Gas-Phase Ion-Molecule Reactions of Fe^+ and Ti^+ with Alkanes

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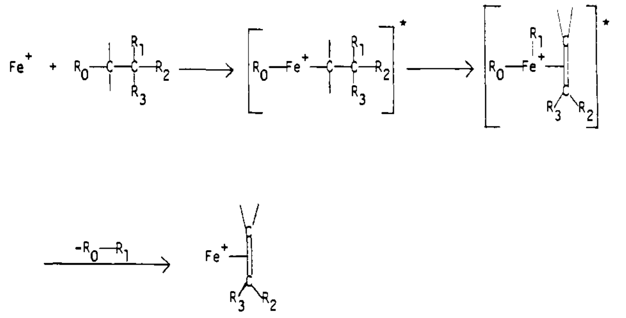
Abstract: A pulsed laser has been used in conjunction with an ion cyclotron resonance mass spectrometer to generate and study the gas-phase ion-molecule reactions of Fe^+ and Ti^+ with a series of alkanes. While C-C insertion leading to alkane elimination and C-H insertion leading to H_2 elimination are competitive in the Fe^+-alkane system, the Ti^+-alkane system is dominated by C-H insertions. Ti^+ also tends to release multiple neutrals from the initial collision complex to create multiple sites of unsaturation in the bound hydrocarbon. The C-C insertions by Fe^+ are somewhat selective for the weaker bonds in the alkane.

Organometallics, in general, have been widely studied in relation to their role as proposed intermediates in various catalytic processes.[1] In spite of this attention, many important catalytic reactions are ill defined in terms of the structure of the intermediates and the mechanisms through which they act. Many of the problems involved stem from the highly variable and complicated chemistry that arises from the reaction of organic material with the metal-based catalysts employed. Also, technical difficulties associated with characterizing adsorbed species on catalytic surfaces have hampered investigations in this area.[2]

The recent interest in gas-phase ion-molecule reactions between simple atomic metal ions and organic molecules has produced a variety of methods that offer a simplified chemical approach to the investigation of organometallic events. Progress has been made with various mass spectrometric techniques, including ion beam,[3] secondary ion mass spectrometry (SIMS),[4] and ion cyclotron resonance (ICR) spectrometry.[5-9] Since most catalytic processes concern the interaction of bulk solid surfaces with solutions, there are limitations to the correlations that can be constructed between condensed and gas-phase work. Nevertheless, many qualitative insights are possible from such experiments.

Our laboratory has been utilizing a laser desorption ionization source in conjunction with ICR spectrometry to produce and study simple atomic metal ions in the presence of various neutral reagent gases.[9] The ability of ICR to trap ions for up to several seconds allows reaction products to be monitored as a function of either time or pressure.[10] Our previous experiments with these techniques have shown that predictable patterns of reactivity exist for Cu^+ and Fe^+ with particular classes of organic species.[11,12] In comparison to Cu^+, Fe^+ consistently produces more reaction products with the larger organics. Furthermore, in contrast to Cu^+, Fe^+ was observed to attack the alkyl portion of the molecule as well as the functional group. The interaction of C-C and C-H bonds with metal surfaces is of much concern in the large-scale processing of alkanes in the petroleum industry.[13]

Scheme I



Ridge et al.[5,6] previously reported the reactions of Fe^+ produced by electron impact on $Fe(CO)_5$ or $Fe_2(CO)_9$ in an ICR spectrometer with some alkanes. The alkanes were observed to be cleaved by the metal ion in an oxidative-addition reaction which was explained by either a C-H or C-C insertion mechanism. Other transition-metal ions were also observed to cleave alkanes, and in an ion-beam study involving the reactions of thermally produced Co^+ with alkanes[3] further evidence was provided for C-H and C-C insertion mechanisms in the gas phase.

In this paper we examine the reactions of Fe^+ with a more extensive range of alkanes in the gas phase to establish patterns of reactivity. For comparisons we also report the reactions of these alkanes with Ti^+, another metal that is used extensively in many catalytic processes.

Experimental Section

All experiments were performed on a modified Varian V-5900 series ion cyclotron resonance spectrometer manufactured by Varian Associates. The open-ended cell was provided with an end plate supporting metal rods of high-purity iron and titanium. Metal ions were generated by focusing the beam from an International Laser Corporation pulsed Nd:YAG laser through a sapphire window onto the selected metal rod as described elsewhere.[12] Sample pressures were less than 10^{-6} torr and trapping time for the ions was 140 ms in order to minimize secondary reactions between primary ion-molecule products and neutrals. Higher mass products resulting from secondary collisions were observed in most cases but are not reported here due to the inability of our conventional ICR to yield accurate mass measurements above 160 amu for the laser ionization products. Investigations are now in progress to examine these high mass products with new instrumentation. Measured product ratios have an absolute error of ±15% due to pulse-to-pulse variations in metal ion production.

Results and Discussion

The results for the primary reactions of Fe^+ and Ti^+ with various alkanes are shown in Table I. Marked trends that distinguish each metal ion are readily seen from this comparison.

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(1) J. K. Kochi, "Organometallic Mechanisms and Catalysis", Academic Press, New York, 1978.

(2) For an overview of current methodology, see: R. B. Anderson and P. T. Dawson, "Experimental Methods in Catalytic Research", Academic Press, New York, 1976.

(3) (a) P. B. Armentrout and J. L. Beauchamp, *J. Am. Chem. Soc.*, **102**, 1736 (1980); (b) P. B. Armentrout and J. L. Beauchamp, *ibid.*, **103**, 784 (1981).

(4) J. Pierce, K. L. Busch, R. A. Walton, and R. G. Cooks, *J. Am. Chem. Soc.*, **103**, 2583 (1981).

(5) J. Allison, R. C. Freas, and D. P. Ridge, *J. Am. Chem. Soc.*, **101**, 1332 (1979).

(6) J. Allison and D. P. Ridge, *J. Am. Chem. Soc.*, **102**, 7129 (1980).

(7) R. C. Burnier, T. J. Carlin, W. D. Reents, Jr., R. B. Cody, R. K. Lengel, and B. S. Freiser, *J. Am. Chem. Soc.*, **101**, 7128 (1979).

(8) T. J. Carlin, M. B. Wise, and B. S. Freiser, *Inorg. Chem.*, **20**, 2743 (1981).

(9) R. B. Cody, R. C. Burnier, W. D. Reents, Jr., T. J. Carlin, D. A. McCrery, R. K. Lengel, and B. S. Freiser, *Int. J. Mass. Specrom. Ion Phys.*, **33**, 37 (1980).

(10) For a general discussion of ICR, see: T. A. Lehman and M. M. Bursey, "Ion Cyclotron Resonance Spectroscopy"; Wiley-Interscience, New York, 1976.

(11) R. C. Burnier, G. D. Byrd, and B. S. Freiser, *Anal. Chem.*, **52**, 1641 (1980).

(12) R. C. Burnier, G. D. Byrd, and B. S. Freiser, *J. Am. Chem. Soc.*, **103**, 4360 (1981).

(13) For a general description of these processes, see: Schrauzer, "Catalytic Conversion of Hydrocarbons", Marcel Dekker, New York, 1971.

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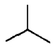
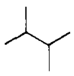
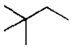
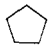
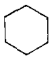
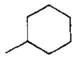
Table I. The Percentages of the Neutral Products Lost in the Primary Reactions of Ti^+ and Fe^+ with Various Alkanes (For Each Reaction the Trapping Time was 140 ms and the Pressure Was ~10^{-6} torr)

	Fe^+		Ti^+	
alkane	neutral lost	% of total	neutral lost	% of total
CH_4	NR		NR	
C_2H_6	NR		H_2	100
	H_2 CH_4	30 70	H_2	100
	H_2 CH_4 C_2H_6	12 (6)[a,b] 29 (10)[a] 59 (75)[a]	$2H_2$	100
	H_2 CH_4 C_2H_6 C_3H_8	11 24 8 57	$2H_2$ H_2, CH_4 C_2H_6	83 12 5
	H_2 CH_4 C_2H_6 C_3H_8 C_4H_{10}	24 17 12 12 35	$2H_2$ $3H_2$ H_2, CH_4 C_2H_6 H_2, C_2H_6	33 28 5 10 24
	H_2 CH_4	38 (16)[a] 62 (84)[a]	H_2 $2H_2$	84 16
	CH_4	100	H_2 $2H_2$ H_2, CH_4	22 16 62
	H_2 CH_4 C_2H_6 C_3H_8	40 22 9 29	$2H_2$ H_2, CH_4 C_2H_6 H_2, C_2H_6	38 44 6 12
	H_2 CH_4 C_2H_6 C_3H_8 C_4H_{10}	4 12 66 13 5	H_2 $2H_2$ H_2, CH_4 C_2H_6 H_2, C_2H_6	7 8 54 8 22
	NR		H_2 CH_4	89 11
	H_2 $2H_2$	77 23	$2H_2$	100
	H_2 $2H_2$ $3H_2$	55 24 21	$3H_2$	100
	H_2 $2H_2$ $3H_2$ CH_4 H_2, CH_4 $2H_2, CH_4$	29 25 20 7 8 12	$3H_2$ $2H_2, CH_4$	64 36

[a] Values in parentheses are estimated from the rate constants given in ref 6. [b] Reference 6 also reports 9% of m/z 110. Our spectra indicated a small amount of this ion for the larger normal alkanes, but it is somewhat obscured by the $^{54}FeC_4H_8{}^+$ peak.

The product ions observed result from the loss of neutral species from the metal ion-alkane collision complex. With the acyclic alkanes, Ti^+ always releases two or more neutrals that are predominantly H_2 molecules while Fe^+ releases only one neutral molecule. Although the Fe^+–cycloalkane collision complexes lose multiple as well as single neutrals, the Ti^+–cycloalkane complexes show only one product resulting from multiple neutral molecule loss.

The reaction between Fe^+ and acyclic alkanes can be generalized by eq 1 and 2. When Ridge first investigated the reaction between Fe^+ and alkanes,[5,6] a mechanism was developed based on initial insertion, i.e., oxidative addition, of the metal ion into either a C–C or C–H bond followed by reductive elimination of an alkane or H_2 as shown in Scheme I. This mechanism is promising in that it is thermodynamically feasible and consistent with most of our observations. Also, the β-hydride shift invoked (when R_1 = H) is recognized as the major step in the decomposition of metal–alkyl bonds in solution,[14] and the absence of other complexing ligands in our gas-phase work would make these shifts even more facile. While β shifts of other groups such as halogens[14] and alkyls[15] are known, they are uncommon. A β-alkyl shift for some of these mechanisms cannot be ruled out,[16] but it would not be expected to be competitive when abundant β-hydrogens are available.

$$Fe^+ + C_nH_{2n+2} \rightarrow Fe[C_{(n-m)}H_{2(n-m)}]^+ + C_mH_{2m+2} \qquad (1)$$

$$Fe^+ + C_nH_{2n+2} \rightarrow Fe[C_nH_{2n}]^+ + H_2 \qquad (2)$$

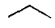
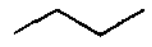
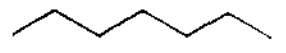
$$n = 3\text{–}6$$

Table II. Bond-Dissociation Energies (kcal/mol)[a]

bond	energy	bond	energy
$H-C_2H_5$	98	CH_3-CH_3	88
$H-CH_3$	104	$CH_3CH_2-CH_3$	85
$H\text{-}i\text{-}C_3H_7$	95	$CH_3\text{-}i\text{-}C_3H_7$	84
$H\text{-}t\text{-}C_4H_9$	92	$CH_3\text{-}t\text{-}C_4H_9$	82

[a] Values taken from "CRC Handbook for Chemistry and Physics", 53rd ed., The Chemical Rubber Co., Cleveland, Ohio, 1972, p F-192.

Table III. Intensities for Neutral Losses from Normal Alkane-Fe^+ Collision Complexes[a]

		neutral lost				
alkane		CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}
	pre	100				
	obsd	100				
	pre	67	33			
	obsd	33	67			
	pre	50	25	25		
	obsd	27	9	64		
	pre	40	20	20	20	
	obsd	22	16	16	46	
	pre	33	17	17	17	17
	obsd	8	19	11	26	36

[a] pre = the predicted relative intensities based on nonselective insertion by the Fe^+ into the carbon chain; obsd = the observed relative intensity.

No reactions of Fe^+ were observed with either methane or ethane, and while methane has no β-hydrogens, the lack of reaction with ethane seems peculiar since a C–H insertion by the Fe^+ would lead to the release of H_2 from an iron–ethylene complex according to Scheme I. This suggests that a terminal C–H insertion by Fe^+ may not be favorable, and this is supported by the bond-dissociation energies listed in Table II which indicates that terminal C–H bonds are the strongest bonds in an alkane. If this supposition is true then H_2 loss from the Fe^+–propane complex can arise only from an insertion into one of the central C–H bonds that are weaker than the terminal C–H bonds by approximately 5 kcal/mol. Unfortunately, this cannot be proven by any labeling experiments.

The systematic loss of small alkanes from n-alkane–Fe^+ collision complexes suggests that Fe^+ is somewhat nonselective in choosing its site of insertion into C–C bonds. Table III lists the relative amounts of products observed for only those reactions which result in cleavage of the carbon chain for normal alkanes as a test of this idea. This ignores H_2 losses that presumably result from C–H insertions and thus deals with only C–C insertions. Also listed in Table III are the product distributions predicted for a nonse-

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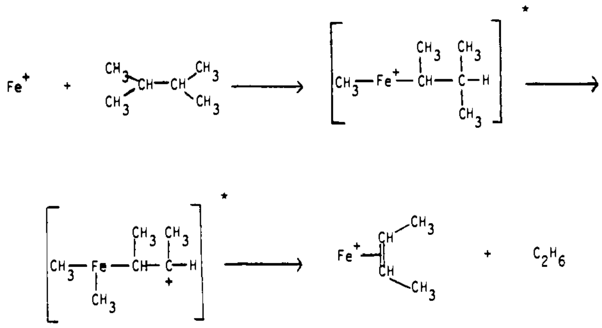
(14) R. F. Heck, "Organotransition Metal Chemistry", Academic Press, New York, 1978, pp 45–54.

(15) Reference 1, pp 246–261.

(16) Reference 3, for example, suggests a possible β-methyl shift in Scheme II.

Scheme II



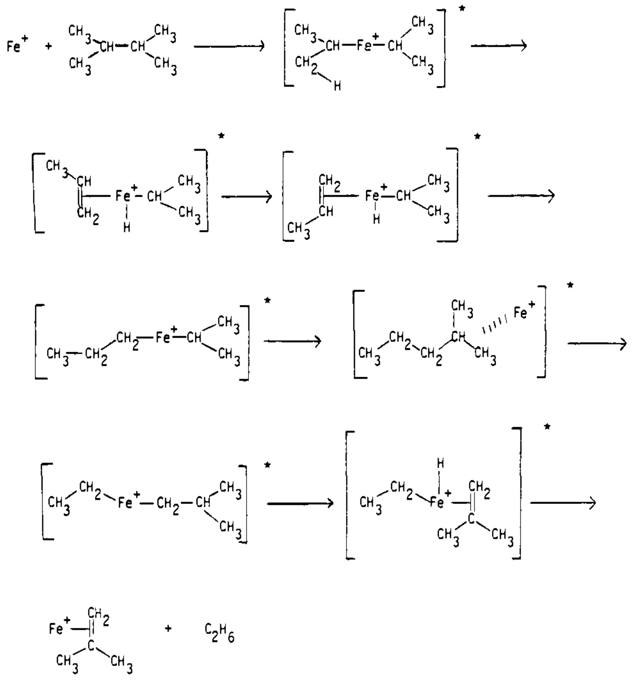
lective mode of insertion that assumes every C–C bond is equally susceptible to attack. For *n*-pentane, as an example, there are four C–C bonds as shown:

$$\mathrm{C_1\underset{a}{-}C_2\underset{b}{-}C_3\underset{c}{-}C_4\underset{d}{-}C_5}$$

An insertion by Fe^+ into either the a or d bond will give CH_4 as the only product based on $R_1 = H$ in Scheme I. The products from b or c insertion will be the same (C_2H_6 and C_3H_8 based on $R_1 = H$ in Scheme I) provided that each of the two hydrogen shifts involved has an equal probability. The fact that C_3H_8 loss dominates C_2H_6 loss in the *n*-pentane reaction and C_4H_{10} loss dominates C_2H_6 loss in the *n*-hexane reaction, however, suggests that in fact hydrogens are more labile on β-methyl carbons than on β-methylene carbons. Nevertheless, if all C–C bonds are equally open for insertion, then the product distribution would be 50% CH_4 loss and 50% C_2H_6 and C_3H_8 loss combined. The trend observed in Table III shows that terminal C–C insertion resulting in CH_4 loss is the least preferred mode of attack, which is expected since these bonds are the strongest along the chain. Also, central C–C bond cleavages resulting in larger alkane loss appear to be favored and, unsurprisingly, these bonds are the weakest in the chain. None of the cleavage sites appear to be completely averted by Fe^+, however, suggesting that the thermodynamic effect for C–C bond insertion selection is limited.

Branched alkanes reveal some interesting insights into the mechanism of these reactions in that certain masses in the product series are expected to be missing. For example, the reaction of Fe^+ with 2,2-dimethylpropane is unique because it is the only alkane that does not lose H_2, and the single loss of CH_4 as predicted by Scheme I is good evidence for this mechanism. Since Table II indicates that the C–C bond cleaved in this reaction is much weaker than the terminal C–C bond in a normal alkane, nothing can be said about the feasibility of terminal C–C insertions. With isobutane and 2,3-dimethylbutane an intact CH_3CH_2– unit does not originally exist so a loss of ethane would not be possible by using only β-hydride shifts as in Scheme I. While isobutane shows no ethane loss as expected, 2,3-dimethylbutane does show a small amount which may be rationalized by several different explanations. An insertion as shown in Scheme II positions the Fe^+ with a β-carbon that has two methyls and one hydrogen attached. The two methyls could, therefore, compete effectively with the hydrogen as the group being shifted. Alternatively, the collision complex could supply enough energy to the alkane to induce scrambling of the carbon skeleton or the metal may catalyze the rearrangement of the alkane before following the mechanism of Scheme I. This is illustrated in Scheme III, which was suggested by Ridge,[17] and is attractive in that it does not invoke a β-methyl shift. However, even though this produces the more stable product, the second insertion of Fe^+ into the new alkane should also produce some amount of C_4H_{10} loss, but this is not observed. Since it is not possible to distinguish C_2H_6 loss from H_2 loss followed by C_2H_4 loss, isomerization and subsequent reactions of a metal-bound alkene must also be considered. Lending some evidence for this type of mechanism is the recent report by Armentrout et al.[18] that C_2H_4 is released in the reaction between Co^+ and 2,3-dimethyl-2-butene. A metallacyclobutane intermediate was proposed in an isomerization mechanism for this reaction. Thus, a mechanism can be postulated in which H_2 is first lost in the encounter between Fe^+ and 2,3-dimethylbutane generating an Fe^+–alkene complex which can then eliminate C_2H_4 in a manner analogous to the Co^+ system. Direct loss of C_2H_6, however, would be more energetically favored. In any event, the complexity of any of these suggested mechanisms could easily explain why the ethane loss is the smallest in this particular spectrum. The case of 2,2-dimethylbutane is also unusual in that the loss of C_3H_8 occurs without an intact C_3H_7– unit present in the original alkane structure. A β-methyl shift mechanism as in Scheme II cannot produce a C_3H_8 loss, thus making a rearrangement of the carbon skeleton appear more likely here. Interestingly, the most favorable reaction is ethane loss, which results from Fe^+ inserted in the weakest bond in this structure between the C_2H_5– and *t*-C_4H_9– units.

Scheme III



The results from the cyclic alkane reactions with Fe^+ are distinguished from the acyclic results in that the carbon skeleton presumably remains intact and some multiple losses are observed. Cleavage of the ring by Fe^+ has been observed in other ring systems such as cyclohexanone and tetrahydrofuran[12] and may be attributed to the weaker bonds in the ring caused by the functional groups in these molecules. In the cycloalkane reactions, the initial complexes may not have enough energy to open the ring twice in order to lose any of the skeletal carbons. The rigid constraint of the ring obviously facilitates multiple hydride shifts onto the metal until a strongly bound polyene ligand is formed. This is comparable to electron impact mass spectrometry of compounds with π-bonded cyclohexene ligands attached to iron which undergo dehydrogenation leading to π-bonded aromatic ligands bound to iron.[19] Some ring fragmentation, however, was also observed in the electron-impact study. The absence of such ring fragmentation in our spectra may be attributed to the softer method of ion formation in our experiment, akin to chemical ionization.[20] A mechanism is proposed for cyclopentane in

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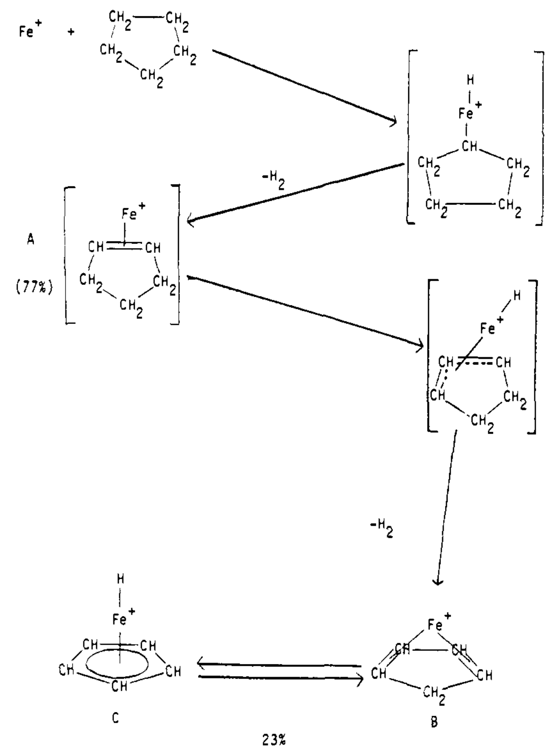
(17) D. P. Ridge, private communication.

(18) P. B. Armentrout, L. F. Halle, and J. L. Beauchamp, *J. Am. Chem. Soc.*, **103**, 6624 (1981); P. B. Armentrout and J. L. Beauchamp, *ibid.*, **103**, 6628 (1981).

(19) J. Muller in "The Organic Chemistry of Iron", E. A. Loerner Von Gustorf, F. Gruels, and I. Fischler, Eds., Academic Press, New York, 1978, pp 145–173.

(20) R. C. Burnier, G. D. Byrd, T. J. Carlin, M. B. Wise, R. B. Cody, and B. S. Freiser, "Lecture Notes in Chemistry", K. P. Wanczek, Ed., Springer-Verlag, West Germany, in press.

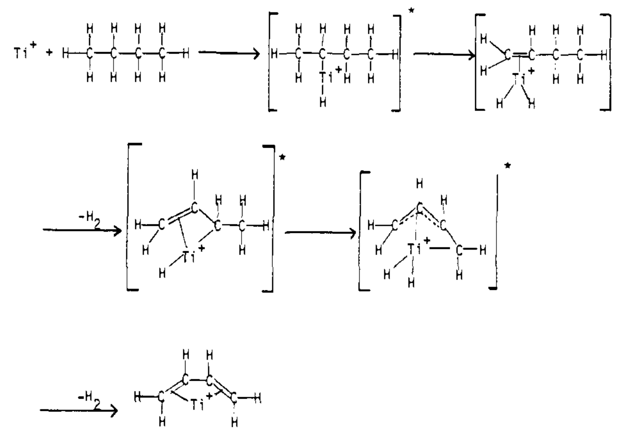
Scheme IV



Scheme IV that involves an initial C–H insertion. After the loss of one H_2, A may either form the stable $FeC_5H_8^+$ ion observed or, if enough energy remains in the complex, proceed to lose another H_2 to produce the iron cyclopentadiene ion. B can be envisioned as rearranging to form the hydride of the cyclopentadienyl iron.[21] A C–C insertion is also possible and would involve a reclosing of the ring to produce a structure like B or C. Methylcyclohexane loses CH_4 and $2H_2$ as well as $3H_2$ and could indicate that insertion into the methyl-ring C–C bond is competitive with the other insertions or that a β-methyl shift is occurring.

Ti^+ reveals less well-defined trends in its reactions with alkanes. The primary reactions of Ti^+ with alkanes leave a more unsaturated ligand attached to the metal than in the Fe^+ reactions where a simple alkene is formed. Since the reactions of ethane, propane, and butane with Ti^+ released no smaller alkanes from the complex, insertion into the carbon chain is not seen as the dominant mechanism here. Instead, a rapid series of hydride shifts onto the metal occurs following an initial C–H insertion by Ti^+ as shown in Scheme V. A second site of unsaturation adjacent to the first is likewise created by the Ti^+ which is localized by the π overlap from the primary site. Initial C–H insertion is probably not selective for the termini of the alkane chain as shown since the Ti^+–n-hexane reaction products include not only the $TiC_6H_8^+$ ion but also substantial amounts of $TiC_6H_{10}^+$. Branching of the alkane apparently hampers secondary product losses shown in Scheme V since isobutane, 2,2-dimethylbutane, and 2,2-dimethylpropane show a single H_2 loss which is absent in the spectra of their unbranched isomers. The multiple losses observed in these branched species may involve some rearrangement to form common polydentate ligands such as butadiene. Small losses of CH_4 and C_2H_6 from n-pentane and n-hexane may indicate either β-methyl shifts onto the metal or that some C–C insertion does occur for the larger alkanes. In an investigation of the reactions of Ti^+ produced by electron impact on $TiCl_4$ with various olefins,[22] Allison and Ridge also observed multiple H_2 losses from the initial collision complex. A possible cyclization of the product was suggested to account for some of the unsaturation present and this may be occurring to a degree in our reactions.

Scheme V



The rigid structure of the cycloalkane systems is seen to facilitate the sequential H_2 losses in Scheme V and, consequently, only the most unsaturated and probably aromatic ligands remain attached to the metal. Like the Fe^+ system, CH_4 and $2H_2$ are lost from methylcyclohexane and $TiC_5H_6^+$ may intercovert between the cyclopentadiene and cyclopentadienyl hydride forms. Thus, with the exception of cyclopropane, all of the reactions of Ti^+ with cycloalkanes have analogous products with the Fe^+–cycloalkane reactions. The small loss of CH_4 from the Ti^+–cyclopropane complex may originate from a metallocyclobutane intermediate which rearranges to a metal carbene complex since two C–C bonds must be broken in this reaction.[23]

Conclusion

When contrasting the reactions of Fe^+ and Ti^+ with alkanes, two important differences are apparent. First, while C–C insertion leading to alkane loss and C–H insertion leading to H_2 loss are competitive with one another in the Fe^+ reactions, the Ti^+ reactions are dominated by C–H insertions. The intermediate formed is a metal hydride, an important species in addition–elimination reactions for catalytic processes such as the oligomerization of olefins.[23] Another distinguishing feature of Ti^+ is its ability to release multiple neutral species creating multiple sites of unsaturation. This extra reducing power of Ti^+ over Fe^+ is explicable by noting that Ti^+, a s^1d^2 system, has more orbital vacancies than Fe^+, a s^1d^6 system, and is, therefore, a better Lewis acid.

Fe^+ readily inserts into any C–C or C–H bond of an alkane except for the stronger terminal C–H bonds. There is a slight tendency for the Fe^+ to cleave central C–C bonds over terminal C–C bonds, probably because of the latter bonds' higher dissociation energy. While β-hydride shifts figure prominently in our schemes for the conversion of free alkanes to olefin ligands, β-alkyl shifts remain as an attractive option in some cases. Recent results in our laboratory[11] and elsewhere[24] have shown that β-methide abstraction by a metal is possible. Also, it has been suggested that β C–C bond cleavage occurs in alkyl–nickel chains and is analogous to β-hydrogen elimination mechanisms.[25] Yet, there is no conclusive evidence of β-methyl shifts in our work.

In comparing our work with that of Ridge for the reactions of Fe^+ with isobutane and n-butane,[5,6] we can see that qualitative agreement again exists. $FeC_4H_6^+$ was reported in ref 6 as 9% of the product but was difficult to quantitate in our experiment due to the interference from the ^{54}Fe isotope. We did, however, observe this mass to increase at higher pressures. Other slight differences in the quantitative values are observed and may be attributed to the different methods used to generate Fe^+. Both laser desorption[27]

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[21] R. F. Heck, "OrganOtransition Metal Chemistry", Academic Press, New York, 1978, p 549.

[22] J. Allison and D. P. Ridge, J. Am. Chem. Soc., **99**, 35 (1977).

[23] Such a mechanism has been proposed for a tungsten–olefin system: J. L. Herisson and Y. Chauvin, Makromol. Chem., **141**, 161 (1970).

[24] Reference 19, pp 76–110.

[25] G. W. Goodloe, E. R. Austin, and F. W. Lampe, J. Am. Chem. Soc., **101**, 3472 (1979).

[26] G. W. Parshall, "Homogeneous Catalysis", Wiley-Interscience, New York, 1980, Chapter 3.

[27] J. F. Ready, "Effects of High-Power Laser Radiation", Academic Press, New York, 1971.

and electron-impact[28] methods are somewhat susceptible to the formation of ions in various excited states.

A comparison of the Fe^+–alkane reactions with the Co^+–alkane reactions reported by Armentrout and Beauchamp[3] shows few qualitative differences in the exothermic products formed by these two systems. Quantitatively, Co^+ releases more H_2 from the normal alkanes in all instances and suggests that Co^+ has more of a preference for C–H insertion than does Fe^+. Co^+ also loses CH_4 less often from these alkane collision complexes which indicates that Co^+ avoids C_1–C_2 insertion even more than does Fe^+. The branched alkane reactions show a better correlation between the product distributions for the two metals, but it is interesting to note that the unusual C_2H_6 loss from 2,3-dimethylbutane is not reported for the Co^+ reaction. That we do not see any of the iron analogues of the high energy products formed in the ion beam such as $CoCH_3^+$ or $CoC_2H_5^+$ is evidence that our trapped metal ions are predominantly of low kinetic energy. Dehydrogenation is the main reaction with cycloalkanes for both the Fe^+ and Co^+ systems.[18] However, the complete absence of any ring-cleavage products for cyclopentane with Fe^+ as opposed to the large ethylene loss in the Co^+–cyclopentane reaction stresses the fact that some differences do exist between the reactions of these metal ions with alkanes.

In gas-phase reactions between simple metal ions and organic molecules, the presence of polar functional groups can greatly influence the site of attack along the molecule. However, results from our laboratory have shown that in reactions of Fe^+ with ketones and ethers,[12] the loss of H_2 and small alkanes from the initial collision complexes becomes more dominant as the alkyl portions of these compounds increase. The results presented here provide a general description as to how these metal ions can react with various saturated hydrocarbon structures and demonstrate how the alkyl portion of a molecule can be as potentially influential in directing product formation as a particular functional group.

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Registry No. Fe^+, 14067-02-8; Ti^+, 14067-04-0; methane, 74-82-8; ethane, 74-84-0; propane, 74-98-6; butane, 106-97-8; pentane, 109-66-0; hexane, 110-54-3; isobutane, 75-28-5; 2,3-dimethylbutane, 79-29-8; 2,2-dimethylbutane, 75-83-2; cyclopropane, 75-19-4; cyclopentane, 287-92-3; cyclohexane, 110-82-7; methylcyclohexane, 108-87-2; 2,2-dimethylpropane, 463-82-1.

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The Mechanism of Specific Acylation of the Active Site of α-Chymotrypsin by *N*-Acylimidazoles

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Abstract: The rates of acylation of α-chymotrypsin by a series of *N*-acylimidazoles have been measured, and values of k_2/K_m have been determined in the pH range 5.0–9.0 at 30 °C. Acylation of the active site could be shown in all cases by (a) the lack of reactivity of the acylated enzyme at pH 5.0 toward *N-trans*-cinnamoylimidazole and (b) the rate of deacylation at pH 6.91, which was nearly identical in each case with that of the acyl-enzyme derivative prepared with the corresponding *p*-nitrophenyl ester. The rate of acylation increases with increasing chain length, *N*-hexanoylimidazole having $k_2/K_m = 5 \times 10^4\ M^{-1}\ s^{-1}$ and *N*-(β-phenylpropionyl)imidazole having $k_2/K_m = 1.2 \times 10^6\ M^{-1}\ s^{-1}$ at pH 7.5. Compounds with alkyl-group branching in the acyl group acylate the enzyme at rates intermediate between those of *N*-butyryl and *N*-acetyl derivatives. These results suggest that proper steric fit in the active site is important although K_m must be very large (plots of k vs. $k/(S)_0$ have infinite slopes). The values of k_2/K_m are nearly independent of pH except in the case of the *N*-(3,3-dimethylbutyryl)-*N*′-methyl imidazolium ion with which k_2/K_m increases with increasing pH until a maximum is reached ($pK_{app} = 6.6$). This difference reflects the fact that reaction of the N-methylated derivative is via a positively charged species at all pH values, whereas the unmethylated compounds react through both the neutral species and conjugate acids with similar rate constants. The rate constants for the corresponding methylated and unmethylated derivatives extrapolate to the same value at pH ~4, showing that the reaction at low pH involves acylation of the enzyme by the *N*-acylimidazole conjugate acid. The limiting value of k_2/K_m for the *N*-(3,3-dimethylbutyryl)-*N*′-methylimidazolium ion is 3.1 times slower in D_2O than in H_2O. Thus, the histidine in the active site is participating in the reaction in the base form, and the reaction involves proton transfer in the transition state. It can be concluded that the nearly pH-independent reactions of the unmethylated derivatives at pH >7 must also represent neutral histidine-57 catalyzed acylation of serine-195 by the neutral *N*-acylimidazole. Thus, histidine-57 participates in the reactions as a general base most likely by partially abstracting a proton from the serine hydroxyl in the transition state. Kinetically equivalent mechanisms involving the histidine-57 conjugate acid acting as a general acid can be ruled out.

The hydrolysis of *N*-acylimidazoles having alkyl group branching in the acyl group is marked by steric effects that are highly abnormal for bimolecular reactions.[1-3] The rates of the general base, general acid, and hydroxide ion catalyzed reactions are not retarded by increased branching of the acyl group at the α-carbon but are actually accelerated.[1] Branching at the β-carbon does produce a rate decrease but to a lesser extent than found for nucleophilic reactions of esters. Similar relative-rate ratios have been found in the hydrolysis of *N*-acylimidazolium ions,[2,3] which rules out steric inhibition of resonance as the cause of the abnormal steric order.[2] In contrast, aminolysis of *N*-acylimidazoles by diethylamine gives rise to a normal steric order.[4] It was suggested that the unusual steric effects in hydrolysis could be due to relief of strain in a transition state in which the carbon–nitrogen bond

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