

JOURNAL

OF THE AMERICAN CHEMICAL SOCIETY

VOLUME 107, NUMBER 5

MARCH 6, 1985

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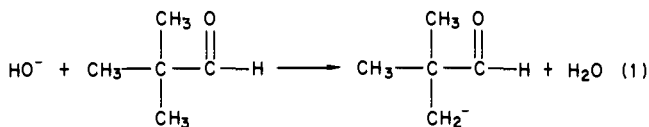
Gas-Phase Reactions of Anions with Methyl Formate and *N,N*-Dimethylformamide

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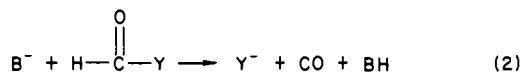
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Abstract: The gas-phase reactions of methyl formate and *N,N*-dimethylformamide with a series of anions have been examined in a flowing afterglow and selected ion flow tube apparatus as well as in a Fourier transform ion cyclotron resonance spectrometer. The relative importance of the various reaction channels, namely, abstraction of a formyl or methyl proton, carbonyl addition, or displacement on the methyl group, has been measured. A number of secondary reactions of the product ions have also been identified. Proton abstraction is the major reaction of either neutral with NH_2^- . Carbonyl addition reactions become significant for methyl formate, especially when weaker bases are used, but this pathway is less important for *N,N*-dimethylformamide. α -Elimination of CO (the Riveros reaction) is also important for both substrates.

Carbonyl addition reactions of anions in the gas phase have been more extensively investigated than any other nucleophilic reaction,¹ and yet much remains to be understood. The experimental difficulties are severalfold. In the first place, gas-phase additions are in general rapid and reversible; simple adducts, for example, to aldehydes and ketones, are not observed at low pressure.² Secondly, most simple exothermic reactions of esters and acid halides occur at nearly every collision,³ and so one traditional tool for the study of reaction mechanism, the determination of reaction rates as a function of structure, is of limited use. At the same time, the presence of a carbonyl group activates a molecule for other reactions, particularly for proton transfer, which compete successfully with carbonyl addition. Even pivalaldehyde has been observed to form an anion by proton abstraction (eq 1).⁴

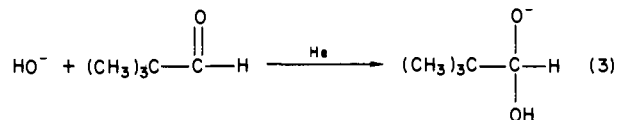


Among simple, relatively volatile carbonyl compounds, derivatives of formic acid have proven reasonably useful for gas-phase mechanistic studies of nucleophilic addition reactions. Even in these cases, however, a rapid α -elimination, referred to as the Riveros reaction, is competitive with nucleophilic addition (eq 2).⁵



Another possible source of confusion arises from the fact that the two principal experimental methods used to study gas-phase

organic reaction mechanisms use quite different pressure regimes. In ion cyclotron resonance (ICR) spectroscopy the pressure is quite low (10^{-5} – 10^{-7} torr); addition reactions, which require collisions with a third body to remove reaction exothermicity, are seldom observed. In the flowing afterglow (FA) technique the overall pressure is much higher (0.3–1.0 torr of helium) so that reaction intermediates which are sufficiently long-lived can be stabilized and observed as products. For example, reaction of pivalaldehyde with hydroxide ion in the flowing afterglow gives mainly the addition product rather than proton abstraction (eq 3).⁶



The studies reported in this paper were initiated by our desire to take a fresh look at gas-phase reactions of some simple carbonyl compounds by both the ICR and FA methods. We felt that a collaborative effort, making use of the strong points of each method, might be more informative than the independent application of either method alone. For example, the FA is especially good for the determination of reaction rate constants, since one

- (1) Nibbering, N. M. M. *Recl. Trav. Chim. Pays-Bas* **1981**, *100*, 297–306.
- (2) Bohme, D. K.; Mackay, G. I.; Tanner, S. D. *J. Am. Chem. Soc.* **1980**, *102*, 407–408.
- (3) Asubiojo, O. I.; Blair, L. K.; Brauman, J. I. *J. Am. Chem. Soc.* **1975**, *97*, 6685–6688.
- (4) Noest, A. J.; Nibbering, N. M. M. *J. Am. Chem. Soc.* **1980**, *102*, 6427–6429.
- (5) (a) Blair, L. K.; Isolani, P. C.; Riveros, J. M. *J. Am. Chem. Soc.* **1973**, *95*, 1057–1060. (b) Isolani, P. C.; Riveros, J. M. *Chem. Phys. Lett.* **1975**, *33*, 362–364. (c) Fernando, J.; Faigle, G.; Isolani, P. C.; Riveros, J. M. *J. Am. Chem. Soc.* **1976**, *98*, 2049–2052. (d) Takashima, K.; Riveros, J. M. *Ibid.* **1978**, *100*, 6128–6132.
- (6) DePuy, C. H., unpublished results.

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† University of Amsterdam.

Table I. Product Ions Formed in the Reactions of Anions with DCO₂CH₃ as Determined by the FT-ICR Method

anion A ⁻	PA(A ⁻), ^a kJ/mol	product ions (%) ^b							
		(M - H) ⁻	(M - D) ⁻	CH ₃ O ⁻	CH ₃ O ⁻ .NH ₃	CH ₃ O ⁻ .DA	CH ₃ O ⁻ .DOCH ₃	(M + A - CH ₃ OH) ⁻	DCO ₂ ⁻
NH ₂ ⁻	1689	23	11	16	12		20	16	2
C ₂ H ₅ NH ⁻	1671	5	5	11	5	8	30	35	1
(CH ₃) ₂ N ⁻	1659		6	27	5	8	49		5
H ⁻	1675	2	12	53	6		21		6
H ¹⁸ O ^{-c}	1635		11	12		16	28	27 ^f	6 ^f
CH ₃ ¹⁸ O ^{-d,e}	1587					95			5
C ₆ H ₅ ⁻	1669			9	1		71	10	9
CH ₂ =CHCH ₂ ⁻	1631						8	92	
NCCH ₂ ⁻	1557							100	

^a Values taken from ref 13. ^b See text. The percentages have been obtained after a reaction time of a few hundred milliseconds. Conversion into product was 50–80%. In the NCCH₂⁻ case, the reaction time was 2500 ms (see also Table III). ^c Generated by reaction between ¹⁸O⁻ and hexane. ^d Generated from CH₃¹⁸ONO (see ref 9). ^e HCO₂CD₃ was used as substrate. ^f See text.

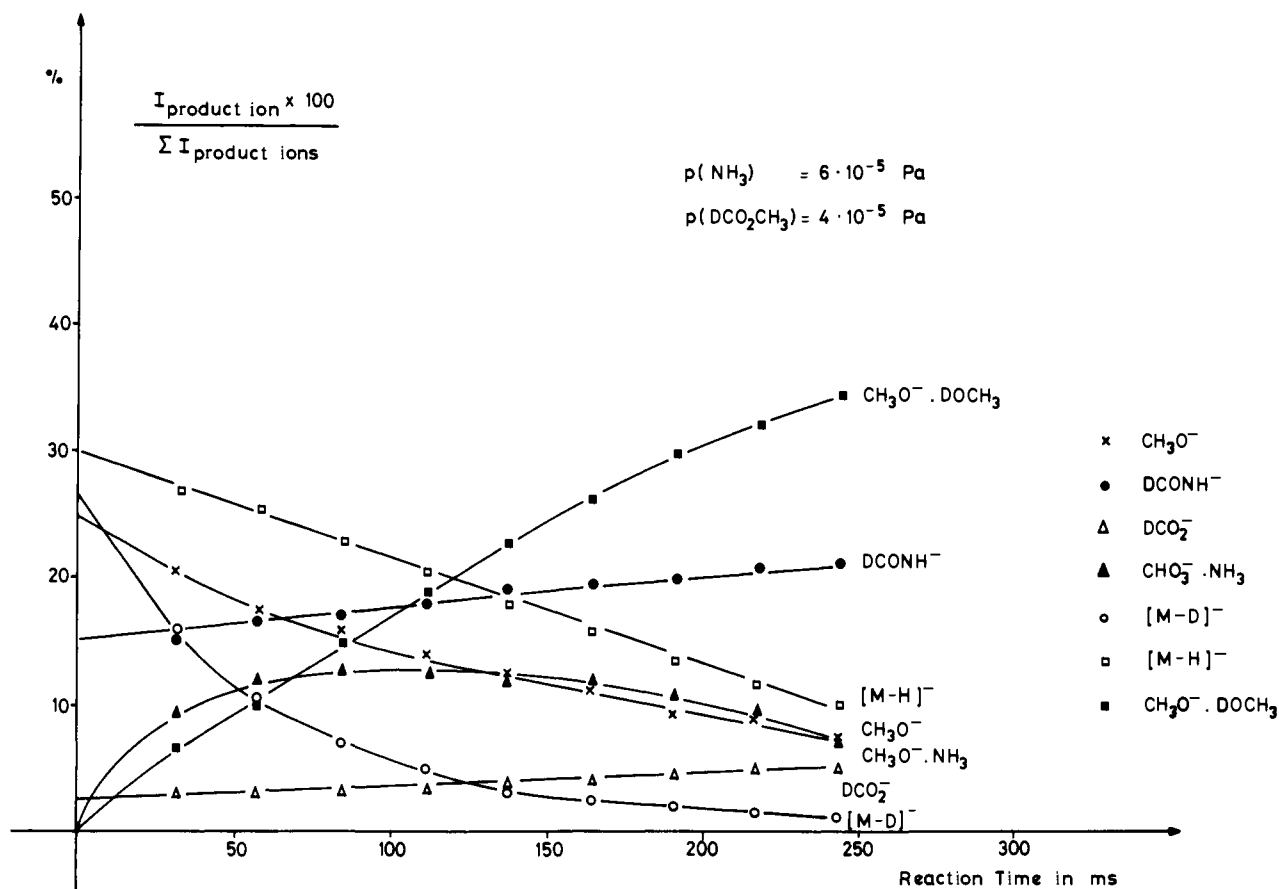


Figure 1. Normalized intensities of product ions for the reaction of NH₂⁻ with DCO₂CH₃ as a function of reaction time in the FT-ICR instrument. Extrapolation of these smooth curves to zero time gives the initial product distribution. The experimental parameters were as follows: magnetic field strength 1.4 T; electron energy 5 eV; emission current 800 nA; recording of *m/z* 12–300.

can be assured that the ions are at thermal energy before reaction. By making use of the selected ion flow tube (SIFT) method,⁷ previous complications introduced by the presence of unwanted neutrals in the flow tube (for example, NH₃ used to prepare NH₂⁻) can be eliminated. Similarly, the recent introduction of the Fourier transform technique to the ICR method (FT-ICR) has greatly extended the experimental capabilities of that method. For our substrates we chose methyl formate and *N,N*-dimethylformamide (DMF). Neither of these compounds possesses highly acidic hydrogens, and both are sufficiently volatile for study in the FA. While this work was in progress, Bartmess and co-workers⁸ reported some related studies of proton abstraction reactions of DMF.

Experimental Section

The home-built Fourier transform ion cyclotron resonance spectrometer (FT-ICR) has been described elsewhere.⁹ The flowing afterglow (FA)¹⁰ and selected ion flow tube (SIFT)¹¹ experiments were carried out at room temperature in instruments which have also been previously described. For all three techniques, reagent ions were generated by standard methods, and reaction rate constants and product branching ratios were determined as described in the cited references.

Results

General Reactivity of Methyl Formate. Methyl formate gives a number of primary and secondary products when it undergoes reaction with an anion in the gas phase. In Table I are reported

(7) Adams, N. G.; Smith, D. *Int. J. Mass Spectrom. Ion Phys.* **1976**, *21*, 349–359.

(8) Bartmess, J. E.; Caldwell, G.; Rozeboom, M. D. *J. Am. Chem. Soc.* **1983**, *105*, 340–344.

(9) Ingemann, S.; Nibbering, N.M.M. *J. Org. Chem.*, in press.

(10) DePuy, C. H.; Bierbaum, V. M. *J. Am. Chem. Soc.* **1981**, *103*, 5034–5038.

(11) Grabowski, J. J.; DePuy, C. H.; Bierbaum, V. M. *J. Am. Chem. Soc.* **1983**, *105*, 2565–2571.

Table II. Initial Product Ion Distributions in the Reactions of NH_2^- with DCO_2CH_3 and HCO_2CD_3 as Determined by the FT-ICR Method

reactant	product ions	percentage ^a
$\text{DCO}_2\text{CH}_3^b$	CH_3O^-	25
	DCONH^-	15
	DCO_2^-	3
	$(\text{M}-\text{D})^-$	27
	$(\text{M}-\text{H})^-$	30
HCO_2CD_3	CD_3O^-	36
	HCONH^-	18
	HCO_2^-	3
	$(\text{M}-\text{D})^-$	13
	$(\text{M}-\text{H})^-$	30

^aThe error on the relative intensities is about 15% of the percentages given. ^bSee Figure 1. Compare with Figure 2 and Table III.

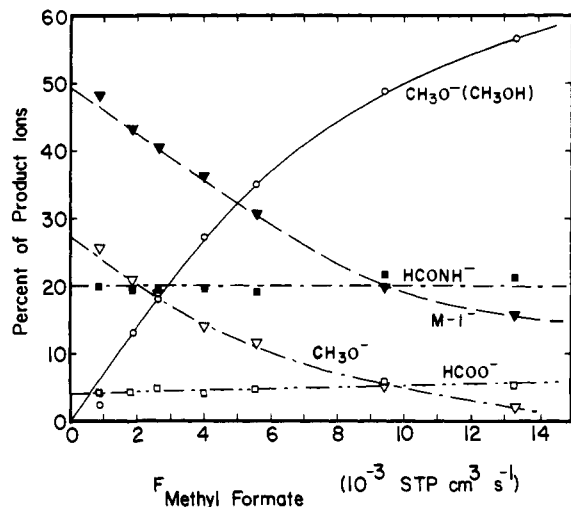


Figure 2. Normalized intensities of product ions for the reaction of NH_2^- with HCO_2CH_3 as a function of the HCO_2CH_3 flow rate in the SIFT instrument. These data have been corrected for mass discrimination. Extrapolation of these smooth curves to zero flow gives the initial product ion distribution.

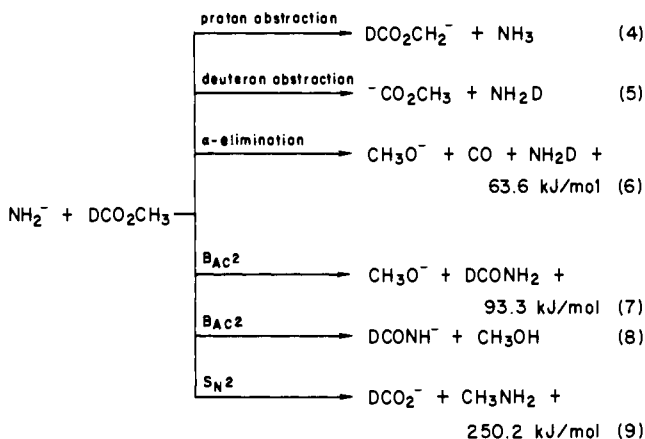
the products and their abundances as observed in the FT-ICR for reactions of DCO_2CH_3 with a variety of anions. These are obviously not initial products, but rather a snapshot of the reaction mixture after an arbitrary reaction time. In order to determine the initial product ion distribution it is necessary to follow the intensities of the ions as a function of reaction time and extrapolate to zero time. The results obtained for the reaction of NH_2^- with DCO_2CH_3 are shown in Figure 1 and are given in Table II.

In a conventional flowing afterglow it is impossible to obtain the initial product ion distribution for this reaction because some of the primary products react rapidly with ammonia, which is present in the flow tube in relatively high concentration (2×10^{-3} torr). This problem can be overcome by using the selected ion flow tube. In the SIFT amide ions are extracted from an external, low-pressure ion source and injected into the flow tube in the absence of ammonia or ions of other masses. Product ion distributions are determined as a function of neutral reactant concentration by varying the flow rate of the neutral reactant at a fixed reaction distance. The SIFT also has the advantage that mass discrimination by the quadrupole mass filter can be determined and accounted for.⁷ The results for the reaction of amide ion with methyl formate, corrected for mass discrimination, are given in Figure 2. The amount of each product (as a percent of all product ions) is plotted against the methyl formate flow. Extrapolation to zero flow (i.e., zero reaction) gives the initial product ion distribution.

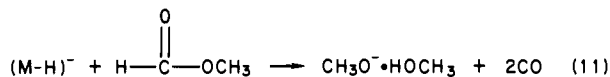
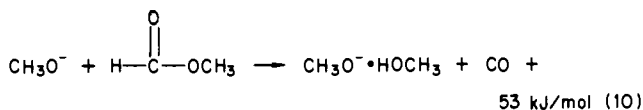
In Table III are collected data for the reactions of anions with methyl formate as determined in the SIFT. In addition to the initial product ion distribution, the overall reaction rate constants are given, together with the reaction efficiency, i.e., the probability of reaction per collision.¹² The initial product ion distributions

determined by the FT-ICR and SIFT method for the reaction of amide ion with methyl formate (compare Tables II and III) are in excellent agreement.

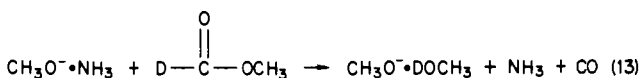
From the data of Tables II and III, the primary reaction pathways open for NH_2^- reacting with methyl formate can be identified as: proton abstraction from the methyl group, formyl proton abstraction, α -elimination (the Riveros reaction), $\text{B}_{\text{AC}2}$ and $\text{S}_{\text{N}2}$ substitution (eq 4-9). For three of the pathways the



exothermicity of the reaction can be calculated from literature values.^{13,14} Note that methoxide ion can, in principle, be formed by two pathways, α -elimination and $\text{B}_{\text{AC}2}$. Both pathways are exothermic, and we cannot estimate their relative importance. As can be seen in Figures 1 and 2, the major secondary ion observed in the FT-ICR and SIFT experiments is $\text{CH}_3\text{O}^- \cdot \text{HOCH}_3$ (or its deuterated analogue). Examination of Figure 2 shows that this ion is formed by secondary reactions of two of the primary ions in the SIFT (eq 10 and 11).¹⁵



Ejection experiments using the FT-ICR indicate that $\text{CH}_3\text{O}^- \cdot \text{HOCH}_3$ (or its deuterated analogue) only partially arises through reactions 10 and 11. In the FT-ICR experiments, the presence of ammonia leads to another major secondary ion, $\text{CH}_3\text{O}^- \cdot \text{NH}_3$, which is not observed in the SIFT experiments. Ejection experiments in the FT-ICR indicate that $\text{CH}_3\text{O}^- \cdot \text{NH}_3$ is formed via eq 12 and reacts via eq 13 to contribute to the



observed $\text{CH}_3\text{O}^- \cdot \text{HOCH}_3$ population. In the FT-ICR, analogous reactions are observed in the other amine/amide ion systems (Table I) and in the hydroxide ion/water system. In the SIFT experiments, where no NH_3 is present in the flow tube, the secondary reactions 12 and 13 are, of course, not observed.

General Reactivity of *N,N*-Dimethylformamide (DMF). The results for reactions of $\text{DCON}(\text{CH}_3)_2$ with a series of anions using

(12) Su, T.; Bowers, M. T. *Int. J. Mass Spectrom. Ion Phys.* **1973**, *12*, 347-356.

(13) ΔH_f° data for the ions have been taken from Bartmess, J. E.; McIver, R. T., Jr. In "Gas Phase Ion Chemistry"; Bowers, M. T., Ed.; Academic Press: New York, 1979; Vol. 2, Chapter 11, pp 87-121.

(14) ΔH_f° data for the neutrals have been taken from: Benson, S. W. "Thermochemical Kinetics", 2nd ed., Wiley Interscience: New York, 1976.

(15) $\Delta H_f^\circ(\text{CH}_3\text{O}^- \cdot \text{HOCH}_3) = -443 \text{ kJ/mol}$ has been calculated using BDE ($\text{CH}_3\text{O}^- \cdot \text{HOCH}_3) = 91.6 \text{ kJ/mol}$ taken from: Jorgensen, W. L.; Ibrahim, M. *J. Comput. Chem.* **1981**, *2*, 7.

Table III. Initial Product Ion Distributions and Kinetic Data for the Reactions of Anions with HCO₂CH₃ as Determined by the SIFT Technique

anion ^a A ⁻	product ions (%) ^b					kinetic data	
	(M - H) ⁻	CH ₃ O ⁻	CH ₃ O ⁻ -HA	(M + A - CH ₃ OH) ⁻	HCO ₂ ⁻	k _{obsd} ^c	eff ^d
NH ₂ ⁻	49	27		20	4	25 ^e	1.0
H ¹⁸ O ⁻	18	22	21	34	5	18	0.8
CD ₃ O ⁻			97		3	13	0.7
C ₆ H ₅ ⁻		major ^f		trace		6.7	0.5
CH ₂ =CHCH ₂ ⁻		3		95	2	4.0	0.2
NCCH ₂ ⁻				100		0.3	0.02

^aSee Table I and ref 13 for values of PA(A⁻). ^bThe error on the relative intensities is about 15% of the percentages given. ^cUnits of 10⁻¹⁰ cm³ molecule⁻¹ s⁻¹. The error in the rate constants is approximately ±20%. ^dReaction efficiency: k_{obsd}/k_{ADO} (see ref 12). ^eMeasured in the flowing afterglow. ^f>95%.

Table IV. Initial Product Ion Distribution in the Reactions of Anions with DCON(CH₃)₂ as Determined by the FT-ICR Method

anion ^a A ⁻	product ions (%) ^b			
	(M - H) ⁻	(M - D) ⁻	(M - 2H + D) ⁻	A ⁻ DN(CH ₃) ₂
NH ₂ ⁻	93	7		
ND ₂ ^{-c}	94	6		
C ₂ H ₅ NH ⁻	94	6		
<i>n</i> -C ₃ H ₇ NH ⁻	93	7		
(CH ₃) ₂ N ⁻	85	15		
HO ^{-d}	13	15		72
DO ^{-d}	16	11	3	70

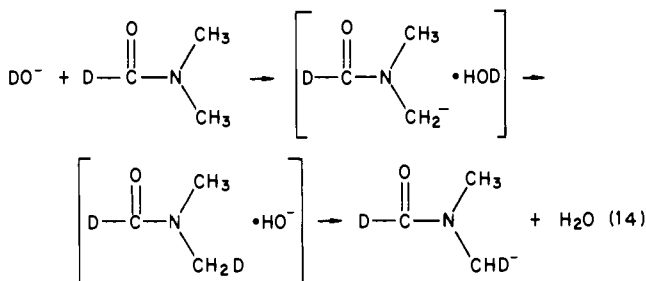
^aSee Table I and ref 13 for PA(A⁻). ^bSee text. ^cSee ref 9. ^dGenerated from reaction between O⁻ and *n*-C₆H₁₄/c-C₆D₁₂; see ref 9.

the FT-ICR technique are summarized in Table IV. The products and rate constants for the reactions of some of these ions, plus a few others, with HCON(CH₃)₂ have been studied in the SIFT; the results are collected in Table V.

As compared with methyl formate, DMF is more selective in its reactions with anions in the gas phase; proton or deuteron abstraction from DCON(CH₃)₂ is the most common pathway (Tables IV and V). The competition between proton and deuteron abstractions in the FT-ICR experiments has been corrected to zero time (as in Figure 1). The results in Table IV have not been corrected for the statistical preference for proton abstraction because the two methyl groups are likely to be nonidentical with respect to gas-phase acidity.^{9,16}

In the case of NH₂⁻ (generated from NH₃) and HO⁻ (generated in the absence of water)⁹ the relative abundances of the (M - H)⁻ and (M - D)⁻ ions in the FT-ICR remain nearly constant during the time interval studied (0–250 ms). For C₂H₅NH⁻, *n*-C₃H₇NH⁻, and (CH₃)₂N⁻, the relative abundances change as a function of reaction time; the relative abundances change considerably faster in the (CH₃)₂N⁻ case than in the other two.

One must be cautious in interpreting labeling studies of proton abstraction reactions because multiple hydrogen–deuterium exchanges can occur within a single ion–molecule complex, even in an exothermic reaction.¹⁷ For example, when DO⁻ reacts with DCON(CH₃)₂ some (M - 2H + D)⁻ ions are formed (Table IV). This must arise by the pathway of eq 14. If, in the final step



in this sequence, a deuteron from the formyl group rather than

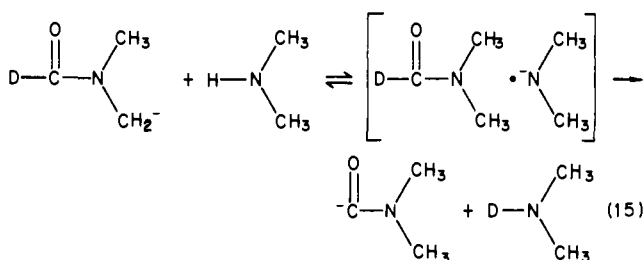
Table V. Initial Product Ion Distributions and Kinetic Data for the Reactions of Anions with HCON(CH₃)₂ as Determined by the FA and SIFT Techniques

anion A ⁻	PA(A ⁻) ^a	product ions	kinetic data	
			k _{obsd} ^b	eff ^c
NH ₂ ⁻	1689	(M - H) ^{-d}	40	1.0
ND ₂ ⁻		(M - H) ^{-d}		
H ¹⁸ O ⁻	1635	H ¹⁸ O ⁻ ·HN(CH ₃) ₂	33	0.9
CH ₃ O ⁻	1587	CH ₃ O ⁻ ·DMF	3.8 ^e	0.1
HO ₂ ⁻	1571 ^f	HCO ₃ ⁻	8.3	0.3
NCCH ₂ ⁻	1557	no reaction		
S ₂ ⁻		no reaction		
N ₃ ⁻	1439	no reaction		

^aValues taken from ref 13. ^bUnits 10⁻¹⁰ cm³ molecule⁻¹ s⁻¹. The error in the rate constants is approximately ±20%. ^cReaction efficiency: k_{obsd}/k_{ADO} (see ref 12). ^dIt is not possible to rule out a small amount (<5%) of carbonyl attack forming HCONH⁻ or HCOND⁻. ^eThis observed bimolecular rate constant is the same at helium pressures of 0.3, 0.4, and 0.5 torr. ^ftaken from ref 24a.

a proton from the methyl were abstracted, the exchange process would be hidden. The mechanism in eq 14 is further supported by the observation that 33% (M - 2H + D)⁻ ions are formed when DO⁻ (generated in the absence of water) reacts with HCON(CH₃)₂ in the FT-ICR. These results have obvious implications for experiments in which ions are generated or their structure probed under conditions where multiple proton transfers are possible. For the reaction of ND₂⁻ with DCON(CH₃)₂ (Table IV) or HCON(CH₃)₂ (Table V) no evidence for multiple exchange has been found. In the case of C₂H₅NH⁻ and *n*-C₃H₇NH⁻ multiple exchange might occur in the initial abstraction process, whereas for (CH₃)₂N⁻ this is not possible.

The ions can, of course, undergo subsequent exchange with excess amine, if it is present, either to alter their structure, to wash out deuterium, or both. For example, in the FT-ICR a rather fast change in the relative abundances of the (M - H)⁻ and (M - D)⁻ ions was observed in the presence of (CH₃)₂NH (eq 15).



In the FT-ICR 27–28% of the product ions from reaction between hydroxide ion and DCON(CH₃)₂ result from proton or deuteron abstraction, while in the SIFT no such ions are observed (compare Tables IV and V). In the FT-ICR experiments the hydroxide ions were formed by reaction of O⁻ with hexane or cyclohexane. This reaction is roughly 65 kJ/mol exothermic.^{13,14} Part of this energy will be retained in the hydroxide ions and might be used to induce a slightly endothermic proton or deuteron abstraction. When hydroxide ions are generated through reaction of H⁻ with water, which is roughly 40 kJ/mol exothermic,¹³ proton and deuteron abstraction is still observed. The ions react rapidly,

(16) Rondan, N. G.; Houk, K. N.; Beak, P.; Zajdel, W. J.; Chandrasekhar, J.; Schleyer, P. v. R. *J. Org. Chem.* **1981**, *46*, 4108–4110.

(17) Squires, R. R.; Bierbaum, V. M.; Grabowski, J. J.; DePuy, C. H. *J. Am. Chem. Soc.* **1983**, *105*, 5185–5192.

Table VI. Summary of the Data on the Formation of Cluster Ions in the α -Elimination Reactions of Anions with HCO_2CH_3

anion A^-	$\text{PA}(\text{A}^-)$, ^a kJ/mol	cluster ion formation	
		ICR	FA/SIFT
NH_2^-	1689	no	no
$\text{C}_2\text{H}_5\text{NH}^-$	1671	no	
C_6H_5^-	1669	no	no
$(\text{CH}_3)_2\text{N}^-$	1659	no	
$\text{CH}_3\text{SCH}_2^-$	1645 ^b	no ^b	
HO^-	1635	yes	yes
$\text{CH}_2=\text{CHCH}_2^-$	1631	no	no
$\text{CH}_2=\text{C}=\text{CH}^-$	1590	no ^c	no ^d
$\text{CH}_3\text{C}\equiv\text{C}^-$	1588	yes ^c	yes ^d
CH_3O^-	1587	yes	yes
$\text{C}_2\text{H}_3\text{O}^-$	1574	yes ^e	
$\text{HC}\equiv\text{C}^-$	1571	yes ^e	
$\text{C}_3\text{H}_7\text{O}^-$	1566	yes ^e	
NCCH_2^-	1557	no ^e	no
F^-	1554	yes ^e	
H_2P^-	1550	no ^e	
HS^-	1479	no ^e	
CN^-	1477	no ^e	
NO_2^-	1415	no ^e	
Cl^-	1396	no ^e	
Br^-	1354	no ^e	no

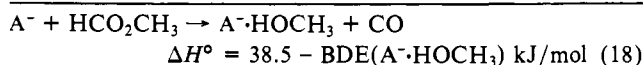
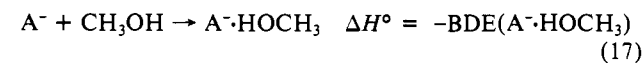
^a Values taken from ref 13. ^b Reference 25. ^c Reference 20a. ^d Reference 20b. ^e Reference 5.

however, with the water present in the FT-ICR cell, and the initial product ion distribution becomes more difficult to determine.

The presence of relatively large amounts of helium (≈ 0.5 torr) in the SIFT ensures that the hydroxide ions are at thermal energy before reacting with DMF. Since only α -elimination is observed when hydroxide ions react with DMF in the SIFT (Table V), DMF is probably slightly less acidic than water. The thermalizing effect of the buffer gas in the SIFT technique is advantageous in this regard. On the other hand, the relatively high concentration of the buffer can be a disadvantage by allowing a termolecular clustering reaction to become fast enough to mask other, slower bimolecular reactions. For example, in the SIFT only the cluster ion $\text{CH}_3\text{O}^- \cdot \text{DMF}$ is observed as a product of the reaction of methoxide ion with DMF because the energy associated with this clustering can be removed by collision with helium. In the FT-ICR, clustering is too slow to be observed and so the slow α -elimination reaction can be detected. This α -elimination yields $\text{CH}_3\text{O}^- \cdot \text{HN}(\text{CH}_3)_2$ ion which rapidly reacts with the methanol present in the FT-ICR cell to form the observed $\text{CH}_3\text{O}^- \cdot \text{HOCH}_3$ ion.

Discussion

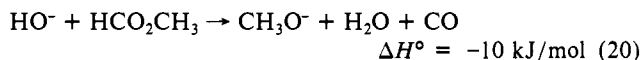
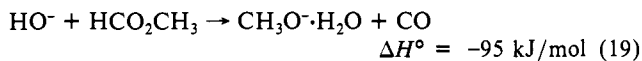
Methyl Formate. (a) α -Elimination. The reaction of formate esters with bases in the gas phase by formyl proton abstraction, loss of CO, and formation of alkoxide ions or alkoxide ion clusters (eq 2) has been extensively studied by Riveros and co-workers.⁵ The relative amount of free methoxide ions formed appears to depend upon the exothermicity of the reactions and the strength of the hydrogen bond between A^- and CH_3OH (or CH_3O^- and HA). As pointed out by Riveros, the formation of the cluster ion can be written as the sum of two parts (eq 16 and 17). In order $\text{HCO}_2\text{CH}_3 \rightarrow \text{CH}_3\text{OH} + \text{CO}$ $\Delta H^\circ = 38.5$ kJ/mol (16)



for $\text{A}^- \cdot \text{HOCH}_3$ to be formed directly in the α -elimination reaction, the bond dissociation energy (BDE) of $\text{A}^- \cdot \text{HOCH}_3$ must be greater than 38.5 kJ/mol (eq 18).

The present results, together with data from other studies, are summarized in Table VI. From these results it can be concluded that no cluster ions are formed directly by anions more basic than HO^- . Instead, exothermic proton abstraction from the formyl

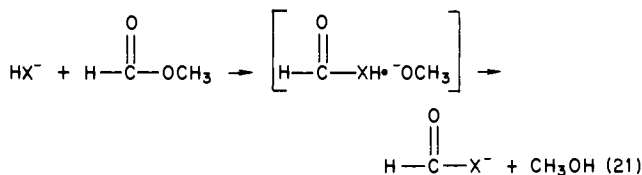
group gives rise initially to a stable, though reactive, $(\text{M} - \text{D})^-$ species (see Figure 1 and eq 12). Dissociation of an initially formed cluster ion, however, can occur if the exothermicity of the reaction is in large excess of the BDE of the cluster. This could be one reason why no cluster ions are formed directly in the cases of the amide ions.^{5b} With HO^- , both clustered and unclustered ions are formed; both reactions are exothermic (eq 19 and 20).



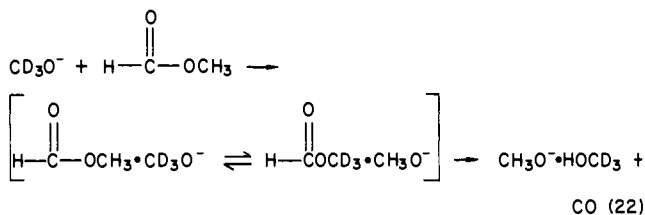
From Table VI it can be further seen that charge localized anions with a somewhat lower basicity than HO^- do give cluster ions whereas no such ions are formed when charge delocalized carbanions react with methyl formate.

Finally, the base A^- must be strong enough to initiate the process by abstracting the formyl proton. From H-D exchange studies it has been shown that there is sufficient energy in some ion-dipole complexes to allow proton abstractions which are up to 80 kJ/mol endothermic.¹⁷ If, as we believe,⁹ the formyl proton in methyl formate is about as acidic as that in water, one might expect α -elimination by F^- but not by weaker bases. This is indeed what is found.

(b) Carbonyl Addition. A second important reaction is nucleophilic addition to the carbonyl group. This reaction ($\text{B}_{\text{AC}2}$) is most obvious if the attacking base has a proton which can be removed by the departing methoxide ion. The reaction is driven



to completion by this exothermic step and the $\text{B}_{\text{AC}2}$ reaction is revealed. This is the case, for example, for NH_2^- , $\text{C}_2\text{H}_5\text{NH}^-$, HO^- , and the several carbanions studied. If the attacking base does not have a proton which can be removed after reaction, one cannot be certain whether or not carbonyl attack occurs, although it is reasonable to suppose that it does. For example, we believe that CD_3O^- and CH_3O^- react both at the carbonyl group and at the formyl proton. However, no unlabeled methoxide ion is observed as a product; α -elimination occurs before CH_3O^- can escape from the complex and only the methoxide-methanol complex is observed (eq 22). The large amount of CH_3O^- and products of its further

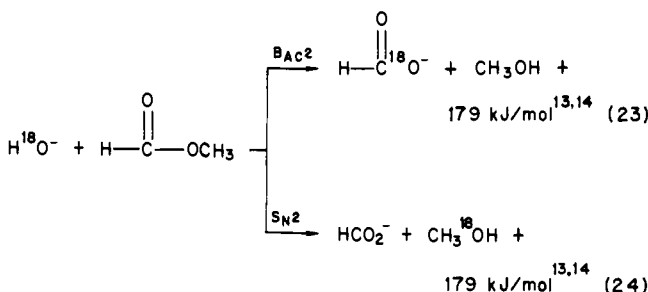


reaction observed in the $(\text{CH}_3)_2\text{N}^- / \text{DCO}_2\text{CH}_3$ experiments (Table I) leads us to believe that CH_3O^- is formed directly by $\text{B}_{\text{AC}2}$ reaction in this case, but we cannot determine the amount.

If we compare carbanions reacting with methyl formate, we see that charge delocalized ones ($\text{CH}_2=\text{CH}-\text{CH}_2^-$, $\text{N}\equiv\text{C}-\text{C}-\text{H}_2^-$, $\text{HC}\equiv\text{C}-\text{CH}_2^-$) react primarily at the carbonyl group, no matter what their basicity; α -elimination is almost nonexistent for these anions. In contrast, charge localized anions (C_6H_5^- , $\text{CH}_3\text{C}\equiv\text{C}^-$) give much more or mainly α -elimination. It seems clear that there is a kinetic barrier to proton transfer from one carbon to another in the gas phase, just as in solution, and that the barrier is greater to and from a charge delocalized anion than to and from a charge localized one. Similar observations have been made for gas-phase H-D exchange reactions, which are rare from one carbon to another.¹⁸

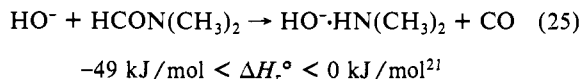
We should note that the reaction between HO^- and 10% ^{18}O -enriched methyl formate has recently been examined in the ICR.¹⁹ The authors did not detect the formation of any H^{18}O^- , and so concluded that reversible addition to the carbonyl group does not occur. We wish to point out, however, that oxygen exchange of this type must involve not only reversible addition but also rapid proton transfer between the oxygens. In our opinion, the lack of exchange may well be due to the slowness of this latter process.

(c) **S_N2 Reaction.** Bimolecular nucleophilic substitution is at best a minor pathway in all of these systems. For hydroxide ion, both carbonyl attack and S_N2 substitution lead to the same products, but distinction is easily achieved with the use of H^{18}O^- (eq 23 and 24). The FT-ICR and SIFT measurements agree

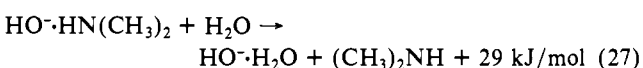
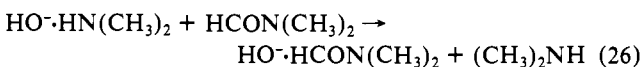


well and are only slightly different from earlier measurements using the drift cell ICR.^{1,5d}

N,N-Dimethylformamide. (a) **α -Elimination.** Amide bases do not give α -elimination with DMF; in all cases studied, the sole or predominant reaction is proton abstraction. Neither cluster ions nor dimethyl amide ions are observed as products. α -Elimination is a significant reaction only for hydroxide ion:



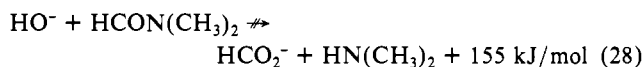
The occurrence of this reaction shows that the BDE($\text{HO}^-\cdot\text{HN}(\text{CH}_3)_2$) is larger than 62 kJ/mol (similar treatment as given for methyl formate). The cluster ion can undergo switching reactions with $\text{HCON}(\text{CH}_3)_2$ and H_2O as shown in eq 26 and 27. Because



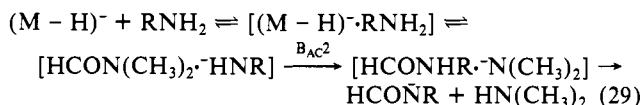
a switching reaction is seen between the hydroxide-dimethylamine complex and water, an upper limit of 111 kJ/mol can be set on the BDE of the former. The enthalpy change for this switching reaction has been calculated using the values given in ref 9. When a value of 105 kJ/mol²² is used for the BDE of $\text{HO}^-\cdot\text{H}_2\text{O}$, the upper limit to the BDE of $\text{HO}^-\cdot\text{HN}(\text{CH}_3)_2$ becomes 105 kJ/mol and the enthalpy change for eq 27 is -23 kJ/mol.

(b) **Carbonyl Addition.** Addition to the carbonyl group of DMF is, as might be expected, more difficult than for addition to methyl formate. Strong bases give predominantly or exclusively proton abstraction whereas HO^- reacts predominantly (Table IV) or

exclusively (Table V) via a fast α -elimination. The reason for the absence of carbonyl addition in these systems is kinetic rather than thermochemical. For example, carbonyl addition by HO^- would result in HCO_2^- and this reaction is more exothermic than the α -elimination (compare eq 25 and 28).^{13,14}



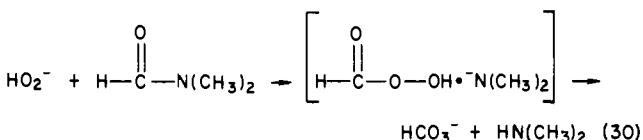
For amide ions, proton abstraction occurs more rapidly than carbonyl addition. However, carbonyl addition can occur in secondary reactions between ($\text{M}-\text{H}$)⁻ ions and the amines (eq 29).²³ The second complex in this reaction sequence will have



a different energy than when formed by reaction of DMF with HNR^- . The B_{Ac^2} reaction can, therefore, be more competitive with proton abstraction.

In the FT-ICR this process is of minor importance for NH_3 . In the FA, where there is a large excess of NH_3 and numerous collisions between ($\text{M}-\text{H}$)⁻ and NH_3 occur, reaction 29 is more pronounced, and approximately equal abundances of the HCONH^- and ($\text{M}-\text{H}$)⁻ ions are observed. The rate of this reaction will, of course, depend on the difference in acidity between DMF and the amine. For example, the process is faster for $n\text{-C}_3\text{H}_7\text{NH}_2$ than for NH_3 in the FT-ICR.

Of the anions studied only HO_2^- reacts exclusively at the carbonyl group. The reaction is quite fast and produces performate ions (eq 30). The difference in reactivity of HO_2^- and HO^- can



be understood in terms of the lower proton affinity²⁴ of HO_2^- which causes the α -elimination to be more difficult. The difference in reactivity between HO_2^- and CH_3O^- with DMF is understood in terms of the intermediate formed in reaction 30. For CH_3O^- , the reaction intermediate has no acidic protons and, hence, cannot be trapped.

For $(\text{CH}_3)_2\text{N}^-$ no exothermic step can follow the displacement of dimethyl amide ion, so no product of carbonyl attack is observed. In the SIFT a stable cluster of CH_3O^- and DMF is observed and in the FT-ICR a very slow α -elimination reaction occurs.

Acknowledgment. C.H.D., J.J.G., and V.M.B. thank the National Science Foundation, under Grant CHE82-03110, and S.I. and N.M.M.N. thank the Netherlands Organization for Pure Research (SON/ZWO) for financial support of this work.

Registry No. DCO_2CH_3 , 23731-38-6; $\text{DCON}(\text{CH}_3)_2$, 2914-27-4; NH_2^- , 17655-31-1; C_2H_5^- , 25013-41-6; $(\text{CH}_3)_2\text{N}^-$, 34285-60-4; H^{18}O^- , 65553-37-9; NCCH_2^- , 21438-99-3; H^- , 12184-88-2; $\text{CH}_3^{18}\text{O}^-$, 94203-51-7; C_6H_5^- , 30922-78-2; $\text{CH}_2=\text{CHCH}_2^-$, 1724-46-5; $\text{CH}_3\text{SCH}_2^-$, 61192-31-2; $\text{CH}_2=\text{C}=\text{CH}^-$, 64066-06-4; $\text{CH}_3\text{C}\equiv\text{C}^-$, 36147-87-2; $\text{C}_2\text{H}_5\text{O}^-$, 16331-64-9; $\text{HC}\equiv\text{C}^-$, 29075-95-4; $\text{C}_3\text{H}_7\text{O}^-$, 26232-83-7; F^- , 16984-48-8; H_2P^- , 13937-34-3; HS^- , 15035-72-0; CN^- , 57-12-5; NO_2^- , 14797-65-0; Cl^- , 16887-00-6; Br^- , 24959-67-9; HO^- , 14280-30-9; CH_3O^- , 3315-60-4; HO_2^- , 14691-59-9; S_2^- , 12185-15-8; N_3^- , 14343-69-2; ND_2^- , 22856-00-4; $\text{C}_3\text{H}_7\text{NH}^-$, 62063-12-1; DO^- , 17693-79-7; CD_3O^- , 51679-31-3; methyl formate, 107-31-3; *N,N*-dimethylformamide, 68-12-2.

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