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EVIDENCE FOR DIAZENYL ALLYL DIRADICALS IN THE THERMOLYSIS OF 4-ALKYLIDENE-1-PYRAZOLINES

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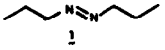
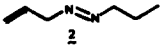
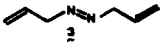
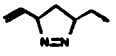
Abstract—Secondary deuterium kinetic isotope effects indicate that the C–N bond *anti* to the Me group on 4-ethylidene-1-pyrazoline breaks preferentially to the *syn* bond. It is suggested that the product determining step involves an intramolecular radical displacement of nitrogen, as well as an electrocyclic rotation of the allylic methylene groups of the diazenyl allyl diradical, to generate the cyclopropane ring concerted with the loss of nitrogen. The position of deuterium in the methylmethylenecyclopropane can best be rationalized by this latter step.

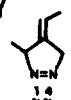
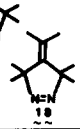
Engel[1] has recently written an excellent review covering the mechanisms of thermolysis and photolysis of cyclic and acyclic azo compounds. Placing a double bond into an alkyl group in such a manner as to render the C–N bond allylic causes a decrease in activation energy of approximately 10 kcal mole^{-1}. As can be seen from the data collected in Table 1 this is distinctly the case in only the first instance[2-4] in the acyclic azoalkanes (compounds **1–3**) but the cyclic systems[5] seem more sensitive to the possible concerted rupture of both C–N bonds as compounds **4–6** demonstrate.[6] Compound **8** places the unsaturation into the structure in a manner such as to make both C–N bonds allylic, and a symmetry allowed electrocyclic process is feasible thus we see a large decrease in activation energy[7,8] in excess of 30 kcal mole^{-1}. While the introduction of the unsaturation into **9** to give **10** similarly makes both C–N bonds allylic there is not a convenient symmetry allowed pathway. Nevertheless the decrease in activation energy[9] and the possibility of producing trimethylenemethane diradicals has lead us to study the thermal decomposition of the 4-alkylidene-1-pyrazolines in some detail. Table 2 gives the activation energies for a series of methylated 4-alkylidene-1-pyrazolines, and certainly it is evident that simple Me substitution to obtain the series 1°, 2° and 3° for C–N[10] bonds and potential radical formation is not

Table 1. Activation parameters for some selected azo compounds

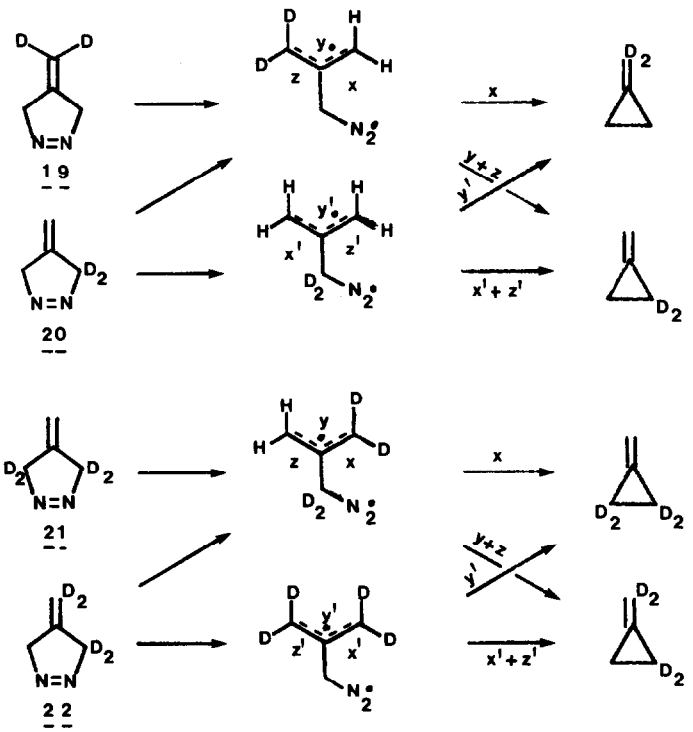
Structure	Cond.[a]		Ea. (kcal mole^{-1})	log A.	Ref.
 **1**	g		47.7	15.4	2
	f		45.7	14.6	
 **2**	g		35.6 ± 0.5	14.8 ± 0.3	3
 **3**	g		36.1 ± 0.2	15.5 ± 0.2	4
 **4**	g	*cis*	40.5 ± 0.4	15.5 ± 0.2	5
		trans	40.3 ± 0.4	15.6 ± 0.2	5
 **5**	Ph_2O	*cis*	31.3 ± 0.3	14.3 ± 0.3	6
 **6**	Ph_2O	*cis*	22.9 ± 0.5	12.8 ± 0.3	6
		trans	25.8 ± 0.4	14.0 ± 0.3	6
 **7**	g		44.5 ± 0.1	15.3 ± 0.1	7
 **8**	-78° Sol'n		< 14		8
 **9**	g		42.3 ± 0.3	15.8 ± 0.3	5
 **10**	g		32.6 ± 0.3	13.24	9

[a] g gas phase, f flow system

Table 2. Activation parameters for some methylated 4-alkylidene-1-pyrazolines

Structure	Ea. (kcal mole^{-1})	log A	Rel. rate (170°)	Ref.
 10	33.6 ± 0.7	13.75 ± 0.35	1.00	9
 11	33.0 ± 1.0	13.4 ± 0.8	1.04	This work
 12	35.3 ± 1.2	14.4 ± 0.6	0.70	"
 13	31.2 ± 1.1	12.9 ± 0.7	2.17	"
 14	30.4 ± 1.1	12.5 ± 0.9	2.30	"
 15	31.1 ± 1.1	12.8 ± 0.9	2.21	"
 16	35.9 ± 1.0	14.6 ± 0.9	0.55	"
 17	40.7 ± 0.4	15.5 ± 0.2	0.020	10
 18	39.8 ± 0.6	13.6 ±	0.00065	11

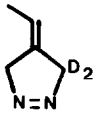
a rational approach in this case wherein the structure is rigid and steric effects[11] may be large. As a consequence we have recently examined the secondary deuterium kinetic isotope effects of a series of deuterated 4-methylene-1-pyrazolines.[9] These data coupled with an analysis of the isomer proportions of the deuterated methylenecyclopropanes and a ^{13}C labelled analogue, were found to be consistent with a mechanism involving cleavage of one C–N bond to irreversibly form a diazenyl allyl diradical. The diradical then, by three possible modes of ring closure gives rise to the products (Scheme 1). Modes *x* (closure between C_3 and C_5 of the reactant) and *z* (between the *exo*-methylene and the diazenyl bearing methylene) are intramolecular S_H2 reactions. The *y*



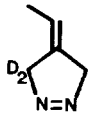
Scheme 1.

mode may be considered an electrocyclic ring closure in which both allylic termini rotate to form the cyclopropane methylenes, probably synchronous with the loss of molecular nitrogen from the diazenyl methylene. Using the kinetic isotope effects observed for **19–22** to predict the proportions of the intermediates from **20** and **22**, along with a k_H/k_D value of 1.31 for the torsional rotation of an allylic methylene, we can construct a system that predicts the product proportions to ±1% as determined by ^{2}HMR.

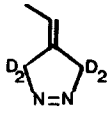
Our success in using Scheme 1 has lead us to attempt to use it in a predictive manner for 4-alkylidene-1-pyrazolines. We have considered the decrease in relative rate of the isopropylidene compounds **16** and **18** to be due to steric hindrance since stretching of the C–N bond will require C3 (or C5) to interact with the Me group of the exocyclic double bond. If this is the case then we would expect the C–N bonds of **13** to break at dissimilar rates and that this will be observed by a difference in the observed kinetic isotope effects for **23** and **24**. We have labelled the bond *anti* to the Me group α and that *syn* to



23



24



25

the Me β. Assuming the step-wise cleavage and that any secondary deuterium isotope effect on a remote site is negligible (e.g. D_2 at α on k_{23}^{β}) then the following equations can be used to assess the rates of cleavage of each bond.

$$k_{12}^{\alpha} + k_{12}^{\beta} = k_{12}^{obs} \quad (1)$$

$$k_{23}^{\alpha} + k_{23}^{\beta} = k_{12}^{\alpha}(k_D/k_H) + k_{12}^{\beta} = k_{23}^{cor} \quad (2)$$

$$k_{24}^{\alpha} + k_{24}^{\beta} = k_{12}^{\alpha} + k_{12}^{\beta}(k_D/k_H) = k_{24}^{cor} \quad (3)$$

$$k_{25}^{\alpha} + k_{25}^{\beta} = (k_{12}^{\alpha} + k_{12}^{\beta})(k_D/k_H) = k_{25}^{cor}. \quad (4)$$

RESULTS AND DISCUSSION

Synthesis. The 4-ethylidene-1-pyrazoline (**12**) was synthesized as described earlier by the regiospecific addition of diazomethane to 1,2-butadiene. Similarly *E*-4-ethylidene-1-pyrazoline-3,3-d_2 (**23**) and *Z*-4-ethylidene-1-pyrazoline-3,3-d_2 (**24**) were prepared by the addition of diazomethane-d_2 to 1,2-butadiene, and of diazoethane to 1,2-butadiene-1,1-d_2 respectively. The tetradeuterio derivative **25** was synthesized using diazomethane-d_2 and 1,2-butadiene-1,1-d_2. Earlier ^{13}CMR and 100 MHz ^{1}HMR spectra of **23** and **24** lead us to suggest that their preparation was stereospecific.[12] A re-examination of the products using 400 MHz ^{1}HMR and ^{2}HMR demonstrated that **23** contained 10% **24**, and what was previously considered pure **24** was shown to be a mixture of 10% **23** and 90% **24** by ^{2}HMR. The proton spectrum of **13** was completely resolved using benzene-d_6 as a solvent, whereas the *syn* and *anti* methylene groups overlapped when deuteriochloroform was used. We have found our deuterium integrations to be precise to ±1% and have used them throughout.

Kinetics. The thermolysis rate constants were calculated from the measured pressure increase in a closed vessel over the course of the reaction. A stainless steel well-conditioned reactor was used at 164° at an initial pressure of 70–80 Torr, conditions under which we were able to minimize the troublesome tautomerism to 2-pyrazolines. The rate constants quoted in Table 3 are the average of five runs using 18 to 20 points for each run. The error limits quoted are the standard deviations and thus our precision is better than ±1%. The rate constants were corrected for the presence of undeuterated material and for the presence of the other isomer by using eqn (5),

$$k_{23}^{obs} = f_H k_{12}^{obs} + f_{23} k_{23}^{cor} + f_{24} k_{24}^{cor}$$

where k_{23}^{cor} and k_{24}^{cor} are the corrected rate constants for fully deuterated **23** and **24**, and f_{12}, f_{23} and f_{24} are the fractions of **12**, **23** and **24** in each of the two mixtures of isomers.

Secondary deuterium kinetic isotope effects have been measured for numerous azo alkanes.[13,14] When there is a loss of HCN vs DCN bending force constant on going to the transition state the change in free energy per deuterium ($\delta\Delta G^{\ddagger}/n$) is generally[14] in the order of 90–120 cal mole^{-1}. Examination of the IR spectra of the deuterated 4-methylene-1-pyrazolines **19–22** and **10** allows the calculation of the free energy change of 110 cal mole^{-1} per deuterium,[9] a value which should be similar in the 4-ethylidene-1-pyrazolines. Table 5 records the value of $\delta\Delta G^{\ddagger}/n$ observed if the reaction is via a

Table 3. Observed and corrected rate constants for the thermolysis of deuterated 4-ethylidene-1-pyrazolines at 164.0°

Reactant	Composition[a] 12	23	24	$10^3 k_{obs}$ (sec^{-1})[b]	$10^3 k^{cor}$ (sec^{-1})
Mixture A	4%	88%	8%	1.66 ± 0.01	k_{23} 1.63 ± 0.02
Mixture B	3%	7%	90%	1.81 ± 0.01	k_{24} 1.82 ± 0.02
C	100%	-	-	1.94 ± 0.01	
D	4%	25%	96%	1.53 ± 0.01	k_{25} 1.51 ± 0.02

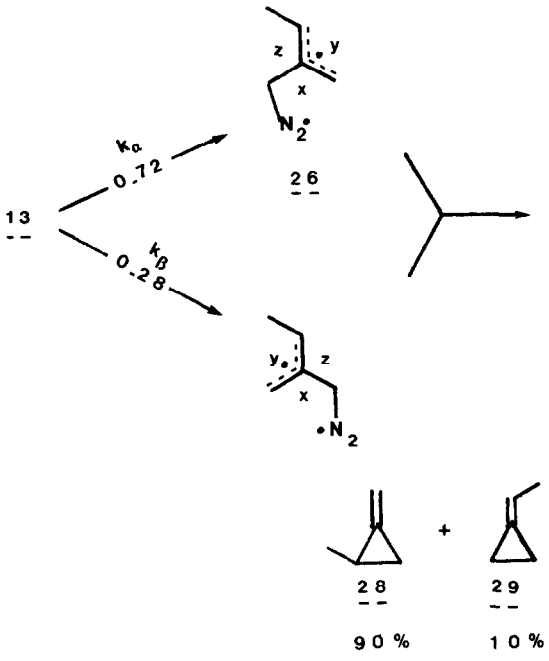
[a] Obtained by the analysis of 400 MHz ^{1}Hmr and mass spectrometry ± 1%
[b] Errors are the 90% confidence limits

Table 4. Secondary deuterium kinetic isotope effects for deuterated 4-ethylidene-1-pyrazolines

Compound	k_H/k_D
23	1.19 ± 0.03
24	1.07 ± 0.02
25	1.29 ± 0.03

one-bond cleavage mechanism as calculated from the k_H/k_D values recorded in Table 4, and the same $\delta\Delta G^{\ddagger}/n$ value if the mechanism involves valence change at both C–N bonds in the rate determining step. Clearly the data in Table 5 are supportive of the one-bond cleavage mechanism. On this basis we can calculate the ratio of α to β C–N bond cleavages from eqns (1)–(4), and these values are also recorded in Table 5.

Product studies. The thermolysis of 4-ethylidene-1-pyrazoline (**13**) gives a 90:10 mixture of 2-methylmethylenecyclopropane (**28**) and ethylidenecyclopropane (**29**). If, as indicated from the kinetic studies the



α C–N bond cleavage contributes 72% of the total reaction then **26** should be the major intermediate and considering the three possible modes of interconversion to the products we see that only *y* and *z* give **28**. We can distinguish between these two modes by examining the position of deuterium in **28**. Correcting for the presence of small amounts of **24** in the synthesis of **23** (and *vice-versa*) we find the proportions of **30** to **31** to be 81:19 from **23** and 11:89 from **24**. These data are readily rationalized if the electrocyclic ring closure mode *y* is the predominant one just as was found for the unsubstituted 4-methylene-1-pyrazolines.[9] Proton and deuterium magnetic resonance on the ethylidenecyclopropane from **23** indicated that greater than 92% of the deuterium is *syn* to the methyl group as in **32** and approximately 8% is *anti* as in **33**.

There exists the possibility of loss of nitrogen from the diazenyl radical to form the trimethylenemethane diradical. The totally planar species is quickly dispelled since pairs of substrates **19** and **20**, and **21** and **22**, would have to give the same proportions of isomeric products. The orthogonal trimethylenemethane, or Chesick[15] type intermediate, generated by the loss of N_2 from the diazenyl radical is more difficult to dismiss. The large amount of *y* closure, that is the electrocyclic closure of the two allylic termini, and the rotation of the orthogonal methylene of the Chesick intermediate into the carbon plane seems to us to be unlikely in terms of the simpler rotation of one allylic methylene to form a cyclopropane ring. It is apparent from both experimental[16,17] and theoretical[18] consideration that the diazenyl radical has a finite lifetime, thus we believe that the ring closures, of the *x* and *y* type, are essentially intramolecular free radical displacements of nitrogen, analogous to the displacement observed by Kopecky *et all*,[19] and that carbon diradicals do not play a major role in the thermal decomposition. This product determining step may change however since the loss of nitrogen from the diazenyl radical may be facilitated by substitution on the diazenyl carbon. Such substitution would readily lead one to the conclusion that the Chesick intermediate plays an important role as in the case of the isomeric pair[24] **12** and **16**. Geometrical constraints such as those involved in the bicyclic systems, so thoroughly studied by Berson[20] *et al.*, may also change the mechanism to the extent that a carbon diradical is required.

It has taken detailed kinetic isotope effect studies, which have the advantage of being kinetically significant and at the same time sterically causing minimal perturbation of the reaction profile, along with product studies to allow us to define a mechanism for the thermolysis of 4-alkylidene-1-pyrazolines.

EXPERIMENTAL

Kinetics. The kinetic experiments were carried out in a static stainless steel vessel as described.[9] The pressure was measured using a transducer and was recorded as a function of time by a Hewlett Packard Model 5150 A thermal printer. Warm samples were injected directly into the vessel and up to 20 measurements taken. The products were trapped in break-seals on a vacuum line and were subjected to mass spectrometry and both ^{1}HMR and ^{2}HMR at 400 MHz using a Bruker WH-400 cryospectrometer.

E-4-*Ethylidene*-1-*pyrazoline*-3,3-d_2 (**23**). The procedure was that described previously[12] for the synthesis of 4-ethylidene-1-pyrazoline except that diazomethane-d_2 was used. A soln of diazomethane-d_2 (6.4 g, 0.15 mol) in absolute ether (60 ml), pre-

Table 5. The ratio of $k_\alpha:k_\beta$ for one-bond cleavage of deuterated 4-ethylidene-1-pyrazolines, and of $\delta\Delta g^{\ddagger}/n$ calculated for one bond and two-bond cleavage mechanism

Reactant	$k_\alpha:k_\beta$	$\delta\Delta G^{\ddagger}/n$ (cal. Mole^{-1})[a] one-bond cleavage	two-bond cleavage
13	72:28		
23	67:33	110 ± 4	78 ± 3
24	77:23	110 ± 4	30 ± 2
25	72:28	110 ± 4	57 ± 2

[a]Calculated from the equation $\delta\Delta G^{\ddagger} = (RT/n)\ln(k_H/k_D)$ where n is the number of deuteriums on the α carbon undergoing valence change in the rate determining step.

pared according to the method of Gassman and Greenlee,[21] with 1,2-butadiene (11 g, 0.20 mol) to give the product (4.7 g, 48 mmol, 35% yield).

The 400 MHz spectrum δ TMS (benzene-d_6) showed: 1.16 (doublet of slight multiplets, J = 6.70 Hz, 3H), 4.40 (doublet of quartets, J = 1.65 Hz and 2.20 Hz, 1.84H), 4.48 (pentet, J = 2.25 Hz, 0.16H) and 4.95 (multiplet, 1H). The mass spectrum indicated 96 ± 1% isotopic purity ($D_0 = 0.9$, $D_1 = 5.8$, $D_2 = 93.3$). The expanded 400 MHz ^{1}HMR spectrum indicated that the % ratio of *E*- vs *Z*-4-ethylidene-1-pyrazoline-3,3-d_2 was 92 ± 1:8 ± 1, and the 54.4 MHz ^{2}HMR spectrum (benzene-d_6) showed the % ratio between the *E* and *Z* was 90 ± 1:10 ± 1.

Z-4-Ethylidene-1-pyrazoline-3,3-d_2 (**24**). The procedure was that described previously[12] for the preparation of 4-ethylidene-1-pyrazoline except that 1,2-butadiene-1,1-d_2 was used. The 1,2-butadiene-1,1-d_2 was prepared according to the method of Hurd and Meinert[22] except that 2-buten-1-ol-1,1-d_2 was produced by lithium aluminum deuteride reduction of crotonyl chloride.[12,23] A soln of diazomethane (6 g, 0.14 mol) in absolute ether (60 ml) reacted with 1,2-butadiene-1,1-d_2 (9 g, 0.17 mol) to give the product (4.5 g, 46 mmol, 33% yield).

The 400 MHz ^{1}HMR spectrum δ TMS (benzene-d_6) showed: 1.18 (doublet of slight multiplets, J = 6.70 Hz, 3H), 4.37 (doublet of quartets, J = 1.65 and 2.20 Hz, 0.14 H), 4.43 (pentet, J = 2.25 Hz, 1.86H) and 4.91 (multiplet, 1H). The mass spectrum indicated 97 ± 1% isotopic purity ($D_0 = 0.7$, $D_1 = 4.8$, $D_2 = 94.5$). The % ratio between *E*- and *Z*-4-ethylidene-1-pyrazolines-3,3-d_2 were 7 ± 1:93 ± 1 by the expanded 400 MHz ^{1}HMR spectrum and 9 ± 1:91 ± 1 by the expanded 54.4 MHz ^{2}NMR spectrum (benzene-d_6).

4-Ethylidene-1-pyrazoline-3,3,5,5-d_4 (**25**). The procedure was that described previously for the synthesis of 4-ethylidene-1-pyrazoline except that 1,2-butadiene-1,1-d_2 and diazomethane-d_2 were used. A soln of diazomethane-d_2 (1.6 g, 38 mmol) in absolute ether (20 ml) reacted with 1,2-butadiene-1,1-d_2 (2.5 g, 45 mmol) to give the product (1.4 g, 14 mmol, 37% yield).

The 400 MHz ^{1}HMR spectrum δ TMS (benzene-d_6) showed: 1.20 (doublet, J − 6.70 Hz, 3H) and 4.96 (quartet, j − 6.70 Hz, 1H). The mass spectrum indicated 96 ± 1% isotopic purity ($D_0 = 0.8$, $D_1 = 0.4$, $D_2 = 1.6$, $D_3 = 7.6$, $D_4 = 89.6$), and the expanded 400 MHz proton ^{1}HMR spectrum indicated 96 ± 1% isotopic purity.

Thermolysis of E- *and* Z-*4-Ethylidene-1-pyrazoline*-3,3-d_2 (**23** *and* **24**). Pyrazolines **23** and **24** contained small amounts of their isomers **24** and **23**. These mixtures were designated A and B respectively. Thermolysis of mixtures A and B were carried out in a break-seal at a pressure of approximately one atmosphere for 15–60 min at 175°. Under these conditions it is known that interconversion between products is negligible.[12] After cooling in an ice-water bath the products were transferred to a sample tube and benzene or chloroform was added. The products were then separated by preparation gc into deuterated 2-methyl-methylenecyclopropenes (**30** and **31**) and ethylidenecyclopropenes (**32** and **33**). The 400 MHz ^{1}HMr and 54.4 MHz ^{2}HMR spectra of the products were then obtained. Mixture A corresponded to a 74:26 ratio for 30:31, and for mixture B the ratio 18:82 was obtained. Continued heating of the mixture for 1 hr did not change these ratios. Correcting for the presence of **24** in the sample of **23** gave the product proportions from **23** for **30**:**31** of 81:19; and from **24** of 11:89. Only a small amount of **32** and **33** was obtained from each reaction nevertheless integration of the ^{2}HMR indicated that from mixture A the ratio of **32**:31 was 83:17 and from B 14:84. From these results we calculated the ratio of **32**:**33** from **23** as 91:9 and from **24** as 7:93.

Thermolysis of 3-*alkylidene-1-pyrazolines* **11**, **12**, **13**, **14**, **15** *and* **16**.[24] The preparation and the nature of the thermolysis products of these compounds have been discussed previously. The rates of thermolysis of each compound was studied at three temperatures, because of the vapour pressure of the materials and the rates of thermolysis they were generally studied 165–175°. The experimental error quoted in Table 2 are at the 90% confidence limits.

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REFERENCES

[1]P. S. Engel, *Chem. Rev.* **80**, 99 (1980).
[2]G. Geisler and J. Hoffman, *Z. Phys. Chem.* **57**, 318 (1968).
[3]R. J. Crawford and K. Takagi, *J. Am. Chem. Soc.* **94**, 7406 (1972).
[4]B. H. Al-Sader and R. J. Crawford, *Can. J. Chem.* **48**, 2745 (1970).
[5]R. J. Crawford and A. Mishra, *J. Am. Chem. Soc.* **88**, 3963 (1966).
[6]R. J. Crawford and M. Ohno, *Can. J. Chem.* **52**, 3134 (1974).
[7]S. G. Cohen and R. Zand, *J. Am. Chem. Soc.* **84**, 586 (1962).
[8]N. Rieber, J. Alberts, J. A. Lipsky, and D. M. Lemel, *Ibid.* **88**, 5668 (1969).
[9]M. H. Chang and R. J. Crawford, *Can. J. Chem.* **59**, 2556 (1981).
[10]R. J. Crawford and H. Tokunaga, *Ibid.* **52**, 4033 (1974).
[11]P. S. Engel and L. Shen, *Ibid.* **52**, 4040 (1974).
[12]R. J. Crawford, H. Tokunaga, L. Schrijver, and J. Godard, *Ibid.* **59**, 998 (1978).
[13]S. Seltzer and F. T. Dunne, *J. Am. Chem. Soc.* **87**, 2628 (1965).
[14]E. A. Halevi, *Progress in Physical Organic Chemistry*, Vol. 1, p. 109. Interscience, New York (1963).
[15]J. P. Chesick, *J. Am. Chem. Soc.* **85**, 2720 (1963).
[16]N. A. Porter, G. R. Dubay and J. G. Green, *Ibid.* **100**, 920 (1978); N. A. Porter and L. J. Marnett, *Ibid.* **95**, 4361 (1973) and refs cited.

[17]W. A. Pryor and K. Smith, *Ibid.* **92**, 5403 (1970).
[18]N. C. Baird, *J. Chem. Phys.* **62**, 300 (1975); N. C. Baird and H. B. Kathpal, *Can. J. Chem.* **55**, 863 (1977).
[19]K. R. Kopecky, P. Pope and J. L. Sastre, *Ibid.* **54**, 2639 (1976).
[20]J. A. Berson, *Acc. Chem. Res.* **11**, 446 (1978), D. Cichra, M. S. Platz and J. A. Berson, *J. Am. Chem. Soc.* **99**, 8507 (1977).
[20]P. G. Gassman and W. J. Greenlee, *Org. Syn.* **53**, 38 (1973).
[22]C. D. Hurd and R. N. Meinert, *J. Am. Chem. Soc.* **53**, 289 (1931).
[23]R. D. Schuetz and F. W. Millard, *J. Org. Chem.* **24**, 297 (1959).
[24]R. J. Crawford, D. M. Cameron and H. Tokunaga, *Can. J. Chem.* **52**, 4025 (1974).