 2482 (1975), N. J. Turro, J. C. Dalton, G. Farrington, M. Niemczyk, and D. M. Pond, *ibid.*, **92**, 6978 (1970).

(4) E. A. Abuin, M. V. Encina, E. A. Lissi, and J. C. Scaiano, *J. Chem. Soc., Faraday Trans. 1*, **71**, 1221 (1975); M. V. Encina, H. Soto, and E. A. Lissi, *J. Photochem.*, **3** 467 (1975).

(5) A. Weller and D. Rehm, *Isr. J. Chem.*, **8**, 259 (1970); H. Knibbe, D. Rehm, and A. Weller, *Z. Phys. Chem. (Frankfurt am Main)*, **56**, 95 (1967); H. Beens, H. Knibbe, and A. Weller, *J. Chem. Phys.*, **47**, 1183 (1967).

(6) Calculations were carried out using the GAUSSIAN 70 program.[7] For the ground state (S_0) the computations were carried out within the framework of Roothaan's Restricted Hartree-Fock formalism.[8] For the triplet state, computations were carried out within the framework of the Pople-Nesbet Unrestricted Hartree-Fock method.[9]

(7) W. J. Hehre, W. A. Latham, R. Ditchfield, M. D. Newton, and J. A. Pople, *Quantum Chemistry Program Exchange*, University of Indiana, Bloomington, Indiana.

(8) C. C. J. Roothan, *Rev. Mod. Phys.*, **23**, 69 (1951).

(9) J. A. Pople and R. K. Nesbet, *J. Chem. Phys.*, **22**, 571 (1954).

(10) L. Salem, *J. Am. Chem. Soc.*, **96**, 3486 (1974).

(11) G. W. Robinson and V. E. DiGiorgio, *Can. J. Chem.*, **36**, 31 (1958).

(12) Our investigation of the best triplet approach failed to show a minimum in the region of space associated with N-O bond distances 1.6-2.4 Å. Failure to find a minimum may be due to (a) our restricted basis set without configuration interaction, (b) an exciplex geometry far removed from our path of best approach, or (c) the absence of a stable exciplex formed between ammonia and triplet formaldehyde.

(13) We have learned that Morokuma and his co-workers have independently carried out similar calculations and have reached conclusions entirely consistent with what we report here. K. Morokuma, G. H. Neems and S. Yamabe, submitted for publication.

Utam Maharaj, Imre G. Czizmadia, Mitchell A. Winnik*

Lash Miller Laboratories, Department of Chemistry and Erindale College, University of Toronto Toronto, Ontario, Canada M5S 1A1

A Convergent Route to α-Substituted Acrylic Esters and Application to the Total Synthesis of (±)-Frullanolide[1]
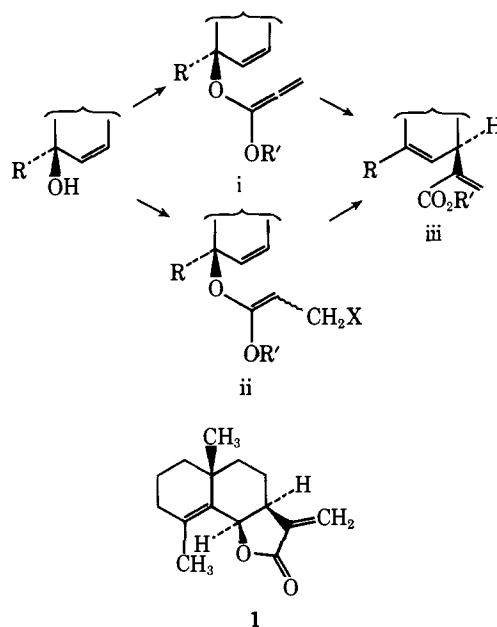
Sir:

Esters of α-substituted acrylic acids are important substructures in a variety of cytotoxic and antineoplastic compounds.[2] As part of a project directed toward the synthesis of terpenoid antitumor agents, we have been examining new methods for the regio- and stereospecific introduction of intact or masked acrylic acid residues into suitable organic substrates. One particularly useful approach to this problem is a methylenic variant of the Claisen rearrangement (i → iii) or a formal equivalent thereof (e.g., ii → iii).[3] In this communication, we describe the first examples of this valuable new strategy for the synthesis of α-substituted acrylic esters, and application of the new method to the first total synthesis of the allergenic sesquiterpene frullanolide, 1.[4]

The approach we have been exploring is summarized by ii → iii. The feasibility of this methylenic Claisen rearrangement equivalent depends largely on the choice of the substituent X in ii. The required substituent would be one which would not be eliminated by an ester enolate or ketene acetal under the conditions of the Claisen rearrangement and yet subsequently could be eliminated under mild conditions to yield the sensitive acrylic ester iii.

We have examined a number of systems related to ii and have found that a particularly convenient pathway exists between an allylic alcohol and a rearranged acrylic ester like iii when X = NR_2. The sequence is outlined in Scheme I for several 2-cyclohexenol derivatives.

The intermediate β-pyrrolidinopropionates **3a–c** (IR (neat) 1725, 1640 cm⁻¹) are readily prepared from the corresponding allylic alcohols by a simple one-flask procedure. An allylic alcohol is first treated with acryloyl chloride and ethyldiisopropylamine in methylene chloride (0 °C) and then excess

pyrrolidine is added to yield the Mannich base (e.g., **3**) directly. Primary, secondary, and relatively unhindered tertiary alcohols are rapidly esterified under these conditions and yields of distilled, analytically pure β-pyrrolidinopropionates are routinely in excess of 90%.

We have found that allylic esters such as **3a–c** are readily rearranged without elimination of pyrrolidine by a modified ester enolate Claisen procedure.[3b] First, the ester is converted to the corresponding silylketene acetal by treatment with lithium diisopropylamide and triethylchlorosilane[5] at −45 °C under argon. Next, Claisen rearrangement is effected by refluxing in THF or, in the case of relatively stable intermediates like that derived from **3a**, by refluxing in toluene. Finally, conversion to the olefinic acrylate **4** is completed by removing the solvents in vacuo, refilling the reaction vessel with argon, and then stirring the residue with a mixture of dimethyl sulfate,[6] methanol, and potassium carbonate. Although a number of steps are involved in the transformation of **3** into **4**, the entire operation may be conducted in a single flask. Thus acrylates **4a–c** may be prepared by what is effectively a two-step procedure from the corresponding allylic alcohols in 65–75% overall yield. The products were identified[7] by their characteristic infrared (1720, 1620 cm⁻¹) and NMR spectra (=CH_2 δ 6.2, 5.5; =CCHC= δ 3.3) or, in the instance of **4a**, by

Scheme I

a, R = H
b, R = CH_3
c, R = $CH_2CH_2CH_2CH_3$