aware of no parallel to the following combination of features and circumstances associated with it, viz., it is an example of a single crystal to single crystal transformation (characterized by X-ray crystallography), occurring with retention of external morphology and internal crystallographic orientation, involving a topological rearrangement of a 3D molecular $[Cd(CN)_2]_n$ host network, driven by the vapor-phase exchange of the solvent guest under very mild conditions.[7]

Preliminary results suggest that $Cd(CN)_2 \cdot {}^2/_3H_2O \cdot t\text{-}BuOH$ may undergo other topological rearrangements which we are presently exploring.

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Supplementary Material Available: Listings of experimental details for X-ray crystallography, crystal data, and data collection together with fractional atomic coordinates for $Cd(CN)_2 \cdot CHCl_3$ (5 pages); listing of observed and calculated structure factors (1 page). Ordering information is given on any current masthead page.

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Substitution versus Elimination in Gas-Phase Ionic Reactions

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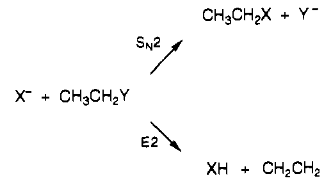
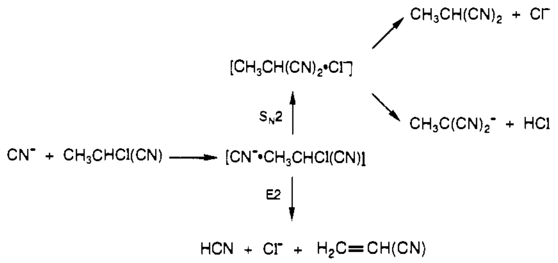
The direct competition between substitution (S_N2) and elimination (E2) pathways for reactions of anionic nucleophiles with alkyl substrates is a fundamental problem. The factors that influence this competition in solution have been studied extensively;[1-3] the results depend strongly on the nucleophile, the substrate, and also on the solvent. In the gas phase, quantitative determination of the relative contribution of competing S_N2 and E2 pathways is very difficult. Both mechanisms give rise to the same product ion, and only ionic species are observed using traditional techniques (Scheme I).

We report here a method which allows us to measure directly the competition between substitution and elimination in the gas phase at the same reaction site using only product ion detection. For reaction of cyanide ion, CN^-, with 2-chloropropionitrile, $CH_3CHCl(CN)$, we can distinguish between the two reaction channels which normally give the same product ion, because the ion-molecule complex formed just after the S_N2 step, $[CH_3CH(CN)_2 \cdot Cl^-]$, undergoes subsequent proton transfer before dissociating (Scheme II). We find that the major product of the reaction is Cl^-, and since we know from previous studies that proton transfer should dominate the products of the S_N2 reaction, most of the overall process must proceed by elimination.

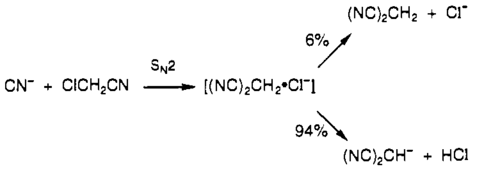
Scheme I



Scheme II



Scheme III



A number of interesting and elegant methods have been used in an attempt to measure the S_N2/E2 competition in the gas phase. Lieder[4] and Jones and Ellison[5] used neutral product detection. Lum and Grabowski,[6] as well as Haib and Stahl,[7] used substrates with multiple reaction sites in order to distinguish between substitution at methyl and elimination at ethyl. The most extensive studies to date have come from the work of DePuy, Bierbaum, and co-workers[8-13] with a variety of techniques, including the use of cyclic substrates[8,9] in which addition of the anion can be seen, relative rate measurements[10,11] in which rates of methyl compounds are compared with larger alkyl substrates, and deuterium kinetic isotope effect studies, in which the elimination reaction is slowed.[12,13] Many of these methods do not measure directly the competition at a single reaction center, but rather a competition between S_N2 at methyl versus E2 at ethyl. It is clear from the limited and somewhat conflicting available data that the factors influencing the S_N2/E2 competition in the gas phase are not completely understood. Results suggest, however, that the nature of the nucleophile is extremely important.[14]

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Table I. S_N2 versus E2 Pathways for $CN^- + RCHCl(CN)$

reaction	k_{obsd}[a]	$[Cl^-]/[RC(CN)_2^-]$	$\%S_N2$	%E2
(1) $CN^- + CH_2Cl(CN)$[b–d]	2.2	0.07[f]	100	
(2) $CN^- + CH_3CHCl(CN)$[d,e]	≤0.01	14.4	7	93

[a] Units of 10^{-10} cm^3 s^{-1}. [b] Reference 16. [c] Thermodynamics was calculated from estimated data ($\Delta H^\circ_f(ClCH_2CN) \approx 21$ kcal mol^{-1}); $\Delta H^\circ(S_N2) \approx -29$ kcal mol^{-1}, $\Delta G^\circ(S_N2) \approx -27$ kcal mol^{-1} (ref 15). [d] CN^- could act as a nitrogen nucleophile or base; however, these pathways are significantly less favored thermodynamically by approximately 16 kcal mol^{-1} (ref 15). [e] Thermodynamics for the S_N2 process in reactions 1 and 2 is assumed equal. Thermodynamics was estimated from data obtained from the prototype reaction ($CN^- + CH_3CH_2Cl$); $\Delta H^\circ(E2) \approx -0.4$ kcal mol^{-1}, $\Delta G^\circ(E2) \approx -12$ kcal mol^{-1} (ref 15). [f] The value of 0.07 (1/15) was used to correct the ratio in reaction 2 by multiplying by the ratio 15/16, since a small amount of Cl^- is formed from the S_N2 mechanism.

Our experiment follows from, and depends on, our previous study of $CN^- + ClCH_2CN$. In this experiment, substitution is the only ionic reaction thermodynamically possible, but the product complex, $[(NC)_2CH_2 \cdot Cl^-]$, can undergo subsequent proton transfer (Scheme III).

The proton-transfer reaction, $(NC)_2CH^- + HCl \rightarrow (NC)_2CH_2 + Cl^-$, is very near thermoneutral ($\Delta H^\circ_{298} = -2$ kcal mol^{-1}; $\Delta G^\circ_{298} = 0$ kcal mol^{-1}),[15] and at energies slightly above the dissociation threshold (e.g., room temperature) the product ions, Cl^- and $(NC)_2CH^-$, are formed in a ratio close to 1:1. At the high energy at which the product complex is formed in the S_N2 reaction, however, dissociation strongly favors formation of $(NC)_2CH^-$.[16] This follows from the entropy change for the reaction due to the two additional rotational degrees of freedom in HCl. This manifests itself as a strong energy dependence of the proton-transfer equilibrium constant and complex dissociation branching ratio. The microscopic interpretation of this energy dependence is related to the relative density (or sum) of available quantum states in each dissociation channel. Although the density of states for the two dissociation channels is similar just above threshold, the HCl rotations contribute to the total density of states much more rapidly than do the corresponding vibrations in the other channel. On the basis of an estimate of the S_N2 reaction enthalpy (−29 kcal mol^{-1}), the product complex is formed with approximately 50 kcal mol^{-1} of excess internal energy relative to the bottom of the well[17] and about 30 kcal mol^{-1} relative to the two dissociation channels. Moreover, at the pressures of our experiment, the complex retains the excess internal energy, dissociating before it can be thermalized. Thus, we predict that the complex should dissociate at high energy in favor of $(NC)_2CH^-$ formation. Consistent with this, the product ions are formed experimentally in a ratio of approximately $Cl^-:(NC)_2CH^- = 1:15$.[16] The results were found to be qualitatively consistent with those obtained from an RRKM analysis.

Our experiments were performed using a Fourier transform IonSpec OMEGA ion cyclotron resonance (FT-ICR) spectrometer equipped with impulse excitation.[18,19] CN^-, formed via electron impact on HCN, was allowed to react with $CH_3CHCl(CN)$ at a variety of pressures in the rnage $(0.2–2) \times 10^{-6}$ Torr. The only product ions observed were Cl^- and $CH_3C(CN)_2^-$. Although the overall reaction rate was slow and difficult to measure, the important experimental measurement, the product ion ratio, was reproducible. 2-Chloropropionitrile, $CH_3CHCl(CN)$, and malononitrile, $(NC)_2CH_2$, were obtained from Aldrich. Methylmalononitrile, $CH_3CH(CN)_2$, was synthesized[20] by alkylation of malononitrile. The acidity of $CH_3CH(CN)_2$ was estimated by measuring the rate of deprotonation with Cl^-. We find that $CH_3CH(CN)_2$ is only slightly less acidic than $CH_2(CN)_2$[21] and comparable to HCl ($\Delta G^\circ_{acid} = 328$ kcal mol^{-1}).[15]

Table I shows the kinetic results for the primary (reaction 1) and secondary (reaction 2) systems, along with the ratio of product ions formed in each reaction and the relative contribution of each reaction pathway. The S_N2 process is highly exothermic for both systems; the enthalpies, $\Delta H^\circ(S_N2)$, were estimated using available thermodynamic data and were assumed to be equal for both systems (see Table I). The elimination pathway for reaction 2 is only slighly exothermic. The enthalpy, $\Delta H^\circ(E2)$, was estimated as that for the elimination reaction of $CN^- + CH_3CH_2Cl$. Entropic effects make the overall free energy change for elimination more favorable, although substitution is still thermodynamically favored (see Table I).

The observation of $CH_3C(CN)_2^-$ in reaction 2 requires that some component of this reaction proceed via the S_N2 channel, since it cannot be formed any other way. Thus, if all of the Cl^- comes from substitution, then the reaction proceeds entirely by the S_N2 mechanism; if all of the Cl^- comes from elimination, then the S_N2 component is only 6% of the reaction. More importantly, however, we can quantify the amount of Cl^- arising from S_N2 if we assume that substitution in both reactions 1 and 2 leads to the same product ion ratio, giving mainly the corresponding deprotonated alkyl nitrile, $RC(CN)_2^-$. In order to make this quantitative argument, we make two important assumptions. First, the S_N2 and subsequent proton-transfer reaction enthalpies for both systems are comparable, so that the ion–molecule complexes, $[RCH(CN)_2 \cdot Cl^-]$, are formed with the same amount of excess internal energy relative to the dissociation channels (i.e., 30 kcal mol^{-1}). Although all of the necessary thermochemical data are not available, we can use methyl versus ethyl chloride as analogs to infer that the S_N2 reaction enthalpies differ by only 1.5 kcal mol^{-1}.[15] Moreover, because $CH_3CH(CN)_2$ and $CH_2(CN)_2$ have comparable acidities (±2 kcal mol^{-1}) relative to HCl, the proton-transfer reaction enthalpies must be similar.[21] Second, the energy dependence of the product branching ratio must be similar. This is also a reasonable assumption, since the energy dependence arises largely from the rotational degrees of freedom of HCl and is present in both systems. Using this information we find that reaction 2 proceeds primarily by elimination (93%) with a small component of substitution (7%).

Finally, the overall rate of reaction, and the rate of the S_N2 process in particular, decreases by several orders of magnitude in going from a primary to a secondary substrate. This provides additional support for the magnitude of steric effects in a gas-phase S_N2 process.[22]

In summary, we have been able to determine the kinetic preference between S_N2 and E2 pathways at the same reaction site. Our results show clearly that, despite the thermodynamic preference for S_N2, E2 is the kinetically preferred pathway for this system. The dominance of the E2 pathway probably results from a combination of a lower activation barrier and a looser transition state. Given the slow rate for the overall process, the activation barriers for both channels may be close to or extend above the entrance channel.

Acknowledgment. We are grateful to the National Science Foundation for support of this research.

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