the resonance energies of **2** and **6** are nearly identical.

The tautomerization of **2** is less exothermic than aromatization of **6**, because the former process entails enolization of a ketone. Enolization of cyclohexanone is substantially endothermic ($\Delta H°_{298}$ = 10 kcal mol^{-1}),[29] whereas the analogous isomerization of methylenecyclohexane to 1-methylcyclohexene, related to the aromatization of **6**, imposes no energetic penalty ($\Delta H°_{298}$ = −2 kcal mol^{-1}).[30,31] Indeed, $\Delta\Delta H°$ for these simple transformations (12 kcal mol^{-1}) is equal to $\Delta\Delta H°$ for the aromatizations of **2** and **6** (13 kcal mol^{-1}), within experimental error. Comparisons of the heats of formation of both nonaromatic (**2** and **6**) and nonconjugated (cyclohexanone and methylenecyclohexane) structures with those of phenol and toluene[32] thus establish that phenol is significantly destabilized relative to toluene (ca. 11–13 kcal mol^{-1})[33] by enolization. As required by these results, the calculated enthalpies for conversion of cyclohexanone enol to phenol and conversion of 1-methylcyclohexene to toluene likewise differ only slightly ($\Delta H°_{298}$ = 21 and 22 kcal mol^{-1}, respectively).[34] The resonance energies of phenol and toluene are approximately equal.

The success of these ambient temperature flowing afterglow experiments suggests that it may be feasible to study **1** and **2** in solution under carefully controlled conditions.

Acknowledgment. We are grateful to Professor Charles H. DePuy for providing generous access to the flowing afterglow apparatus and to Dr. Veronica M. Bierbaum for helpful discussions. The flowing afterglow studies were supported by the National Science Foundation (Grant CHE-8503505).

Registry No. **1**, 24599-57-3; **2**, 5664-33-5; **3**, 103201-40-7; **4**, 103301-79-7; PhOH, 108-95-2.

Supplementary Material Available: Synthetic protocols and spectral data for **3** and **4** (2 pages). Ordering information is given on any current masthead page.

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[29] The heat of formation of the enol of cyclohexanone was calculated (−43.7 kcal mol^{-1}) by using the group additivity method: Benson, S. W. *Thermochemical Kinetics*, 2nd ed.; Wiley: New York, 1976. The group value for O-(C_d)(H) proposed by Holmes and Lossing (−44.6 kcal mol^{-1}; ref 4a) was employed. For the heat of formation of cyclohexanone, see footnote 28.

[30] The heat of formation of 1-methylcyclohexene is −10.34 ± 0.20 kcal mol^{-1} (ref 25, pp 152–153). For estimation of the heat of formation of methylenecyclohexane, see footnote 28.

[31] A similar argument involving **1** and **5** likewise suggests that enolization is primarily responsible for the smaller exothermicity of the aromatization of **1**, compared with tautomerization of **5**.

[32] $\Delta H°_{f\,298}$(toluene) = 11.99 ± 0.10 kcal mol^{-1} (ref 25, pp 152–153).

[33] $\Delta\Delta H°$ for (cyclohexanone → phenol + $2H_2$) and (methylenecyclohexane → toluene + 2 H_2) is 11 kcal mol^{-1}.

[34] By using heats of formation given above, enthalpies of reaction were calculated for (cyclohexanone enol → phenol + $2H_2$) and (1-methylcyclohexene → toluene + $2H_2$).

Product-Determining Steps in Gas-Phase Brønsted Acid–Base Reactions. Deprotonation of 1-Methylcyclopentyl Cation by Amine Bases

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Abstract: Experimental results are presented for deprotonation of 1-methylcyclopentyl cation (**1**) by ammonia, trimethylamine, and 1-methylcyclopentylamine at pressures below 10^{-3} Torr, which yields two neutral products, 1-methylcyclopentene (**2**) and methylenecyclopentane (**3**). The isomer ratio varies from **2**:**3** = 2.74 for ammonia to 1.34 for trimethylamine, consistent with previous reports. FTMS measurement of ion–molecule reaction rates of **1** plus ammonia gives an efficiency of 0.34 when **1** is generated by a 20–70 eV electron impact on bromocyclohexane. Reaction of the perdeuterated cation **1**-d_{11} with ammonia yields products that reveal only a very low level of hydrogen scrambling between acid and base. Isotope effects on the reaction rate and the neutral product ratio, determined from experiments using **1**-d_{11} or ND_3, are found to be small. Two mechanistic alternatives are discussed: Lewis (in which covalent acid–base complexes are formed) and Eigen (in which hydrogen-bonded intermediates are formed). Reaction of **1**-d_{11} with 1-methylcyclopentylamine shows only a small amount of interchange of deuterated and undeuterated alkyl groups, which argues against a Lewis mechanism as an obligatory pathway. Experimental results are interpreted in terms of orbiting intermediates, in which acidic C–H bonds and the basic nitrogen experience large deviations from collinearity. More than one subsequent step is required for the reactants to engage chemically. In order for Eigen mechanisms to operate, a C–H bond must point toward the nitrogen, which requires loss of some internal degrees of freedom. For proton transfer to be completed, the nitrogen lone pair must be pointed along the C—H···N axis, which requires loss of additional degrees of freedom. Progress of the reaction beyond the initially formed orbiting intermediate is described by a scheme in which these stages of approach to reactive orientation represent discrete steps.

When a Brønsted acid transfers a proton to a base, the reaction passes through several transition states. In solution, participation of solvent molecules plays an important role, and it may happen that no single step is rate-determining. In the gas phase, the absence of solvent reduces the complexity of the molecular interactions, but the intervention of at least one intermediate, as represented by reaction 1, demands that there be at least two transition states.[1] Several years ago we reported distributions of isomeric olefins from deprotonation of tertiary alkyl cations that possess chemically nonequivalent acidic hydrogens.[2] Using a specially constructed Electron Bombardment Flow (EBFlow) reactor for collecting the neutral products of ion–molecule reactions, we observed that the thermodynamically less stable olefins were recovered in high proportions, sometimes exceeding the yield of their more stable isomers. We pointed out that this could not be explained in terms of a single intermediate that decomposes

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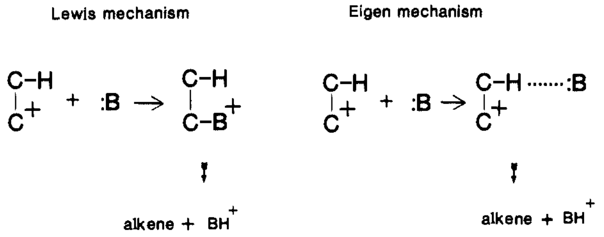
[1] Chesnavich, W. J.; Su, T.; Bowers, M. T. *J. Am. Chem. Soc.* **1978**, *100*, 4362–4367.

[2] Marinelli, W. J.; Morton, T. H. *J. Am. Chem. Soc.* **1978**, *100*, 3536–3539; **1979**, *101*, 1908.

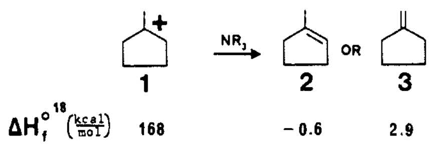
Scheme I



directly to give more than one product, regardless of the structure of that intermediate.[3]

$$\begin{array}{ccccccc} AH^+ + B: & \rightleftarrows & [AH^+\ B]^* & \rightarrow & A & + & BH^+ \\ \text{acid}\quad\text{base} & & \text{vibrationally excited intermediate} & & \text{conjugate base} & & \text{conjugate acid} \end{array} \qquad (1)$$

Reaction 1 must therefore be amended to include more than one intermediate (and, hence, more than two transition states). This paper will consider several alternative ways to do this for the deprotonation of 1-methylcyclopentyl cation (**1**) by amine bases. As depicted in reaction 2, this proton transfer yields two neutral products, 1-methylcyclopentene (**2**) and methylenecyclopentane (**3**). The two isomeric products are formed in comparable yields by bimolecular reactions in the gas phase, even though **2** is more stable than **3** by $\Delta H = 3.5$ kcal/mol. With a tertiary amine as base (R = alkyl), the product ratio **2**:**3** is approximately 4/3, the same as the ratio of acidic methylene to acidic methyl hydrogens in **1**.[2] With ammonia as base (R = H), the product ratio is approximately 3:1.[3] We can envisage two types of intermediates along the reaction coordinate, which we shall designate as a Lewis and an Eigen intermediate. In a Lewis intermediate, a covalent bond between acid and base (a Lewis acid–base complex) forms an ammonium ion. In an Eigen intermediate, a hydrogen bond between an acidic hydrogen and the base forms the sort of intermediate that Eigen has proposed for proton-transfer reactions in solution.[4] These two types of mechanism are depicted in Scheme I. Mautner has argued against the intervention of Lewis intermediates in the very exothermic ($\Delta H < -30$ kcal/mol) deprotonation of gaseous isopropyl cation by primary amines.[5] Moylan, Jasinski, and Brauman[6] have recently reported ionic product yields from infrared multiphoton decompositions of gaseous secondary ammonium ions, which corroborate Mautner's inference. Since Lewis acid–base adducts are observed in the gas phase in addition to proton transfer at high pressures,[7] the question becomes not only whether they might be obligatory intermediates for less exothermic Brønsted reactions but also whether they are accessible from the potential surface for gas-phase proton transfer.



(2)

We want to inquire what will be the most economical representation of the reaction coordinate for proton transfer. Will two intermediates suffice to accommodate the experimental data? Or must additional intermediates be put forth in order to account for observed product channels? In addition to examining experimental data for deprotonation of **1**, we have also studied the theoretical model for the simplest example of an Eigen mechanism, proton transfer from hydrogen molecular ion to a hydrogen atom on the *triplet* potential energy surface.[8,9] On the basis of both experimental and theoretical results, we propose that the most realistic reaction coordinates for proton transfer involve more than two intermediates.

This paper will seek to interpret the following experimental results. The neutral product distribution from **1** varies with the identity of the base, as previously reported.[3] For deprotonation by strong bases ($\Delta H < -20$ kcal/mol) the isomer ratio **2**:**3** is close to the ratio of acidic methylene to methyl hydrogens. When the base is weaker, the isomer ratio tends toward the thermodynamic value (which is > 100:1). The reaction rate and isomer ratio are unaffected by deuteration of the base and only slightly affected by deuteration of the acid.

It will be helpful to distinguish between a transition state and a critical configuration.[10] As usually described, a transition state corresponds to a maximum on the minimum-energy pathway on a potential energy surface. The term "critical configuration" refers to the bottleneck for a chemical reaction, which may or may not correspond to a potential energy maximum. If, for example, progress along a reaction coordinate requires a severe loss of degrees of freedom, entropic requirements may lead to such a bottleneck even in the absence of a local maximum on the potential energy surface. In other cases, where a critical configuration is sufficiently far from a potential energy maximum, it is conceivable that intermediates may persist with finite lifetimes, hemmed in on one side by potential energy barriers and on the other side by entropic bottlenecks. For an ion–molecule reaction in the gas phase, such an intermediate may occur between the effective potential energy barrier for capture and an entropic barrier to reaction.

We call this type of ion–molecule complex an orbiting intermediate. For reactions of Brønsted acids with polyatomic bases we consider a picture that includes two angular degrees of freedom: the collinearity of the three atoms involved in proton transfer and the orientation of the lone pair of the base with respect to the triatomic axis. A locked-rotor critical configuration connects two intermediates, one in which there are large deviations for both angular coordinates and one in which these are large deviations for only one angular coordinate. This critical configuration is not, in general, associated with any potential energy maximum. It represents the product-determining step for very exothermic deprotonations. For weaker bases, there is no single product-determining step. Other locked-rotor critical configurations, which come earlier than the potential energy barriers for proton transfer, correspond to freezing the second angular degree of freedom. This depiction of proton transfer accounts for the sensitivity of reaction 1 to thermodynamics and its insensitivity to isotopic substitution of the acid.

Experimental Section

Bromocyclohexane (Fluka), bromocyclohexane-d_{11} (MSD Isotopes, 99 atom % D), ammonia-d_3 (Cambridge Isotope Laboratory), and methylenecyclopentane (ChemSampCo) were used without further purification, and 1-methylcyclopentylamine was prepared by published methods.[11] Fourier transform mass spectra (FTMS) were recorded on a Nicolet FTMS 1000 at 3 T, with trapping plates biased at +1.0 V with respect to ground unless otherwise specified. Nominal energies of ionizing electrons are reported as the bias voltage of the filament (negative) with respect to ground. Relative partial pressures of reactants were measured with a Bayard-Alpert ionization gauge, whose readings were corrected as described by Bartmess and Georgiadis.[12] The efficiency for reaction of **1** with ammonia was determined on the basis of reported values of efficiencies of deprotonation of *tert*-butyl cation by NH_3 (0.65 at 10.8 eV and 0.51 at 20 eV[13]), correcting for the greater reduced mass for a **1** + NH_3 collision. Relative ion-molecule reaction rate constants were measured at more than one pressure of ammonia and were reproducible, in duplicate determinations, to within 3%. Reported values are subject to an experimental uncertainty of ±10%.

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[3] Morton, T. H. *Radiat. Phys. Chem.* **1982**, *20*, 29–40.

[4] Eigen, M. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 1–18.

[5] Mautner, M. *J. Am. Chem. Soc.* **1979**, *101*, 2389–2395.

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[8] Redman, E. W.; Stams, D. A.; Morton, T. H. In *Progress in Mass Spectrometry 1985, Part B* Todd, J. F. J., Ed.; Wiley: New York, 1986; pp 1177–1178.

[9] Stams, D. A. M.S. Thesis, U.C. Riverside, 1985.

[10] Hase, W. L. *Acc. Chem. Res.* **1983**, *16*, 258–264.

[11] Barber, H. J.; Lunt, E. *J. Chem. Soc.* **1960**, 1187–1194.

[12] Bartmess, J. E.; Georgiadis, R. M. *Vacuum* **1983**, *33*, 149–153. The gauge sensitivities of **2** and **3** were taken to be the same as reported for cyclohexene, which is 4.3 times greater than the gauge sensitivity of ammonia.

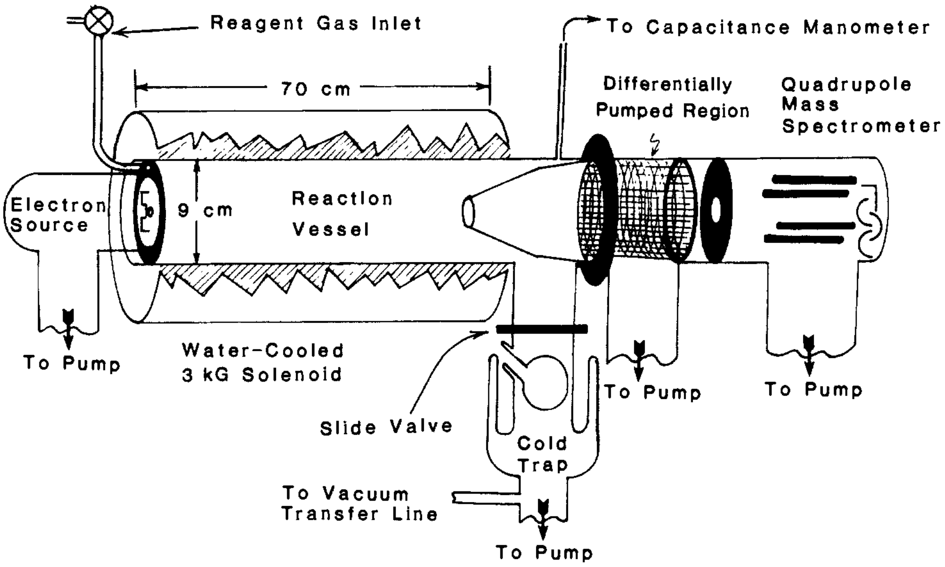

Figure 1. Schematic diagram of the EBFlow reactor. A UTI 100C quadrupole mass analyzer is connected to the reaction vessel via a differentially pumped region biased at +100 V. A conical Faraday plate, biased at +10 V, connects the reaction vessel to this differential region. Under ordinary operating conditions the filament is biased at -70 V and the reaction vessel is grounded. The aperture to the mass spectrometer is closed by a grounded slide valve during neutral product collection, and approximately half of the electron current strikes it (the other half strikes the walls of the differentially pumped region). During a typical run, a positive ion current (on the order of -10 μA) strikes the wall of the reaction vessel. Neutral products are collected in the liquid-nitrogen-cooled cold trap, which is closed off after a run while its contents are vacuum transferred over a period of several hours to a sample tube, which is then sealed. The water-cooled solenoid can provide uniform magnetic flux densities up to 0.3 T, although it was ordinarily run at 0.2 T during the present study.

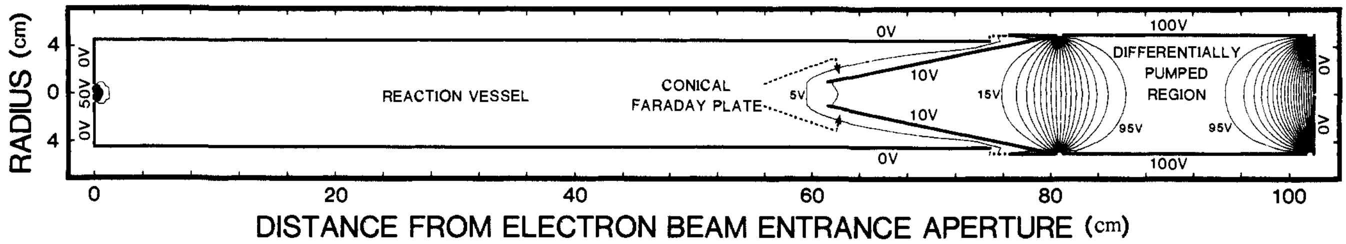

Figure 2. Electrostatic potentials in the reaction vessel and differential region, as computed with the finite element method.[15] Space-change effects of the electron beam are not shown (based on calculations performed by D. A. Stams, N. Orlans, and W. H. Orttung).

Neutral product studies were performed with the EBFlow reactor, many features of which have been previously described.[14] In these experiments, bromocyclohexane and amine were bombarded with 0.2–0.7 mA of 70-eV of 70-eV electrons, and the neutral products were analyzed by GLC with a β,β'-ODPN packed column[2] on a Varian Model 3750 gas chromatograph with flame ionization detection or by GC/MS with a VG ZAB 1F mass spectrometer. Duplicate determinations of the ratio of peak areas were made for each experiment.

The EBFlow apparatus is shown schematically in Figure 1. The electrostatic potentials within the reaction vessel and differential region are shown in Figure 2. The reaction vessel is largely field-free in the absence of the electron beam. When the beam is on, the electrical potential at radial distance r off the cylinder axis due to the beam of 70-eV electrons may be approximated as that arising from a static pencil of charge uniformly distributed along the axis, $V = 0.0036I \ln (r_0/r)$, where V is the potential in volts, I the electron beam current in μA, and r_0 the radius of the reaction vessel (4.5 cm). This provides a trapping potential, which retards positive ions from striking the walls.

In the present experiments, a quadrupole mass spectrometer was connected to the apparatus as a residual gas analyzer, so as to assess the degree of isotopic purity of ammonia and ammonia-d_3. Studies of isotopically labeled reactants were interspersed with one another and with experiments using unlabeled reagents, in order to rule out systematic variations of experimentally measured product ratios. To minimize isotopic exchange between ammonia and the walls, the apparatus had to be equilibrated with D_2O for several days before experiments with ND_3 could be performed. For subsequent experiments using undeuterated ammonia, the apparatus was reequilibrated with water.

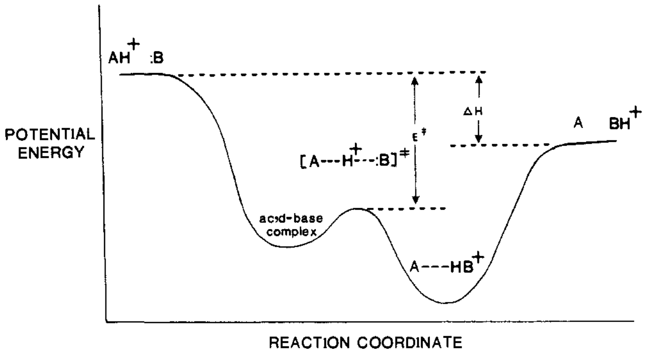

Figure 3. Cross section of potential surface for gas-phase proton transfer from Brønsted acid AH^+ to base B. Intermediate in the right-hand well corresponds to a cluster ion containing the neutral conjugate base A and the charged conjugate acid BH^+. The intermediate in the left-hand well is an acid–base complex between AH^+ and B, whose structure depends on whether a Lewis or an Eigen mechanism is invoked. The transition state $[A{-}{-}{-}H^+{-}{-}{-}B]^‡$ corresponds to the critical configuration for unimolecular conversion of the acid–base complex via proton transfer.

Results

A cross section of the potential surface for proton transfer is represented schematically in Figure 3. This depicts the simplest reaction coordinate diagram for either of the mechanisms shown in Scheme I.[6,16] The Lewis and Eigen mechanisms differ with respect to the structure of the intermediate acid–base complex in the left-hand well. Experiments presented below explore features of the potential surface and the adequacy of Figure 3 as a

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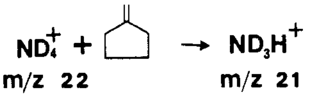
(13) Su, T.; Bowers, M. T. *J. Am. Chem. Soc.* **1973**, *95*, 7611–7613.

(14) Redman, E. W.; Johri, K. K.; Morton, T. H. *J. Am. Chem. Soc.* **1985**, *107*, 780–784.

(15) Computed using the finite-element method, as described by the following: Orttung, W. H. *Ann. N.Y. Acad. Sci.* **1977**, *303*, 22–37. We are grateful to Professor Orttung for allowing us to use his computer program.

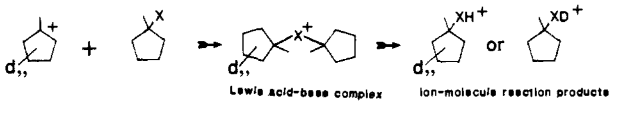
description of proton transfer in the gas phase.

The first feature that we have explored concerns the height of the central barrier, as measured by E^*, its energy with respect to the reactants. If the magnitude of the exothermicity of the reaction, ΔH, is less than E^*, then it ought to be possible to enter the left-hand well coming in from the right. In other words, a thermal collision between A and BH^+ should access the complex between AH^+ and B and, regardless of the structure of that complex, lead to scrambling of any interchangeable hydrogens. We have examined this using FTMS to study collisions between ND_4^+ and **3**, as portrayed by reaction 3. We find that methylenecyclopentane does, indeed, scramble hydrogens with ND_4^+ that was generated by 12-eV electron impact on ND_3. It was not possible to measure the rate of this reaction precisely because the ND_3 contained a few atom % of hydrogen (probably from exchange between ND_3 and water on the walls of the inlet) and because ND_3H^+ (m/z 21) undergoes rapid exchange with ND_3 to produce ND_4^+ (m/z 22). Comparison of the extent of ND_3H^+ production (after ejection of any that was initially formed) in the presence of **2** with the extent in the presence of **3** showed that the latter was substantially greater. From the steady-state ND_3H^+/ND_4^+ ratios in the presence of various pressures of **2** and **3**, the second-order rate constant for reaction 3 is estimated to be 0.7 ± 0.3 that for exchange between ND_3H^+ and ND_3, while exchange between **2** and ND_4^+ has a rate constant less that 0.015 relative to ND_3H^+ exchange with ND_3. Since the rate constant for NH_4^+ exchange with ND_3 has been reported to be 1.9×10^{-9} cm^3 $molecule^{-1}$ s^{-1} at 295 K,[17] with nearly statistical scrambling of hydrogens, reaction 3 therefore has a rate constant in the range $0.5\text{–}1 \times 10^{-9}$ cm^3 $molecule^{-1}$ s^{-1}. We conclude that the magnitude of ΔH in Figure 2 (which is 4 kcal/mol, based on a proton affinity for ammonia of 204 kcal/mol[18]) must be no greater than E^* for A = **3**, AH^+ = **1**, and B = ammonia.



(3)

We now wish to probe Figure 3 as a depiction of the reaction coordinate for reaction 2. As has been pointed out many times before,[10] a cross section of a potential energy surface may not necessarily give an accurate depiction of a reaction coordinate suitable for representing kinetics, since entropic effects are not taken into account. Dodd, Golden, and Brauman[19] have argued convincingly that, insofar as overall rates of ion–molecule associations are concerned, reactions that proceed with less than unit efficiency "do so as a result of potential energy barriers rather than as a result of the entropy bottleneck." Nevertheless, it may be possible for an entropy bottleneck to play a role in determining relative rates for competing product channels.



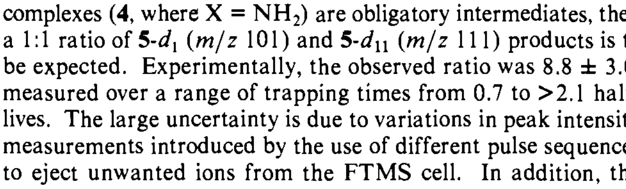
(4)

1-d₁₁ **4**

In one experiment, we strove to decide whether a Lewis intermediate intervenes in a proton-transfer reaction. As portrayed by reaction 4, proton transfer from deuterated 1-methylcyclopentyl cation (**1**-d_{11}) to an n-donor base will proceed via a symmetrical intermediate, **4**, if the basic atom has a 1-methylcyclopentyl group as an alkyl substituent. The symmetrical intermediate will then decompose to give roughly equal proportions of a d_{11} and d_1 ions. If there are large isotope effects, then the ratio d_{11}:d_1 may deviate from unity. Therefore, we have measured the deuterium isotope effect for the acid–base reaction. For **1** generated by 10-eV electron impact on bromocyclohexane[2] and **1**-d_{11} generated from bromocyclohexane-d_{11} at the same time (under which conditions the $C_6H_{11}^+$ and $C_6D_{11}^+$ cations represent >80% of the total ionization and do not react with parent neutral molecules), the rates of disappearance by reaction with ammonia are the same (within an experimental uncertainty of FTMS measurements of ±10%) over at least 3 half-lives under pseudo-first-order reaction conditions. This result was also obtained with use of a trapping voltage of 0.4 V to make sure that it was not a consequence of the presence of translationally excited ions in the FTMS cell.

Table I. The C_6H_{10} Isomer Ratio **2**/**3** from Reaction of **1** (from 70 eV EBFlow Radiolysis of Bromocyclohexane) with 1×10^{-4} Torr of Amine Base

base	$C_6H_{11}Br$ pressure (Torr × 10^4)	**2**/**3**
NH_3	1	2.79
NH_3	3	2.74
NH_3	5	2.65
NH_3	10	2.52
NH_3	20	2.46
NH_3	25	2.50
none	3	>7.5
$N(CH_3)_3$	3	1.34



(5)

Given the small magnitude of deuterium isotope effects on reaction 2, the intermediacy of Lewis acid–base complexes can be explored as represented in reaction 5. If Lewis acid–base complexes (**4**, where X = NH_2) are obligatory intermediates, then a 1:1 ratio of **5**-d_1 (m/z 101) and **5**-d_{11} (m/z 111) products is to be expected. Experimentally, the observed ratio was 8.8 ± 3.0, measured over a range of trapping times from 0.7 to >2.1 half-lives. The large uncertainty is due to variations in peak intensity measurements introduced by the use of different pulse sequences to eject unwanted ions from the FTMS cell. In addition, the measurement is complicated by proton-transfer reactions of the deuterated ions with the neutral amine to generate a d_0 ion (m/z 100), a reaction that is approximately twice as fast as the reaction of **1**-d_{11} with the neutral amine. The d_1:d_{11} ratio shows no systematic change with reaction time, and the value at 70 eV is within experimental uncertainty of the value at 10 eV.

Relative rate constants for reaction 2 were measured by FTMS. The rate constant of $C_6H_{11}^+$ generated by 10-eV electron impact on bromocyclohexane was observed to be approximately 1.2 times greater than the rate constant at 20 eV, while the 20- and 70-eV rates were within 3% of one another. The reaction rates of **1** (m/z 83) with ammonia were measured relative to the reaction of tert-butyl cation (m/z 56) with ammonia. The tert-butyl cation was generated in the FTMS at the same time as **1** by electron impact on neopentane.[13] At 10.8 eV, the rate constant for disappearance of m/z 83 was 0.84 times as large as the rate constant for disappearance of m/z 56. At 20 eV, the rate constant for disappearance of m/z 83 is 0.72 times as large as the rate constant for disappearance of m/z 56. We conclude, therefore, that the efficiency of deprotonation of **1** by ammonia is 0.34 when **1** is generated by 70-eV electron impact on bromocyclohexane.

Neutral product distributions for **1** plus ammonia and **1** plus tertiary amine had been previously determined with an earlier version of the EBFlow reactor, with a reaction vessel diameter

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(16) (a) Jasinski, J. M.; Brauman, J. I. *J. Am. Chem. Soc.* **1980**, *102*, 2906–2913. (b) Han, C.-C.; Dodd, J. A.; Brauman, J. I. *J. Phys. Chem.* **1986**, *90*, 471–477.

(17) Adams, N. G.; Smith, D.; Henchman, M. J. *Int. J. Mass Spectrom. Ion Phys.* **1982**, *42*, 11–23.

(18) (a) Pollack, S. K.; Wolf, J. F.; Levi, B. A.; Taft, R. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1977**, *99*, 1350–1353. (b) Lias, S. G.; Liebman, J. F.; Levin, R. D. *J. Phys. Chem. Ref. Data* **1984**, *13*, 695–808. (c) Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Acadamic Press: New York, 1970.

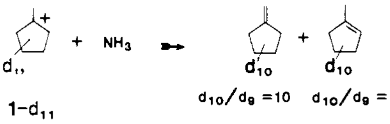
(19) Dodd, J. A.; Golden, D. M.; Brauman, J. I. *J. Chem. Phys.* **1984**, *80*, 1894–1899.

of 2.5 cm and a 0.02 T solenoid. Because of the possibility that those values might have been subject to contamination with products from wall collisions of **1**, these studies were replicated with the latest version of the EBFlow reactor, shown in Figure 1, whose reaction vessel has a diameter of 9 cm and is surrounded by a 0.2 T solenoid electromagnet. Table I summarizes the experimentally determined C_6H_{10} isomer ratios. These are close to the previously reported values, confirming that they represent the true neutral product distributions from the ion-molecule reactions of **1** with the corresponding amines.

The product ratio when ammonia is used as base appears to show a slight systematic decrease when the partial pressure of bromocyclohexane is raised. However, the range of variation summarized in Table I for reaction of **1** with ammonia lies within experimental error of the mean value determined from 7 independent experiments performed with a partial pressure of bromocyclohexane of 3×10^{-4} Torr (sample standard deviation = 0.18), and further experiments were performed with that partial pressure.

In a calibrated experiment under these conditions, the C_6H_{10} yields (in micromoles per ampere-second of bombarding electrons[20]) were 1.47, 0.53, and 5.05 for **2**, **3**, and cyclohexene. The C_6H_{10} isomer yields for a control experiment where base was omitted were 0.32, <0.05, and 1.13 μmol A^{-1} s^{-1} (product **3** was undetectable). The absence of **3** and the substantial diminution of the yield of **2** demonstrate that reaction of **1** with base is producing these isomers when amine is present. What **2** was produced in the control experiment can be ascribed to the small fraction of **1** that is neutralized by collision with the walls of the reaction vessel.

Product yields from a 70-eV radiolysis of bromocyclohexane in the presence of trimethylamine were 2.20, 1.64, and 6.71 μmol A^{-1} s^{-1} for **2**, **3**, and cyclohexene. Formation of cyclohexene is attributable to dehydrobromination of the starting material by the base, which occurs in the sample tube simply upon standing. The **2**:**3** ratio is 1.34 (average of 4 independent experiments, with a sample standard deviation of 0.01). This value is within experimental error of the statistical ratio of acidic methylene to methyl protons, 4/3.

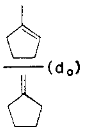
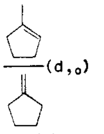


(6)

It was of special importance to assess whether isotopic exchange takes place between **1**-d_{11} and ammonia during the Brønsted acid-base reaction. The neutral products were therefore analyzed by GC/MS. After correction of the resulting mass spectra for incomplete deuteration of the starting material, the fraction of d_{10} product from **1**-d_{11} was determined to be 90%, with the remainder being d_9, as summarized in reaction 6. Isotopic exchange thus occurs to a very small, but not completely negligible, extent.

In light of the small isotope effect observed for reaction of **1** with ammonia, an effort was made to assess the effects of deuterium substitution of the product ratio **2**:**3**. A factorial experimental design was used, in which the acid was deuterated (**1**-d_{11}), the base was deuterated (ND_3), or both were deuterated, as summarized in Table II. The values of **2**:**3** for 18 independent experiments were subjected to a one-way analysis of variance (ANOVA),[21] for which the result ($F_{3,14}$ = 6.26) indicates that the odds are greater than 150:1 against the values in Table II being the result of random sampling of a normal distribution about a single mean. In other words, there is a high probability that real isotope effects were observed. Significant differences between means were identified with t-tests,[22] with a significance criterion of $p < 0.05$. Significant differences are indicated by the arrows in Table II. The isotope effect on the **2**:**3** ratio as a consequence of deuterating **1** (mean of the value for NH_3 and the value for ND_3) gives an increase of the **2**:**3** ratio by a factor of 1.09 ± 0.04 when the acid is deuterated. The isotope effect from deuteration of the base (mean of the value for **1** and **1**-d_{11}) is 1.03 ± 0.04.

Table II. Mean Ratios of 1-Methylcyclopentene and Methylenecyclopentane from Reactions of 1-Methylcyclopentyl Cations and Ammonia with Various Isotopic Modifications[a]

	NH_3 as base		ND_3 as base
 from bromocyclohexene	2.74 (7,.18)	t = −1.90 ↔	2.93 (4,.08)
	t = −3.09 ↕	↖ t = −3.05 ↘	↕ t = −2.66
 from bromocyclohexane-d_{11}	3.08 (4,.15)		3.08 (3,.08)

[a] All experiments run at 70 eV with 3×10^{-4} Torr of bromocyclohexane and 1×10^{-4} Torr of ammonia. Numbers in parentheses represent the number of independent experiments followed by the sample standard deviation. Values of the t-statistics for comparisons of means that show significant differences ($p < 0.05$) are shown with arrows.

Discussion

In Figure 3, the transition states that connect separated ions and molecules (the extreme left- or right-hand sides) with ion-molecule complexes (the wells) are usually described in terms of local energy maxima that result, mathematically, from the addition of two opposing, monotonic terms: a decreasing electronic energy (the potential energy surface) and an increasing rotational energy (the centrifugal repulsion).[3] These "loose" or "orbiting" transition states often occur at large separations between ion and molecule. Another possibility for a critical configuration corresponds to a freezing out of rotational degrees of freedom as ion and molecule begin to interact more strongly.[10,19,23] This has been termed a "tight" or "locked-rotor" critical configuration. Although it has been cogently argued that locked-rotor critical configurations are not, as a rule, rate-determining for ion-molecule reactions, they may be product-determining. Perhaps there is an intermediate that lies between an orbiting transition state (local maximum in potential energy) and locked-rotor critical configurations (entropy bottleneck).

The experimental results argue for an Eigen mechanism. Failure to observe evidence for a Lewis mechanism in reaction 5 cannot be ascribed to steric interactions alone. A molecular mechanics (MM2) estimate of steric interactions in bis(1-methylcyclopentyl)amine, the conjugate base of intermediate **4** (X = NH_2) for the Lewis mechanism, shows a heat of formation only 0.8 kcal/mol higher than can be accounted for by ring strain alone.[9] Protonation of nitrogen is expected to lengthen the C-N bonds by more than 0.05 Å,[24] which ought to reduce this steric interaction. This means that formation of intermediate **4** (X = NH_2) from the reactants ought to be >40 kcal/mol exothermic. If we suppose that the most stable intermediate on the potential energy surface for an Eigen mechanism is a complex between 1-methylcyclopentylammonium (**5**) and product **2**, and take the

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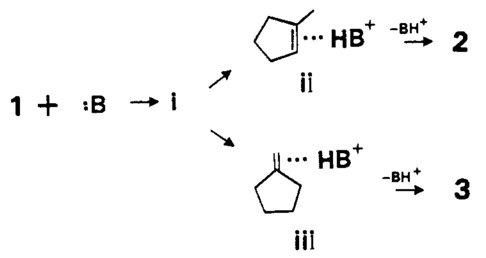
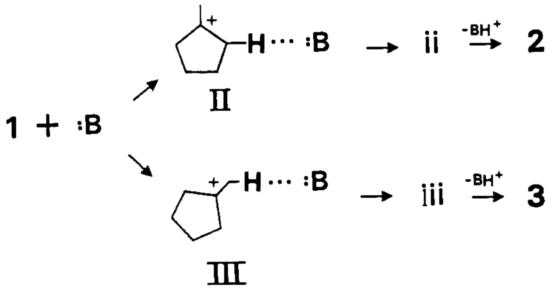
Scheme II

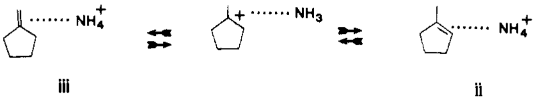


Scheme III



binding energy of that complex to be the same as for methylammonium plus cyclohexene, 12 kcal/mol,[25] then we estimate that Lewis complex **4** (X = NH_2) has a heat of formation at least 2 kcal/mol lower than that of the complex between **5** and **2** (based on the assumption that the proton affinity for 1-methylcyclopentylamine is no greater than that of cyclohexylamine[26]). We believe that the following two generalizations can be made for reactions of **1** with amines, based on the results of reaction 5 and the data in Table II: (1) Lewis intermediates (which represent global minima) are not obligatory, but neither are they inaccessible, and (2) deuterium isotope effects are not detectable with respect to the overall rate, nor is the product ratio greatly affected by deuterium substitution.

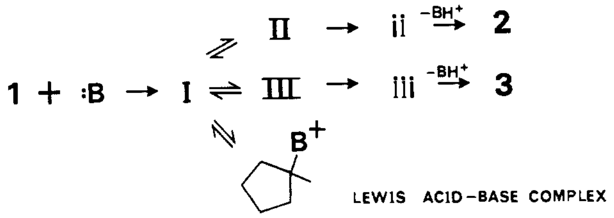
Reaction 2 yields two neutral products, **2** and **3**. Figure 1 can be elaborated in several ways to depict this. Schemes II-IV represent three of the simplest kinetic schemes. In Scheme II, a common intermediate, i, branches to two intermediates, ii and iii, each leading to a different product channel. The stability of such intermediates as ii and iii is suggested by the work of Wood, Burinsky, Cameron, and Cooks,[27] who report the observation of an adduct from reaction of ethyl cation with aniline, whose collisionally activated decomposition mass spectrum corresponds to no known covalent complex but does show extensive loss of ethylene (as would be expected for a hydrogen-bonded complex of ethylene with anilinium ion). A Lewis mechanism is one example of Scheme II, for which formation of i from **1** plus ammonia would be exothermic by $\Delta H \approx -35$ kcal/mol (based on the assumption that 1-methylcyclopentylamine and cyclohexylamine have the same proton affinities[26]). Nevertheless, it is clear from reaction 5 that Scheme II cannot be a correct representation for base :B = 1-methylcyclopentylamine, unless intermediate i is to have a structure that renders the deuterated and undeuterated alkyl groups nonequivalent. Although the overall proton transfer is more exothermic ($\Delta H \approx -22$ kcal/mol for production of **3**)[18,26] than for :B = NH_3, we suppose that Scheme II is inadequate for ammonia as base, too.



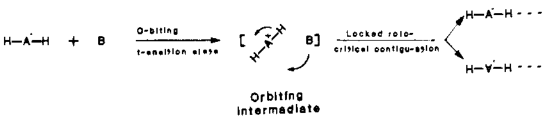
(7)

Scheme III invokes completely separate pathways for each product. Each pathway is drawn as an Eigen mechanism. Two distinct acid–base complexes, II and III, are shown. It is clear from reaction 6 that the conversions II → ii and III → iii must be essentially irreversible, for if the backwards rates were greater than one-tenth the forward rates, more isotopic scrambling would have been observed. In other words, the interconversion represented by reaction 7 occurs to only a very slight extent in the reaction of **1** with ammonia.

Scheme IV



If we wish to include the possibilities that II and III interconvert with one another as well as with a Lewis acid–base complex, then Scheme III becomes complicated. A more parsimonious picture is shown in Scheme IV, where a common intermediate, l, partitions among II, III, and the Lewis acid–base complex. What might the structure of I be?



(8)

Theoretical studies of the simplest proton transfer, hydrogen molecular ion plus hydrogen atom on the triplet energy surface, show that there are some vibrational states of the linear intermediate, H_3^+ ($^3\Sigma_u^+$), that tunnel rapidly along a bending coordinate on the picosecond time scale and other states that do so slowly.[9] Such tunneling interchanges the inner atom with the two outer atoms. This is true for the interconversion of identical atoms (e.g., in H_3^+ or D_3^+) and may also be true for isomerizations (e.g., $HHD^+ \rightleftarrows HDH^+$).[8] For polyatomic complexes, the density of states is much greater than for a triatomic, and vibrational energy will flow rapidly between states that interchange the hydrogen-bonded proton rapidly and states that do not. A locked-rotor critical configuration can be viewed as representing the divide between hydrogen-bonded complexes in which facile interconversion occurs and complexes in which the C—H···N hydrogen bond is not labile. In the former, structures such as II and III are not discrete isomers but represent different phases of a rapidly interconverting system. In the latter, Eigen intermediates retain separate identities. Reaction 8 presents a classical picture of this behavior. An ion with two acidic hydrogens, HAH^+, passes through an orbiting transition state to form an orbiting intermediate. Acid and base in this intermediate still have comparatively unrestricted rotation about their own centers of mass. After passing through a locked-rotor critical configuration, the base becomes preferentially associated with one or the other of the acidic hydrogens, as represented schematically to the right. In the case of **1**, this step gives a statistical distribution (4:3) of II and III. For a sufficiently strong base (e.g., a tertiary amine) virtually every Eigen complex goes on to products, yielding the 4/3 ratio of **2**:**3** reported in Table I.

For weaker bases, the conversions II → ii and III → iii are no longer unit efficient, and return of II and III to l plays a role. As in the case of ammonia, the **2**:**3** ratio tends toward the thermodynamic product distribution, since the barrier for II → ii (the more exothermic product channel) is lower than the barrier for III → iii. However, this critical configuration cannot come so late that there are large primary deuterium isotope effects, since the overall rates for NH_3 with **1** and with **1**-d_{11} are virtually the same, and the **2**:**3** ratios are very close to one another.

If the critical configuration in Figure 3, $[A\cdots H^+\cdots B]^*$, were to represent a potential energy maximum, loosening of the A–H bond would have to be taking place. Unless this is compensated by the developing H–B bond, one should expect a substantial difference between E^* for a proton transfer and E^* for a deuteron transfer.

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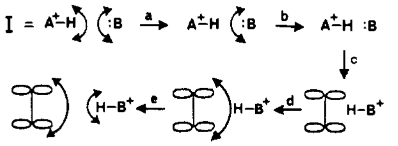
Scheme V



The difference in zero-point energies for the stretching vibration, which is being loosened, is approximately 1.2 kcal/mol. If $E^{\ddagger}$ were changing by even one-fifth of that value, one would anticipate a larger primary isotope effect than is observed, since proton transfer from **1** to ammonia is clearly not unit efficient.

Statistical phase space calculations can be used to account for isotope effects in ion-molecule reactions.[28] Using such calculations (with a FORTRAN program graciously provided by Dr. Martin F. Jarrold and Professor M. T. Bowers of the University of California, Santa Barbara) for Scheme II (as a Lewis mechanism), Scheme III (as an Eigen mechanism), or Scheme IV (either Lewis or Eigen), we find that it is possible to account for the efficiency and product distributions of the reactions of **1** with trimethylamine and ammonia. But if the sum of zero-point energies in the critical configuration for a deuteron transfer step (e.g., for II → ii) is more than 130 cm^{-1} greater than the sum for proton transfer (when the enthalpies of **1** and **1**-d_{11} at absolute zero are set equal), then these calculations predict that the **2**:**3** ratio ought to change by a factor of at least 1.2 when deuterium is substituted for the acidic hydrogen. It is conceivable that the primary isotope effect in reactions of **1**-d_{11} is obscured by secondary isotope effects that oppose it. The magnitude of secondary isotope effects, however, may be gauged from the effects of deuteration of the base. Since the **2**:**3** ratio for ND_3 is within experimental error of the **2**:**3** ratio for NH_3, there is no evidence to support the notion that the primary isotope effect is substantially greater than would be determined by comparing deprotonation of **1** with **1**-d_{11}. Statistical phase space calculations with Lewis mechanisms predict that the **2**:**3** ratio should decrease when the acid is deuterated and predict that the ratio should increase if Eigen mechanisms are operating. The direction of the isotope effect is consistent with an Eigen mechanism in the reaction of **1** with ammonia, although its small magnitude could be explained in terms of a fortuitous cancellation of effects in a regime where both Lewis and Eigen pathways operate. It is worth noting, though, that Jasinski and Brauman[16a] have reported low values of k_H/k_D for proton transfer between unhindered pyridines, a reaction in which the intervention of Lewis complexes is highly unlikely. Moreover, the isotope effects that Jasinski and Brauman predicted using an RRKM model with a ≥232-cm^{-1} difference (relative to the difference in enthalpies of the deuterated and undeuterated reactants at absolute zero) in zero-point energies between the transition states for H-transfer and for D-transfer were significantly larger than the values observed experimentally.

An alternative (and, in our view, preferable) explanation for the smallness of the primary isotope effect is that the critical configurations for proton-transfer steps may be earlier than the potential energy maxima. A locked-rotor bottleneck can be envisaged, in which the lone pair of the amine has to become oriented toward the acidic hydrogen. This can be described in terms of a loss of degrees of freedom, which correspond to large root-mean-square deviations from the collinearity required for atom transfer. As Scheme V depicts schematically, locked-rotor critical configurations **a**, **b**, **d**, and **e** divide the bound complexes of Figure 3 into five regions. These represent discrete steps in the engagement of reactants and the disengagement of products. To the left, in intermediate I, AH^+ and B exhibit large deviations from a collinear arrangement of the A-H bond with the *n*-donor atom, represented schematically by curved, double-headed arrows. In step **a**, the A-H bond and the *n*-donor atom become collinear, but the orientation of the sp^3-hybridized lone pair of the base retains large deviations from the bond axis. In the critical configuration of step **b**, the lone pair becomes collinear with the A-H bond. At this point, the potential energy maximum for proton transfer, step **c**, may present a negligible barrier. For reasons of symmetry, two further locked-rotor transition states have been added for separation of the conjugate base (represented as a π-bond) and the conjugate acid BH^+. As pointed out in reaction 3, this sequence can be run from right to left, as well.

Conclusions

Previous microscopic treatments of ion-molecule reactions have divided the reaction coordinate into two parts: a bimolecular regime, in which AH^+ and B become associated with one another; and a unimolecular regime, in which the ion-molecule complex isomerizes from reactants to products.[1] Bowers, Chesnavich, and co-workers[23] have presented discussions that embrace virtually all of the types of transition states and critical configurations described here. Our experimental data appear to require the details of Scheme IV and steps **a** and **b** of Scheme V to account for the following results: (1) Deprotonation of **1** by tertiary amines yields a statistical (4/3) product ratio. (2) Deprotonation of **1** by ammonia is not unit efficient and gives a product ratio closer to the thermodynamic value. (3) A small primary isotope effect is observed for reaction of **1**-d_{11} with ammonia. (4) Lewis acid-base complexes are not obligatory intermediates, despite the fact that they represent the deepest well on the potential surface. They are, however, kinetically accessible. (5) Hydrogen scrambling between **1**-d_{11} and NH_3 occurs to only a slight extent in the course of the Brønsted acid-base reaction.

From these results we draw the following conclusions regarding the unimolecular regime for deprotonation of **1** by amines: (1) An acid-base complex intervenes prior to channel selection and, in a product-determining step, partitions statistically between pathways leading to **2** or **3**. (2) For strong bases, progress along the reaction coordinate is essentially irreversible, and the product distribution reflects the statistical partition in the product-determining step. For weaker bases, reversion from subsequent intermediates back to reactants takes place to an appreciable extent. (3) Proton transfer cannot be occurring in the product-determining step (otherwise the product distributions from **1** and **1**-d_{11} would have differed to a much greater extent). The small isotope effect is most easily explained by invoking entropic bottlenecks along the reaction coordinate. (4) Lewis acid-base complexes do not appear to form prior to the product-determining step. However, a Lewis acid-base complex can be a minor product of the product-determining step. (5) Protons pass back and forth between acid and base to only a slight extent during the course of reaction. Chemical engagement can be portrayed as comprising three successive stages: an orbiting intermediate from physical ion-dipole capture, locked rotation of the acid with respect to the base, and mutually locked rotation of the reactants.

The picture that emerges depicts product-determining steps that involve channel selection from orbiting intermediates. As we have previously discussed, ion-molecule complexes with lifetimes >1 ps play an analogous role in unimolecular ion decompositions.[29] Although the distribution of rotational angular momenta around the center of mass of the complex differs greatly between complexes generated from ion-molecule reactions and those from molecular ion decompositions,[1] one can be viewed as the microscopic reverse of the other. It is therefore reassuring to find evidence for complexes that build up behind locked-rotor critical configurations under both sets of conditions.

The presence of orbiting intermediates in ion-molecule reactions has special importance with regard to comparisons between gas-phase and solution-phase reactions. In solution, reacting molecules experience encounters within a solvent cage. Thus constrained, they sample many orientations before reacting. This paper has presented a model for gas-phase reactions that has many of the same dynamical features: an electrostatic well that plays

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[29] Morton, T. H. *Tetrahedron* **1982**, *38*, 3195-3243 (Report No. 137).

[30] **Note Added in Proof.** Subsequent to submission of this manuscript, Ausloos and Lias [*J. Am. Chem. Soc.* **1986**, *108*, 1792-1796] have published ICR studies consistent with Scheme IV as a generalized mechanism.

the role of the solvent cage; rapid interconversion among Eigen complexes that allows reaction partners to explore many geometries within this well; and locked-rotor critical configurations that present entropic barriers to reaction, which permit ion–molecule complexes to live long enough to play a major role in selection of product channels. The similarities in dynamics between acid–base reactions in the gas phase and in solution reinforce the expectation that mechanistic insights from one realm will be pertinent to the other.

Acknowledgment. The authors are grateful to Dr. M. F. Jarrold and Prof. M. T. Bowers of the University of California, Santa Barbara, for a copy of their computer program for statistical phase space calculations, to Kevin Plaxco for preparing 1-methylcyclopentylamine, and to Drs. R. Kondrat and R. Tsao for recording GC/MS on the UCR ZAB-1F, which was purchased with the partial support of NIH Grant No. RR01750-01. The Fourier Transform Mass Spectrometer was purchased with the assistance of NSF Instrumentation Grant No. CHE 82-17610 and by BRSG Grant No. RR07010-8 from the NIH. This work was supported by the NSF (CHE 83-06081) and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

Registry No. 1, 17106-22-8; NH_3, 7664-41-7; $N(CH_3)_3$, 75-50-3; 1-methylcyclopentylamine, 40571-45-7; bromocyclohexane, 108-85-0; deuterium, 7782-39-0.

The Use of Global and Local Molecular Parameters for the Analysis of the Gas-Phase Basicity of Amines

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Contribution from the Department of Chemistry, University of North Carolina, Chapel Hill, North Carolina 27514, and K. U. Leuven, Laboratorium voor Oppervlaktescheikunde Kard. Mercierlaan 92, B-3030 Leuven (Heverlee), Belgium. *Received July 19, 1985*

Abstract: It is demonstrated that the variation of the gas-phase basicities of amines can be analyzed by using two parameters: one global and one local (that is, site-dependent). Two global quantities (the average "effective" electronegativity and the geometric average of the isolated-atom electronegativities) and two local quantities (the fukui function and the residual charges) are tested. A two-parameter linear model containing one global and one local quantity produces satisfactory correlations with the experimental gas-phase basicities. It is shown how to express the fukui function, which reflects the site reactivity in density functional theory ($f(\vec{r}) = [\partial\rho(\vec{r})/\partial N]_{v(\vec{r})}$), in terms of the variation of the Mulliken gross charges (q_i) of an atom in a molecule, which is accompanied with a change in the total number of electrons (N) in this molecule: $f_i^+ = q_i(N + 1) - q_i(N)$; $f_i^- = q_i(N) - q_i(N - 1)$ and $f_1^\circ = {}^1/_2[q_i(N + 1) - q_i(N - 1)]$.

The electron density distribution is fundamental for understanding chemical reactivity and naturally leads to explaining nucleophylic and electrophylic attack on the basis of electrostatic interactions. However, the electron density by itself does not explain everything, and it was recognized that the change in electron density under the influence of an approaching reagent is also of importance. The frontier-electron theory of chemical reactivity by Fukui[1,2] recognizes the key role of the valence electrons in forming molecules and considers therefore the distribution of the highest energy orbital electron density as being most important for electrophilic attack and the lowest energy vacant orbitals in nucleophilic substitution reactions. In reactions with radicals both orbitals become important. The highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) are in this way considered as the principal factors governing the easiness of chemical reactions and the stereoselective path.

It was recently demonstrated by Parr et al.[3,4] that most of the frontier-electron theory of chemical reactivity can be rationalized from the density functional theory of the electronic structure of molecules.[5,6] For a system of N electrons with ground-state energy $E[n,v]$, where v is the potential energy acting on an electron due to the presence of all nuclei, several quantities of fundamental importance can be defined. The chemical potential μ of the electrons, i.e., the negative of the electronegativity χ, is given by $\mu = (\partial E/\partial N)_{v(\vec{r})}$ and has the same value everywhere. The change of μ with the number of electrons was defined by Parr and Pearson[7] as a measure for the "absolute hardness" as $\eta = (\partial\mu/\partial N)_{v(\vec{r})} = (\partial^2 E/\partial N^2)_{v(\vec{r})}$. The frontier function or fukui function for a molecule, reflecting the reactivity of a site, was defined by Parr and Yang[3] as

$$f(\vec{r}) = [\delta\mu/\delta v(\vec{r})]_N = [\partial\rho(\vec{r})/\partial N]_{v(\vec{r})} \tag{1}$$

i.e., the functional derivative of the chemical potential with respect to a change in the external potential or, because of the Maxwell relations, identical with the change in electron density accompanied with a change in the number of electrons. The hardness and the fukui function are local quantities and reflect the properties of the different sites within the molecule.

Probing the reactivity of the different sites within a molecule, being of importance for understanding reaction mechanisms, only partially meets the chemists aspirations. A comparison of different molecules is also of importance. The object of the present study is to explore different ways to make this comparison by using easily obtainable parameters. Substituent group properties have been used extensively in this context. However, as the atomic properties change from molecule to molecule, so will substituent groups be subject to variations. Alkyl groups, e.g., may act either as electron donors or as electron acceptors, depending on the substrate. One of the properties of interest of substituent groups is their tendency to attract electrons, i.e., their electronegativity. Depending on the actual molecular configuration, this may qualify a group as electron donor or electron acceptor. In a study of the gas-phase

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[†] University of North Carolina.

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