59–60 °C, the spectral properties of which were identical to those of the original sample.

Competitive Rate Studies. Since the relative rates of each reaction were measured by VPC analysis of the ratio of unreacted starting materials, the detector responses to **2a–c** were calibrated. This was accomplished by the preparation of standard solutions of the olefins containing an internal standard and VPC analysis of the mixtures to obtain correction factors according to eq 2.[57]

$$F = \left[\frac{(\text{wt of olefin})(\%\ \text{purity})}{(\text{wt of standard})(\%\ \text{purity})}\right]\left[\frac{\text{standard area}}{\text{olefin area}}\right] \qquad (2)$$

Since it was necessary (because of retention times) to use two sets of VPC parameters, one for comparing olefins **2a** and **2b** and another for **2a** and **2c**, two standard solutions were prepared by using two separate internal standards (dibenzyl ether and 2-methylnaphthalene, respectively).

Three VPC traces were made for each solution and the average of the relative areas measured by an accurate weighing of the photoreproduced peaks of the chromatographs.

The reactions were conducted as described earlier using a limiting amount of electrophile (0.4 equiv) on a mixture of **2a** and **2b** or **2a** and **2c**, followed by analysis of unreacted starting materials. The reaction conditions were precisely those used to ascertain stereoselectivities of each substrate–reagent pair. Each reaction was run in duplicate to assure reproducibility.

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Gas-Phase Reactions of Negative Ions with Alkyl Nitrites

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Abstract: The gas-phase reactions of F^-, NH_2^-, OH^-, and a variety of carbanions with a series of alkyl nitrites (methyl, ethyl, *n*-butyl, isoamyl, and neopentyl) are reported. The reactions of F^- were studied by the selected ion flow tube technique while all other reactions were examined in a conventional flowing afterglow system. For fluoride ion, E2 reactions occur exclusively for nitrites containing β-hydrogens, S_N2 processes dominate for methyl nitrite, and $E_{CO}2$ reactions occur for neopentyl nitrite. The high specificity of product formation is discussed in terms of potential surfaces, and reaction rate constants are compared to calculated collision rates. The reactions of carbanions with neopentyl nitrite proceed primarily by nitrosation followed by proton transfer or by nitrosation followed by a reverse Claisen-type condensation. Finally, NH_2^- and OH^- react rapidly with most nitrites to form NO_2^-; NH_2^- reacts with neopentyl nitrite to generate HN_2O^-. These data are compared and contrasted to some recent results from ion cyclotron resonance experiments.

Introduction

Alkyl nitrites are highly reactive reagents[1] capable of undergoing many different types of reactions, both in solution and in the gas phase. The nitroso group is electrophilic and hence susceptible to attack by nucleophiles; in solution carbanions react readily with alkyl nitrites, forming nitroso compounds and, by tautomerization, oximes. The mechanism involves a typical Claisen-type condensation which has often been exploited in synthesis. The nitrite ion is also a potentially good leaving group in substitution and elimination reactions. Thermally and photochemically, alkyl nitrites undergo homolytic cleavage to form NO and alkoxy radicals. This great diversity of reaction pathways makes nitrites potentially useful substrates for gas-phase ion synthesis reactions and for studies of the mechanisms of gas-phase ion–molecule interactions.

Although alkyl nitrites have been widely used as sources of alkoxide ions upon their interaction with low-energy electrons, relatively little is known about their gas-phase ion–molecule chemistry. McAllister and Pitman[2] have compared the ion–molecule reactions of methyl nitrite and nitromethane in an ion cyclotron resonance (ICR) experiment. McMahon and Farid[3] have studied some of the primary and secondary products resulting from electron impact on a series of alkyl nitrites. Recently, Noest and Nibbering[4] have described negative ion reactions of a variety of alkyl nitrites in an ICR, and Klass and Bowie[5] have reported the reactions of a series of enolate ions with methyl nitrite also in an ICR spectrometer.

In this paper we report a flowing afterglow (FA) and selected ion flow tube (SIFT) study of the reactions of methyl, ethyl, *n*-butyl, isoamyl, and neopentyl nitrites with a variety of negative ions. The reactions of fluoride ion proceed by substitution and/or elimination channels and shed some new light on the mechanisms and energy surfaces of gas-phase ion–molecule reactions. Carbanions react in the gas phase mainly as they do in solution, i.e., by nitrosation. The resulting nitroso compounds, however, can undergo further interesting and informative fragmentation reactions which imply the existence of long-lived ion–dipole complexes.

Our results reveal some important and intriguing differences between gas-phase ion–molecule chemistry in the relatively high-pressure (0.5 torr) regime of the FA and in the low-pressure (10^{-5} torr) technique of ICR spectroscopy.

Experimental Section

The reactions of alkyl nitrites with amide ion, hydroxide ion, and a variety of carbanions were carried out in a conventional flowing afterglow apparatus which has been described previously.[6] Typical pressures and

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Table I. Reactions of F^- with RX

RX	products	%	ΔH_{rxn},[a] kcal/mol	k_{exptl}, 10^{-9} cm^3 $molecule^{-1}$ s^{-1}	k_{exptl}/k_{ADO}[b]
CH_3ONO	$NO_2^- + CH_3F$	79	−64	2.1	0.83
	$NO^- + HF + CH_2O$	18[c]	+6[d]		
	$NO^-(HF) + CH_2O$	3	−9[e]		
CH_3CH_2ONO	$NO_2^- + HF + C_2H_4$	100	−51	3.4	1.2
$CH_3(CH_2)_3ONO$	$NO_2^- + HF + C_4H_8$	100	−53	3.0	1.0
$(CH_3)_2CH(CH_2)_2ONO$	$NO_2^- + HF + C_5H_{10}$	100	−52	3.4	1.1
$(CH_3)_3CCH_2ONO$	$NO_2^- + (CH_3)_3CCH_2F$	0	−58	3.1	1.0
	$NO^- + HF + (CH_3)_3CCHO$	85[c]	+7[d]		
	$NO^-(HF) + (CH_3)_3CCHO$	15	−8[e]		
CH_3Cl	$Cl^- + CH_3F$	100	−29	0.8[f] 1.9[g]	0.35 0.83
$(CH_3)_3CCH_2Cl$	$Cl^- + (CH_3)_3CCH_2F$	100	−29	0.49[f]	0.17

[a] Thermochemical data from references 10-15. [b] k_{ADO} = theoretical collision rate constant. See reference 8. [c] The production of NO^- was not directly detected but was inferred as described in the text. [d] The entropy contribution makes the free energy term negative. [e] The $NO^- \cdots HF$ bond strength is assumed to be 15 kcal/mol. [f] ICR rate constants.[16] [g] FA rate constants.[17]

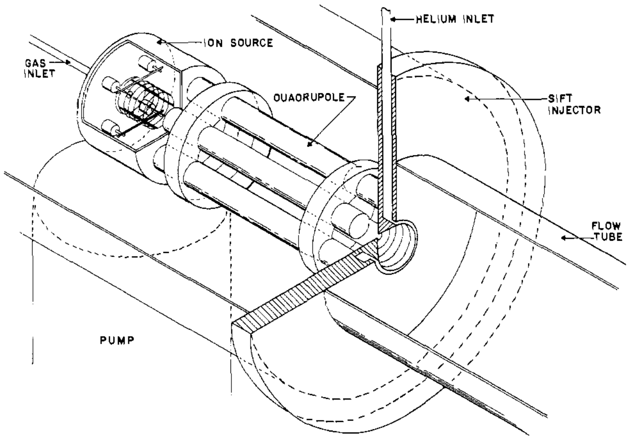

Figure 1. Schematic diagram of the ion source region of the selected ion flow tube.

flow rates of the helium buffer gas were 0.4 torr and 200 STP cm^3 s^{-1}, respectively. Amide ion was generated by dissociative electron attachment to ammonia while hydroxide ion was produced by electron bombardment on nitrous oxide to form $O^-\cdot$, with subsequent hydrogen atom abstraction from methane. Carbanions were generated by proton abstraction with amide from the parent hydrocarbons.

The reactions of fluoride ion were studied in a flowing afterglow system modified to function as a selected ion flow tube (SIFT);[7] in this configuration, a quadrupole mass filter is interposed between a low-pressure ion source and the flow tube. The ion injection region is shown in detail in Figure 1. Fluoride ions are generated in a Brinks-type ion source (10^{-3} torr) by electron impact on NF_3. A tungsten filament (0.008-in. diameter) maintained at −100 V is used as an electron source. Tantalum and thoriated iridium were also tried as filament materials but were found to have very short lifetimes, 1–20 min, in NF_3. The tungsten filaments generally lasted 3–6 h. The ions are born within a cylindrical grid which is held at a potential between −1 and −40 V; this potential determines the injection energy of the ions. The ions are mass selected in a quadrupole mass filter (4-in.-long, 1/4-in.-diameter rods) and injected through a 2-mm orifice into the flow tube (100 cm × 7.6-cm i.d.) by the venturi action of an annular helium inlet of radius $^7/_{16}$ in. and width $^1/_{64}$ in. The helium flow is normally 150–250 STP cm^3 s^{-1}, resulting in flow tube pressures of 0.3–0.5 torr. The neutral reactants are added 40–50 cm downstream from the ion injector. Ionic products are sampled through a 0.5-mm orifice into a low-pressure region, mass analyzed by a quadrupole mass spectrometer, and detected by an electron multiplier.

Under normal operating conditions fluoride ion signals were 4000 ions/s. Adding 20% argon upstream from the injector increases the ion intensity by a factor of about 2 and does not affect the reaction rates or branching ratios. Addition of a trace amount of SF_6 downstream of the injector did not change the fluoride intensity and $SF_6^-\cdot$ was not observed under these conditions, confirming that few electrons are present in the flow tube. Experimental results were independent of injection energies over the range 10–40 V.

Kinetic data were obtained from semilog plots of reactant ion intensity vs. flow rate of the neutral reactant. Neutral flow rates were obtained by measuring the pressure increase with time in a calibrated volume. Branching ratios were calculated by extrapolation of the percent product spectrum to zero neutral flow. Average dipole orientation collision rate constants (k_{ADO}) were calculated by the method of Su and Bowers.[8]

Most nitrites were prepared by dripping hydrochloric acid into a solution of the appropriate alcohol and sodium nitrite in water.[9] The crude nitrites were purified by distillation from solid KOH and stored for periods of less than 1 week at −40 °C before use. Isoamyl nitrite was obtained from Matheson and purified before use. The deuterated alcohols used to prepare the deuterated nitrites were made by reduction of pivalaldehyde and pivalic anhydride with lithium aluminum deuteride and an isotopic purity of >95% was confirmed by NMR.

Results and Discussion

Reactions of F^- with Alkyl Nitrites. Fluoride ion, produced in the SIFT, was allowed to react with a series of alkyl nitrites, RONO (R = methyl, ethyl, *n*-butyl, isoamyl, and neopentyl). The rate constants, product distributions, and reaction enthalpies are summarized in Table I. For the first four nitrites NO_2^- is the sole or major product.

The reaction of fluoride with neopentyl nitrite generates an ion of *m/z* 50, and an ion of the same mass is formed in small amounts from methyl nitrite. We formulate this species as a hydrogen-bonded complex of NO^- and HF resulting from an elimination reaction to form a carbon–oxygen double bond ($E_{CO}2$ reaction) (eq 1). Hydrogen bonding between a neutral formed in the

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$$F^- + (CH_3)_3CCH_2ONO \rightarrow NO^-(HF) + (CH_3)_3CCHO \qquad (1)$$

reaction complex and the eliminated ion has been observed previously by Riveros and co-workers[18] in the α-elimination of alkoxide ions from alkyl formates, by Beauchamp and Sullivan[19] in the alkoxide-catalyzed elimination of fluoride from fluoroethanes, and by our laboratory in β-elimination reactions of ethers.[20] To confirm the proposed reaction mechanism we prepared deuterated neopentyl nitrite and found as predicted by eq 1 that an ion of m/z 51 is formed (eq 2). Reaction of fluoride with mono-

$$F^- + (CH_3)_3CCD_2ONO \rightarrow NO^-(DF) + (CH_3)_3CCDO \qquad (2)$$

deuterioneopentyl nitrite ($(CH_3)_3CCHDONO$) yields both $NO^-(HF)$ and $NO^-(DF)$ with relative rates, k_H/k_D, of approximately 2, indicating a significant deuterium isotope effect for this reaction.

Although $NO^-(HF)$ is the only ionic product observed in our study of the reactions of fluoride with neopentyl nitrite, this species accounts for only 15% of the fluoride ion decay. This net loss of ion signal can be explained by assuming that most of the elimination reaction results in formation of unclustered NO^-. The electron is so weakly bound in this ion (EA(NO) = 0.55 kcal)[21] that collisional detachment readily occurs at thermal energies.[22] To test this possibility we added the electron-scavenging agent sulfur hexafluoride[23] to the reaction mixture. The reaction rate and $NO^-(HF)$ intensity remained unchanged; however, $SF_6^-\cdot$ appeared in the product spectrum, demonstrating that electrons are generated in the reaction of fluoride with neopentyl nitrite. These data support the following reaction scheme:

$$F^- + (CH_3)_3CCH_2ONO$$

$$\xrightarrow{15\%} NO^-(HF) + (CH_3)_3CCHO \qquad (3a)$$

$$\xrightarrow{85\%} NO^- + HF + (CH_3)_3CCHO \qquad (3b)$$

$$NO^- + He \rightarrow e^- + NO + He \qquad (4)$$

The reaction of fluoride with methyl nitrite exhibits both the $E_{CO}2$ mechanism (eq 5a,b) as well as a substitution process (eq 5c).

$$F^- + CH_3ONO \xrightarrow{3\%} NO^-(HF) + CH_2O \qquad (5a)$$

$$\xrightarrow{18\%} NO^- + HF + CH_2O \qquad (5b)$$

$$\xrightarrow{79\%} NO_2^- + CH_3F \qquad (5c)$$

Since NO^- is not detected as a product, the relative contribution of reactions 5a and 5b is assumed to be similar to that of reactions 3a and 3b. The production of NO_2^- must occur by an S_N2 reaction since the only other available mechanism (α-elimination to form NO_2^-, HF, and CH_2) is endothermic by approximately 20 kcal/mol.[10-15] Gas-phase nucleophilic substitution reactions involving methyl halides are common and have been studied in detail.[16,17]

For alkyl nitrites containing β-hydrogen atoms (ethyl, n-butyl, and isoamyl) $E_{CO}2$, S_N2, and E2 processes are energetically accessible. However, reaction of fluoride with these nitrites forms exclusively NO_2^-, implicating either an S_N2 or E2 mechanism (eq 6a,b). In solution, compounds with good leaving groups on

$$F^- + CH_3CH_2ONO \xrightarrow{S_N2} NO_2^- + CH_3CH_2F \qquad (6a)$$

$$\xrightarrow{E2} NO_2^- + HF + C_2H_4 \qquad (6b)$$

primary carbons react primarily by substitution processes and S_N2 mechanisms have been assumed for analogous gas-phase reactions. Elimination mechanisms have generally been postulated only in cases where the ionic product is clustered with a neutral species generated in the elimination process. We believe, however, that gas-phase E2 reactions are more common than previously inferred and, in fact, predominate in the reaction of fluoride with alkyl nitrites containing β-hydrogen atoms. A comparison of the results of methyl and neopentyl nitrites demonstrates that steric factors are important in determining the relative contribution of S_N2 and $E_{CO}2$ mechanisms. Therefore methyl nitrite should have the largest $S_N2/E_{CO}2$ ratio ($\sim$4); our inability to detect any product from an $E_{CO}2$ mechanism in the reactions of fluoride with ethyl, n-butyl, and isoamyl nitrites therefore suggests that NO_2^- arises mainly from E2 rather than S_N2 pathways. In independent experiments we have shown that elimination is highly preferred over substitution in the reactions of amide and hydroxide ions with dialkyl ethers and epoxides.[20]

Use of the SIFT technique is essential for unambiguous assignment of product identities and distributions from the reactions of fluoride with the alkyl nitrites. Most other ion–molecule techniques, including the conventional FA, are complicated by the presence of electrons in the reaction region. Previous studies have shown that alkyl nitrites react readily with thermal electrons to form alkoxide ions.[24] The reaction of these ions with precursor alkyl nitrite can seriously obscure the reactions of interest. By utilizing our newly constructed selected ion flow tube, we obtained clean fluoride ion signals in the absence of electrons and precursor neutrals.

The reactions of fluoride ion with alkyl nitrites are intriguing mechanistically and can shed light on the detailed pathways of ion–molecule interactions. Recently, Olmstead and Brauman[16] and Pellerite and Brauman[25] have discussed a double-well potential model for gas-phase ion–molecule processes. Although the ionic and neutral reactants approach along an attractive surface, barriers may exist within the potential well due to a variety of factors. There is striking experimental evidence in support of this theory and the model has proven very useful in describing many reactive processes.

Olmstead and Brauman have shown that the variations in the rates of gas-phase S_N2 reactions can be explained by variations of the central barrier height in the double-well model; they demonstrated that the barrier height need not be greater than the initial energy of the reactants in order to decrease the rate appreciably. For those reactions which occur with high efficiency, for example

$$F^- + CH_3Cl \rightarrow Cl^- + CH_3F \qquad (7)$$

$$F^- + (CH_3)_3CCH_2Cl \rightarrow Cl^- + (CH_3)_3CCH_2F \qquad (8)$$

the central barrier lies sufficiently below the potential energy of the reactants as to have minimal effect. The similarity of the gas-phase rate constants for eq 7 and 8, as indicated in Table I, is surprising since nucleophilic attack on a neopentyl group in solution is several orders of magnitude slower than that on a methyl group.[1]

The experimental rate constants for reaction of fluoride with methyl, ethyl, n-butyl, isoamyl, and neopentyl nitrites are also summarized in Table I. Reaction efficiencies are determined from the ratio of the experimental rate constant, k_{exptl}, to the theoretical collision rate constant, k_{ADO}. For this calculation, dipole moments for some nitrites were obtained by extrapolation from known values and polarizabilities were calculated from refractive index data. The efficiency of reaction of fluoride with all alkyl nitrites is very high and therefore little information about the central barrier heights can be inferred.

However, there is an important difference in a comparison of the reactions of alkyl chlorides and nitrites. The nitrites contain two labile bonds, allowing for multiple reaction pathways. In the

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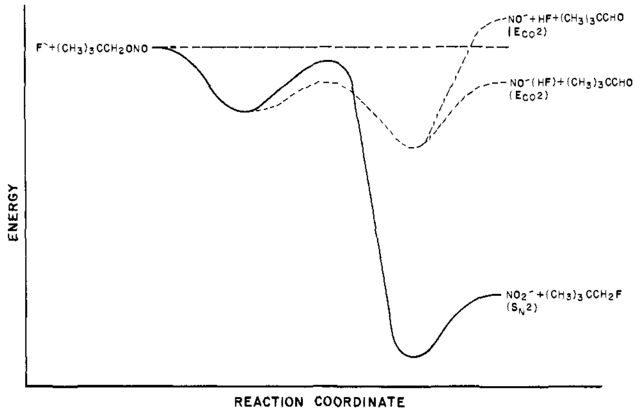


Figure 2. Schematic potential energy–reaction coordinate diagram for the reaction of fluoride ion with neopentyl nitrite. The channel producing NO⁻, although endothermic, is exoergic due to the increase in entropy. Products are observed from the $E_{CO}2$ pathways.

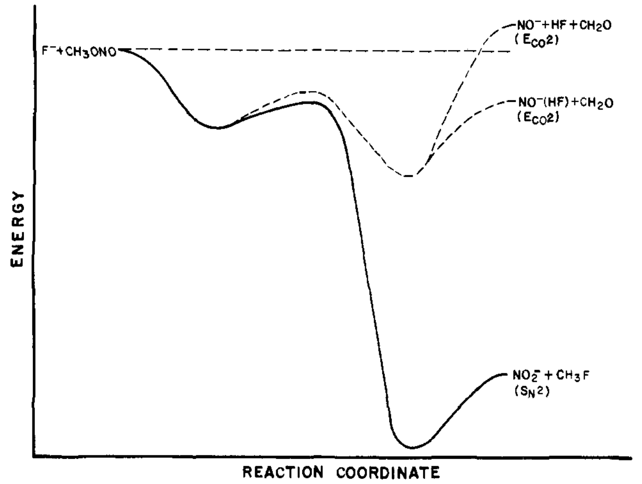


Figure 3. Schematic potential energy–reaction coordinate diagram for the reaction of fluoride ion with methyl nitrite. The channel producing NO⁻, although endothermic, is exoergic due to the increase in entropy. Products are observed from the S_N2 and $E_{CO}2$ pathways.

reaction of fluoride with neopentyl nitrite, three product channels are energetically accessible: two arising from an $E_{CO}2$ mechanism and a third arising from the highly exothermic S_N2 process. However, this latter channel is completely suppressed by the large steric hindrance of the neopentyl group and NO_2^- is not observed as a product. A schematic of the inferred potential energy diagram is shown in Figure 2. The relative energies of the reactants and three possible sets of products are shown as the initial and final asymptotes. The first potential well corresponds to a simple ion–dipole cluster of the reactants and the second set of wells corresponds to clusters of the products. The relative energy barriers for the $E_{CO}2$ and S_N2 reactions are deduced from the observed product distributions and are therefore not simple potential energy barriers; rather they include contributions from several sources, including differing densities of states for the two mechanisms. The high selectivity of this process is further illustrated by the significant isotope effect observed in the reaction of F^- with $(CH_3)_3CCHDONO$.

When the neopentyl group is changed to a methyl group, the steric barrier is decreased and products from both S_N2 and $E_{CO}2$ reactions are observed. Figure 3 summarizes the energetics of this reaction.

Nitrites containing β-hydrogen atoms may react via a third pathway, β-elimination. As described above, this channel dominates for the reactions of fluoride with ethyl, *n*-butyl, and isoamyl nitrites. This implies that E2 processes have low energy barriers relative to S_N2 or $E_{CO}2$ mechanisms. These results are schematically represented in Figure 4 for ethyl nitrite.

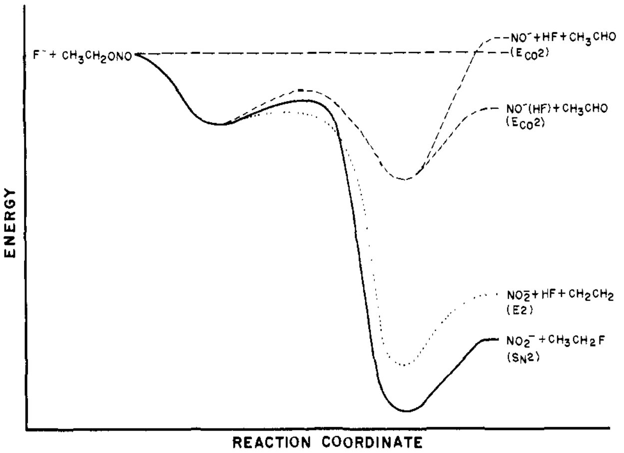
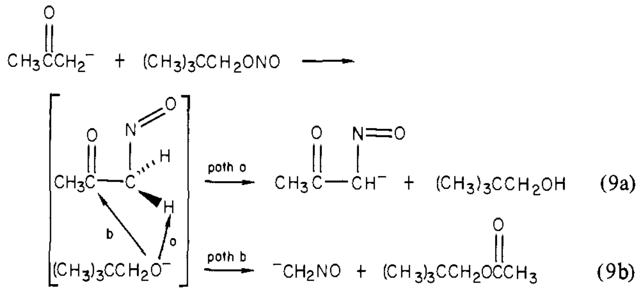


Figure 4. Schematic potential energy–reaction coordinate diagram for the reaction of fluoride ion with ethyl nitrite. The channel producing NO⁻, although endothermic, is exoergic due to the increase in entropy. Products are observed from the E2 pathway.

In summary, the efficiencies of reaction of fluoride with methyl, ethyl, *n*-butyl, isoamyl, and neopentyl nitrites are exceedingly high. The high specificity of reaction mechanism indicates that even though the barriers have little effect on the rate of the reaction, they completely control the outcome of the process when several channels are accessible. The double-well potential model is indeed useful for the description of these organic gas-phase ion–molecule reactions.

Chloride ion is a substantially poorer nucleophile and weaker base than fluoride ion (PA(F^-) = 371 kcal/mol; PA(Cl^-) = 333 kcal/mol).[15] Accordingly, chloride ion was found to be completely unreactive toward methyl, ethyl, *n*-butyl, isoamyl, and neopentyl nitrites under our experimental conditions.

Reactions of Carbanions with Alkyl Nitrites. The gas-phase reactions of carbanions with alkyl nitrites result in a wealth of interesting products as summarized in Table II. Many of these reactions involve complicated multiple rearrangements which imply the existence of a long-lived intermediate complex. These processes are exemplified by the reaction of acetone enolate with neopentyl nitrite, eq 9. The initial step involves nucleophilic attack by the carbanion on the nitrogen, generating alkoxide ion and a nitroso ketone. Before decomposition of this complex (I) two further reactions are possible. The most common pathway is proton abstraction to produce the resonance hybrid of a nitroso anion and oxime anion (path a). We have observed this reaction with ions derived from ketones, aldehydes, nitriles, alkenes, dienes, and alkynes. As Table II indicates, path a is generally the exclusive reaction channel for those anions without a carbonyl function (eq 10). In those cases where the nitrosation takes place α to a carbonyl group, the alkoxide may act as a nucleophile in a reverse Claisen-type condensation (path b). For the reaction of acetone enolate this generates the interesting product ion CH_2NO^-. If the enolate ion contains no abstractable hydrogens, then the re-



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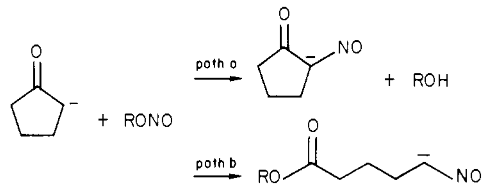
$$CH_2{=}CHCH_2^- + RONO \xrightarrow{\text{path a}} CH_2{=}CH\overset{-}{C}HNO + ROH \quad (10)$$

action proceeds exclusively by path b, for example

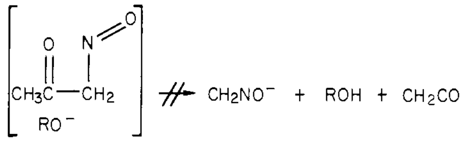
$$(CH_3)_2\bar{C}CHO + RONO \xrightarrow{\text{path b}} (CH_3)_2\bar{C}NO + ROCHO \qquad (11)$$

Both paths a and b are observed in the reactions of the enolates of the cyclic ketones cyclopentanone and cycloheptanone with the alkyl nitrites. In these examples, however, path b leads to the incorporation of the alkoxide into the anionic product.



(12)

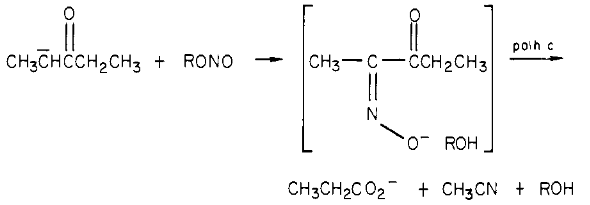
Reactions 11 and 12 are important in confirming the postulated reverse Claisen mechanism for path b and disproving an alternative elimination process which forms ketene



(13)

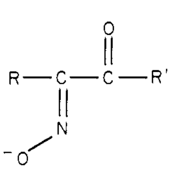
For an aldehydic reactant ion this second mechanism is not possible while for cyclic ketone anions this mechanism predicts anionic products different from those observed.

Anions from ketones larger than acetone can undergo a third reaction (path c) involving a rearrangement of the intermediate to give a carboxylate anion (eq 14). As shown in eq 14 diethyl ketone anion generates propionate ion in small but readily detectable quantities. The enolate anions generated by proton abstraction from methyl ethyl ketone ($^-CH_2COCH_2CH_3$ and $CH_3CO^-CHCH_3$) react with alkyl nitrites to form small amounts of acetate ion but no propionate ion. We thus have the apparent anomaly that dimethyl ketone forms no acetate, diethyl ketone forms propionate, and methyl ethyl ketone forms acetate but no propionate.

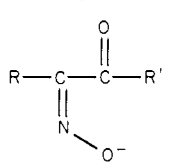


$$CH_3\bar{C}HC(=O)CH_2CH_3 + RONO \rightarrow \left[CH_3-C(=N-O^-)-C(=O)CH_2CH_3 \;\; ROH\right] \xrightarrow{\text{path c}} CH_3CH_2CO_2^- + CH_3CN + ROH \qquad (14)$$

These initially surprising results can be explained by assuming that proton abstraction from the initially formed nitroso ketone generates two stereoisomeric oxime anions, an anti (II) and a syn (III) form. We hypothesize that only the syn species can fragment to form the carboxylate anion. In an anion of a methyl ketone, R = H, the anti anion will be strongly favored by steric factors. Thus acetone enolate and the enolate from the methyl group of the methyl ethyl ketone are presumed to form only the anti anion and no detectable cleavage to acetate ion in the former or propionate in the latter occurs. For the enolate of diethyl ketone or from the ethyl moiety of methyl ethyl ketone, R = CH_3, and the anti oxime anion will be sterically hindered to some extent. Hence some syn anion will be formed and cleavage will result in the formation of propionate ion from diethyl ketone and acetate ion from methyl ethyl ketone.

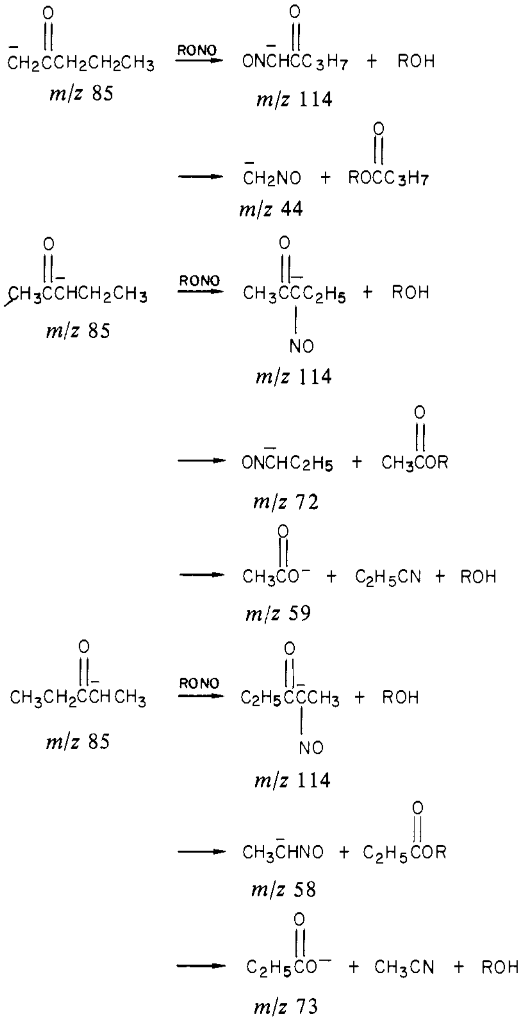


II



III

The various channels available for enolates reacting with neopentyl nitrite and the use of these reactions for the determination of ion structure are nicely illustrated by comparing the products from the reactions of the 2- and 3-pentanone anions:



$$\bar{C}H_2C(=O)CH_2CH_2CH_3 \xrightarrow{RONO} ON\bar{C}HC(=O)C_3H_7 + ROH \qquad (15a)$$

m/z 85 → m/z 114

$$\rightarrow \bar{C}H_2NO + ROC(=O)C_3H_7 \qquad (15b)$$

m/z 44

$$CH_3C(=O)\bar{C}HCH_2CH_3 \xrightarrow{RONO} CH_3C(=O)\bar{C}(NO)C_2H_5 + ROH \qquad (16a)$$

m/z 85 → m/z 114

$$\rightarrow ON\bar{C}HC_2H_5 + CH_3C(=O)OR \qquad (16b)$$

m/z 72

$$\rightarrow CH_3C(=O)O^- + C_2H_5CN + ROH \qquad (16c)$$

m/z 59

$$CH_3CH_2C(=O)\bar{C}HCH_3 \xrightarrow{RONO} C_2H_5C(=O)\bar{C}(NO)CH_3 + ROH \qquad (17a)$$

m/z 85 → m/z 114

$$\rightarrow CH_3\bar{C}HNO + C_2H_5C(=O)OR \qquad (17b)$$

m/z 58

$$\rightarrow C_2H_5C(=O)O^- + CH_3CN + ROH \qquad (17c)$$

m/z 73

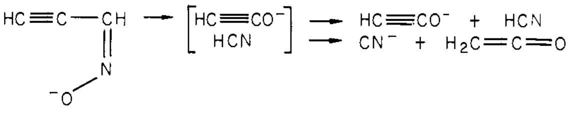
We are able to generate specific isomeric anions, such as propargyl anion and methylacetylide ion, by fluoride displacement reactions of substituted trimethylsilanes.[26] Reaction of these ions with neopentyl nitrite confirms that these species are indeed distinct isomers. The propargyl anion has two hydrogens at the active site and therefore reacts quickly and completely by path a.

$$HC{\equiv}CCH_2^- + (CH_3)_3CCH_2ONO \rightarrow HC{\equiv}C\bar{C}HNO + (CH_3)_3CCH_2OH \qquad (18)$$

The isomeric methylacetylide ion, in contrast, does not react significantly with neopentyl nitrite.

$$CH_3C{\equiv}C^- + (CH_3)_3CCH_2ONO \nrightarrow \qquad (19)$$

About 45% of the nitroso ion formed by the reaction of propargyl anion with neopentyl nitrite fragments to produce three additional ions, which we have identified as CN^-, $HC{\equiv}CO^-$, and CNO^-. The first two might arise by a reaction similar to path c.



$$HC{\equiv}C-CH{=}N-O^- \rightarrow \left[\begin{matrix}HC{\equiv}CO^- \\ HCN\end{matrix}\right] \rightarrow HC{\equiv}CO^- + HCN \qquad (20a)$$

$$\rightarrow CN^- + H_2C{=}C{=}O \qquad (20b)$$

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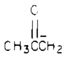
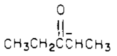
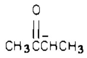
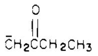
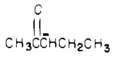
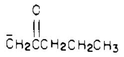
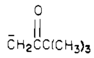
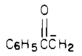
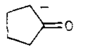
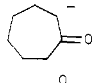
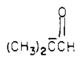
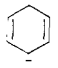
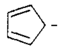
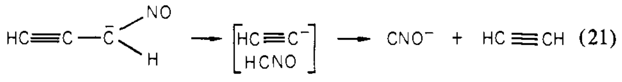
[26] DePuy, C. H.; Bierbaum, V. M.; Flippin, L. A.; Grabowski, J. J.; King, G. K.; Schmitt, R. J.; Sullivan, S. A. *J. Am. Chem. Soc.* **1980**, *102*, 5012–5015.

Table II. Reactions of R^- with Neopentyl Nitrite

R^-	products		
	path a[a]	path b[b]	path c[c]
 $CH_3C(=C)\bar{C}H_2$	+[d]	+	–[d]
 $CH_3CH_2C(=O)\bar{C}HCH_3$	+	+	+
 $CH_3C(=O)\bar{C}HCH_3$	+	+	+
 $\bar{C}H_2C(=O)CH_2CH_3$	+	+	–
 $CH_3C(=C)\bar{C}HCH_2CH_3$	+	+	+
 $\bar{C}H_2C(=C)CH_2CH_2CH_3$	+	+	–
 $\bar{C}H_2C(=O)C(CH_3)_3$	+	+	–
 $C_6H_5C(=O)\bar{C}H_2$	+	+	–
	+[e]	+	+[e]
	+[e]	+	+[e]
 $(CH_3)_2\bar{C}C(=O)H$	–	+	–
$\bar{C}H_2CN$	+	–	–
$\bar{C}H_2NO_2$	+	–	–
$CH_2{=}CHCH_2^-$	+	–	–
	+	–	–
$CH_2{=}CHCH{=}CHCH_2^-$	+	–	–
$\bar{C}H_2C{\equiv}CH$	+	–	–
$CH_3C{\equiv}C^-$	–	–	–
$CH_3CH_2C{\equiv}C\bar{C}HCH_3$	+	–	–
$[(C_3H_7C{\equiv}CH){-}H]^-$	+	–	–
	–	–	–

[a] Nitrosation followed by proton transfer; for example, eq 9a. [b] Nitrosation followed by reverse Claisen-type condensation; for example, eq 9b. [c] Path a followed by fragmentation to a carboxylate ion; for example, eq 14. [d] "+" indicates the product was observed. "–" indicates the product was not observed. [e] Reaction products from paths a and c have the same *m/z* value. An ion corresponding to this mass was observed.

The cleavage product $HC{\equiv}CO^-$ has also been observed in the reaction of O_2 with propargyl anion. The third ion, CNO^-, can also arise by dissociation of the nitroso anion.

 (21)

$$HC{\equiv}C{-}\bar{C}(NO)H \rightarrow \left[\begin{matrix} HC{\equiv}C^- \\ HCNO \end{matrix}\right] \rightarrow CNO^- + HC{\equiv}CH \quad (21)$$

The reactions of carbanions described in this section are general for a variety of alkyl nitrites. However, with most nitrites (methyl, ethyl, *n*-butyl, and isoamyl) NO_2^- is also a major product, arising by either an elimination (E2) or a substitution reaction (S_N2).

$$CH_2{=}CHCH_2^- + CH_3ONO \xrightarrow{S_N2} NO_2^- + CH_2{=}CHCH_2CH_3 \quad (22)$$

$$CH_2{=}CHCH_2^- + CH_3CH_2ONO \xrightarrow{E2} NO_2^- + CH_2{=}CH_2 + CH_2{=}CHCH_3 \quad (23)$$

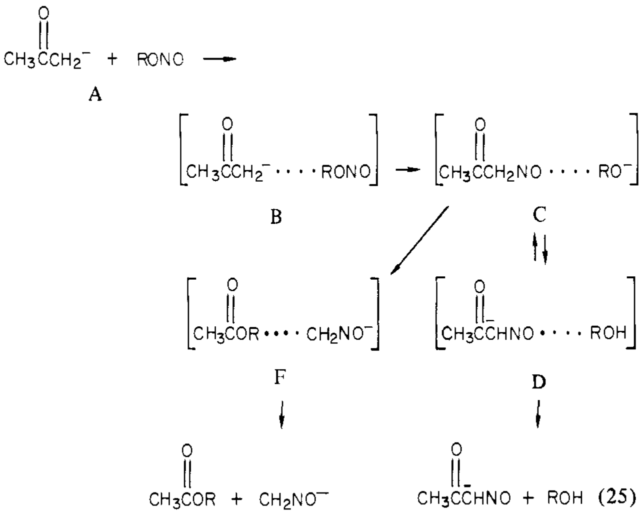
For the reactions of neopentyl nitrite both of these pathways are blocked and NO_2^- production is minimized.

The reactions of carbanions with alkyl nitrites exhibit a wealth of ion–molecule chemistry. Many of the products can be explained in terms of simple organic mechanisms which have been well characterized in solution. Most of the reactions suggest the initial formation of an intermediate reaction complex in which the ionic and neutral components are bound for periods long enough to facilitate one or more rearrangements. These multiple reactions must occur within the initially formed complex because under our reaction conditions a neutral product (e.g., nitroso ketone in I) which leaves the complex will never be reionized. The existence of long-lived ion-dipole complexes appears to be a common phenomenon in gas-phase anion chemistry. One example was previously reported for the reaction of allyl and other carbanions with nitrous oxide in which the initial products are a complex of a diazomethane derivative and hydroxide ion but from which only the diazomethane anion emerges as a product.[27]

$$CH_2{=}CHCH_2^- + N_2O \rightarrow [CH_2{=}CHCH{=}N{=}N + OH^-] \rightarrow CH_2{=}CH\bar{C}{=}N{=}N + H_2O \quad (24)$$

Although the rearrangements required in the alkyl nitrite reactions are complex, they do not significantly decrease the overall efficiency of the reaction; for example, the rate constant for reaction of acetone enolate with neopentyl nitrite is 4.4×10^{-10} cm^3 $molecule^{-1}$ s^{-1}, which is about 20% of the theoretical (ADO) collision rate. It is interesting to note that although nitrosation and formation of an alkoxide ion is a reasonable initial step in the reaction sequence, we have not been able to observe this product directly. The products of the reaction are certainly consistent with the picture of a "free" alkoxide ion within the complex, and the reactions involving the cyclic enolate ions indicate that alkoxide is capable of nucleophilic attack on the carbonyl group. Further fragmentation of the ions formed after loss of the alcohol, for example, reactions 14, 20, and 21, indicates that these ions may be produced with considerable internal energy.

An extended potential energy surface is required to describe the more complex reactions of carbanions with alkyl nitrites. Consider the interaction of the acetone enolate with an alkyl nitrite, RONO:



(25)

The separated reactants A are attracted by ion–dipole and ion–induced dipole forces and generate an ion–molecule cluster complex, B. Nitrosation results in a new complex C, which has two

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(27) Bierbaum, V. M.; DePuy, C. H.; Shapiro, R. H. *J. Am. Chem. Soc.* **1977**, *99*, 5800–5802.

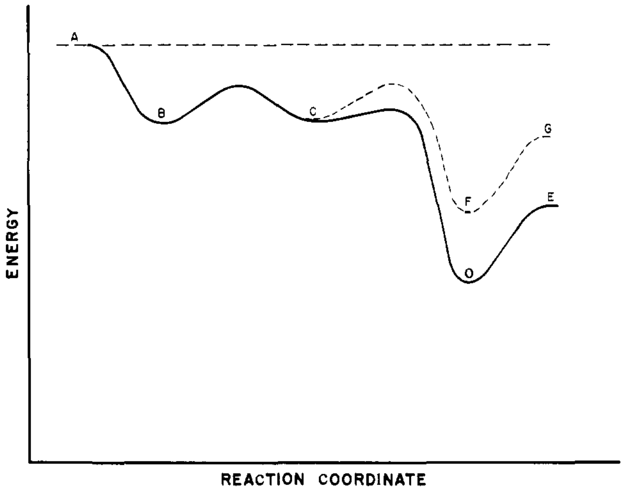

Figure 5. Schematic potential energy–reaction coordinate diagram for the reaction of acetone enolate with neopentyl nitrite as described by eq 25. Products are observed from both pathways.

possible fates. Simple proton abstraction by the alkoxide ion forms a cluster, D, which dissociates to observed products E. Alternatively, the alkoxide ion in complex C can initiate a reverse Claisen-type condensation, generating the cluster F and subsequently the separated products G. This reaction sequence is summarized schematically in Figure 5. The energy barriers between complexes B and C and complexes C and F are expected to be high since they involve nucleophilic displacement processes. In contrast, the barrier between complexes C and D involves simple proton transfer; this barrier is therefore very low and the interconversion of complexes C and D may in fact be reversible.

Reactions of NH_2^- and OH^- with Alkyl Nitrites. The reactions of the strong gas-phase bases NH_2^- and OH^- were studied with methyl, *n*-butyl, isoamyl, and neopentyl nitrites. With the exception of neopentyl nitrite, the reactions of amide resulted exclusively in formation of NO_2^- by substitution (S_N2) or elimination (E2) pathways. In neopentyl nitrite these mechanisms are suppressed and nucleophilic attack at nitrogen becomes relatively more favorable, in analogy with path a for the carbanion reactions, forming HN_2O^- as the major product:

$$NH_2^- + (CH_3)_3CCH_2ONO \rightarrow HN_2O^- + (CH_3)_3CCH_2OH \quad (26)$$

Reaction 26 serves as a highly efficient gas-phase synthesis of this interesting ion.[28]

Reaction of alkyl nitrites with hydroxide by any of the possible pathways should result in the production of NO_2^- and indeed this is the only product experimentally observed. By analogy with the reactions of amide, we believe that simple nitrites react by S_N2 or E2 processes and neopentyl nitrite reacts by hydroxide ion attack on the NO group.

A large variety of inorganic anions (PH_2^-, SiH_3^-, GeH_3^-) can readily be prepared in the gas phase; conversion of these species to their corresponding nitroso anions should readily occur upon reaction with neopentyl nitrite. Measurements of the relative proton affinities of these nitroso anions or determination of the electron affinities of the corresponding neutral radicals should provide important information about stabilizing effects of third- and fourth-row elements on anions.

Comparison of FA and ICR Results. In a parallel study, Noest and Nibbering[4] have examined the reactions of a variety of anions with alkyl nitrites in an ion cyclotron resonance spectrometer. For the reactions of carbanions they have also observed products corresponding to eq 9a, namely, nitrosation followed by proton transfer. However, in striking contrast to our results they found that the acetone enolate and other similar ions do not exhibit nitrosation with reverse Claisen-type condensation to generate nitrosomethane anions, eq 9b. Similar results are reported by Klass and Bowie[5] but these latter authors did observe pathway 9b in anions (for example, the enolate of diisopropyl ketone) for which pathway 9a is impossible. There is thus a fundamental difference in the ionic products from these gas-phase ion–molecule reactions in a FA and an ICR. One of the major differences in the two techniques is that of pressure and, correspondingly, collision frequency of the ions. In the typically 0.5-torr buffer gas pressures of the flowing afterglow, there are 10^7–10^8 collisions per second between an ion and the bath of helium atoms; in the ICR technique, pressures are usually a factor of 10^5 lower and collision frequencies are 10^5 lower. One explanation of the differing results from these two techniques therefore can be that there are different energy distributions of the reactant ions. If the reactant ions in the ICR experiment contain excess kinetic or internal energy, then the initial nitroso–alkoxide complex C will have more internal energy and perhaps a shorter lifetime than in a flowing afterglow experiment. As a general rule proton transfer reactions are rapid in the gas phase while carbonyl addition reactions are slower. If the ion–dipole lifetime is shortened, the proton transfer reaction will be favored relative to the carbonyl addition reaction leading to the reverse Claisen process. Indeed, considering the expected rapidity of the proton transfer reaction, we believe that it may occur reversibly within the complex in order for the slower and essentially irreversible carbonyl addition reaction to be observed. Such reversible proton transfers occur readily in H–D exchange reactions of carbanions with ND_3, D_2O, or ROD. Equation 25 and Figure 5 summarize these ideas. If the ion–dipole complex in the flowing afterglow experiments has a sufficiently long lifetime, the more extensive molecular rearrangements required by carbonyl addition can occur and this intrinsically slower reaction can be observed.

An alternative but similar explanation assumes that the reactant ions in ICR experiments are at thermal energies but that in ion–dipole complexes in a FA the energy may be partially removed or redistributed by collisions with helium, thus increasing their lifetime. As described above, an ion collides with helium every 10^{-7}–10^{-8} s in a flowing afterglow experiment. Ion–dipole complexes can have lifetimes of this magnitude since third-body collisional stabilization of even simple complexes has been observed. Complexes involving large organic ions and neutrals will have considerably longer lifetimes since the excess energy can be dispersed into many vibrational and rotational states. In an exothermic reaction proceeding from the enolate ion and alkyl nitrite to the keto oxime anion and alcohol, the product complex will contain both the reaction exothermicity and the ion–dipole attraction energy. If even a small fraction of this energy is removed or redistributed by collision with helium, the complex lifetime may be prolonged enough to allow slower reactions to compete. In contrast, in the low-pressure regime of an ICR, the complex D may rapidly dissociate.

There is a second apparent contrast between FA and ICR results. Noest and Nibbering[4] have reported that fluoride ion does not react with alkyl nitrites in their drift cell ICR experiments while in our studies reaction was observed to occur on essentially every collision. Recently, Noest and Nibbering[29] have concluded that this difference arises from experimental difficulties associated with a low signal to noise ratio; in their newly constructed Fourier transform ICR, reaction 1 is observed to occur.

Conclusions

The reactions of gas-phase negative ions with alkyl nitrites reveal a rich and interesting chemistry. Fluoride ion reacts rapidly with methyl, ethyl, *n*-butyl, isoamyl, and neopentyl nitrites with rate constants exceeding 80% of the theoretical collision rate. S_N2 and $E_{CO}2$ pathways are energetically accessible for all of these reactants and an E2 channel becomes available for nitrites containing β-hydrogen atoms. Despite the variety of possible channels and the large rate constants, these reactions demonstrate high mechanistic

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[28] DePuy, C. H.; Bierbaum, V. M.; Schmitt, R. J.; Shapiro, R. H. *J. Am. Chem. Soc.* **1978**, *100*, 2920–2921.

[29] Noest, A. J.; Nibbering, N. M. M., private communication.

specificity. For example, the reaction of fluoride with neopentyl nitrite proceeds exclusively by the $E_{CO}2$ pathway, which is 60 kcal/mol less exothermic than the S_N2 reaction channel. The high selectivity in this reaction is further illustrated by a k_H/k_D isotope effect of about 2. These results provide important data on the relative barrier heights for these reactions in the double-well potential model described by Brauman and co-workers. Thus a coupling of organic probes with kinetic data can be useful in the detailed description of the potential energy surfaces which determine the course of the reaction.

The reactions of most carbanions with alkyl nitrites suggest the initial formation of an intermediate reaction complex in which the components are bound for periods long enough to permit one or more rearrangements. Many of the reactions can be explained in terms of simple organic mechanisms which have been well characterized in solution. A comprehensive mechanism for the reactions of carbanions with neopentyl nitrite involves nitrosation followed by proton transfer (path a) or nucleophilic attack on the carbonyl moiety (path b). In several cases fragmentation of the nitroso anion from path a can occur to generate a carboxylate ion (path c). These reactions generate a host of new and interesting species and can allow for the differentiation of isomeric reactant ions.

Finally, the strong gas-phase bases NH_2^- and OH^- react rapidly with most alkyl nitrites to form exclusively NO_2^- by mechanisms analogous to those discussed above. The reaction of amide with neopentyl nitrite generates the interesting product HN_2O^-.[28]

A comparison of flowing afterglow and ion cyclotron resonance results for the reactions of negative ions with alkyl nitrites identifies a few striking contrasts. An understanding of the origin of these differences may provide fundamental information about the nature of the potential energy surfaces on which gas-phase ion-molecule reactions occur.

Acknowledgment. We gratefully acknowledge support of this work by the U.S. Army Research Office.

Nucleophile Competition in Aromatic $S_{RN}1$ Reactions. Evaluation of Nucleophilic Reactivities and Evidence of Reaction Mechanism[1a]

Carlo Galli[1b] and Joseph F. Bunnett*

Contribution from the University of California, Santa Cruz, California 95064.
Received April 10, 1981

Abstract: Pairs of nucleophiles were allowed to react in ammonia with single substrates, mostly under irradiation, and relative nucleophilicities were evaluated from product yields. The $(EtO)_2PO^-$/pinacolone enolate ion reactivity ratio is 1.37 ± 0.11 with six substrates, PhI, PhBr, PhCl, PhF, Ph_2S, and $PhNMe_3{}^+I^-$. The constancy of this ratio is consistent with the $S_{RN}1$ mechanism but not with a conceivable alternative dubbed $S_{RN}2$. Three other nucleophiles were studied in pairwise competition with each of the original two. The five have the following relative reactivity: Ph_2P^-, 5.9 > Ph_2PO^-, 2.7 > $(EtO)_2PO^-$, 1.4 > $Me_3CCOCH_2^-$, (1.00) > PhS^-, 0.08. These and literature data show that, except for the obvious special case of PhS^-, nucleophile reactivities differ in aromatic $S_{RN}1$ reactions by not more than a factor of 10. The reason is possibly that the combination of aryl radical with nucleophile occurs virtually at encounter-controlled rate. *tert*-Butoxide ion (t-BuO^-), present in most experiments, has undetectably low nucleophilic reactivity vs. phenyl radical. The probable reason is that a σ^* radical anion, $[t\text{-}BuOPh]^{-\cdot}$, would be the initial product of combination of Ph· with t-BuO^-, and that it is energetically inaccessible because of the high energy level of the σ^* orbital of the aryl-oxygen bond.

The $S_{RN}1$ mechanism is a radical-chain mechanism of nucleophilic substitution.[2] It is well-supported by good evidence[2,3] but much of the evidence is indirect in the sense that the postulated intermediates have not been directly observed. Also, there are few quantitative data on reactivity.

Heretofore there has been little attention to competition between two nucleophiles reacting with a single substrate in $S_{RN}1$ systems.[1c] Studies of such competition can be doubly valuable, first because they probe the mechanism itself, and second for the information they provide about nucleophilic reactivities.

The propagation steps for $S_{RN}1$ reactions of one aromatic substrate (ArX) with two nucleophiles, Y^- and Z^-, are shown in Scheme I.

Scheme I

$$[ArX]^{-\cdot} \rightarrow Ar\cdot + X^- \qquad (M1)$$

$$Ar\cdot + Y^- \rightarrow [ArY]^{-\cdot} \qquad (M2y)$$

$$Ar\cdot + Z^- \rightarrow [ArZ]^{-\cdot} \qquad (M2z)$$

$$[ArY]^{-\cdot} + ArX \rightarrow ArY + [ArX]^{-\cdot} \qquad (M3y)$$

$$[ArZ]^{-\cdot} + ArX \rightarrow ArZ + [ArX]^{-\cdot} \qquad (M3z)$$

According to this mechanism, nucleophiles participate in steps leading to their incorporation into reaction products chiefly in steps M2y and M2z. If the chain is long, that is, if propagation events are much more frequent than termination events, or if the termination steps do not form bonds between the aryl and nucleophile moieties, the relative yields of ArY and ArZ should, when account is also taken of the nucleophile concentrations, be indicative of the relative rate constants for steps M2y and M2z. Moreover, if the mechanism is correctly represented in Scheme I, if it is truly an aryl radical, from which nucleofugal group X has been separated, that interacts with the nucleophiles, the relative reactivity of two nucleophiles should be independent of the leaving group.

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