Hydrogen−Deuterium Exchange Studies in Platinum(II) Complexes of 1-Methylimidazole[1]

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Abstract: A kinetic study of hydrogen−deuterium (H/D) exchange in Pt(II)−1-methylimidazole complexes has been performed in D_2O/NaOD solution, at 60 °C, by means of ^{1}H NMR spectroscopy. Isotopic exchange has been observed at C(2)−H, C(4)−H, and C(5)−H of the imidazole moiety. Kinetic data analysis of H/D exchange in the complexes *cis*-$[Pt(NH_3)_2(MeIm)_2]Cl_2$ (**3**), *trans*-$[Pt(NH_3)_2(MeIm)_2]Cl_2$ (**4**), $[Pt(en)(MeIm)_2]Cl_2$ (**5**), and $[Pt(MeIm)_4](ClO_4)_2$ (**6**) revealed that Pt(II) enhances C(2)−H exchange in the coordinated 1-methylimidazole (MeIm) by ca. 10^2 to 10^3, relative to the neutral substrate. However, it is ca. 10^4−10^5 times less effective compared to H^+ and CH_3^+. In complex **5**, C(5)−H exchange is ca. 6 times faster than C(4)−H exchange, in contrast with expectations based on an inductive/field effect by Pt(II). The observation of the relative reactivity order, C(5)−H exchange > C(4)−H exchange in **5**, is discussed by consideration of contributing resonance structures of the intermediates formed upon abstraction of C(4)−H and C(5)−H, which would place the positive charge at the more favorable N(1)−CH_3 position. An X-ray crystal structure determination of **6** was also performed. The complex crystallizes in the *triclinic* space group $P\bar{1}$, with $a = 8.219(1)$ Å, $b = 9.424(1)$ Å, $c = 9.139(3)$ Å; $\alpha = 107.68(2)°$, $\beta = 83.72(2)°$, $\gamma = 114.87(1)°$; and $Z = 1$. The complex has a center of symmetry with the 1-methylimidazole ligands coordinated in a square-planar arrangement around the Pt(II) atom.

Introduction

Current research into metal ion−biomolecule interactions is varied and, indeed, very diverse. The focus in our laboratory has been on studies relating to isotopic C−H exchange in biomolecules such as thiazole,[1] imidazole,[2] 1-methylimidazole,[2−4] histidine,[3,5,6] purines,[7] etc., in the presence and absence of metal ions.[1−7] In the present work we have extended our studies to Pt(II)-coordinated imidazoles.

The study of metal ion effects on isotopic C−H exchange rates in heterocycles is generally carried out in two ways:[8a] (a) addition of increasing amounts of a metal ion salt into an aqueous solution of the heterocycle with concomitant measurement of the rate of exchange in the metal−heterocycle species formed in solution[3,8,9] and (b) preparation, isolation, and characterization of the metal−heterocycle complex followed by isotopic exchange measurements of the resulting complex.[1,2,6,8a,10]

The use of method (a) above often leads to complications since the metal ions usually form complexes that are *kinetically labile*, e.g. for addition of Co^{II}, Zn^{II}, Ni^{II}, $MeHg^{II}$, etc.[3,11] In solutions containing these metal ions and the heterocycle, several stoichiometric species involving hydroxide ion, hydron, neutral species, protonated, and metal-complexed species are formed.[3,8a] Under such conditions, analysis of the kinetic data in isotopic exchange becomes difficult and hence interpretation of isotopic C−H exchange rates in the presence of these metal ions is not a trivial matter.

The procedure in method (b) eliminates the above complications by employing *substitution-inert* metal ions such as Pt(II),[1,8a,10] Cr(III),[2,6] and Co(III).[9c] In these studies, the metal−heterocycle complexes of known stoichiometries were isolated[1,2,6,8a,9c] and characterized[1,2,6] prior to isotopic C−H exchange measurements. The use of the latter technique has allowed quantitative and unambiguous rate comparisons of the metal-complexed heterocycles with those of the neutral, protonated, and alkylated species.

Thus far, metal ions have been found to enhance the rate of C(2)−H exchange in imidazole[2,3,8] and thiazole,[1] as well as C(8)−H exchange in purines,[7,8a,10,12] by ca. 10^3−10^6, relative to exchange of the neutral heterocyclic species, the so-called *metal activating factor* (***maf***).[8b] However, metal ions are ca.

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Table 1. Characterization Data of Pt(II)−1-Methylimidazole Complexes Synthesized in This Study

complex	color	mp (°C)	^{1}H NMR[a] δ (ppm) H-2	H-4	H-5	CH_3
1-methylimidazole (MeIm)			7.30, br s	6.74, s	6.80, s	3.40, s
cis-$[Pt(MeIm)_2Cl_2]$[b]	lt yellow		8.07, br s	6.84, t	7.26, t	3.71, s
			8.07, d[c]	6.85[c]	7.23[c]	3.72[c]
			^3J = 22 Hz	^3J = 23 Hz	^3J = 9 Hz	
cis-$[Pt(NH_3)_2(MeIm)_2]Cl_2\cdot 2H_2O$ (**3**)	white	168−169	7.73, br t	6.89, t	7.01, t	3.58, s
			^3J = 18 Hz	^3J = 22 Hz		
trans-$[Pt(NH_3)_2(MeIm)_2]Cl_2\cdot 2H_2O$ (**4**)	white	213−215	8.00, br s	7.09, t	7.13, t	3.76, s
			$^3J \sim$ 18 Hz	$^3J \sim$ 18 Hz		
$[Pt(en)(MeIm)_2]Cl_2\cdot 2H_2O$[d] (**5**)	white	314−316	7.81, br s	7.00, br t	7.19, br t	3.74, s
			^3J = 16.7 Hz	^3J = 20.2 Hz		
$[Pt(MeIm)_4](ClO_4)_2$ (**6**)	white	239−242	7.74, br s	6.84, br d	7.15, br d	3.72, s
			^3J = 19 Hz	$^3J \sim$ 21 Hz		

[a] ^{1}H NMR data obtained on Bruker ACF-200 (200 MHz). In D_2O (referenced to HOD peak at δ 4.69 ppm), ^3J represents the ^{195}Pt−^{1}H coupling constant. [b] In DMSO-d_6 (referenced to DMSO-d_5 H peaks centered at δ 2.49 ppm). [c] Reference 16 (in DMSO-d_6/TMS). [d] δ 2.78 (en-CH_2, s, ^3J = 42.2 Hz).

10^3-10^5 times less effective as catalysts for this exchange, relative to protonation (H^+) or alkylation (R^+),[3,7,8a,b,10] correspondingly referred to as *the proton activating factor* (***paf***).[8b]

However, in a recent study, Buncel, Clement, and Onyido[2] reported the first observation of a metal ion coordinated imidazole complex, *cis*-$[Cr(en)_2(MeIm)Cl]Cl_2$, where catalysis was found to be more effective by Cr(III) than by H^+, by a factor of ca. 20. We have also recently reported the first known determination of the rates of isotopic C(2)−H exchange in Pt(II)−thiazole complexes.[1] The study[1] revealed for the first time a quantitative estimate of the catalytic effect of a complexed metal ion (Pt(II)) on C(2)−H and C(5)−H exchange of thiazole relative to a similar exchange in neutral,[13a,b] protonated,[13c] and alkylated[13a] thiazole derivatives.

A primary interest in Pt(II) complexes derives from the finding that a number of its amine complexes possess antitumor properties,[14] accounting for the large number of investigations into its coordination properties with a host of biological molecules.[14] The work described here provides further insight into the catalytic effect of Pt(II) on isotopic C−H exchange of all the ring protons of a complexed imidazole moiety. To the best of our knowledge, there is no previous report of isotopic exchange in Pt(II)−1-methylimidazole complexes.

Results and Discussion

1. Synthesis and Characterization of Pt(II)−1-Methylimidazole Complexes. The synthesis of Pt(II)−amine−1-methylimidazole complexes **3**−**5** (amine = NH_3 or en) was accomplished using the procedure of Johnson and co-workers,[15] analogous to the corresponding Pt(II)−amine−thiazole complexes described previously.[1] Complex **6** was obtained following a modified procedure of Reedijk and co-workers.[16] In Table 1 are listed some representative characterization data of the Pt(II)−1-methylimidazole complexes synthesized in this study. In the synthesis of the *cis*-diamminebis(1-methylimidazole)-platinum(II) complex, *cis*-$[Pt(NH_3)_2(MeIm)_2]Cl_2\cdot 2H_2O$ (**3**), reaction of *cis*-$Pt(NH_3)_2Cl_2$ with stoichiometric mole equivalents of 1-methylimidazole gave a mixture of *cis* and *trans* products. The proposed mechanism of formation of isomeric *cis*−*trans* mixtures in such reactions has been provided previously.[1] The pure *cis* complex was obtained from the reaction of *cis*-Pt-$(MeIm)_2Cl_2$ and concentrated aqueous ammonia (see Experimental Section).

Chart 1

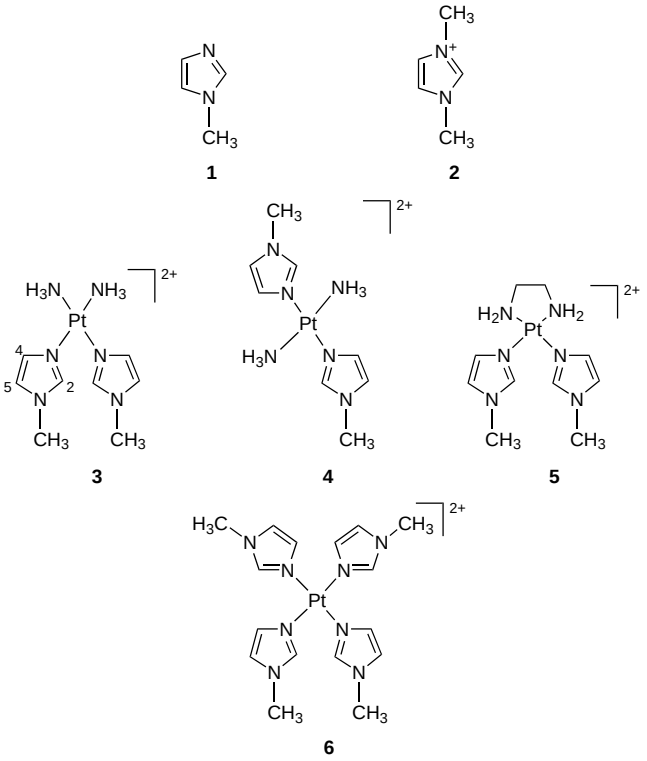

Figure 1 shows the structure of the molecular cation of $[Pt(MeIm)_4](ClO_4)_2$ (**6**) produced by the program ORTEPII[17] together with the atom numbering scheme. Interatomic distances and bond angles for the non-H atoms of the cation are given in Table 3. Pt(II) coordination is via the pyridinyl nitrogen atom of the four 1-methylimidazole ligands which are arranged around Pt in a square-planar geometry. The molecular cation has a center of symmetry which is located in the crystallographic special position ($\bar{1}$) at the origin of the unit cell. The angle between the two crystallographically independent ligands (N11−Pt−N21) is 91.6(2)°.

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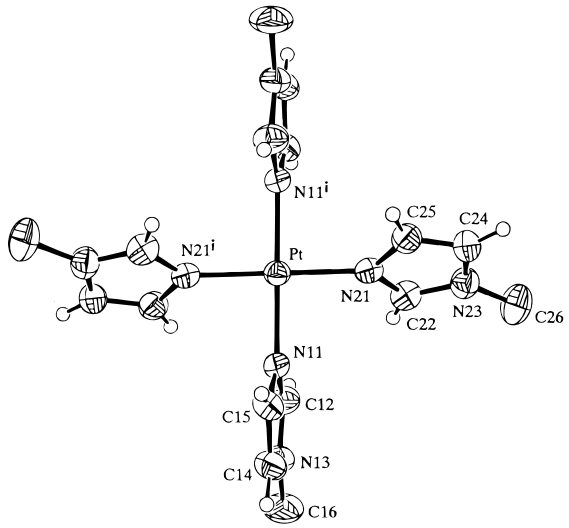

Figure 1. Molecular structure of the cation of $[Pt(MeIm)_4](ClO_4)_2$ (**6**) showing the atom numbering scheme. Displacement ellipsoids are shown at the 50% probability level, and H atoms are drawn as unlabeled spheres of aribtrary size.

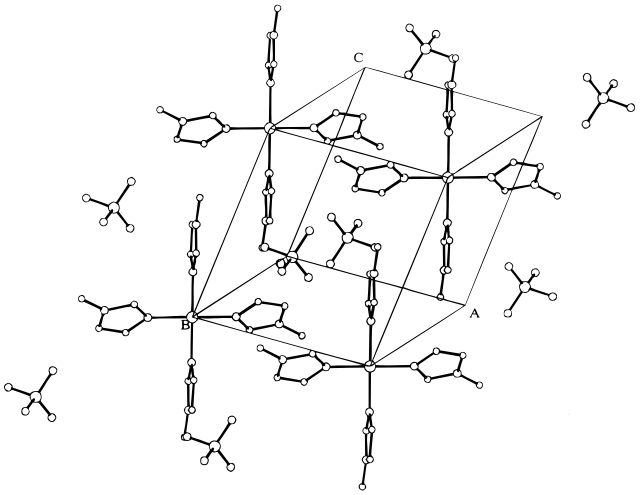

Figure 2. Crystal packing of $[Pt(MeIm)_4](ClO_4)_2$ (**6**). Cations are shown approximately in the same orientation as in Figure 1.

The packing of the $[Pt(MeIm)_4]^{2+}$ cations and the ClO_4^- anions is represented in Figure 2.[18] Cations are located approximately in layers parallel to and on both sides of the $a-c$ faces of the unit cell, while the anions are located in-between these layers.

The Pt−N distances of 2.003(6) and 2.006(6) Å are in good agreement with distances observed in other *N*-alkylimidazoles[19] and are significantly shorter than the average Pt−N distance of 2.050 Å observed for Pt(II)−ammonia bonds.[19] This may suggest some π-bonding character for the ring-to-platinum bonds. Alternatively, the difference might be associated with differences in hybridization of the donor atoms.[15] Previously, in the crystal structure of tetrakis(1,2-dimethylimidazole)-platinum(II) bis(triiodide)[20] the Pt−N distances were found to be 2.014(5) and 2.009(8) Å, in the tetrakis(1-methylimidazole)-platinum(II) hexachloroplatinate(IV) complex[21] they were 1.986(14) and 2.012(14) Å, and in *trans*-diamminebis(1-methylimidazole)platinum(II) chloride dihydrate[15] they were 2.01(2) Å.

Table 2. Crystal Data, Experimental Details, and Refinement Summary for $[Pt(MeIm)_4](ClO_4)_2$ (**6**)

A. Crystal Data	
empirical formula	$PtCl_2O_8N_8C_{16}H_{24}$
formula weight	722.42
crystal color	colorless
crystal dimensions	0.28 × 0.15 × 0.07 mm
crystal system	triclinic
space group	$P\bar{1}$ (No. 2)
unit cell dimensions	$a = 8.219(1)$ Å, $\alpha = 107.68(2)°$ $b = 9.424(1)$ Å, $\beta = 83.72(2)°$ $c = 9.139(3)$ Å, $\gamma = 114.87(1)°$ $V = 611.8(2)$ Å^3
Z value	1
D_{calc}	1.961 g/cm^3
μ(Mo Kα)	6.01 mm^{-1}
B. Intensity Measurements	
diffractometer	Enraf-Nonius CAD-4
radiation	Mo Kα ($\lambda = 0.71069$ Å)
temperature	298 K
cell parameters from 25 reflns	$33° \le 2\theta \le 39°$
scan type	$\omega-2\theta$
index ranges	$0 \le h \le 10$, $-12 \le k \le 10$, $-11 \le l \le 11$
$2\theta_{max}$ measured	54°
no. of reflcns measured	total: 2856, unique: 2666 ($R_{int} = 0.026$)
no. of obsd data [$I > 2\sigma(I)$]	2581
corrections	Lorentz polarization absorption: empirical (transmission factors: 0.837−1.274)
C. Structure Solution and Refinement	
solution method	Patterson and Fourier methods
refinement method	full-matrix least-squares on F^2 (all unique data)
no. of parameters refined	150
reflection/parameter ratio	17.8
function minimized	$\sum w(F_o^2 - F_c^2)^2$
weighting scheme	$w = 1/[\sigma^2(F_o^2) + (0.0742P)^2 + 1.25P]$ where $P = (F_o^2 + 2F_c^2)/3$
final residuals	$R(F) = 0.0416$ (for observed data) $wR(F^2) = 0.1080$ (for all unique data)
goodness-of-fit indicator	$S = 1.153$ (for all unique data)
max shift/esd	0.005 (final cycle)
max peak in final ΔF map	2.93 e/Å^3 (near Pt atom)

The distances and endocyclic angles in the two independent 1-methylimidazole ligands of **6** are equal within two standard deviations (compare data in two columns of Table 3) and are in very good agreement with the average metal-coordinated *N*-alkylimidazole dimensions.[19]

The dihedral angles between the least-squares planes of the two imidazole rings and the PtN_4 coordination plane are 83.7(3)° and 56.2(4)°, respectively, for ligand 1 (N11···C16 atoms) and ligand 2 (N21···C26 atoms). These angles probably result from steric interactions between two neighboring ligands and/or from the crystal packing interactions between the cation and the surrounding ions. In the crystal structure of **6**, the imidazole rings form π-stacking-type intermolecular contacts with symmetrically equivalent rings of the neighbor cations. Ligand-1 rings are related by the center of symmetry located in the middle of the *c* edge of the unit cell (see Figure 2) and stack edge-to-edge with an interplanar distance of 3.382(6) Å. Ligand-2 rings are related by the center of symmetry located in the middle of the *a* edge forming more extended stacking with partial overlap

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Table 3. Selected Bond Lengths (Å) and Angles (deg) for $[Pt(MeIm)_4](ClO_4)_2$ (**6**)[a]

Pt−N11	2.003(6)	Pt−N21	2.006(6)
N11−C12	1.322(10)	N21−C22	1.331(10)
N11−C15	1.371(10)	N21−C25	1.374(10)
C12−N13	1.339(11)	C22−N23	1.348(11)
N13−C14	1.367(11)	N23−C24	1.383(11)
N13−C16	1.461(11)	N23−C26	1.471(11)
C14−C15	1.367(11)	C24−C25	1.353(12)
N11−Pt−N21	91.6(2)	$N11^{i}$−Pt−N21	88.4(2)
C12−N11−Pt	127.3(5)	C22−N21−Pt	127.8(5)
C15−N11−Pt	125.7(5)	C25−N21−Pt	125.6(5)
C12−N11−C15	107.0(6)	C22−N21−C25	106.6(6)
N11−C12−N13	110.7(7)	N21−C22−N23	110.5(7)
C12−N13−C14	107.4(7)	C22−N23−C24	107.0(7)
C12−N13−C16	126.3(8)	C22−N23−C26	126.2(8)
C14−N13−C16	126.4(8)	C24−N23−C26	126.7(8)
N13−C14−C15	106.9(7)	N23−C24−C25	106.8(7)
C14−C15−N11	108.0(7)	C24−C25−N21	109.0(7)

[a] Symmetry transformation used to generate equivalent atoms: (i) $-x,-y,-z$.

of rings and an even shorter interplanar distance of 3.290(5) Å. Additionally, there are several short intermolecular contacts between the imidazole H atoms and the adjacent perchlorate oxygen atoms.[22]

It is of note that the dihedral angles between the coordinated imidazole ligands and the PtN_4 coordination plane in the crystal structures of related compounds were all observed in the range of 40° to 90°.[23] For example, in the structure of tetrakis(1-methylimidazole)platinum(II) hexachloroplatinate(IV)[21] these angles were 51.9° and 71.6°, in the tetrakis(1,2-dimethylimidazole)platinum(II) bis(triiodide) complex[20] they were 85°, and in *trans*-diamminebis(1-methylimidazole)platinum(II) chloride[15] they were 49.2°. The larger angle for the 1,2-dimethylimidazole complex[20] may be due to the additional steric effect of the 2-methyl substituent (absent in **6**), while the smaller angle observed in *trans*-$[Pt(NH_3)_2(MeIm)_2]Cl_2$[1]15 is probably due to the smaller size of the neighboring ammonia ligands.

2a. Hydrogen Exchange Rates. Rates of C−H → C−D exchange in the Pt(II)−1-methylimidazole complexes **3**−**6** were measured in D_2O/NaOD solutions, at 60 °C, using the ^{1}H NMR technique. Owing to the slow rates of C(2)−H exchange in these complexes, measurements were made only in the high pD region, i.e. pD 10−13, and C−H exchange was generally monitored for a minimum of 1 half-life. The decrease in the integral intensity of exchanging protons at C(2), C(4), and C(5) was followed relative to the non-exchanging $N-CH_3$ group. Typical sequential ^{1}H NMR spectra that show C(2)−H exchange (pD 10.62, 60 °C) and C(4)−H and C(5)−H exchange (pD 13.3, 60 °C) in complex **5** are given in Figures 3 and 4, respectively. Pseudo-first-order rate constants for C(2)−H, C(4)−H, and C(5)−H exchange (see, for example, Figures 5 and 6) were obtained from the negative slopes of linear plots of log[C−H(exchanging)/(NCH_3/3)] *vs* time.

Complexes **3**−**5** contain two equivalent MeIm moieties while complex **6** has four and the NMR spectra (e.g. Figure 3) show that each C(2)−H, C(4)−H, and C(5)−H of a MeIm moiety is indistinguishable from its counterpart in the other MeIm ring(s), i.e. singlet peaks. Thus it is necessary to make appropriate corrections for the experimental pseudo-first-order rate constants derived using the NMR technique by dividing these by a statistical factor corresponding to the number of equivalent

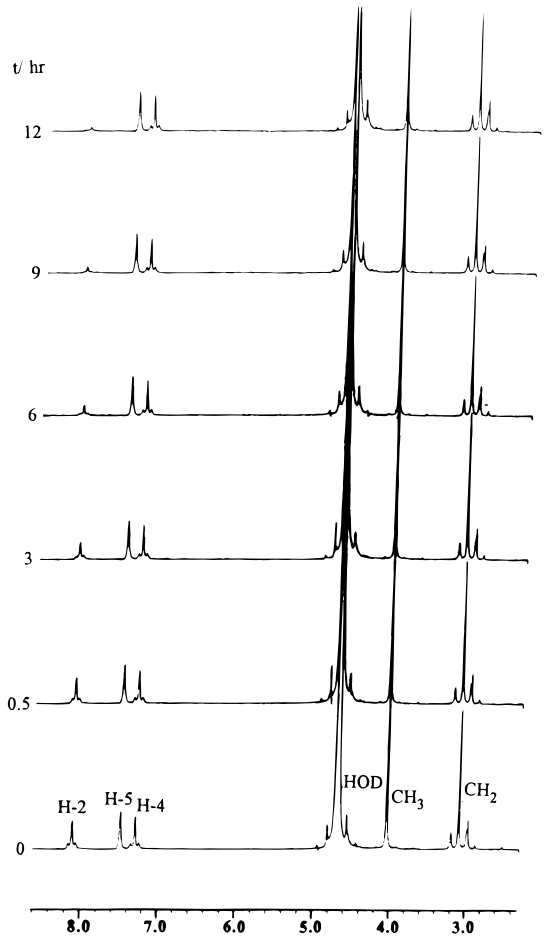


Figure 3. ^{1}H NMR spectra showing C(2)−H exchange in **5** (pD 10.62, 60 °C) as a function of time.

exchangeable sites in each substrate. The resulting k_{obs} values are given in Table 4. According to the rate law in eq 1, where k_m is the second-order rate constant of exchange in these complexes, k_m values (M^{-1} s^{-1}) were determined from the ratio $k_{obs}/[OD^-]$ (eq 2), using the corrected k_{obs} values; these values are also shown in Table 4.

$$\text{rate} = k_m[\text{Pt}-\text{MeIm}][OD^-] \quad (1)$$

$$k_{obs} = k_m[OD^-] \quad (2)$$

C(2)−H exchange is the only measurable process at pD < 12 (and 60 °C) in complexes **3**−**6**; however, at pD ≥ 13 (and 60 °C), exchange at all ring positions, i.e. C(2)−H, C(4)−H, and C(5)−H, becomes measureable. Under the latter conditions, C(2)−H exchange was too fast for accurate measurement by the ^{1}H NMR technique employed in this study, and hence only the slower C(4)−H and C(5)−H exchange processes were monitored.

In order to compare rates of exchange at all ring positions of the Pt(II)-coordinated 1-methylimidazole (MeIm) ligand, i.e. C(2), C(4), and C(5), with previously reported data for similar exchange processes in neutral,[24,25] protonated (H^+),[24,25] methylated (CH_3^+),[24] and metal ion complexed systems (M^{n+}; where M^{n+} = Co^{3+} and Cr^{3+}),[2,9c] it was necessary to determine the activation energy (E_a) for C(2)−H exchange in Pt(II)−1-methylimidazole complexes, so that the rate of C(2)−H

(22) Some of these contacts could be seen as possible C−H···O hydrogen bonds; see Table S6 in the supporting information.

(23) Based on 14 compounds retrieved from the Cambridge Structural Database: Allen, F. H.; Kennard, O.; Taylor, R. *Acc. Chem. Res.* **1983**, *16*, 146.

(24) Wong, J. L.; Keck, J. H., Jr. *J. Org. Chem.* **1974**, *39*, 2398.

(25) Takeuchi, Y.; Yeh, H. J. C.; Kirk, K. L.; Cohen, L. A. *J. Org. Chem.* **1978**, *43*, 3565.

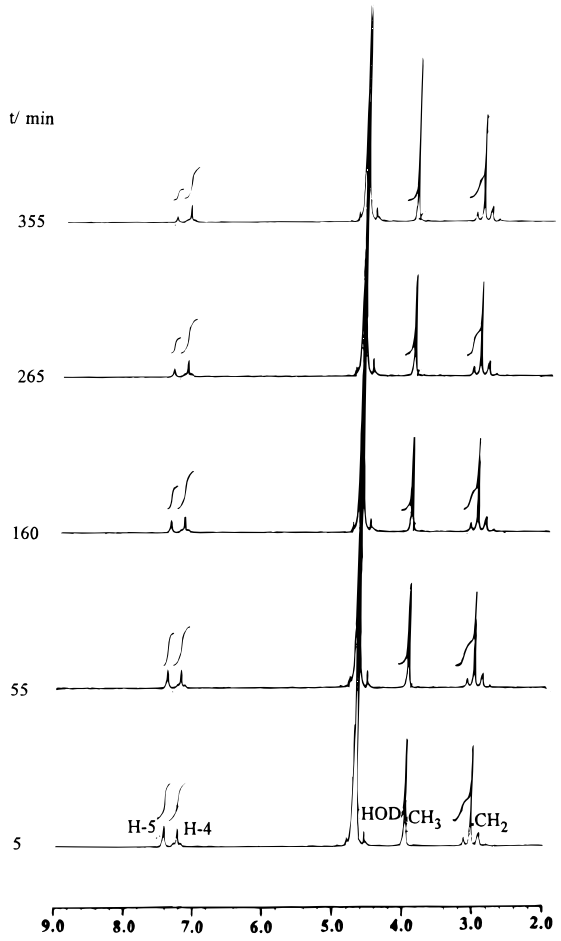


Figure 4. ^{1}H NMR traces showing C(4)−H and C(5)−H exchange in **5** (pD 13.3, 60 °C) as a function of time.

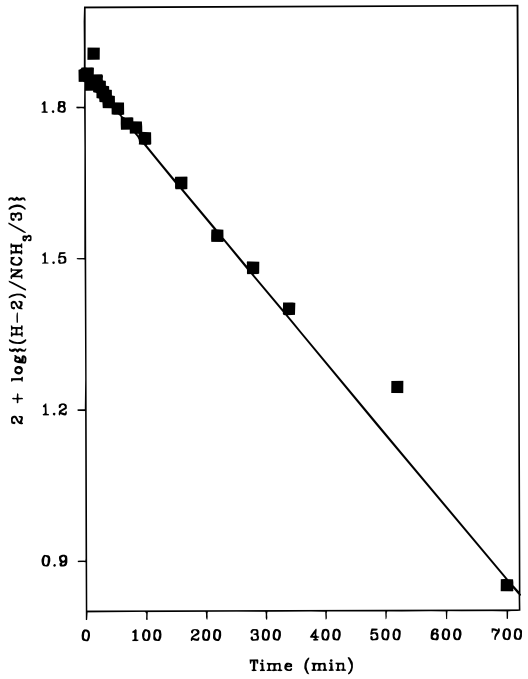


Figure 5. First-order plot for C(2)−H exchange in **5** (pD 10.62, 60 °C).

exchange under conditions in which the slower C(4)−H and C(5)−H exchanges are measureable (*vide infra*) may be deduced. Since C(2)−H exchange rates in these complexes are of similar magnitude (see Table 4), complex **5** was chosen for determination of E_a. The value of E_a obtained (17.7 ± 0.4 kcal/mol, from data in Table 4) was then assumed for C(2)−H exchange in the other complexes of the series shown in Chart 1.

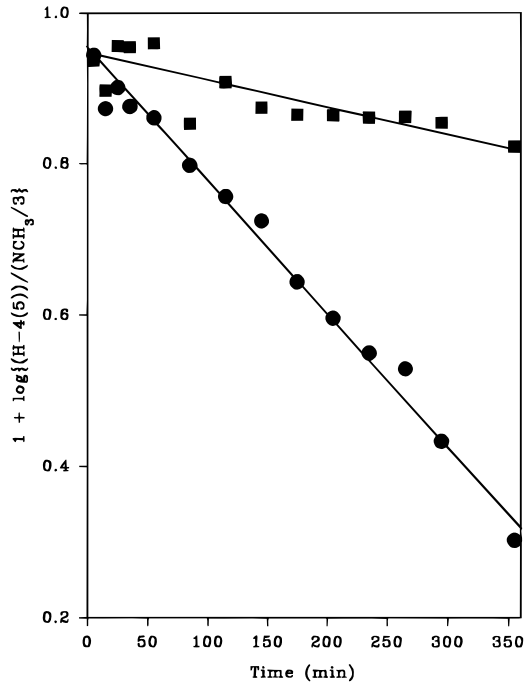


Figure 6. First-order plots showing C(4)−H (■) and C(5)−H (●) exchange in **5** (pD 13.3, 60 °C).

C(2)−H exchange in the Pt(II)−MeIm complexes is expected to occur faster than in the free, uncomplexed MeIm ligand as evidenced by the 2.5 kcal/mol lower value of the activation energy, E_a, for this process in the Pt(II) complexes relative to the neutral ligand. Such rate comparisons are made in Tables 5 and 6.

Also included in Table 5 are the corresponding second-order rate constants (k, M^{-1} s^{-1}) for C(4)−H and C(5)−H exchange in the Pt(II)−MeIm complexes **3**−**6**, as well as Co(III)- and Cr(III)-complexed MeIm moieties.

2b. Mechanism of Isotopic C−H Exchange. In this study we have performed the first investigation of isotopic H/D exchange in 1-methylimidazole complexed to substitution-inert Pt(II). Exchange at all three positions of the imidazole moiety has been observed, the relative order of reactivities being C(2)−H ≫ C(5)−H > C(4)−H.

The mechanism for isotopic C−H exchange in 1-methylimidazole (**1**) is believed to follow that shown in Scheme 1, paths (a) and (b), while path (c) depicts the pathway for exchange in the presence of a metal ion (M^{n+}).[3,4,8,10,24,25] The study described here involves direct measurement of isotopic exchange on the isolated substitution-inert Pt(II)−1-methylimidazole complexes in accord with the boxed-in portion of Scheme 1.

2c. Reactivity of Pt(II) *vs* H^+ or CH_3^+ in H/D Exchange. It is of interest to compare catalysis of H/D exchange in 1-methylimidazole by Pt(II) with that by H^+ or CH_3^+, which had been studied previously by two groups of workers. Wong and Keck in 1978 reported a detailed ^{1}H NMR study of hydrogen−deuterium exchange in 1-methylimidazole (**1**) and 1,3-dimethylimidazolium iodide (**2**) in D_2O, pD 0−14, at 81 and 25 °C, respectively (for C(2)−H exchange), and 163 °C (for C(4)−H and C(5)−H exchange).[24] These workers found that isotopic exchange in **1** follows the order **C(2)−H** ≫ **C(4)−H** > **C(5)−H**, while in **2** the reactivity order is **C(2)−H** ≫ **C(4)−H, C(5)−H.**[24] The observation of higher reactivity of C(4)−H relative to C(5)−H exchange in **1** was rationalized

Table 4. C(2)−H Exchange Rates in Pt(II)−1-Methylimidazole Complexes[a]

complex	pD[b]	T (°C)	10^2[OD$^-$][c] (M)	$10^4 k_{obs}$[d] (s^{-1})	$10^2 k_m$[e] (M^{-1} s^{-1})
cis-[Pt(NH_3)$_2$(MeIm)$_2$]Cl_2·2H_2O (**3**)	11.64	60	0.692	0.96	1.38
	13.3[f]	60	31.6	80.8[g]	2.56
trans-[Pt(NH_3)$_2$(MeIm)$_2$]Cl_2·2H_2O (**4**)	11.69	60	0.776	2.13	2.75
	13.3[f]	60	31.6	82.2[g]	2.60
[Pt(en)(MeIm)$_2$]Cl_2·2H_2O (**5**)	10.62	60	0.066	0.261	3.95
	13.3[f]	25	2.70[h]	0.97	0.36[j]
	13.3[f]	40	8.22[h]	11.2	1.36[j]
	13.3[f]	50	15.7[h]	49.2	3.13[j]
	13.3[f]	60	31.6	112.0[i]	3.54
[Pt(MeIm)$_4$](ClO_4)$_2$ (**6**)	10.76	60	0.091	0.151	1.65

[a] ^{1}H NMR studies, in D_2O/NaOD solution. [b] Room temperature measurement (pD = measured pH + 0.4).[34] [c] Calculated from pK_w(D_2O) at 60 °C = 13.8 (extrapolated value), except for footnote *h*.[33] [d] Rate constants have been corrected by means of a statistical factor for equivalent reactive sites in these substrates. [e] Calculated as $k_m = k_{obs}$/[OD$^-$] (from eq 2). [f] In 0.1 M NaOD solution (pD 13.3). [g] Calculated value at 60 °C from values determined at 40 °C ($k_{obs} = 1.48 \times 10^{-3}$ s^{-1} (**3**); $k_{obs} = 1.50 \times 10^{-3}$ s^{-1} (**4**)) using $E_a = 17.7 \pm 0.4$ kcal/mol, obtained for C(2)−H exchange in **5** (results shown in Table, see footnote *j*). [h] Using pK_w(D_2O) = 14.869 at 25 °C; pK_w(D_2O) = 14.385 at 40 °C and 14.103 at 50 °C.[33] [i] This exchange was too fast to measure via the ^{1}H NMR technique used in the study and was calculated (at 60 °C) using $E_a = 17.7 \pm 0.4$ kcal/mol determined in this work (*vide infra*). [j] Data used to calculate the activation energy, E_a, for C(2)−H exchange in complex **5**.

Table 5. Comparison of C−H Exchange Rates of 1-Methylimidazole Coordinated to Different Electrophiles (H^+, CH_3^+, Pt^{2+}, Co^{3+}, and Cr^{3+})[a]

		k_{obs} (s^{-1})			k (M^{-1} s^{-1})			
substrate	pD[b]	C(2)−H	C(4)−H	C(5)−H	C(2)−H	C(4)−H	C(5)−H	ref
MeIm	12.4	2.25×10^{-6} [c]	1.4×10^{-8} [d]	8.2×10^{-8} [d]	5.65×10^{-5}	3.52×10^{-7}	2.06×10^{-6}	24
H^+−MeIm[e]	3.4−6.4				1.98×10^{3}	1.26×10^{-1}	1.99×10^{-1}	24
CH_3^+−MeIm[f]	5.7−13.4				4.79×10^{3}	2.60×10^{-1} [g]	2.60×10^{-1} [g]	24
cis-Pt^{2+}(MeIm)$_2$[h] (**3**)	13.3	8.08×10^{-3} [i]	—[j]	5.70×10^{-6}	2.56×10^{-2}		1.80×10^{-5}	*k*
trans-Pt^{2+}(MeIm)$_2$[h] (**4**)	13.3	8.22×10^{-3} [i]			2.60×10^{-2}			*k*
enPt^{2+}(MeIm)$_2$[h] (**5**)	13.3	1.12×10^{-2} [i]	5.35×10^{-6}	3.15×10^{-5}	3.54×10^{-2}	1.69×10^{-5}	9.95×10^{-5}	*k*
Pt^{2+}(MeIm)$_4$[h] (**6**)	10.8	1.51×10^{-5}			1.65×10^{-2}			*k*
Co^{3+}−MeIm[l]	12.4	2.73×10^{-4}			6.86×10^{-3}			9c
Cr^{3+}−MeIm[m]	4.0−6.5				6.0×10^{3}	7.2×10^{2}	7.2×10^{2}	2

[a] Represents C−H/C−D (except for Cr^{III}, below). All data have been corrected to 60 °C, unless otherwise noted. [b] Room temperature measurement (pD = measured pH + 0.4).[34] [c] Calculated value at 60 °C from values obtained at 81 °C ($k_{obs} = 2.94 \times 10^{-3}$ and $E_a = 20.2$ kcal/mol).[24] [d] Calculated values at 60 °C from values obtained at 163 °C (assuming an $E_a = 20.2$ kcal/mol for these exchange processes).[24] [e] C(2)−H exchange rate extrapolated to 60 °C (from value at 81 °C) using $E_a = 17.7$ kcal/mol (for complex **5** of present study), C(4)−H and C(5)−H exchange rates extrapolated to 60 °C (from values at 163 °C) using $E_a = 20.2$ kcal/mol (for C(2)−H exchange in MeIm).[24] [f] C(2)−H exchange rate extrapolated to 60 °C (from value at 25 °C) using $E_a = 17.7$ kcal/mol (for complex **5** of present study), C(4)−H and C(5)−H exchange rates extrapolated to 60 °C (from values at 163 °C) using $E_a = 20.2$ kcal/mol (for C(2)−H exchange in MeIm). [g] Here, both C(4)−H and C(5)−H are equivalent in 1,3-dimethylimidazolium ion and rate constants were corrected for equivalent reactive sites. [h] Complexes contain equivalent reactive sites and rates quoted have been corrected. [i] Calculated value at 60 °C (from values at 40 °C, except for complex **5**) using $E_a = 17.7$ kcal/mol (see Table 4). [j] Poor linearity of first-order plot ($r = 0.88$) for C(4)−H exchange under these conditions. [k] Present study. [l] [(NH_3)$_5$$Co^{III}$(MeIm)]$Cl_3$, calculated value at 60 °C from data at 25 °C ($k_{obs} = 1.2 \times 10^{-5}$ s^{-1}),[9c] using $E_a = 17.7$ kcal/mol). [m] Represents C−^{3}H/C−^{1}H (detritiation), at 35 °C, for *cis*-[(en)$_2$$Cr^{III}$(MeIm)Cl]$Cl_2$ complex.[2]

Table 6. Relative Rates of C−H Exchange for Protonated, Methylated, and Metal Ion-Complexed 1-Methylimidazoles, with Respect to Neutral 1-Methylimidazole

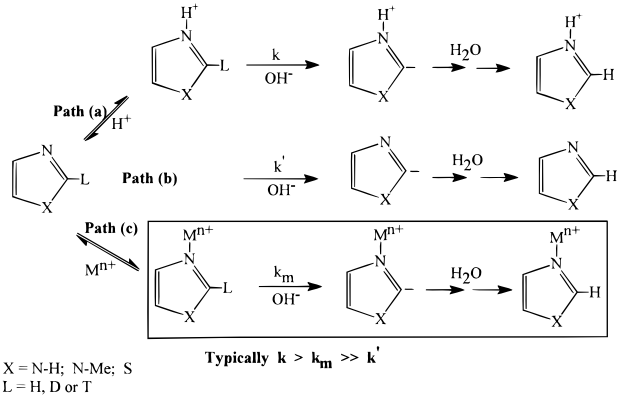
	relative rates[a]			
substrate	C(2)−H	C(4)−H	C(5)−H	ref
MeIm	1	1	1	24
H^+−MeIm	3.5×10^7	3.6×10^5	9.7×10^4	24
CH_3^+−MeIm	8.5×10^7	7.4×10^5	1.3×10^5	24
3	4.5×10^2	—[b]	8.7	this work
4	4.6×10^2	—[c]	—[c]	this work
5	6.3×10^2	4.8×10^1	4.8×10^1	this work
6	2.9×10^2	—[d]	—[d]	this work
Co^{III}−MeIm[e]	1.2×10^2	—[d]	—[d]	9c

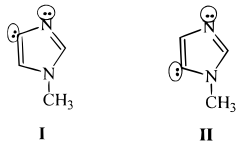
[a] Rate constants for C(2)−H, C(4)−H, and (C)5−H exchange for these substrates are shown in Table 5. [b] C(4)−H exchange was not determined due to poor linearity of the first-order plot. [c] C(4)−H/C(5)−H exchange in this complex could not be determined separately due to "merging" of both peaks in the ^{1}H NMR spectra, under conditions of exchange (pD 13.3, 60 °C). [d] C(4)−H and C(5)−H exchange were not observed under conditions employed in these studies (see Table 5). [e] Represents H/D exchange in [(NH_3)$_5$$Co^{III}$(MeIm)]$Cl_3$.[9c]

as being caused by the hyperconjugative/inductive effect of the N(1)−CH_3 group for the intermediate carbanion formed at C(5) upon proton abstraction, which is absent at C(4).[24]

In a later study of similar exchange in 1-methylimidazole (**1**), Takeuchi and co-workers[25] reversed the ^{1}H NMR assignment of C(4)−H and C(5)−H of Wong and Keck,[24] effectively reversing the above order of reactivity. Evidence from a number of ^{1}H NMR techniques, such as nuclear Overhauser enhancement (nOe), solvent effects on chemical shifts, and spin-decoupling experiments,[25] showed conclusively that the C(2)−H signal is the most downfield peak while C(4)−H is the most upfield in the ^{1}H NMR spectrum of 1-methylimidazole, contrasting with the view by Wong and Keck[24] where the most

Scheme 1. Mechanism of Isotopic C(2)−L (L = H, D, T) Exchange in Heterocycles





I **II**

Figure 7. Adjacent lone pair effect (ALP) of carbanions generated upon abstraction of C(4)−H (structure **I**) and C(5)−H (structure **II**) in 1-methylimidazole (**1**).[25]

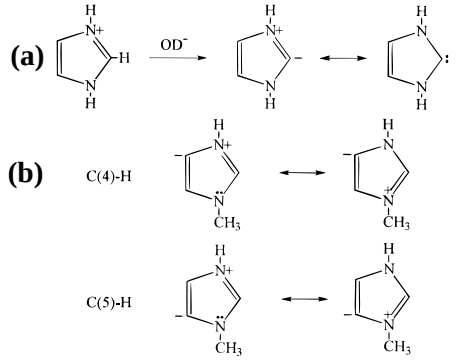


Figure 8. (a) Resonance stabilization of the ylide intermediate formed upon abstraction of imidazole C(2)−H.[1−6,8−10,24,25] (b) Resonance stabilization of carbanionic intermediates formed upon deprotonation of C(4)−H and C(5)−H in N-protonated 1-methylimidazole.

upfield signal was assigned to C(5)−H. Finally, Takeuchi and co-workers found that C(5)−H exchange occurs ca. 3-times ***faster*** than C(4)−H exchange, at pD 10−11 and 100 °C.[25] Rationalization of the reactivity order C(5)−H > C(4)−H for exchange in 1-methylimidazole (**1**) was provided by invoking an Adjacent Lone Pair (ALP) effect (Figure 7).[25] Structures **I** and **II** shown in Figure 7 represent intermediates formed upon abstraction of C(4)−H and C(5)−H, respectively. On energetic grounds, structure **I** is expected to be less favored due to electrostatic repulsion between the adjacent, co-planar, sp^2 orbitals, relative to structure **II**. This effect was deemed to support C(5)−H exchange being faster than C(4)−H exchange in neutral 1-methylimidazole (**1**).[25]

The results in the present work of H/D exchange in complexes **3**−**6** by ^{1}H NMR spectroscopy support the assignments of the imidazole ring protons, C(2)−H, C(4)−H, and C(5)−H, previously made by Takeuchi and co-workers[25] (*vide supra*), as well as the order of reactivity for C(2)−H, C(4)−H, and C(5)−H exchange processes.[25] We have taken advantage of the diagnostic ^{195}Pt−^{1}H coupling in these complexes[26] which provides unambigous assignment of proton chemical shifts of C(2)−H, C(4)−H, and C(5)−H in the ^{1}H NMR spectra of the Pt(II)−1-methylimidazole complexes (see Table 1). Since this coupling decreases with increasing distance from the metal ion, 3-bond coupling to C(2)−H and C(4)−H ($^3J_{Pt-H} \sim 10-30$ Hz) is clearly observed (see, for example, Figure 3), while coupling to the more distanced C(5)−H peak was not observed with the 200-MHz NMR spectrometer used in the study. Hence, we can conveniently monitor the various exchanging proton(s) of the Pt(II)-coordinated 1-methylimidazole rings by the ^{1}H NMR technique.

Analysis of the kinetic data for H/D exchange in the Pt(II)−1-methylimidazole complexes **3**−**6** investigated in this work reveals the following order of reactivity: C(2)−H ≫ C(5)−H > C(4)−H exchange. Thus C(5)−H exchange was found to be consistently ***faster*** than C(4)−H exchange, under conditions in which both protons exchange (i.e. pD ∼ 13, 60 °C). Once again, as in the thiazole series,[1] the order of reactivity for C(2)−H exchange in 1-methylimidazole (MeIm) coordinated to different electrophiles is $\mathbf{H^+ \sim CH_3^+ \gg Pt^{2+} \sim (Co^{3+}) \gg}$ **neutral**, with relative rates of $\mathbf{10^7-10^8:10^2-10^3:1}$, respectively. The order of reactivity and magnitude of the rate differences in this series follows that in Scheme 1, as previously reported for C(2)−H exchange in other heterocyclic substrates.[1−6,8−10,13,24,25]

It is noteworthy that protonation (H^+) or alkylation (CH_3^+) at N(3) of 1-methylimidazole enhances C(2)−H exchange ca. 10^5 times greater than does coordination to the Pt^{2+} ion (Table 6). Interestingly, the magnitude of rate enhancement by H^+ relative to Pt^{2+} found for C(2)−H exchange is similar to that observed for C(4)−H and C(5)−H exchange, i.e. ca. 10^4 (Table 6). Of equal significance is the fact that in all cases where C(4)−H and C(5)−H exchange is measureable in the Pt(II)-complexed 1-methylimidazoles, C(5)−H exchange is always ***faster*** than C(4)−H exchange.

The observation of C(5)−H exchange > C(4)−H exchange in the Pt(II)−1-methylimidazole complexes contrasts with expectation based on inductive, through-bond electron withdrawal by Pt(II) coordinated at N(3), which should moderately enhance exchange of the adjacent C(4)−H, relative to C(5)−H. That that is not the case in the present study, as well as in the neutral and protonated forms of the heterocycle, suggests that some form of stabilization is provided at C(5) relative to C(4) in these substrates.

In order to place these relative reactivities into perspective, it is desirable to review briefly the rationalization of enhanced reactivity of C(2)−H, relative to C(4)−H and C(5)−H in imidazoles.[1−6,8−10,24,25] In the case of C(2)−H exchange, protonation at N(3), followed by rate-determining abstraction of the C(2)−H by hydroxide ion, results in a resonance-stabilized ylide intermediate (Figure 8a).[1−6,8−10,24,25] This enhanced stabilization is not available at C(4) or C(5) upon proton abstraction at these positions. This factor has been held largely responsible for the higher reactivity of C(2)−H, with respect to C(4)−H and C(5)−H.

Now, considering N(3)-protonated 1-methylimidazole, a resonance structure can be drawn such that the positive charge at N(3) is located at N(1), as depicted in Figure 8b, since the two nitrogens of imidazole form a delocalized system. One can expect that a positive charge would be more stable on N(1)−CH_3 than on N(3)−H, due to the inductive/hyperconjugative effect of the CH_3 substituent at N(1) relative to H on N(3). This would lead to greater stabilization of the intermediate formed on deprotonation of C(5)−H relative to C(4)−H. It is therefore expected that C(5)−H exchange should be faster than C(4)−H exchange in protonated 1-methylimidazole,[25] as is in fact observed.[27]

In the Pt(II)−1-methylimidazole complexes examined in this work where C(5)−H > C(4)−H exchange, it can be envisaged that a similar stabilization at C(5) to that proposed for the N(3)-protonated form of the heterocycle (Figure 8b) is provided by Pt(II), where the partial positive charge ($\delta+$) at N(3) is propagated through-bond to the more stable N(1) position. This would explain the observed faster C(5)−H exchange relative to C(4)−H exchange in the Pt(II)−1-methylimidazole complexes **3** and **5** (Tables 5 and 6).

(26) Belluco, U. *Organometallic and Coordination Chemistry of Platinum*; Academic Press: New York, 1974.

(27) An argument could also be made that the methyl group in H^+−MeIm would *reduce* the magnitude of the positive charge on nitrogen relative to the proton, which would then lead to a *lesser stabilization* of the structure formed on deprotonation of C(5)−H relative to C(4)−H. However, since such consideration is expected to make C(4)−H slightly *more* reactive than C(5)−H, in direct contrast with experimental results, we anticipate that this latter consideration is less important in this case.

Considering other aspects of this study from the data in Tables 4−6, one finds no significant structure−reactivity relationship in the Pt(II)−1-methylimidazole complexes investigated in this study. For example, the rate of C(2)−H exchange for *cis*-$[Pt(NH_3)_2(MeIm)_2]Cl_2$ (**3**) is approximately equal to that in its *trans* analog **4**, as shown in Tables 4−6. Higher reactivities of *trans* complexes, relative to their *cis* analogs in reactions at the metal ion site (e.g. ligand substitution reactions) are well documented.[28] The lack of observation of this phenomenon in the present study is presumably due to the fact that the reactive site is the coordinated ligand and not the metal ion.

In conclusion, this work has provided the first quantitative estimate of the magnitude of catalytic effectiveness of Pt(II) on exchange of imidazole C(2)−H, C(4)−H, and C(5)−H, relative to that of H^+ and CH_3^+. The 10^4-10^5 times greater effectiveness of H^+ or CH_3^+ relative to Pt(II) may be ascribed to the fact that Pt(II) participates in π-type metal-to-ligand back-bonding with ligands containing low-lying pπ orbitals, which would result in a net increase in electron density in the imidazole ring with a concomitant decrease in exchange rate with respect to protonation or alkylation. The probable occurrence of Pt(II) back-bonding to imidazole has been noted in the earlier discussion of the crystal structures of complexes **4**[15] and **6** in the present study.

Experimental Section

1. Materials. Potassium tetrachloroplatinate (>99.9%) and *cis*-$[Pt(NH_3)_2Cl_2]$ were purchased from Johnson Mathey. 1-Methylimidazole (MeIm, 99%) and 1,2-diaminoethane (en, 99.9%) were obtained from Aldrich. Dimethyl sulfoxide (DMSO) was distilled from sodium hydride and stored over molecular sieves No. 4. D_2O (99.9% atom D) and DMSO-d_6 (99.9%) were obtained from Matheson. The starting complexes $[Pt(en)Cl_2]$,[29] *trans*-$[Pt(NH_3)_2Cl_2]$,[29] *cis*-$[Pt(dmso)_2Cl_2]$,[30] and *cis*-$[Pt(MeIm)_2Cl_2]$[16] were all synthesized using literature procedures.

2. Synthesis of Complexes. (a) *cis*-Diamminebis(1-methylimidazole)platinum(II) Chloride Dihydrate (*cis*-$[Pt(NH_3)_2(MeIm)_2]Cl_2\cdot 2H_2O$, 3). The synthesis of *cis*-$[Pt(NH_3)_2(MeIm)_2]Cl_2$ from stoichiometric molar amounts of *cis*-$[Pt(NH_3)_2Cl_2]$ and 1-methylimidazole (MeIm) led to a mixture of *cis* (90%) and *trans* (10%) products based on ^{1}H NMR spectral data. ^{1}H NMR (D_2O): *major product* δ 7.74 (H-2, br s, $^3J_{Pt-H} \sim 18$ Hz), 6.91 (H-4, t, $^3J_{Pt-H} \sim 22$ Hz), 7.03 (H-5, t), 3.60 (N−CH_3, s), 2.10 (acetone, CH_3); *minor product* δ 7.95 (H-2, br s), 7.12 (H-4, t), 7.55 (H-5, t), 3.69 (N−CH_3, s).

The synthesis and isolation of the pure *cis* isomer was accomplished as follows: A weighed amount of *cis*-$[Pt(MeIm)_2Cl_2]$[16] (0.160 g, 0.37 mmol) was suspended in water (5 mL), heated, and stirred while concentrated aqueous ammonia (1.5 mL) solution was added dropwise until all the solid had dissolved and the yellow color of the solution was fully discharged. The reaction mixture was allowed to cool to room temperature, filtered, and evaporated almost to dryness *in vacuo* (45 °C). Following the addition of acetone (200 mL) the solution was allowed to stand at room temperature (2 h) whereupon a white precipitate formed. The solid was filtered, washed with acetone and anhydrous diethyl ether, and dried in vacuo overnight. The crude product was then dissolved in a minimum amount of water (2 mL) and filtered, and dropwise addition of acetone resulted in a white microcrystalline solid. This was filtered and dried in vacuo: yield 0.094 g (55%), mp 168−169 °C. ^{1}H NMR (D_2O): δ 7.73 (H-2, br t, $^3J_{Pt-H}$ = 18 Hz), 6.89 (H-4, t, $^3J_{Pt-H}$ = 22 Hz), 7.01 (H-5, t), 3.58 (N−CH_3, s). ^{13}C{^{1}H} NMR (D_2O): δ 128.08 (C-5), 122.71 (C-4), 34.46 (N−CH_3); C-2 (very weak signal). Anal. Calcd for $C_8H_{22}N_6Cl_2O_2Pt$: C (19.20), H (4.40), N (16.80). Found: C, (19.29), H (4.34), N (16.38).

(b) *trans*-Diamminebis(1-methylimidazole)platinum(II) Chloride Dihydrate (*trans*-$[Pt(NH_3)_2(MeIm)_2]Cl_2\cdot 2H_2O$,[15] 4). This complex has been previously reported by Johnson and co-workers.[15] To a solution of *trans*-$[Pt(NH_3)_2Cl_2]$[28] (0.10 g, 0.33 mmol) in water (2 mL) was added 1-methylimidazole (55 μL, 0.66 mmol). The reaction mixture was stirred at 60 °C for ca. 30 min, producing a yellow solution. To this was added a small amount of activated carbon (decolorizing charcoal) and the mixture was heated for another 20 min. The solution was then filtered and acetone (60 mL) was added to the filtrate; cooling in ice for 1 h produced a white flaky solid, which was filtered, washed with acetone and anhydrous diethyl ether, and dried in vacuo: yield 0.085 g (51%), mp 213−215 °C. ^{1}H NMR (D_2O): δ 8.00 (H-2, bs), 7.19 (H-5, t), 7.13 (H-4, t), 3.76 (CH_3, s).

(c) 1,2-Diaminoethanebis(1-methylimidazole)platinum(II) Chloride Dihydrate ($[Pt(en)(MeIm)_2]Cl_2\cdot 2H_2O$, 5). This was obtained by the procedure described by Johnson and co-workers[15] for the *trans*-diamminebis(1-methylimidazole)platinum(II) complex (*vida supra*). The reaction of $[Pt(en)Cl_2]$[28] (0.10g, 0.30 mmol) and 1-methylimidazole (50 μL, 0.60 mmol) in water (5 mL) yielded 0.064 g (44%) of a white flaky solid product. The complex was purified by re-dissolving in water, filtering, and re-precipitating with acetone to give a final yield of 0.050 g (38%), mp 314−316 °C (darkens at ca. 250 °C). ^{1}H NMR (D_2O): δ 7.81 (H-2, bs, $^3J_{Pt-H}$ = 16.7 Hz), 7.19 (H-t, bt), δ 7.00 (H-4, bt, $^3J_{Pt-H}$ = 20.2 Hz), 3.74 (N−CH_3, s), 2.78 (CH_2, s, $^2J_{Pt-H}$ = 42.2 Hz). ^{13}C{^{1}H} NMR (D_2O): δ 130.6 (C-2), 128.0 (C-5), 122.42 (C-4), 47.25 (CH_2), 34.17 (N−CH_3). Anal. Calcd for $C_{10}H_{24}N_6O_2Cl_2Pt$: C (22.81), H (4.56), N (15.97). Found: C (22.54), H (4.22), N (15.87).

(d) Tetrakis(1-methylimidazole)platinum(II) Perchlorate ($[Pt(MeIm)_4](ClO_4)_2$, 6). To a stirred methanolic (5 mL) solution of *cis*-$[Pt(dmso)_2Cl_2]$[30] (0.1017g, 0.24 mmol) was added dropwise a methanolic (10 mL) solution of 1-methylimidazole (40 μL, 0.70 mmol). The homogenous solution was set aside for 1 week following which it was filtered and the filtrate concentrated in vacuo to ca. 2 mL. To this was added excess $LiClO_4$ (2.0 g) whereupon a white crystalline solid was obtained. It was filtered, washed with methanol and acetone, and dried in vacuo: yield 0.039 g (30%). ^{1}H NMR (D_2O): δ 7.74 (H-2, br s, $^3J_{Pt-H}$ = 19Hz), 6.84 (H-4, br d, $^3J_{Pt-H} \sim 21$Hz), 7.15 (H-5, br d), 3.72 (N−CH_3, s). Anal. Calcd for $C_{16}H_{24}N_8O_8Cl_2Pt$: C (26.59), H (3.32), N (15.51). Found: C (26.37), H (3.30), N (15.26).

3. Kinetic Data Measurements. The kinetic data for isotopic C−H exchange processes in these complexes were recorded on a Bruker ACF-200 NMR spectrometer operating at 200.1 MHz using the kinetic program REACT1H·AU[31] which automatically acquires and stores the spectra of the exchanging complex at preset time intervals.

Kinetic Data Collection and Analysis. Before beginning any kinetic measurement, the variable-temperature (VT) unit of the spectrometer was set to the temperature of the study while an NMR tube containing a blank D_2O solution was placed inside the probe to lock and shim the instrument at this temperature. Next, kinetic parameters for the experiment to be performed, e.g. the time intervals between acquisition of the kinetic data, the number of scans for each spectrum (FID), etc., were then input into the kinetic program;[31] this ensured minimal time loss in the setup and acquisition of the first kinetic result in the exchange reaction. At this time the probe temperature was set for a minimum of 30 min to equilibrate at the temperature of study (60 ± 0.1 °C) before the NMR tube containing the kinetic sample was introduced. Preparation of kinetic solutions for this study was as follows:

A weighed amount of the complex (10−20 mg) was dissolved in 0.5−1 mL of D_2O solution in a 1.5 mL microcentrifuge tube and the pH (in D_2O) of the solution was measured immediately with a Beckman Φ71 pH meter fitted with a combination glass (Ag/AgCl) electrode. The solution pH was then adjusted to the desired value with micro-amounts of a standardized 0.1 M NaOD solution, followed by transfer of a 0.5-mL aliquot of this solution into a 5-mm NMR tube via a syringe.

As soon as the NMR tube containing the kinetic sample was introduced into the NMR probe, a quick shimming was done again before spectral acquisition starts. Typically, about 1−2 min are required between introduction of the kinetic sample into the NMR probe and

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acquisition of the first spectrum because most of the parameters had been preset earlier (*vide supra*). At the completion of each kinetic run, stored FID's were processed (Fourier Transformed (FT), etc.) and plotted over the 0−10 ppm (δ) range where the residual HOD peak at δ 4.69 served as an internal reference. Plots of the logarithm of the electronically determined area under the exchanging peak(s) with respect to a standard non-exchanging peak in these compounds, i.e. log[C−H(exchanging)/C−H(non-exchanging)], *versus* time, were linear over a minimum of 1 half-life for C(2)−H, C(4)−H, and C(5)−H exchange processes in these complexes.

Exchange reactions at pD $\sim$ 13 were conducted in 0.1 M NaOD solution. The measured pD values at the end of the kinetic runs were usually not more than 0.1 pD unit lower than the initial value. Pseudo-first-order rate constants for exchange (uncorrected) were calculated from the negative slopes of the computer-generated[32] first-order plots. The values so obtained were corrected by inclusion of a factor corresponding to the number of equivalent exchangeable sites. The resulting corrected values have been listed as k_{obs} in Table 4. The second-order rate constants (k_m, M^{-1} s^{-1}) for C(2)−H, C(4)−H, and C(5)−H exchange were calculated from the ratio of the k_{obs} and [OD^-] values at the final measured pD and the corresponding [OD^-] values, $k_m = k_{obs}/[OD^-]$. The [OD^-] values were calculated from extrapolated literature[33] pK_w(D_2O) at 60 °C (pK_w = 13.8). The reported pD values were obtained by adding 0.4 to the measured pH values.[34]

4. Crystal Structure Determination of $[Pt(MeIm)_4](ClO_4)_2$ (6).[35,36] Crystals suitable for X-ray study were harvested from the reaction solution (*vide supra*). A crystal of dimension 0.28 × 0.15 × 0.07 mm was used in data collection. Table 2 presents the crystal data, some experimental measurements, and the summary of the refinement procedure. Three standard reflections monitored throughout the data collection showed no significant changes in intensity. The data were corrected for absorption using the program DIFABS,[37] with the transmission factors ranging from 0.837 to 1.274. The structure was solved by heavy-atom techniques (Patterson and Fourier maps) using the program SHELXS86.[38] Full-matrix least-squares refinement on F^2 data with the anisotropic displacement parameters for all non-H atoms except the O atoms of the perchlorate ion was performed using the program SHELXL92[39] (the atomic scattering factors used were those from the International Tables of Crystallography).[40] The ClO_4^- ion was found disordered and showed two different orientations of the O atoms around the central Cl atom; the restrained refinement was used to maintain a similar geometry of these two orientations, and O atoms were refined with isotropic thermal displacement parameters. All H atoms except the methyl hydrogen were included in the refinement in calculated positions and allowed to ride on the carbon atoms to which they are attached; their isotropic thermal displacement parameters were kept equal to 120% of the equivalent thermal displacement parameters of these carbon atoms. Positions of the methyl hydrogens were not determined. The refinement converged at the final R (conventional, based on F) of 0.0416. The final difference Fourier map showed a peak at 2.93 e/Å^3 close to the Pt atom.

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Supporting Information Available: Listings of fractional coordinates and thermal displacement parameters for all atoms, anisotropic displacement parameters for non-H atoms, bond lengths and bond angles for the perchlorate ions, and for H atoms, as well as short intermolecular contacts for **6** (4 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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(35) **Note Added in Proof**: Very recently we have obtained another polymorphic form of compound **6**, which crystallized in the monoclinic space group $P2_1/n$, with 2 molecules in the unit cell. In the monoclinic form, two *trans*-MeIm ligands are *exactly* perpendicular to the Pt coordination plane, while the other pair is almost coplanar to this plane. This is the first reported instance of near coplanarity of two *trans*-MeIm ligands complexed to the Pt(II) ion.[36]

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